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Langley Station, Hampton, Va.

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SUMMARY

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An analytical study has been made to determine whether a previously developed technique for performing the lunar landing trajectory can be applied to landings from an elliptic orbit established by a Hohmann transfer. The Hohmann transfer maneuver is initiated from a circular parking orbit 80 international nautical miles above the lunar surface, and the pericyynthion altitude of the resulting elliptic orbit is 50,000 international feet. The technique consists of maintaining a constant angle between the thrust vector and the line of sight to the command module in a parking orbit. Trajectory computations based on the use of the orbiting vehicles for thrust-vector orientation resulted in efficient landings. The variation of terminal conditions due to errors in thrust direction, thrust magnitude, and initial condition of the lander at initiation of the braking maneuver was examined. In general, the terminal conditions were relatively insensitive to these errors. The most critical errors appear to be those associated with thrust magnitude and thrust direction.

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INTRODUCTION

In the future moon journey, it may be necessary for man to control the attitude of his spacecraft and to perform some function with only a limited amount of instrumentation. Thus, techniques which allow pilot control of various phases of the lunar mission have been under consideration at the Langley Research Center for some time, and simulations have been made to demonstrate man's capabilities in space. (See references listed in ref. 1, for example.)

The phase of the lunar mission to be considered here is the descent to the lunar surface from pericynthion of an elliptic transfer orbit. The present transfer orbits being considered for the lunar mission are the synchronous transfer orbit and the Hohmann transfer orbit. These transfer orbits are initiated from a circular parking orbit about 80 international nautical miles above the lunar surface and have pericynthion altitudes of about 50,000 international feet. In reference 2 it was shown that efficient landings can be made from the synchronous orbit by simply aiming the thrust vector of the landing vehicle at a constant angle behind the spacecraft left in parking orbit.

However, since the Hohmann transfer orbit is also being considered for the mission because of its fuel economy, it is of interest to determine whether this technique is still applicable.

The purpose of this study is to determine whether the technique of reference 2 remains applicable to an elliptic orbit established by a Hohmann transfer and, if it is applicable, to determine the subsequent sensitivities involved.

SYMBOLS

In cases where distances are expressed in nautical miles or in feet, the international nautical mile and the international foot, respectively, are intended. The following factors are included for use in converting English units to metric units: 1 international nautical mile = 1,852 meters (exact) and 1 international foot = 0.3048 meter (exact).

F	thrust, lb
g_e	gravitational acceleration at surface of earth, 32.2 ft/sec ²
h	altitude, ft
I_{sp}	specific impulse, 305 sec
K	angle between the thrust vector and the line of sight to a specified reference, deg
m	mass, slugs
R	range of travel over lunar surface, ft
r	radial distance from center of moon, ft
r_m	radius of moon, 5,702,000 ft
t	time, sec
V	total velocity, fps
ΔV	characteristic velocity, $I_{sp}g_e \log_e \frac{m_0}{m_0 - \dot{m}t}$, fps
W	earth weight, mg_e , lb
α	thrust attitude with respect to local horizontal, positive when thrust is directed upward, deg or radians (fig. 1(b))
γ	vehicle flight-path angle, deg (fig. 1(b))

- θ angular travel over lunar surface, deg or radians
- θ^* angular separation of lunar excursion and orbiting modules, measured with vertex at moon's center, deg

Subscripts:

- 0 initial value (at landing initiation)
- t condition at end of landing trajectory
- S orbiting command and service modules

A dot over a symbol denotes the derivative with respect to time.

ANALYSIS

The landing maneuver studied in the present investigation is illustrated in figure 1. The spacecraft, consisting of an excursion module, a command module, and a service module, is placed in an 80-nautical-mile-altitude circular orbit around the moon. At the appropriate time the excursion module is separated from the spacecraft and a Hohmann maneuver (180° transfer) is used to establish an orbit having a pericyynthion of 50,000 feet (closest approach to the moon). At the pericynthion of the elliptic orbit, a braking maneuver is performed in order to land the excursion module. The purpose of the present study is to determine whether the technique of reference 2 can be applied to this powered descent.

As in reference 2 the approach used was to compute a gravity-turn landing trajectory, to analyze the thrust orientation with respect to the orbiting command and service modules for this gravity turn, and then to try to fly a close approximation to the gravity-turn descent by maintaining an average constant thrust angle with respect to the orbiting spacecraft. Some of the characteristics of the reference gravity-turn descent are shown in figure 2. The braking maneuver is initiated at an altitude of 50,000 feet, which is the pericynthion of the Hohmann transfer orbit. The braking maneuver terminates with zero vehicle velocity at an altitude of about 4,700 feet. The equations of motion used were for a point mass moving in a central force field and subject to a thrust force in the plane of motion (eqs. (1) and (2) of ref. 2). A constant-thrust engine producing an initial thrust—earth-weight ratio of 0.485 and having a specific impulse of 305 seconds was assumed.

RESULTS AND DISCUSSION

The results of this study are presented in two sections. The first section is an examination of the orientation of the thrust vector throughout the reference gravity-turn descent with respect to the orbiting spacecraft and a comparison of the gravity turn and a nominal trajectory which is generated by

maintaining a constant thrust angle relative to the orbiting vehicle. The second section is an examination of the variations in terminal conditions of this nominal trajectory as a result of errors in the constant thrust angle, thrust level, and initial conditions existing at the time the powered descent is initiated.

The Orbiting Spacecraft as a Thrust-Direction Reference

The angle between the thrust vector, in the gravity turn, and the line of sight to the modules remaining in parking orbit can be determined from the geometric relationships shown in figure 3 and is given by equation (8) of reference 2 as

$$K_S = 90^\circ - \left[\theta^* + \tan^{-1} \left(\frac{\sin \theta^*}{\frac{r_m + h_S}{r_m + h} - \cos \theta^*} \right) \right] - \alpha$$

where $\theta^* = (\theta^*)_0 + \theta - \dot{\theta}_{st}$. The time t and angular travel θ are measured from initiation of the powered descent, and $(\theta^*)_0$ is the separation angle at landing initiation. The variation of K_S throughout the gravity-turn landing maneuver is shown in figure 4 as a function of altitude. As in reference 2 the angle remains essentially constant throughout most of the landing. Note that from the point of thrust initiation ($h = 50,000$ feet) down to an altitude of about 10,800 feet the angle remained about $18^\circ \pm 1^\circ$. A nominal landing trajectory generated by thrusting 18.3° (that is, $K_S = 18.3^\circ$) behind the orbiting spacecraft is compared with the reference gravity turn in figure 5. The terminal conditions (defined as those conditions existing below 50,000 feet when one of the velocity components \dot{r} or $\dot{r}\theta$ first become zero), of the two trajectories are presented in the following table:

Condition	Terminal condition for -	
	Gravity turn	$K_S = 18.3^\circ$
\dot{r}_t , fps	0	-127
$r\dot{\theta}_t$, fps	0	0
h_t , ft	4,753	4,709
R_t , ft	832,812	832,073
ΔV_t , fps	5,754	5,702

These results show that the trajectory generated with $K_S = 18.3^\circ$ is a very good approximation of the gravity turn. It appears, therefore, that using

the orbiting spacecraft as an aiming reference would be convenient for manual control or for monitoring the progress of an automatic powered descent.

It should be noted, however, that in order for the pilot of the lunar excursion module (LEM) to use the orbiting spacecraft for thrust-orientation purposes, he must first be able to observe the orbiting spacecraft while flying the nominal powered descent. At present, it appears that this observation could be accomplished either by visual sighting or by using the rendezvous radar.

As the LEM vehicle approaches the lunar surface, the pilot should be able to complete the last 10,000 to 12,000 feet of the landing by using immediate-terrain observations. In consequence, it may be desirable to select a different K_S in order to match the gravity turn at a specific altitude rather than at the terminal condition. The following table shows that a closer approximation to the gravity-turn parameters at an altitude of 12,000 feet is obtained by using a thrusting angle of 18.4° than by using 18.3° ; however, this is a change of only 0.1° in K_S and the additional accuracy is slight.

Condition	Condition at an altitude of 12,000 feet for -		
	Gravity turn	$K_S = 18.4^\circ$	$K_S = 18.3^\circ$
\dot{r} , fps	-287	-298	-285
$r\dot{\theta}$, fps	896	889	818
R, ft	816,049	816,017	818,480
ΔV , fps	4,739	4,743	4,817

Error Analysis

The error analysis consisted in examining the accuracy with which the aiming angle must be held and the sensitivity of the technique to errors in the initial conditions. The initial conditions are those conditions existing at the time the braking descent is initiated. These conditions can be related to errors in any portion of the elliptic coasting orbit through the standard orbital-mechanics equations. The individual error effects which follow were obtained by varying only one initial condition from the nominal value at a time. Comments on combination error effects will be made after the individual effects are discussed.

Thrust-vector direction. - The variations in terminal conditions with change in thrust direction are shown in figure 6. As noted previously, terminal conditions are defined as those conditions existing below 50,000 feet at the time one of the vehicle velocity components (\dot{r} or $r\dot{\theta}$) first becomes zero. Figure 6 shows the following interesting results:

(a) The range covered during the braking maneuver and the time required to attain terminal conditions are rather insensitive to errors in thrust-vector direction as large as $\pm 2^\circ$.

(b) The terminal altitude and velocity vary approximately linearly with thrust direction.

The sharp discontinuity in the velocity curve which occurs at $K_S = 16.7^\circ$ is associated with the fact that for $K_S < 16.7^\circ$ the radial component is reduced to zero while the tangential velocity $r\dot{\theta}$ has some magnitude. Values of $K_S > 16.7^\circ$ cause the velocity component $r\dot{\theta}$ to be reduced to zero while the radial velocity has a finite value.

The altitude sensitivity to K_S is about 11,000 feet for each degree in K_S and the radial velocity sensitivity is about 77 feet per second for each degree in K_S .

Thrust level. - The sensitivity of terminal conditions to thrust level (or F/W_0) is shown in figure 7. The curves show that terminal conditions vary almost linearly with thrust level. Depending upon the possible magnitude of thrust error anticipated for the LEM vehicle, the terminal conditions could become rather intolerable if no corrective measures are made during the descent. It does not appear, however, that errors of, say, ± 1 or ± 2 percent would be too serious. The sensitivities of terminal altitude and terminal range for each percent of error in thrust level are 800 feet and 7,400 feet, respectively.

Initial altitude. - The variations of terminal conditions with change in initial altitude are presented in figure 8 and again are approximately linear. The most sensitive condition shown is the terminal altitude which varies from the nominal altitude ($\Delta h = 0$) by about one-half of the initial altitude error.

Initial rate of descent. - The nominal powered descent is initiated at the orbit pericynthion with zero rate of descent. The sensitivity of terminal conditions to variation in initial rate of descent is shown in figure 9. It is apparent that the terminal conditions are not critically sensitive to initial rate of descent if the magnitudes of the initial rates are less than 10 feet per second.

Initial tangential velocity. - The sensitivity of terminal conditions to initial errors in tangential velocity is shown in figure 10. Notice in particular the negligible variation in altitude with initial tangential velocity. Perhaps the most sensitive parameter is the range although it appears that errors as large as ± 100 feet per second in initial tangential velocity do not seriously alter the terminal conditions.

Initial separation angle. - The initial separation angle referred to here is $(\theta^*)_0$, the separation angle between the lander and the orbiting spacecraft at initiation of the landing maneuver. (Refer to fig. 3.) The variations in terminal conditions due to errors in this initial separation angle are shown in figure 11. Here the most sensitive condition is the terminal altitude; however,

even this variation does not appear to be a serious problem. The reason for this is that the error in initial separation angle will be very small unless gross errors are made in establishing the Hohmann transfer. Such errors should be detectable, and thus corrective action can be taken before initiation of the powered descent. This corrective action could consist in orbit adjustment; however, in most instances a simple alteration in the sighting angle K_S would suffice.

Combination errors. - In the previous discussions, the variations in the terminal conditions were examined only for single errors in the initial conditions - that is, only one initial condition was varied from the nominal condition at a time. Consequently, there could be some question regarding the effects of a combination of these individual errors on terminal conditions. For instance, none of these individual errors by themselves would correspond to a landing from pericyynthion of an off-nominal Hohmann transfer since the conditions at pericyynthion would differ from the nominal condition not only in altitude but also in tangential velocity and separation angle. This does not present a problem, however, since the terminal conditions resulting from a combination of these relatively small errors should be given approximately by a linear combination of the individual effects.

As a check case and for illustrative purposes, an off-nominal Hohmann transfer was considered which has a pericyynthion altitude of 55,000 feet instead of the nominal altitude of 50,000 feet. The conditions at pericynthion of this elliptic transfer orbit were then used as initial conditions for the landing trajectory. These conditions corresponded to combination errors in the nominal initial conditions; specifically, altitude, tangential velocity, and separation angle. The actual terminal conditions were then compared with those calculated by using the linear addition of the individual effects. The change in terminal altitude was predicted as

$$\Delta h_t = \frac{\alpha h_t}{\alpha (r\dot{\theta})_0} \Delta (r\dot{\theta})_0 + \frac{\alpha h_t}{\alpha h_0} \Delta h_0 + \frac{\alpha h_t}{\alpha \theta_0^*} \Delta \theta_0^*$$

The ratios are referred to as sensitivity coefficients and are given in this case by the slopes of the individual curves. For the off-nominal initial conditions at pericynthion

$$\Delta (r\dot{\theta})_0 = -3.59 \text{ fps}$$

$$\Delta h_0 = 5,000 \text{ ft}$$

$$\Delta \theta_0^* = -0.107 \text{ deg}$$

and from the individual error plots

$$\frac{ah_t}{a(r\dot{\theta})_0} = 0$$

$$\frac{ah_t}{ah_0} = 0.5$$

$$\frac{ah}{a\dot{\theta}_0^*} = -35,000 \frac{ft}{deg}$$

Substituting these values into the equation for terminal altitude change and adding the result to the nominal terminal altitude gives a value of 10,954 feet. The actual flight trajectory indicated a terminal altitude of 10,900 feet. The other terminal conditions were calculated similarly and are presented in the following table for comparison with the actual values:

Condition	Terminal condition for -	
	Trajectory value	Calculated value
h_t , ft	10,900	10,954
\dot{r}_t , fps	-110.5	-112
$r\dot{\theta}_t$, fps	0	0
R_t , ft	830,441	830,440
t_t , sec	277.15	277

This table indicates close agreement between the predicted and the actual terminal conditions obtained by performing a powered descent from pericyynthion of the off-nominal transfer.

The landing technique examined in this investigation appears to be an efficient means of reducing most of the vehicle velocity and altitude so that the final phase of the landing can be accomplished by using immediate-terrain observations as is done by pilots of conventional aircraft. Flight simulations are now required to determine how well a pilot can utilize the technique and how well he can sense possible errors in the trajectory near terminal conditions in order to perform the necessary corrections to compensate for them.

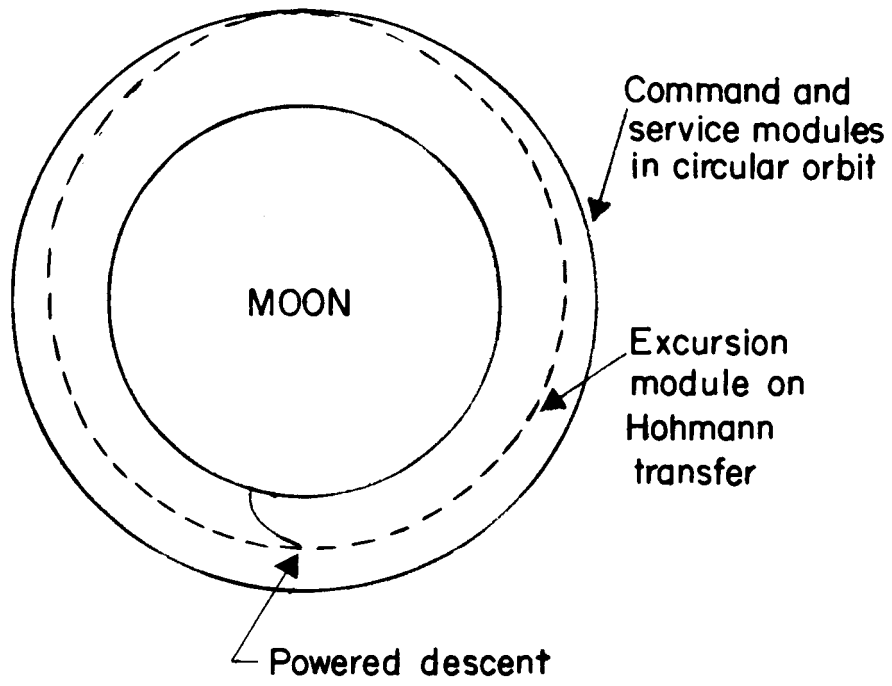
CONCLUDING REMARKS

An analytical study has been made to determine if a previously developed technique for performing the lunar landing trajectory can be applied to landings from an elliptic orbit established by a Hohmann transfer. The Hohmann transfer maneuver is initiated from a circular parking orbit 80 international nautical miles above the lunar surface, and the pericyynthion altitude of the resulting elliptic orbit is 50,000 international feet. The technique consists of maintaining a constant angle between the thrust vector and the line of sight to the command module in a parking orbit. Trajectory computations based on the use of the orbiting spacecraft for thrust-vector orientation resulted in efficient landings. The variation of terminal conditions due to errors in thrust direction, thrust magnitude, and initial condition of the lander at initiation of the braking maneuver was examined. In general, the terminal conditions were relatively insensitive to these errors. The most critical errors appear to be those associated with thrust magnitude and direction.

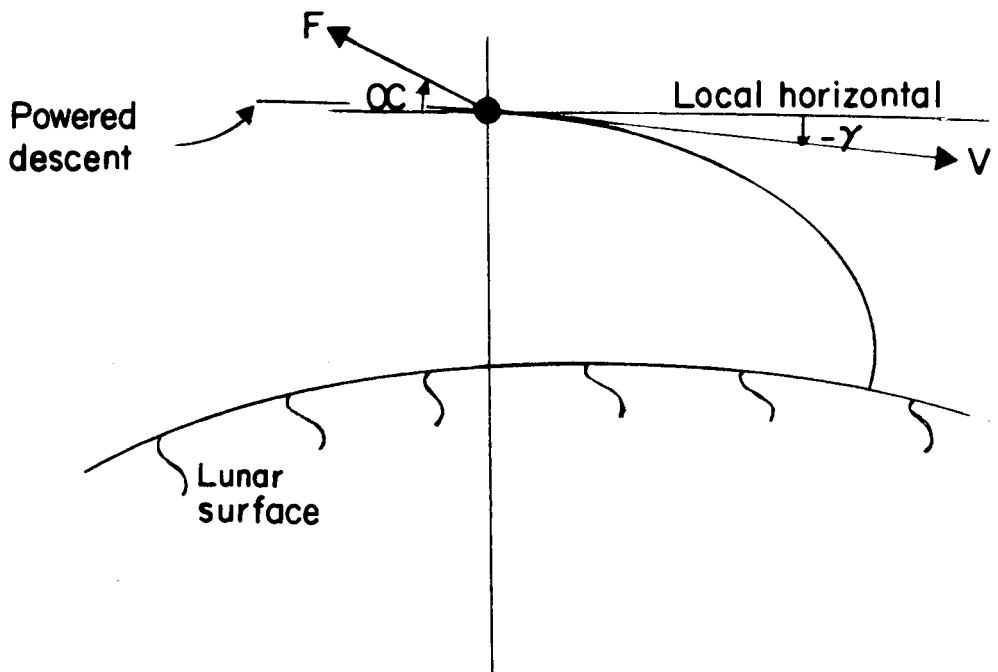
Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 10, 1964.

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2. Barker, L. Keith; and Queijo, M. J.: A Technique for Thrust-Vector Orientation During Manual Control of Lunar Landings From a Synchronous Orbit. NASA TN D-2298, 1964.

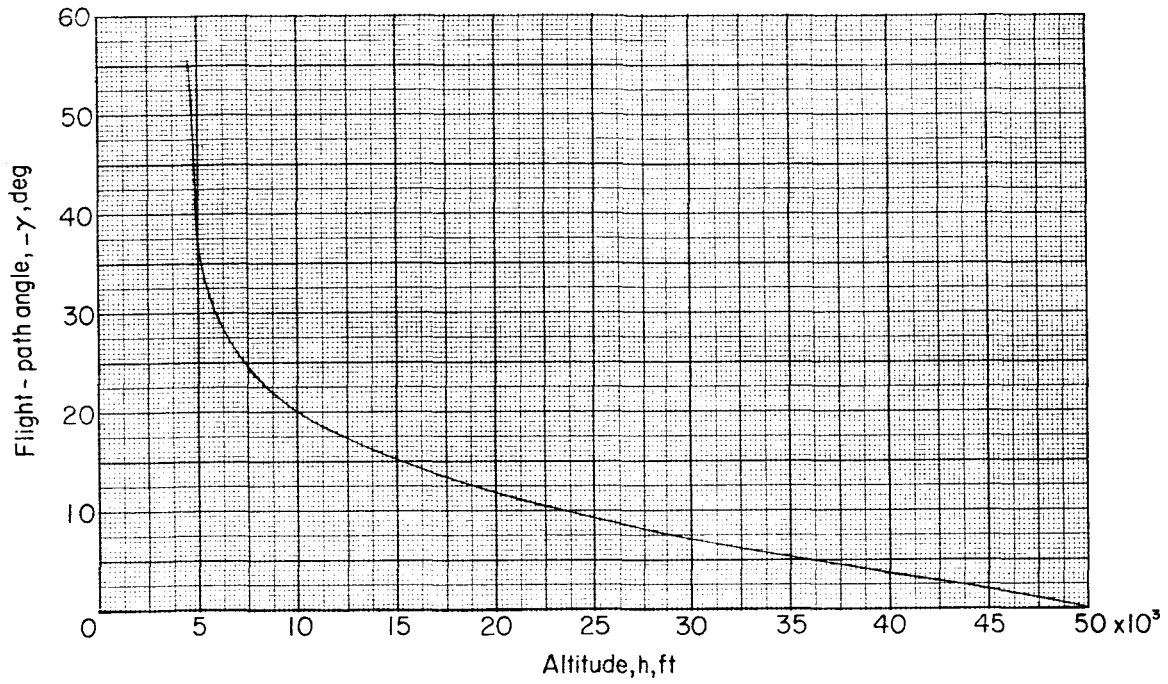


(a) Mission phases.

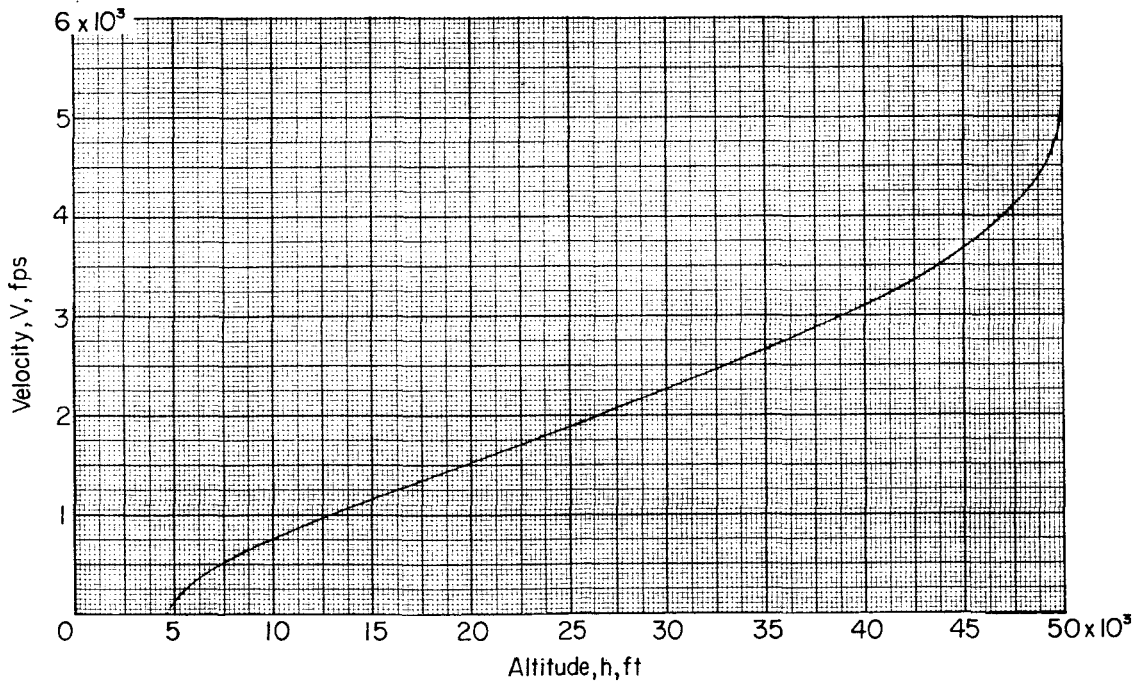


(b) Details of powered descent.

Figure 1.- Illustration of orbits and landing trajectory at moon.

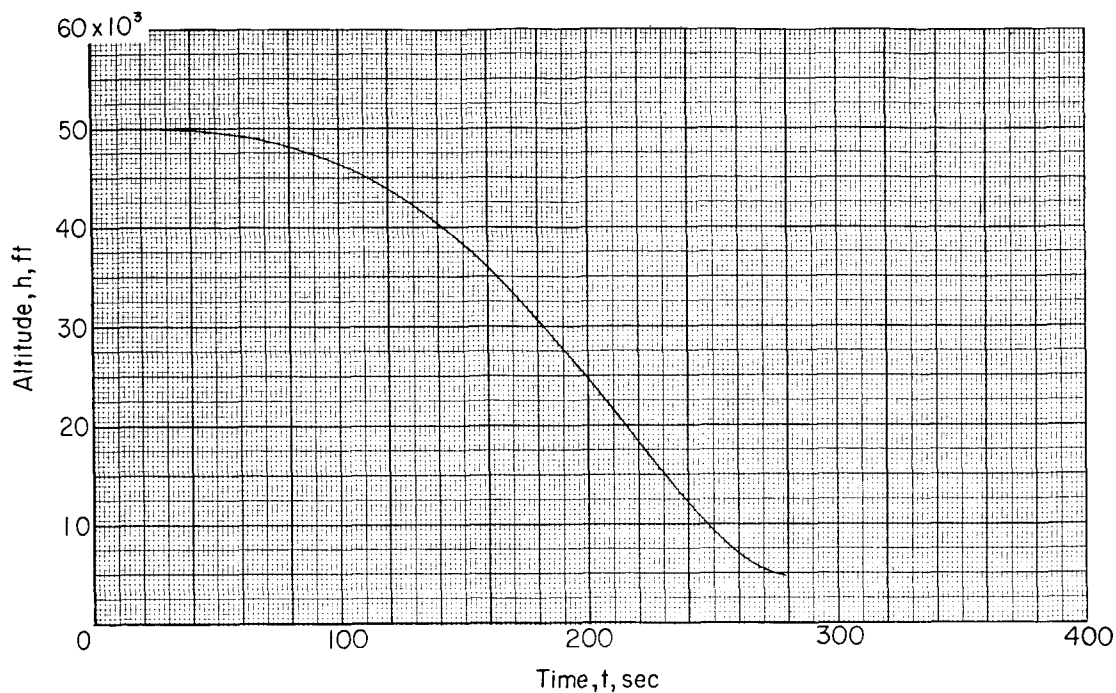


(a) Variation of flight-path angle with altitude.

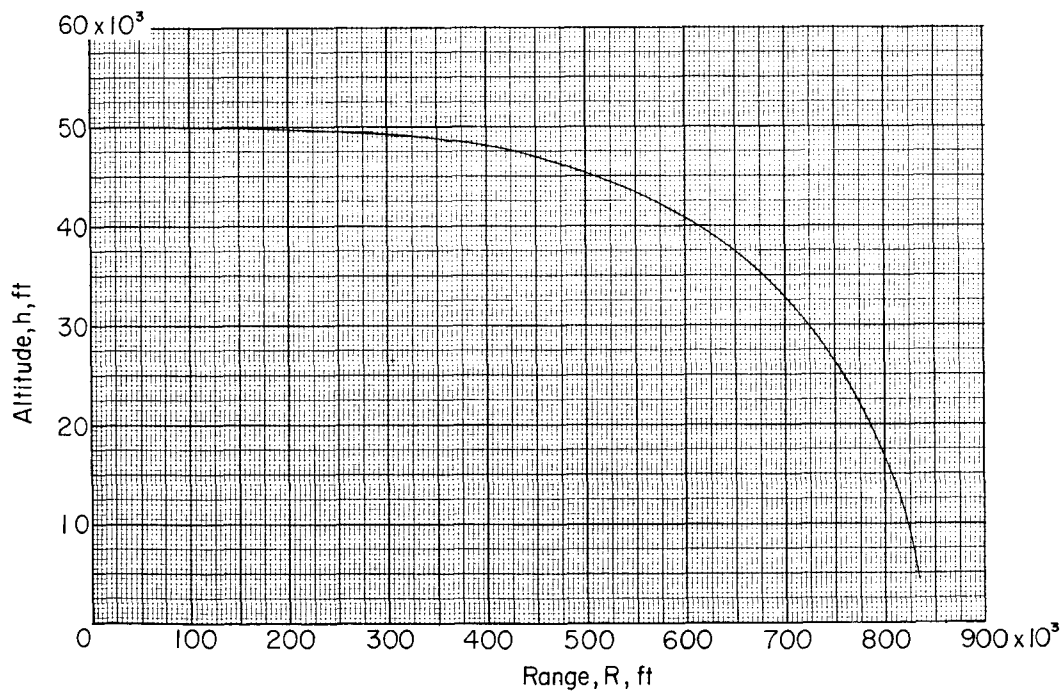


(b) Variation of velocity with altitude.

Figure 2.- Characteristics of reference gravity-turn braking descent.



(c) Variation of altitude with time.



(d) Variation of altitude with range.

Figure 2.- Concluded.

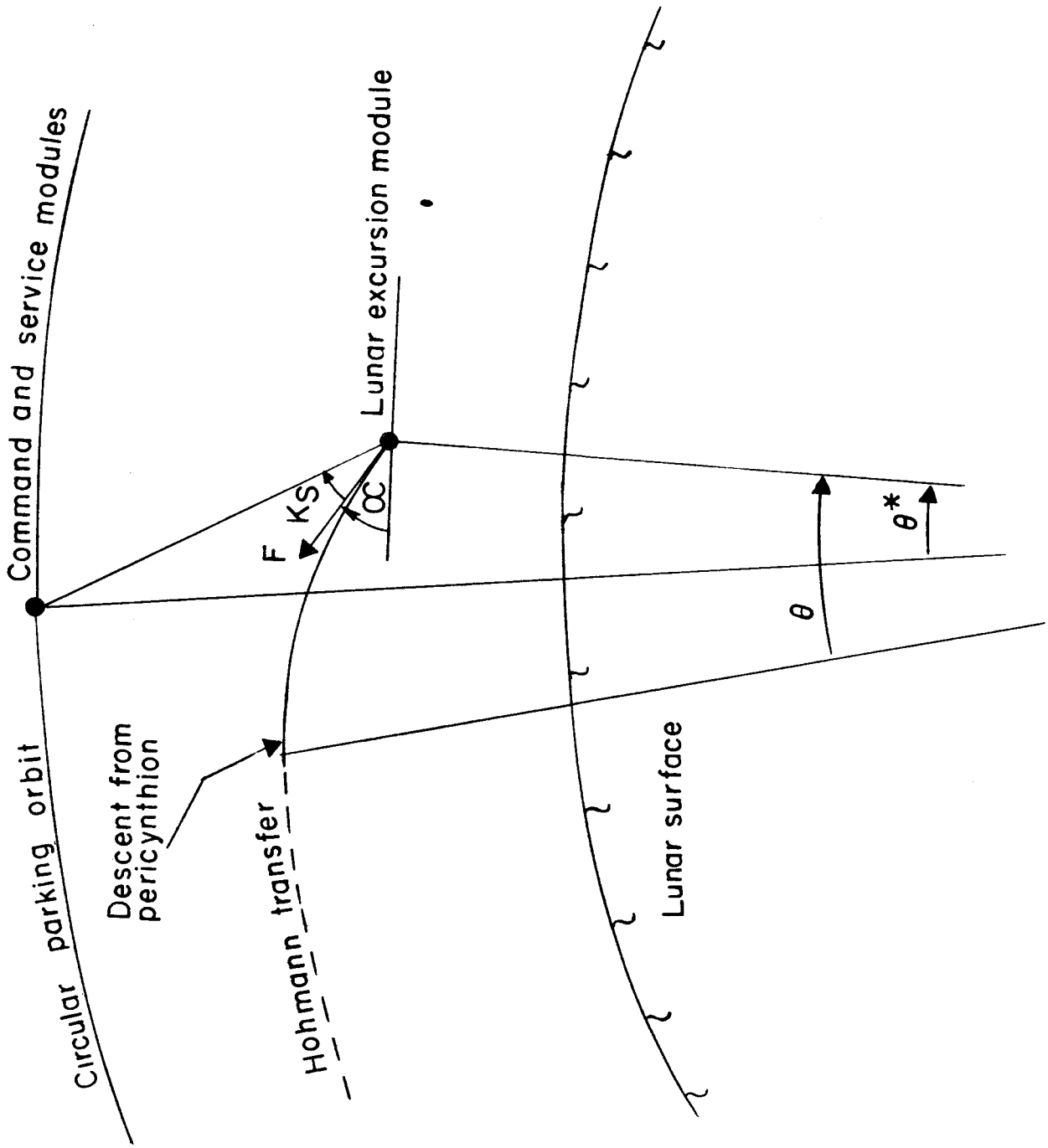


Figure 3.- Geometric relationship between vehicle thrust axis and line of sight to an orbiting spacecraft.

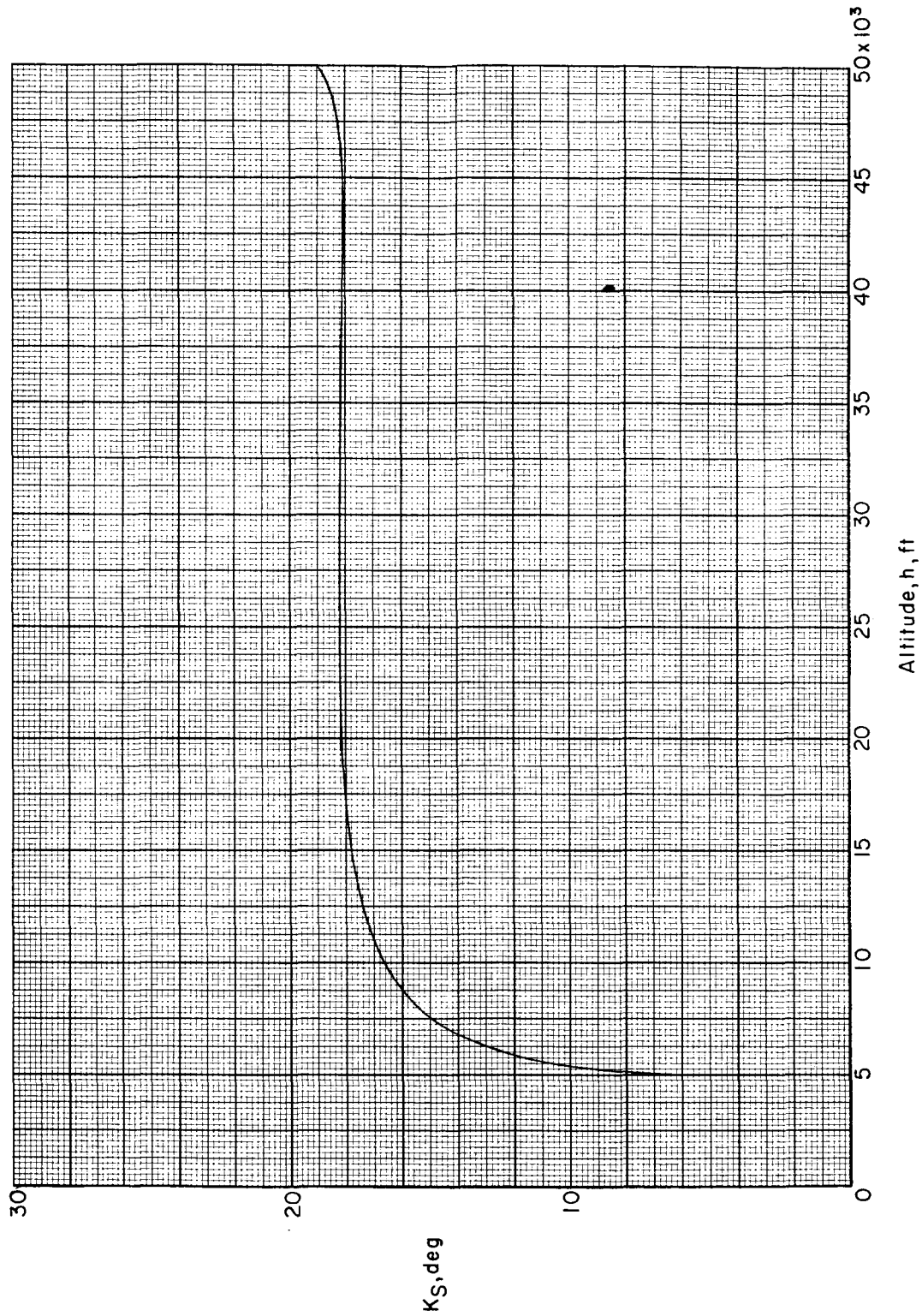
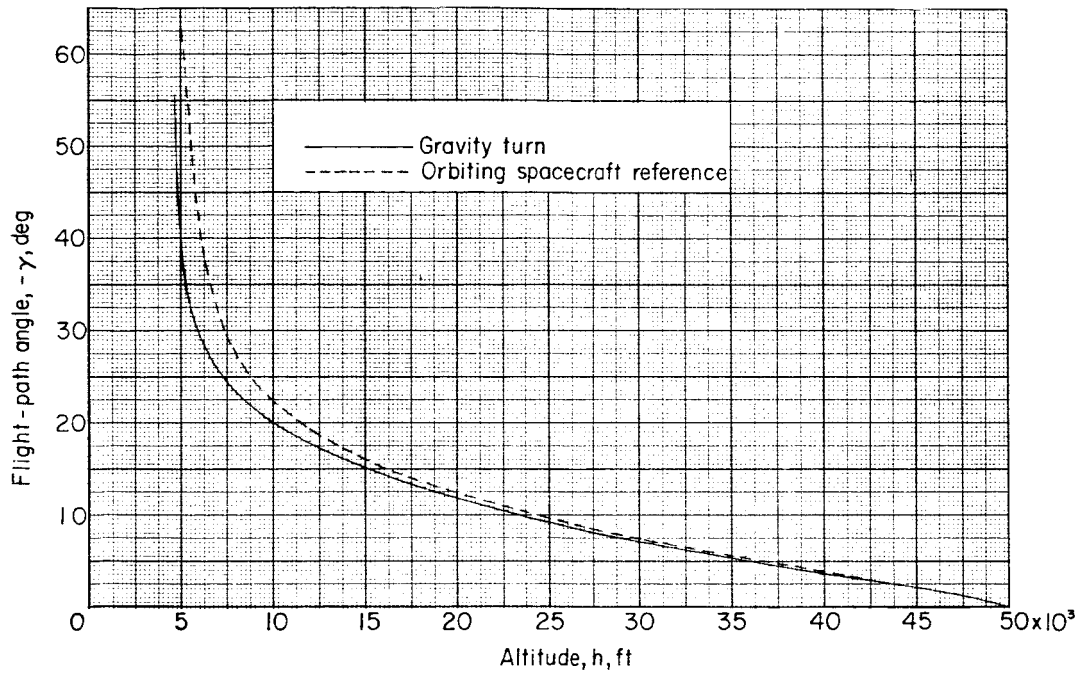
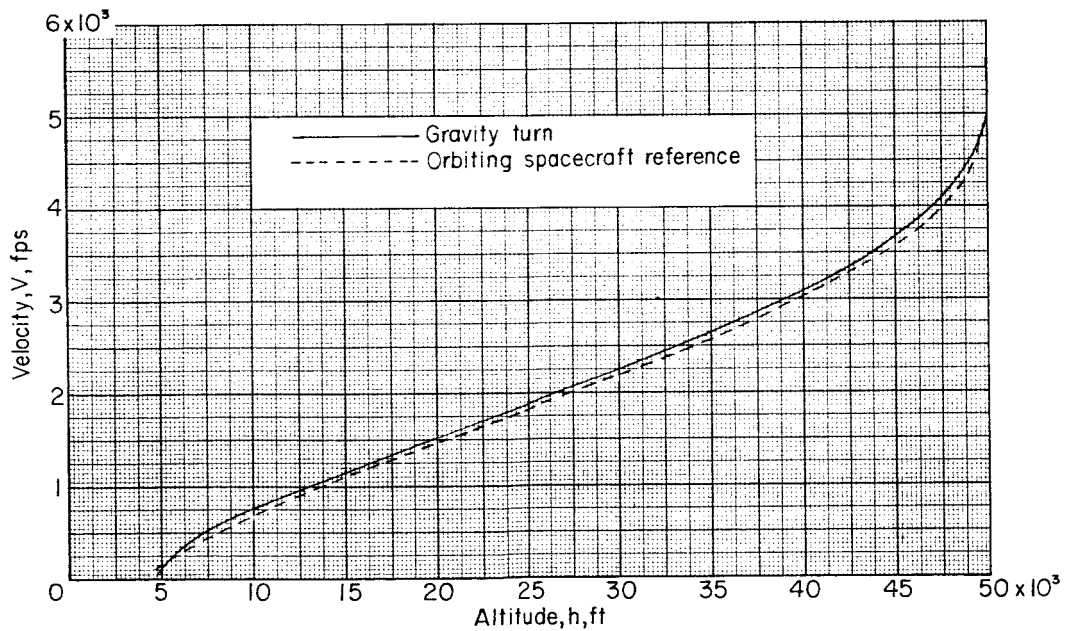


Figure 4. - Variation of angle between thrust vector and line of sight to orbiting spacecraft for reference gravity-turn trajectory.

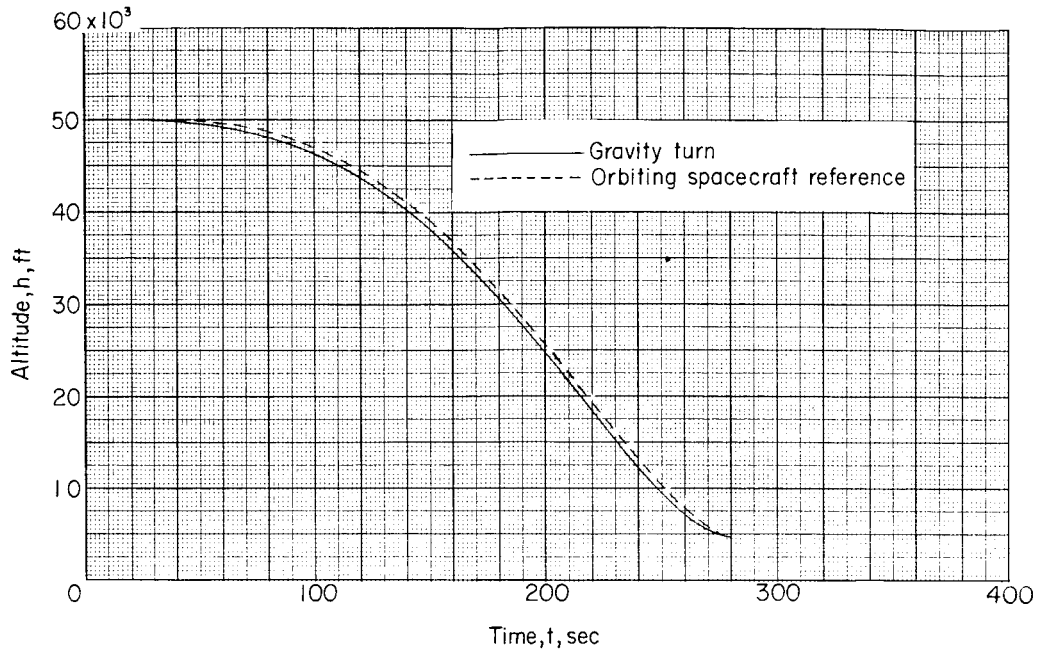


(a) Variation of flight-path angle with altitude.

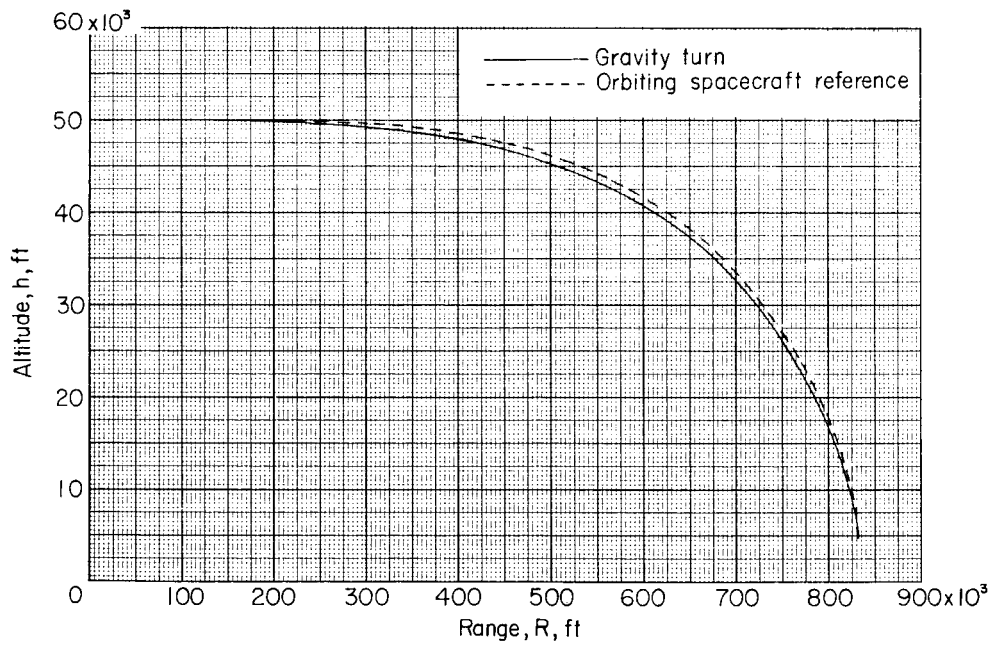


(b) Variation of velocity with altitude.

Figure 5.- Comparison of characteristics of reference gravity-turn descent with those generated by thrusting 18.3° behind orbiting spacecraft.



(c) Variation of altitude with time.



(d) Variation of altitude with range.

Figure 5.- Concluded.

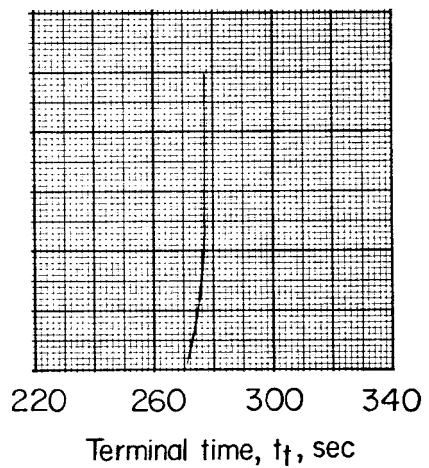
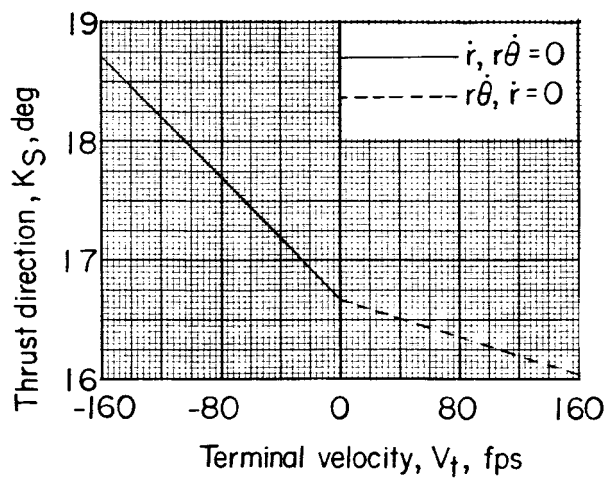
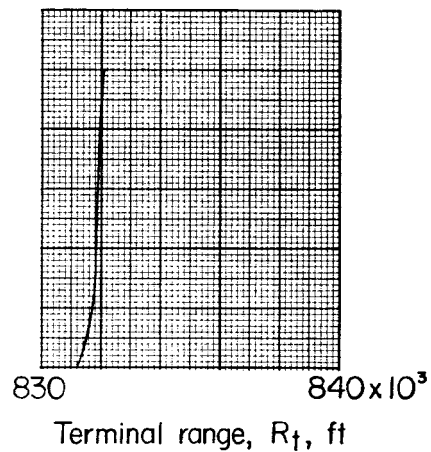
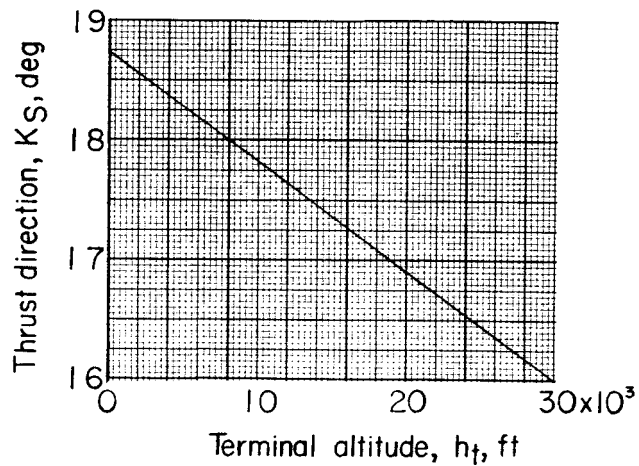


Figure 6.- Variation in terminal conditions with change in direction of thrust vector relative to orbiting spacecraft.

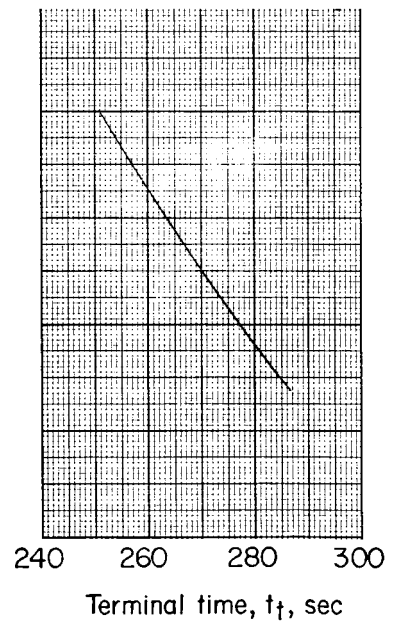
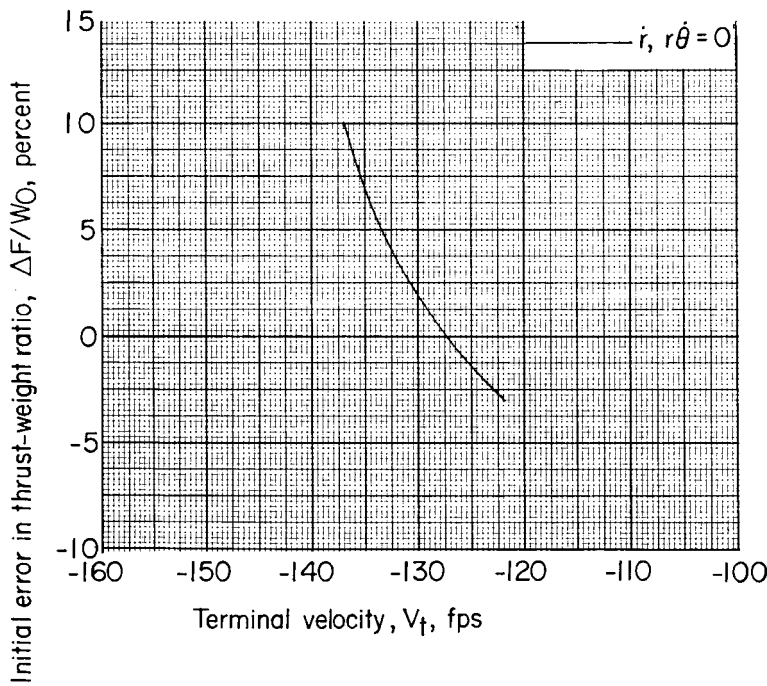
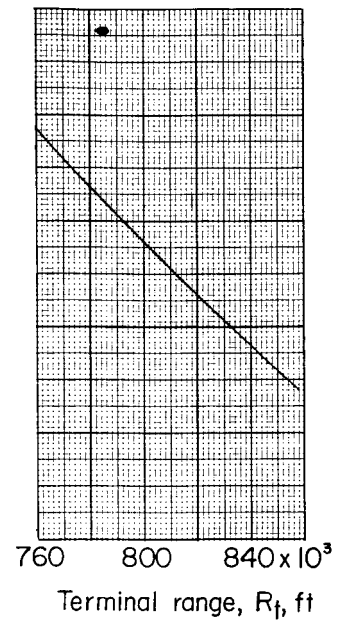
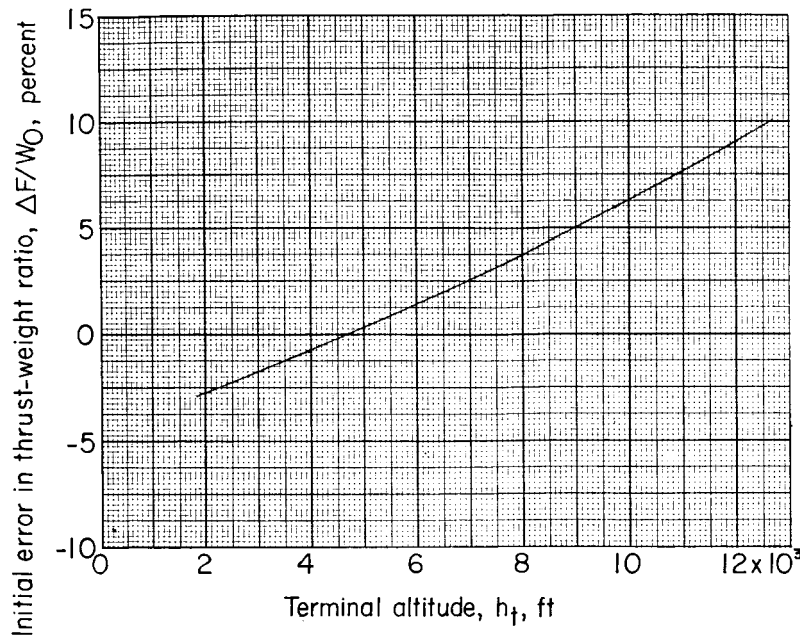


Figure 7.- Variation of terminal conditions with thrust level when orbiting spacecraft is used as thrust-orientation reference. $K_S = 18.3^\circ$.

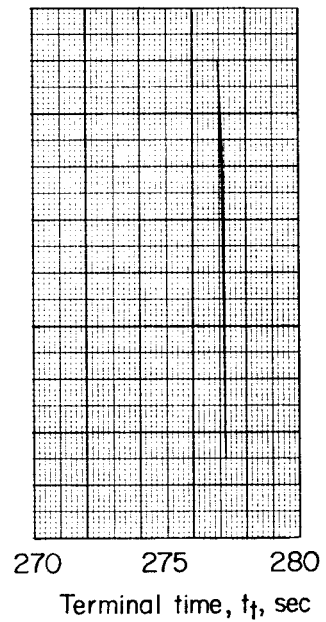
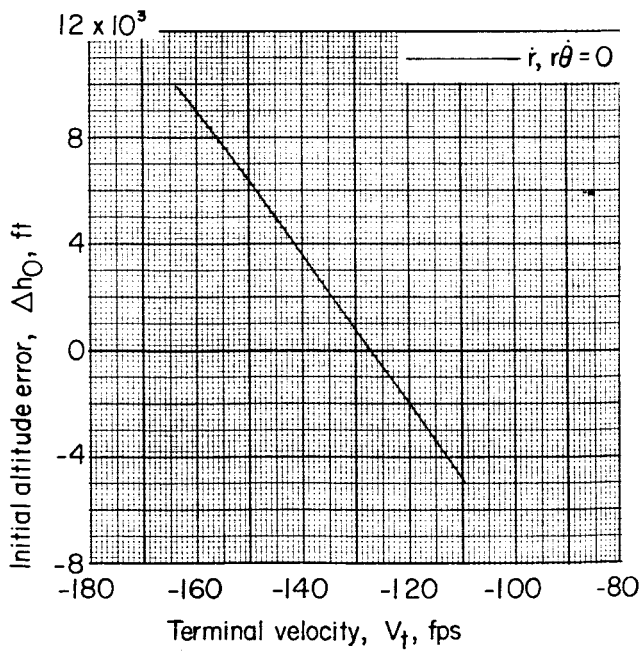
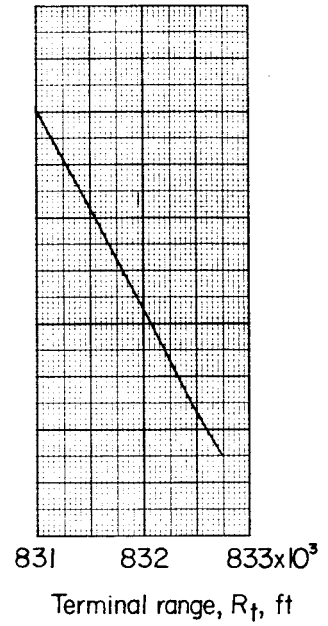
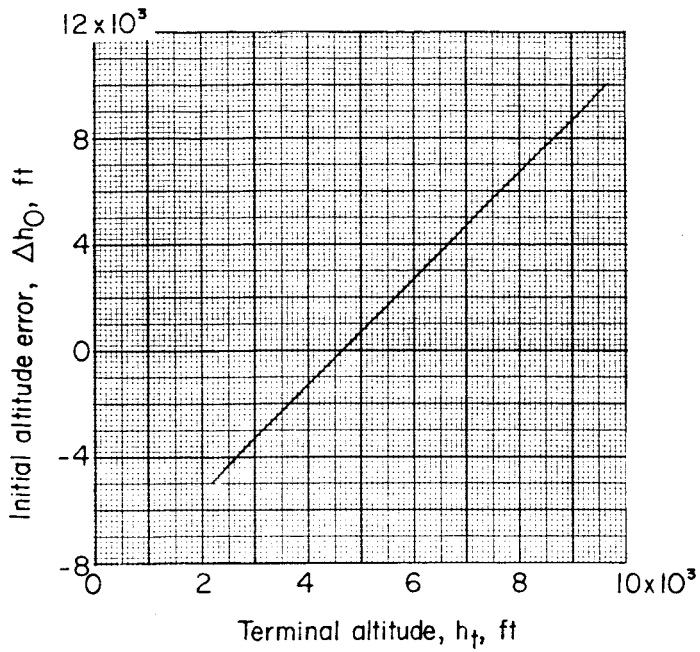


Figure 8.- Variation of terminal conditions with initial altitude when orbiting spacecraft is used as thrust-orientation reference. $K_G = 18.3^\circ$.

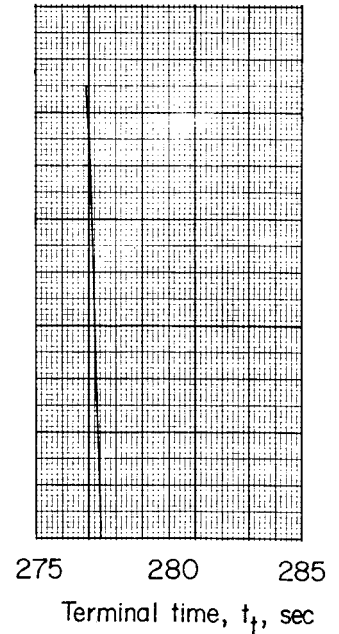
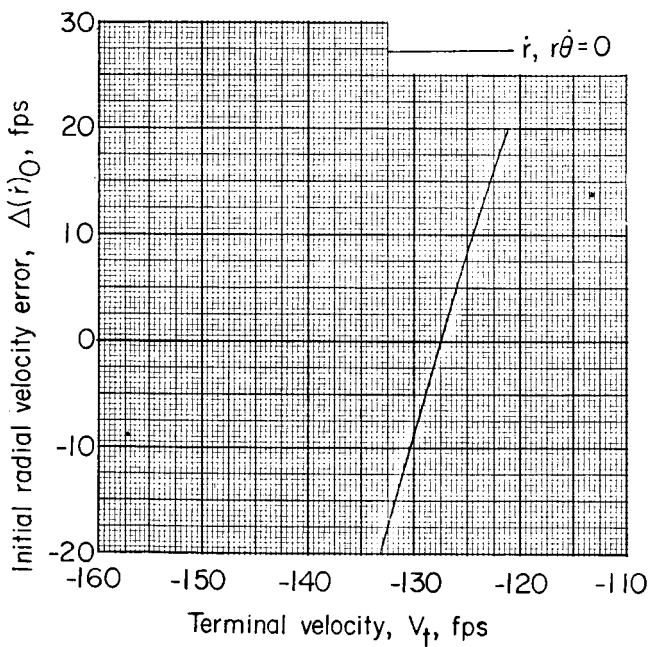
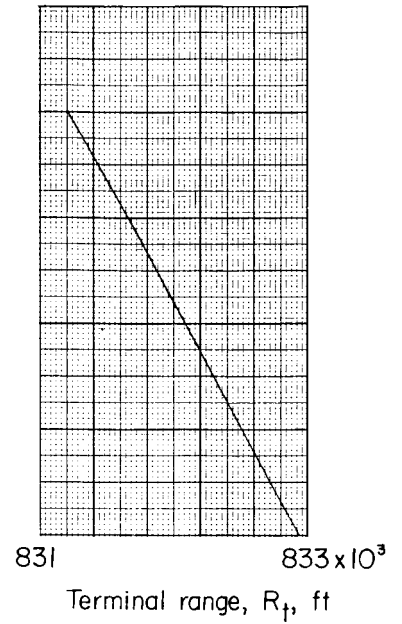
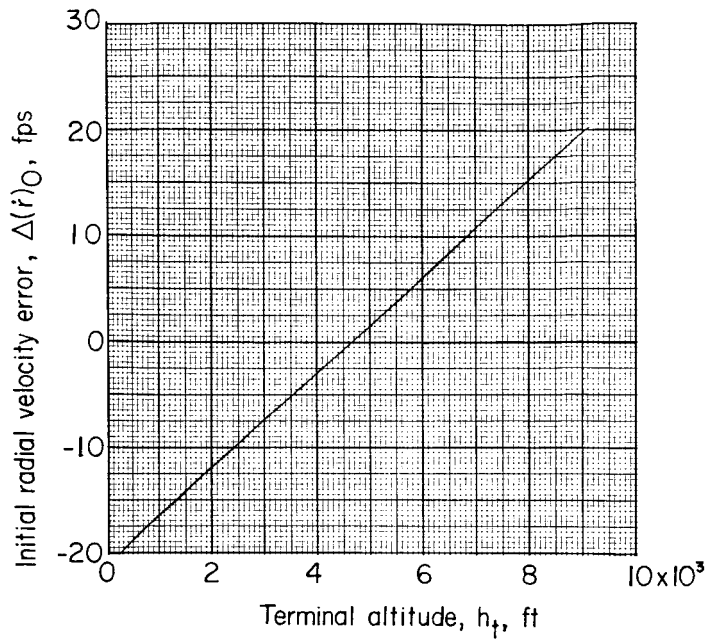


Figure 9.- Variation of terminal conditions with initial rate of descent when orbiting spacecraft is used as thrust-orientation reference. $K_S = 18.3^\circ$.

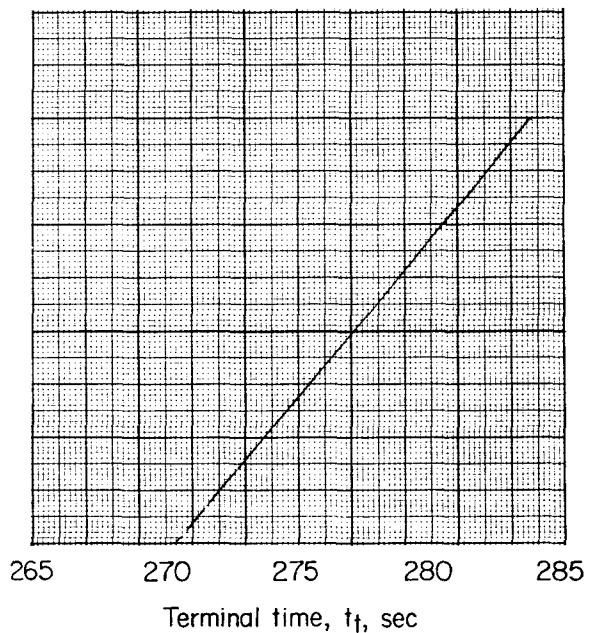
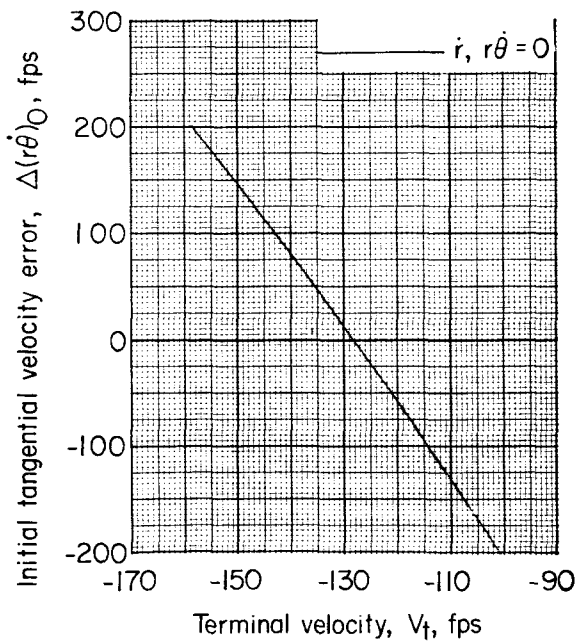
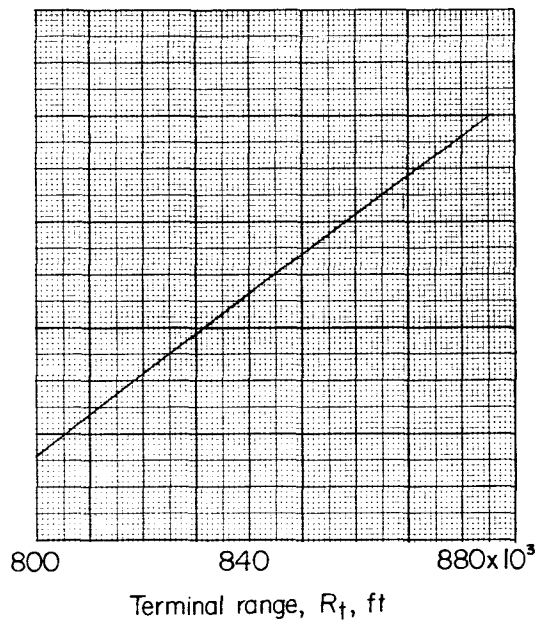
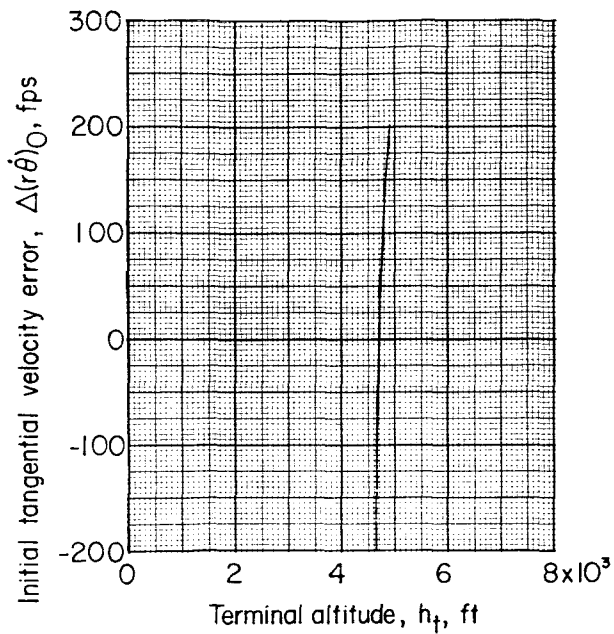


Figure 10.- Variation of terminal conditions with initial tangential velocity when orbiting spacecraft is used as thrust-orientation reference. $K_S = 18.3^\circ$.

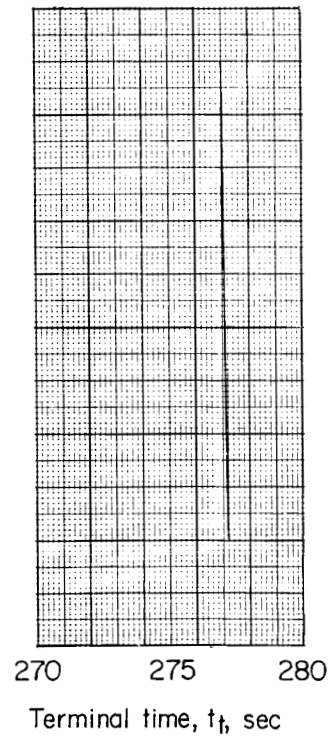
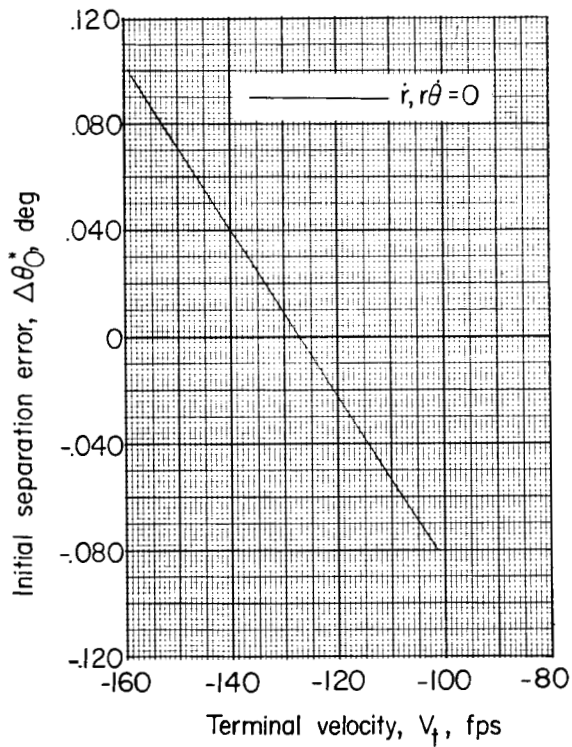
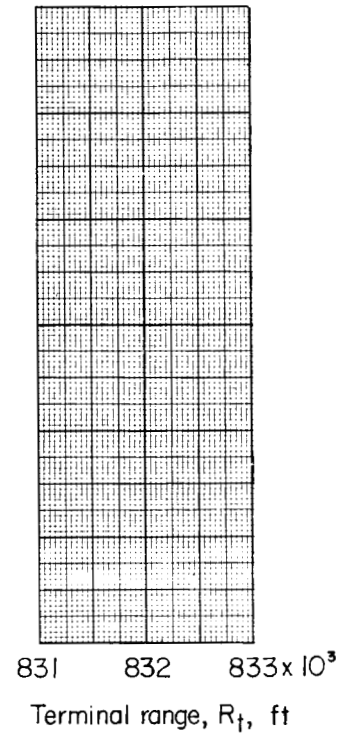
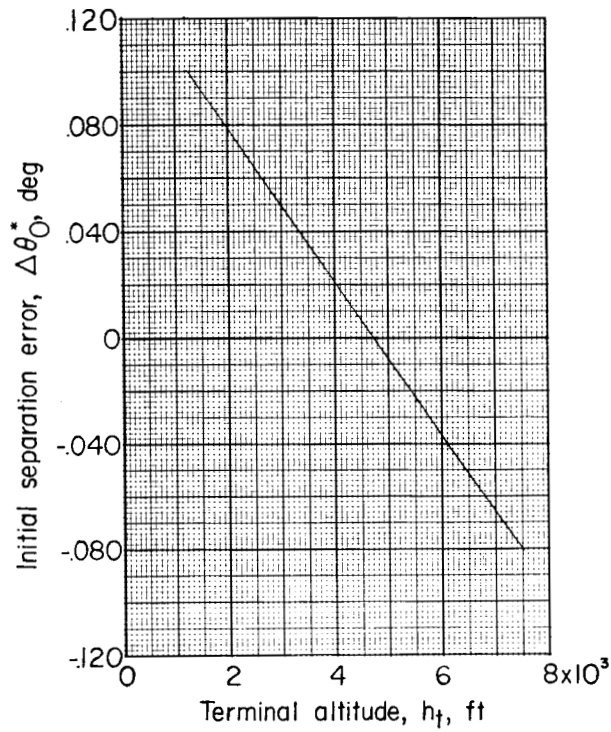


Figure 11.- Variation in terminal conditions with separation when orbiting spacecraft is used as thrust-orientation reference. $K_G = 18.3^\circ$.