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A STUDY OF THE PILOT'S ABILITY TO CONTROL AN APOLLO TYPE VEHICLE DURING ATMOSPHERE ENTRY

by Rodney C. Wingrove, Glen W. Stinnett, and Robert C. Innis

Ames Research Center
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1964

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SUMMARY

Studies have been conducted on the manual control during entry of a space vehicle into the earth's atmosphere at parabolic velocities. These studies were conducted on a centrifuge where the pilot experienced the acceleration forces associated with the simulated flight. The pilot tasks in this study included (1) control to various acceleration levels, (2) control of range with various displays and various modes of short-period stability augmentation, and (3) monitoring and recovery procedures.

The pilot control to maintain a constant level of acceleration between 2 and 6 g was characterized by small "hunting" oscillations about the desired acceleration level. Control to the 3 g level was found satisfactory and allowed the best control response in terms of available lift force. This appears to be a simple control procedure that can be used in emergency situations.

The more sophisticated task of controlling range was shown to represent a sixth-order pilot control function. This study documents the variations of the pilot's ability to control this system with various lead information. It was found that displays which give only basic velocity and range-to-go information were unsatisfactory for normal operation; whereas those that gave roll rate or roll command information were found satisfactory. Removing the short-period stability augmentation increased the pilot control tasks but did not significantly affect the pilot's ability to attain the desired destination.

A pilot's task of monitoring the trajectory for an undesired skip out of the atmosphere was simulated. Successful transition from the uncontrolled skip-out trajectories into other controlled trajectories was documented.

INTRODUCTION

This report investigates the ability of a pilot to control a fixed trim capsule during atmosphere entry upon return of a manned lunar mission. The vehicle roll angle, used for trajectory control, must be varied in such a manner that the vehicle does not skip uncontrolled out of the atmosphere or exceed a given acceleration limit. In addition, the roll angle must be regulated to guide the vehicle to the desired destination. The pilot's function

during entry is to monitor the performance of the primary guidance system (on-board computer and inertial platform) and short-period augmentation system (rate gyros, reaction jets, etc.). In the event of malfunctions in this equipment, the pilot must be able to assume control of the vehicle through the use of back-up display information and/or back-up control systems.

Previous simulator studies for this type of entry (refs. 1 to 5) indicated that a pilot can satisfactorily control the short-period dynamics if the vehicle has artificial stability augmentation. Without short-period stability augmentation (ref. 1) the control was considered acceptable only for emergency operations. Pilot control of the trajectory was considered in references 2 and 3 and particular guidance display arrangements were developed. The studies indicated successful participation of the pilot in entry control, but did not systematically analyze which display and control factors enable the pilot to perform the entry tasks. It is the purpose of the present study to illustrate the effect of various arrangements of display and control parameters on the pilot's ability to perform the desired control functions during entry. This study investigates the interaction of the short-period control with the trajectory control, and also investigates new pilot monitoring tasks and emergency control procedures. The results of this study are intended to show the pilot's ability to perform the entry with progressive failures in the primary guidance and control system.

In this study the Ames five-degrees-of-freedom simulator is used to give the pilot motion cues during the simulated entries. The closed-loop operation of the simulator gives the three angular accelerations and linear acceleration levels up to 6 g.

NOTATION

A	surface area on which coefficients are based, ft^2
a	acceleration, g
a_D	drag acceleration, $\frac{D}{m}$, g
a_T	total acceleration, $\frac{D}{m}\sqrt{1 + \left(\frac{L}{D}\right)_o^2}$, g
C_D	drag coefficient, $\frac{D}{qA}$
D	drag force, lb
g	gravitation acceleration unit, 32.2 ft/sec^2
K	gain constant
L	lift force, lb

m	mass of vehicle, slugs
q	dynamic pressure, lb/ft^2
s	differential operator notation
t	time, sec
V	total velocity, ft/sec
V_c	circular orbit velocity, ft/sec
W	vehicle weight, lb
x	range to destination, miles
α	angle of attack, deg
γ	flight-path angle relative to local horizontal direction, deg
φ	vehicle roll angle, deg
$(\ )_{com}$	commanded value
$(\ )_{eq}$	value along constant trim equilibrium glide trajectory
$(\ )_i$	initial value
$(\ )_o$	with respect to zero roll angle
$(\dot{\ })$	derivative with respect to time

SIMULATION DETAILS

The entry vehicle chosen for this study was a lifting capsule similar to the Apollo configuration: $(L/D)_o = 0.48$, $W/C_DA = 50$ psf trimmed to $\alpha = -30^\circ$ by offsetting the vehicle center of gravity.

Control of the vehicle was maintained through the use of simulated reaction control systems which were an on-off type with a maximum angular acceleration capability of $10^\circ/sec^2$ about each of the three body axes. The pilot's control consisted of a three-axis side-arm stick. Figure 1 illustrates two modes of controlling the vehicle. With the stability augmentation mode (fig. 1(a)), there was a linear relationship between the stick deflection and the commanded angular rate, with a maximum of $20^\circ/sec$ rate available with full stick deflection. In this mode, angular rate feedback is used to damp the actual rate to within $\pm 1^\circ/sec$ of the commanded value. When the stability augmentation mode was not used (fig. 1(b)), the reaction control jets were activated whenever the stick deflection became greater than one-third of full travel.

The pilot's display used in this study is shown in figure 2. The display consisted of the following:

1. A three-axes horizon-ball indicator
2. A yaw rate meter
3. A pitch rate meter
4. A roll angle error meter
5. An acceleration rate and acceleration-rate command meter
6. An acceleration and acceleration command meter
7. A velocity and velocity command meter
8. A crossrange indicator
9. A scope display
10. A clock

The equations of motion were programmed on an analog computer to describe the vehicle with six degrees of freedom over an altitude range of 300,000 to 100,000 feet. The accelerations encountered during atmosphere entry were simulated by the Ames five-degrees-of-freedom motion simulator, shown schematically in figure 3 and described in reference 6. Simulated entries made with the motion devices operating are referred to as dynamic runs; those with no acceleration or motion cues are referred to as fixed-base runs. Figure 4 illustrates the motions imposed upon the pilot during a dynamic run. In starting a dynamic run on the simulator the arm was brought up to 10 rpm and the inner pitch gimbal was rotated 45° thereby impressing on the pilot an acceleration vector of 1.414 g in an "eyeballs-in" direction. The arm was then driven in response to the vehicle acceleration as computed from the equations of motion. The three gimbals of the cab were driven through an appropriate coordinate transformation to orient the vehicle acceleration vector properly with respect to the pilot. The roll, pitch, and yaw angular accelerations were also imposed on the pilot by gimbal motion computed in a coordinate transformation.

Three NASA test pilots, each highly experienced in flying aircraft and space-flight simulators, were used as subjects for these tests. Prior to the dynamic runs, the pilots made fixed-base runs to familiarize themselves with the control task and control system. During each dynamic run, the subjects were asked to comment on the control problems encountered and to rate their ability to perform the control tasks according to the Cooper rating scale (ref. 7) shown in table I. These observations, along with the recorded data taken during the simulated entries, provide the data for the following discussions.

VEHICLE DYNAMICS

The dynamics of the entry vehicle will be outlined briefly before the simulation results are discussed. The entry trajectory dynamics associated with the roll control system will be discussed first.

Roll Control and Trajectory Dynamics

Figure 5 is a simplified block diagram showing the relationship between vehicle roll control and range control. The diagram depicts range variation in only the vertical plane. This figure shows the chain of events that result from the application of a roll control moment by the reaction jets. The roll control jets produce a torque about the roll axis which is integrated (fig. 5) to produce a roll rate. An integration of the roll rate results in changes in the roll angle. The control of the roll angle is a part of the vehicle "short-period dynamics." The dynamic response of the system which follows a change in roll angle is termed the "long-period" or trajectory dynamics.

The roll angle determines the component of the aerodynamic lift force vector in the vertical plane. The integrated changes in this vertical lift force determines the changes in the vehicle rate of climb. Integrating this vertical velocity determines the changes in the vehicle altitude and consequently the changes in drag acceleration. The subsequent integration of drag acceleration determines changes in horizontal velocity, and a final integration determines the subsequent changes in the downrange.

Figure 5 illustrates that a pilot guiding to a given point on earth is, in effect, controlling a sixth-order function. With an on-board computer and inertial platform, the trajectory position and velocity information can be accurately determined during entry, and guidance logic equations within the computer can determine the proper roll angle required to reach the destination. Either an autopilot or the pilot, using a roll angle display, can follow this roll angle command to guide to the desired destination. If the primary guidance system should fail though, the pilot must determine the proper roll angle through the use of back-up display information. One simple method of emergency control investigated in this study is for the pilot to fly at a constant acceleration. The pilot needs only simple measurements of acceleration and horizon roll angle to perform this task. This method provides a safe entry but not accurate range control. To determine the information required by the pilot to guide to the destination, a progressive arrangement of display information was investigated. The study showed how the pilot's performance varied with different amounts of lead information.

Pitch and Yaw Dynamics and Control

The dynamics of the vehicle pitch and yaw modes are characterized by short-period oscillations resulting from the positive static stability of the vehicle. During entry this oscillation frequency is primarily a function of dynamic pressure or corresponding vehicle acceleration. For the particular configuration in this study, the highest pitch and yaw oscillations were 0.55 cps at 6 g.

Random disturbances were introduced as shown in figure 6 to give a realistic pilot control task. Without stability augmentation (and with no pilot input about the pitch and yaw axis), it is seen that the oscillations increase

in magnitude to about $\pm 20^{\circ}$/sec at the end of the trajectory. The pilot control task about the pitch and yaw axes then was to keep these angular rates small (within $\pm 2^{\circ}$/sec).

There is significant geometric coupling between the roll and yaw degrees of freedom because the vehicle rolls about the wind axis which is inclined 30° to the symmetrical body axis. Therefore, to minimize the influence of this coupling, the yaw rate displayed to the pilot and the yaw rate signal used in the stability augmentation system were computed from the body axis yaw and roll rates according to the following equation:

$$\text{yaw rate signal} = (\text{yaw rate})_{\text{body axis}} + \tan 30^{\circ} \times (\text{roll rate})_{\text{body axis}}$$

The pitch rate and roll rate signals were those computed on the respective body axes.

RESULTS AND DISCUSSION

The results of this study are presented in three parts. The first part discusses the pilot's ability to control to a given acceleration level. The second section is concerned with the effect on the pilot's ability to control range with the guidance information displayed. (Various modes of stability augmentation as well as various guidance display arrangements are discussed.) Finally, the third part discusses a simple pilot monitoring system designed to insure that the vehicle will not inadvertently skip out of the atmosphere. This monitoring system was evaluated and results were obtained with the pilot maneuvering (or transitioning) from an undesired skip-out trajectory to a safe trajectory.

Pilot Control of Acceleration Level

For this series of runs the pilot was asked to control to a specified constant acceleration level between 2 and 6 g. The pilot display consisted of an acceleration indicator and an attitude indicator. Vehicle stability augmentation was used for this series of runs so there was essentially no control task about the pitch or yaw axes.

Figure 7 illustrates typical pilot-controlled trajectories. During the initial dive into the atmosphere the pilot held roll angle near zero until the rate of build-up in acceleration could be determined. If the acceleration was increasing too fast (such as for the steep entry, $\gamma_i = -5^{\circ}$ in fig. 7), the roll angle would be kept near zero, thus holding the maximum vertical lift force. If the acceleration build-up was too slow (as for an initial shallow dive $\gamma_i = -2.5^{\circ}$ in fig. 7), the pilot would roll the vehicle so the lift vector pointed down thereby pulling the vehicle farther down into the atmosphere.

As the acceleration nears the desired level, the pilot goes into a "hunting" or oscillatory control mode to search for the roll angle variation to hold the acceleration near constant (fig. 7). The pilot cannot control onto and hold the desired acceleration level, primarily because the roll angle to hold a given acceleration is continually changing. This is illustrated with the aid of figure 8. On the upper portion of the figure is shown the lift force needed to keep the vehicle in equilibrium flight. This force is a function of the gravity minus centrifugal forces. At low forward velocities, 1 g is needed to keep the vehicle in equilibrium; at circular satellite velocity (V_c), zero lift force is needed; and at the supercircular velocities, negative lift is needed to keep the vehicle in equilibrium. From the bottom of figure 8 it can be seen that for an acceleration level of 6 g the roll angle for equilibrium flight varies from about 105° at 36,000 fps to about 75° at lower velocities. At the lower acceleration level of 2 g there is less available aerodynamic force, and the roll angle for equilibrium flight varies from about 160° to 20°. Prior knowledge of the variation of equilibrium roll angle helped the pilot to judge the vehicle roll angle for control to the desired acceleration level, but the hunting oscillation was always present.

Time histories of pilot controlled runs at acceleration levels of 2, 4, and 6 g are shown in figure 9. As the acceleration level increases the frequency of the hunting oscillation increases primarily because of the increased magnitude of the aerodynamic forces. The pilot uses this increased vehicle lifting capability in making more rapid changes in the trajectory (i.e., fig. 9(c)) as compared with slower changes that are made at the low acceleration levels (i.e., fig. 9(a)).

Pilot ratings and performance data taken at various acceleration levels are shown in figure 10. The pilots found it easiest to control to the 3 g level. At lower acceleration levels the pilots indicated that too much roll control must be used because of relatively small amount of total force available. On the other hand, for acceleration levels above 4 to 5 g, the pilots noted that small changes in roll angle resulted in large changes in the vertical lift, and trajectory control became too sensitive. The control at the higher acceleration levels was characterized by the increased hunting frequency and, as shown in figure 10(b), an increase in acceleration error away from the desired level.

In figure 10 the pilot ratings from the dynamic runs are compared with static runs. Up to the 6 g level there is very little difference in the performance data. The pilots indicated that at the 6 g level the dynamic runs were about 1/2 a pilot rating point harder to control than the static runs. The pilots noted, however, that the dynamic motions of the simulator gave a more realistic environment and greater pilot concentration was required in order to keep the vehicle under control. These observations on pilot performance up to the 6 g level are in general agreement with previous studies such as in reference 8.

Pilot Control of Range

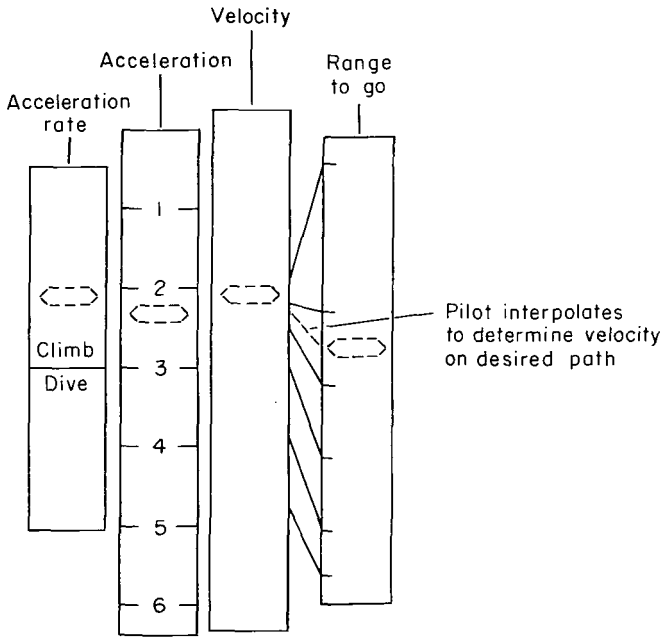
For this series of runs various guidance display configurations were investigated with each of the following three modes of stability augmentation.

1. "Stability augmentation in." There was rate damping about each of the roll, pitch, and yaw axes.

2. "Roll rate damping out." The vehicle motions were undamped about the roll axes, and rate damping was provided about the pitch and yaw axes.

3. "Stability augmentation removed." No rate damping was provided about any vehicle axes.

The general guidance concept used in the study is illustrated in figure 11. The guidance problem was to maneuver the vehicle onto an equilibrium glide trajectory (for $\varphi = \pm 60^{\circ}$) which terminates at the desired destination. An ordered variation in vertical lift force is necessary to fly onto and down the equilibrium glide path. This vertical lift force determines the magnitude of the roll angle. The sign of the roll angle (i.e., right or left) was determined by the crossrange (ref. 9). As shown in the figure, the vehicle is allowed to fly to one side until the crossrange to the destination exceeds a reference envelope at which time the sign of the roll angle is reversed. This crossrange information is displayed to the pilot on a dial in a normalized form (crossrange to go/V^2). A typical roll-angle history is shown on the figure with three roll reversals corresponding to the crossrange reversal points. With this crossrange control method, the trajectory converges to the destination as shown. The ability of the pilot to guide during entry using this crossrange control concept with various types of downrange guidance display arrangements will be illustrated.



Sketch (a)

Range-to-go display.- The display that was used to show range control information is shown in figure 12. The four quantities, range to go, velocity, acceleration, and acceleration rate, were mechanized on a 5-inch cathode-ray tube with the indicators driven by analog computer voltages. (See sketch (a).) This display has lines drawn between the range and velocity scales. The lines represent the desired velocity, as a function of the range to

go, for an equilibrium glide trajectory to the target. In effect, these lines give the pilot a let-down schedule of velocity versus range to go to follow so that the vehicle arrives at the destination with the proper velocity. To control onto the desired path, the pilot compares the actual vehicle velocity with the desired velocity and then flies an acceleration pattern so as to achieve the desired vehicle velocity. When this is accomplished, the spacecraft is on the equilibrium glide path and the roll angle can be controlled near $\pm 60^{\circ}$ (the equilibrium glide value) throughout the rest of the trajectory.

A typical time history of a pilot controlled trajectory with this display is shown in figure 13. The difference between the actual and desired velocity (velocity error on fig. 13) is shown to vary from about 11,000 fps to 3,000 fps. This final error in velocity represents an end-point error of about 39 miles downrange. The end-point error resulting from this range control technique never exceeded about 40 miles, which is close to the maximum resolution capability of the range-to-go display.

The pilot ratings with this range-to-go display were as follows:

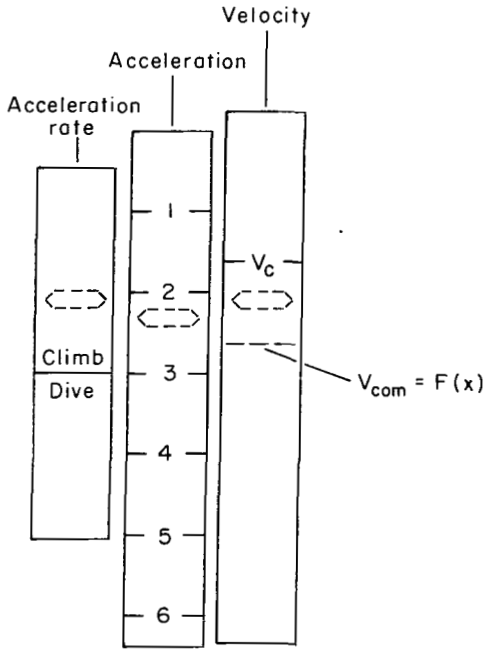
Mode of short-period augmentation	Average pilot rating
Stability augmentation in	5-3/4
Roll augmentation out	6
Stability augmentation out	6-1/2

With stability augmentation in, the pilot's task was primarily to scan the roll angle, acceleration, velocity, and range-to-go displays and effect the appropriate vehicle control. Because of the degree of concentration and skill required to fly the vehicle, the pilots felt that this display arrangement should only be considered for an emergency situation and was not satisfactory for normal operation.

With the roll dampers out, the level of difficulty of the pilot's task was increased. In this case the pilot was required to fly a roll acceleration command system rather than the roll rate command system. As shown in figure 5, the pilot is, in effect, controlling a sixth-order system. Observing six pieces of information and applying the appropriate control action is a demanding task. The pilot's usual routine was to scan the range and velocity display and decide upon a desired acceleration level, then for the next minute or so hold the vehicle near this desired acceleration value. About every 30 to 60 seconds the pilot would repeat his scan of the range and velocity displays to decide whether a new acceleration level was required.

With dampers inoperative it was necessary for the pilot to include in his scan pattern the pitch and yaw rate indicators. The rate meters provided the primary cue for damping the vehicle oscillations rather than the imposed motion cues. The technique used was to make one corrective input about each axis in turn. The control task with all dampers out demanded the pilot's full attention but, nevertheless, it was possible, as shown by the time history of figure 13, for the pilot to successfully control the trajectory with this type of guidance display. In all cases, the vehicle arrived within about 40 miles of the desired destination.

Velocity command display.- A velocity command was presented as a function, F(x), of the range to go along the equilibrium glide trajectory. The display is schematically shown in sketch (b). Using this display, the pilot did not have to interpret between the range-to-go and velocity scales. In this case the pilot was effectively controlling a fifth-order function.



Sketch (b)

A typical time history of a pilot controlled trajectory resulting from this display is shown in figure 14. The difference between the actual and command velocities (velocity error on fig. 14) is shown to vary from the initial value of about 11,000 fps to a final value of 1,000 fps. This final error resulted in an end-point error of about 13 miles. The maximum range error with this display was about 20 miles.

The double-pointer dial instrument as well as the scope display shown in the sketch indicated the commanded velocity. The pilots showed no preference for either type of display. For the various modes of short-period stability augmentation and the velocity command displays the pilot ratings were as follows:

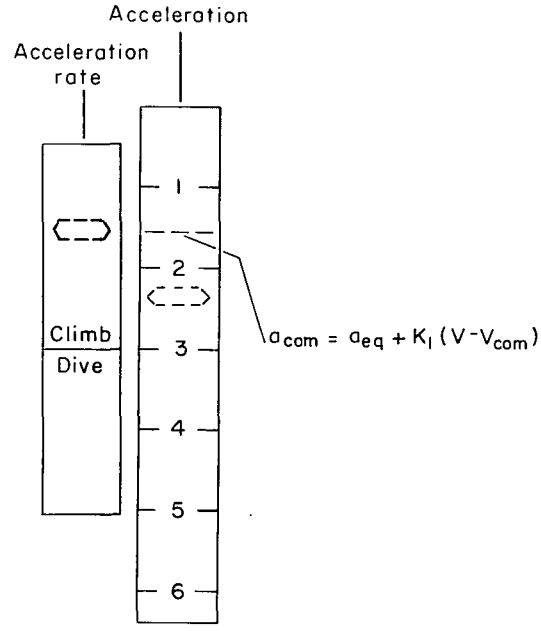
Mode of short-period augmentation	Average pilot rating
Stability augmentation in	4
Roll augmentation out	4-1/2
Stability augmentation out	5-3/4

When the velocity command display was used, the pilot ratings were about 1-1/2 points better than ratings for the range-to-go displays. The reason for these ratings was that the velocity along the desired path was indicated directly, so by watching the relative rate of change between the actual and desired velocity indicators, the pilot could readily obtain lead information to judge the proper acceleration level. The task was still demanding though, and the pilots considered this display arrangement unsatisfactory for normal operation and suitable only for emergency situations.

Acceleration command display.- In this display, the pilot was given an acceleration command computed from the equilibrium glide acceleration and a constant times the difference in actual velocity from the command velocity. This display is shown in sketch (c).

This display gives the pilot one order of lead information over the command velocity display. In this case the pilot is in effect controlling a fourth-order function.

A typical entry time history with the pilot using this display is shown in figure 15. The difference between the actual and command acceleration (acceleration error on fig. 15) is shown to vary from an initial value of 3.3 g to a final value of about 1/2 g. The final range error was found to be strongly affected by the value of the gain K_1. When this gain was large near the end of trajectory, the vehicle could usually be flown within about a mile of the destination. It is interesting to note from the time history that hunting oscillations, similar to those encountered when the pilot tried to hold a constant g level, were present during these runs.



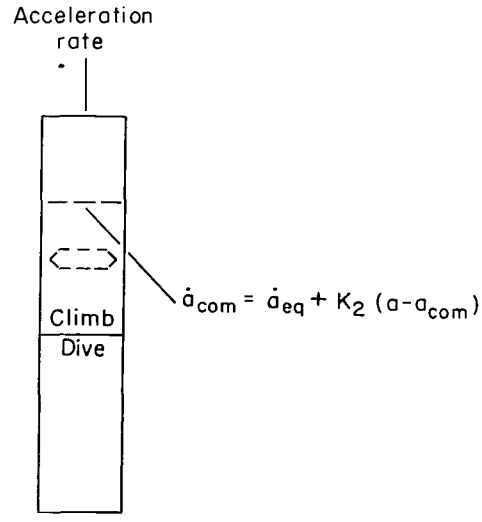
Sketch (c)

For the double-pointer dial instrument as well as the scope display of command acceleration information, the pilot preferred an instrument that displayed the higher g levels toward the bottom of the scale (such as with the scope presentation) to correspond with the increasing g for diving flight in the atmosphere.

The pilot rated the command acceleration displays as follows:

Mode of short-period augmentation	Average pilot rating
Stability augmentation in	3-1/4
Roll augmentation out	4
Stability augmentation out	5

The pilots rated the acceleration command display about 3/4 point better than the velocity command display. Pilot opinion indicated that with stability augmentation this display arrangement is satisfactory for normal operation. Without stability augmentation, they considered this arrangement suitable only for emergency operations.



Sketch (d)

Acceleration-rate command display.- An acceleration-rate command is computed from the equilibrium glide acceleration rate and a constant times the difference between vehicle acceleration and the command acceleration. The display is shown in sketch (d). This display gives the pilot one order of lead information over the acceleration command display. In this case the pilot is effectively controlling a third-order function.

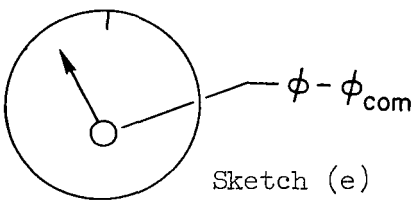
A typical time history for a pilot using this display is shown in figure 16. The difference between the actual and command acceleration rate (acceleration-rate error on fig. 16) is shown to vary from an initial value of -0.1 g/sec to a final value of about -0.05 g/sec. The final range error could be reduced to about 1 mile if large gains were used near the end of the trajectory.

The double-pointer dial instrument as well as the scope display indicated the command acceleration-rate information. The orientation in both of these instruments was considered satisfactory by the pilots because a dive into the atmosphere corresponds to an increasing acceleration rate toward the bottom of the instrument. The pilots rated the command acceleration rate displays as follows:

Mode of short-period augmentation	Average pilot rating
Stability augmentation in	3
Roll augmentation out	3-1/2
Stability augmentation out	4-1/2

The pilot ratings for the acceleration-rate command display were about 1/2 pilot rating point better than those for the acceleration command display. The pilots consider this display and control arrangement satisfactory for normal operation with stability augmentation and unsatisfactory for normal operation without stability augmentation.

Roll-angle error display.- This display gives the pilot one order of lead information over the acceleration-rate command display. This display arrangement is shown in sketch (e). The magnitude of the command roll angle is determined by range to the destination and the sign of the command roll angle is determined by the crossrange error in a manner similar to the method of reference 9.



Sketch (e)

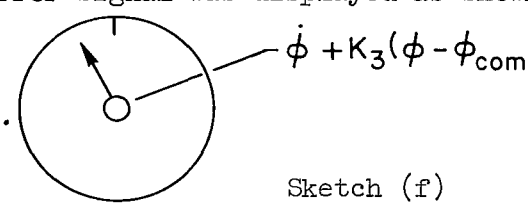
A typical time history for a pilot using this display is shown in figure 17. The roll-angle error during this run is shown on the figure. At about 1-1/2 minutes after the start of the run a roll reversal command from +100° to -100° can be seen. Because there is no roll damping in this particular run, the pilot made the roll reversal slowly so as not to excite the vehicle short-period motions. During the portion of the run when the pilot was trying to fly a constant command roll angle, he held the vehicle roll attitude to within about 20° of the command value.

The pilots rated the roll-angle error display as follows:

Mode of short-period augmentation	Average pilot rating
Stability augmentation in	2-3/4
Roll augmentation out	3
Stability augmentation out	4

With all dampers in operation the pilot's task was to null the roll-angle error. This task was simple and required very little learning. With dampers removed it was necessary for the pilot to scan the roll-angle error, pitch rate, and yaw rate, and to refer occasionally to the altitude indicator. Without stability augmentation the pilots rated the task marginally unsatisfactory for normal operation.

Roll-rate error display.- A roll-rate error signal was displayed as shown in sketch (f). This display gives the pilot one order of lead information over the roll-angle error display. In this case the pilot is controlling a simple first-order function.



Sketch (f)

The pilots rated the roll-rate error display as follows:

Mode of short-period augmentation	Average pilot rating
Roll augmentation out	2-3/4
Stability augmentation out	3-1/4

With stability augmentation removed, the pilots found this display satisfactory for normal operation. The pilot task was simply to look at the three rate instruments (roll-rate error, pitch rate, yaw rate) and correct the rate about each axis in turn.

Comments on range control tasks.- Figure 18 presents a plot of pilot ratings for the various guidance displays. This figure shows the variation of pilots' opinion of controlling a sixth-order system with various amounts of lead information. The effect of the display lead is shown to improve the pilot rating by about 1/2 a pilot rating point for each order of increase in lead information. Decreasing the amount of lead information caused the pilot to make larger roll maneuvers to control the trajectory. This is illustrated in figure 19 where the relative amount fuel used for roll jets is presented as a function of the guidance displays. As the pilot is given less lead information the amount of fuel required is seen to increase. This is apparently because the pilot is making big maneuvers to determine experimentally the proper vehicle roll angle rather than having the roll-angle command information presented to him. Finally, when the pilot is given no command information, with the range-to-go display, the pilot instead of making many small corrections waits a longer time to see the results of each control input and as a result uses less fuel.

Pilot Monitoring and Transition Tasks

A simple pilot monitoring concept was devised (see appendix) to insure that the vehicle did not inadvertently skip out of the atmosphere at above circular velocity. In actual operation the purpose of such a monitoring system is to give the pilot information independent of the primary guidance

system with which to assess the flight situation. This monitoring device consists of a light that warns the pilot if the primary system is guiding the vehicle to an undesired skip out of the atmosphere. When the light goes on the pilot, using back-up information (attained from simple accelerometer and gyros, etc.), can take over the control and maneuver onto a new safe trajectory.

In this part of the study it was assumed that the pilot was given primary guidance information on the roll-angle error indicator and that back-up information was used for the warning light and the acceleration-rate, acceleration, velocity, and range-to-go displays. Various trajectories were programmed that would skip the vehicle out of the atmosphere. The pilot would fly these trajectories until the warning light went on. At this time the pilot would recover from the undesired trajectory by rolling the vehicle full lift down so as to dive deeper into the atmosphere. The pilot would then use one of the designated display arrangements for controlling the vehicle during the rest of the run. In these runs the monitoring system was evaluated and the various display arrangements were used.

Typical trajectories with a pilot transferring from the primary guidance display to the back-up displays are shown in figure 20. In each case the vehicle would have skipped out of the atmosphere above circular velocity if the pilot had continued to obey the primary guidance information. Figure 20(b) illustrates the pilot's ability to control using acceleration command information after transition from the skip-out trajectory. The pilot's ability to transfer to the acceleration-rate command display, the velocity command display, and the range-to-go display was also investigated. In each case the pilot had very little difficulty. The pilot ratings for the transition and subsequent guidance control task were about 1/2 a pilot rating point worse than the ratings given previously when the pilot used the same display throughout a run.

CONCLUDING REMARKS

The results of this study illustrate several considerations in the pilot control of a lifting entry capsule.

This study shows that control to a given acceleration level is acceptable for emergency entry operations. The pilot control response is characterized by small hunting oscillations about the given acceleration level and the results indicate a preference for controlling to an acceleration near the 3 g level.

The results of this study illustrate the effect of various lead-information displays on the pilot's ability to perform a range control task. It is concluded that displays which give only basic velocity and range-to-go information are unsatisfactory for normal operation; whereas display which includes roll rate or roll-angle command information are satisfactory.

For the vehicle used in this study, failure of short-period stability augmentation increased the pilot's tasks but did not significantly affect the pilot's ability to reach the desired destination.

A simple method of pilot monitoring to insure that the vehicle does not skip out of the atmosphere was investigated and the results indicate that such a system is feasible. Successful pilot-controlled transitions from skip-out trajectories to safe trajectories were documented.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., June 11, 1964

APPENDIX

CONCEPT OF SKIP-OUT MONITOR

This appendix outlines the monitoring system which was used in this simulation and describes the possible hardware implementation of this system.

The objective of the monitoring system is to insure that the pilot will never let the vehicle skip out of the atmosphere above circular velocity. The system works as follows: A light goes on at the last possible moment when a roll control maneuver, to full negative lift, will just keep the vehicle from leaving the atmosphere at above circular velocity. The hardware for this system is simple, reliable, and independent of the primary guidance system.

The basis for this monitoring system is illustrated in figure 21 which shows trajectories out of the atmosphere for a vehicle holding negative lift ($L/D = -0.4$). These trajectories represent boundaries beyond which the vehicle will skip out above circular velocity regardless of attitude. It should be noted that these boundaries are three-dimensional and are defined by acceleration, acceleration rate, and velocity. From this figure it can be seen that a linear approximation to these boundaries can be of the form:

$$a_{Limit} = K_V(V - V_c) - K_{\dot{a}}\dot{a}$$

This equation was used in this study so that a warning display was activated when the vehicle acceleration was below the computed acceleration limit. The values of K_V and $K_{\dot{a}}$ were empirically adjusted to give adequate warning without giving false warning when the primary guidance system was operating normally. The values of K_V and $K_{\dot{a}}$ could have conceivably been taken from the slope of the curves in figure 21 but it was found that two important factors made empirical adjustments necessary. These were: (1) the adjustments due to linearization of the skip-out boundaries, (2) the adjustment due to the time required to roll to full negative lift. Thus the values $K_V = 0.00055$ g/fps and $K_{\dot{a}} = 11$ g/(g/sec) were found satisfactory.

The implementation of this equation requires the measurement of acceleration, acceleration rate, and velocity. It appears feasible that the acceleration and acceleration rate can be measured with a single strapped-down accelerometer. The measurement of velocity though is of the form:

$$V = V_i - \int_{t_i}^{t} (a_D + g \sin \gamma)dt$$

Because of the small flight-path angles characteristic of manned entry trajectories, the time integral of drag acceleration is sufficient to obtain an approximate measurement of incremental velocity changes. The measurement of the drag acceleration (a_D) which is needed in order to calculate vehicle velocity can be obtained from the strapped-down accelerometer; however, the mounting of the instrument relative to the spacecraft is an important

consideration. Figure 22 illustrates the method of finding the best mounting position to minimize uncertainties in the measurement of drag acceleration. On the top of the figure the measured acceleration is shown as a function of the orientation of the measurement axis. Uncertainties in the trim angle are shown to affect the measured acceleration. On the bottom of the figure the ratio of measured acceleration to drag acceleration, the quantity of interest, is shown. It can be seen that a mounting position of about $+45^{\circ}$ from the symmetrical body axis will allow a measurement directly related to the drag acceleration and will minimize the effect of uncertainties in the trim angle of attack.

From the foregoing discussion, it appears feasible for the pilot to use a strapped-down accelerometer and a warning display to monitor skip-out trajectories. Such a system would be independent of the primary guidance system.

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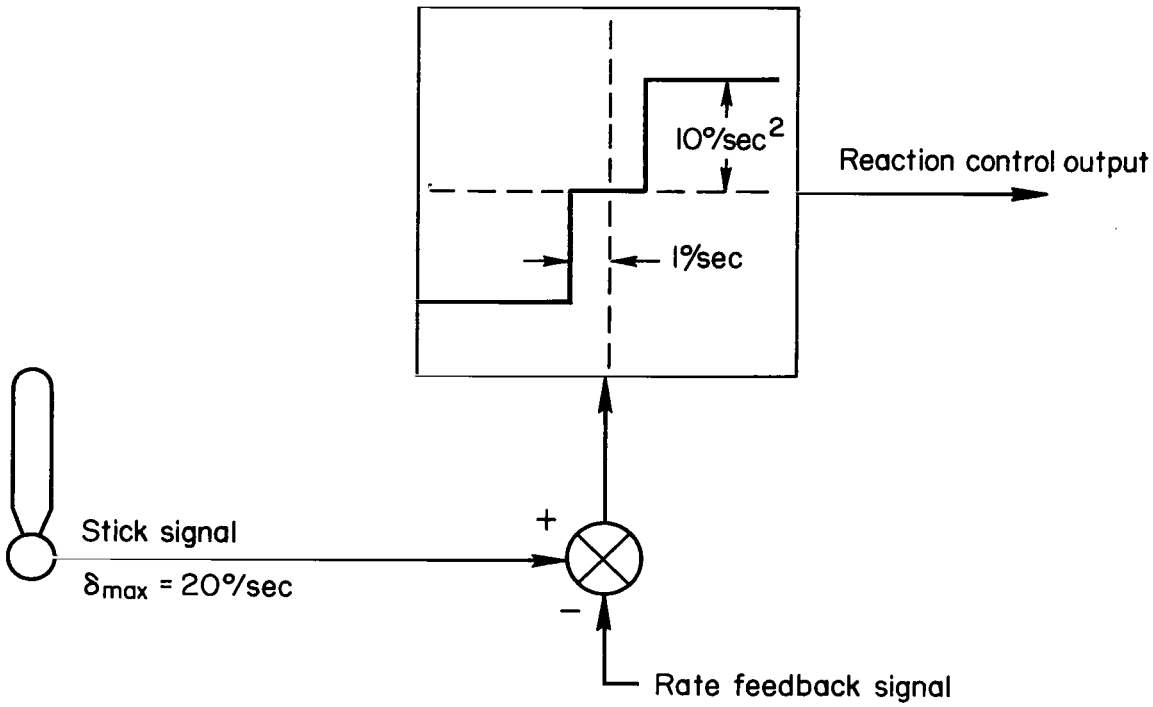
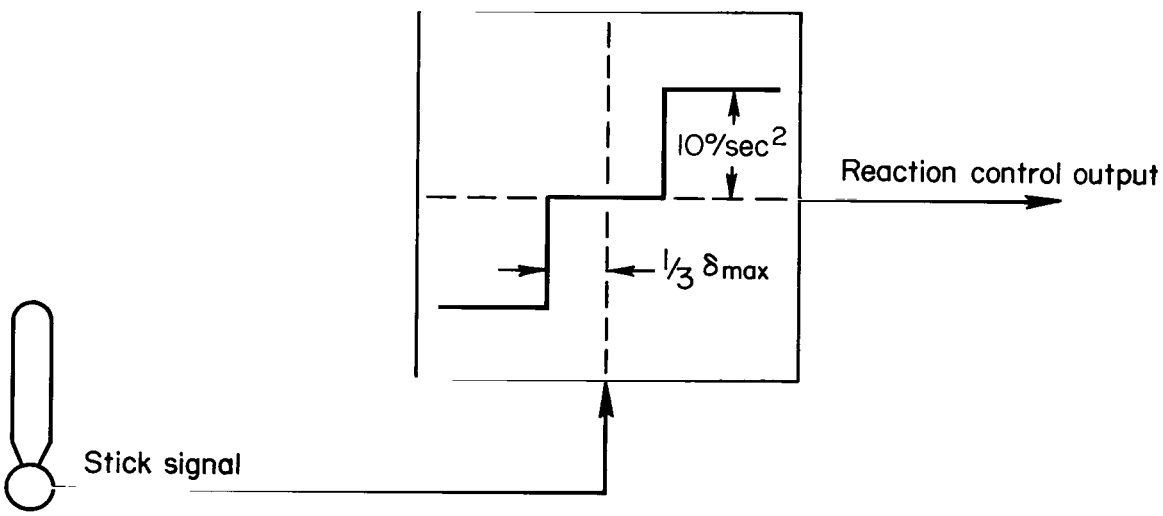
TABLE I.- PILOT OPINION RATING SCHEDULE

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[1]Failure of a stability augmenter



(a) Rate damping system.



(b) Direct command system.

Figure 1.- Simulated reaction control systems.

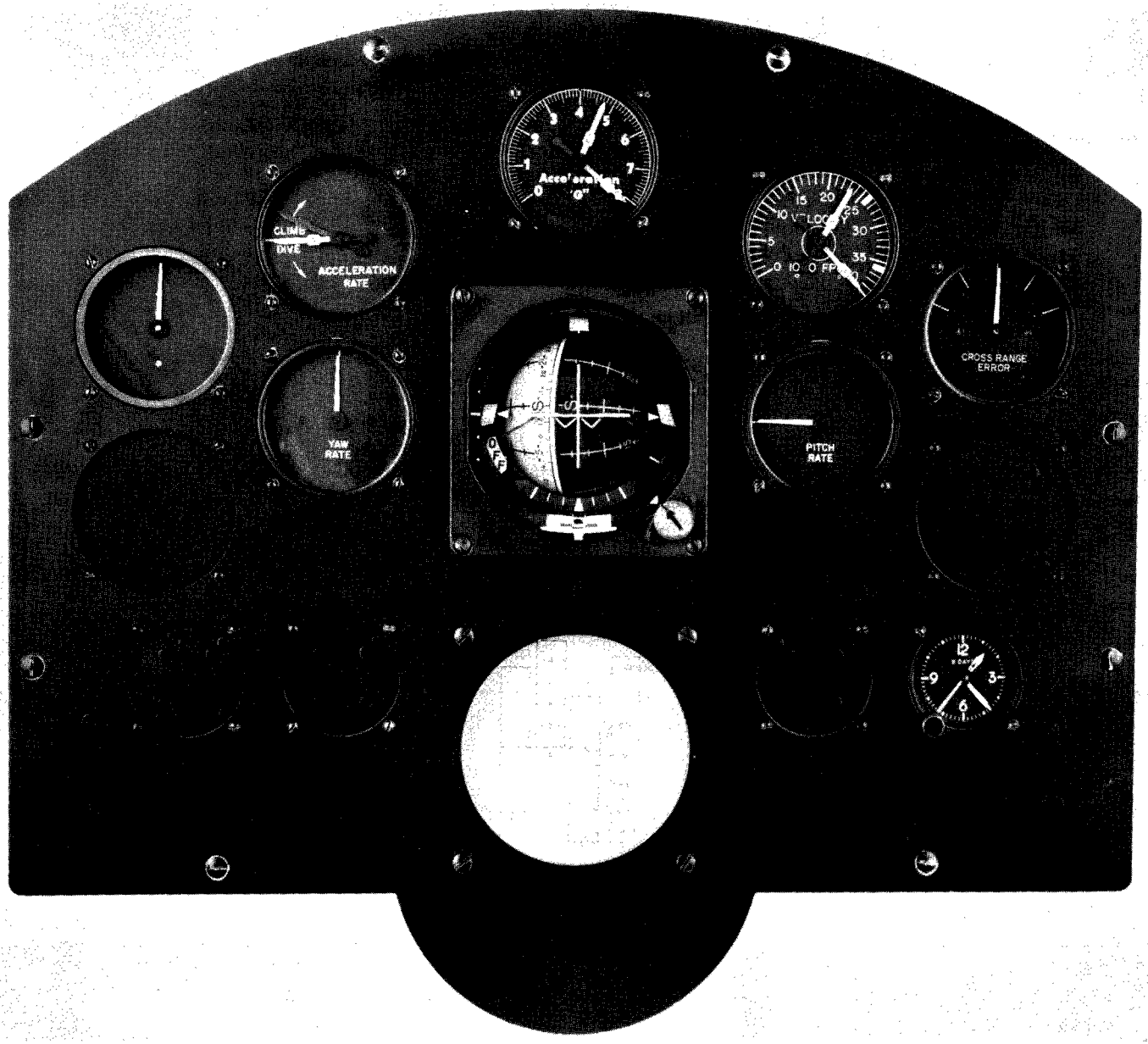


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Figure 2.- Pilot display.

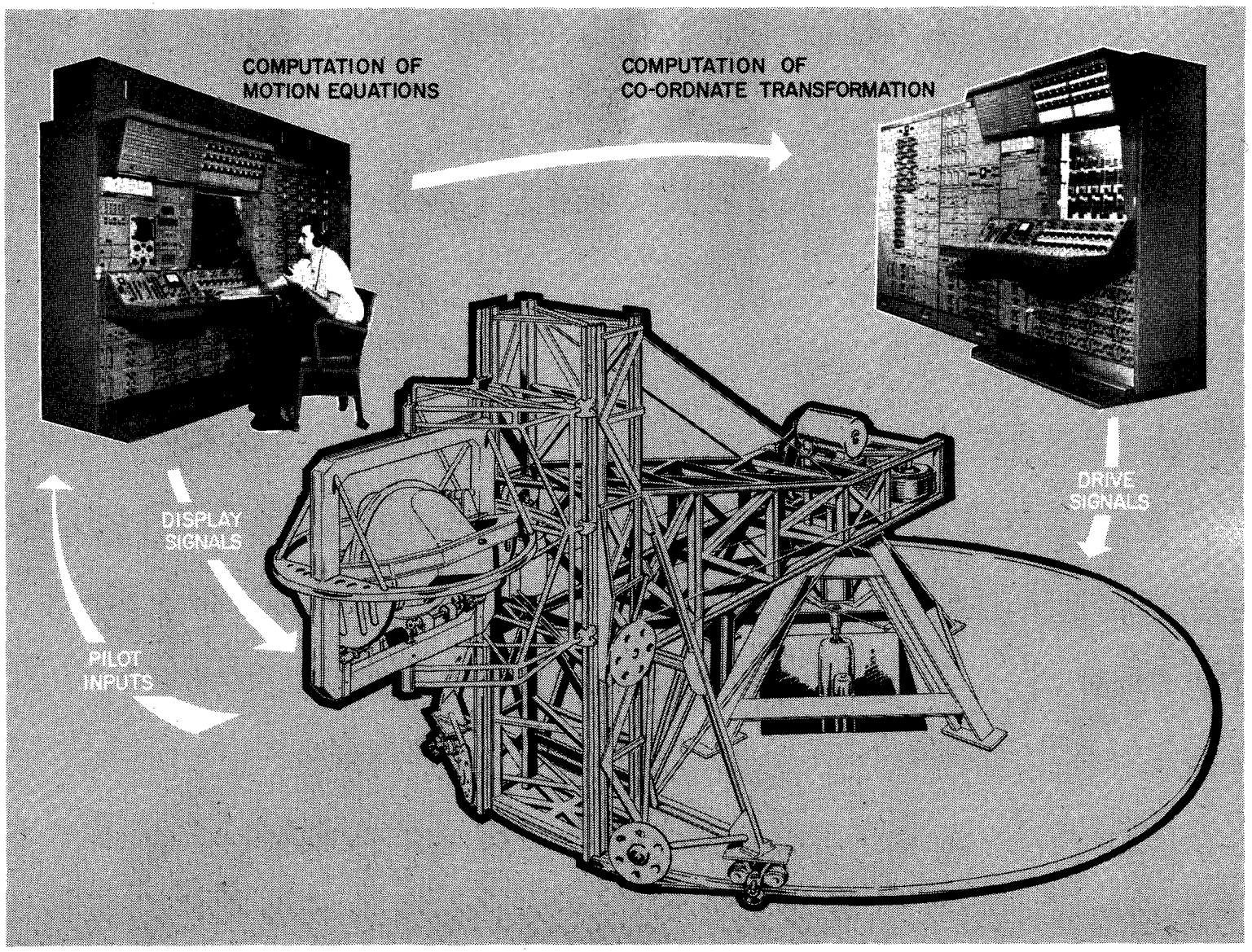


Figure 3.- Ames five-degrees-of-freedom simulator and associated computing equipment.

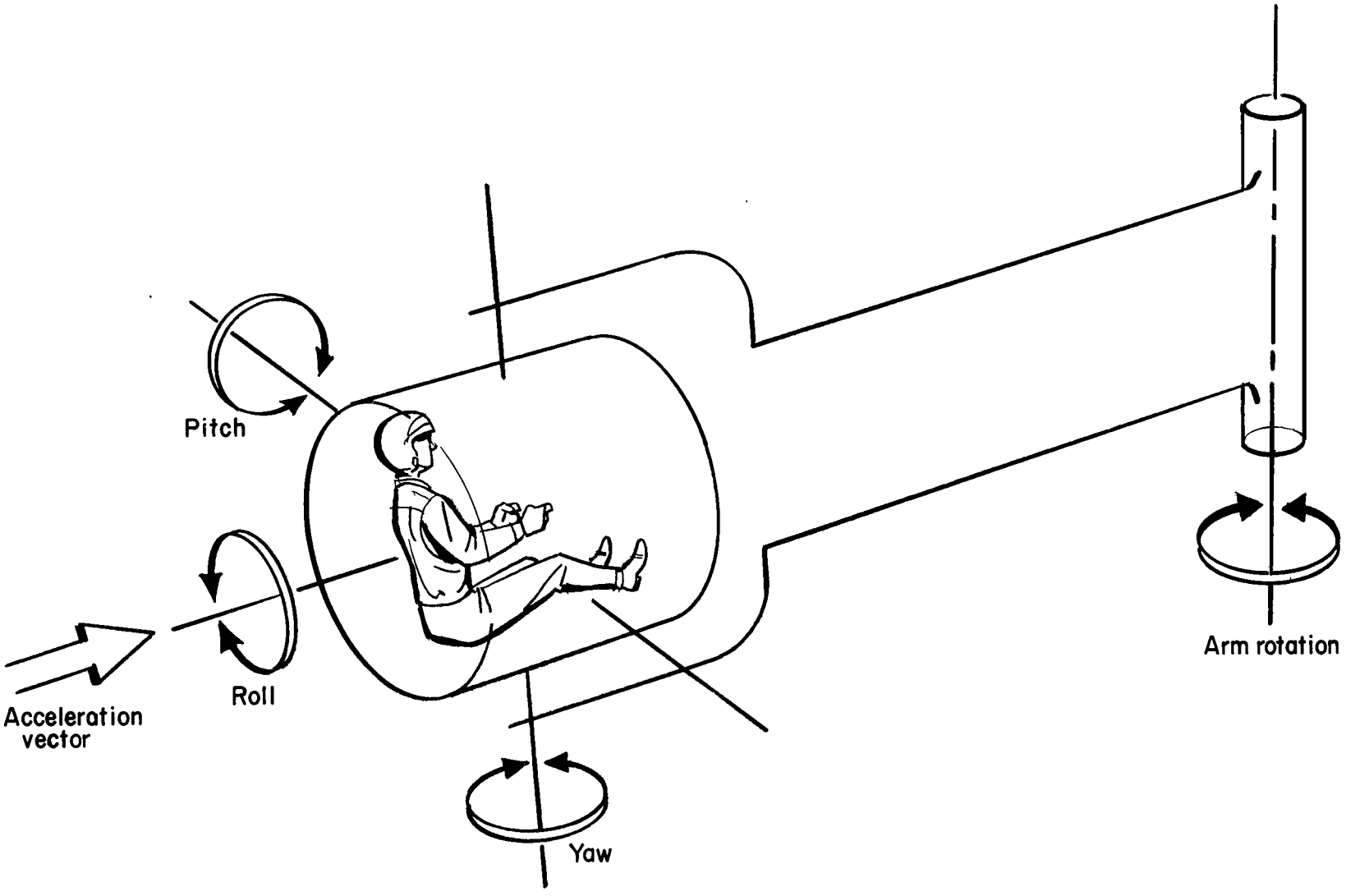


Figure 4.- Position of pilot with respect to motion simulator.

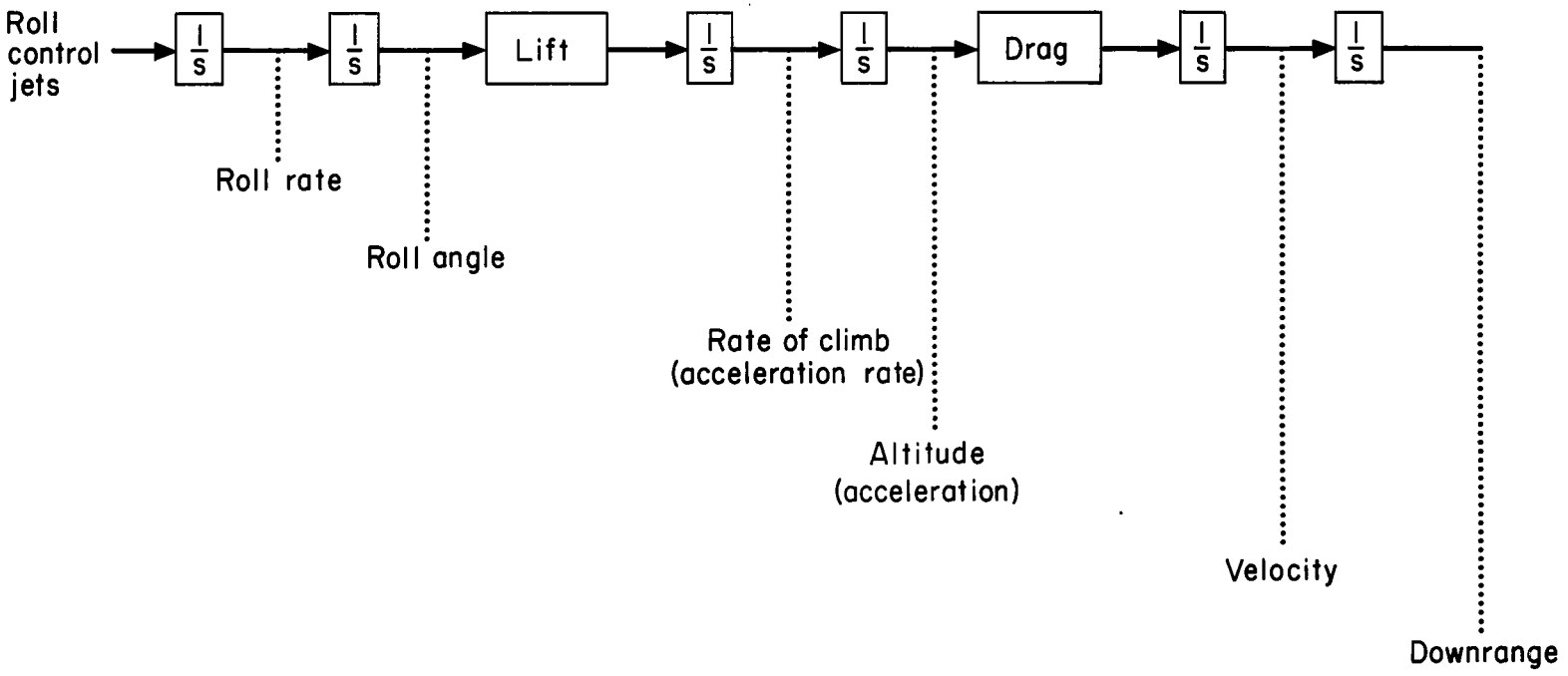


Figure 5.- Simplified block diagram of the control system and the entry dynamics in the plane of the trajectory.

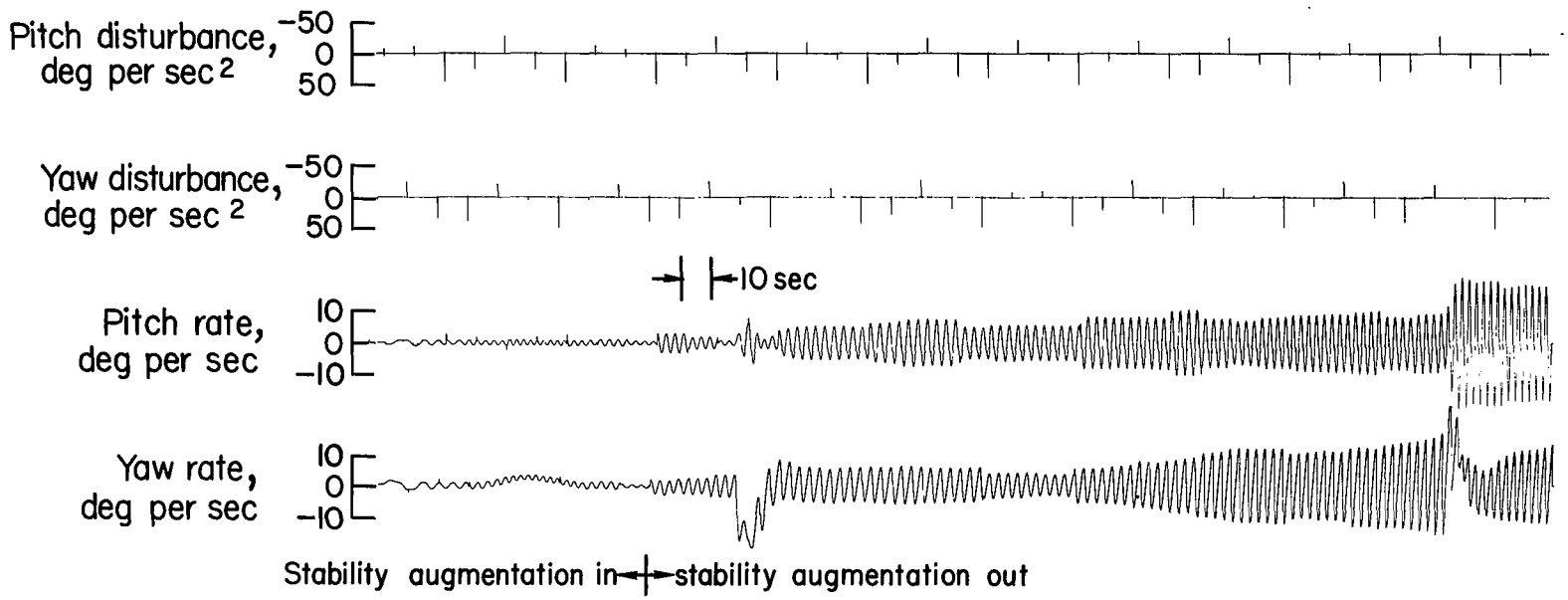
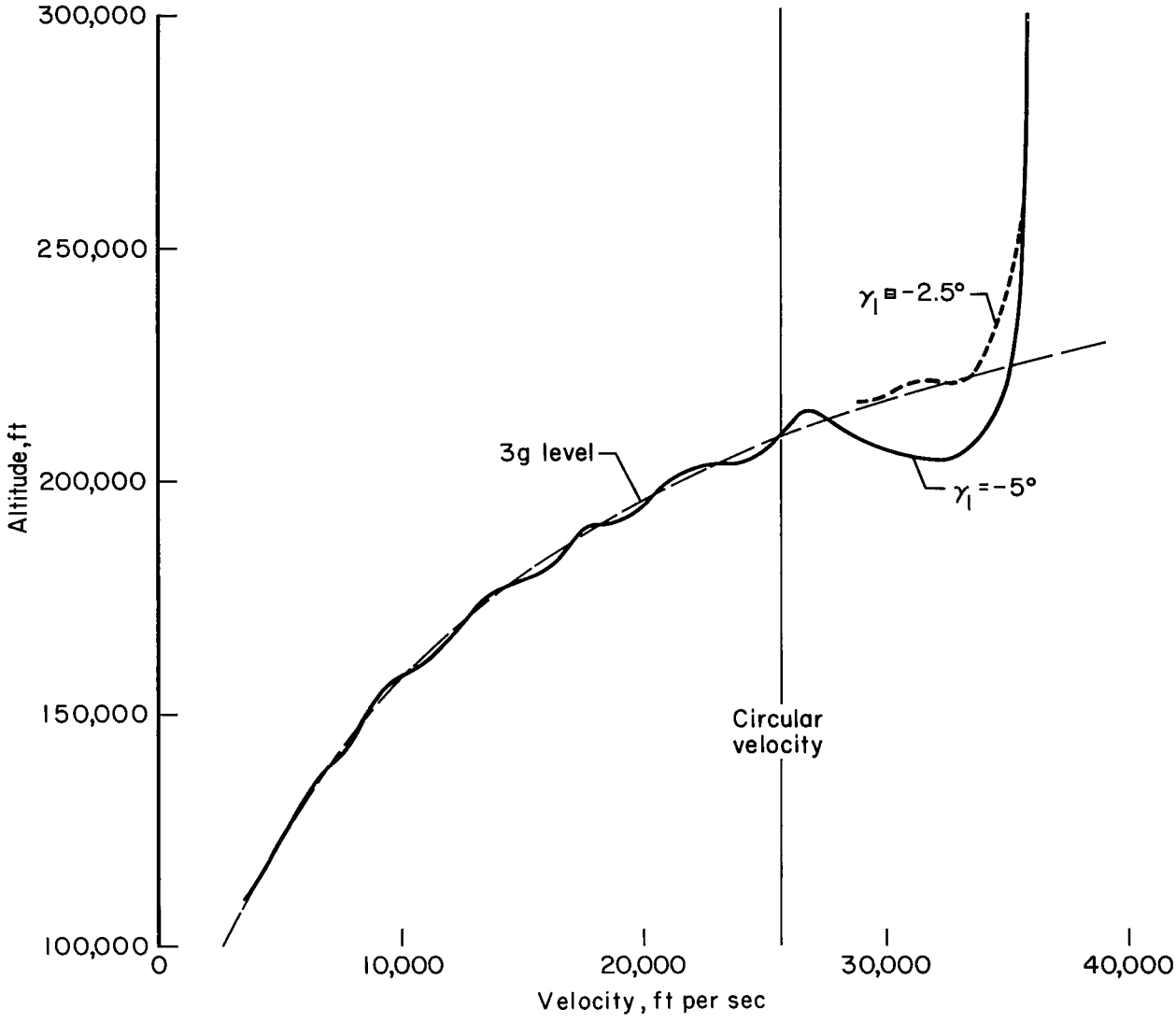
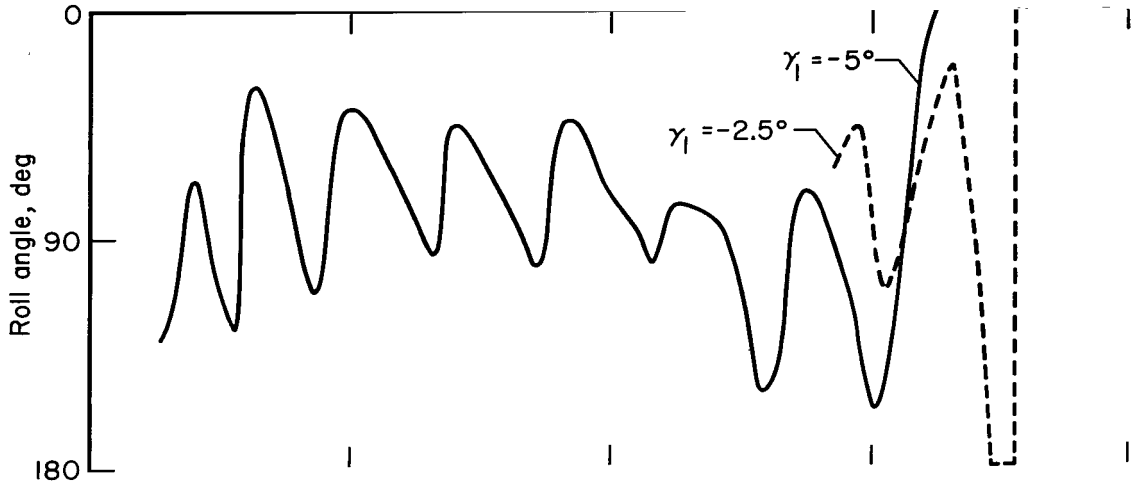


Figure 6.- Pitch and yaw oscillations with random disturbances.

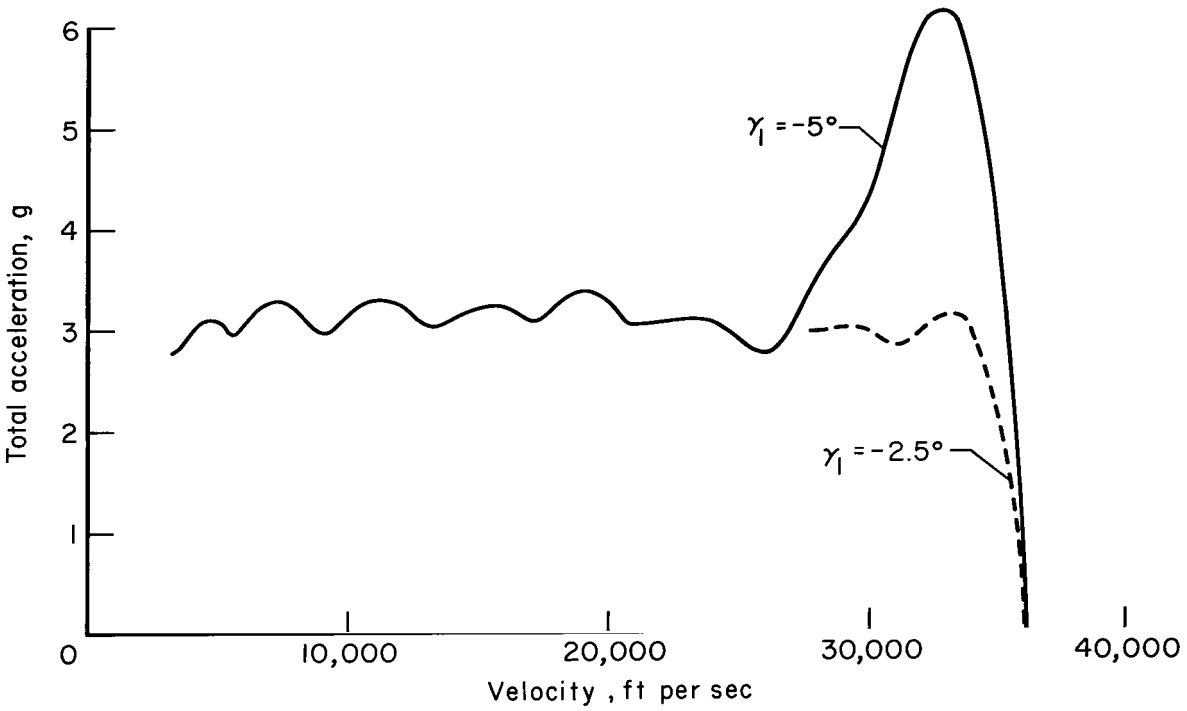


(a) Variation of altitude with velocity.

Figure 7.- Pilot control to the 3 g level; V_i = 36,000 fps, h_i = 300,000 ft, γ_i = -2.5° and -5.0°.



(b) Variation of roll angle with velocity.



(c) Variation of acceleration with velocity.

Figure 7.- Concluded.

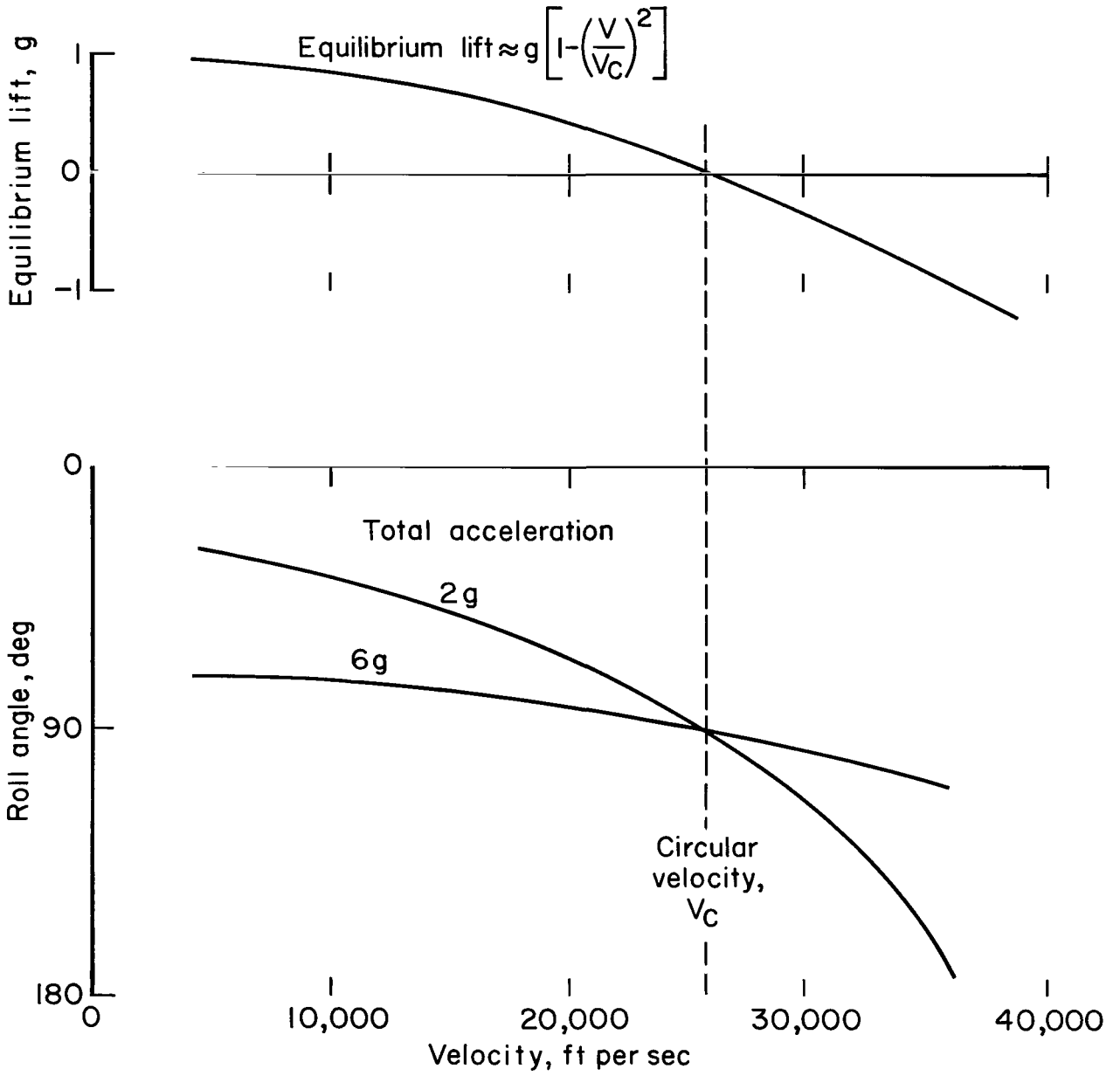
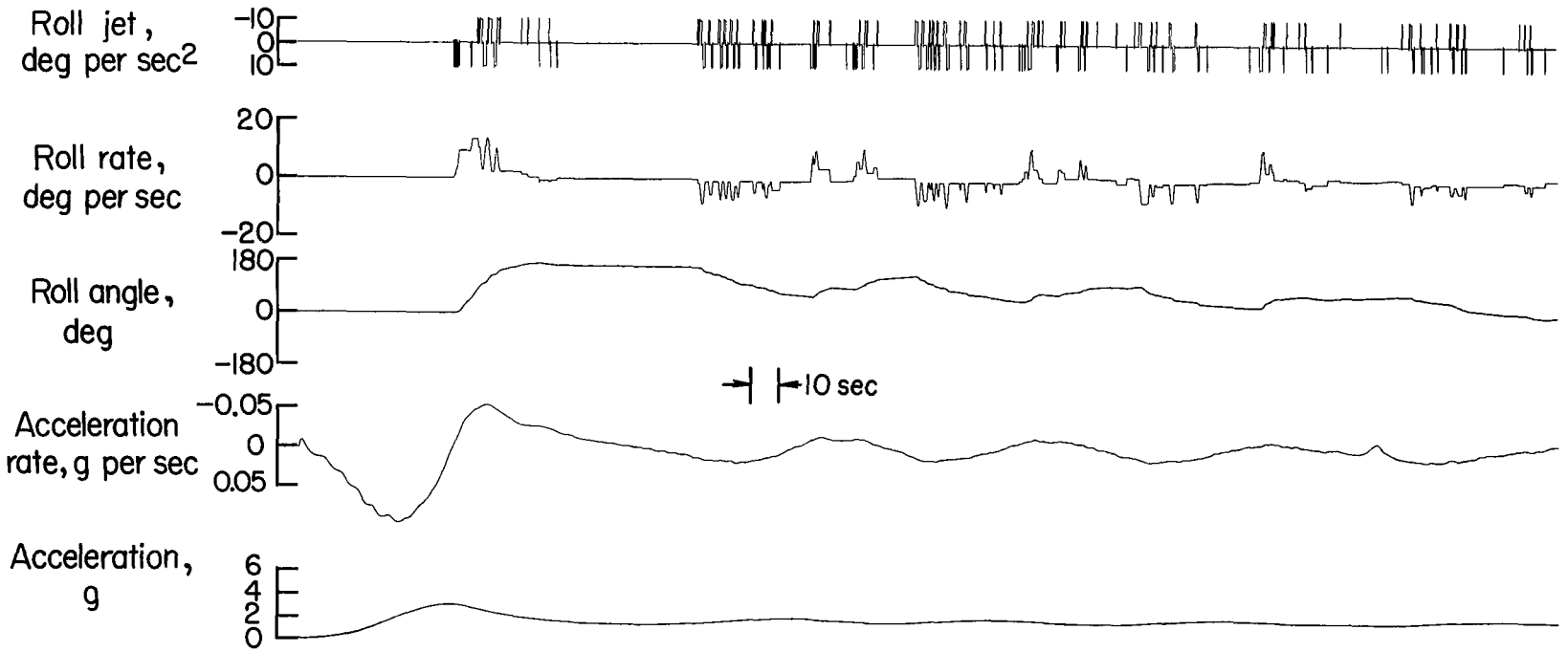
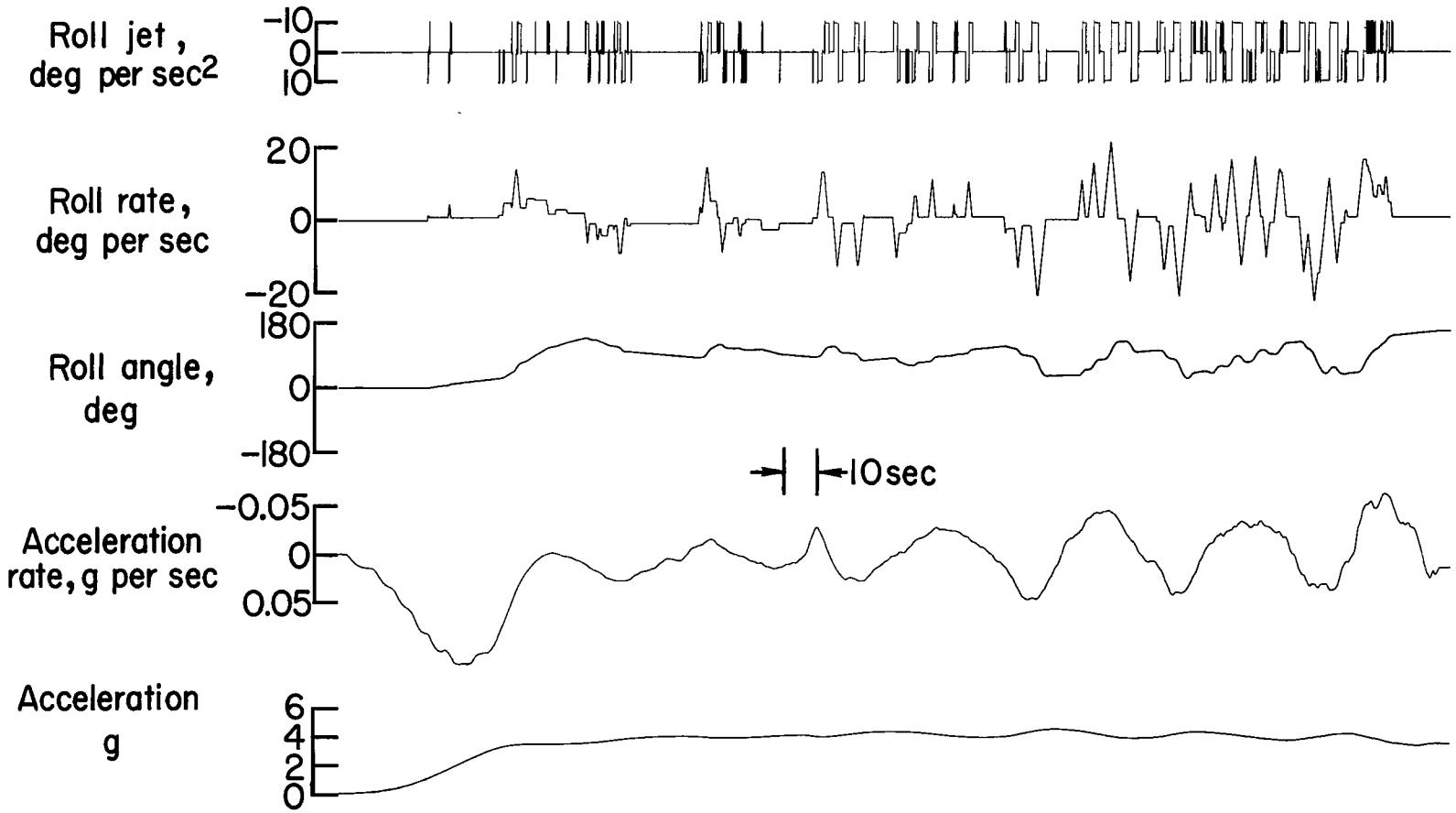


Figure 8.- Lift and associated roll angle required to hold an entry vehicle near equilibrium flight; $(L/D)_o = 0.48$.



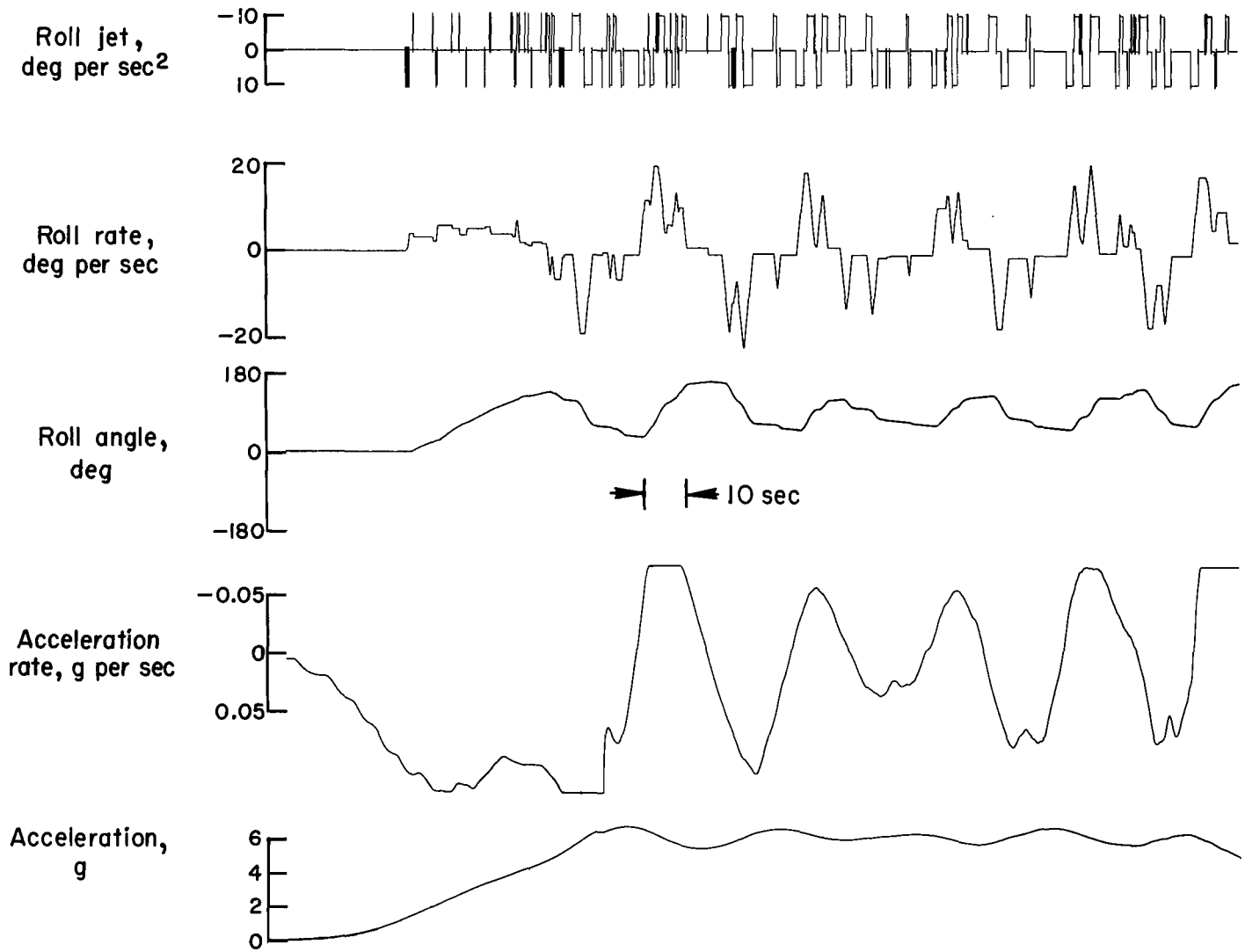
(a) Control to 2 g level.

Figure 9.- Pilot control to various acceleration levels; V_i = 36,000 fps, h_i = 300,000 ft, γ_i = -4.0°.



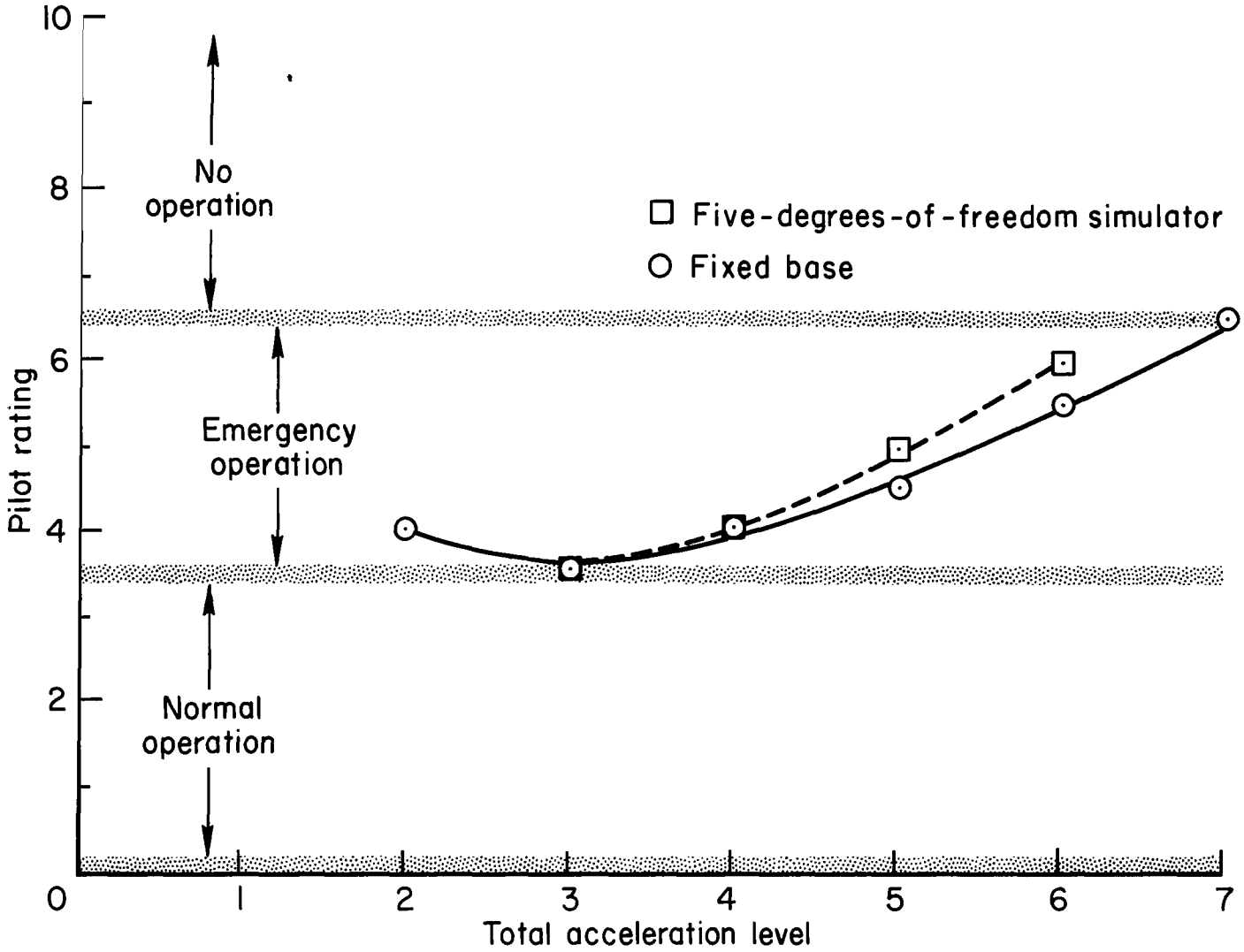
(b) Control to 4 g level.

Figure 9.- Continued.



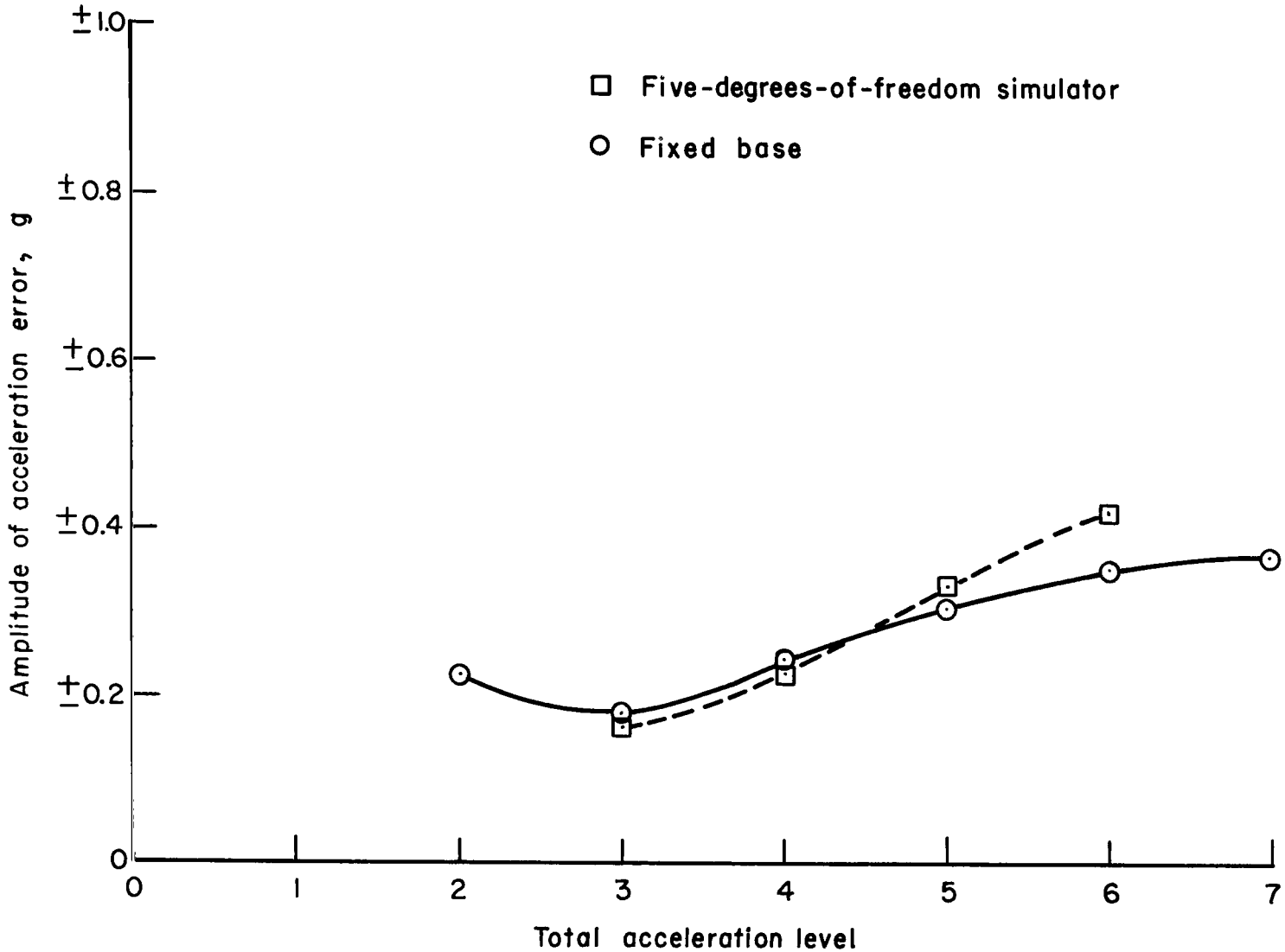
(c) Control to 6 g level.

Figure 9.- Concluded.



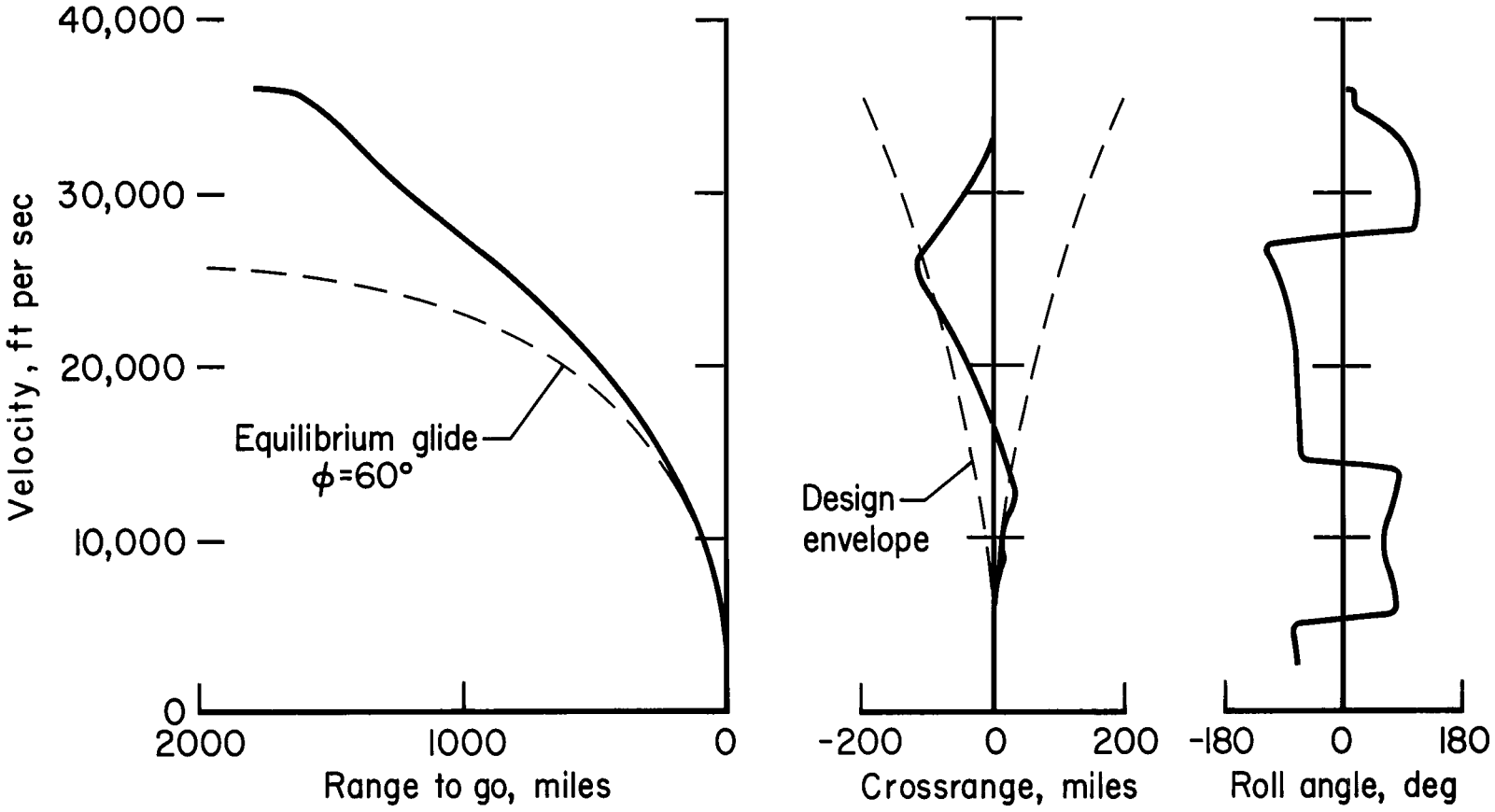
(a) Average pilot ratings.

Figure 10.- Pilot ratings and acceleration errors for control about given acceleration levels.



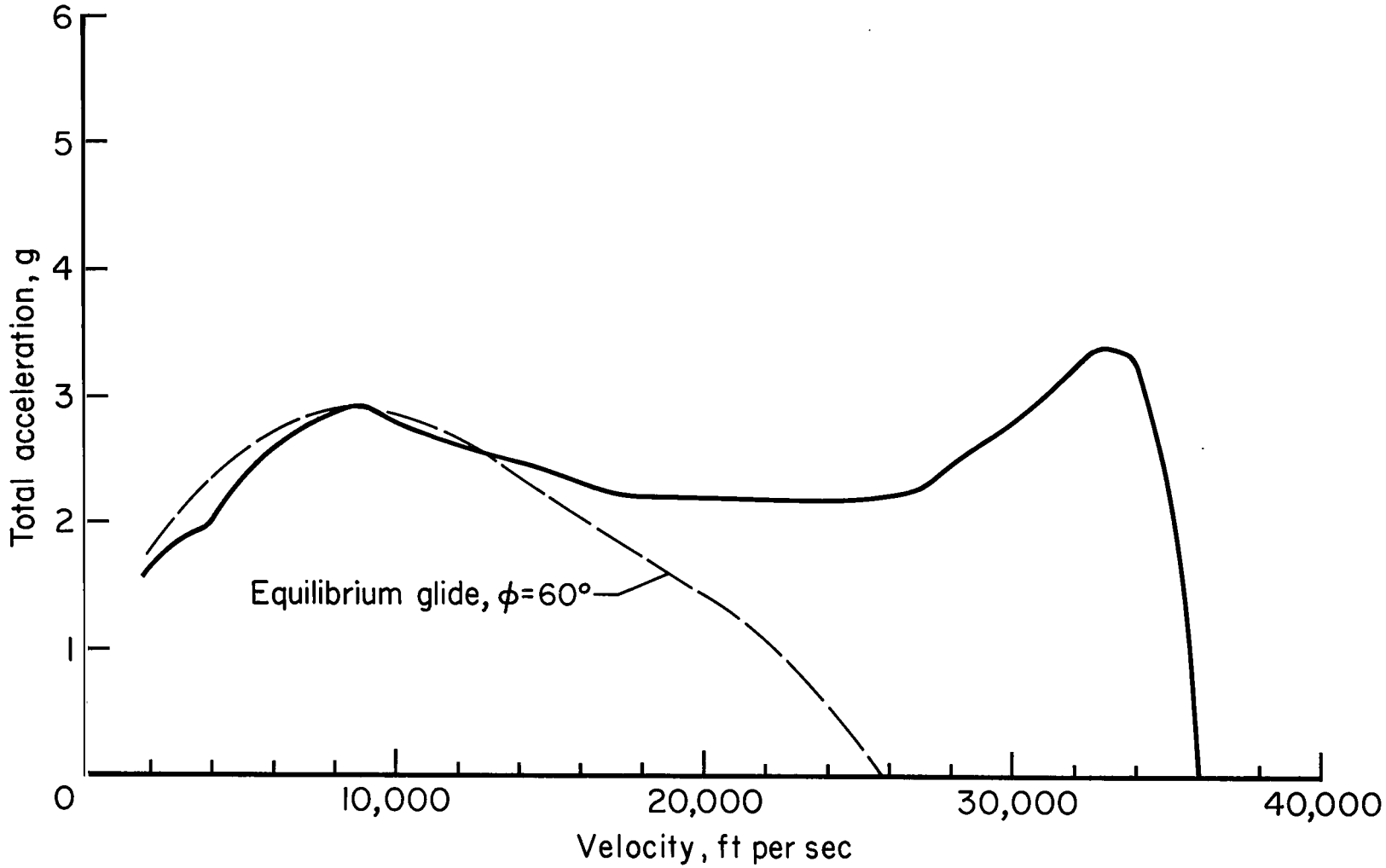
(b) Amplitude of acceleration error.

Figure 10.- Concluded.



(a) Variation of range to go, crossrange, and roll angle.

Figure 11.- Typical trajectory controlled onto subcircular ($\varphi = 60^{\circ}$) glide path; x_i = 1,800 miles, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^{\circ}$.



(b) Variation of acceleration.

Figure 11.- Concluded.

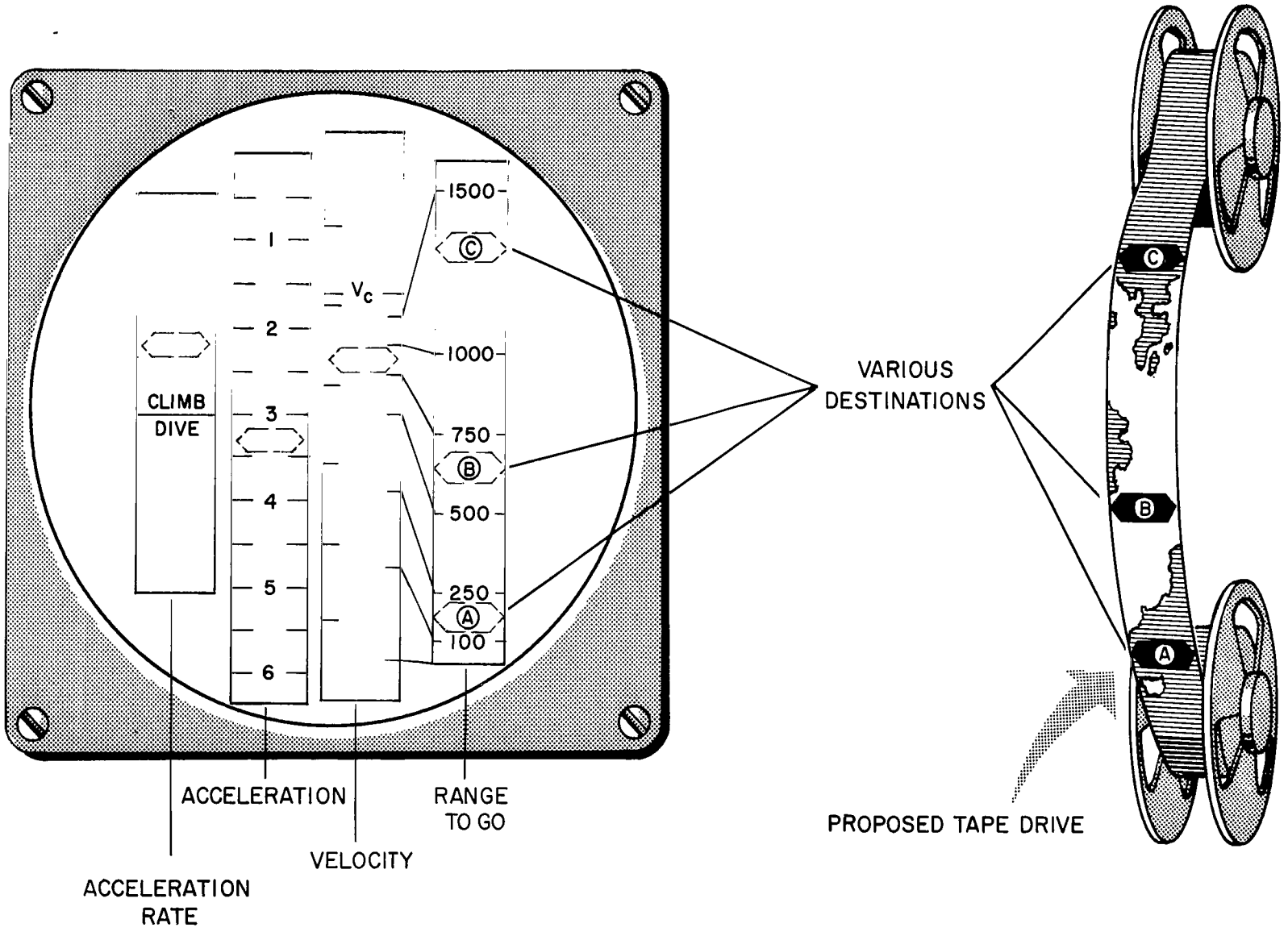


Figure 12.- Display for control of range with no command information.

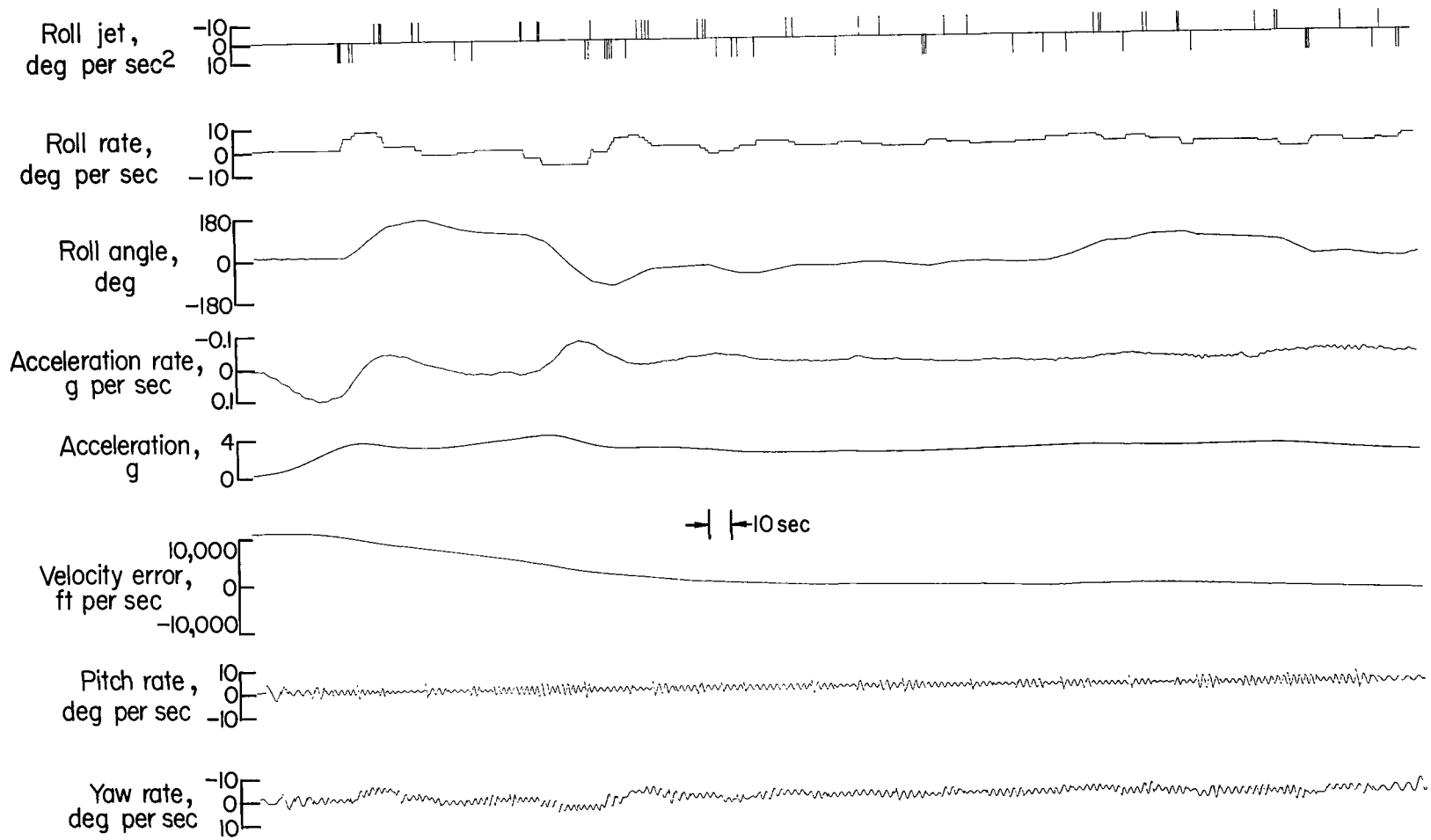


Figure 13.- Time history of pilot control with range display; stability augmentation out; V_i = 36,000 fps, h_i = 300,000 ft, γ_i = -4.0°, x_i = 1,800 miles.

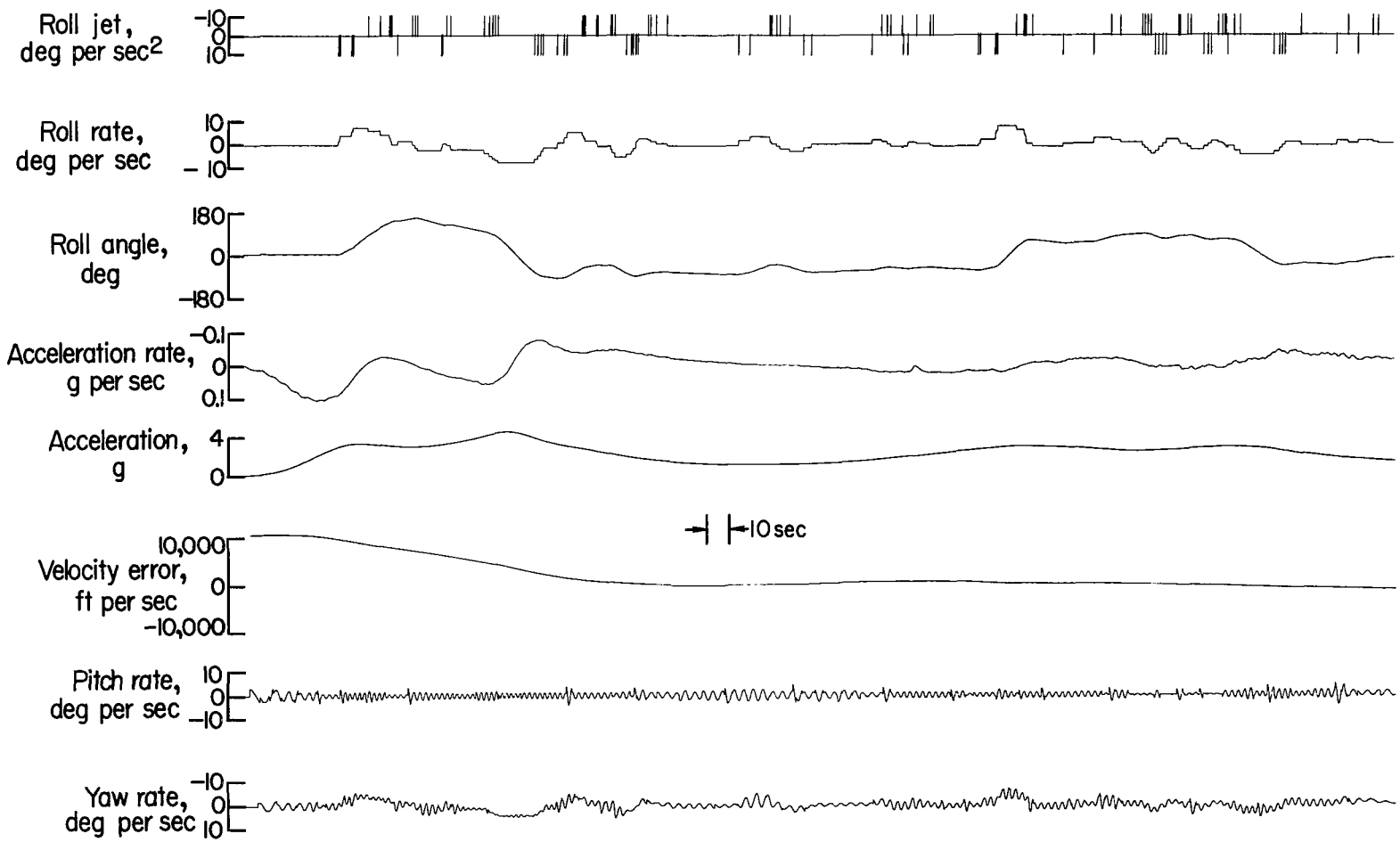


Figure 14.- Time history of pilot control with command velocity display; stability augmentation out, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^{\circ}$, x_i = 1,800 miles.

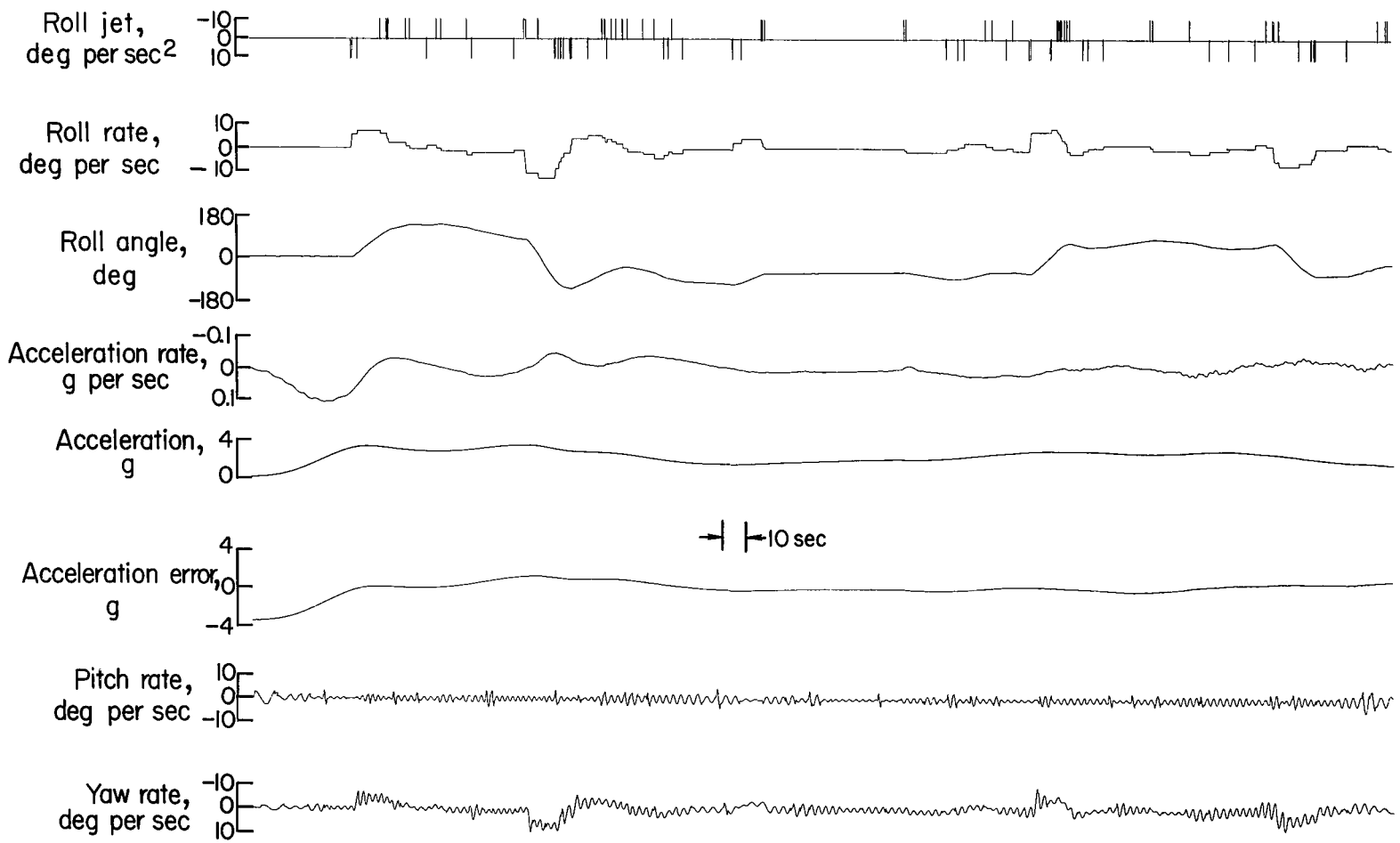


Figure 15.- Time history of pilot control with command acceleration display; stability augmentation out, V_i = 36,000 fps, h_i = 300,000 ft, γ_i = -4.0°, x_i = 1,800 miles.

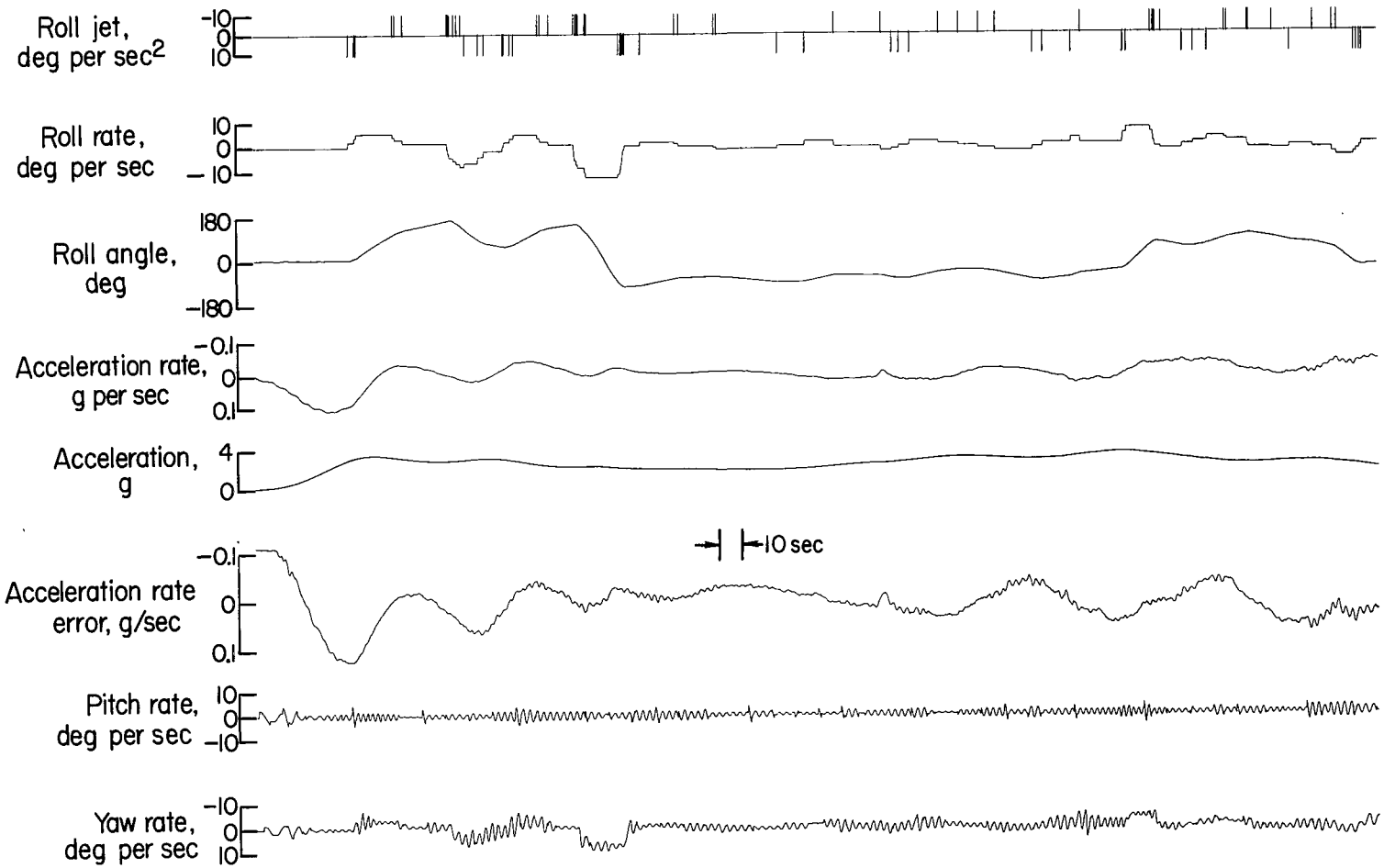


Figure 16.- Time history of pilot control with command acceleration-rate display; stability augmentation out, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^{\circ}$, x_i = 1,800 miles.

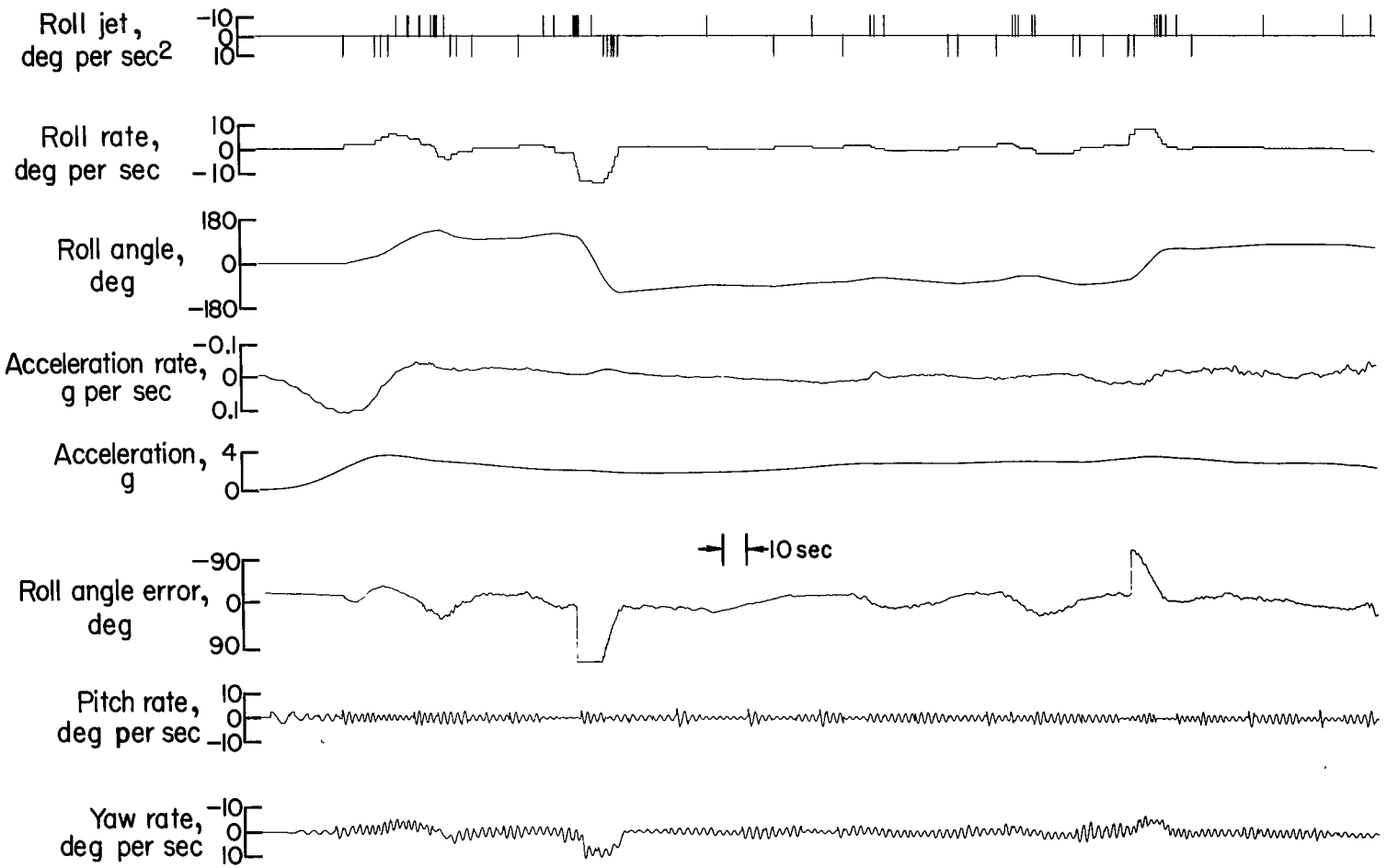


Figure 17.- Time history of pilot control with command roll angle display; stability augmentation out, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^\circ$, x_i = 1,800 miles.

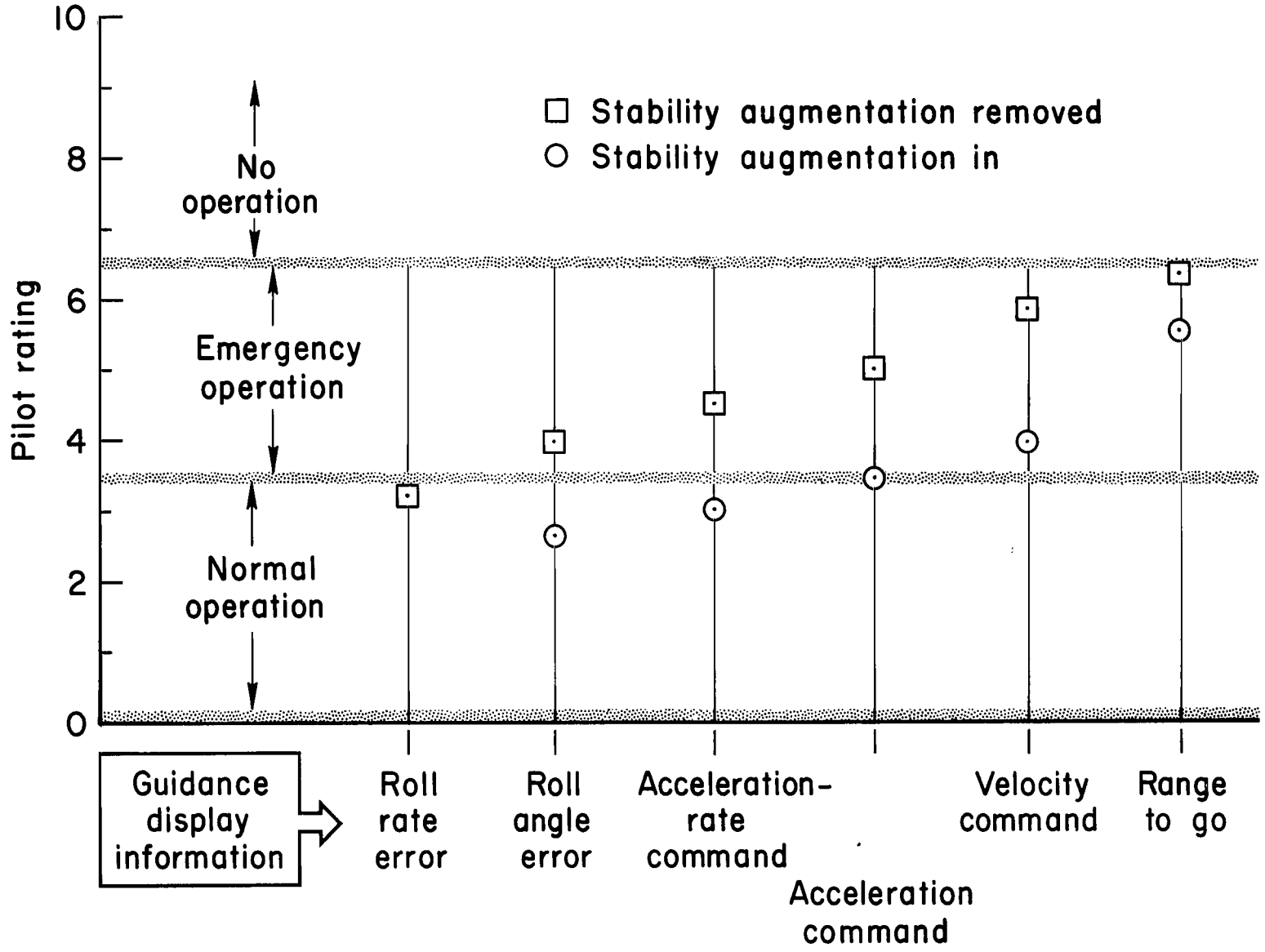


Figure 18.- Average pilot ratings for the various guidance and control tasks; x_i = 1,800 miles, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^{\circ}$.

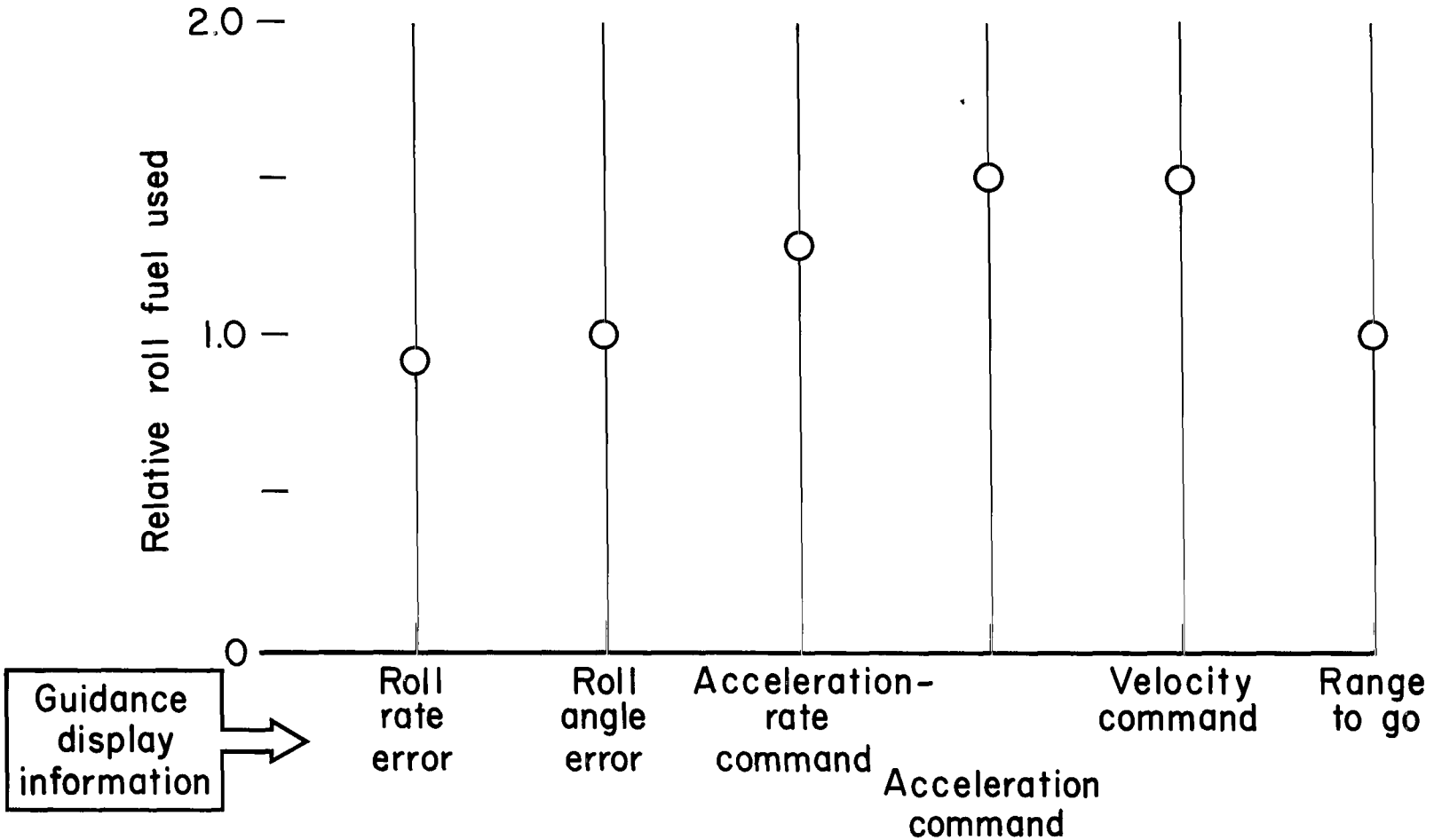
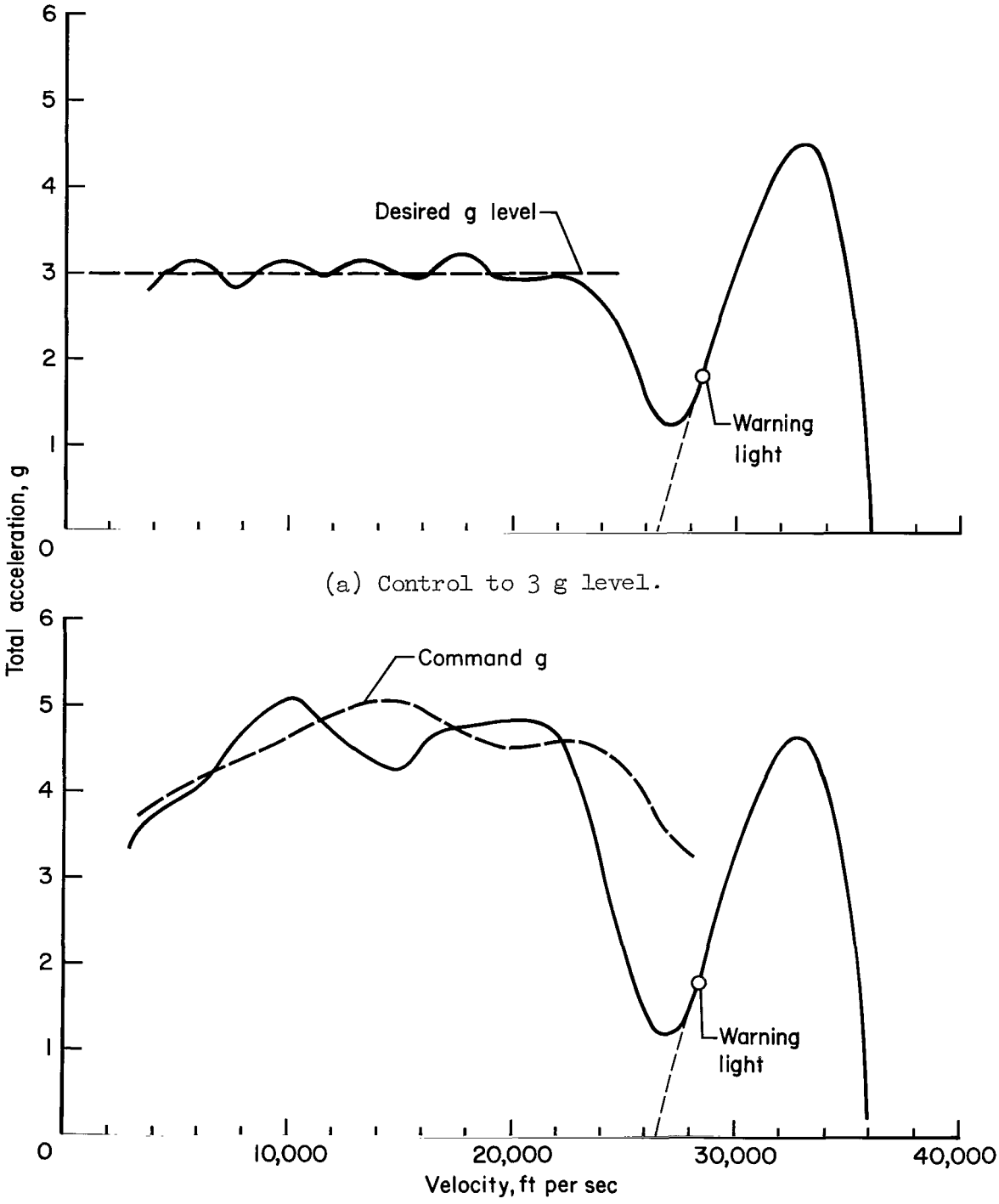


Figure 19.- Relative fuel used for roll jet during the guidance and control tasks; stability augmentation removed, x_i = 1,800 miles, V_i = 36,000 fps, h_i = 300,000 ft, $\gamma_i = -4.0^{\circ}$.



(a) Control to 3 g level.

(b) Control to command g.

Figure 20.- Piloted trajectories with transition from command roll angle display.

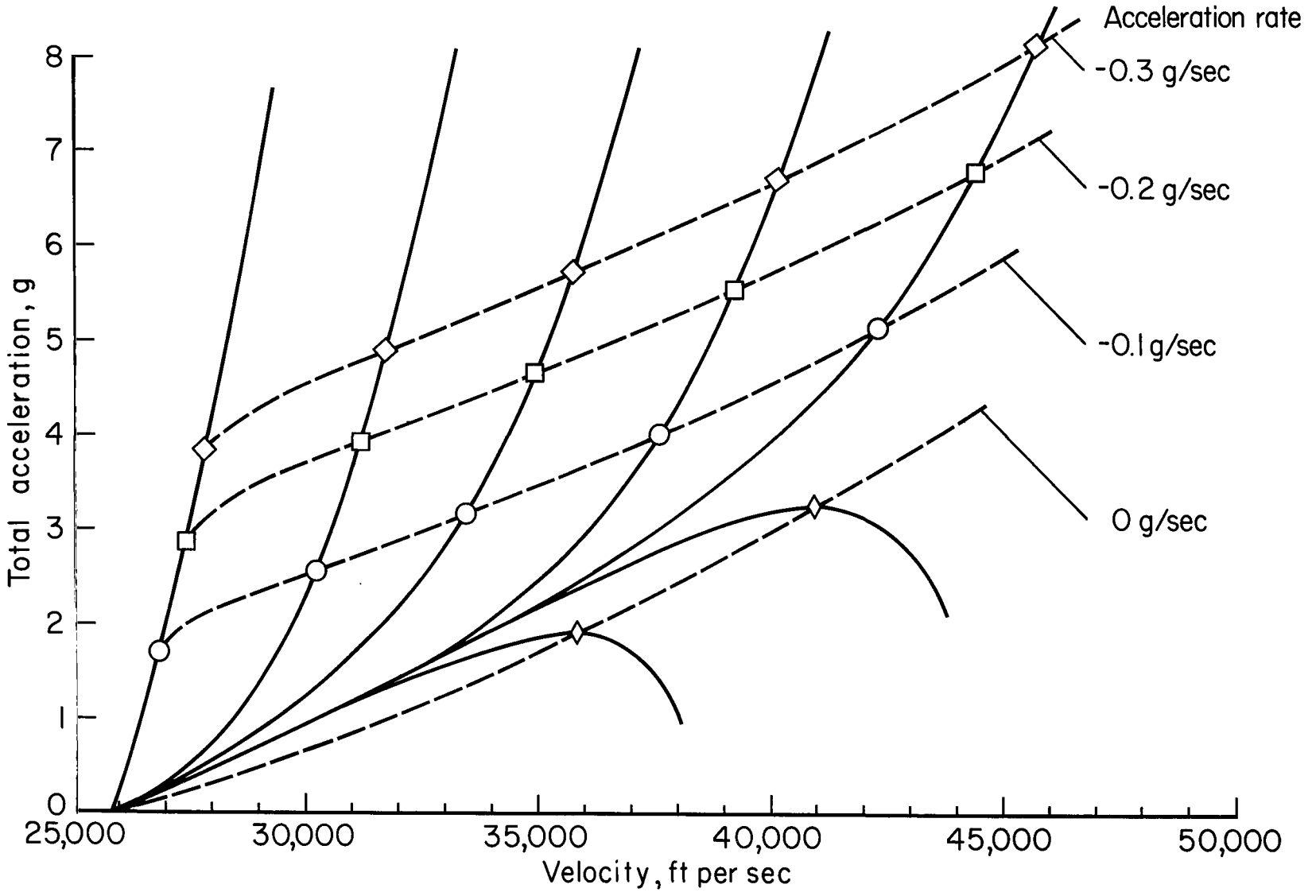


Figure 21.- Trajectories for an L/D = -0.4 vehicle which exits at 300,000 ft at a velocity of 25,753 fps (V_c).

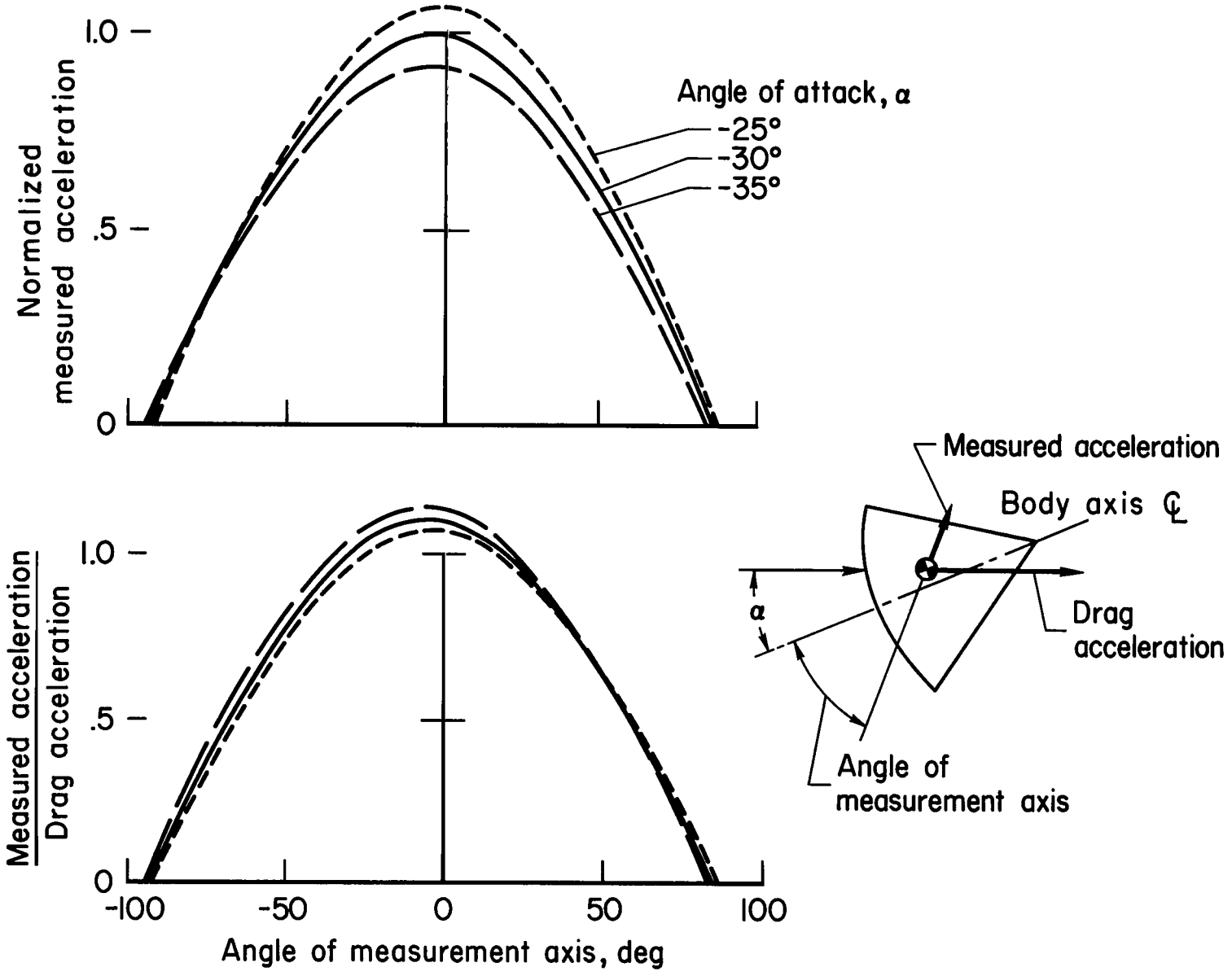


Figure 22.- Effect of acceleration measurement axis on the measured drag acceleration.

NASA-Langley, 1964 A-900

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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