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FIXED-BASE VISUAL-SIMULATION STUDY OF MANUALLY CONTROLLED TRANSLATION AND HOVER MANEUVERS OVER THE LUNAR SURFACE

by G. Kimball Miller, Jr.

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SUMMARY

A fixed-base visual-simulation study has been conducted to determine the ability of the human pilot to control a lunar landing vehicle manually during translation to and hover above various landing sites in a given landing area. The general landing area used in this investigation was the interior of the crater Alphonsus as created by the lunar orbit and landing approach (LOLA) simulator located at Langley Research Center. The investigation employed a closed-circuit television system for image generation and permitted all six rigid-body degrees of freedom of the vehicle. The pilot controlled the vehicle through a fixed main-engine thruster in conjunction with a rate-command attitude control system. During the final portion of the automatically controlled landing-approach transition phase of a typical lunar landing trajectory, the pilot was required to switch to manual control in order to place the landing vehicle in near-hover conditions over any one of a number of sites that he felt would be acceptable for landing.

The results of the investigation showed that the pilots, using only a three-axis gyro-horizon nulled to the local vertical and an out-the-window view of the lunar surface, could consistently establish near-hover conditions over a fairly large lunar area. The landing sites attained by the pilots extended from approximately 2300 feet (701.0 m) up range of (before) to approximately 7700 feet (2347.0 m) down range of (beyond) the nominal landing site.

INTRODUCTION

Spacecraft control during the initial manned lunar missions will be provided primarily by automatic guidance and control systems. One exception occurs during the final phase of the lunar landing maneuver when the pilot manually controls the landing vehicle during translation to and hover above a desirable landing site.

A previous lunar landing study (ref. 1) employed complete instrumentation of the trajectory parameters, which included altitude, range, velocity components, and vehicle attitude. It was believed that acceptable landing sites could be attained without the benefit of much of this instrumentation when the pilot was provided with an out-the-window view of the lunar surface. For example, the pilot should be able to detect velocity components, vehicle attitude, and range relative to the landing site by using purely visual information.

The present fixed-base visual-simulation study was performed to determine, within the limits of the experiment, the ability of pilots to control the landing vehicle manually during translation to and hover above various sites in a given landing area. For these maneuvers, the pilots used only a throttle-setting indicator, a three-axis gyro horizon, and an out-the-window view of the lunar surface. The general landing area used in this study was the interior of the crater Alphonsus as created by the lunar orbit and landing approach (LOLA) simulator located at the Langley Research Center. A closed-circuit television system was employed for image generation. The equations of motion permitted all six rigid-body degrees of freedom of the vehicle and were solved on an analog computer operating in real time. The pilot closed the control loop and had direct inputs into the force and moment equations.

SYMBOLS

Measurements for this investigation were made in the U.S. Customary Units but are also given parenthetically in the International System of Units (SI). (See ref. 2.)

F rocket thrust along X body axis, positive in positive X-direction, pounds (newtons)

g_e acceleration due to gravitational attraction at surface of earth, 32.2 feet/second^2 (9.815 meters/second^2)

h altitude above lunar surface, feet (meters)

I_{sp} specific impulse, 301 seconds

I_X,I_Y,I_Z moments of inertia about vehicle body axes, slug-feet^2 (kilogram-meters^2)

I_{XY},I_{XZ},I_{YZ} products of inertia about vehicle body axes, slug-feet^2 (kilogram-meters^2)

M_X,M_Y,M_Z control moments exerted about vehicle body axes, foot-pounds (meter-newtons)

m vehicle mass, slugs (kilograms)

p,q,r vehicle angular velocities about X, Y, and Z body axes, respectively, degrees/second

R radial distance from center of moon, feet (meters)

R_a ground range from beginning of translation and hover phase (1000-ft (304.8-m) altitude point), feet (meters)

S displacement out of reference-orbit plane, feet (meters)

T throttle setting, F/F_{max}

t time, seconds

V_c characteristic velocity, $g_e I_{sp} \log_e \frac{m_i}{m}$, feet/second (meters/second)

V_R,V_λ,V_β vehicle velocity components in spherical coordinates; referred to as radial velocity (negative values indicate rate of descent), forward velocity, and out-of-plane velocity, respectively, feet/second (meters/second)

W earth weight of landing vehicle, mg_e, pounds (newtons)

X,Y,Z vehicle body axes with origin located at vehicle instantaneous center of mass

X_E,Y_E,Z_E reference axes with origin located at vehicle instantaneous center of mass and with X_E-axis alined with local vertical and positive outward, Y_E-axis positive in direction of increasing λ, and Z_E-axis positive in direction of increasing β (see fig. 1)

x,y,z assumed inertial reference axes with origin located at center of moon (see fig. 1)

β angular displacement in out-of-plane direction, radians or degrees (see fig. 1)

λ angular displacement in xy-plane, radians or degrees (see fig. 1)

ψ,θ,ϕ Euler angles of rotation relating body axes and X-, Y-, and Z-axes; referred to as yaw, pitch and roll angles, respectively (order of rotation θ, ψ, ϕ), radians or degrees

ϵ rate-command error signal defined as difference between commanded and actual vehicle angular rate, degree/second

Subscripts:

i initial conditions

max maximum

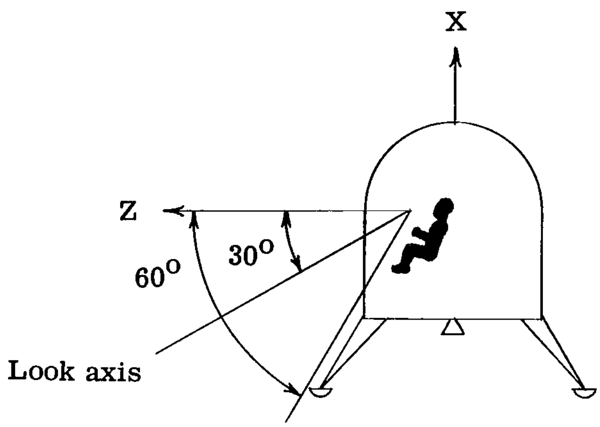
o fully loaded condition of landing vehicle

EQUATIONS OF MOTION

The equations of motion used in this investigation are essentially the same as those presented in the appendix of reference 3. The only differences are that, in the present study, products of inertia were included and motion was not constrained to the reference-orbit plane. Consequently, the equations of motion used in this study permitted all six rigid-body degrees of freedom. The force equations were written in spherical coordinates in perturbation form about a circular reference orbit which has an altitude equal to one-half the initial altitude for scaling purposes. In addition, the plane of the reference orbit was inclined with respect to the lunar equatorial plane and it was assumed that the displacement of the vehicle out of the reference-orbit plane would be small. The three moment equations were written with respect to the body axes. The assumed inertial reference frame was a fixed-axis system with its origin at the center of the moon (fig. 1). The moon was assumed to be a nonrotating homogeneous sphere. The pilot closed the vehicle control loop with direct input into the force and moment equations. The mass and moments of inertia of the vehicle were varied as thrust was applied to account for mass reduction during thrusting. Mass change due to moment control was neglected because it was small in comparison with mass change due to main-engine thrust.

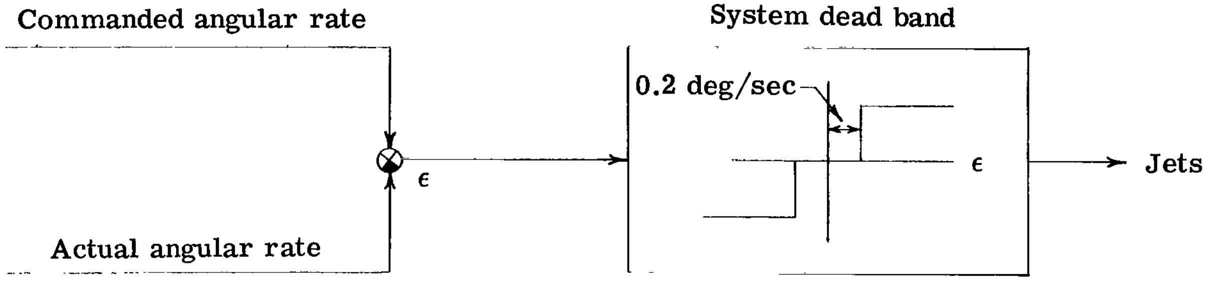
VEHICLE DESCRIPTION

The landing vehicle assumed in this study is similar to that intended for use in the Apollo program. The field of view of the simulated vehicle is depicted in the following sketch:



The window of the simulated vehicle had a field of view in the pitch plane of approximately 60° about a look axis that was angularly offset from the vehicle Z-axis or yaw axis by 30°. The field of view in the YZ-plane was approximately 45°.

The vehicle had a single fixed engine which provided thrust along the longitudinal axis (X-axis) with a maximum capability of accelerating the orbital weight of the vehicle at $0.355g_e$ (that is, $F/W_o = 0.355$) and the empty weight of the vehicle at $0.763g_e$. Thrust was assumed throttleable from full thrust to 10 percent of full thrust ($T = 1.0$ to 0.1). A rate-command system providing moment control about the vehicle body axes was generated by on-off reaction jets operating in pairs to produce pure couples. Maximum vehicle rates of ±20 deg/sec could be generated by deflecting the attitude controller to the maximum position about the appropriate axes. The attitude controller operated outside a dead band of 10 percent of the maximum controller deflection which is approximately 1.5° for pitch and 3.0° for roll and yaw. The rate command system, which operated outside a dead band of 0.2 deg/sec about all three axes, is depicted in the following sketch:



The variations of the vehicle moments and products of inertia with vehicle mass are presented in figure 2.

SIMULATOR

Cockpit and Controls

The general layout of the cockpit used in the investigation is presented in figure 3 and shows the relative position of the pilot's seat with respect to the television monitor, the instrument panel, and the controls. It should be noted that of the numerous instruments included in this general purpose cockpit, only the throttle-setting indicator and the three-axis gyro horizon (eight ball) were used in this study. The eight ball was nulled to the local vertical and presented attitude and attitude rate of the vehicle to the pilot. The instruments that present the velocity components and the vehicle altitude were used only for checkout and familiarization purposes.

Vehicle thrust was commanded by using the throttle located to the left of the pilot's seat. Thrust varied linearly with control displacement between full thrust and 10 percent of full thrust. Attitude control was provided through a rate-command system by using the three-axis hand controller located to the right of the pilot's seat.

Image Generation

The view through the window of the simulated landing vehicle was generated by a closed-circuit television system. The model of the lunar surface and the television camera used in this study are shown in figure 4. The lunar model is a 22- by 35-foot (6.7- by 10.7-m) three-dimensional map of a portion of the interior of the crater Alphonsus at a scale of 2400 to 1. The model, which is made of fiber glass and then hand-painted, is illuminated with a backlight so that it is capable of simulating only direct overhead lighting.

The three rotational degrees of freedom of the simulated vehicle were obtained by mounting the television camera in a gimbal system that moved in response to the attitude control inputs of the pilot. The three translational degrees of freedom were obtained by moving the television camera with respect to the lunar model in response to the force equations. The camera mount is driven along a line perpendicular to the lunar model to represent the altitude of the landing vehicle above the lunar surface. The camera mount also moves parallel to the model to simulate latitudinal or out-of-plane translation. (See fig. 4.) The cart on which the camera is mounted moves along the track to simulate longitudinal translation. The size of the lunar model limits the maximum altitude of the simulation to 4500 feet (1371.6 m). Model protection considerations impose a minimum-altitude restriction of about 650 feet (198.1 m), at which point an electrical stop is activated.

The resulting image was presented to the pilot on the television monitor mounted in the cockpit. A collimating lens mounted in front of the television monitor (see fig. 3) placed the image at infinity and thus added to the realism of the display.

LANDING TRAJECTORIES

The present investigation is concerned only with the final phase of the powered-descent portion of the lunar landing mission. However, because the final phase is dependent upon the previous phases, the entire powered-descent phase is described. A sketch of the landing trajectory relative to the lunar surface is presented in figure 5. The nominal trajectory used in this study consisted of a fuel-optimum descent from the pericynthion of the descent transfer orbit to an altitude of 15 000 feet (4572.0 m), followed by a constant-attitude transition to an altitude of 1000 feet (304.8 m). A translation and hover phase then followed. The present study was initiated with conditions corresponding to those occurring 62 seconds before the 1000-foot (304.8-m) altitude point was reached. The initial conditions used for this study were as follows: an altitude of 4500 feet (1371.6 m), a rate of descent of 106 ft/sec (32.3 m/sec), a forward velocity of 442 ft/sec (134.7 m/sec), an out-of-plane velocity of zero, and with the range-to-go to the 1000-foot (304.8-m) altitude point being 16 200 feet (4937.8 m). The landing vehicle was initially oriented so that the nominal 1000-foot (304.8-m) altitude point would be attained after 62 seconds. (The thrust vector was directed 40° back from the local vertical and the throttle setting T was 0.465.) The fuel remaining in the landing vehicle at the point of problem initiation corresponded to a characteristic-velocity capability of 1920 ft/sec (585.2 m/sec).

PILOTING PROCEDURE

It was assumed that the automatic guidance and control system of the landing vehicle had been used prior to the point of problem initiation. In the fixed-base visual-simulation, the pilot assumes command of the landing vehicle at any time he chooses during the 62 seconds after problem initiation. The general procedure is to maintain the initial pitch angle with respect to the local vertical and the initial throttle setting until 62 seconds have elapsed. At this point the landing vehicle will have descended to an altitude of approximately 1000 feet (304.8 m) and will have a rate of descent of zero and a forward velocity of 75 ft/sec (22.9 m/sec). Knowing the altitude to be approximately 1000 feet (304.8 m), the pilot pitches the vehicle to a vertical attitude and reduces thrust in order to translate over the lunar surface at nearly constant altitude until a desirable landing site is reached. At this point the pilot pitches the vehicle back from the vertical attitude in order to bring the forward velocity to zero. He then returns the vehicle to the vertical position and slowly descends to the surface. Because of the 650-foot (198.1-m) minimum-altitude restriction inherent in the present simulation, the pilot was instructed to bring the translational velocity components to zero at an altitude slightly exceeding 650 feet (198.1 m) and with a rate of descent not to exceed 20 ft/sec (6.1 m/sec). It was anticipated that altitude would be difficult to judge visually. However, it was believed that altitude changes could be detected and knowing that altitude would be approximately 1000 feet (304.8 m) at the end of the landing-approach transition phase (62 sec after problem initiation) the pilots could estimate altitude sufficiently well to avoid the minimum-altitude stop.

The primary landing site chosen for the simulation was defined by a crater located approximately 3150 feet (960.1 m) down range from (beyond) the 1000-foot (304.8-m) altitude point. The center of the crater locates the site at which lunar landings would nominally be made. Essentially no constant-altitude translation maneuver was required to attain the front slope of this crater. A second crater located approximately 10 040 feet (3060.2 m) down range from the 1000-foot (304.8 m) altitude point was chosen as a secondary landing site. This second landing site is approximately 6890 feet (2100.1 m) down range from the primary (nominal) landing site. In order to attain this secondary landing site, the pilot was required to modify the landing procedure to perform a constant-altitude translation maneuver over the extended range. (See fig. 5.)

On any given flight the pilots were instructed to land in a specific area. Landings could be made at any point between the two craters but were generally to be made on or near the slopes of the craters where recognizable features were prevalent. The walls of the craters have slopes of only 2° and, thus, should constitute reasonable landing areas.

RESULTS AND DISCUSSION

The results of this investigation are divided into two sections: one pertaining to landings made in the vicinity of the primary landing site and the other to landings made in the vicinity of the secondary landing site. Two test pilots and one engineer acted as pilots during the study. Because the performance of the various pilots did not differ significantly, no distinction was made in the presentation of results.

Primary Landing Site

The problem was initiated at the 4500-foot (1371.6-m) altitude point of the landing-approach transition phase of a typical lunar landing trajectory. Results of a typical piloted trajectory are presented in figure 6. The time history shows that the pilot maintained the initial throttle setting of 0.465 and initial 40° pitch angle for approximately 62 seconds. He then reduced thrust and pitched the vehicle to a vertical attitude. At this point the vehicle was about 3000 feet (914.4 m) up range from the nominal landing site at an altitude of approximately 1000 feet (304.8 m). The pilot maintained the vertical attitude and kept the rate of descent near zero, as he translated down range at an altitude near 1000 feet (304.8 m). After 102 seconds had elapsed, the pilot believed he was near a good landing site and pitched the vehicle back to about 28° to bring the forward velocity to zero. Simultaneously, the pilot yawed the landing vehicle over to about -20° in order to translate to the left-hand slope of the crater. At 130 seconds the pilot, having brought the forward velocity to zero, reduced the pitch angle to zero. He then manipulated yaw to reduce the out-of-plane velocity and brought the yaw angle to zero at about 157 seconds. When the translational velocities were sufficiently small, he descended toward the lunar surface and terminated the flight at 176 seconds. The terminal conditions for this flight were a forward velocity of 4.0 ft/sec (1.2 m/sec), a rate of descent of 2.7 ft/sec (0.8 m/sec), an out-of-plane velocity of -4.7 ft/sec (-1.4 m/sec), and an altitude of 707 feet (215.5 m). A characteristic velocity of 1215.4 ft/sec (370.5 m/sec) was required to perform the maneuver.

The results of this phase of the investigation are presented in the following table in the form of the arithmetic mean and the standard deviation from the mean of the terminal conditions for a total of 162 flights:

Parameter	Arithmetic mean	Standard deviation
Radial velocity, V_R	-5.8 ft/sec (-1.8 m/sec)	10.3 ft/sec (3.1 m/sec)
Forward velocity, V_λ.	1.7 ft/sec (0.5 m/sec)	7.5 ft/sec (2.3 m/sec)
Out-of-plane velocity, V_β	-4.4 ft/sec (-1.3 m/sec)	5.7 ft/sec (1.7 m/sec)
Characteristic velocity, V_c . . .	1268.4 ft/sec (386.6 m/sec)	226.2 ft/sec (69.0 m/sec)

It should be noted that although these terminal velocities constitute near-hover conditions they were obtained under the influence of a 650-foot (198.1-m) minimum-altitude restriction imposed by the simulation equipment with the resulting average terminal altitude being approximately 730 feet (222.5 m). The terminal velocity conditions for hovering near the lunar surface should be smaller.

The locations of the landing sites chosen by the pilots relative to the crater that constitutes the primary landing site are shown in figure 7. In order to determine how well the pilots could attain a specified landing site, several flights were made in which the pilots attempted to land inside the rim of the crater. The pilots could generally set up hover conditions within about 250 feet (76.2 m) of the nominal landing site. In general, however, the interior of the crater was avoided and the pilots maneuvered in order to land at various points on the slopes of the crater. The shortest range that the pilots were able to attain without reversing their direction of motion was approximately 800 feet (243.8 m) down range from (beyond) the 1000-foot (304.8-m) altitude point or about 2300 feet (701.0 m) up range of (before) the nominal landing site. The maneuvers performed to attain these up-range landing points are in general the most economical and require characteristic velocities on the order of 860 ft/sec (262.1 m/sec). In general, the landing sites out of the reference-orbit plane (which contains the primary landing site) required a larger characteristic velocity than did in-plane landing sites. This difference is due to the increased flight time required for translation to an out-of-plane landing site. Consequently, even though the pilots translated out of the plane of the nominal trajectory to demonstrate their ability to do so, they generally chose landing sites within 1000 feet (304.8 m) of the reference-orbit plane.

Secondary Landing Site

In order to attain the secondary landing site, the pilot was required to extend the range considerably. The general procedure for extending range was to perform a nearly constant altitude translation maneuver from the 1000-foot (304.8-m) altitude point to the area of the secondary landing site. Results of a typical piloted trajectory are presented in figure 8. The time history shows that the pilot reduced the throttle setting and pitched the vehicle to a nearly vertical attitude after approximately 57 seconds. This maneuver occurred about 5 seconds earlier than was nominal and resulted in the attainment of a zero rate of descent at an altitude of 1200 feet (365.8 m) with a forward velocity of approximately 100 ft/sec (30.5 m/sec). The pilot then maintained a nearly vertical attitude as he kept the rate of descent near zero and translated down range. After 130 seconds had elapsed, the pilot saw that he was approaching the secondary landing site and he pitched the vehicle back to about 28° from the vertical to reduce the forward velocity while allowing the landing vehicle to descend toward the lunar surface. While the pilot was concentrating on attaining a rate of descent and forward velocity acceptable for hover conditions, the yaw angle of the vehicle began to increase. The pilot brought the yaw angle to nearly zero and terminated the run at 204 seconds. The terminal conditions for this flight were a forward velocity of -6.0 ft/sec (-1.8 m/sec), a rate of decent of 5.3 ft/sec (1.6 m/sec), an out-of-plane velocity of -8.1 ft/sec (-2.5 m/sec), and an altitude of 815 feet (248.4 m). A characteristic velocity of 1348.18 ft/sec (410.9 m/sec) was required to perform the maneuver.

The results of the extended range phase of the investigation are presented in the following table in the form of the arithmetic mean and the standard deviation from the mean of the terminal condition for a total of 102 flights:

Parameter	Arithmetic mean	Standard deviation
Radial velocity, V_R	-5.5 ft/sec (-1.7 m/sec)	12.9 ft/sec (3.9 m/sec)
Forward velocity, V_λ	6.1 ft/sec (1.9 m/sec)	8.5 ft/sec (2.6 m/sec)
Out-of-plane velocity, V_β	-5.7 ft/sec (-1.8 m/sec)	5.2 ft/sec (1.6 m/sec)
Characteristic velocity, V_c . . .	1520.0 ft/sec (463.3 m/sec)	180.9 ft/sec (55.1 m/sec)

The average terminal altitude above the secondary landing site was approximately 230 feet (70.1 m) higher than that for the primary landing site. This increase in average terminal altitude exists because the minimum-altitude stop at the secondary landing site was 240 feet (73.2 m) higher than it was at the primary landing site; therefore, the pilots were required to terminate the flights at a higher altitude. The terminal translational velocities for the secondary landing site are also slightly larger than for the primary landing site. This increase in velocity is attributed to the increase in average terminal altitude which occurred at the secondary landing site. (The pilot actually detects the angular displacement of a landmark. For a given angular velocity, the corresponding translational velocity increases as the altitude increases.)

The location of the various landing sites chosen by the pilots relative to the crater that constitutes the secondary landing site are shown in figure 9. In order to demonstrate their ability to attain a wide range of landing sites, the pilots attempted a number of landings in the area up range of the second crater but generally landed on or near the slopes of the second crater. When the pilots chose landing sites that were not in close proximity of the crater, they essentially landed anyplace because the entire area constituted safe landing sites and possessed no distinguishing features at which to aim. When sites close to the crater were chosen, the pilot attempted to land in some given area. For example, the shaded symbols of figure 9 designate flights during which the pilot attempted to land on the left-hand side of the front slope of the second crater. Fuel was critical at the down-range location of the second crater and the pilots were not so diligent in their attempts to attain a given landing site. The sites selected by the pilots for landing, however, were acceptable and the terminal velocities were low enough to constitute near-hover conditions. Thus, the range of landing sites accessible from the 1000-foot (304.8-m) altitude point extends approximately 10 800 feet (3291.8 m) down range from the 1000-foot (304.8-m) altitude point or about 7700 feet (2347.0 m) down range from the nominal landing site. The constraining factor is available fuel.

Although precise determination of the 1000-ft (304.8-m) altitude point was very difficult to judge visually, the pilot could generally estimate altitude accurately enough to avoid the minimum-altitude restriction of the simulation equipment and to establish near-hover conditions over a wide range of landing sites. Nevertheless, the minimum-altitude stop was activated during 40 flights pertaining to landings made in the vicinity of the primary as well as the secondary landing site. The results of these 40 flights have not been included in any previous discussion of this investigation; however, they are presented in the following table in the form of the arithmetic mean and the standard deviation from the mean of the terminal conditions:

Parameter	Arithmetic mean	Standard deviation
Radial velocity, V_R	-29.9 ft/sec (-9.1 m/sec)	7.8 ft/sec (2.4 m/sec)
Forward velocity, V_λ	5.6 ft/sec (1.7 m/sec)	7.3 ft/sec (2.2 m/sec)
Out-of-plane velocity, V_β	-2.4 ft/sec (-0.7 m/sec)	5.9 ft/sec (1.8 m/sec)
Characteristic velocity, V_c . . .	1337.5 ft/sec (407.7 m/sec)	206.4 ft/sec (62.9 m/sec)

The translational velocities are acceptable for near-hover conditions and it is believed that if the minimum-altitude stop had not been required, the rate of descent could have been reduced to an acceptable level before reaching zero altitude. The accuracy with which the velocity components and altitude can be determined increases as the altitude of the vehicle decreases.

CONCLUDING REMARKS

A fixed-base visual-simulation study has been conducted to determine the ability of the human pilot, using only a three-axis gyro horizon nulled to the local vertical and an out-the-window view of the lunar surface for visual reference, to control a lunar landing vehicle manually during translation to and hover above various landing sites in a given landing area. The study included all six rigid-body degrees of freedom of the vehicle. The pilot's task was to assume command of the landing vehicle during the final portion of the automatically controlled landing-approach transition phase of a typical lunar landing trajectory and to control the landing vehicle manually to attain near-hover conditions over any one of a number of landing sites in the area of a preselected nominal landing site.

Within the limits of the simulation, the results of the study showed that landing sites could consistently be attained with low terminal velocities, although accurate altitude determination at altitudes of approximately 1000 feet (304.8 m) was very difficult. Knowing the approximate altitude at the end of the landing-approach transition phase, the pilots were able to establish near-hover conditions above landing sites at any point within a fairly large landing area, with range errors from a given site being on the order of 250 feet (76.2 m). The landing sites attained by the pilots extended from approximately 2300 feet (701.0 m) up range of (before) to approximately 7700 feet (2347.0 m) down range of (beyond) the nominal landing site. Landing sites in the plane of the nominal trajectory were readily attainable and the pilots translated out of the plane of the nominal trajectory only to demonstrate their ability to do so. In general, the pilots chose landing sites that were within about 1000 feet (304.8 m) of the reference-orbit plane, which contained the nominal landing site. The accessible landing area could, of course, be extended by diverging from the nominal landing trajectory at some point during the landing-approach transition phase.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 19, 1966.

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3. Miller, G. Kimball, Jr.; and Sparrow, Gene W.: Visual Simulation of Lunar Orbit Establishment Using a Simplified Guidance Technique. NASA TN D-3524, 1966.

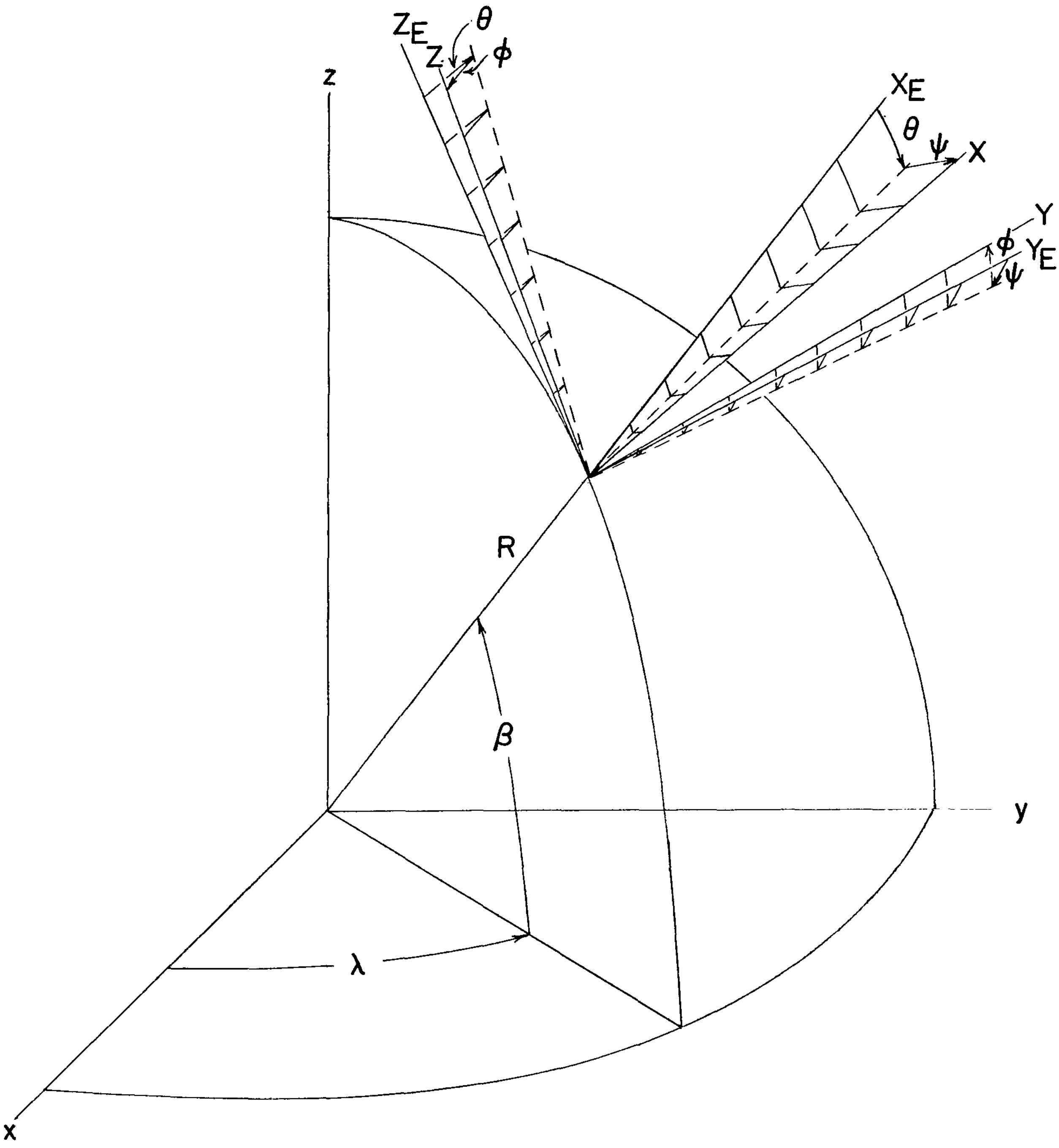

Figure 1.- Assumed axis systems.

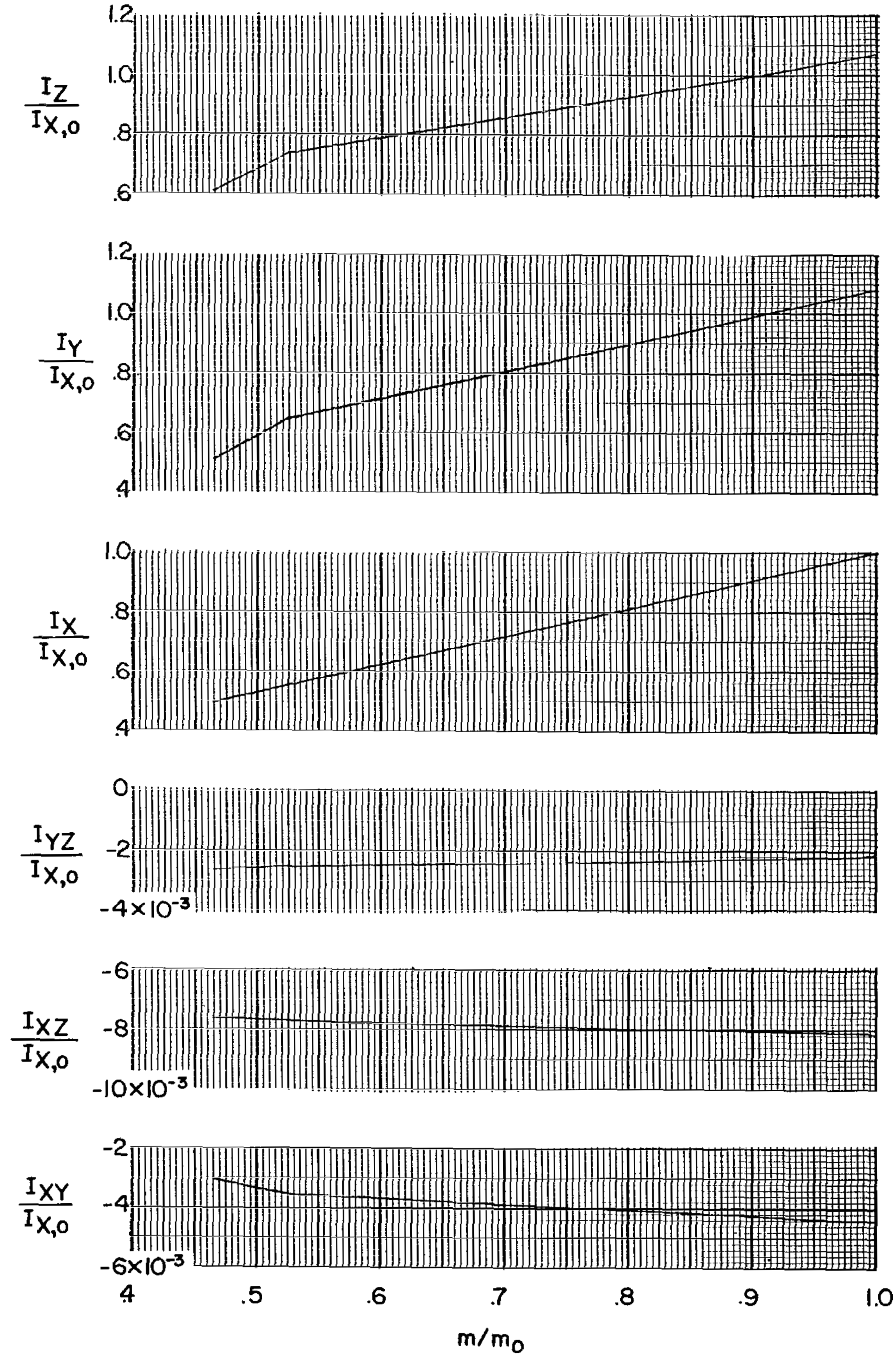

Figure 2.- Nondimensionalized vehicle characteristics $\left(\frac{m_i}{m_o} = 0.582\right)$.

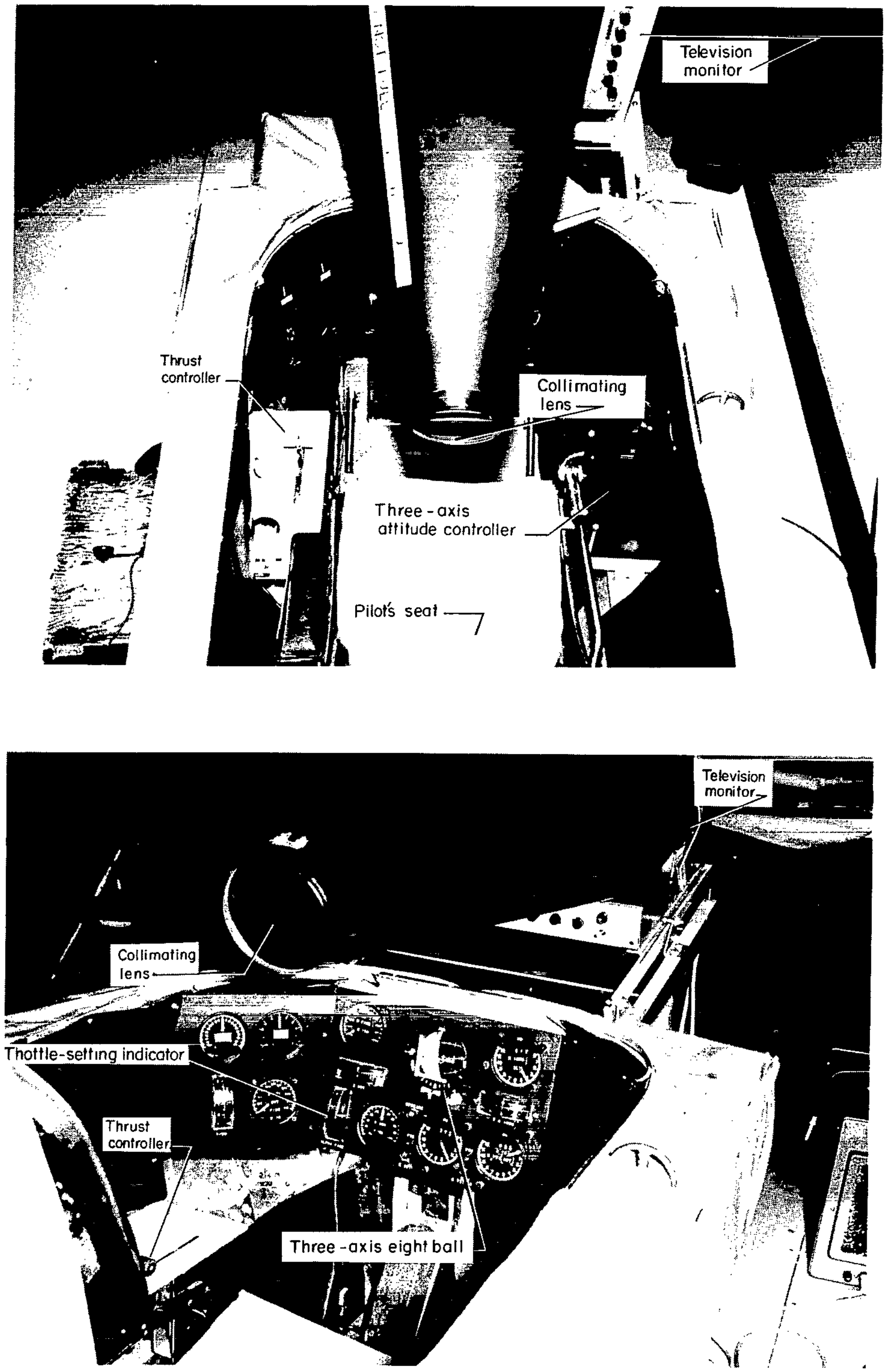

Figure 3.- General layout of cockpit. L-66-4525

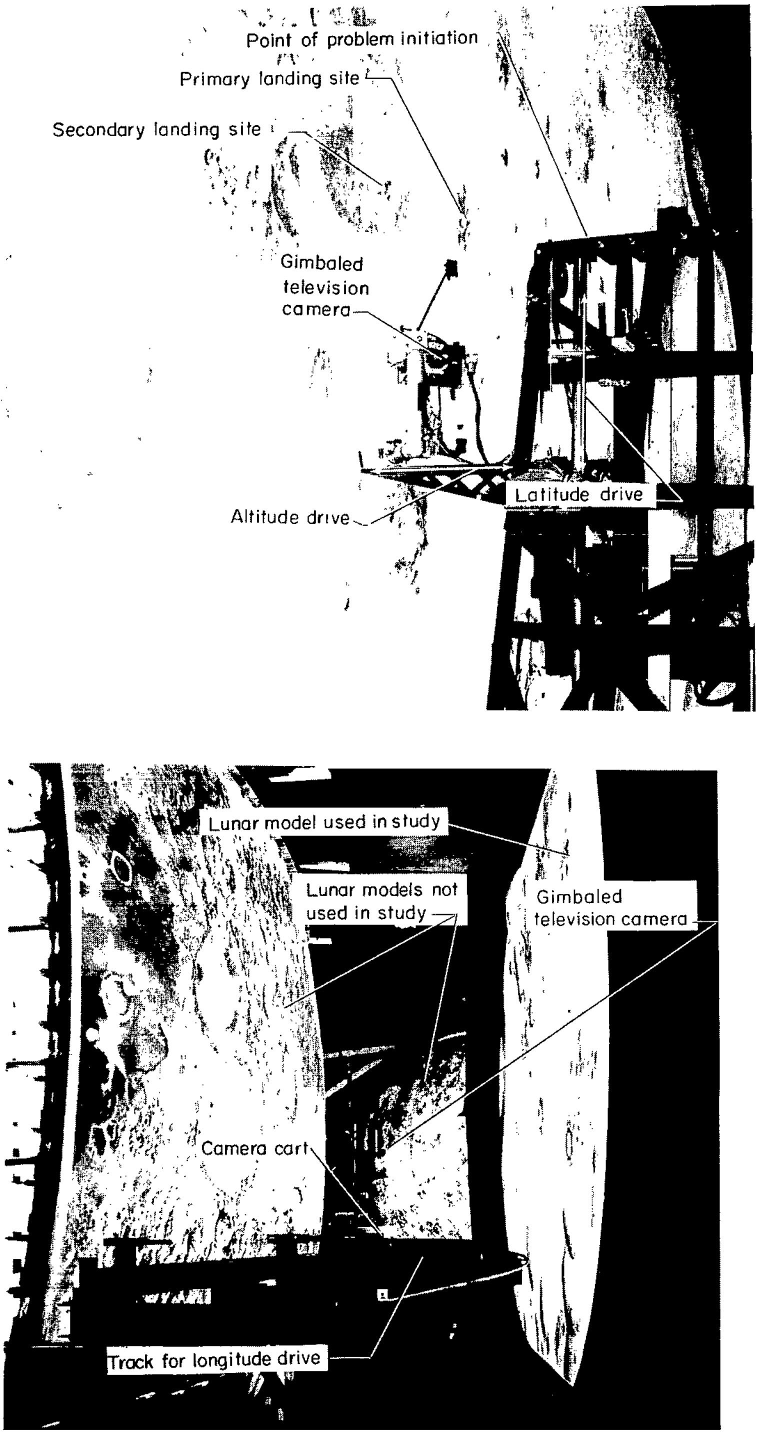

Figure 4.- Lunar model and television camera. L-66-4526

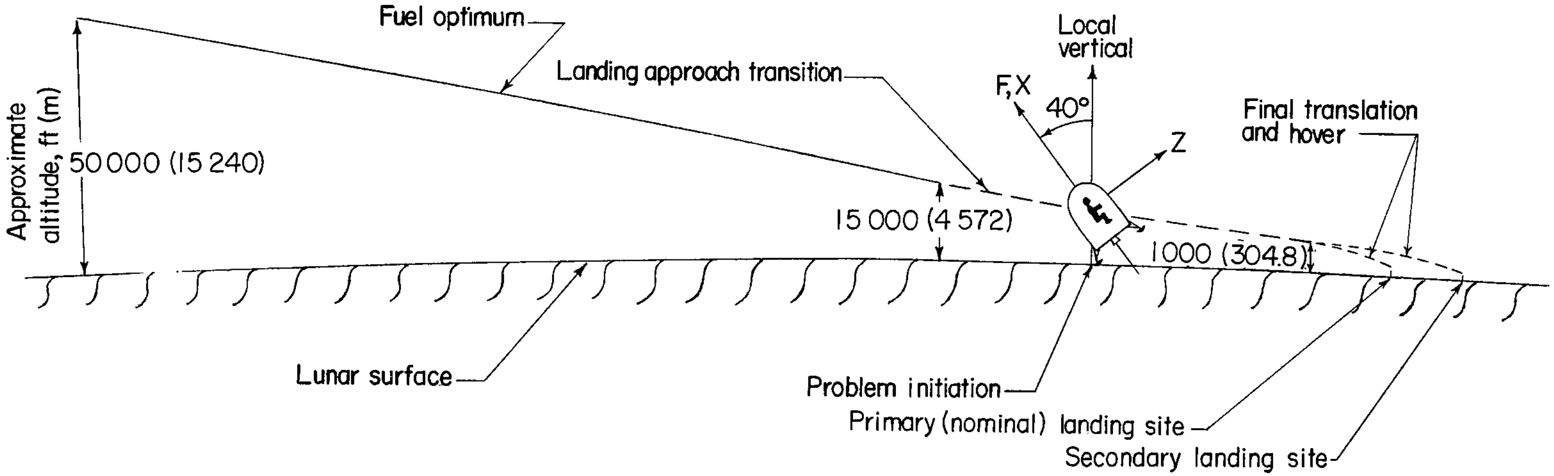

Figure 5.- Lunar landing trajectory.

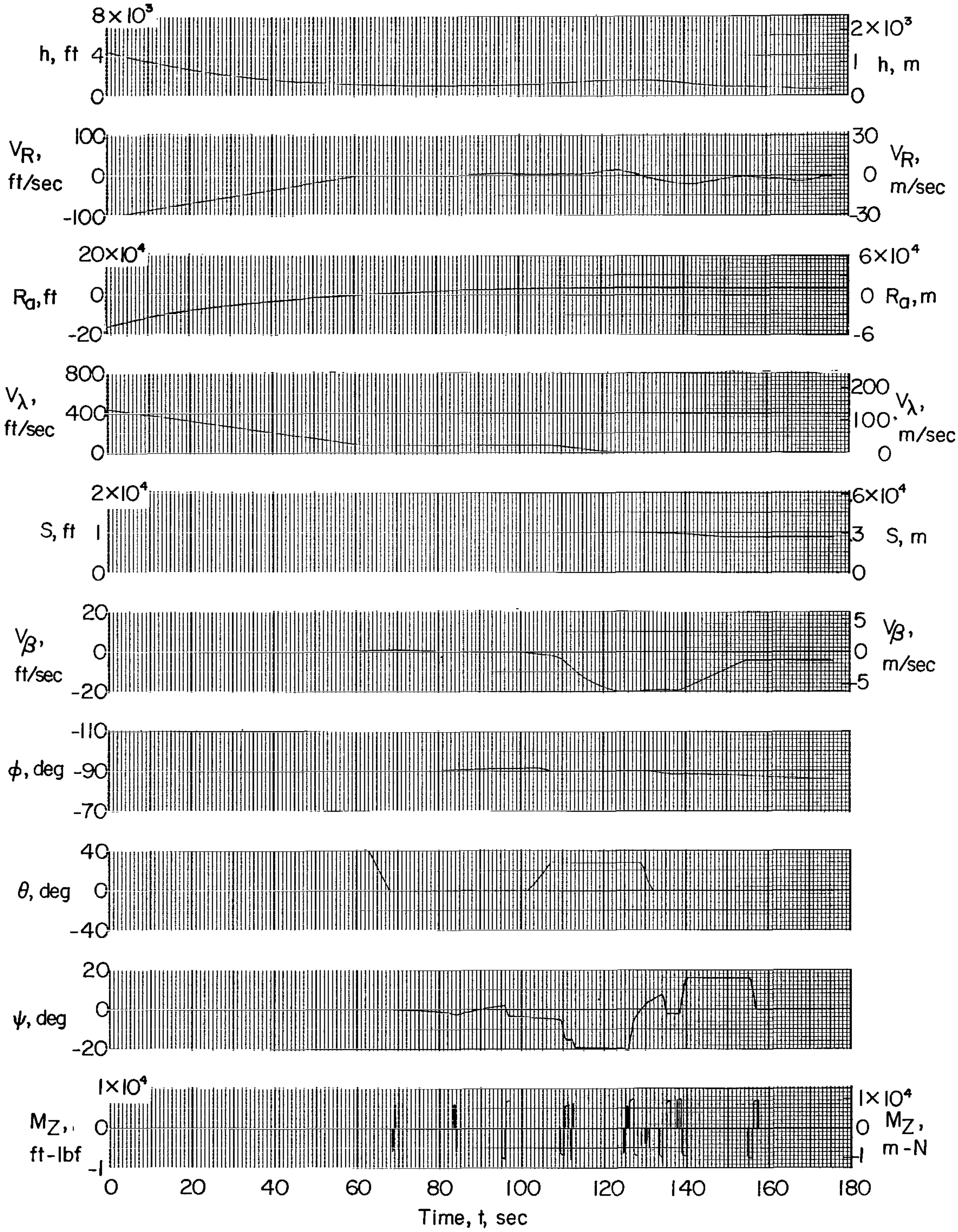

Figure 6.- Results of a typical piloted flight to primary landing site.

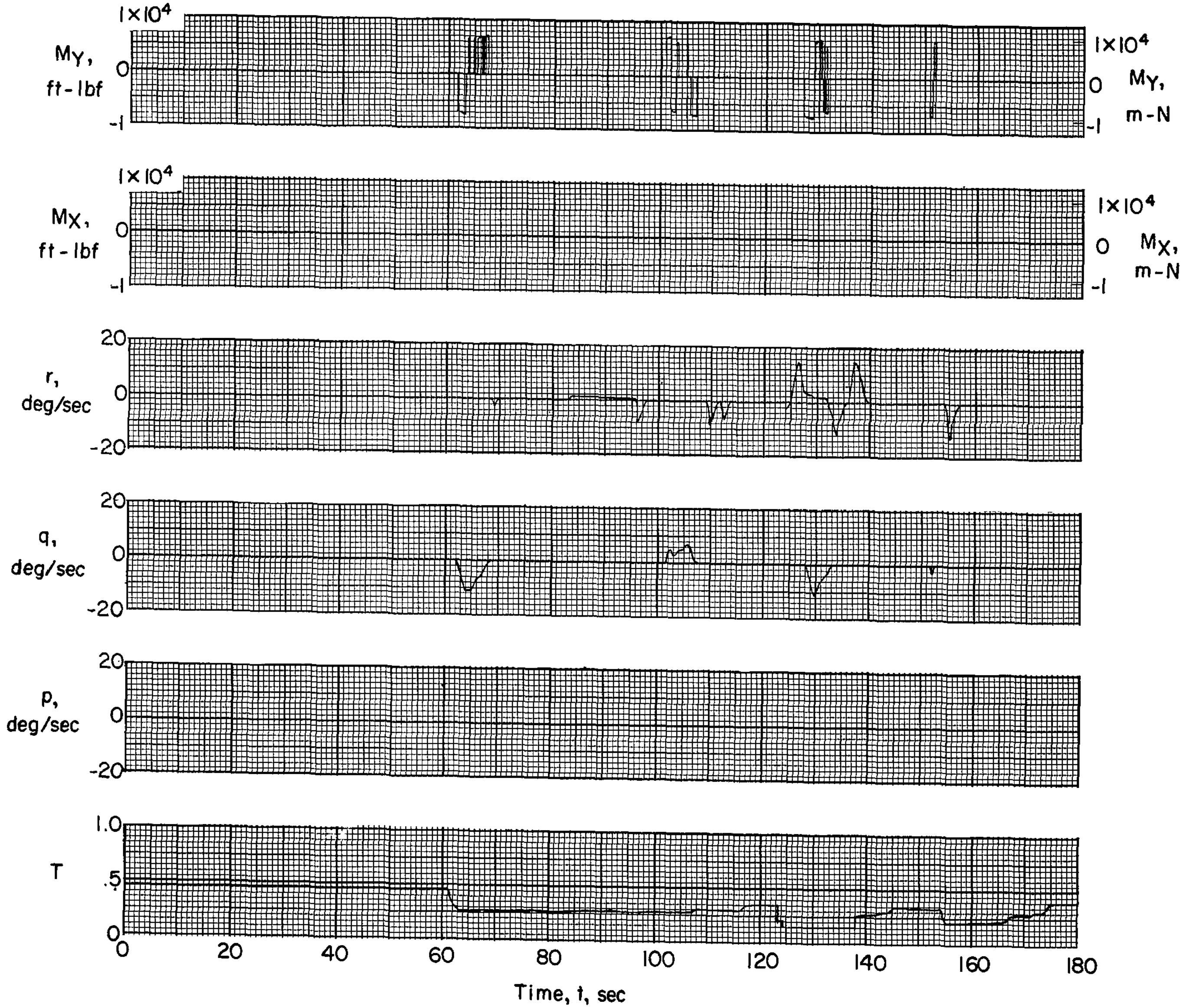

Figure 6.- Concluded.

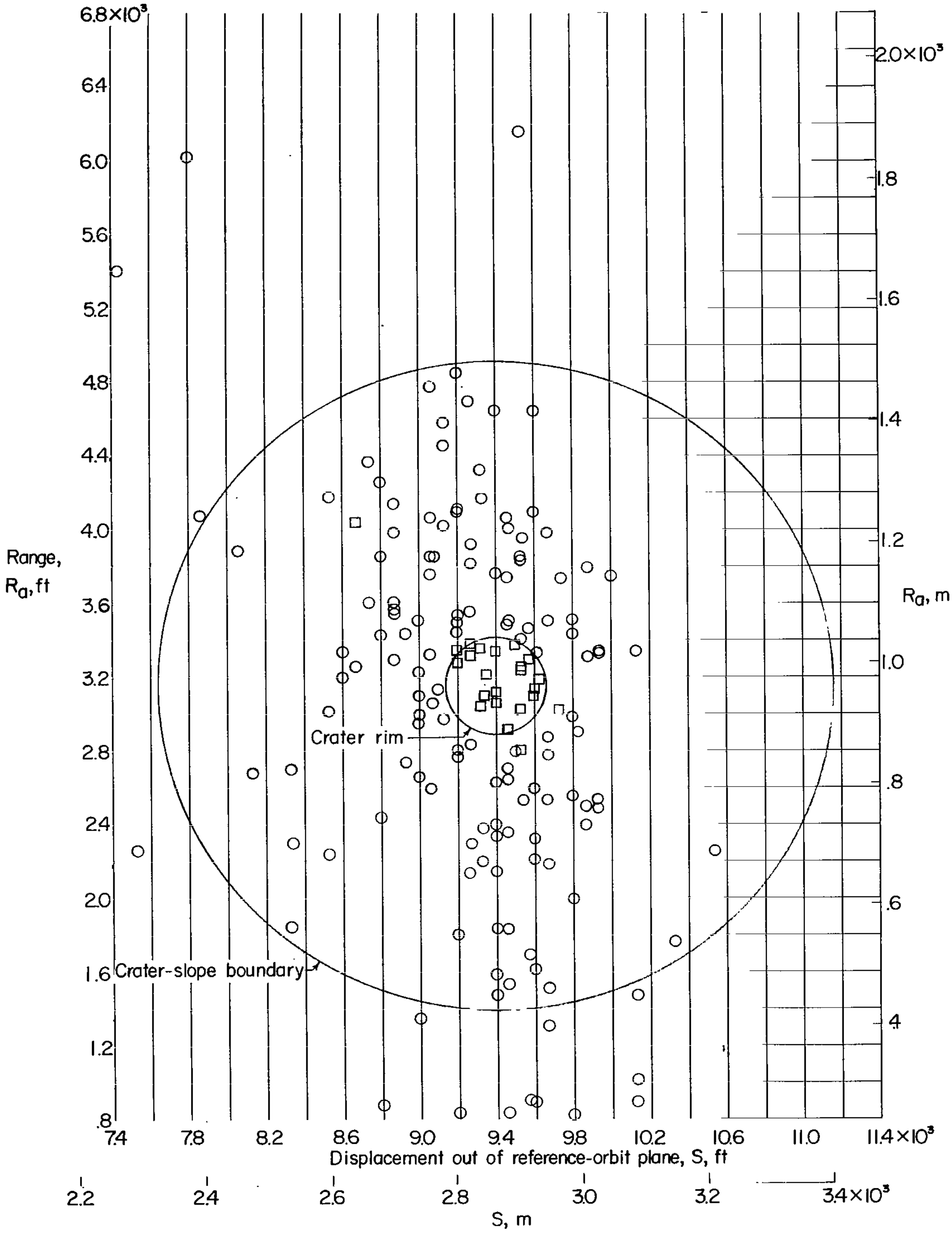

Figure 7.- Location of landing sites relative to first crater. (Square symbols denote flights in which pilots attempted to land inside rim of crater.)

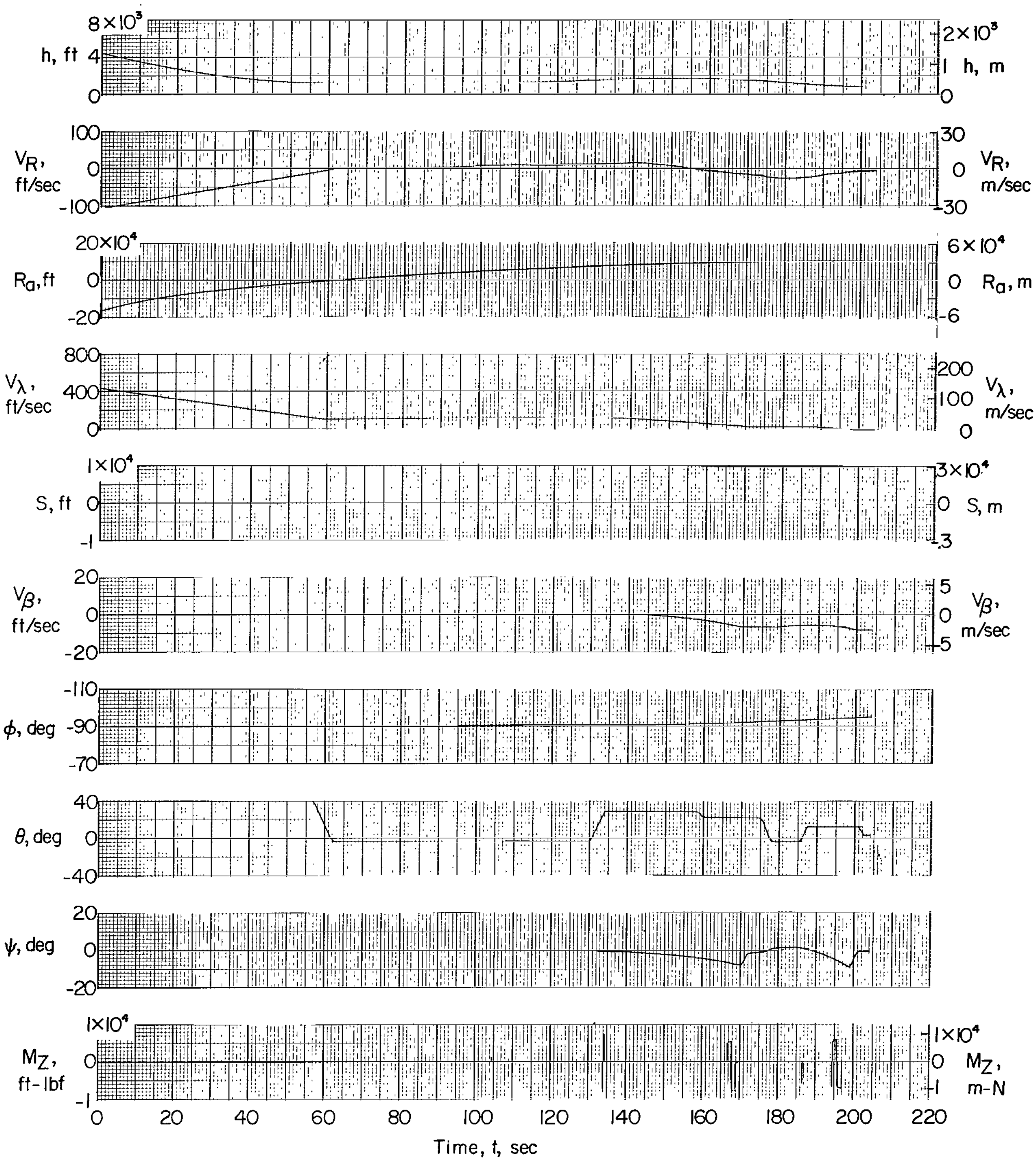

Figure 8.- Results of a typical piloted flight to secondary landing site.

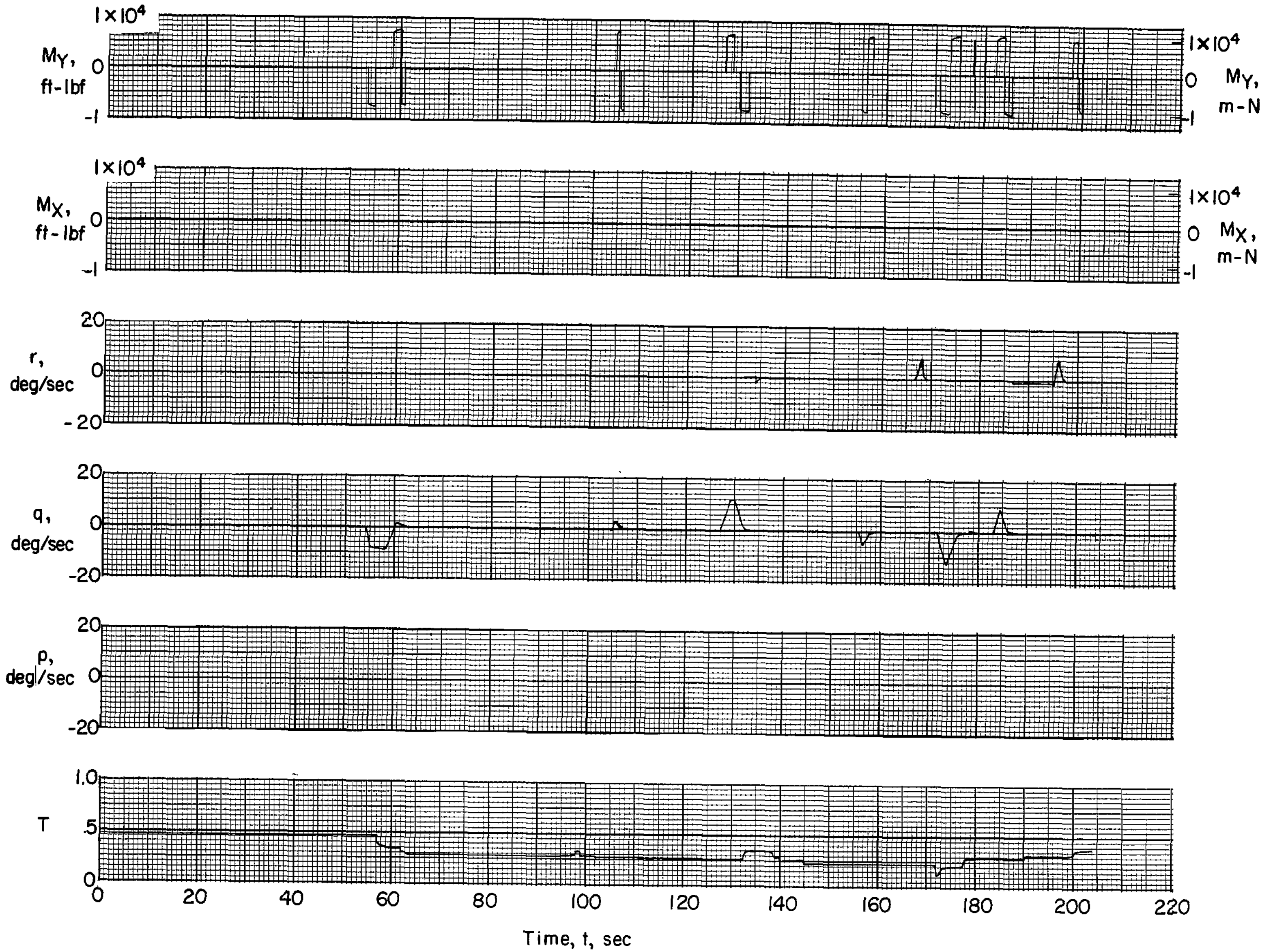

Figure 8.- Concluded.

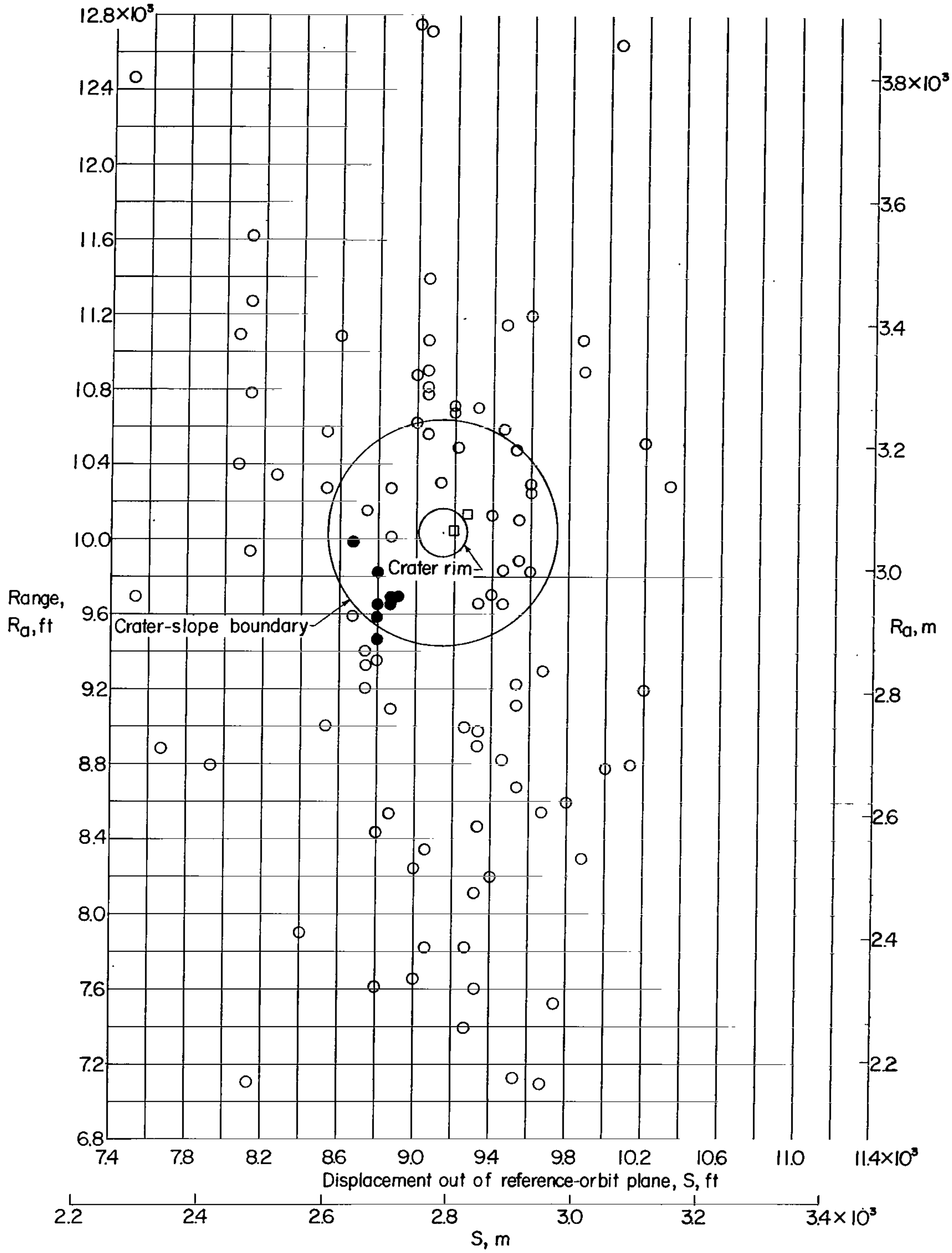

Figure 9.- Location of landing sites relative to second crater. (Square symbols denote flights in which pilots attempted to land inside rim of crater. Shaded symbols denote flights in which pilots attempted to land on left side of front slope of second crater.)

NASA-Langley, 1966 L-5071

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