NTE

HANDLING QUALITIES FOR PILOT CONTROL

OF

APOLLO LUNAR-LANDING SPACECRAFT

by

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Introduction

The lunar-landing maneuver, in addition to being a climatic point in the Apollo Lunar Landing Mission, presents perhaps the most critical problem of spacecraft control. To overcome some of the difficulties of avoiding local terrain obstructions while locating a good landing site and to utilize fully the crew's judgment capability, provision is being made for the astronaut crew within the lunar excursion module to take over from the automatic control system, select a suitable landing site, and control the landing touchdown. The ability of the astronaut to satisfactorily control this maneuver will depend upon the success of the design engineers in anticipating the nature of the control task and upon the subsequent provision of a control system satisfactory for the task. Because the gravitational environment of the moon differs from that of the earth, the astronaut will not have opportunity to practice this maneuver except under simulated conditions; hence, the success of anticipating the control requirements of the maneuver will only be known for sure after the first lunar landing has been made.

The control of the touchdown part of the lunar-landing maneuver will probably resemble the control of vertical take-off and landing (VTOL) aircraft in the earth environment. Some application of the wealth of information on VTOL handling qualities may thus be in order; however, the effects attributable to such factors as the differences in gravitational environment and differences in control-system mechanization must first be understood. From an overall standpoint, the time-critical aspects of the control of the landing-approach maneuver is such that there is little parallel experience in earth-atmospheric flight and the problem must be considered new and requiring careful examination prior to finalizing control-system design.

The purpose of this paper is to describe the lunar-landing maneuver in sufficient detail to allow appreciation of the problem of control and to present the results of simulation studies aimed at establishing handling qualities data upon which to base a control-system design.

Description of the Lunar-Landing Maneuver

The Apollo lunar excursion module (LEM) pictured in figure 1 must provide the means for retromaneuvering out of lunar orbit, decelerating to a soft landing, and then, after a stay on the surface, accelerating back into orbit for a rendezvous with the Apollo command module. These overall aspects of the LEM mission are portrayed in figure 2. Detailed analysis of the system requirements for performing these maneuvers have led to a design configuration having two stages (fig. 1). Staging would normally occur on the lunar surface so that the weight of the descent stage and the landing gear would not have to be carried back into orbit. An early design decision made in the interests of saving weight was to utilize a single attitude-control system to serve both stages. With a single attitude-control system, the possibility of control-sensitivity problems becomes important because the inertias of the spacecraft, due partly to staging, change by approximately an order of magnitude during the time from initial separation from the command module to the time that rendezvous is completed after the lunar landing. The landing maneuver, though it takes place about half way through the powered portion of the LEM mission, occurs before most of the change in moment of inertia. The result is that extreme care must be used in selecting control powers that will provide satisfactory landing control and, at the same time, avoid excessive control powers during the powered ascent and/or docking maneuvers.

Analysis of the descent maneuver, including consideration of operational factors for pilot manual control, have led to the three-phased trajectory design shown in figure 3. The descent trajectory covers approximately 200 nautical miles over the surface of the moon while the altitude is decreased from 50,000 feet to the surface. The first phase, which covers most of the distance traveled, is designed primarily to provide the most reduction in velocity for the least expenditure of fuel. The vehicle during this phase is oriented so that the thrust of the main engine is essentially opposite to the direction of flight. In this attitude, the astronaut crew will not be able to observe in the direction of the landing site because of the limited field of view afforded by the windows. As the landing area is approached, however, transition is made to the second phase where the spacecraft is pitched up to an attitude that allows the astronaut crew to begin observing the landing area. The planned position and velocity at the point of transition to the second phase is attained through explicit guidance and is planned to allow the approach to the landing site to be made at a deceleration level considerably lower than the maximum descent engine thrust capability. The advantage of the lower deceleration, obtained by reducing the throttle level of the descent engine, is that the rate of velocity change becomes more in line with the pilot's ability to keep track of the situation. This phase will last about 2 minutes, in which time the trajectory will cover 6 to 8 miles and the velocity will decrease from about 800 ft/sec to perhaps 100 ft/sec entering the final or touchdown phase. Even though the second phase is purposely lengthened in time duration, it represents a maneuver that has no parallel in earth-bound experiences of landing approaches. In addition to monitoring the large changes in velocity and altitude in this short phase, the pilot must also begin to evaluate the suitability of the landing area, to pick out a desired landing position, and to evaluate the need to take over and manually fly the final phase of the descent maneuver. All of this takes place in a period of time roughly equivalent to the time available to an airplane pilot during an instrument approach between the final checkpoint and the landing touchdown.

The third phase of the descent is called the touchdown phase, and it is within this phase that the spacecraft is pitched up to essentially a vertical attitude and flown much like VTOL aircraft. It is in this phase that the final selection of the touchdown position is made and the spacecraft is maneuvered to that position for the actual touchdown on the lunar surface. Translation velocities over the surface during this phase are controlled by tilting (roll or pitch) the spacecraft in the direction of the desired velocity change in order to utilize the horizontal component of the descent propulsion to accelerate the spacecraft in that direction.

Because of the similarity of the flight maneuver during the touchdown phase with that of VTOL aircraft, there is a temptation to limit the concern over the handling qualities of the LEM to just this phase and to extrapolate data for VTOL aircraft to the LEM handling qualities application. Although such data may have application to the LEM control problem, the large changes in the attitude of the spacecraft and the short time actually involved in the transition from the landing-approach phase to the touchdown phase must also be considered. The time-critical nature of the pilot task during the landing-approach phase may lead to important and significantly different handling-qualities requirements.

Description of Study Approach

General. The need for knowledge of lunar-landing control requirements preceeded the evaluation of contract proposals for the LEM, and thus the need, at least for preliminary information, was recognized some $2\frac{1}{2}$ years ago. At that time, such research facilities as the Lunar Landing Research Vehicle of the NASA Flight Research Center and the Lunar Landing Research Facility of the NASA Langley Research Center were both in the conceptual stage, and there were no flight vehicles suitable for other than extremely limited studies of the lunar-landing control problems. The decision was made to obtain the needed information through fixed-base simulation. After an initial study phase conducted under contract, the studies have been conducted in-house by the Guidance and Control Division of the Manned Spacecraft Center. The study has actually been a series of studies in which the simulation facilities and the fidelity of the simulated problem have grown as the knowledge of control requirements allowed the definition of the LEM control system. The studies, which will be described in the succeeding sections, represent essentially the growth of handling-qualities knowledge from the pre-LEM-contract period to the present time.

Information Requirements. The objectives of the simulation program were to provide answers to a series of questions about the LEM control system. The subjects of these questions were as follows: (1) required control characteristics, (2) effect of disturbance torques, and (3) effect of deadband and other control-system detail characteristics.

Description of Simulations

Cockpit

The handling-qualities studies have been implemented by coupling an analog solution of the dynamic equations of motion to fixed base, with partial simulation of the spacecraft cockpit containing pilot flight instruments and controllers. The simulations of the cockpit used for these studies have ranged from functional layouts (fig. 4) to arrangements that are almost identical to the current LEM vehicle (fig. 5). Flight displays used varied in arrangement for the various studies, but all included (1) an attitude indicator, (2) body-angular rates, (3) forward and lateral velocities, (4) altitude, (5) altitude rate, (6) main engine thrust-to-weight ration, and (7) main engine thrust. The downrange and crossrange landing-site location was indicated to the pilot on an oscilloscope for the studies using the cockpits shown in figure 4, but a virtual-image display of the landing was available to the pilot for the simulation using the cockpit of figure 5. The attitude controllers used have consisted of the pencil type shown in figure 4(a) which was used in the early studies, and the hand controller, shown in figures 4(c) and 5(a) which approximates the controller configuration of the LEM. Both were three-axis types. The main engine for these simulations were throttleable over a 10:1 ratio and were controlled by the throttle indicated in figures 4(c) and 5(a). Minimum throttle setting gave a thrust output which resulted in approximately $\frac{1}{2}$ of a lunar g (2.6 ft/sec^2) at landing-approach weights.

Equations of Motion

The equations of motion for the studies were for 6 degrees of freedom of the spacecraft over a "flat" moon. The simulations were concerned with flight operation within a few thousand feet of the lunar surface; therefore, in order to simplify equations, the gravitational field was assumed constant. The mass of the vehicle was varied but the moments of inertia were maintained constant. A flow diagram representative of the simulations is shown in figure 6.

Control System

The attitude-control systems covered in the studies included rate-command systems and an open-loop system where pilot actuation of the controller produced direct actuation of the attitude thrusters and a corresponding angular acceleration. The rate-command system is depicted by the block diagrams shown in figures 7(a) and 7(b). The study program included two variations of the thruster response to rate-error signals as shown in figure 7(a). Early studies assumed a linear thruster response, but considerations of limited thruster performance led to the quasi-linear thruster response where the thruster response is linear up to thruster saturation. Early design considerations of the LEM control system indicated the probability of utilizing thrusters which would operate either full on or off, and the simulation of such a system configuration is shown in figure 7(b). This simulated mechanization allowed variations in the electronics deadband shown in the on-off thruster logic block as well as variations in the thrust output levels. This electronic deadband should be separately recognized from the electro-mechanical deadbands that are incorporated in the pilot's control actuator to avoid inadvertent control input coupling.

Test Maneuver

The test maneuver, which was utilized in evaluating the attitude-control system, resembled the latter part of the lunar-landing approach maneuver previously described and pictured in figure 3. For most of the early studies, the initial limits of the run were approximately 3,000 feet uprange and 1,000 feet crossrange from the intended landing site. Initial altitude was 500 feet and velocities ranged from 0 to 50 ft/sec. The pilot was instructed to proceed from his initial point to the landing site, establish a momentary hover over the site, and then execute a touchdown. Later in the series of studies, the approach maneuver was started at ranges of up to 50,000 feet, altitudes to 15,000 feet, and velocities of the order of 1,000 feet/sec. Throughout the studies, the hovering portion of the maneuver was used to obtain evaluation data that were later verified during the longer duration landing approaches.

Test Subjects

Throughout the studies of handling qualities, the test subjects were principally currently qualified pilot engineers attached to the Manned Spacecraft Center Flight Crew Support Division. In the later studies where the cockpit simulators began to resemble that of the LEM spacecraft, astronauts also participated in the evaluation.

Results and Discussion

Rate Command

Proportional Thruster Operation. The evaluation of lunar-landing handling qualities utilizing a rate-command attitude-control system with proportionally firing thrusters resulted in curves which defined boundaries of satisfactory, acceptable, or unacceptable control as shown in figure 8. The curves, or boundaries, are plotted for combinations of controller sensitivity in deg/sec^2/in. and time constant. While the boundaries have been shown as distinct lines, there is a degree of uncertainty associated with their determination, and thus they would be more appropriately shown as bands separating the various areas. These lines, however, represent very nearly the center of the bands of uncertainty, and can be used to evaluate control characteristics, providing the bands are considered in the final evaluation. The boundaries shown are applicable to both pitch and roll. For yaw control, a limited amount of test data indicated a slightly larger area of satisfactory control, but not enough to warrant a separate figure. Tests conducted on the quasi-linear (limited thruster output) control system indicated that the pilots rated this system very nearly the same as the linear system, and thus, the boundaries of figure 8 are also applicable to the quasi-linear control mechanization.

On the log-log scale used in figure 8, most of the satisfactory and acceptable boundaries consist of straight-line relationships of controller sensitivity and time constant. These straight lines are lines of constant rate command and are equivalent to an upper rate command of 35 deg/sec/in.

and a lower value of 10 deg/sec/in. for satisfactory control. Acceptable control-rate commands are equivalent to 90 deg/sec/in. and 5 deg/sec/in. for the upper and lower boundaries, respectively.

The results shown in figure 8 indicate that satisfactory handling qualities can be obtained over a wide range of controller sensitivities, providing the time constant is related as shown to the sensitivities. It was recognized early that the controller sensitivity of the LEM would be low, as a consequence of the limited available control power, and these studies pointed out quite clearly that there was a small area of controller sensitivities less than about 10 deg/sec^2/in. that would provide satisfactory control operation.

The results presented in figure 8 indicate that satisfactory handling qualities for lunar-landing vehicles can be obtained at significantly lower controller sensitivities than VTOL aircraft. This is apparent from the satisfactory boundary for VTOL plotted on figure 8 (obtained from ref. 2). However, the primary difference lies not so much in the spread of controller sensitivities as in the extremely large differences in the absolute values of control power required to obtain satisfactory handling qualities in the two vehicles. The controllers used in the present studies had throws of approximately 1 inch, and thus the sensitivity of figure 8 is almost a direct measure of available control power, whereas the vertical/short take-off and landing (V/STOL) aircraft used a center stick which had a throw of several inches. The available control power in the V/STOL is the product of controller throw and controller sensitivity. For the lunar-landing vehicle, the pilot would be able to command and use the maximum control power with small displacements but, as indicated in reference 2, V/STOL control sensitivity is not only higher, but requires many times the available LEM control power to obtain these sensitivities. Another factor contributing to the differences in controller sensitivity is that of reduced lunar gravity, but precisely how much this effects handling qualities and controller sensitivities is not known, since investigations in this area have been limited. Sufficient tests have been made, however, to indicate the environment does have some effect.

The straight-line relationship between controller sensitivity and time constant indicated on figure 8 leads to the conclusion that the important parameters are rate command and time constant rather than controller sensitivity and time constant. This is a logical conclusion, since it seems the describing parameter for a rate-command attitude control system should be rate command. For this reason, the curves of figure 8 have been replotted, based on maximum rate command and time constant as shown in figure 9(a). The upper and lower boundaries for satisfactory operation are located at maximum rate commands of 34 deg/sec and 10 deg/sec, respectively, for time constants of less than about 1.2 seconds. The inference here is that maximum rate command is the important parameter, and, within a satisfactory range of this variable, the pilot will tolerate time constants of up to 1 second. Such an inference is reasonable, because, for low control powers, a high maximum rate is undesirable because of the time required to reduce high rates once they have been commanded. For large control powers, there exists for the pilot an upper limit of rate which provides safe maneuvering, although this is probably more influenced by controller sensitivity than the actual rate. The lower rate limit is set by what the pilot believes necessary to perform a given maneuver.

On-Off Thruster Logic Operation. Investigations during the proportional thruster studies indicated handling qualities could be improved by increasing the thruster on slope from its normal 1:1 ratio (fig. 7(a)). The reason for the noticeable improvement is that as the thruster-on slope is increased, the proportional operation approaches the characteristics of an on-off thruster logic. With the on-off thruster logic, full thruster output is always used to change attitude rather than an output proportional to the difference between actual and commanded rates. This is particularly significant for small attitude-rate changes, for the maneuver is made rapidly because of the large control moment employed. For large rate changes, the difference between proportional and on-off thruster-system response is not large, but it is still noticeable.

To investigate the effect of on-off thruster operation on handling qualities, further studies were made using the refined control mechanization shown in figure 7(b). This control system arrangement had, as far as the pilot is concerned, almost identical response characteristics to the control system employed in the LEM spacecraft. The results of the studies in a control system having a rate deadband of 0.1 deg/sec are given in figure 9(a). The satisfactory boundary has been plotted as a function of maximum rate command and time constant, although time constant has no meaning for a non-linear system. However, using the normal definition of time constant (time to reach 63 percent of commanded value) allows the proportional and on-off thruster operation to be plotted and discussed in similar terms. As indicated in figure 9(a), the satisfactory region extends from rate commands of 10 to 100/deg/sec for time constants of up to 5 seconds. The upper limit on rate command is probably not closed as shown by the dotted line, as the upper boundary is a function of controller sensitivity and this was not varied during the study. There is, however, a significant improvement of the satisfactory region over the proportional thruster region discussed previously. In fact, the satisfactory boundary for the on-off thruster operation is almost as large as the acceptable region for the proportional thruster operation. No attempt was made to obtain the boundary for acceptable control and thus the region beyond the satisfactory boundary has been described as "acceptable for emergency operation only".

Effect of Deadband on On-Off Thruster Operation Handling Qualities. The effect of the size of the rate deadband on handling qualities of on-off thruster operation was also determined. A knowledge of this effect was necessary, since the rate deadband must be incorporated into the control logic to prevent inner loop instability and to also limit attitude fuel usage during steady-state control operation. There are, however, trade-offs associated with the selection of the proper deadband, for a small rate deadband results in excessive fuel consumption, and large deadbands cause high residual rates with the attendant drift from a selected attitude. The deterioration in handling qualities resulting from increased rate deadbands is shown in figure 10. The satisfactory boundary decreases as the deadband is increased from 0.1 deg/sec to 1.0 deg/sec, although the deterioration in handling qualities is not appreciable until the deadband has been increased beyond 0.5 deg/sec. As noted before, the chief reason for derating as the deadband is increased is the high residual rates which force the pilot to concentrate heavily on attitude control to the neglect of other flight variables. The primary effect of increased deadbands is to increase significantly the lower satisfactory boundary. The pilot desires high rates to compensate for attitude drift, although increasing the controller sensitivity might produce the same effect. In addition, the control power required to obtain satisfactory handling qualities for a deadband of 1.0 deg/sec is almost twice the minimum required for a 0.1 deg/sec deadband. This can be seen by drawing lines through the original tangent to the lower boundaries of the 0.1 and 1.0 deg/sec curves and calculating the slopes of the two lines.

The upper boundaries for the three deadbands in figure 10 are shown as dotted rather than solid lines. Actually, the upper boundaries for the 0.5 and 1.0 deg/sec deadbands were determined, but as they are functions of controller sensitivity (which was not varied), they are subject to change. Scattered data indicated the upper boundary for the 0.1 deg/sec deadband exists near the 100 deg/sec limit, but the rate command used in the study was limited to 100 deg/sec, and thus the boundary may actually be higher than the dotted lines indicates.

Effect of Main Engine Thrust Misalinement

A lunar-landing spacecraft such as the LEM will, of necessity, carry a fuel load that represents a large percentage of the total weight. Spacecraft design procedures will attempt to locate this fuel load so that, as the fuel is utilized, the center-of-gravity of the spacecraft remains close to the thrust vector of the main engine to keep disturbance torques to a minimum. In spite of design efforts, the center-of-gravity will undergo adverse shifts, and it is important to assess the effects of the resulting disturbing torques upon control handling qualities. To accomplish this assessment a range of disturbing torques typical of the magnitude attributable to CG movements were introduced to the spacecraft dynamics, and the handling qualities with a series of typical control powers were evaluated. The results of this portion of the study are shown in figure 11, which plots pilot rating as a function of the ratio of misalinement to control power acceleration for three separate control powers. As indicated in the curves, pilot ability to compensate for thrust misalinement torques deteriorates rapidly with decreasing control power. The satisfactory boundary for a control power of 23 deg/sec^2 occurs at a ratio of 3.5, at 5.5 for an 11.5 deg/sec^2 control power, and at 6.5 for a 7 deg/sec^2 control power. This indicates, as would be expected, that pilot reaction in the presence of misalinement torques is a function of both the available control power and magnitude of the misalinement torques. The pilot requires enough control power in excess of the disturbing torque to perform the required maneuver, with response times compatible with the basic handling qualities evaluation. The evaluation is subtle in that the vehicle response is different in each direction about a given axis, since the true control power in the direction of the misalinement acceleration is the sum of the actual control power and misalinement acceleration; whereas, in the other direction, the true control power is the difference between the two accelerations. Thus the pilot can maneuver in one direction quite readily; whereas, maneuvering is much more difficult in the other direction. However, if the basic vehicle control power is large compared to the misalinement acceleration, the pilot cannot detect as readily the difference between maneuvering in opposite directions. The results obtained were conclusive enough to indicate that compensation for misalinement torques should not be made through pilot operation of the attitude-control system. Studies of the effect of thrust misalinement on on-off thruster operation were limited, but enough test cases were investigated to determine that the handling qualities were unsatisfactory. In any event, practical considerations make it impossible to supply sufficient control power to design a control system having satisfactory handling qualities. For example, a control power of 5 deg/sec^2 with a time constant of 4 seconds provides a satisfactory system, but to provide a control system having satisfactory handling qualities in the presence of the expected misalinement torques of the LEM spacecraft would require a control power of about 15 deg/sec^2.

Direct Thruster Operation

The direct attitude-control system was examined as both a linear proportional control system and an on-off control system, although the data obtained for the on-off mode were extremely limited. The data obtained indicate the system to be acceptable, but for emergency operation only, for control powers between about 3 and 15 deg/sec^2. Figure 12 shows that the best rating was 5.5 and occurred at about 10 deg/sec^2.

Relationship of Studies to Present LEM Attitude-Control System

The results of these studies have been applied to the design of the LEM spacecraft attitude-control system. As a primary mode, the attitude-control system employs a rate-command mode having attitude-hold features. Maximum rate command available to the pilot is 20 deg/sec and the rate deadband equivalent to 0.2 deg/sec. The operating points for two thruster operation is at a time constant of 2.3 seconds which, for a 0.2 deg/sec deadband, is just within the satisfactory boundary shown in figure 9(b).

Four thruster operations at 1.15 seconds are well within the satisfactory region. As a backup to the primary mode, the attitude-control system can be operated in the direct mode, but the handling qualities are at best acceptable. Compensation for misalinement torques is done automatically through a gimballed main-engine operation from the attitude-control system by the summing junction error signals.

Concluding Remarks

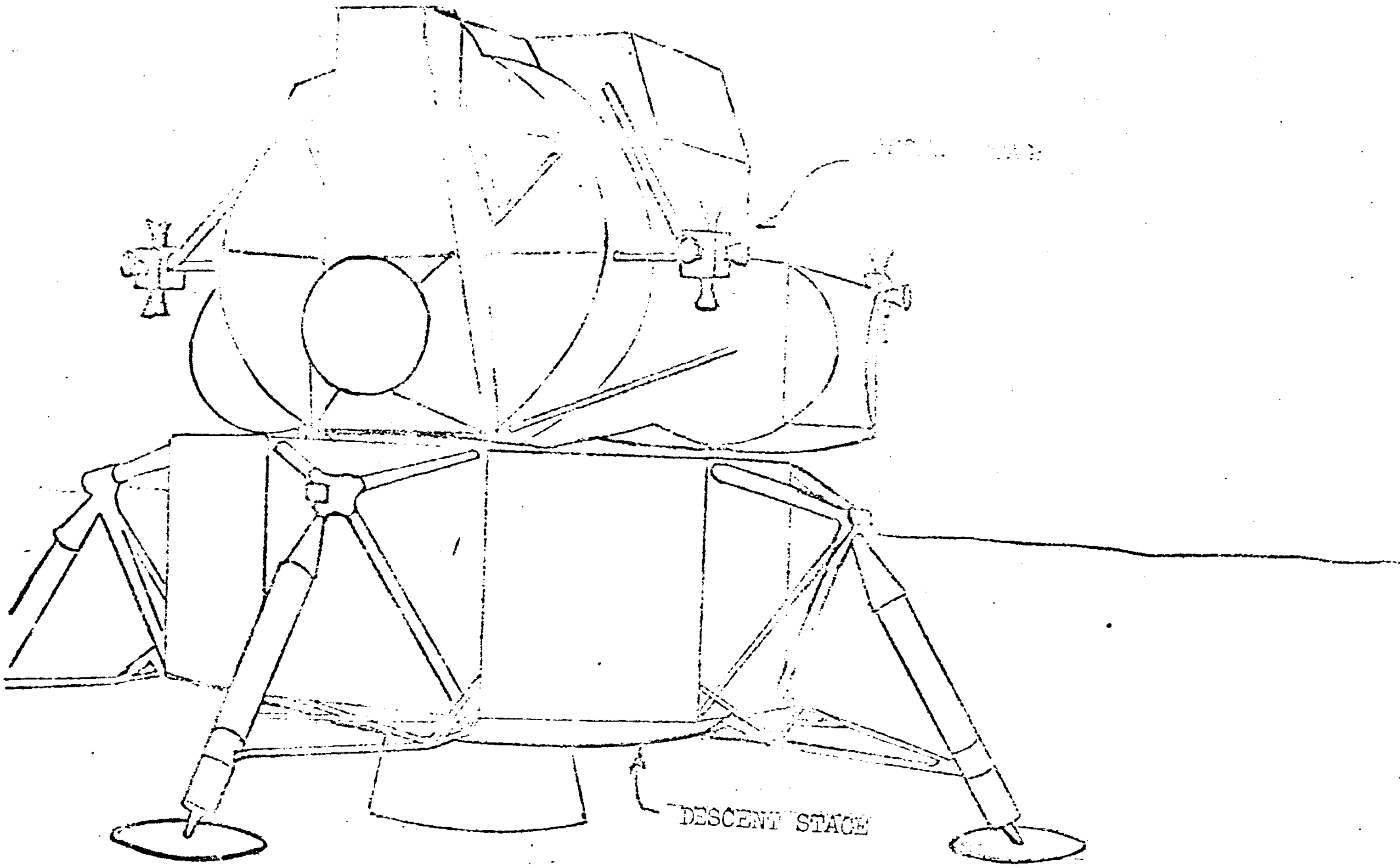
The handling qualities of a lunar-landing vehicle have been examined and assessed in a series of piloted simulations of the lunar-landing maneuver. The results of these studies indicated that the differences between the earth and lunar environment influences handling qualities of earth-bound vehicles performing maneuvers similar to those discussed in the lunar landing. The studies that have been conducted to date have not examined the effect of gravitational field differences in depth sufficiently to discuss the reasons for the variations in handling qualities in detail.

It is anticipated that the study results will be verified in a least two operational research vehicles. The first of these is a tethered-flight vehicle located at the Langley Research Center, and the second is a free-flight vehicle presently undergoing flight tests at the Flight Research Center. Both of these vehicles will operate in a simulated lunar-gravitational field and will employ control systems similar to the LEM spacecraft.

References

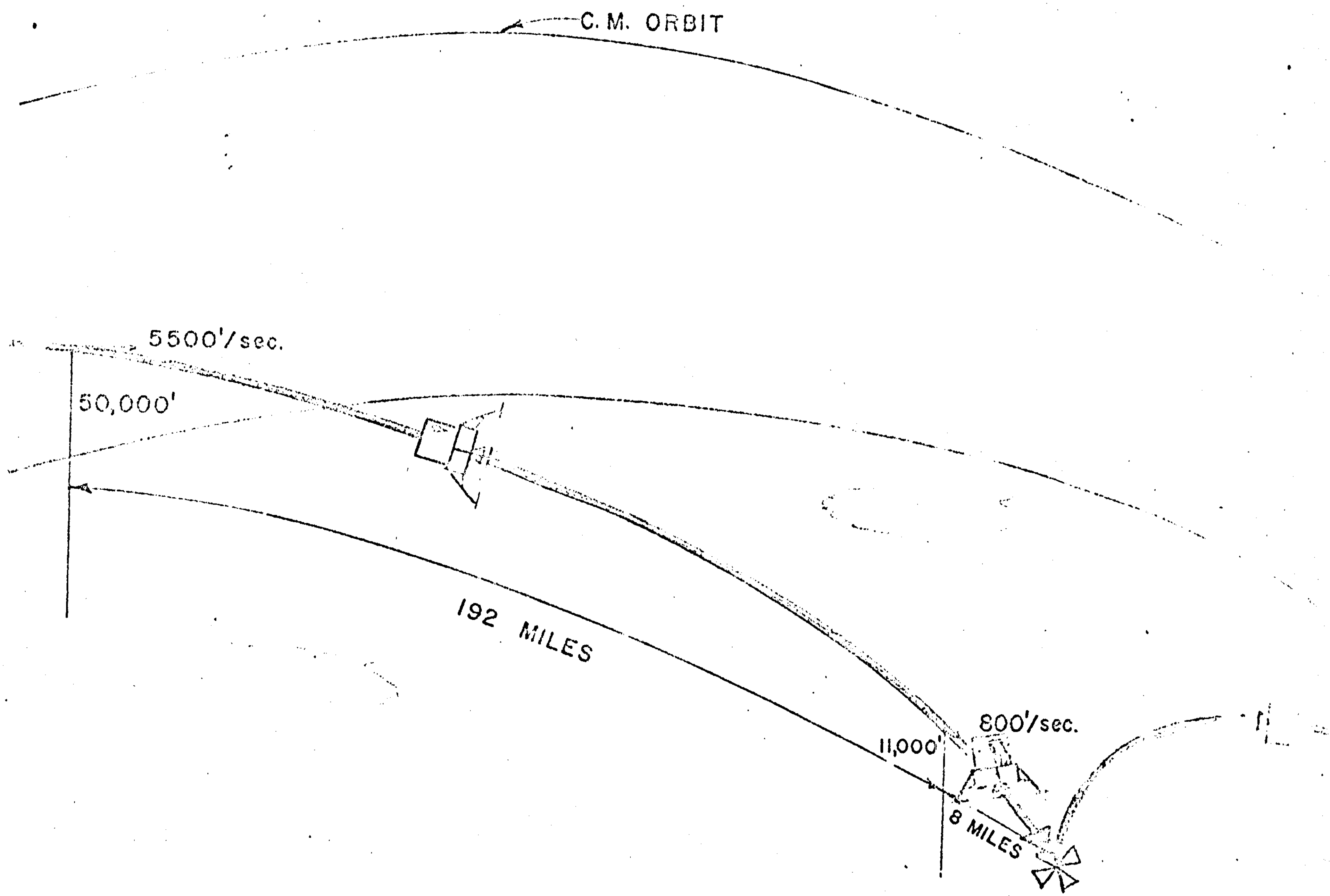
1. Hill, J. A.: A Piloted Flight Simulation Study to Define the Handling Qualities Requirements for a Lunar Landing Vehicle. North American Aviation, Inc., (Columbus Division). NA 62H-660, Sept 13, 1962.

2. Anderson, Seth B.: An Examination of Handling Qualities Criteria for V/STOL Aircraft. NASA TN D-331, July 1960.

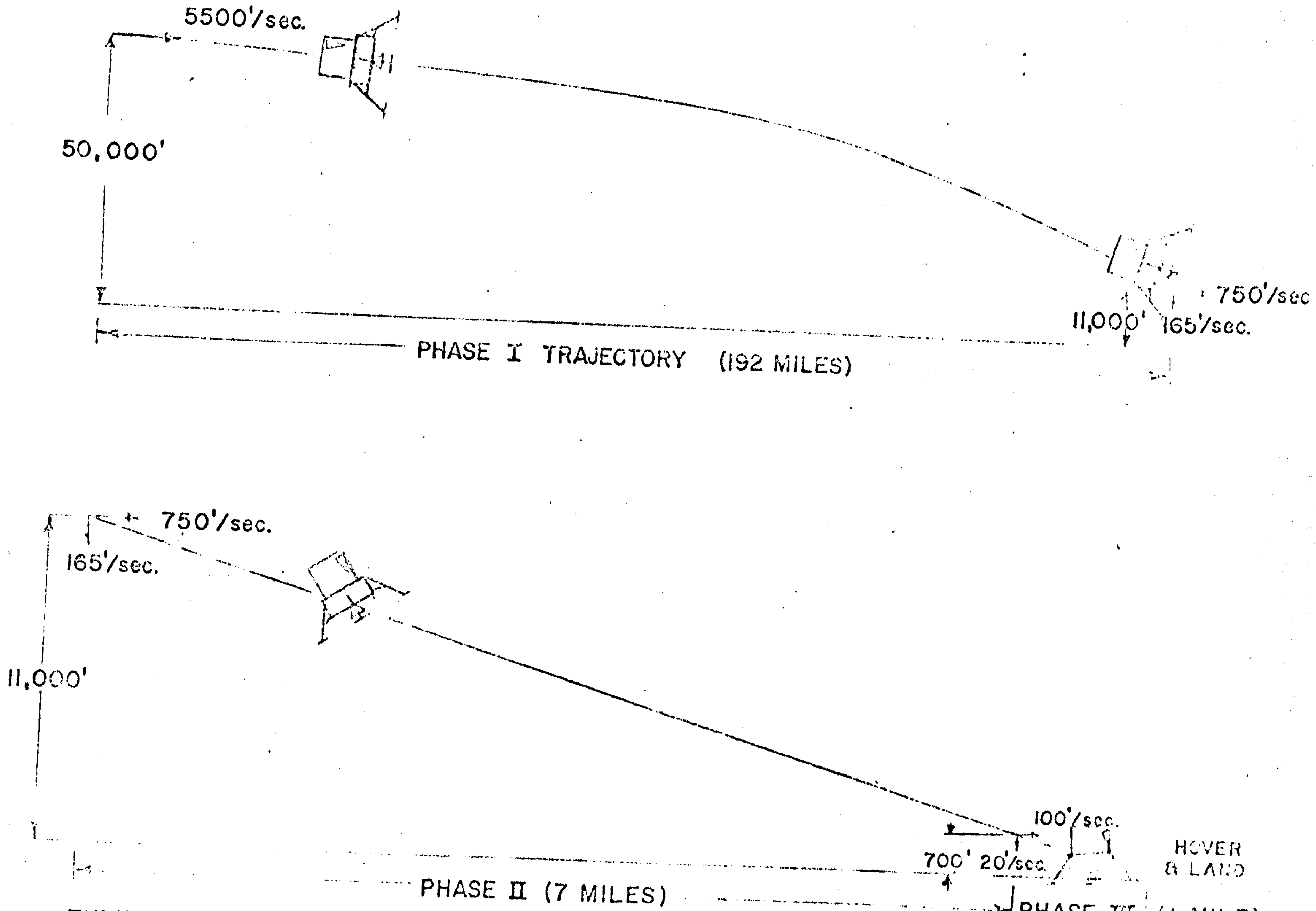


ARTIST CONCEPTION OF LEM SPACECRAFT

FIGURE 1

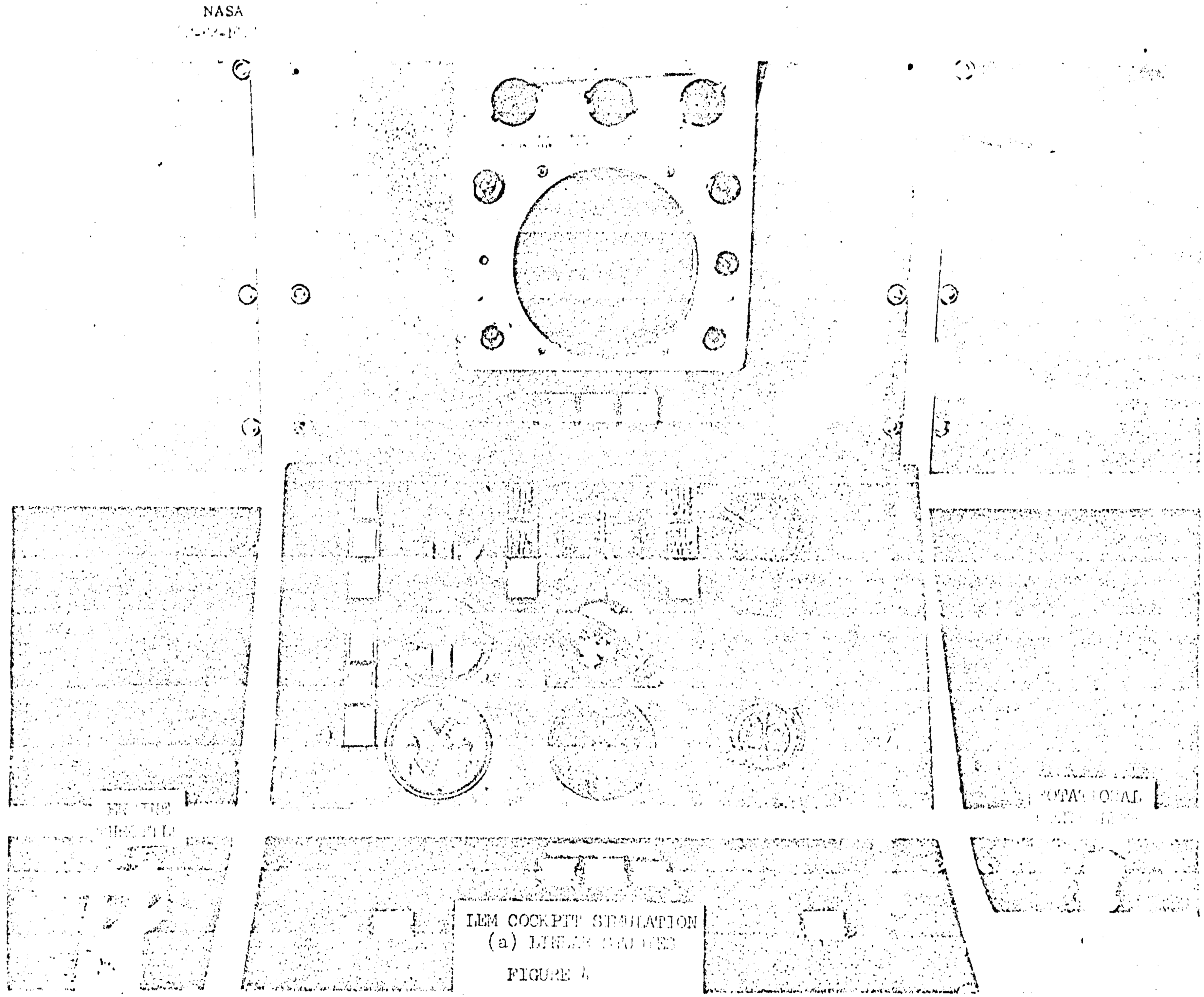


LEM LUNAR LANDING MISSION



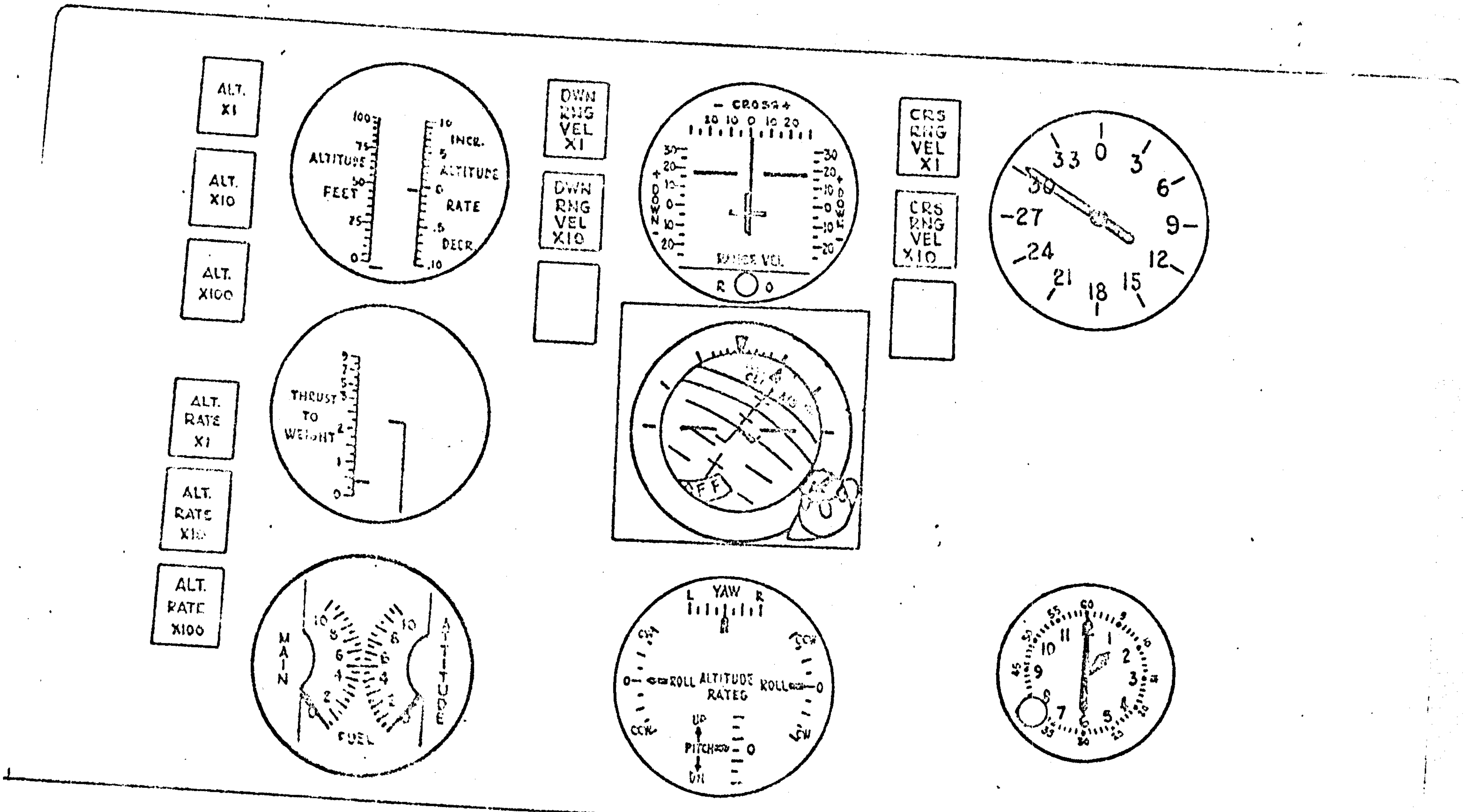
THREE PHASE TRAJECTORY SHOWING NOMINAL VELOCITY AND ATTITUDE CONDITIONS

FIGURE 3



LEM COCKPIT SIMULATION
(a) LINEAR GAUGES

FIGURE 4

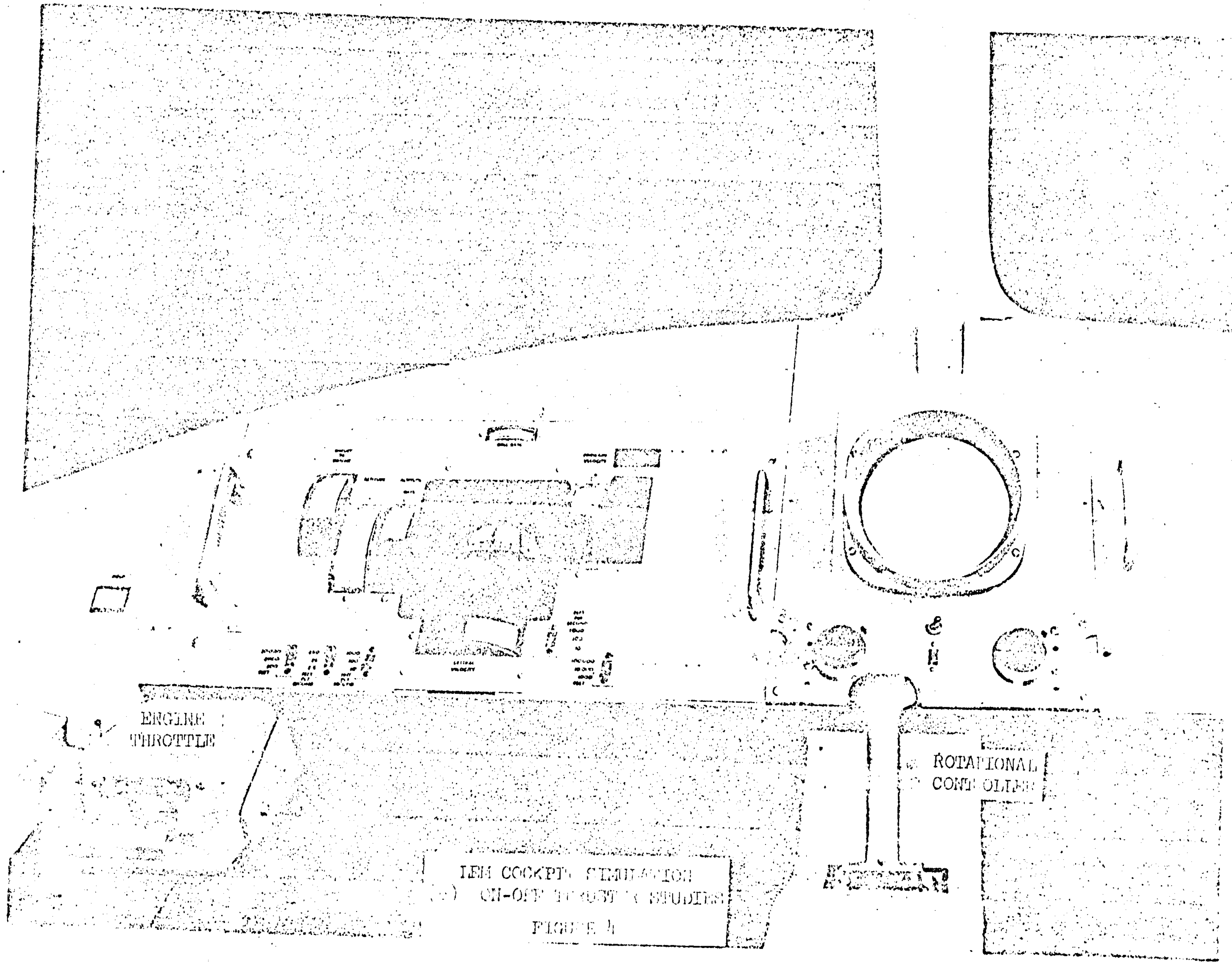


LEM COCKPIT SIMULATION

(b) INSTRUMENT PANEL FOR LINEAR STUDIES

FIGURE 4 (cont.)

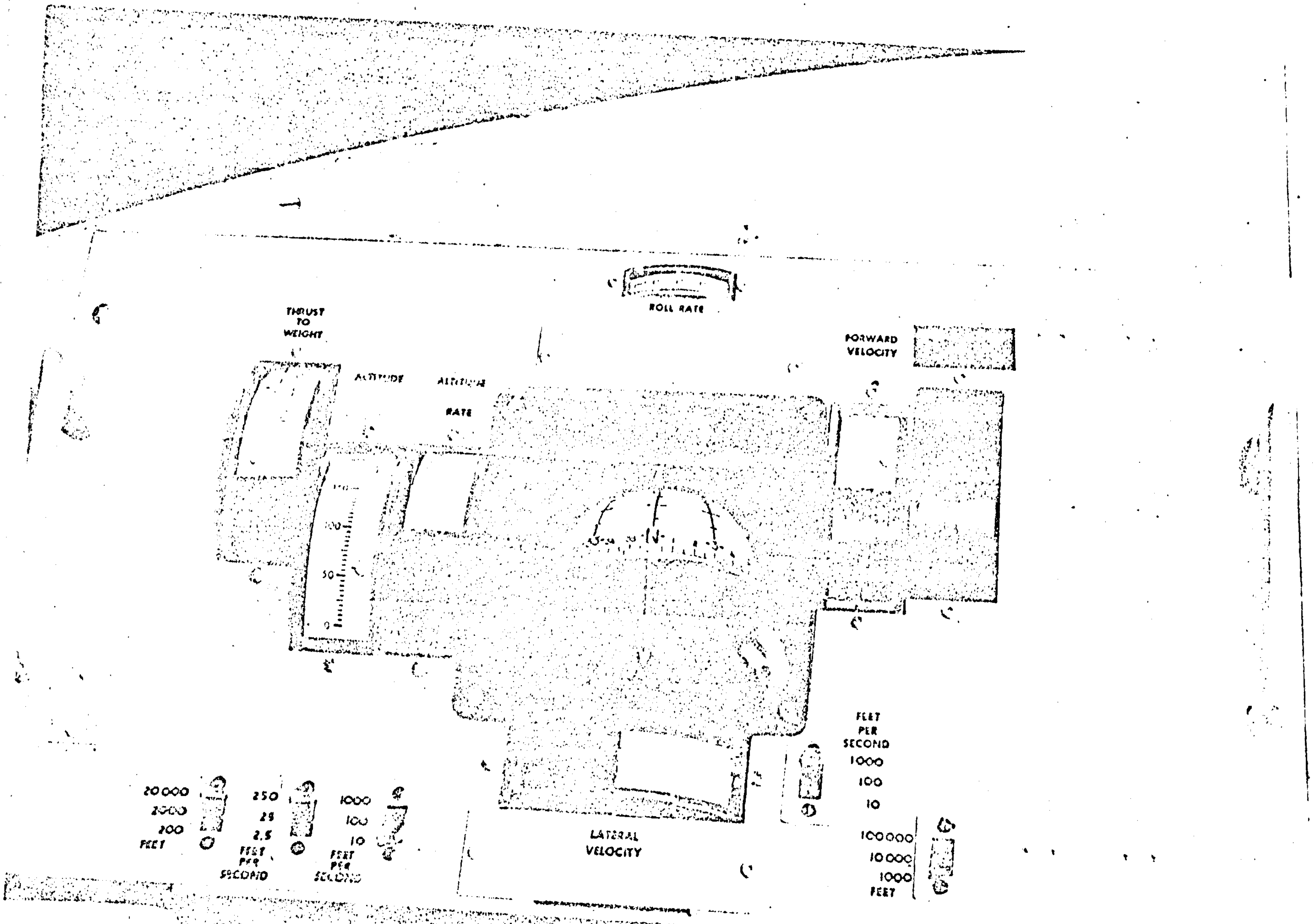
NASA



LEM COCKPIT SIMULATION
[illegible] ON-OFF THRUST STUDIES

FIGURE 4

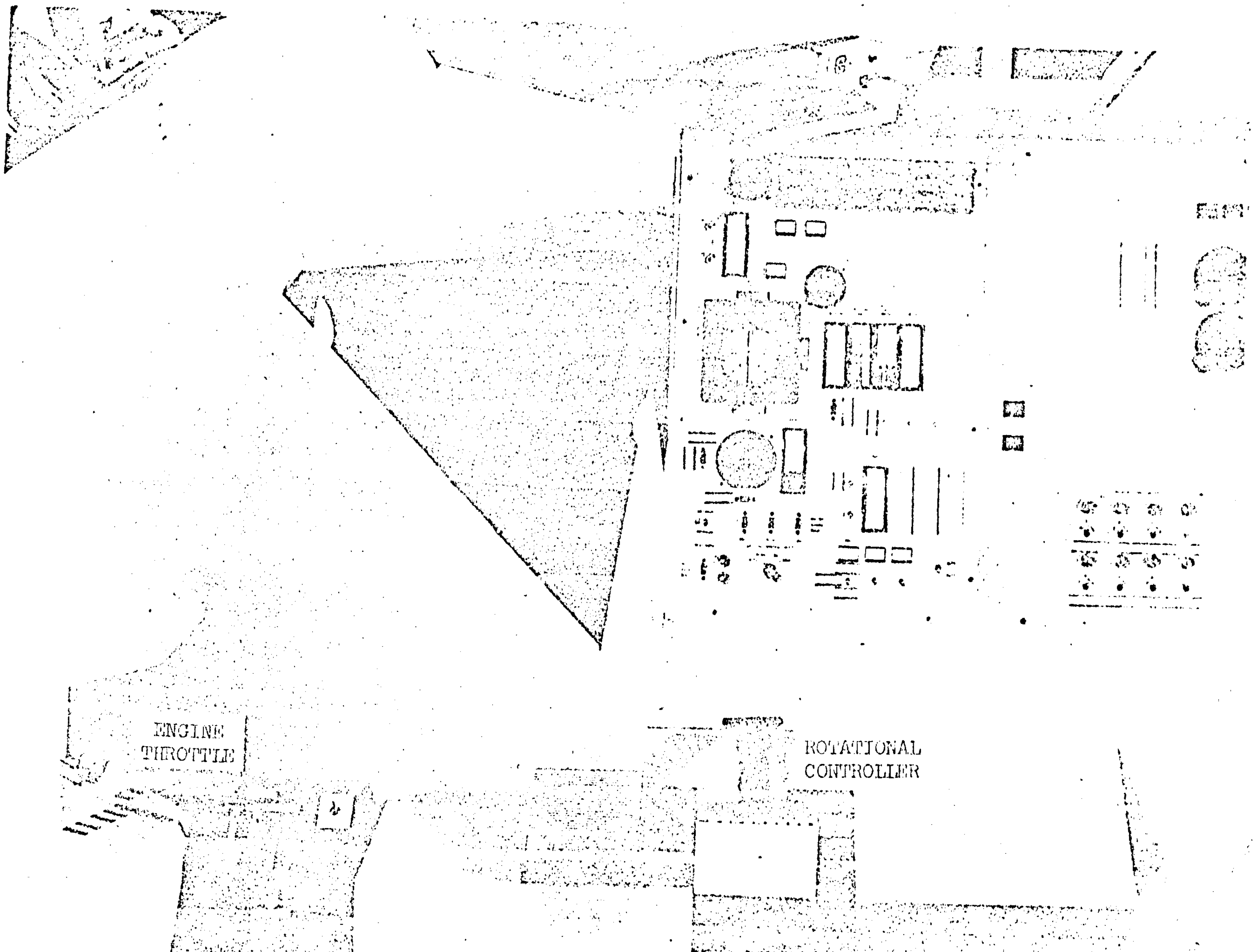
NASA



LEM COCKPIT SIMULATION
EXPERIMENT PANEL FOR ON-OFF THRUSTER STUDIES

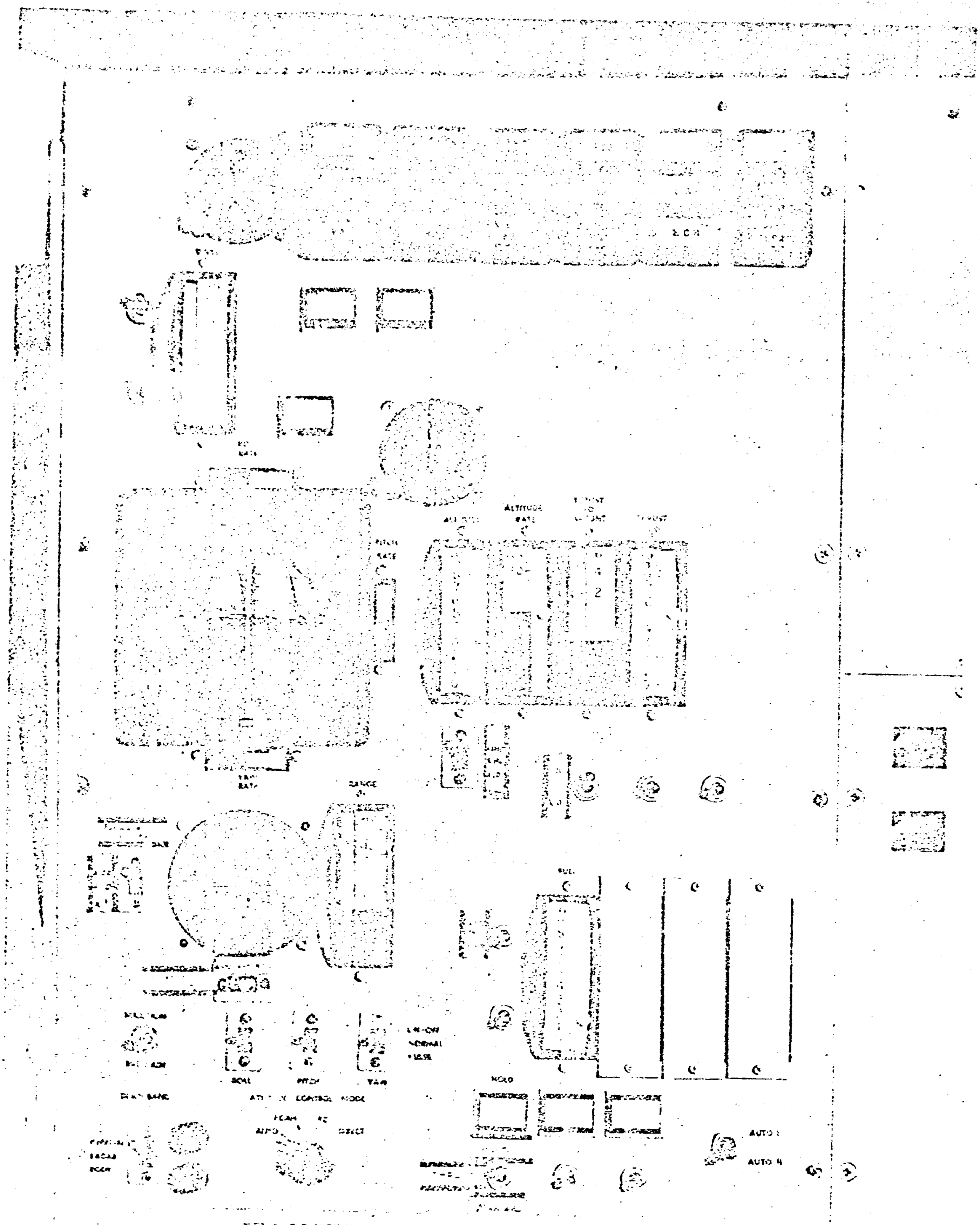
FIGURE 4(cont.)

NASA
[illegible]



LEM COCKPIT USED FOR HANDLING QUALITIES VERIFICATION
a. OVERALL VIEW

FIGURE 5

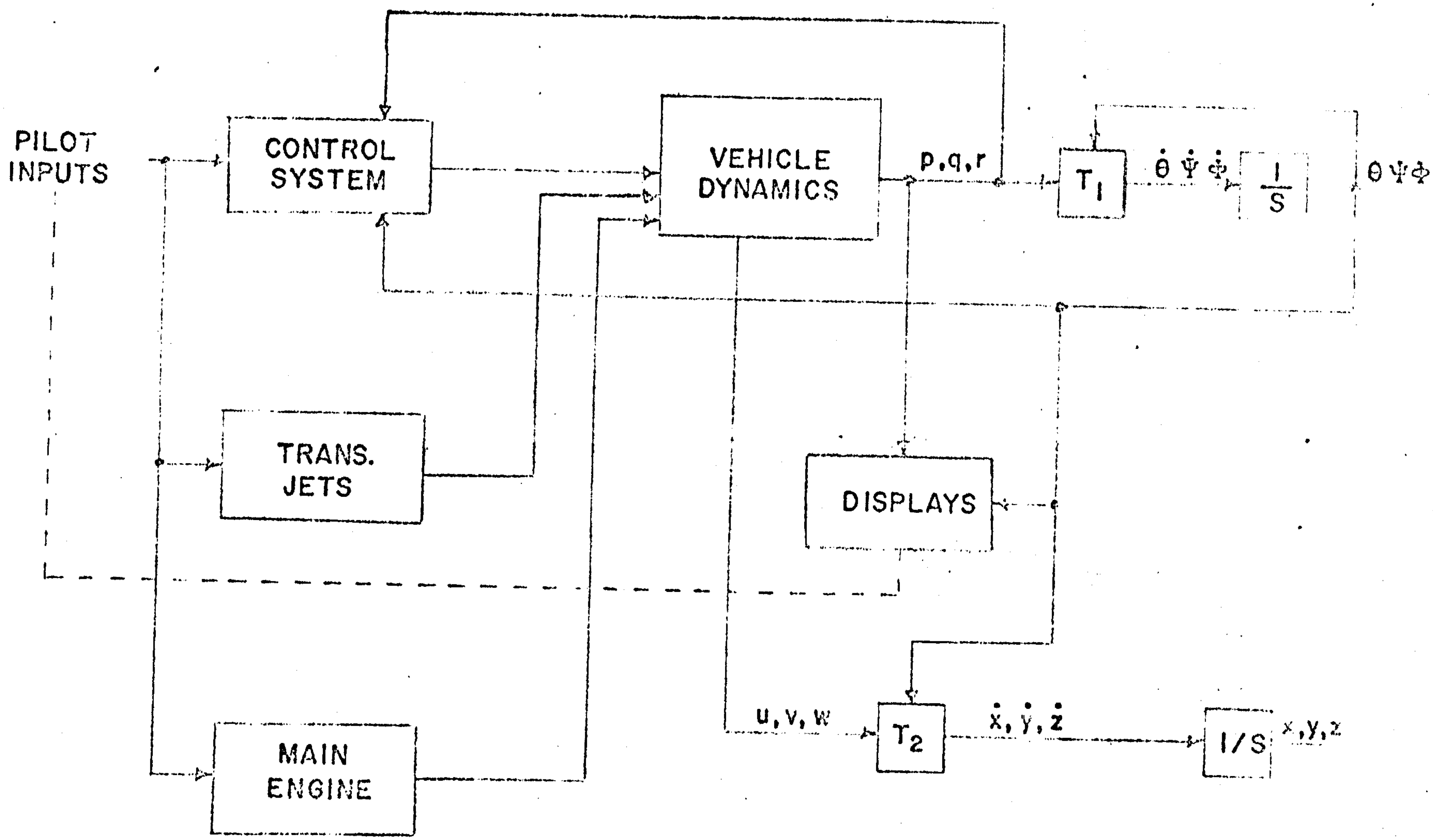


LEM COCKPIT USED FOR HANDLING QUALITIES VERIFICATION

(b) INSTRUMENT PANEL

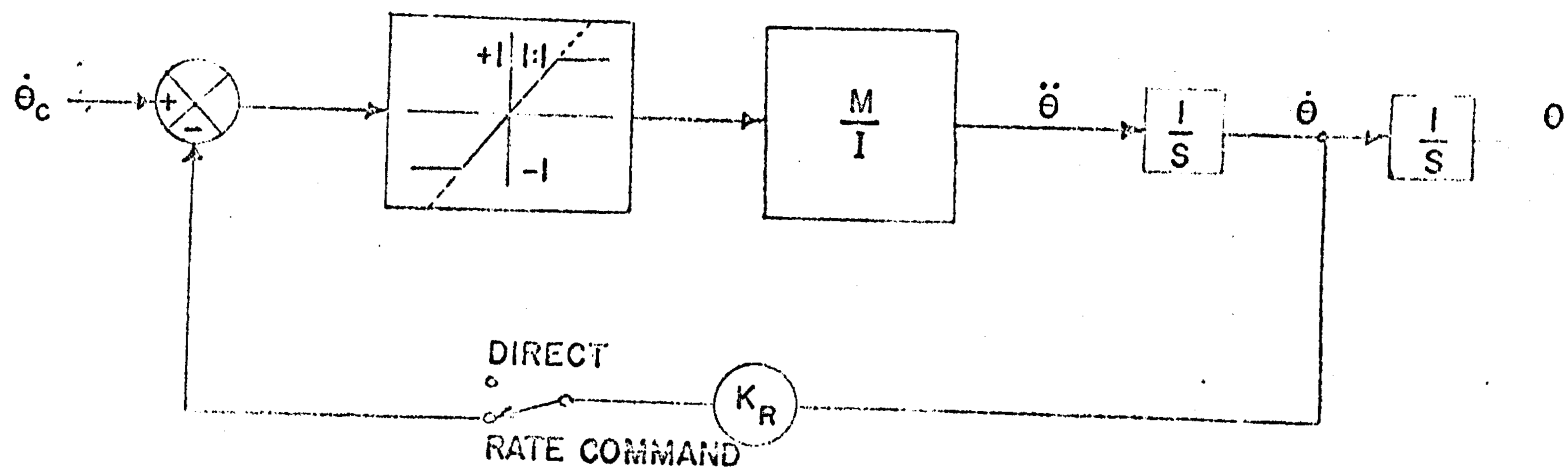
FIGURE 7 (cont)

NASA L-20308

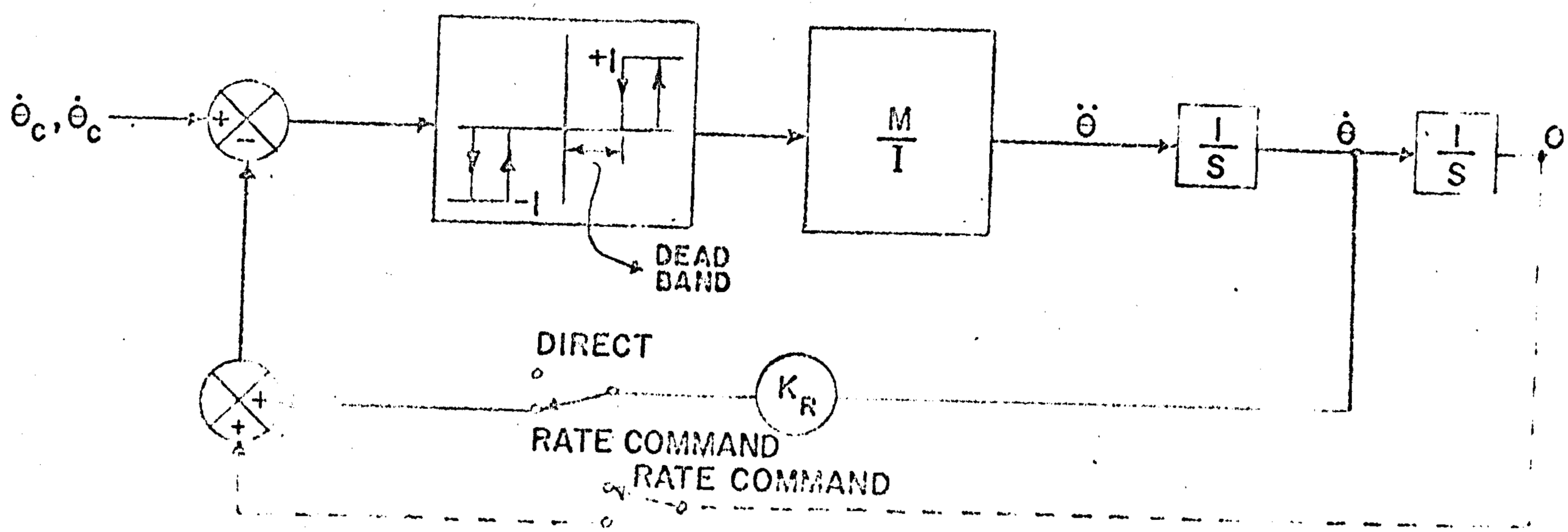


FLOW DIAGRAM OF SIMULATIONS

FIGURE 6



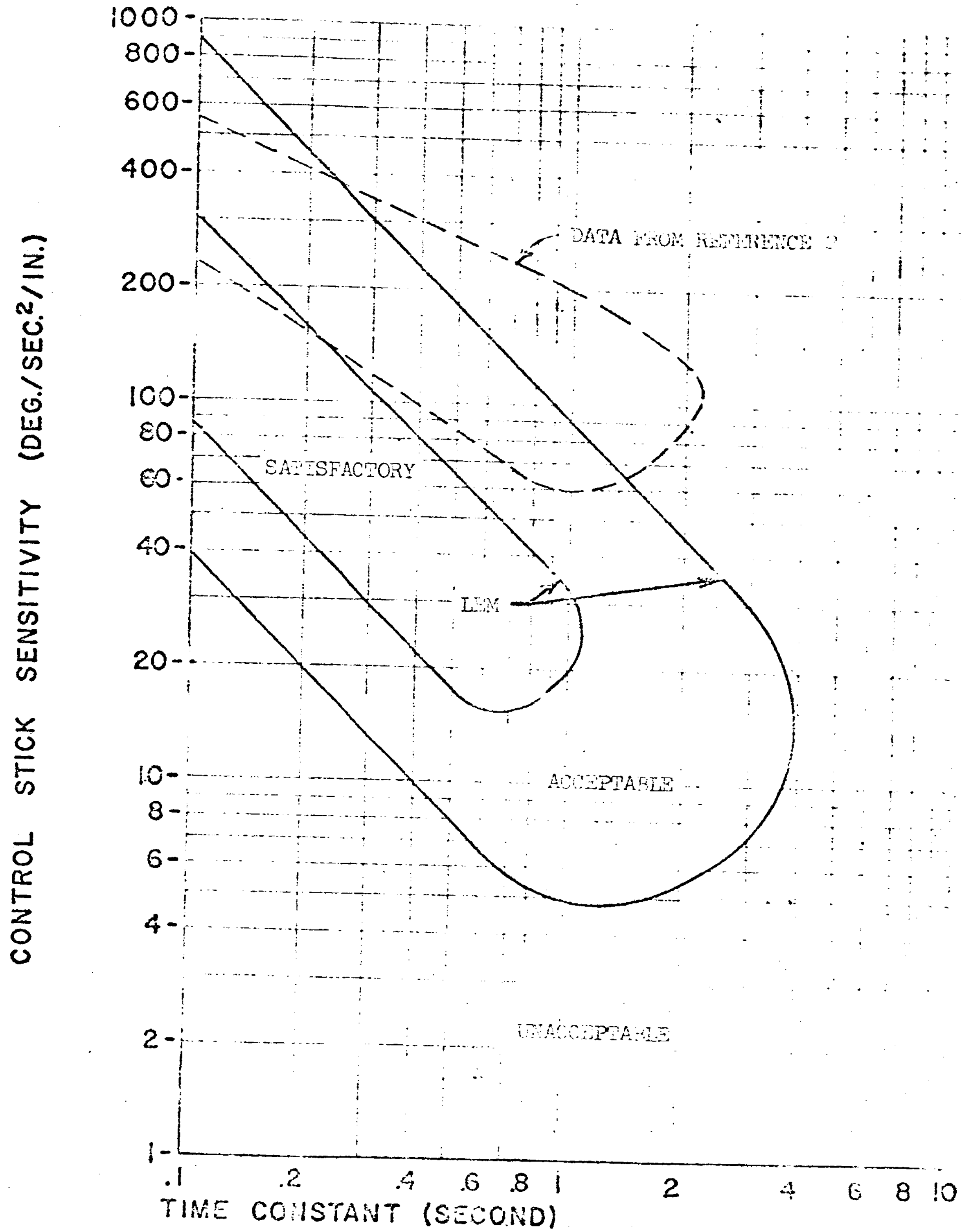
a. LINEAR AND QUASI-LINEAR



b. ON-OFF THRUSTER LOGIC

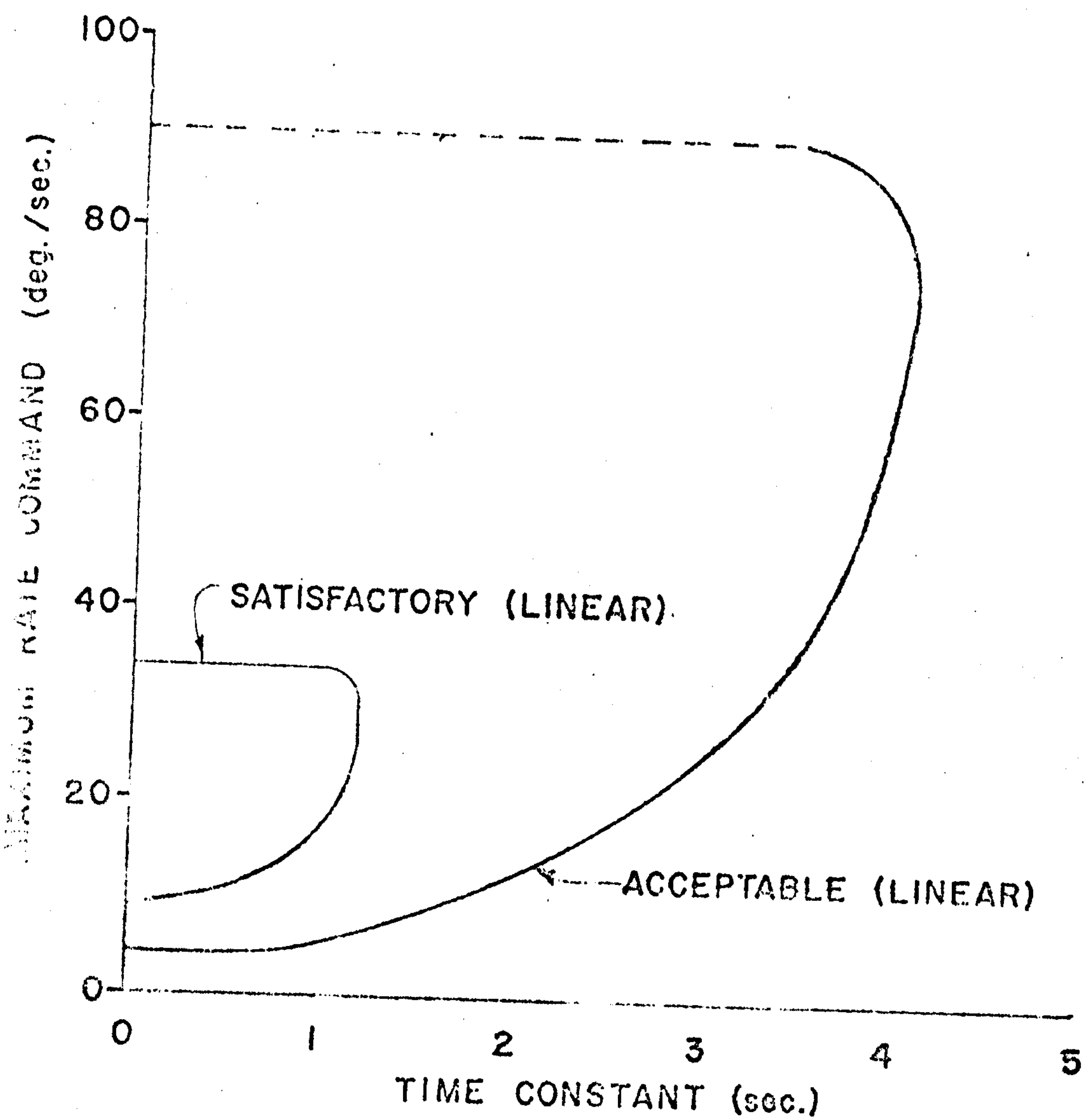
BLOCK DIAGRAMS OF CONTROL SYSTEMS INVESTIGATED

FIGURE 7



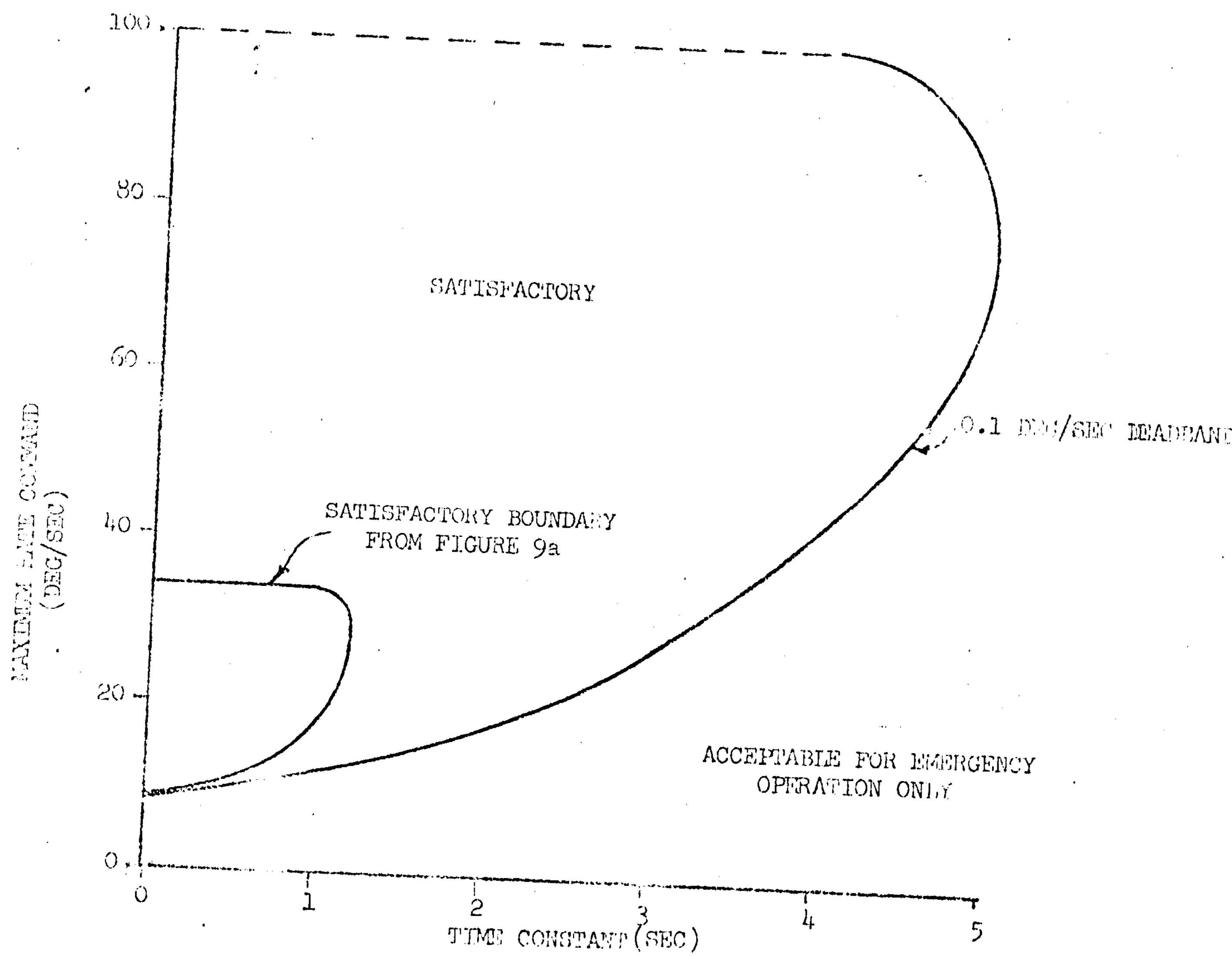
SATISFACTORY AND ACCEPTABLE BOUNDARIES FOR RATE COMMAND SYSTEM (LINEAR THRUSTER OPERATION)

FIGURE 8



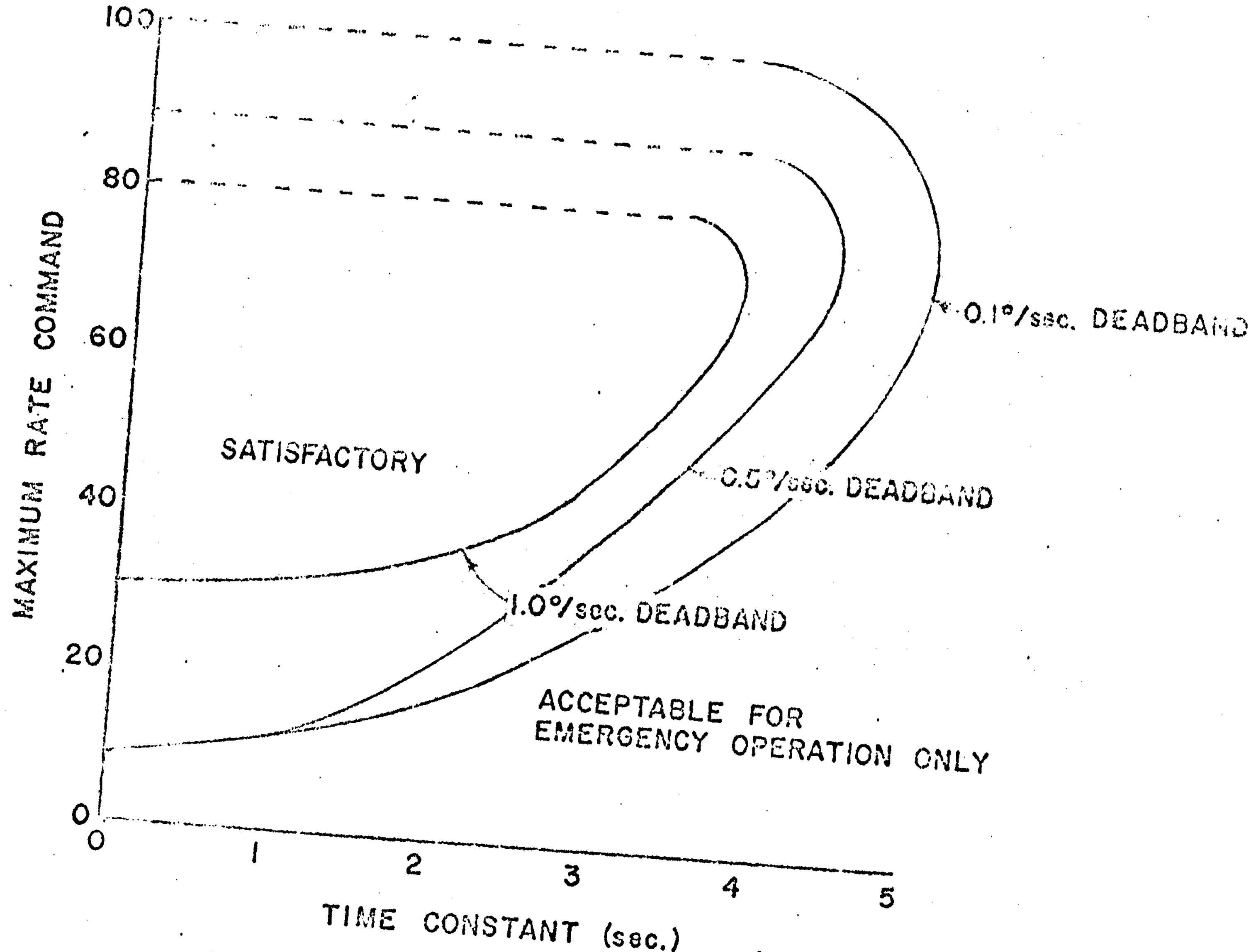
SATISFACTORY AND ACCEPTABLE BOUNDARIES
FOR RATE COMMAND CONTROL MODE
(PROPORTIONAL THRUSTER OPERATION)

FIGURE 9a



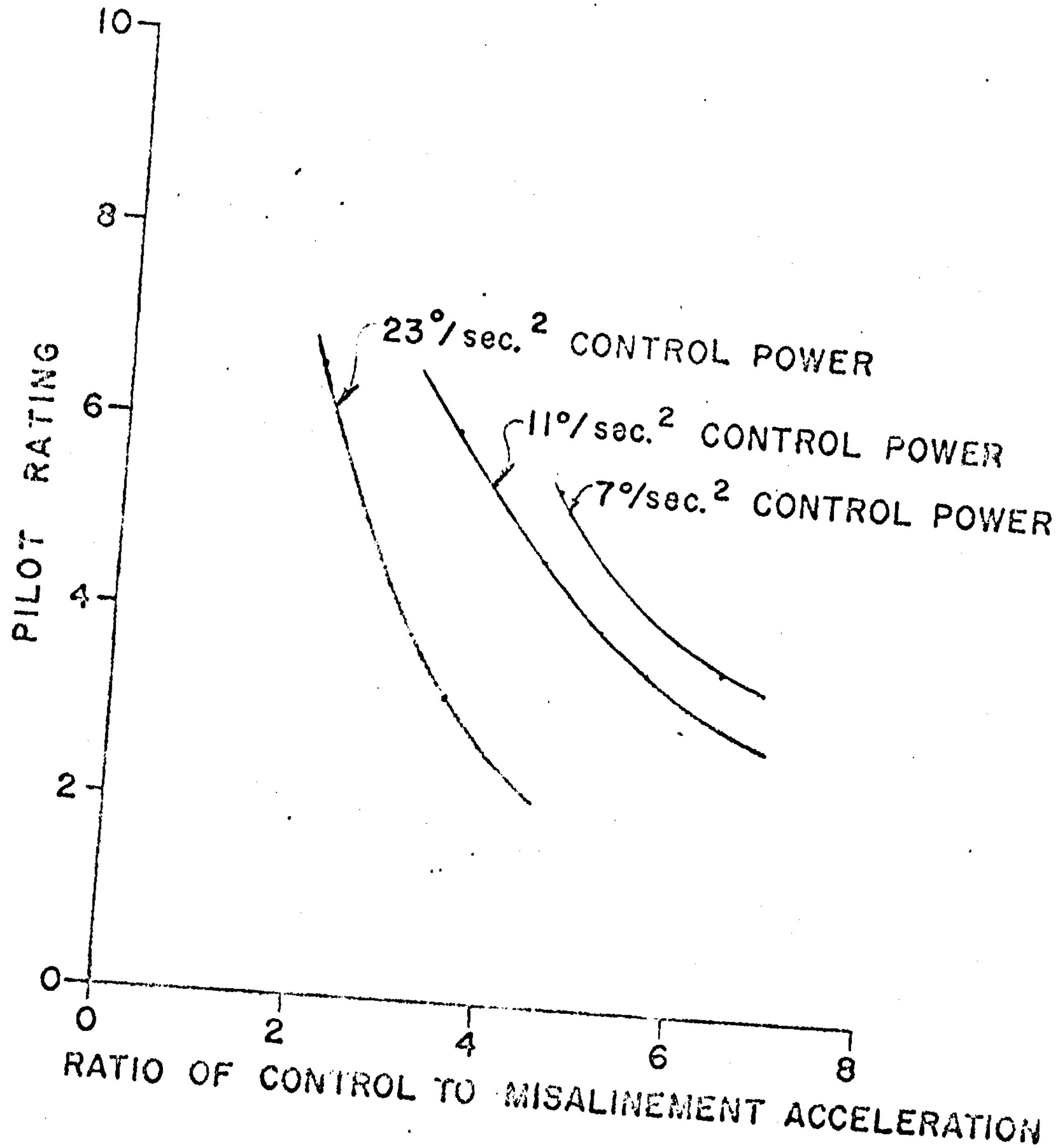
SATISFACTORY AND ACCEPTABLE BOUNDARIES
FOR RATE COMMAND CONTROL MODE
(ON-OFF THRUSTER OPERATION)

FIGURE 9b



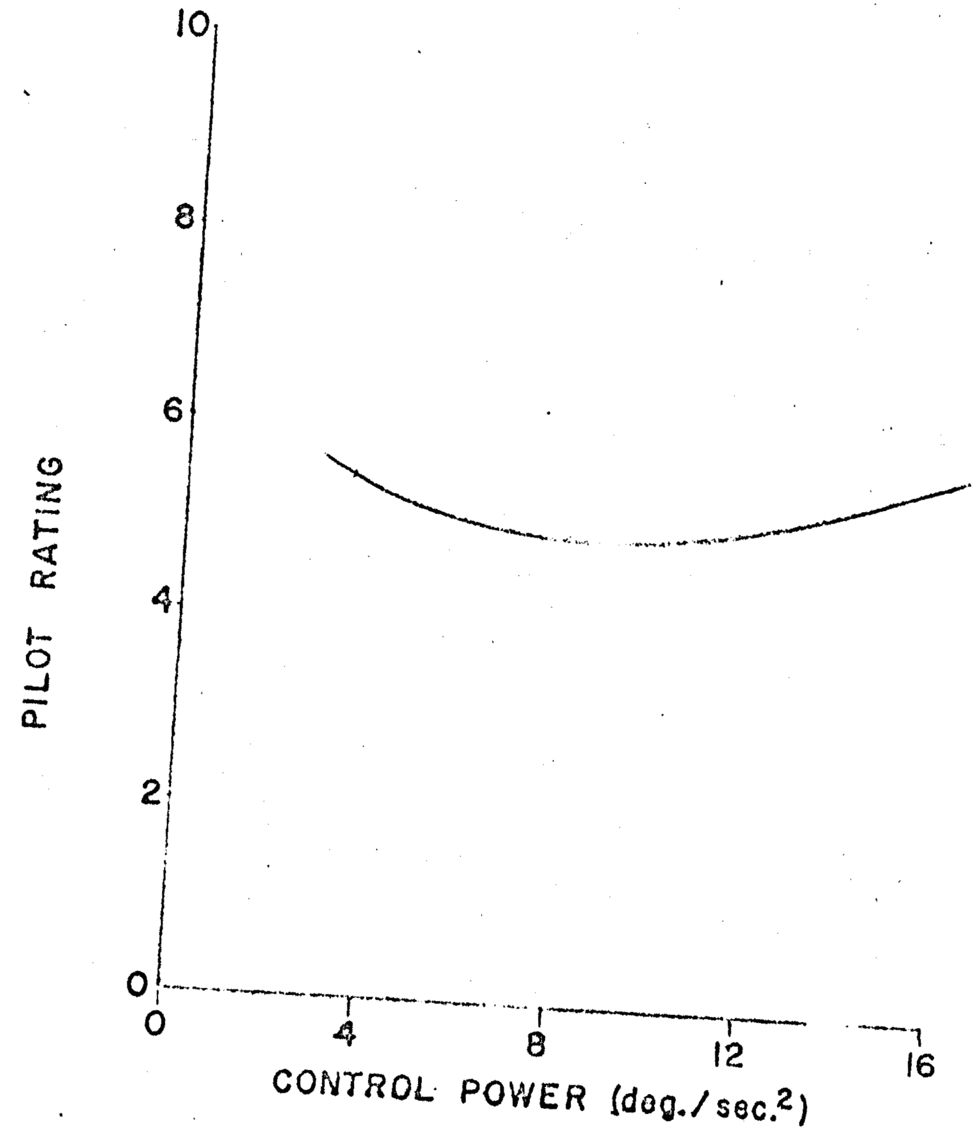
EFFECT OF DEADBAND ON SATISFACTORY
BOUNDARY OF ON-OFF RATE
COMMAND CONTROL MODE

FIGURE 10



EFFECT OF MISALINEMENT
TORQUE ON PILOT RATING

FIGURE 11



PILOT RATING FOR DIRECT
THRUSTER CONTROL MODE

FIGURE 12