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EXAMINATION OF THE ANOMALOUS BEHAVIOR OF THREE GRAVITY GRADIENT SATELLITES

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

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By

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SUMMARY

The anomalous oscillatory behavior of three satellites orbited by the Naval Research Laboratory has been examined. The satellites, a part of the 160 series of experiments, were all hinged two-body gravity gradient configurations passively stabilized about their three principal axes by gravity gradient and damper torques. Two basic behavior patterns were observed. Either the satellites were stable with attitude perturbations less than $\pm 5^\circ$ or their behavior tended towards a low frequency rigid body oscillation dominated by large yaw motions and in some cases by yaw inversions. A causal relationship between sun angle and the character of satellite behavior was observed that appears to indicate that thermal distortion is a critical factor in a gravity gradient satellite's dynamic behavior. The behavior appeared to be further modified by the existence of response frequencies that were higher than anticipated values.

INTRODUCTION

Three-axis, passive, gravity gradient stabilization of spacecraft through the use of extendable booms has been demonstrated as a practical means for providing an earth-pointing equilibrium orientation (ref. 1). The success of these gravity gradient systems, however, has, for certain satellite configurations, been inexplicably associated with a low frequency anomalous oscillatory behavior. This unpredictable behavior has usually appeared as a sustained large-amplitude, rigid-body oscillation modified, in some cases, by one or more attitude inversions. A typical example of this type of behavior is illustrated in figure 1. Such a performance was clearly seen in the flight data collected during an initial series of gravity gradient experiments conducted by the Naval Research Laboratory (NRL) (ref. 2) and more recently in the data collected from the latest series of gravity gradient satellites orbited by NRL.

This new NRL flight test data is used in the present report as a basis for a further examination of a passive gravity gradient satellite's low frequency behavior. The investigation has been directed towards the collection, display, identification, interpretation and evaluation of data from three of these satellites, and is oriented to the objective of attempting to ascertain the essential ingredients of the behavior mechanism.

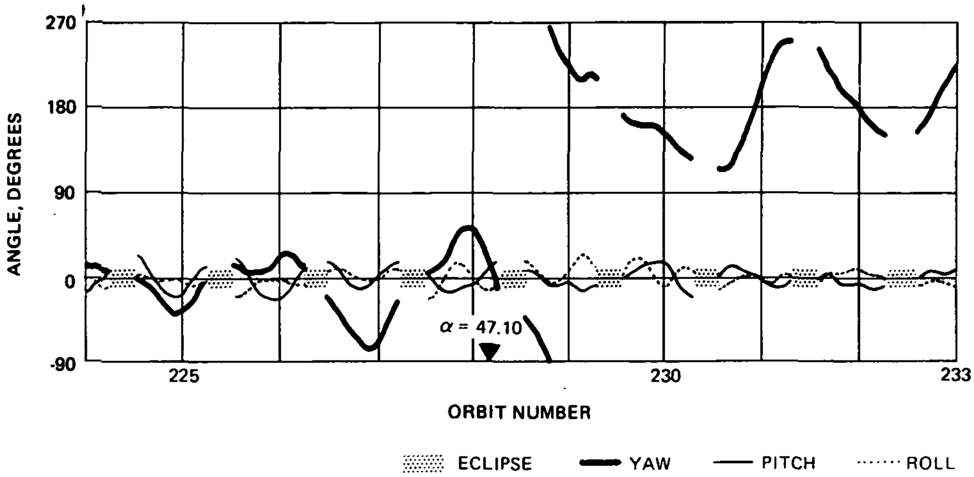

Figure 1. Typical Yaw Inversion, Satellite 163

The anomalous low-frequency behavior of a passive gravity gradient satellite can be viewed in its most general sense as an unstable interaction phenomenon involving coupling between internal dynamic properties of the satellite and external environmental energy sources. Depending upon the satellite's orbital distance and eccentricity, environmental energy sources (such as those due to aerodynamics, solar radiation and magnetic fields) may introduce destabilizing torques that are large when compared to the satellite's stabilizing gravity gradient torques (ref. 3). An adequate understanding of the dynamics of the anomalous behavior is required before any logical attempt can be made to eliminate the problem. The task that arises in the present study, therefore, is one that tries to find out which of the many internal and external system characteristics clearly dominates the unstable interaction phenomenon. Since the flexibility of a gravity gradient satellite's booms and the influence of solar pressure and thermal bending are generally suspected as being principal offenders in boom instabilities (refs. 4 to 9), they have been given principal consideration.

SPACECRAFT CHARACTERISTICS

The gravity gradient satellites in the NRL 160 series were launched together in the latter part of 1969 and successfully placed in a nearly circular 500 nautical mile orbit at an inclination of approximately 70° to the earth's equator. Their orbital parameters are summarized in Table 1. The satellites essentially moved along the same orbital path with a spacing of roughly 100 nautical miles between them. The orbital period and precession rate were such that the satellites came close (within 5°) to passing over the same point on the Earth's surface every 14 orbits.

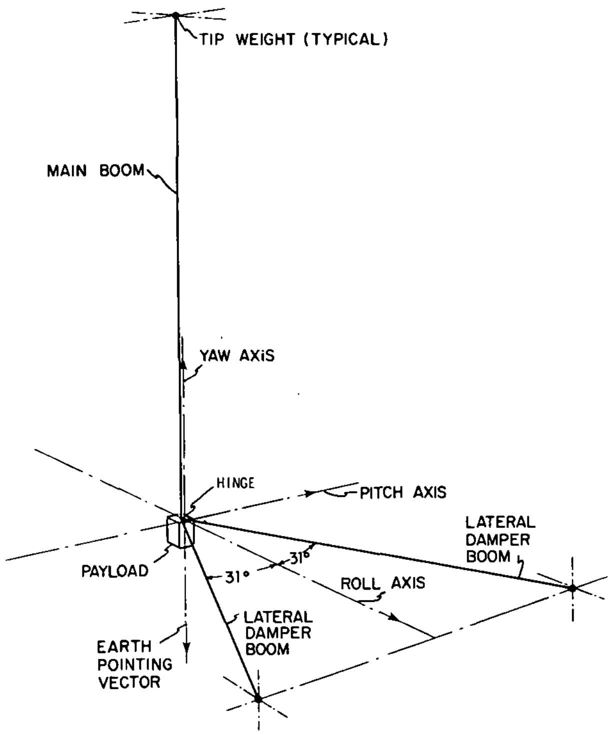

Figure 2. Satellite Geometry, Payloads 161 and 163

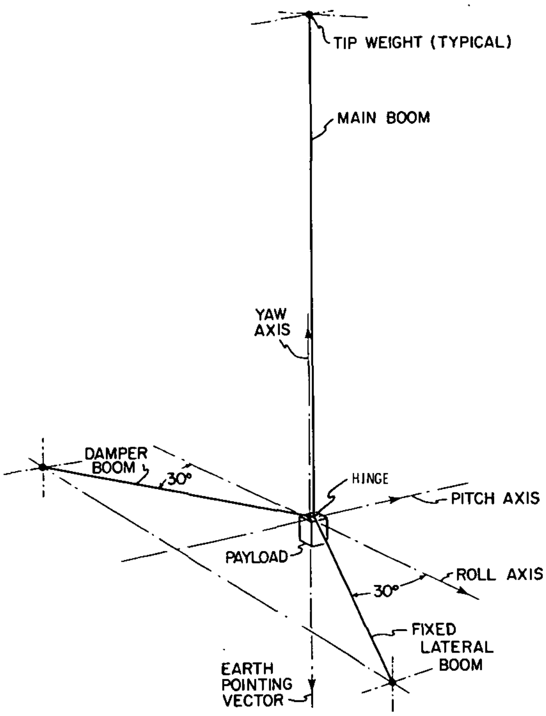

Figure 3. Satellite Geometry, Payload 164

Because of their susceptibility to rigid-body anomalous oscillations and their geometric similarity, three of these satellites, payloads 161, 163 and 164, shown in figures 2 and 3, have been singled out for examination. These particular satellites were hinged two-body configurations (ref. 10), passively stabilized about their three principal axes by gravity gradient and damper torques. The satellites were asymmetric with respect to both their geometrical shape and mass properties, but each had a plane of geometrical symmetry with respect to their principal axes. They each used three long extendable booms with a passive hinge damper attached to one or more of the booms. Tip weights were located at the deployed ends of the booms. The long booms and tip weights were needed in order to obtain a large enough moment of inertia for gravity torques to be effective, while the damper mechanism was designed to dissipate energy in order to inhibit tumbling and limit librational motions. Although active devices, such as momentum wheels and thrusters, were available on these payloads, their use was not required for stability. The important physical characteristics of the three satellite configurations are summarized in Table 2. The inertial properties listed in Table 2 are consistent with the definitions used in the formulation of the general equations of motion for a hinged two-body satellite given in reference 10.

Satellites 161 and 163

Gravity gradient satellites 161 and 163, illustrated in figure 2, have basically the same geometry. They differ mainly in their boom construction, a dissimilarity that makes examination of their motion attractive,

Table 1—Orbital Parameters

Parameter	Valve
Eccentricity	0.00203
Inclination	70.014°
Period	103.46 min/orbit
Perigee altitude	490.5 naut miles
Apogee altitude	506.5 naut miles
Orbital precession (eastward)	2.121 deg/day

Table 2—Satellite Physical Properties

Property	Units	Satellite		
		161	163	164
Payload weight	lb	235	247	283
Main boom tip weight	lb	5.28	5.28	5.12
Lateral tip weight (each)	lb	3.76	3.76	3.78
Main boom weight	gm/ft	6.866	4.584	6.866
Lateral boom weight (each)	gm/ft	2.709	4.584	2.709
Main boom length	ft	60	60	60
Lateral boom length	ft	37	37	35
Reduced inertias about hinge:				
Main body pitch	slug-ft^2	641	631	623
Main body roll	slug-ft^2	641	631	623
Main body yaw	slug-ft^2	3	3	4
Secondary body pitch	slug-ft^2	240	243	220
Secondary body roll	slug-ft^2	87	85	73
Secondary body yaw	slug-ft^2	327	328	293
Total inertia about hinge:				
Pitch	slug-ft^2	881	874	843
Roll	slug-ft^2	728	716	696
Yaw	slug-ft^2	330	331	297
Two-axis hinge:				
Pitch spring	ft-lb/rad	0.182×10^{-2}	0.194×10^{-2}	
Roll spring	ft-lb/rad	0.382×10^{-3}	0.403×10^{-3}	
Pitch damper	ft-lb-sec/rad	0.162	0.155	
Roll damper	ft-lb-sec/rad	0.029	0.0268	
Single-axis hinge:				
Spring	ft-lb/rad			0.714×10^{-3}
Damper	ft-lb-sec/rad			0.395
Damper stops		±27.5°	±27.5°	±29.5°

since observed variations in their librational behavior may possibly be due to differences in their boom properties. The three-axis, two-body gravity gradient stabilization system used on 161 and 163 (ref. 11) consisted of three extendable booms arranged in a symmetric pattern about the plane of the roll-yaw axes. The primary body was composed of the payload and the main boom; the secondary body consisted of the two lateral damper booms fixed in a V shape relative to each other. The lateral booms were nominally located in the horizontal pitch-roll plane. The secondary body was connected to the primary body through a two-axis (pitch and roll axes) hinge mechanism employing an eddy current damper and a torsion wire spring suspension system. Because of the inherent gyroscopic roll-yaw coupling in the libration of a gravity gradient satellite, restriction of the rotational hinge motion of the secondary body to two axes is theoretically sufficient to achieve three-axis damping of the entire satellite.

Self-extending SPAR BI-STEM booms manufactured by SPAR Aerospace Products, Ltd., of Canada were used on 161 (main boom 1/2" dia., lateral booms 1/4" diam.). Self-extending booms manufactured by the Westinghouse Electric Corp. of Baltimore, Md. were used on 163 (main and lateral booms 1/2" diam.). Both types of booms were interlocked, a feature which tended to give these booms a higher torsional stiffness than the open cross section booms used on earlier satellites. Perforations were provided on the Westinghouse booms in an attempt to better distribute the solar radiation energy picked up by the boom and thus reduce the magnitude of thermally induced boom distortions. The SPAR booms were not perforated.

Satellite 164

The basic geometry of satellite 164 is illustrated in figure 3. The three-axis, two-body gravity gradient stabilization system used on 164 (refs. 12 and 13) consisted of three extendable booms arranged in a symmetric pattern about the plane of the pitch-yaw axes. The booms were the interlocked, nonperforated SPAR BI-STEM type used on payload 161. The primary body was made up of the payload, main boom and front lateral boom (fixed to the payload); the secondary body consisted solely of the lateral damper boom. The lateral booms were nominally located in the horizontal pitch-roll plane. The secondary body (damper boom) was connected to the primary body through a single-axis hinge mechanism that constrained boom motion to a vertical plane. The hinge provided hysteresis damping torques and torsion wire spring restoring torques.

The design of this single axis damper configuration was based on the inertial coupling concept suggested by Tinling and Merrick (ref. 14). By skewing the horizontal principal axis of the secondary body (damper boom) out of the orbital plane, all motions become strongly coupled. Under these conditions, three-axis damping of the entire satellite is achieved by the single degree of freedom motion of the damper boom about its hinge.

FLIGHT DATA

The three satellites were equipped with attitude instrumentation for determining the Euler angle relationships in pitch, roll and yaw between the satellite's local vertical coordinate system and its body fixed axes. The angles in this case are defined in the usual sense so that in its preferred equilibrium orientation the satellite's body fixed axes are assumed to coincide exactly with its local vertical coordinate system (pitch axis with the orbital angular momentum vector, roll axis with the orbital velocity vector and yaw axis with the local vertical vector).

Attitude Reference System

The method of solving for these attitude angles, described in reference 2, depended upon an accurate determination in both local vertical and body fixed coordinates of the direction vectors to the sun and the Earth's magnetic field. A digital computer program, based on tracking data, was used to calculate these vectors in a local vertical coordinate system*; satellite sensor data was used to determine these same vectors in a body-fixed coordinate system. A digital computer orthogonal matrix transformation was then used to determine the desired Euler angle relationship between the two coordinate systems as defined by the two sets of identical vectors.

The sun data was obtained from a set of three Adcole solar sensors (Adcole Digital Solar Aspect System) manufactured by the Adcole Corp. of Waltham, Mass. These sensors had a pyramidal field of view of about 128° and were judiciously arranged on the top of the payload so that there was nearly complete coverage of the celestial sphere. However, certain fields of view (e.g., directly over the payload) were not covered, while others were covered by two sensors. The sensors measured the angles of the incident sunlight with respect to the body-fixed coordinate system of the spacecraft. These angles, in the form of digital outputs, were sampled and stored in the satellite's memory system.

The magnetic field data was obtained from a triaxial flux-gate magnetometer (Triaxial Magnetic Aspect Sensor) manufactured by the Schonstedt Instrument Co. of Reston, Va. The unit consisted of three sensors orthogonally aligned with the spacecraft's body-fixed axes. Each sensor produced an analog output voltage which was dependent upon the magnitude of the ambient magnetic field and the angle between the field vector and the sensor's axis. Sampled values of the three output signals, stored in the satellite's memory system, were later used to digitally compute the direction of the Earth's magnetic field vector in a body-fixed coordinate system. The digital program used in this computation included provisions for correcting the flight measurements for that portion of the ambient

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* These calculations were based on an empirical formulation of the components of the Earth's magnetic field obtained by Jensen and Cain (see ref. 15) and the known Earth-Sun ecliptic relationship.

magnetic field emanating from the spacecraft. This correction was based on laboratory pre-flight measurements of the spacecraft's magnetic properties.

The accuracy of the attitude reference system depended not only upon the sensor resolution and alignment but also upon the accuracy of the tracking data, the computer formulation of the Earth's magnetic field and the magnetic field compensation. An independent check on the accuracy was obtained by comparing the scalar angle between the sun vector and the magnetic field vector in both the local vertical and body-fixed coordinate system. If the error difference between these two separate computations was less than 5° the results were considered to be acceptable.

Data Collection

The flight attitude data provided by NRL covered the first six months of satellite operation. It consisted of printed time histories of each satellite's pitch, roll and yaw attitudes as determined by the day-to-day interrogation of their memory storage systems. The memory systems stored about one day's worth of satellite sensor data sampled at a range of about one sample every 154 seconds*. These attitude plots were carefully compiled, edited and assembled in chronological order. After an initial review it became apparent that certain of these plots tended to capture the essential characteristics of each satellite's behavior. These individual plots were therefore singled out for further examination and have been reproduced in their entirety in Appendix A. They have been individually enhanced by tracing through the computed data points so as to bring out the distinctive features of each satellite's motions. For reference purposes the time for each south-north equatorial crossing, starting with Orbit 1 at launch, is also indicated.

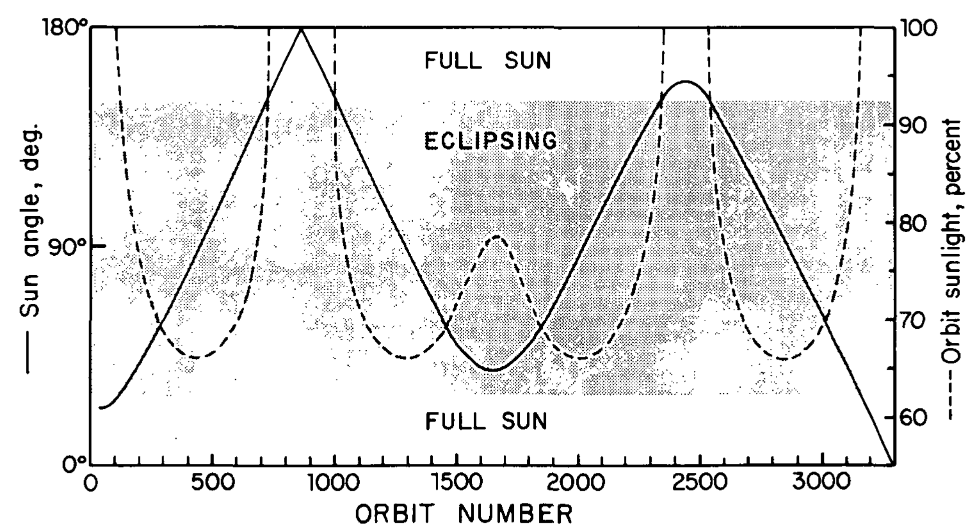

Figure 4. Solar Aspects Data for NRL 160 Series Satellites

* Real time interrogation was also available for the short period of time the satellites were in view of a ground station; during this time, data could be directly sampled at rates as high as one sample per second.

Solar aspect data for these satellites is shown in figure 4. The percent sun in figure 4 is indicative of the period in each orbit in which the satellite is not shaded by the Earth's shadow (eclipsed). The sun angle, α, in figure 4 is the angle between the sun vector and the normal to the satellite's orbital plane. When $\alpha=0°$, for example, the sun vector is perpendicular to one side of the orbit plane, when $\alpha=180°$ it is perpendicular to the other side, and when $\alpha=90°$ it is in the orbit plane. Because of symmetry, sun angles do not exceed 180°. Since sun angle, α, appeared to be such a significant parameter, it has been identified in the attitude plots in this report by marking the point in time at which a designated sun angle was reached.

SUMMARY OF OBSERVATIONS

An overall examination of the collected flight data for payloads 161, 163 and 164 leads to the general observation that there are two basic behavior patterns. The satellites are either stable with attitude perturbations less than $\pm5°$ or their behavior tends toward a low-frequency rigid-body oscillation dominated by large yaw motions. It is these two behavior patterns that are examined in the following discussion. The events leading into and through these patterns are described by referring to figures 5 to 7. The figures provide information on sun angle versus orbit number as well as the location of key events. They begin with the first orbit on day 273 of 1969 and end on day 144 of 1970. The broad lines (solid and dotted) superimposed on the sun angle line indicate the characteristic behavior patterns for those periods when actual flight data for each satellite was available. The figures are supplemented in the discussion by referring to copies of appropriate sections of the flight data in Appendix A and to the ground commands summarized in Table 3.

Satellite 161

This satellite displayed a simple form of anomalous behavior. It was either very stable or it oscillated in yaw. There were no yaw inversions. Pitch and roll motions were generally small and they did not appear to play a significant role in the behavior mechanism.

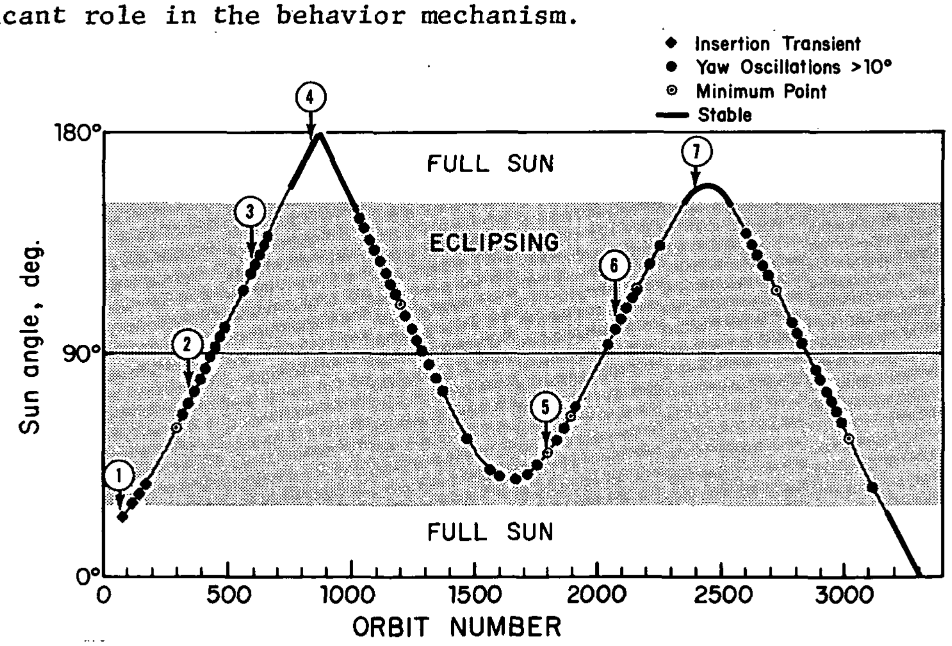

Figure 5. Sequence of Events, Payload 161

Table 3–Summary of Ground Commands

Payload	Orbit	Command
161,163	6	Primary modulation
163	7	Boom motor 1 on and off
164	7	Primary modulation
163	8	Lateral booms released
161	20	Lateral booms released
164	21	Lateral booms released
163	34	Thrusters 1 & 2 on and off, heaters 1 & 2 on
163	40	Heaters 1 & 2 off
163	48	Command main boom in and out
161,163 164	90	Command memory slow read
161	145	Thrusters and heaters on and off
163	159	Thrusters and heaters on and off
164	159	Pitch momentum wheel on and off
161	325	Voltage control on
161	335	Thruster 1 on
161	394	Thruster 1 off
163	491	Pitch momentum wheel on
161	494	Thruster 2 on
163	494	Thruster 2 on
163	504	Thruster 2 off
161	506	Thruster 2 off
163	506	Pitch off
161	1096	Truster 2 on, pitch on
161	1099	Pitch off
164	1179	Pitch on
164	1180	Thruster 2 on
164	1185	Thruster 2 off, pitch off
163	1413	Thruster 2 on, pitch on
163	1415	Thruster 2 off
163	1418	Thruster 2 on
163	1420	Thruster 2 off, pitch off
161	1689	Pitch on
164	1689	PCM bad
161	1690	Pitch off
161	1703	Pitch on
161	1704	Thruster 1 on
161	1709	Thruster 1 off, pitch off
164	1689-2054	PCM inoperative
164	2054	Last orbit with successful command
163	2867	Pitch on
163	2868	Thruster 2 on
163	2877	Thruster 2 off, pitch off, thruster 1 on, yaw on due to failure of thruster 2
163	2884	Yaw off
163	2889	Yaw on
163	2896	Thruster 1 off
163	2898	Yaw off
163	2903	Yaw on
163	2908	Yaw off
161	3151	Heater 2 on to reduce charge current
161	3165	Heater 1 on for load
163	3165	Heater 1 on for load
163	3254	Heater 1 off
163	3262	Thruster 1 on, pitch on
163	3267	Thruster 1 off
163	3268	Thruster 1 on and off
163	3270	Pitch off
163	3276	Thruster 1 on and off
163	3277	Thruster 1 on
163	3282	Thruster 1 off
163	3290	Heater 1 on for load

At point 1, see figure 5 and Appendix A, shortly after insertion into orbit and in full sunlight, the satellite is oscillating as a rigid body in response to the insertion transient. The spacecraft has settled down into an inverted yaw position. Pitch motion is almost completely damped out, roll is decaying rapidly, and yaw is dieing out slowly.

Yaw motions continue to fall as the satellite enters into its first period of eclipsing orbits, reaching a minimum amplitude of less than $\pm 10°$ at around point 2. After this point, however, the oscillations in yaw unexpectedly start to grow so that by the time point 3 is reached, the yaw oscillations are actually greater than they were at insertion. The yaw response frequency during this time was about .73 cycle-per-orbit, varying from .75 cycle-per-orbit at insertion to .69 cycle-per-orbit at point 3.

After the satellite enters its first period of full sunlight (orbit 720) the amplitude of this large yaw oscillation starts to decrease and is gradually replaced by a low amplitude, decaying one-cycle-per-orbit oscillation in yaw, pitch and roll. At point 4 the oscillation has just about disappeared and the satellite is extremely stable. After passing through the 180° sun angle position (a position in which the vector from the sun lined up with the satellite's pitch axis), the low amplitude one-cycle-per-orbit oscillation in yaw, pitch and roll very slowly reappears. This full sunlight region of stability ends as the satellite enters into its second period of eclipsing orbits, and the one cycle per orbit motion is gradually replaced by the .73 cycle-per-orbit, large amplitude yaw oscillation that was seen earlier.

The oscillation pattern that followed persisted for the next 1300 orbits (i.e., until the satellite was again in full sunlight). The behavior throughout this long period was repetitive. The yaw oscillation first gradually rose in amplitude, then, after reaching a maximum value, it slowly fell in amplitude; finally, after reaching a minimum value, it started rising all over again. The location of regions of minimum values are indicated on figure 5. A good view of this rise and fall pattern can be seen by examining the flight data in Appendix A near the minimum value at point 5 and the maximum value at point 6.

Coming out of this long period of eclipsing orbits, the satellite, at orbit 2240, enters its second period of full sunlight. As before, the yaw oscillations decrease and are gradually replaced by one-cycle-per-orbit perturbations in all three attitude traces, point 7. The sun angle on this pass, however, does not reach 180°, and the oscillations do not completely disappear as they did during the first full sun pass.

As the satellite leaves full sunlight and enters into a third period of eclipsing orbits, the oscillations again begin to grow. The low-amplitude one-cycle-per-orbit motions are replaced by the larger amplitude .73 cycle-per-orbit yaw oscillations, and the rise and fall pattern that was seen earlier is repeated. The whole behavior pattern, in fact, is repeated, starting all over again at orbit 3160 as the satellite enters into its third period of full sunlight.

Satellite 163

The behavior of this satellite was quite complex. It appeared to be susceptible to one per orbit pitch oscillations throughout its entire flight and large amplitude yaw oscillations and yaw inversions during periods of eclipsing orbits. The only prolonged periods of stability were during full sunlight.

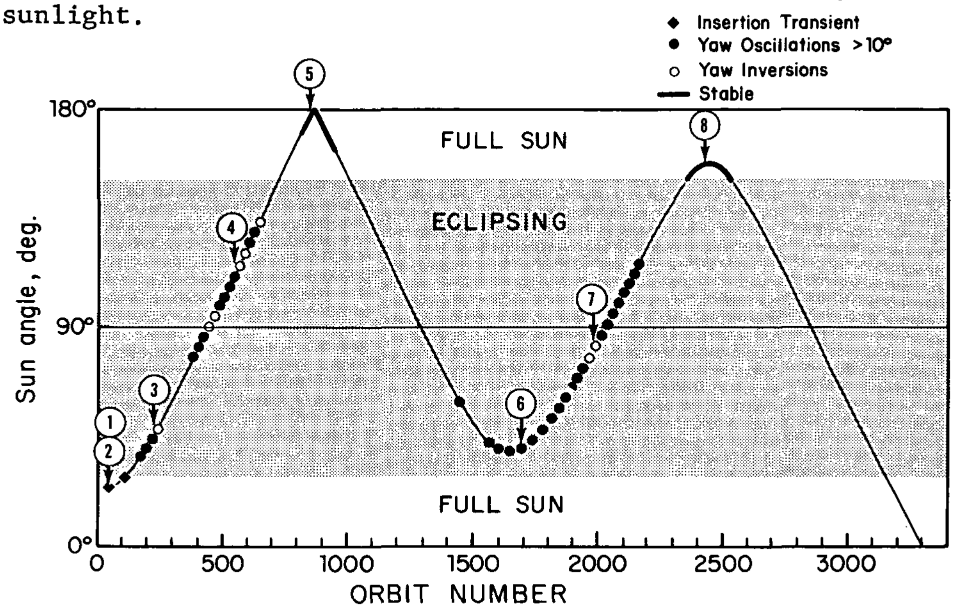

Figure 6. Sequence of Events, Payload 163

At point 1, see figure 6 and Appendix A, the satellite, captured in an inverted pitch position, is still responding to the insertion transient. Roll and yaw rigid body frequencies are damping out very slowly. Pitch, on the other hand, is responding at a one-cycle-per-orbit frequency and is exhibiting no tendency towards dieing out. At point 2 the 180° pitch error is successfully corrected by moving the main boom in and out. After this controlled inversion, the resulting transient in roll and yaw is still damped while pitch continues its sustained one-cycle-per-orbit response.

As the satellite makes it first entrance into eclipsing orbits, the yaw oscillations unexpectedly grow quite large. The satellite rapidly becomes unstable in yaw and by the time point 3 is reached, the behavior is so erratic that the satellite undergoes a yaw inversion. This undesirable yaw performance continues through point 4. In fact, during the entire first passage through eclipsing orbits the behavior is marked by numerous yaw inversions and several large amplitude oscillations in pitch and roll. The yaw frequency in this region seemed to generally be about 1/2 cycle-per-orbit.

The erratic behavior ends soon after the satellite enters its first period of full sunlight. By the time point 5 is reached the satellite is very stable with no pronounced attitude perturbations. This stability was probably maintained throughout the full sunlight period.

Although data for the time between orbit 940 and 1450 was lacking, it seems probable that the satellite again became unstable in yaw after entering its second period of eclipsing orbits. By the time points 6 and 7 are reached, the satellite's yaw behavior is again completely erratic, with several yaw inversions occurring near point 7. Large, one-cycle-per-orbit pitch oscillations are prevalent, while large yaw oscillations occur that appear to be a mixture of one-cycle-per-orbit motions and 1/2 cycle-per-orbit motions.

As the satellite continues into full sunlight the yaw instability once again disappears. At point 8 the satellite is again stable, its angular perturbations having been reduced to a relatively low level one-cycle-per-orbit oscillation in all three attitude traces. In all probability this stable characteristic continued until the next eclipsing period was entered.

Satellite 164

The behavior of this satellite was markedly different from that of 161 and 163. It was stable throughout its initial period of eclipsing orbits and unstable in yaw during its first excursion into full sunlight. This pattern did not persist, however, for during its second passage through eclipsing orbits its behavior rapidly deteriorated and the spacecraft ended up in a sustained, large amplitude yaw instability.

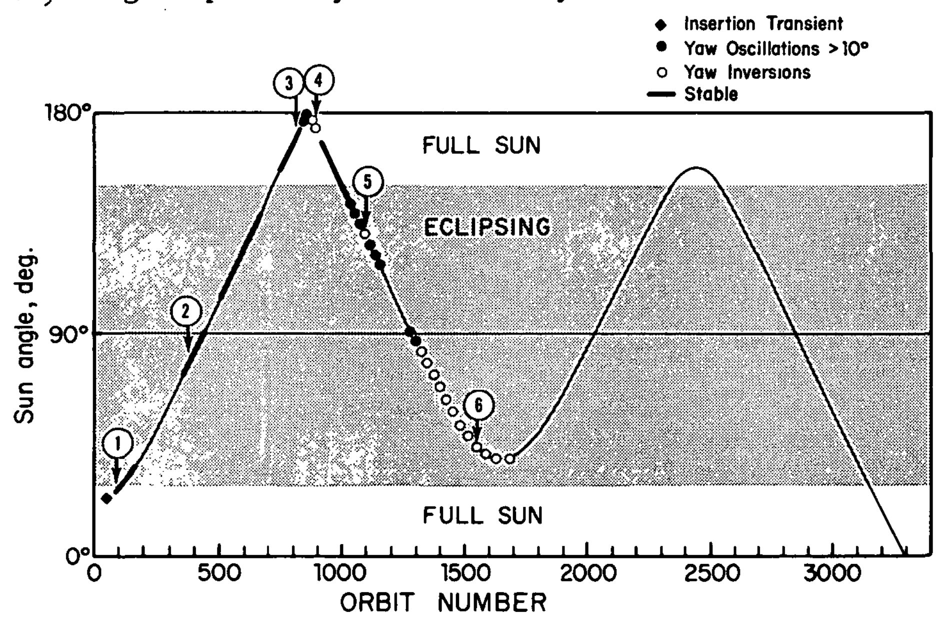

Figure 7. Sequence of Events, Payload 164

At point 1, see figure 7 and Appendix A, shortly after insertion and in full sunlight, the satellite has settled down into a well stabilized orbit. Its attitude in yaw is inverted* and the perturbations in pitch, roll and yaw are small. This satisfactory performance continues through points 2

* This inversion error was corrected in orbit 159 by energizing and de-energizing a pitch momentum wheel.

and 3. In fact, during the entire first passage through eclipsing orbits and first entrance into full sunlight all attitude errors are small. During the sequence of events from point 1 to point 3 there were only slight changes in attitude behavior; and in general the resulting small amplitude perturbations were confined to approximately one-cycle-per-orbit oscillations in pitch and 1/2 cycle-per-orbit oscillations in yaw.

As the satellite continues into the 180° sun angle position, the amplitude of the 1/2 cycle-per-orbit oscillation in yaw unexpectedly increases. The satellite rapidly becomes unstable and by the time point 4 is reached its behavior is completely erratic with numerous yaw inversions and several large amplitude oscillations in pitch and roll. Just as suddenly as the instability appeared, however, it ceases and by orbit 900 the erratic behavior has not only disappeared, but is followed for several days by a period of extremely stable operation.

Entering into the second period of eclipsing orbits the performance of the satellite begins to slowly degrade as the amplitude of the 1/2 cycle-per-orbit yaw oscillation gradually increases. Shortly before point 5 the satellite again breaks into an instability with several successive yaw inversions, ending up at point 5, in an inverted yaw position. What follows is a large amplitude, limit cycle oscillation in yaw at a frequency of about 1/2 cycle-per-orbit that persists through orbit 1130 and probably longer.

Data for the time between orbit 1130 and 1280 is lacking. Between orbits 1179 and 1185, however, the satellite was successfully inverted in yaw through the use of the pitch momentum wheel, so that when the satellite data is picked up again at orbit 1280 it is now in a limit cycle yaw oscillation about the 0° yaw position. Within the next few days the yaw amplitudes become excessive and the satellite's behavior is again completely erratic. Yaw inversions now occur nearly every day, and as typified by the traces near point 6, the instability persists to the very end*.

EVALUATION OF FLIGHT DATA

In seeking to provide an insight into those factors that most directly influenced the anomalous behavior of the three satellites, it became apparent that any attempt to single out one or two characteristics could not easily be substantiated solely on the available flight data. The complexity of actually defining (at least in a mathematical sense) the interaction phenomenon between a satellite's internal dynamic properties and its external environmental energy sources precludes the simple pin-pointing of these critical factors. For example, the effects of aerodynamic torques cannot be readily discerned without some additional measurements. Despite

* On orbit 1689 the PCM telemetry transmission from 164 was lost. Subsequent attempts to correct this malfunction or to send commands to the satellite were unsuccessful.

these restrictions, however, the observations summarized in the previous section indicate several relationships that warrant discussion.

Magnetic Torque

Although attitude responses due to variations in the Earth's magnetic field can be seen in the flight data, there is no evidence that the generating magnetic torques were large enough to contribute adversely to the anomalous behavior. For satellite 163 the effect, although small, seemed to be most pronounced in pitch as the satellite passed over the equator, see figure 8. Even the magnitudes of these small attitude perturbations are believed to be somewhat exaggerated due to computational inaccuracies resulting from slight errors in the magnetometer compensation factors and in the empirical description of the Earth's magnetic field.

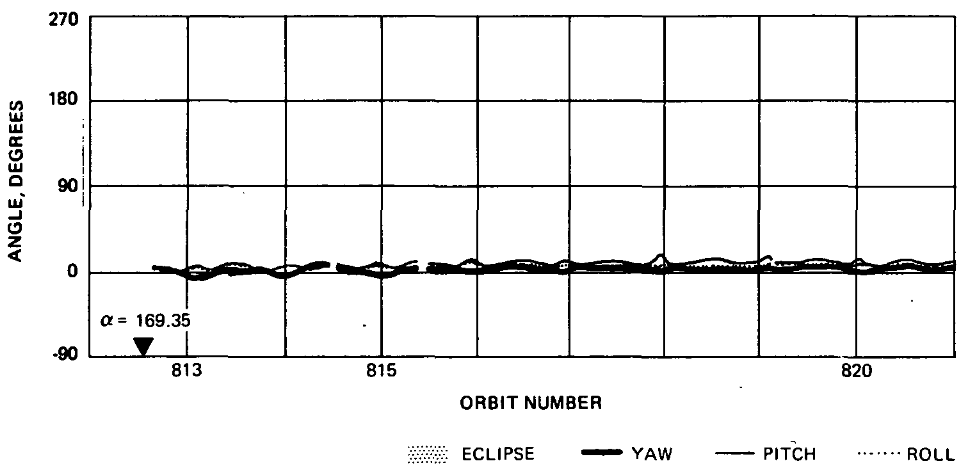

Figure 8. Magnetic Field Effect on Satellite 163

An interesting 14-orbit repetitive pattern can be seen in some of the flight data (e.g., orbits 606 to 620 on satellite 163). The pattern probably can be related to the Earth's magnetic field, since at the end of 14 orbits the satellite nearly retraces its path over the Earth's surface.

Solar Radiation

The relationship between sun angle and satellite behavior that can be seen in the flight data tends to indicate that the effect of either solar pressure or thermal bending due to solar radiation plays a significant role in a gravity gradient satellite's stability. Since a boom's thermal bending and twist is related to sun angle, it can be expected that a satellite's stability will be influenced by its thermal distortion properties.

The sudden instability of satellite 164 as it reaches the 180° sun angle position (see point 4 on figure 7) is a case in point. The instability appears to be related directly with the sun angle, disappearing as soon as the sun gets a few degrees away from 180°.

Similarly, in comparing data from 161 and 163, at least three regions of sun-related characteristic responses, illustrated in figure 9, can be discerned.

In Region 1 the satellites are in full sunlight with the sun nearly perpendicular to the orbit plane. Both satellites are quite stable with no pronounced attitude perturbations.

In Region 2 they are still in full sunlight but the sun is now inclined about 20° to the orbit plane. Although both satellites are still stable, a one-cycle-per-orbit perturbation appears in all three attitude traces.

In Region 3 the satellites have gone into an eclipsing orbit with the sun inclined about 50° to the orbit plane. Satellite 163 is now unstable in yaw with a period of about 2.0 orbits. Pitch perturbations on 163 continue at one-cycle-per-orbit. Satellite 161 has begun to undergo relatively large yaw oscillations with a period of about 1.5 orbits. Pitch and roll perturbations on 161 are now small.

Some perception into the mechanism of thermally induced instabilities of gravity gradient satellites can be deduced from Kanning's studies reported in reference 6. In this work the behavior of several gravity-oriented satellite configurations under the influence of solar radiation was examined. The effects of solar pressure torques as well as changing geometry and mass distributions due to thermal distortion on the performance of symmetrical and asymmetrical satellites were considered for a 1200 km orbit inclined 45° to the sun line. Kanning concluded that thermal distortion changes can be a critical consideration in the design of an asymmetrical satellite configuration. Although only one sun angle and only a few isolated configurations were examined, it appears that the simulated performance was significantly degraded (none of the cases examined were unstable) by the inclusion of thermal distortion.

An indication of the effect of sun angle on satellite stability can also be partially inferred from the recent study by Flanagan and Modi (ref. 16). They examined the behavior of a very simple representative satellite (no booms) under the influence of solar pressure (thermal distortion neglected) and found that in an elliptical orbit the sun angle significantly affected the satellite's response. Reviewing their work, it appears that the influence of sun angle would probably be much more pronounced for an asymmetrical satellite than for a symmetrical satellite.

Consideration of thermal bending and twist as a contributing factor to the anomalous behavior is complicated to a degree by the effect of "thermal twang" (ref. 4). The "thermal twang" excitation is associated with eclipsing orbits and is a repetitive disturbance that occurs every orbit. In full sunlight the booms are bent due to thermal distortion. Upon entering into the earth's shadow the booms return rapidly to an unbent position, introducing an impulse to which the satellite must respond. The reverse, of course, occurs as the booms enter into full sunlight. The shape of the resulting impulse can be broken down into a Fourier series so that sustained

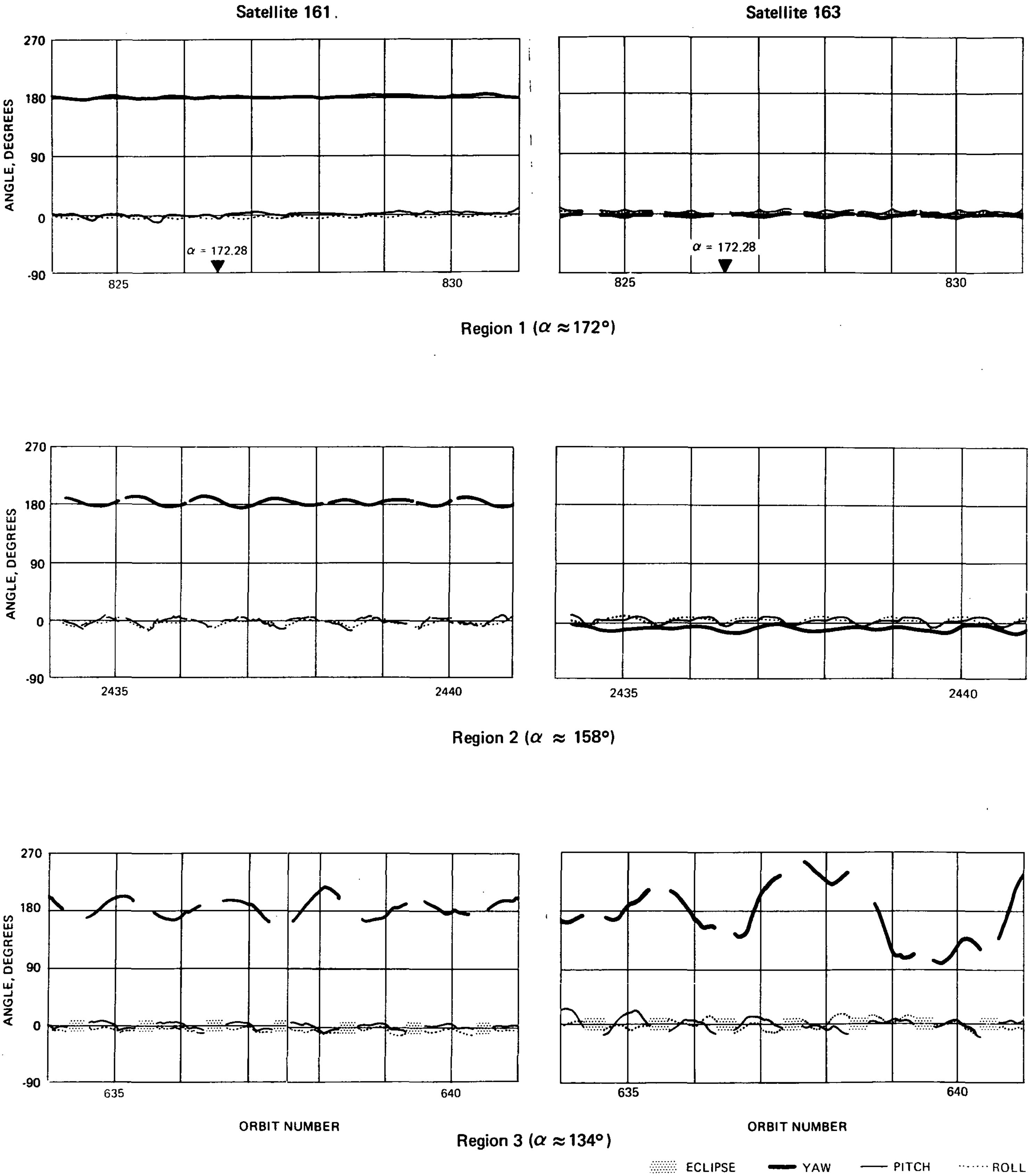

Figure 9. Effect of Sun Angle on Response, Satellites 161 and 163

satellite inputs can be anticipated at the orbital frequency and its harmonics. Since sustained responses during the anomalous performance of the three satellites were at frequencies that did not approach these "thermal twang" frequencies, it can be assumed that the behavior is not being driven solely by these impulses. The impulses on the other hand probably contribute to an instability mechanism and may be a feature in a feedback path that has not been accounted for.

Considerable evidence has previously been presented in references 7 to 9 that relates high frequency flexural oscillations of a sun-lighted boom with an instability that is sometimes referred to as thermal flutter. There were also some qualitative conjectures in references 2 and 3 that the low frequency anomalous behavior of a gravity gradient satellite is associated with thermal flutter. Although there is some evidence that the final degradation of satellite 164's behavior was coincident with a higher frequency boom oscillation, the preponderance of flight data tends to rule out thermal flutter as a controlling factor.

Dynamic Response Frequencies

The rigid body frequencies and stability of a hinged two-body satellite are controlled to a great extent by the size of the springs used in its damper unit. If the springs are too stiff, relative displacement between the two bodies is small and energy dissipation due to amplitude dependent damping is negligible. If the springs are not stiff enough, that is below some critical value, the satellite will oscillate about a cocked position. The ultimate selection usually involves an optimization procedure that ends up with springs that have stiffnesses that are slightly above the critical value.

The linearized equations for determining the small amplitude response of configurations such as 161 and 163, in which the hinge lies on the principal axes, leads to the characteristic equations given in Appendix B. Roll and yaw in such a case are decoupled from pitch. The characteristic equations for configuration 164, in which the hinge does not lie on a principal axis, are given in reference 12 and are somewhat more complex than the equations given in Appendix B. Roll and yaw in this case are not decoupled from pitch.

The theoretical response frequencies change as a function of spring stiffness and in the case of satellite 163 lead to the plots shown in figures 10 and 11. The plot for satellite 161 is similar. The pitch, roll and yaw frequencies for the selected pitch and roll springs are appropriately noted on these figures. In observing flight data one would expect that the frequencies during transient, and even during an anomalous performance, would bear some relationship to these characteristic frequencies. This, however, was not observed. Instead, as noted on figures 10 and 11, the flight frequencies for 161 and 163 (even at small amplitudes)* were close

* The pitch frequency observed in the flight data for 161 and 163 may be a response to a one-per-orbit excitation rather than a transient responses.

to the stiff spring frequencies, a condition which cannot occur without either assuming some change in the mechanical properties of the satellite (e.g., a locked damper spring) or by postulating an additional but unknown attitude-dependent torque.

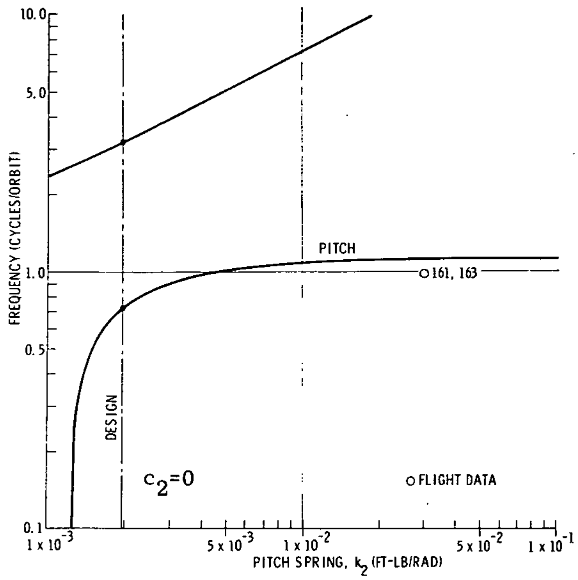

Figure 10. Pitch Frequency Variation with Spring Constant, Satellite 163

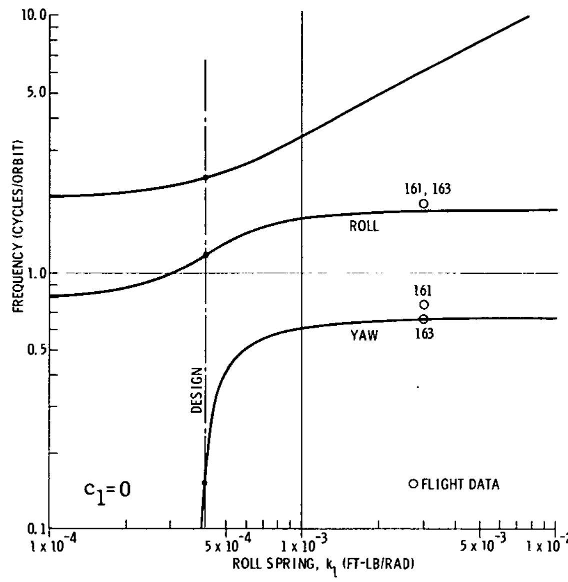

Figure 11. Roll-Yaw Frequency Variations with Spring Constant, Satellite 163

The observation that the roll frequency on 161 and 163 and the yaw frequency on 161 exceeded the theoretical rigid damper frequency is not easily explained without assuming some further change in the satellite's structural properties. Whether this change was due to an unanticipated variation in inertial properties or thermal bending is subject to speculation.

Because of the inertial coupling in a configuration such as 164, it is difficult to ascertain modal responses or to completely distinguish between pitch, roll and yaw disturbances. A configuration of this type, because of its inherent dependence on coupling for stability, is sensitive to both thermal distortion and variation in damper spring properties. Whatever the outcome of this coupling mechanism on 164, there is a change in its dynamic character, somewhere around orbit 1020, that leads to a rapid degradation in its behavior.

CONCLUDING REMARKS

The interaction phenomena observed in the flight data appear to establish a causal relationship between sun angle and the character of a satellite's response. Since thermal distortion and solar pressure are the two disturbance factors directly influenced by solar radiation, it can probably be assumed that they are influential in the anomalous behavior. Thermal distortion properties, bending and twist of each of the satellite's booms, may in fact be critical; even though a boom might be perforated to minimize thermal bending at normal sun angles, it still may deflect substantially at acute sun angles.

The observations related to discrepancies in the rigid body frequencies could be associated with a faulty hinge damper; however, the possibility of unanticipated boom deflections inhibiting the operation of the hinge cannot be ruled out. Further analytical clarification and classification of the mechanism of solar interaction is probably required. If a correct analytical model of this interaction can be obtained, then the chances of designing to avoid an instability are much enhanced.

A case in point is a configuration such as 164 that relies heavily on inertial coupling for three-axis stability. Such a configuration is particularly sensitive to thermal distortion, and it seems as if such a scheme should be avoided until a better understanding of thermal distortion effects is obtained.

A theoretical examination should be directed towards discerning the influence of thermal distortion and solar pressure on the long term or orbital stability of a satellite as opposed to boom stability. The study should consider a complete range of sun angles, boom thermal properties, damper unit properties, initial conditions, orbit eccentricity and eclipse times consistent with anticipated conditions.

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APPENDIX A

SELECTED FLIGHT DATA

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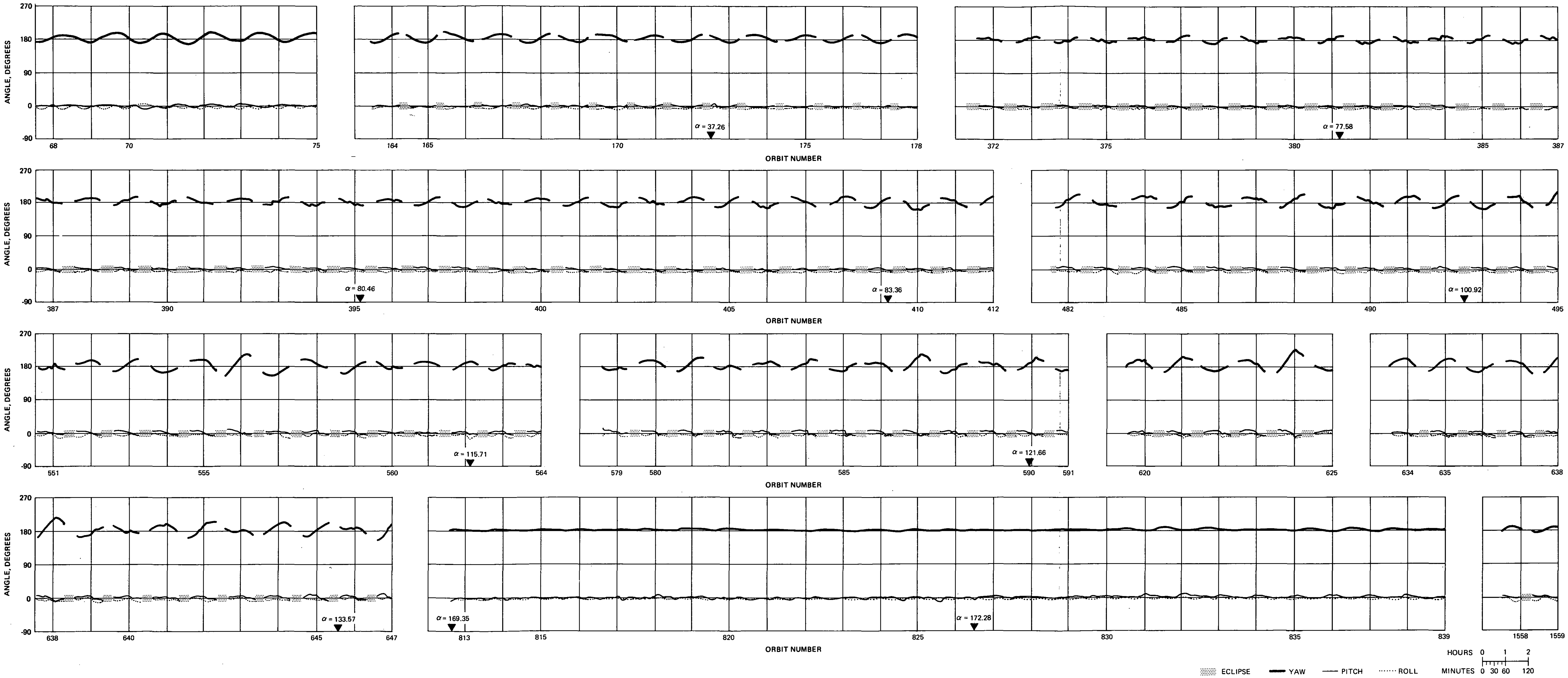

Figure A-1. Flight Data, Satellite 161

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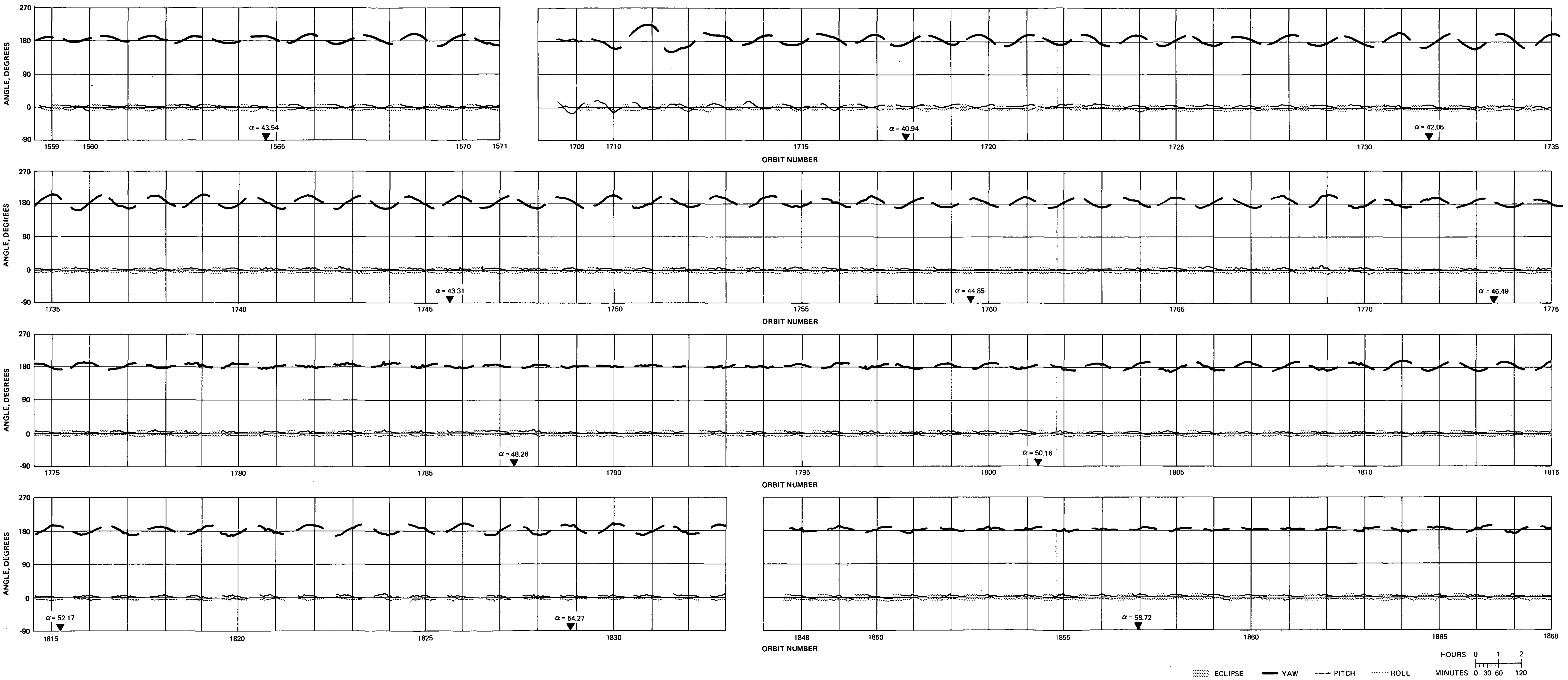

Figure A-1 (continued). Flight Data, Satellite 161

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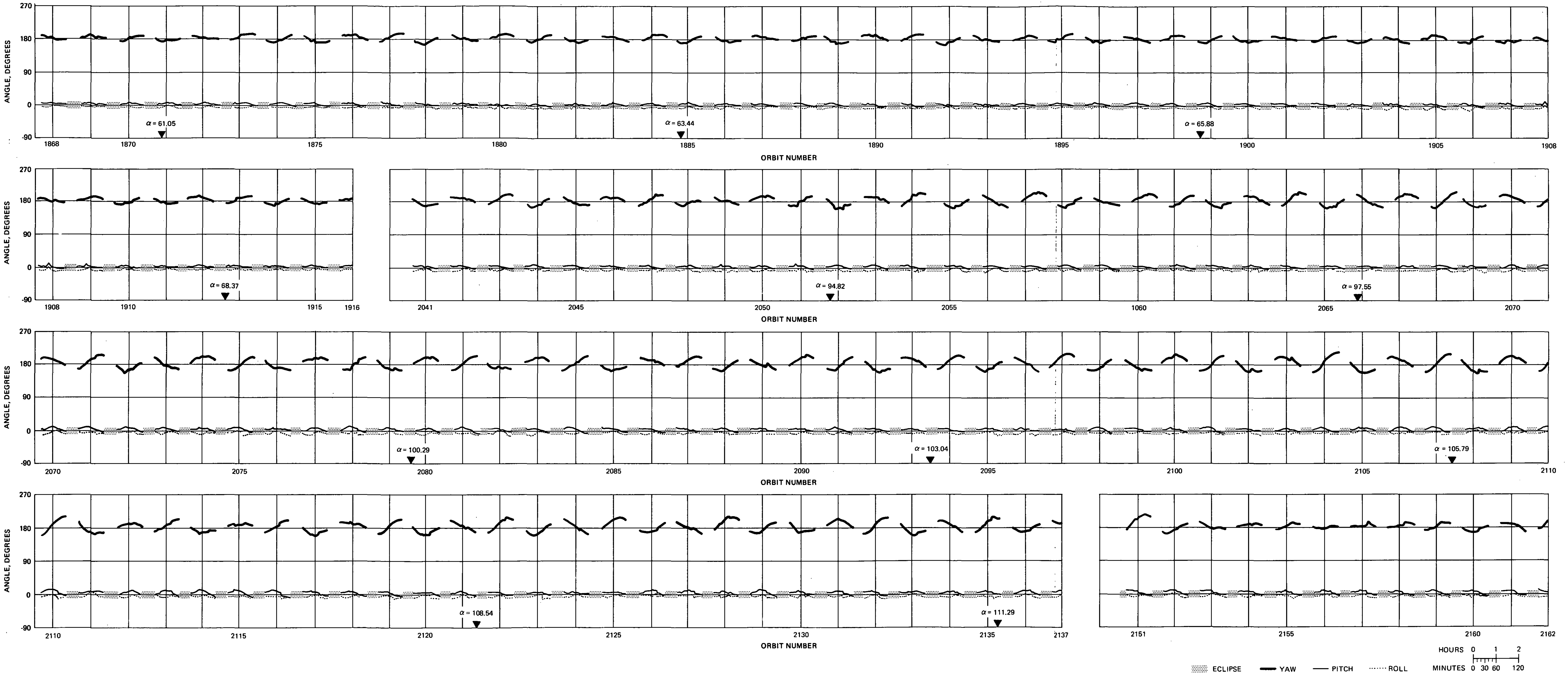

Figure A-1 (continued). Flight Data, Satellite 161

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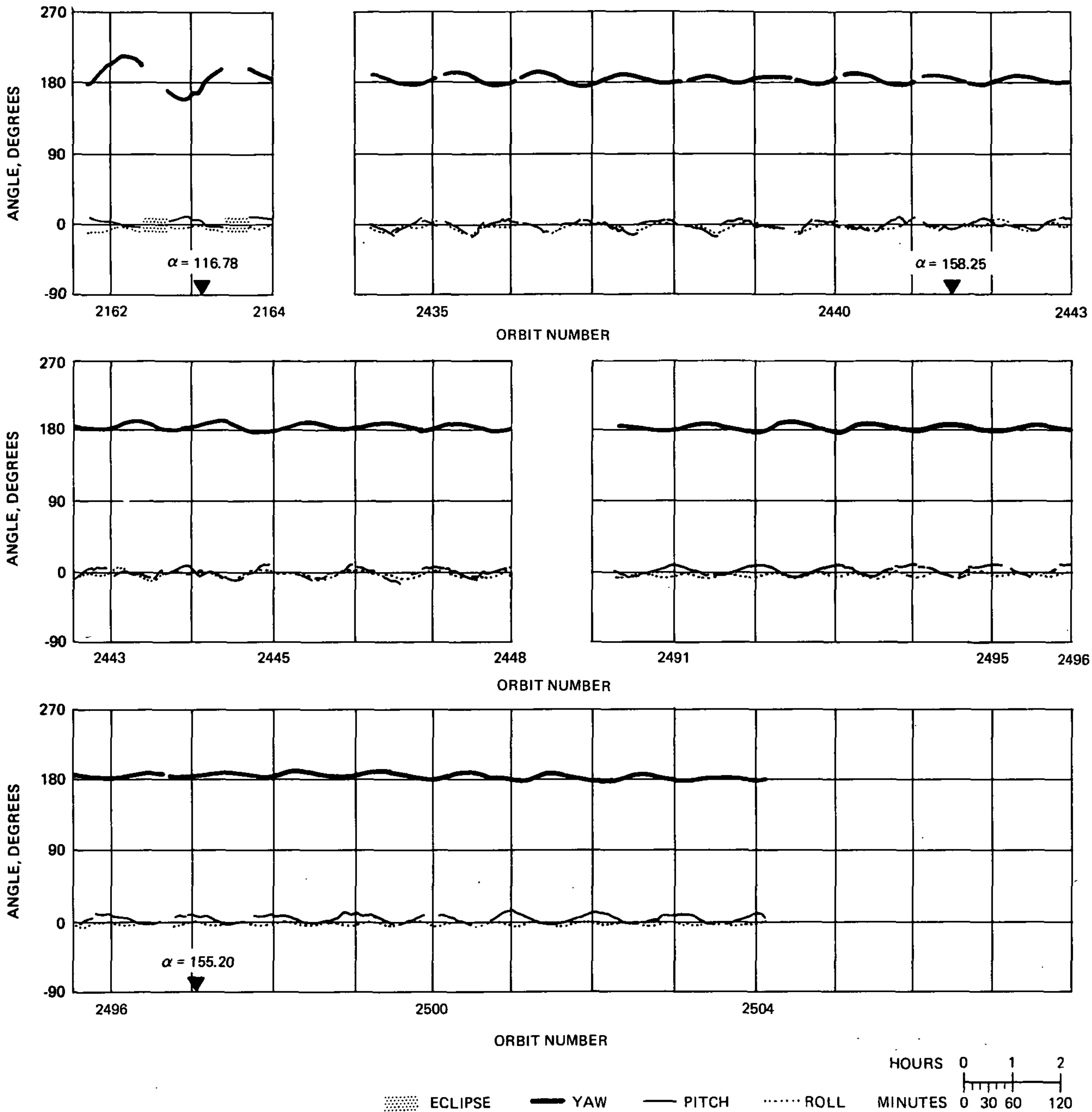

Figure A-1 (continued). Flight Data, Satellite 161

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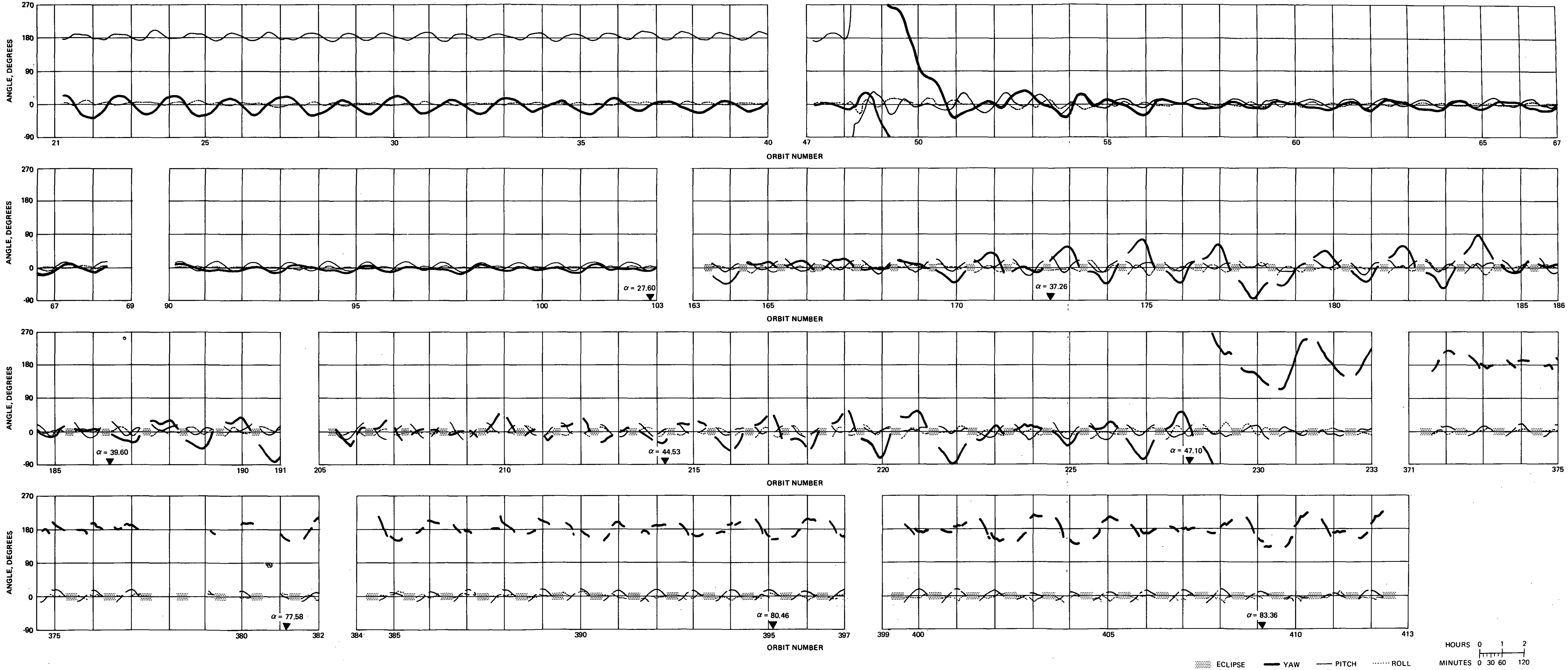

Figure A-2. Flight Data, Satellite 163

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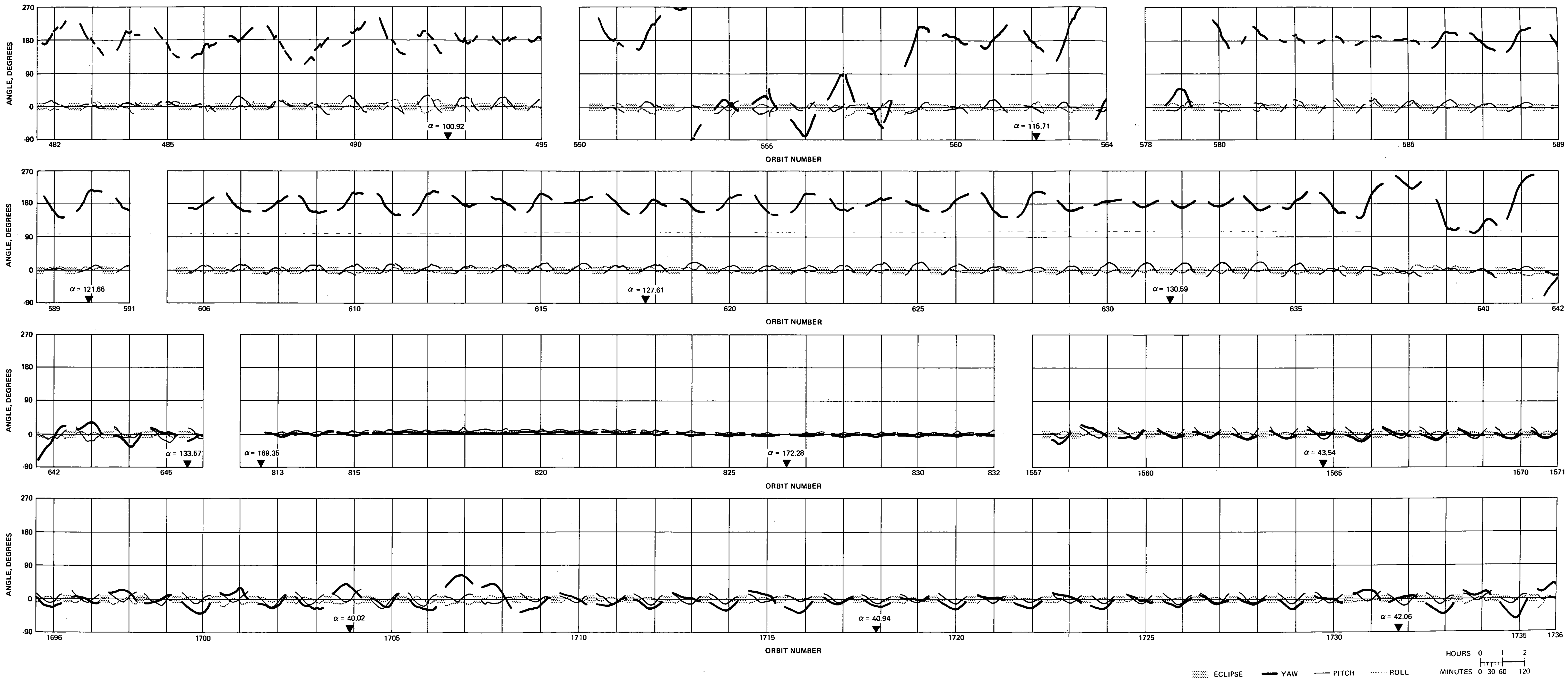

Figure A-2 (continued). Flight Data, Satellite 163

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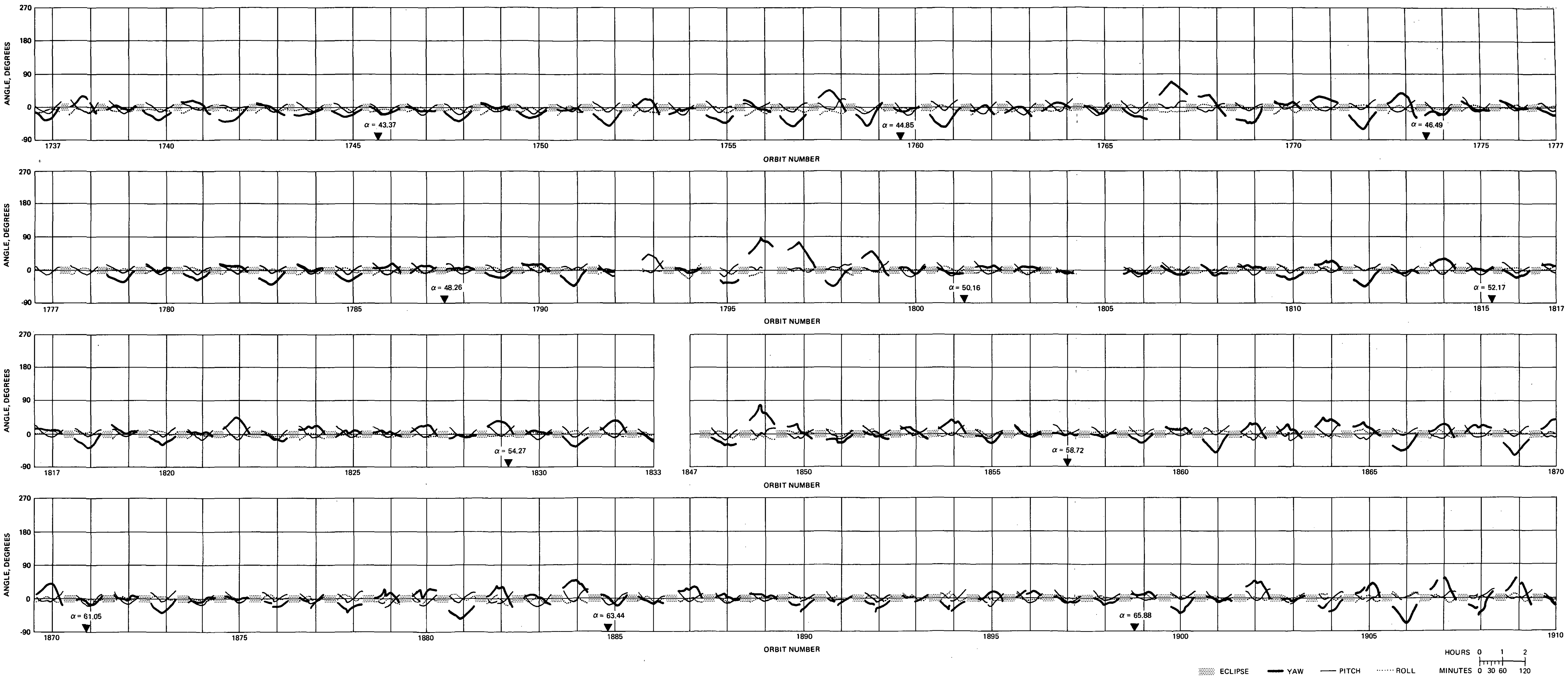

Figure A-2 (continued). Flight Data, Satellite 163

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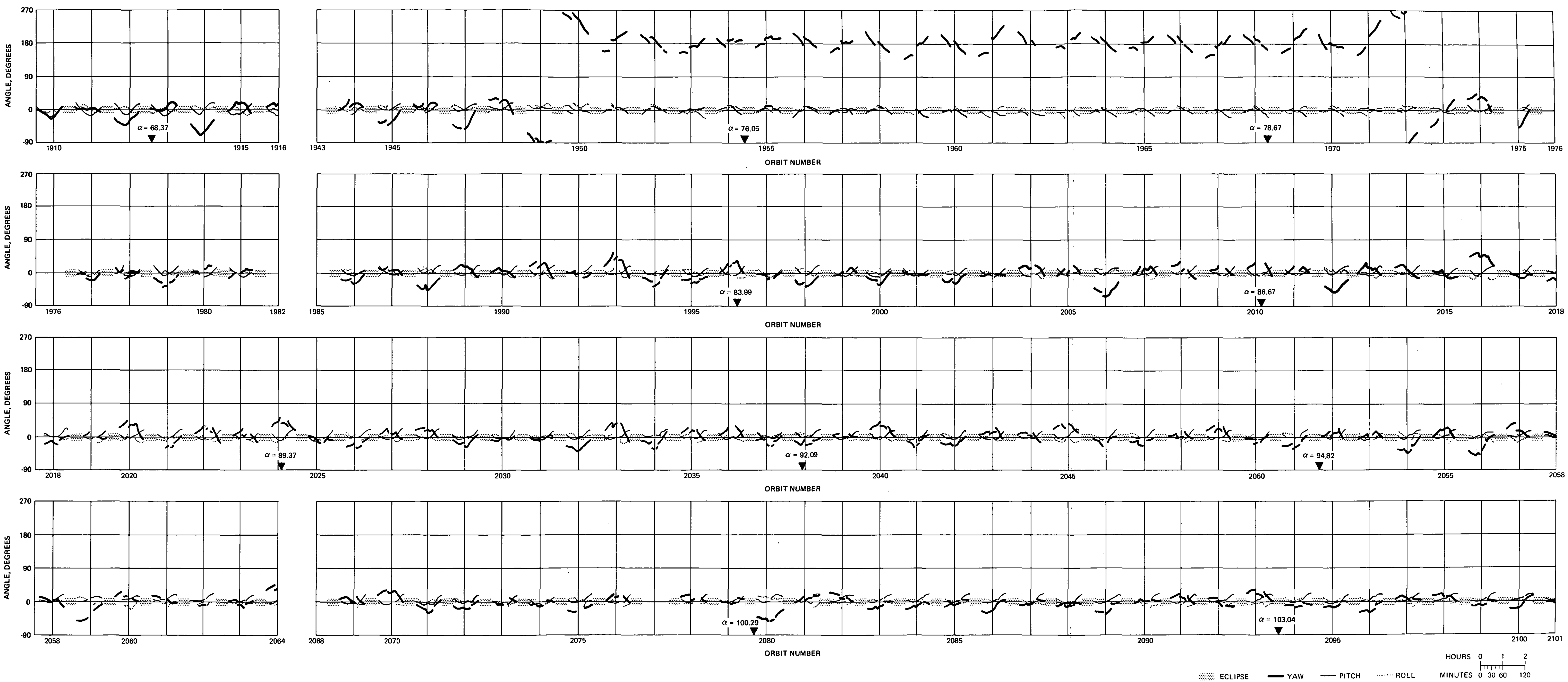

Figure A-2 (continued). Flight Data, Satellite 163

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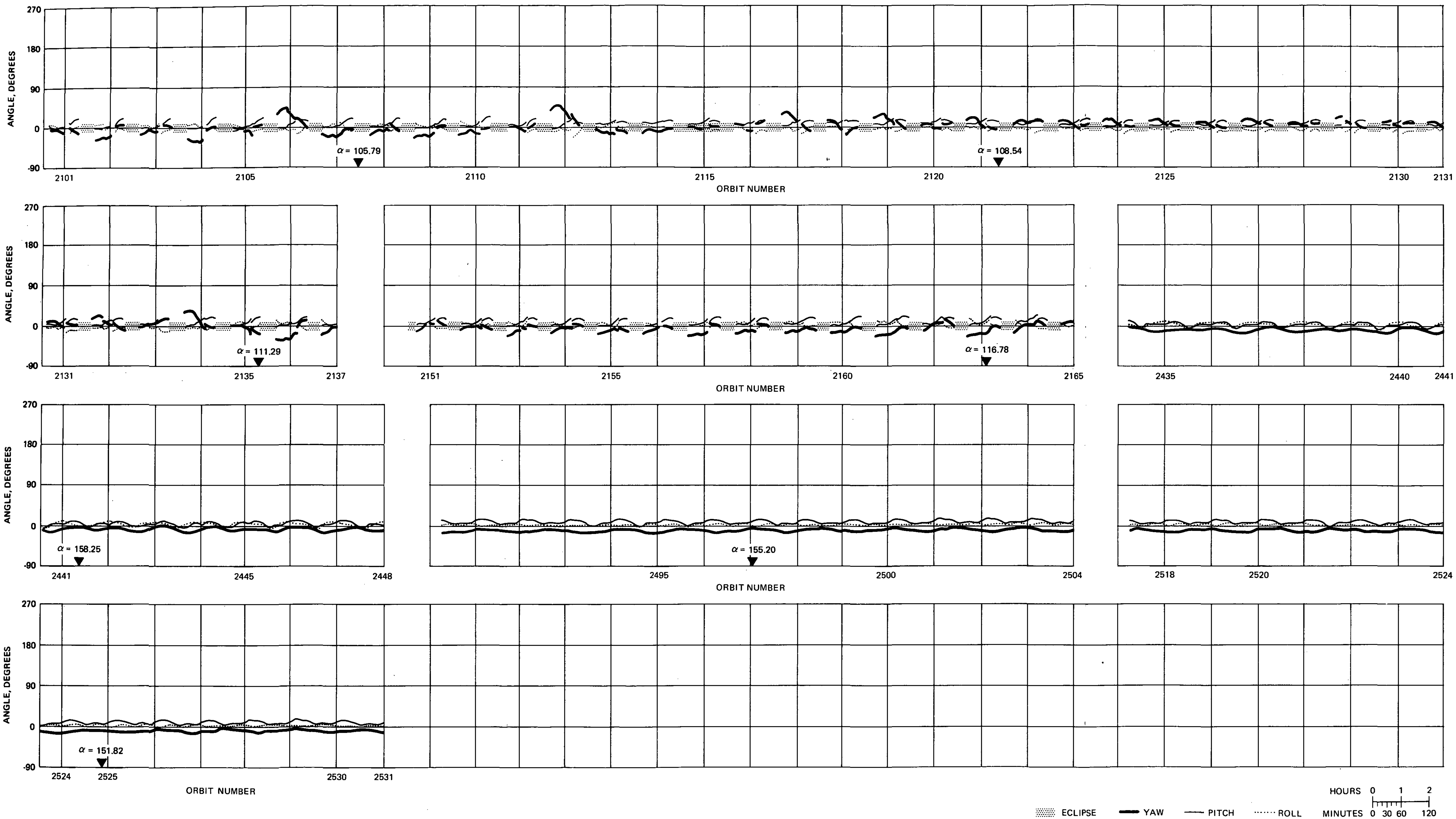

Figure A-2 (continued). Flight Data, Satellite 163

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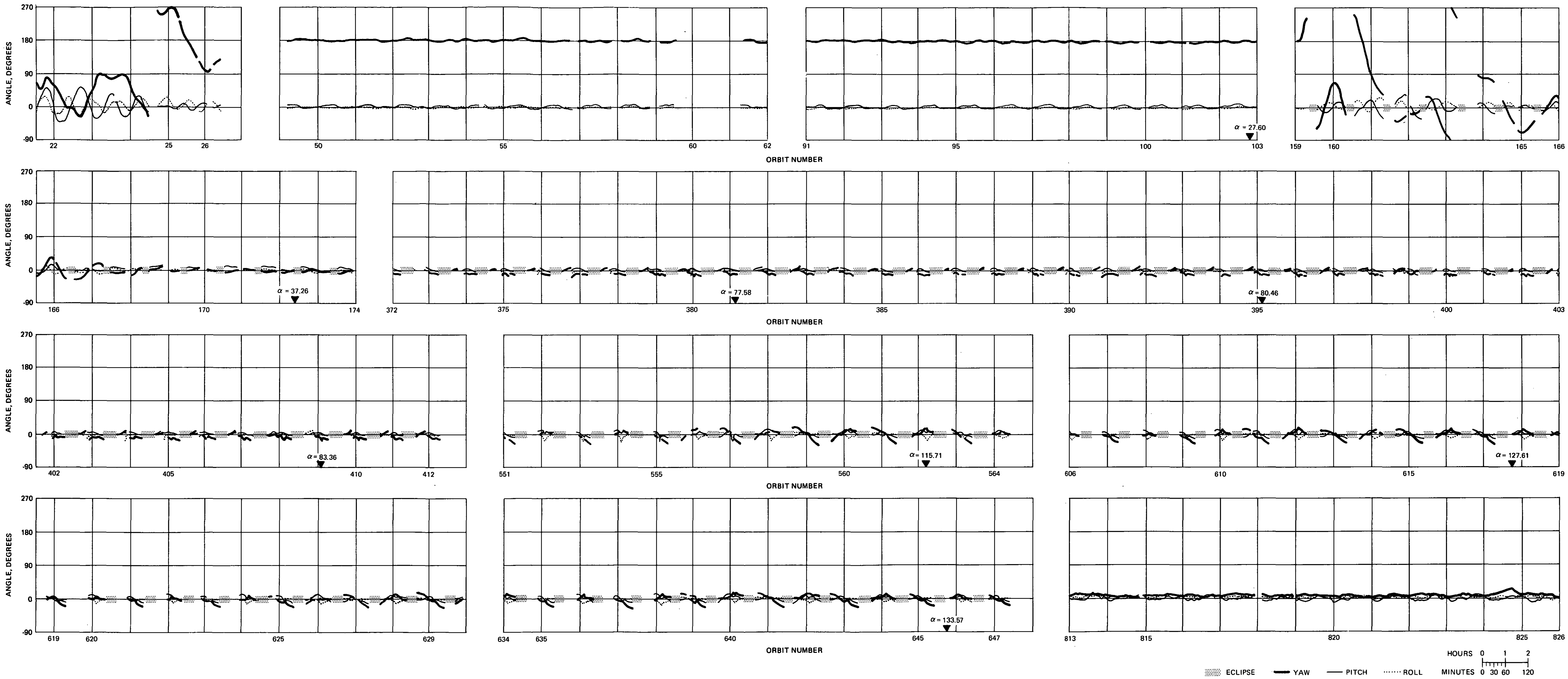

Figure A-3. Flight Data, Satellite 164

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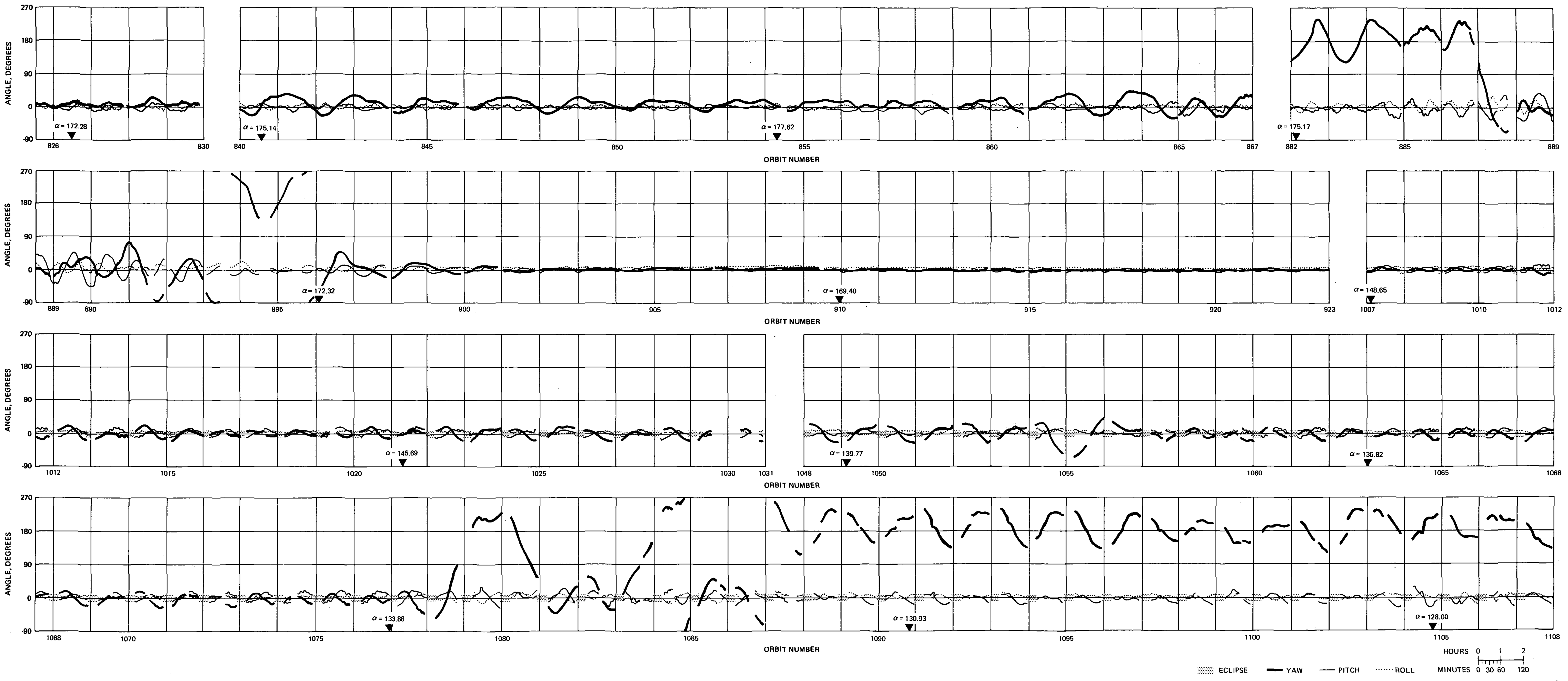

Figure A-3 (continued). Flight Data, Satellite 164

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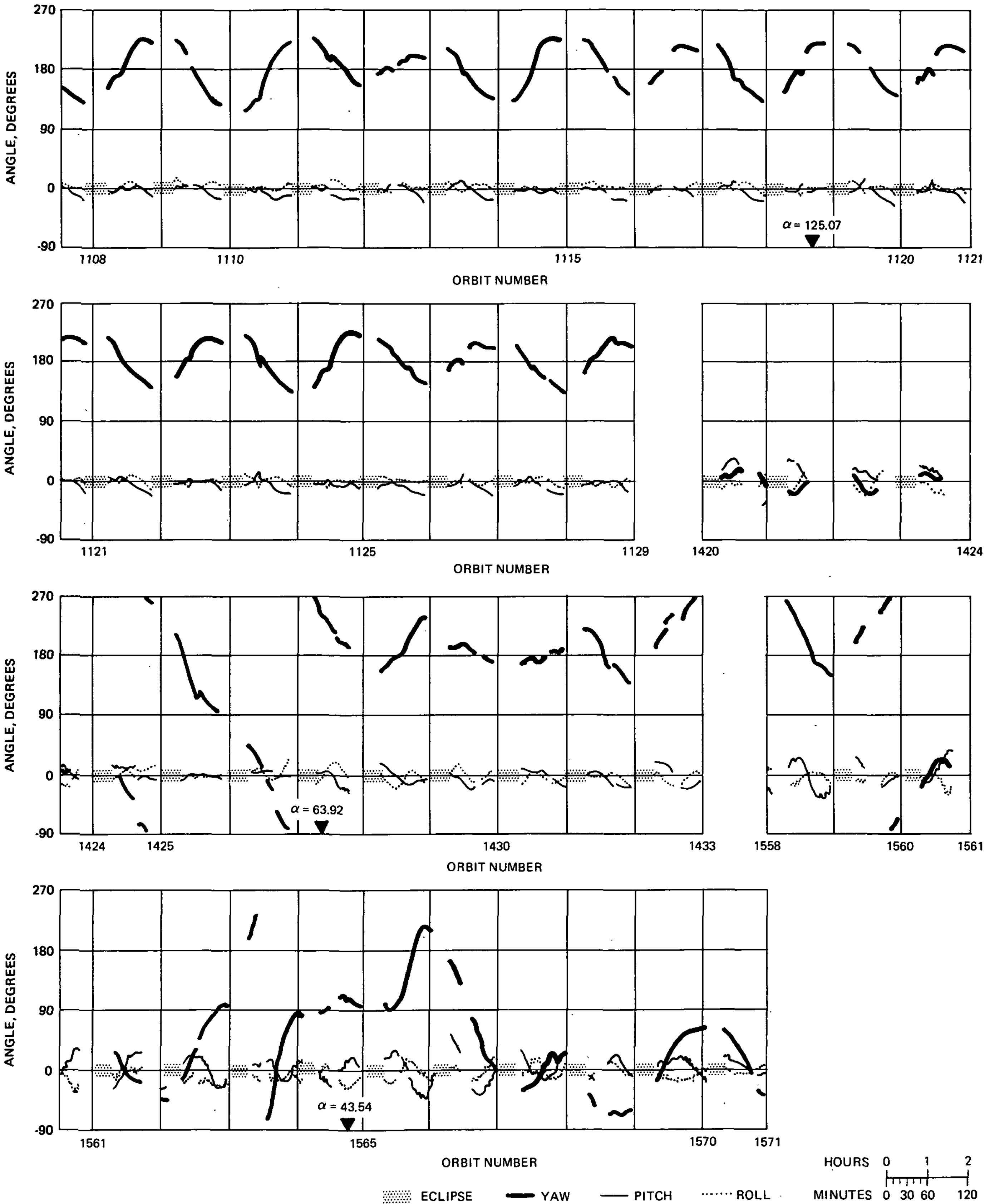

Figure A-3 (continued). Flight Data, Satellite 164

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APPENDIX B

CHARACTERISTIC EQUATIONS

It can be shown that the small-angle attitude motion of a two-axis hinged, two-body satellite about its equilibrium position is described by the following set of linearized equations.

$$\ddot{\eta}_1 + C_1'(\dot{\eta}_1 - \dot{\eta}_2) + d_1\eta_1 - k_1'\eta_2 = 0 \tag{B-1}$$

$$\ddot{\eta}_2 + C_2'(\dot{\eta}_2 - \dot{\eta}_1) + d_2\eta_2 - k_2'\eta_1 = 0 \tag{B-2}$$

$$\ddot{\xi}_1 + C_1''(\dot{\xi}_1 - \dot{\xi}_2) + q_1\Omega\dot{\zeta} + u_1\xi_1 - \bar{k}_1\xi_2 = 0 \tag{B-3}$$

$$\ddot{\xi}_2 + C_2''(\dot{\xi}_2 - \dot{\xi}_1) + q_2\Omega\dot{\zeta} + u_2\xi_2 - \bar{k}_2\xi_1 = 0 \tag{B-4}$$

$$\ddot{\zeta} + (1 - f_1 - f_2)\Omega^2\zeta - \Omega f_1\dot{\xi}_1 - \Omega f_2\dot{\xi}_2 = 0 \tag{B-5}$$

where

$C_1' = C_2/I_2$, $\quad C_2' = C_2/I_5$

$k_1' = k_2/I_2$, $\quad k_2' = k_2/I_5$

$d_1 = 3\Omega^2(I_1 - I_3)/I_2 + k_1'$

$d_2 = 3\Omega^2(I_4 - I_6)/I_5 + k_2'$

$C_1'' = C_1/I_1$, $\quad C_2'' = C_1/I_4$

$q_1 = (I_1 + I_3 - I_2)/I_1$

$q_2 = (I_4 + I_6 - I_5)/I_4$

$u_1 = 4\Omega^2(1 - q_1) + k_1/I_1$

$u_2 = 4\Omega^2(1 - q_2) + k_1/I_4$

$\bar{k}_1 = k_1/I_1$ $\quad \bar{k}_2 = k_1/I_4$

$f_1 = (I_1 + I_3 - I_2)/(I_3 + I_6)$, $\quad f_2 = (I_4 + I_6 - I_5)/(I_3 + I_6)$

η_1 = pitch motion of primary body

η_2 = pitch motion of secondary body

ξ_1 = roll motion of primary body

ξ_2 = roll motion of secondary body

ζ = yaw motion

k_1 = roll spring constant

k_2 = pitch spring constant

C_1 = roll damping coefficient

C_2 = pitch damping coefficient

I_1, I_2, I_3 = roll, pitch and yaw inertia of primary body about hinge

I_4, I_5, I_6 = roll, pitch and yaw inertia of secondary body about hinge

Ω = 2π divided by orbital period

The pitch equations (B-1) and (B-2) are decoupled from the roll and yaw equations (B-3) to (B-5). The resulting characteristic equation in pitch is then

$$S^4 + (C_1' + C_2')\,S^3 + (d_1 + d_2)\,S^2 + (d_1C_2' + d_2C_1' - C_1'k_2' - C_2'k_1')\,S$$

$$+ (d_1d_2 - k_1'k_2') = 0 \tag{B-6}$$

The roll and yaw equations (B-3) to (B-5) are all coupled, a result that makes the use of a damper only in roll practical. The characteristic equation in roll and yaw is

$$b_6S^6 + b_5S^5 + b_4S^4 + b_3S^3 + b_2S^2 + b_1S + b_0 = 0 \tag{B-7}$$

where

$$b_0 = \Omega^2(1 - f_1 - f_2)\,(u_1u_2 - \bar{k}_1\bar{k}_2)$$

$$b_1 = \Omega^2(1 - f_1 - f_2)(C_2''u_1 + C_1''u_2 - \bar{k}_1C_2'' - \bar{k}_2C_1'')$$

$$b_2 = \Omega^2(1 - f_1 - f_2)(u_1 + u_2) + u_1u_2 - \bar{k}_1\bar{k}_2$$
$$+ \Omega^2(f_1q_2\bar{k}_1 + f_2q_1\bar{k}_2 + f_1q_1u_2 + f_2q_2u_1)$$

$$b_3 = \Omega^2(1 - f_1 - f_2)(C_1'' + C_2'')$$
$$+ C_1''(u_2 + \Omega^2f_1q_2 + \Omega^2f_2q_2 - \bar{k}_2)$$
$$+ C_2''(u_1 + \Omega^2f_2q_1 + \Omega^2f_1q_1 - \bar{k}_1)$$

$$b_4 = \Omega^2(1 - f_1 - f_2) + u_1 + u_2 + \Omega^2(f_1q_1 + f_2q_2)$$

$$b_5 = C_1'' + C_2''$$

$$b_6 = 1$$

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16. Abstract

The anomalous oscillatory behavior of three satellites orbited by the Naval Research Laboratory has been examined. The satellites, a part of the 160 series of experiments, were all hinged two-body gravity gradient configurations passively stabilized about their three principal axes by gravity gradient and damper torques. Two basic behavior patterns were observed. Either the satellites were stable with attitude perturbations less than $\pm 5°$ or their behavior tended towards a low frequency rigid body oscillation dominated by large yaw motions and in some cases by yaw inversions. A causal relationship between sun angle and the character of satellite behavior was observed that appears to indicate that thermal distortion is a critical factor in a gravity gradient satellite's dynamic behavior. The behavior appeared to be further modified by the existence of response frequencies that were higher than anticipated values.

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