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SUMMARY

An analytical study has been made of the possibility of using visual references as an aid in thrust-vector orientation during lunar landings. The procedure was to compute a gravity-turn descent, and then to examine the thrust-vector orientation relative to the uprange horizon, the downrange horizon, the nominal landing site, and an orbiting spacecraft to determine whether some simple, useful geometric relationships existed. It was found that during the gravity turn the angle between the thrust vector and the line of sight to the orbiting vehicle remained very nearly constant until the landing was almost completed. The orbiting spacecraft therefore appears to be a convenient reference for manual control of the lander thrust vector.

Trajectory computations based on using the line of sight to an orbiting spacecraft for thrust-vector orientation resulted in efficient landings. The effect of errors in thrust direction, thrust magnitude, and initial condition of the lander at initiation of the braking maneuver on terminal condition also was examined. In general, the terminal conditions were relatively insensitive to these errors. The exceptions were the effect of thrust-direction error on terminal altitude and tangential velocity, and of thrust level on range.

INTRODUCTION

Manual procedures for controlling various phases of the lunar mission have been and are currently being examined at the Langley Research Center. (See bibliography of ref. 1, for example.) Such procedures could be used as backup modes for the mission phases, or if simple and reliable, might be considered as primary control modes. One of the more critical phases of the mission appears to be the lunar landing. This phase is critical because it requires a rather large amount of fuel (or characteristic velocity) and therefore must be performed very efficiently, and because of the stringent conditions that must be met at touchdown.

A simulator study of pilot control of the lunar landing reported in reference 2 showed that with proper information displays, the pilot could make satisfactory landings. The displays were in the forms of various instruments and two plotters which presented useful integrated information. Although the piloting procedure used in reference 2 was simple, the display and sensor requirements to obtain the displayed information would be very complex for an actual spacecraft. It is desirable, therefore, to search for landing procedures which require as little display information as possible, and still permit satisfactory landings. The present investigation is an analytical study of a procedure for control of the landing maneuver, and appears to offer a means of satisfactory pilot control.

The primary control function over most of the landing run is the proper orientation of the thrust vector for braking. The procedure used in this investigation was to examine the orientation of the thrust vector for an efficient landing maneuver (specifically, a gravity turn), and then try to duplicate the thrust orientation by aiming the thrust vector relative to available visual references.

SYMBOLS

F	thrust, lb
g_e	gravitational acceleration at surface of earth, 32.2 ft/sec^2
g_m	gravitational acceleration at surface of moon, 5.32 ft/sec^2
h	altitude, ft
I_{sp}	specific impulse, 305 sec
K	angle between thrust vector and line of sight to a specified reference, deg
m	mass, slugs
r	radial distance from center of moon, ft
$\dot{r}$	radial velocity component, ft/sec
$\ddot{r}$	radial acceleration, ft/sec^2
r_m	radius of moon, 5,702,000 ft
t	time, sec
V	total velocity, ft/sec

ΔV characteristic velocity, $I_{sp}g_e \log_e \frac{m_0}{m_0 - \dot{m}t}$, ft/sec

W earth weight, mg_e, lb

γ vehicle flight-path angle, deg (fig. 1(b))

θ angular travel over lunar surface, deg or radians

$\dot{\theta}$ angular rate, radians/sec

$\ddot{\theta}$ angular acceleration, radians/sec^2

α thrust attitude with respect to local horizontal, positive when thrust is directed upward, deg (fig. 1(b))

θ^* angular separation of lunar excursion and orbiting modules, measured with vertex at moon's center, deg

R range of travel over lunar surface, ft

Subscripts:

0 initial value (at landing initiation)

t refers to conditions at end of landing trajectory

S refers to orbiting command and service modules

DR downrange

UR uprange

LS landing site

B bisector

Dots over symbol indicate derivatives with respect to time.

ANALYSIS

The landing maneuver studied in the present investigation is illustrated in figure 1(a) and is one of the maneuvers presently contemplated for the Apollo lunar landing mission. The spacecraft, consisting of an excursion module, a command module, and a service module establishes an 80-nautical-mile-altitude circular orbit around the moon. At the appropriate time the excursion module separates from the spacecraft and establishes an elliptic orbit having a period equal to that of the circular orbit. This is referred to as a synchronous orbit. The orbit of the excursion module has a pericynthion of 50,000 feet (point of closest approach to moon). At the pericynthion of the elliptic orbit, the excursion module performs a braking maneuver and makes a landing. The primary control function over most of the landing is proper orientation of the thrust vector for the braking maneuver. This can be done in any number of ways; however, it is desirable to make the landing maneuver efficient with regard to fuel usage. The purpose of the present study therefore was to search for an efficient landing maneuver which could be controlled manually by a pilot by using a minimum of information for thrust-vector orientation.

Equations of Motion

The equations of motion used in the present study were for a point mass moving in a central force field and subject to a thrust force in the plane of motion. The equations of motion used were:

$$\ddot{r} - r\dot{\theta}^2 = \frac{F}{m} \sin \alpha - g_m\left(\frac{r_m}{r}\right)^2 \tag{1}$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = -\frac{F}{m} \cos \alpha \tag{2}$$

where

$$m = m_0 - \int \dot{m}\, dt$$

and

$$\dot{m} = \frac{F}{g_e I_{sp}}$$

The thrust-vector orientation is defined by the angle α; that is, α is the angle between the thrust vector and the local horizontal (fig. 1(b)). The equations of motion were solved on an electronic digital computer.

Reference Descent Trajectory

As was mentioned in the Introduction, the approach used in this study was to select an efficient landing trajectory, examine its thrust orientation, and determine whether the trajectory could be closely approximated by aiming the thrust vector relative to some convenient reference. The reference descent trajectory selected was a gravity-turn descent, which by definition is a maneuver in which the thrust is directed against the vehicle velocity vector. In this case the angle α of equations (1) and (2) is specified by

$$\alpha = \tan^{-1}\left(\frac{-\dot{r}}{r\dot{\theta}}\right).$$

RESULTS AND DISCUSSION

The results of this investigation are presented in three sections: the first presents the characteristics of the gravity-turn reference trajectory; the second examines the orientation of the gravity-turn thrust vector relative to several available references to determine whether convenient or useful geometric relationships exist; and the third selects one particular reference and examines the effects of various sighting errors and variations in initial conditions on the braking trajectory. A constant-thrust engine producing an initial thrust—earth-weight ratio of 0.485 was assumed in this investigation.

Gravity-Turn Descent

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 elliptic trajectory with the same period as a circular orbit having an 80-nautical-mile altitude. The braking maneuver terminates with zero vehicle velocity at an altitude of about 5,400 feet. The data of primary interest with regard to this descent are the thrust-vector orientation and the terminal conditions. If orientation of the thrust vector could be duplicated by aiming relative to some convenient reference, then the gravity-turn trajectory would automatically be duplicated. The thrust-vector orientation α is the negative of the flight-path angle γ since in a gravity turn the thrust is directed against the vehicle velocity (or flight path). If the thrust axis is fixed relative to the vehicle, then the flight-path angle is also equal to the vehicle attitude relative to the local horizontal. Note that the flight-path angle varies almost linearly with altitude over most of the braking maneuver. (See fig. 2(a).) At altitudes below about 15,000 feet, however, the flight-path angle varies rapidly in a nonlinear fashion. Therefore, even if the local horizontal could be determined very accurately, it does not appear to be a particularly convenient reference for manual control of thrust-vector orientation.

Orientation of Thrust Vector for Gravity Turn

Relative to Various References

This section is concerned with determining the orientation of the thrust vector (during a gravity turn) relative to various references to determine whether there exists some reference such that the angle between the thrust vector (or body axes) and the line of sight to that reference is a constant or varies in some very simple (linear) manner. The various references examined were the lunar horizons, the landing site, and the orbiting vehicle.

Lunar horizon in direction of motion.- The geometric relationships between the vehicle thrust axis and the downrange horizon are shown in figure 3. The angle between the thrust vector and the line of sight to the downrange horizon is given by

$$K_{DR} = \theta_{DR} - \alpha \tag{3}$$

or

$$K_{DR} = \cos^{-1}\left(\frac{r_m}{r_m + h}\right) - \alpha \tag{4}$$

Figure 4 is a plot of K_{DR} as a function of altitude. The plot shows approximately the same characteristics as shown for γ in figure 2(a) ($-\gamma = \alpha$ for gravity turn). This is to be expected since the variation of θ_{DR} is small over the landing range. Although the use of the horizon has its drawback in the rapid variation of K_{DR} with altitude at low altitudes, it does provide a more convenient reference than the local horizontal would.

Horizon in direction of thrust.- The geometric relationship between the vehicle thrust axis and the horizon in the direction of thrust (uprange) are shown in figure 5. The angle between the thrust vector and the line of sight to the horizon is given by

$$K_{UR} = \theta_{UR} + \alpha \tag{5}$$

or

$$K_{UR} = \cos^{-1}\left(\frac{r_m}{r_m + h}\right) + \alpha \tag{6}$$

The variation of K_{UR} with altitude for the gravity-turn descent is shown in figure 6. In this case also, the angle K_{UR} varies slowly and linearly with altitude over most of the landing range, but varies very rapidly at altitudes below about 15,000 feet.

Landing site.- The rather large variation in angle between the rocket thrust vector and the horizons noted previously is associated with the large turning angle of the spacecraft near the lunar surface. It appeared desirable to find some reference aiming point which would tend to move more rapidly toward the spacecraft during the descent than does the downrange horizon. The landing site is such a reference; therefore an examination was made of the angle between the line of sight to the nominal landing point and the thrust vector for a gravity turn. The geometric relationships involved are shown in figure 7. The angle between the thrust vector and the line of sight to the nominal landing point is given by

$$K_{LS} = -\alpha + \tan^{-1} \frac{r - r_m \cos \theta_{LS}}{r_m \sin \theta_{LS}} \tag{7}$$

In this case the angle remains relatively constant over a large part of the trajectory, but varies very rapidly at low altitudes. (See fig. 8.) Note however, that the thrust vector always points above the line of sight to the landing point. The thrust vector generally pointed below the line of sight to the downrange horizon. Comparing figures 4 and 8 indicates a similarity in variation of the angles between the thrust axis and the sighting references, with a difference in sign of the angles. One might then ask how the thrust vector was oriented relative to the bisector of the angle between the lines of sight to the horizon and to the landing site. This variation is shown in figure 9 and shows that for the nominal gravity turn, the thrust vector pointed from about $2\frac{1}{2}^{\circ}$ to 9° above the bisector of the angle between the lines of sight to the downrange lunar horizon and to the landing site. It appears that a reasonably good approximation of the gravity turn could be made by holding a constant angle of about 5° between the thrust vector and the angle bisector specified above. However, it does appear somewhat awkward to aim the thrust vector in this manner.

Orbiting spacecraft.- The angle between the thrust vector, in the gravity turn, and the line of sight to the modules remaining in the 80-nautical-mile-altitude parking orbit can be determined from the geometric relationships shown in figure 10. The variation of this angle throughout the landing maneuver is shown in figure 11 as a function of altitude. Note that from the point of thrust initiation ($h = 50{,}000$ feet) down to an altitude of about 7,500 feet, the angle remained at about $23.75^{\circ} \pm 1^{\circ}$. Also note that at an altitude of 7,500 feet the vehicle velocity is about 450 feet per second. (See fig. 2(b).) It appears, therefore, that if the lander thrust vector is oriented to point at approximately 23° or 24° behind the orbiting spacecraft, it will very closely duplicate a gravity-turn descent.

The Orbiting Spacecraft as a Thrust-Direction Reference

The results of the previous section indicated that the gravity-turn descent could be approximated by maintaining the thrust vector at a constant angle behind the orbiting modules. This section is concerned with the comparison of the characteristic velocity ΔV (a measure of fuel consumption) and terminal conditions obtained by maintaining a constant-thrust-angle bearing, with the corresponding results for a gravity turn. The terminal conditions and ΔV for the gravity turn were as follows:

$$\dot{r} = 0$$

$$r\dot{\theta} = 0$$

$$h = 5{,}466 \text{ ft}$$

$$R = 857{,}158 \text{ ft}$$

$$\Delta V = 5{,}870 \text{ ft/sec}$$

It should be noted that for a nongravity-turn landing, the two velocity components $\dot{r}$ and $r\dot{\theta}$ will not be nulled simultaneously; therefore there could be some question regarding the specification of terminal condition. For the purpose of this study, the term "terminal condition" indicates that one of the velocity components has been nulled.

The angle α which is used in equations (1) and (2) when thrust is applied at a fixed bearing relative to the orbiting module is given by

$$\alpha = 90^\circ - \left[\theta^* + \tan^{-1}\left(\frac{\sin \theta^*}{\frac{r_m + h_S}{r_m + h} - \cos \theta^*}\right)\right] - K_S \qquad (8)$$

where

$$\theta^* = (\theta^*)_0 + \theta - \dot{\theta}_S t$$

The time t and angular travel θ are measured from initiation of the powered descent (pericynthion), and $(\theta^*)_0$ is the initial separation angle of the lunar excursion and orbiting modules.

Several landing trajectories were computed for a range of values of the angle K_S. A close approximation to a gravity turn was obtained by thrusting 23° behind the orbiting spacecraft - that is, $K_S = 23^\circ$. The terminal conditions for this landing maneuver are compared with those of the gravity turn in the following table:

Condition	Terminal condition for -	
	Gravity turn	$K_S = 23^{\circ}$
$\dot{r}$	0	-15.2
$r\dot{\theta}$	0	0
h	5,466	4,748
R	857,158	858,073
ΔV	5,870	5,850

Some of the trajectory parameters of the $K_S = 23^{\circ}$ trajectory are compared with those of the gravity-turn trajectory in figure 12. The results show that the trajectory characteristics are nearly identical. It appears therefore that using the orbiting spacecraft as an aiming reference would be convenient for manual control of the landing maneuver. It is necessary, however, to examine the accuracy with which the aiming angle must be held and the sensitivity of the procedure to various possible errors.

Error Analysis for Constant Line-of-Sight Thrust-Vector Control

The error analysis consisted of determining the change in terminal conditions caused by departures from the nominal initial conditions, thrust-vector orientation, and thrust level. The initial conditions referred to here are the conditions existing at the time the powered braking descent is initiated. These conditions can be related to errors in any portion of the coasting elliptic orbit through the standard orbital mechanics equations.

Thrust-vector direction.- The variations in terminal conditions with change in thrust direction are shown in figure 13. As noted previously, "terminal conditions" are defined as conditions existing at the time when one of the vehicle velocity components ($\dot{r}$ or $r\dot{\theta}$) is nulled. The results of figure 13 show the following points of interest:

(a) The range covered during the braking maneuver and the time required to attain terminal conditions are rather insensitive to thrust-vector direction errors of reasonable magnitude (about $\pm 2^{\circ}$).

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

The sharp discontinuity in the velocity curve which occurs at $K_S = 22.8^{\circ}$ is associated with the fact that for K_S less than 22.8°, the radial component is reduced to zero and the tangential velocity $r\dot{\theta}$ has some magnitude. Values of K_S greater than 22.8° cause the tangential component to be reduced to zero and the radial velocity has a finite value.

The altitude sensitivity to K_S is about 11,000 feet per degree in K_S, and the tangential velocity sensitivity is about 212 feet per second per degree in K_S.

Thrust-vector-orientation errors could originate from two sources: (a) the inability of the pilot to maintain the desired thrust direction, and (b) the thrust vector not being alined with the body reference axis. In the former case the aiming error during descent should be a variable quantity and may average out close to zero. In the latter case the terminal conditions could become unacceptable if the sighting angle was maintained during the entire braking maneuver. During an actual landing maneuver, however, the pilot should be able to observe departures from the nominal conditions near the end of the braking maneuver and should be able to compensate for them. For example, the nominal terminal conditions will probably include low altitude and low velocity components. The pilot should be able to judge these quantities reasonably well by out-of-the-window observations, such as is done by airplane pilots. Flight simulations are needed to determine how well a pilot can perform the technique.

Thrust level.- The sensitivity of terminal conditions on thrust level (or F/W_O) is shown in figure 14. The curves show that terminal altitude, velocity, and range all vary almost linearly with thrust level. It appears, however, that thrust level errors of ±1 or 2 percent would not be serious, except possibly in range error. The terminal range sensitivity is approximately 10,000 feet for each percent error in thrust level.

Initial altitude.- The variations of terminal conditions with change in initial altitude are shown in figure 15. Here again the variations are approximately linear. The curves indicate that terminal conditions are not particularly sensitive to initial altitude errors. The most sensitive terminal condition appears to be the altitude, and here the terminal altitude error is 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 16. It is apparent that the terminal conditions are not very sensitive to initial rate of descent, if the initial rates are of reasonable magnitude (±10 ft/sec).

Initial tangential velocity.- The sensitivity of terminal conditions to initial errors in tangential velocity is shown in figure 17. It appears that errors even as high as ±100 ft/sec in initial tangential velocity do not seriously alter the terminal conditions.

CONCLUDING REMARKS

An analytical study has been made of the possibility of using visual references as an aid in thrust-vector orientation during lunar landings. The procedure was to compute a gravity-turn descent, and then to examine the thrust-vector orientation relative to the uprange horizon, the downrange horizon, the nominal landing site, and an orbiting spacecraft to determine whether some simple, useful geometric relationships existed. It was found that during the gravity turn the angle between the thrust vector and the line of sight to the orbiting vehicle remained very nearly constant until the landing was almost completed. The orbiting spacecraft therefore appears to be a convenient reference for manual control of the lander thrust vector.

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Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 4, 1964.

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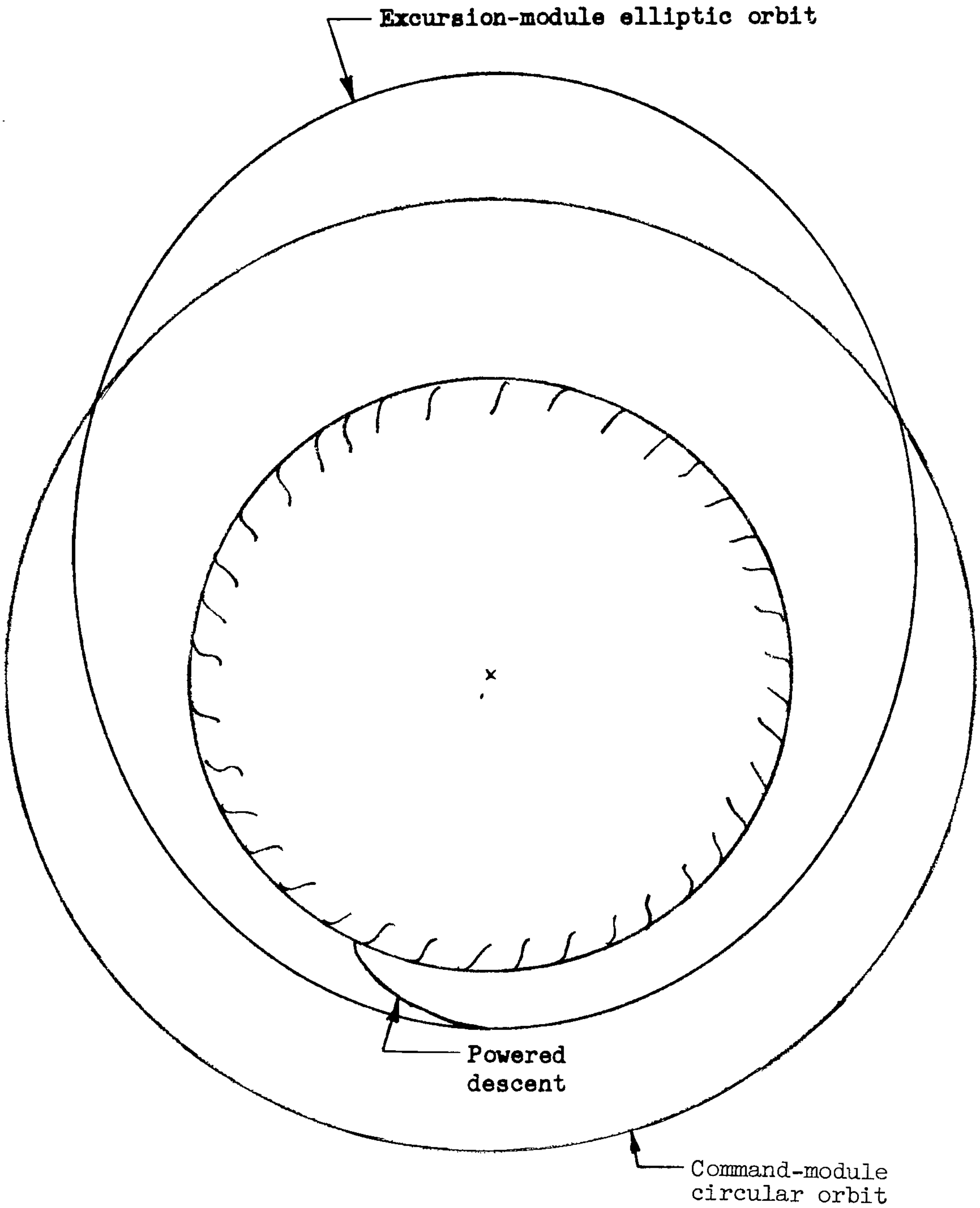
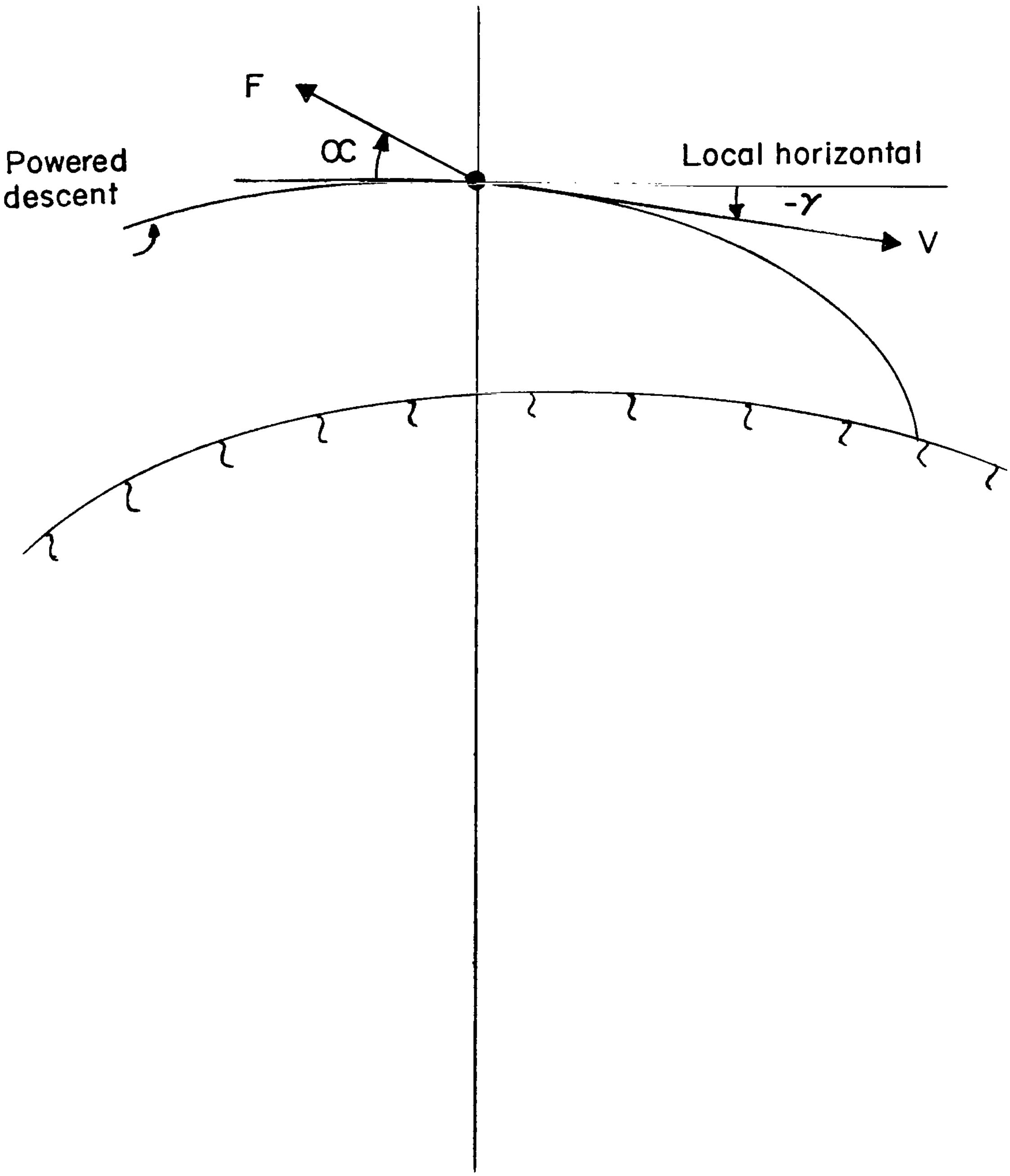
1. Phillips, William H., Queijo, M. J., and Adams, James J.: Langley Research Center Simulation Facilities for Manned Space Missions. Paper No. 63-AHGT-91, ASME, Mar. 1963.

2. Queijo, M. J., Miller, G. Kimball, Jr., and Fletcher, Herman S.: Fixed-Base-Simulator Study of the Ability of a Pilot To Perform Soft Lunar Landings. NASA TN D-1484, 1962.



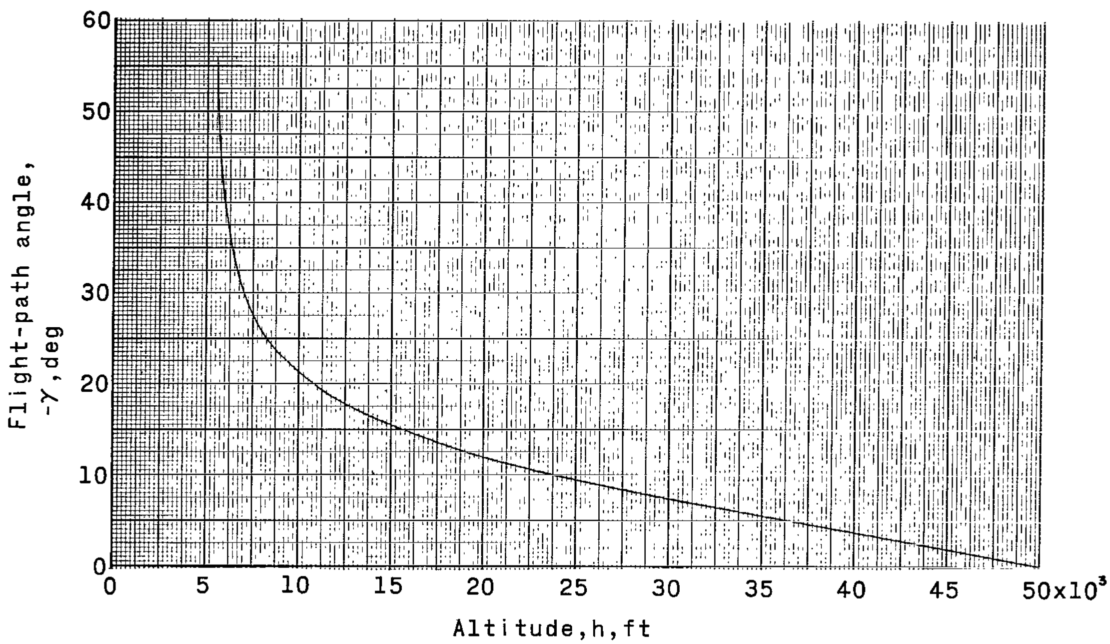
(a) Mission phases.

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

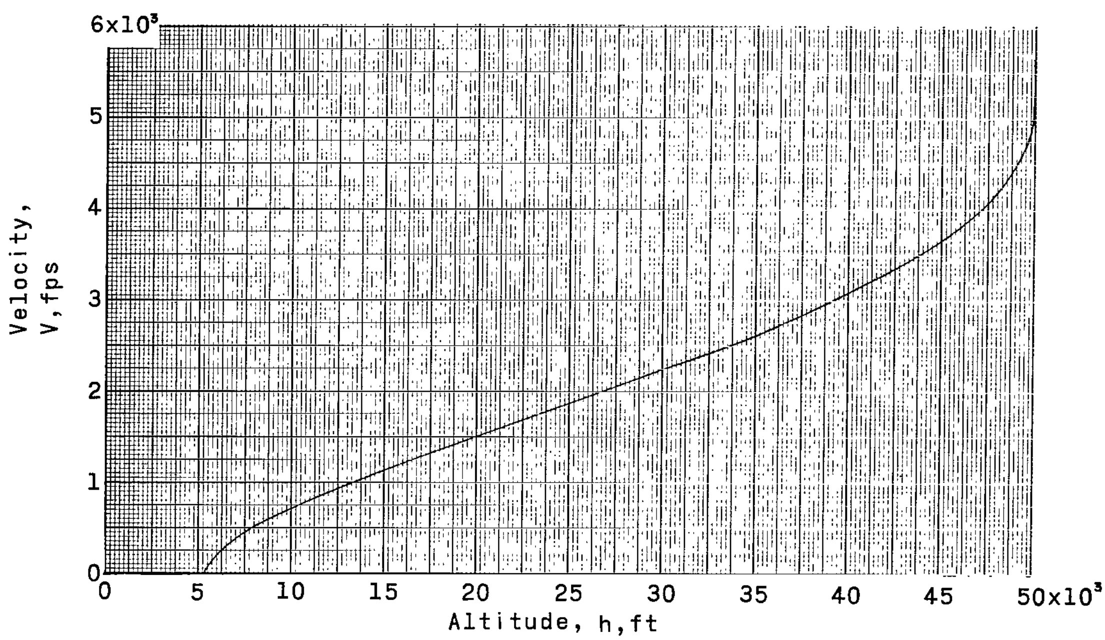


(b) Details of powered descent.

Figure 1.- Concluded.

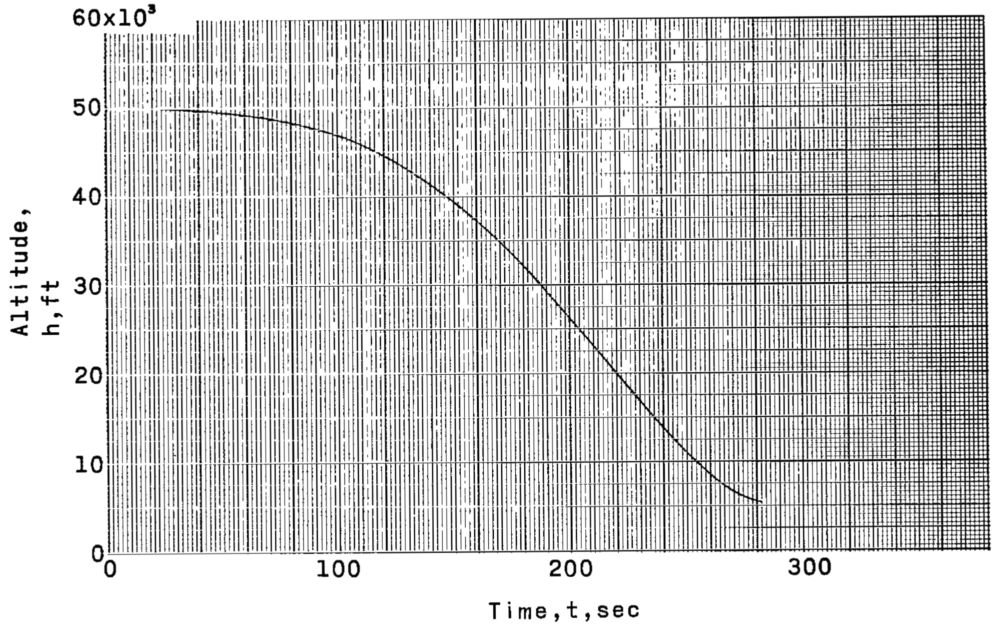


(a) Variation of flight-path angle with altitude.

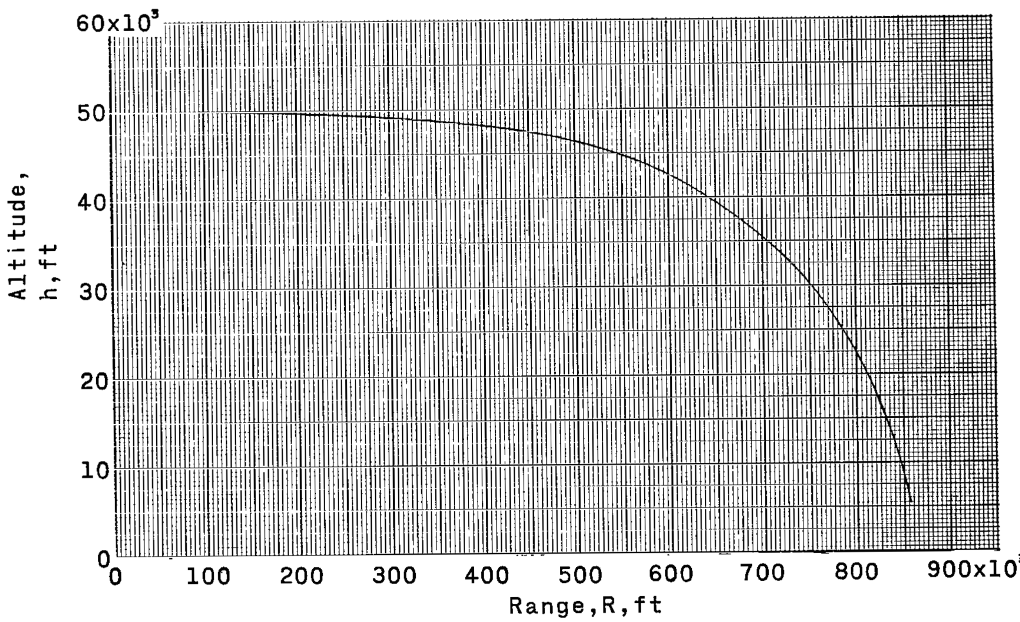


(b) Variation of velocity with altitude.

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



(c) Variation of altitude with time.



(d) Variation of altitude with range.

Figure 2.- Concluded.

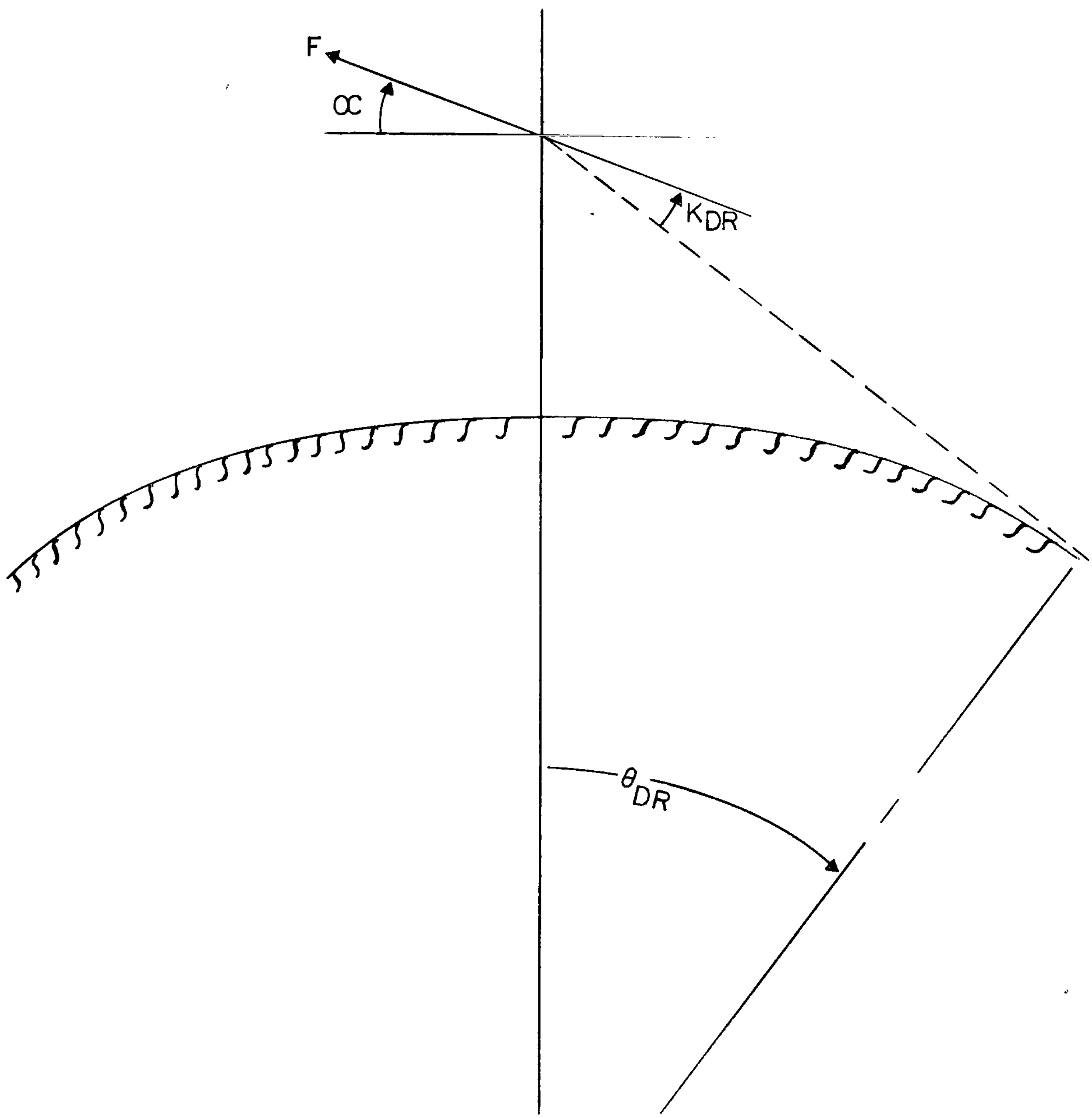


Figure 3.- Geometric relationship between vehicle thrust axis and the downrange horizon.

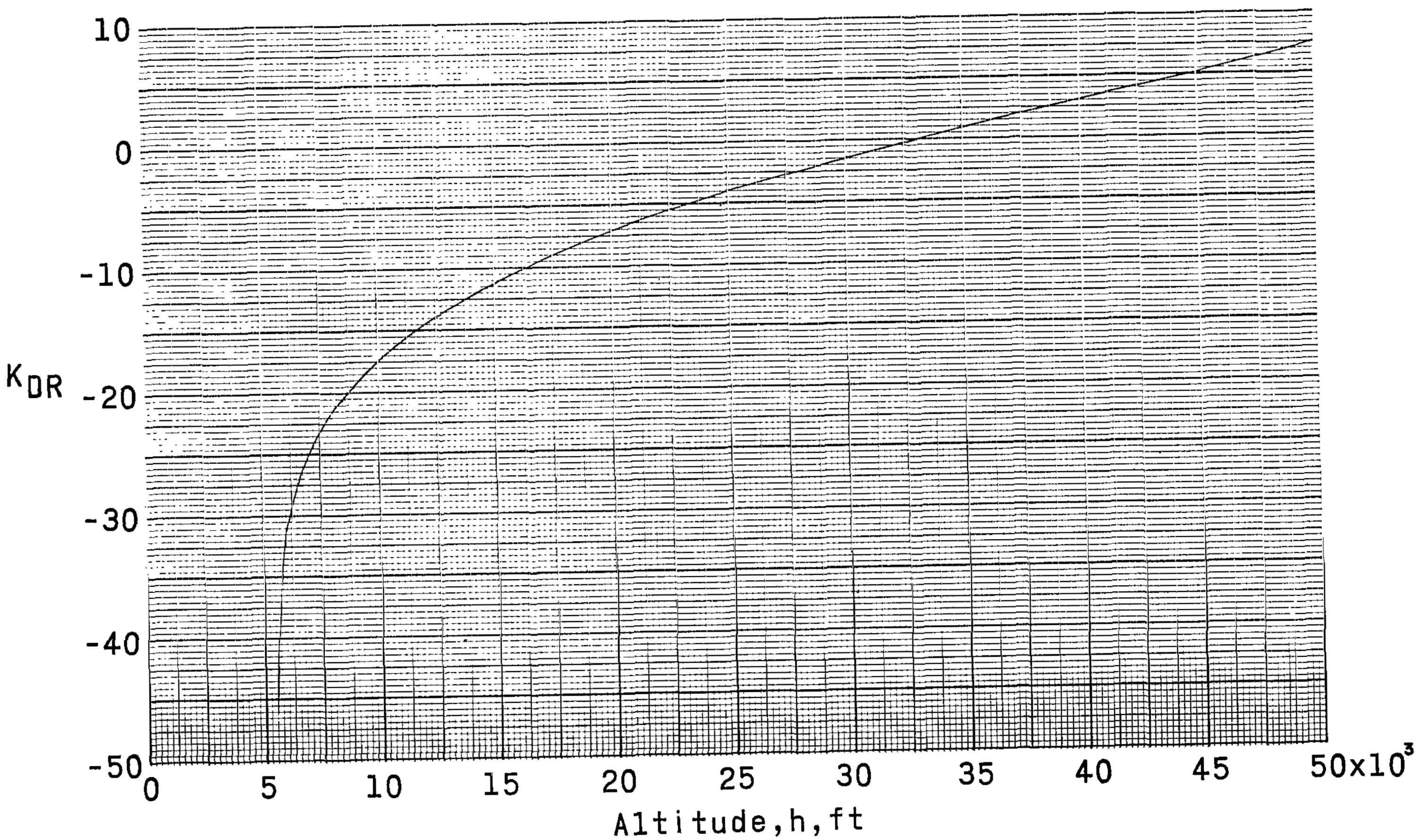


Figure 4.- Variation of the angle between the thrust vector and the line of sight to the downrange horizon (K_{DR}) with altitude for the reference gravity-turn trajectory.

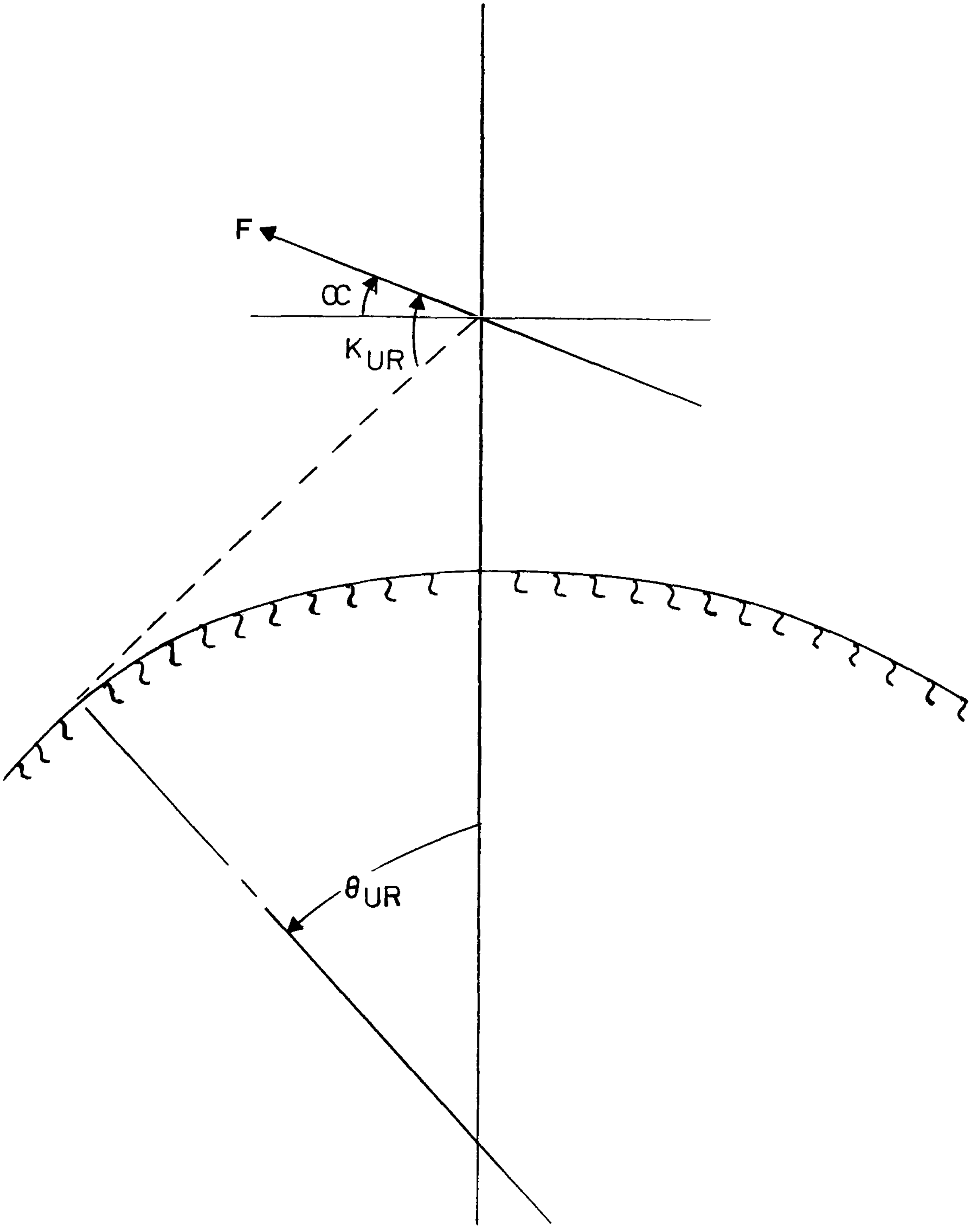


Figure 5.- Geometric relationship between vehicle thrust axis and the uprange horizon.

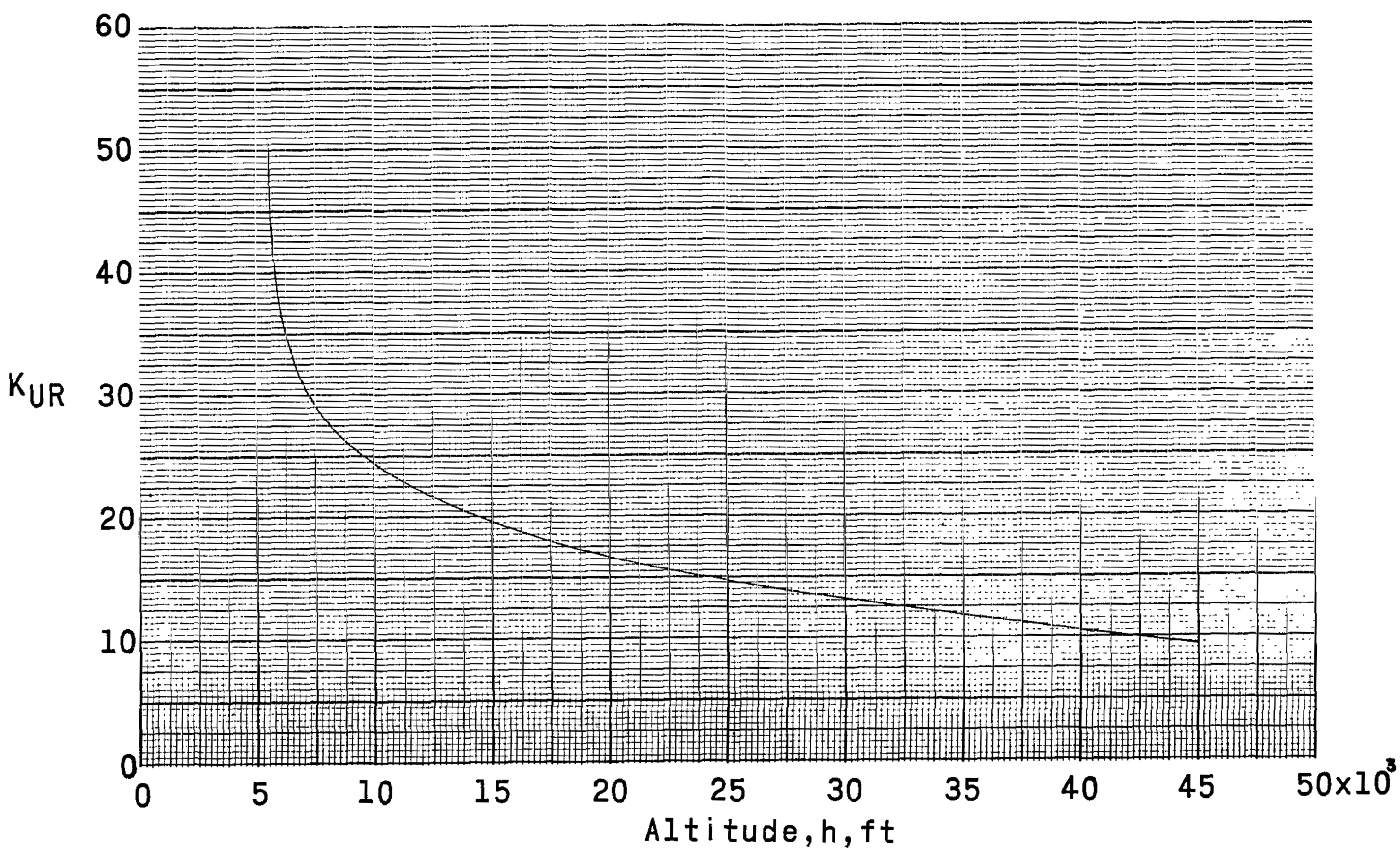


Figure 6.- Variation of the angle between the thrust vector and the line of sight to the uprange horizon (K_{UR}) with altitude for the reference gravity-turn trajectory.

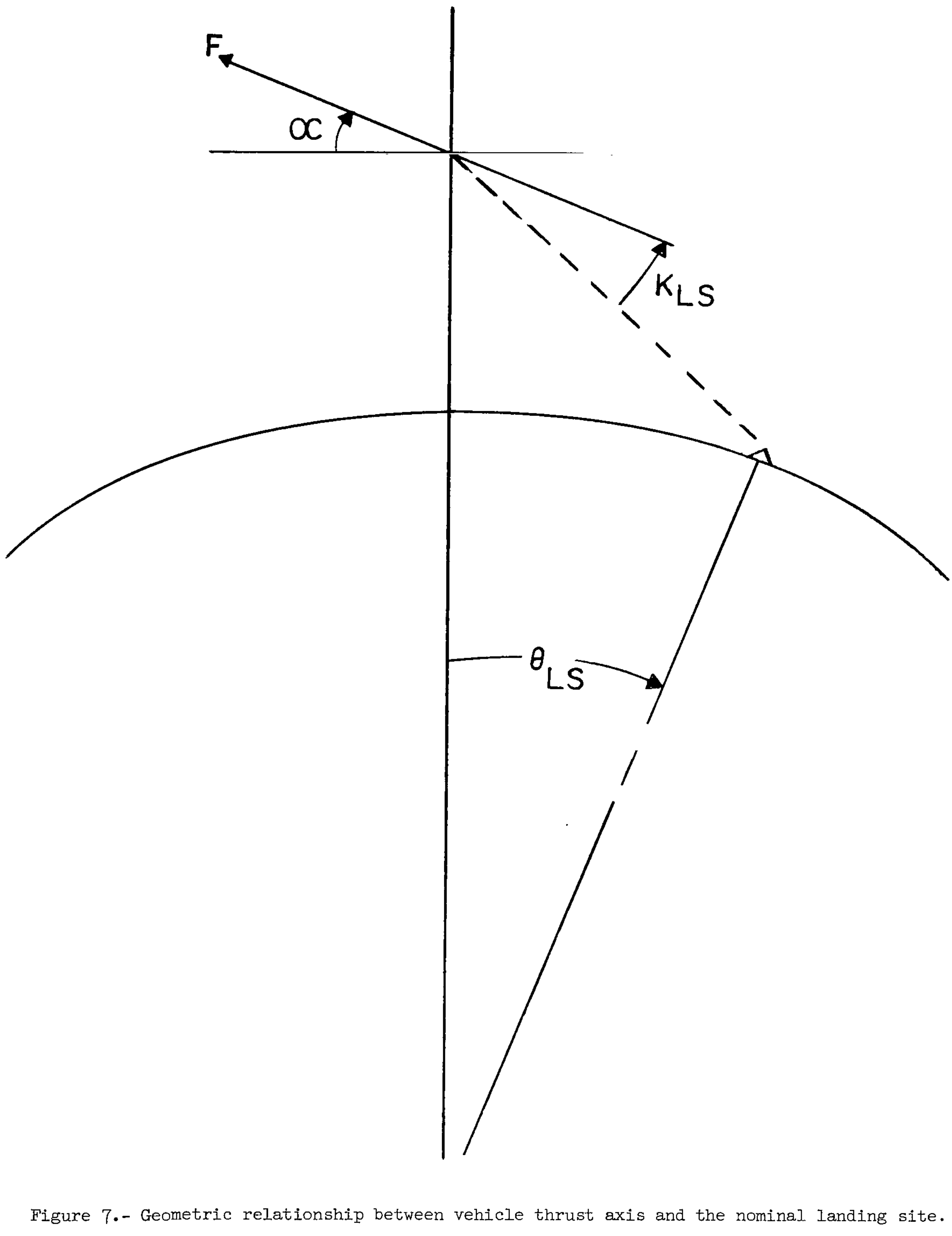


Figure 7.- Geometric relationship between vehicle thrust axis and the nominal landing site.

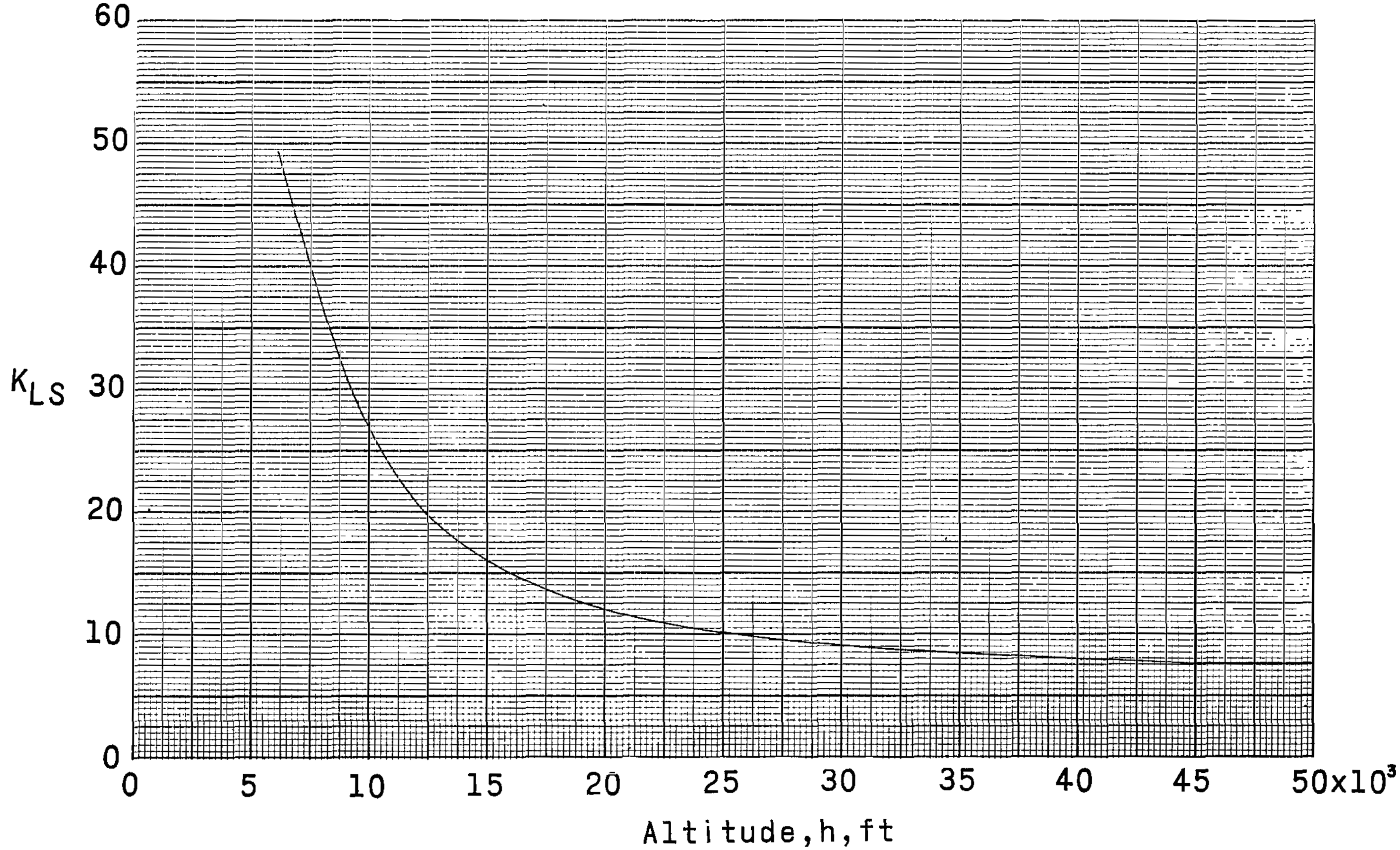


Figure 8.- Variation of the angle between the thrust vector and the line of sight to the nominal landing point for the reference gravity-turn trajectory.

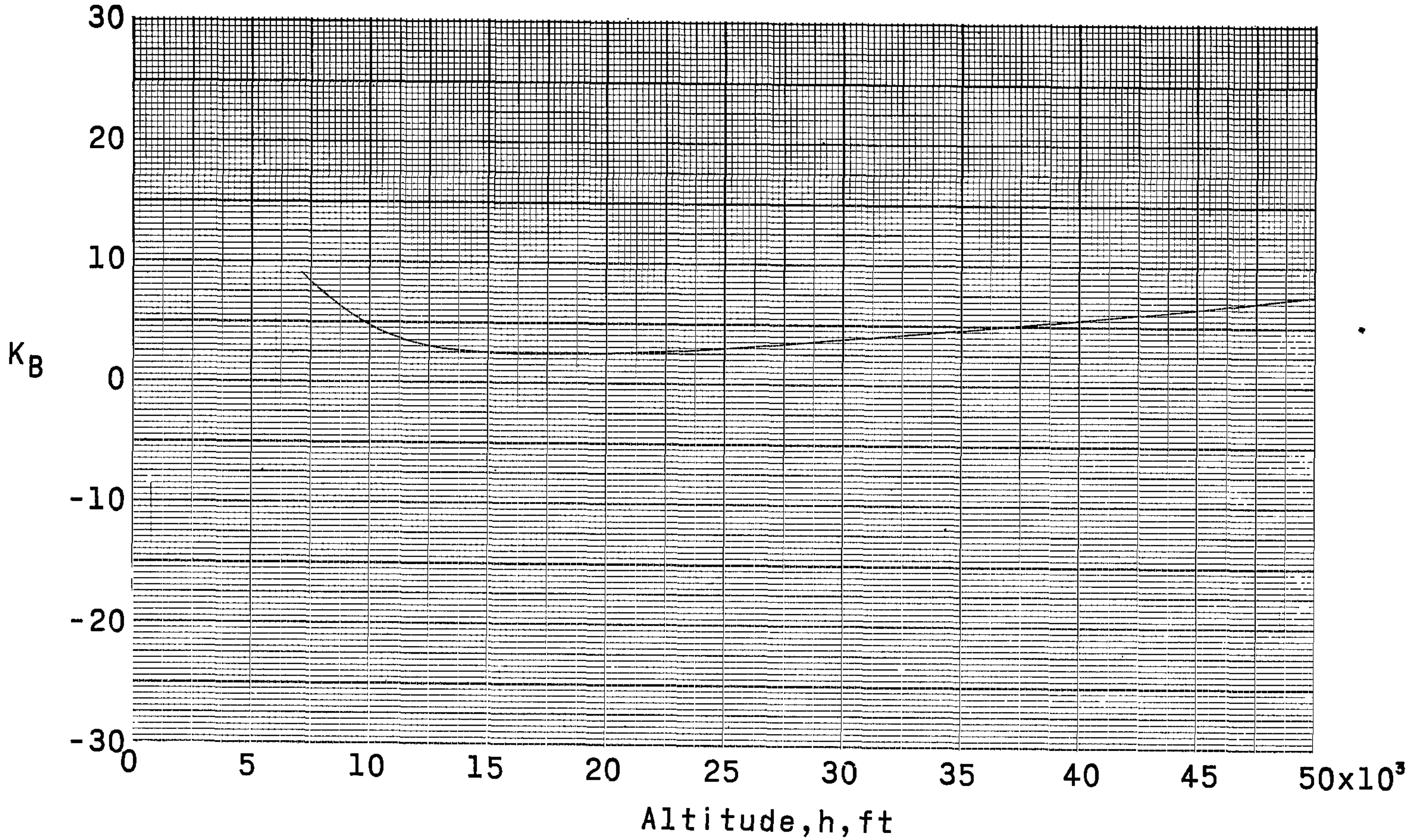


Figure 9.- Variation of the angle between the thrust vector and the bisector of the angle formed between the lines of sight to the downrange horizon and the nominal landing point for the reference gravity-turn trajectory.

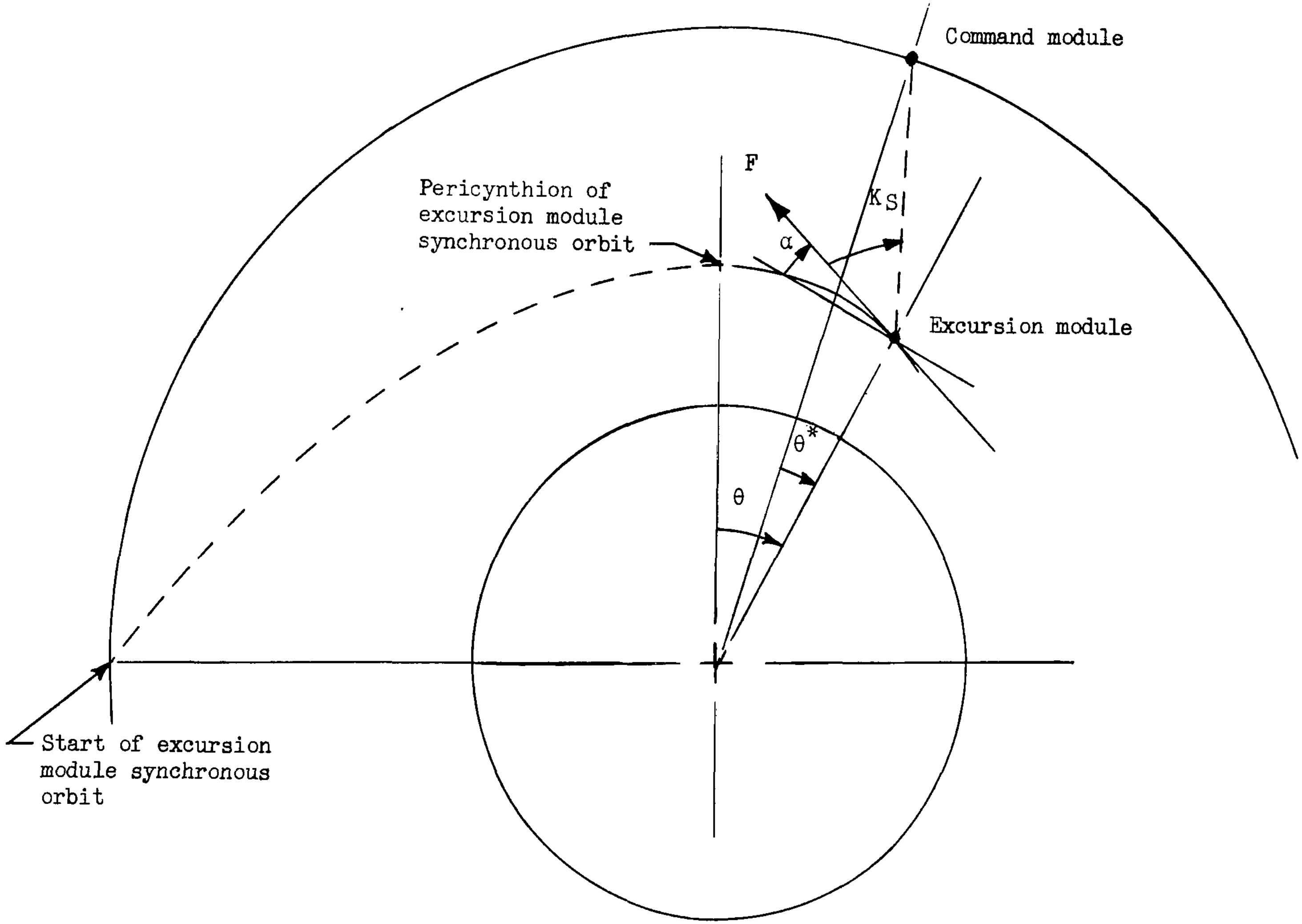


Figure 10.- Geometric relationship between the vehicle thrust axis and the line of sight to an orbiting spacecraft.

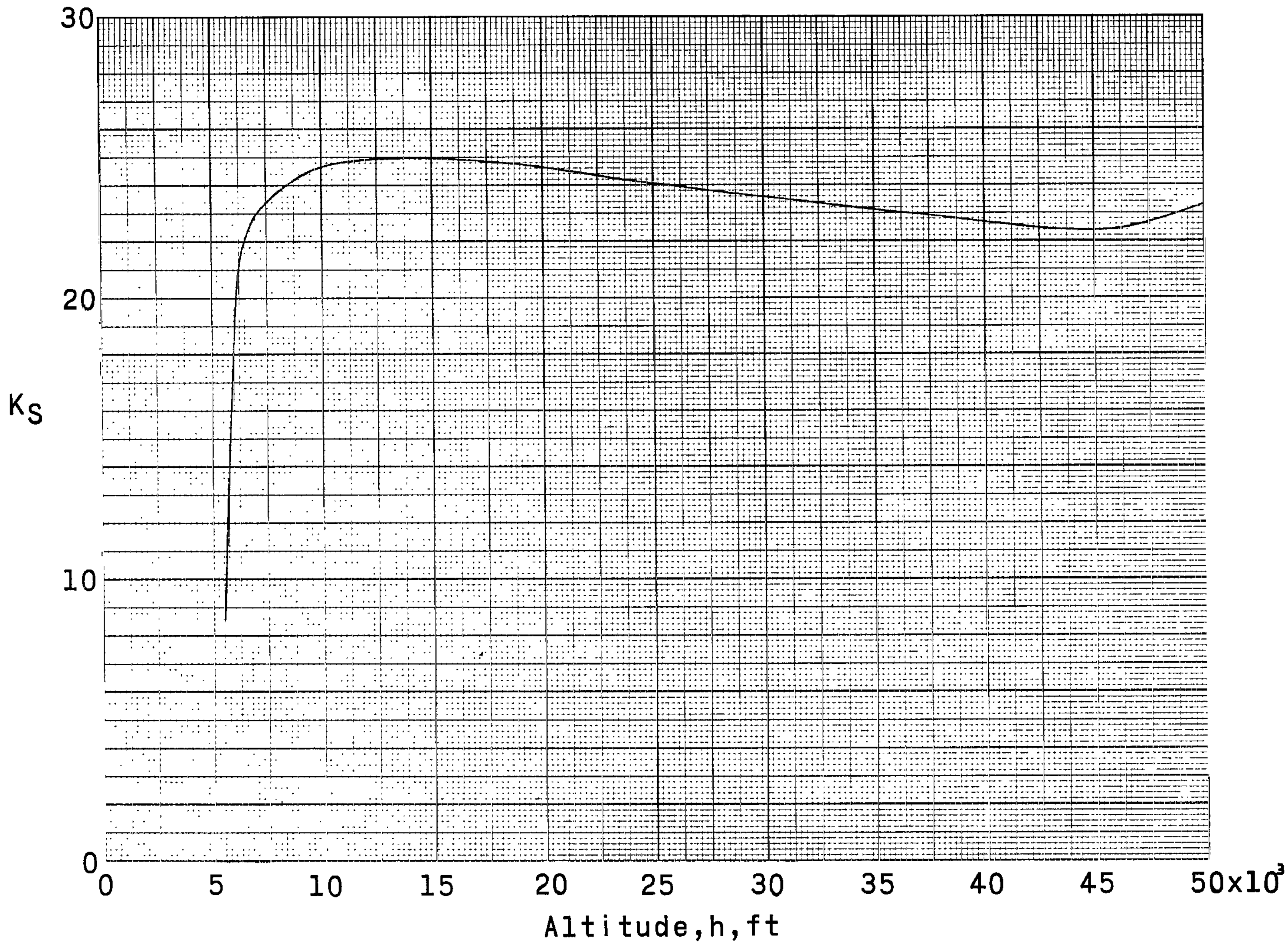
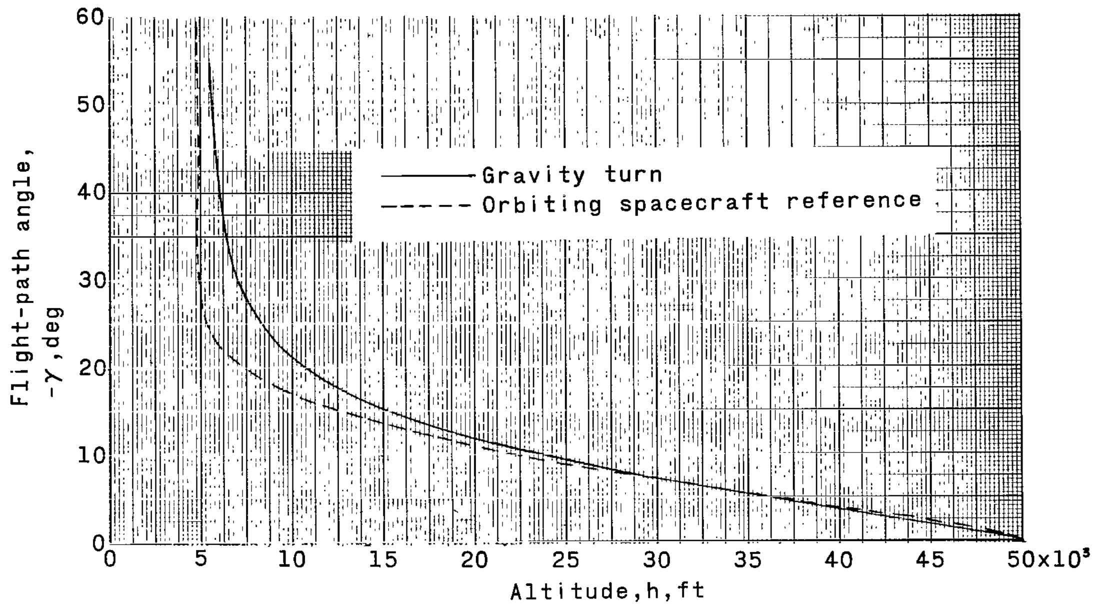
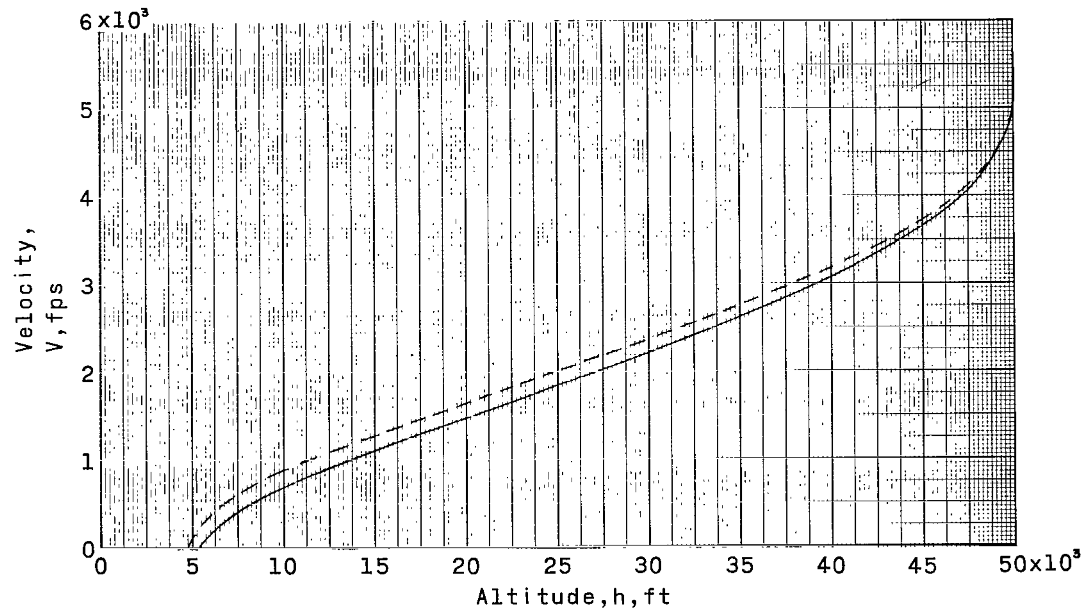


Figure 11.- Variation of the angle between the thrust vector and the line of sight to the orbiting spacecraft for the reference gravity-turn trajectory.

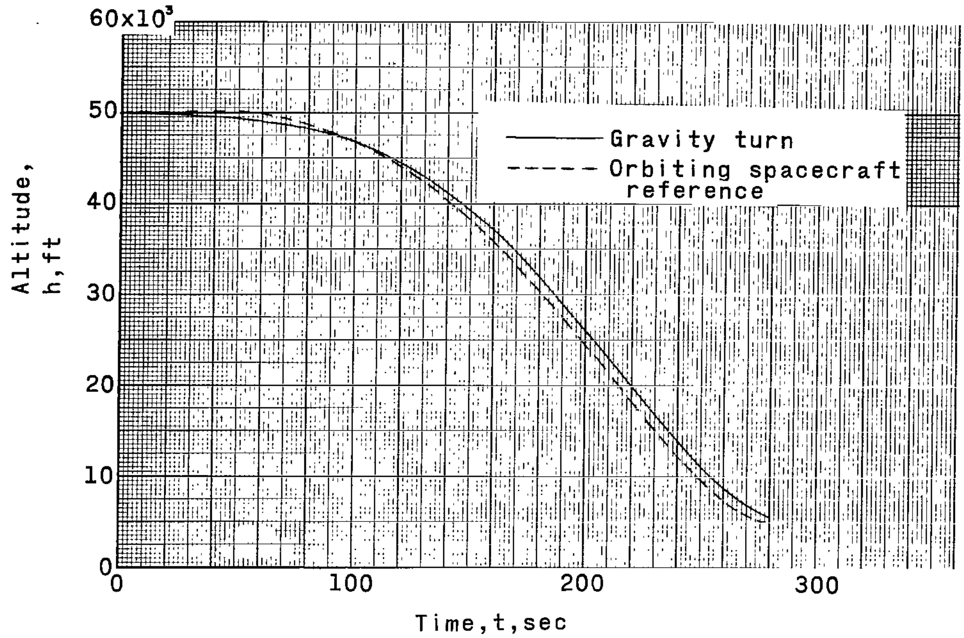


(a) Variation of flight-path angle with altitude.

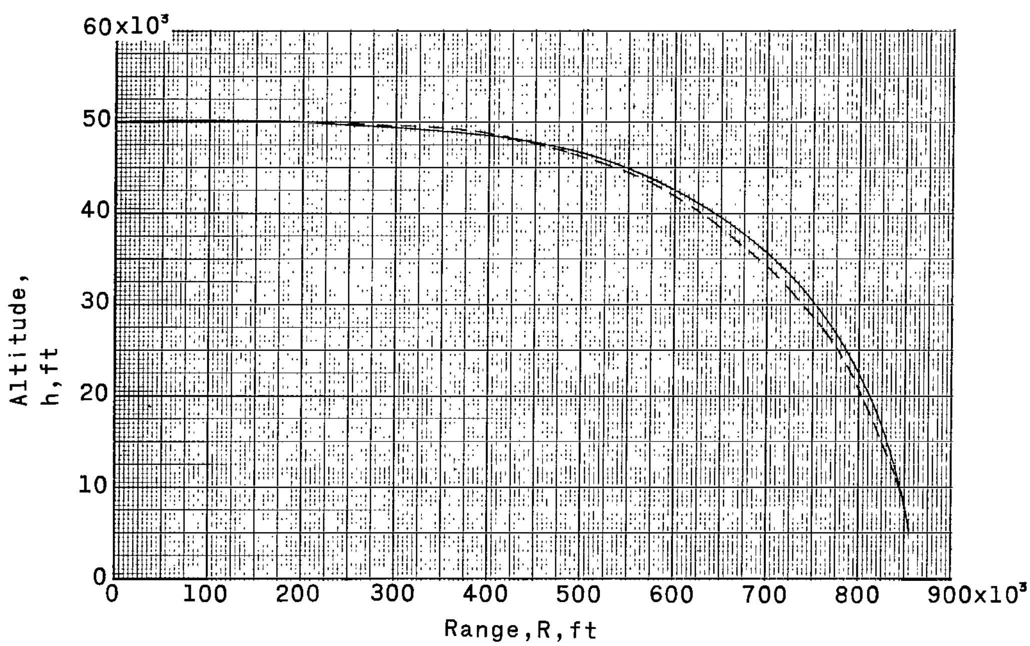


(b) Variation of velocity with altitude.

Figure 12.- Comparison of characteristics of the reference gravity-turn descent with those generated by thrusting 23° behind the orbiting spacecraft.



(c) Variation of altitude with time.



(d) Variation of altitude with range.

Figure 12.- Concluded.

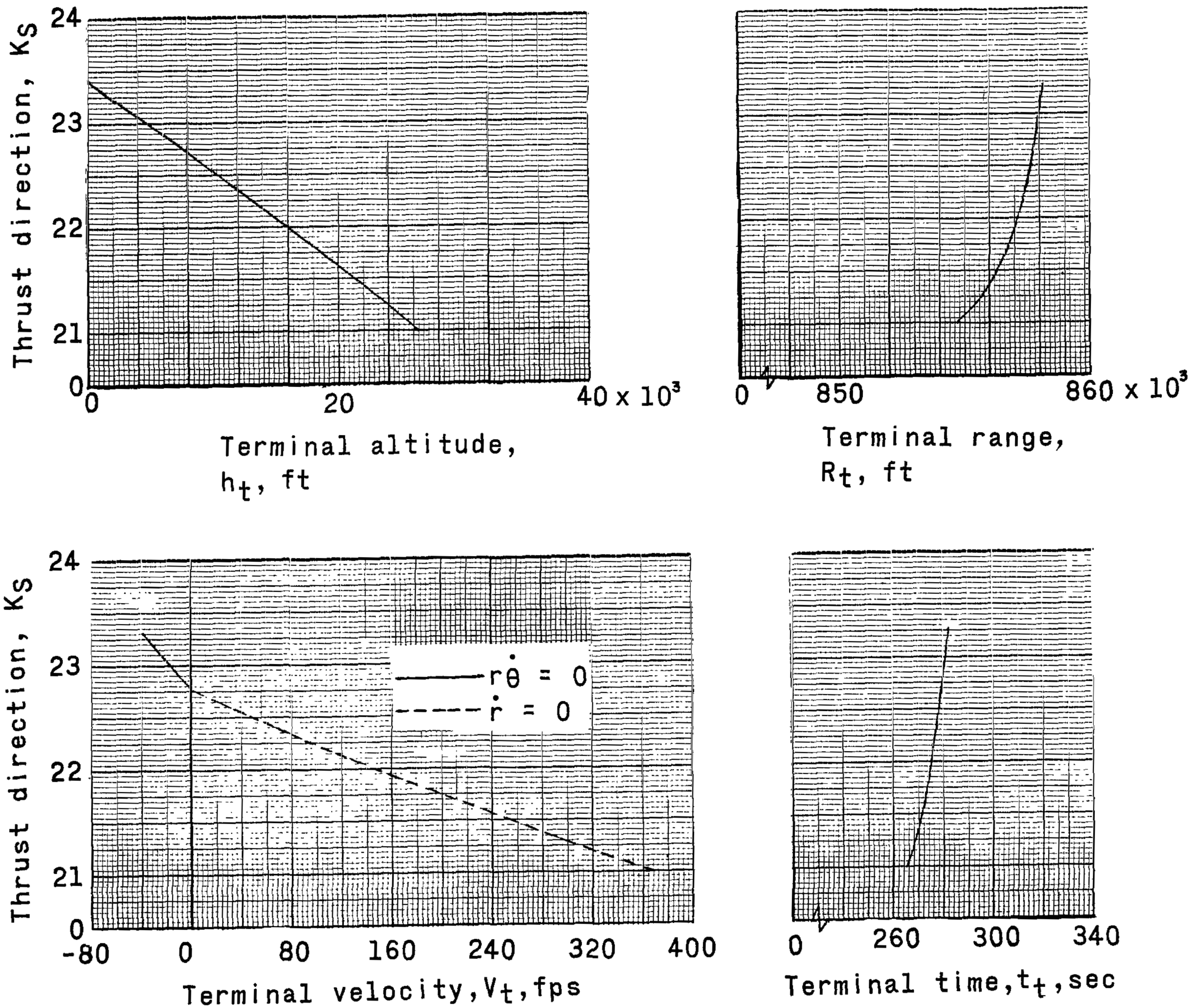


Figure 13.- Variation in terminal conditions with change in direction of thrust-vector attitude relative to the orbiting spacecraft. $K_S = 23^{\circ}$.

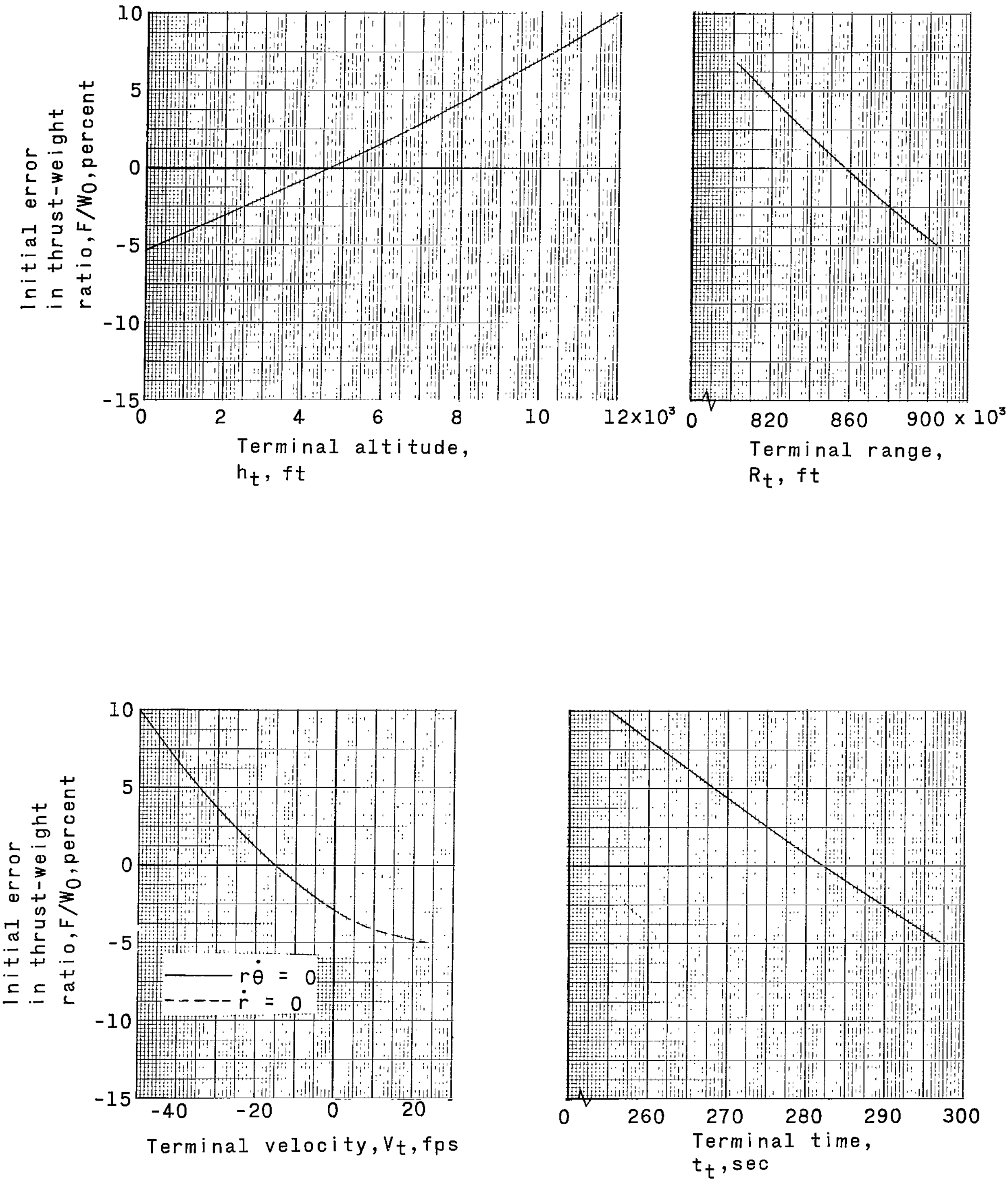


Figure 14.- Variation of terminal conditions with thrust level when orbiting spacecraft is used as thrust-orientation reference. $K_S = 23^{\circ}$.

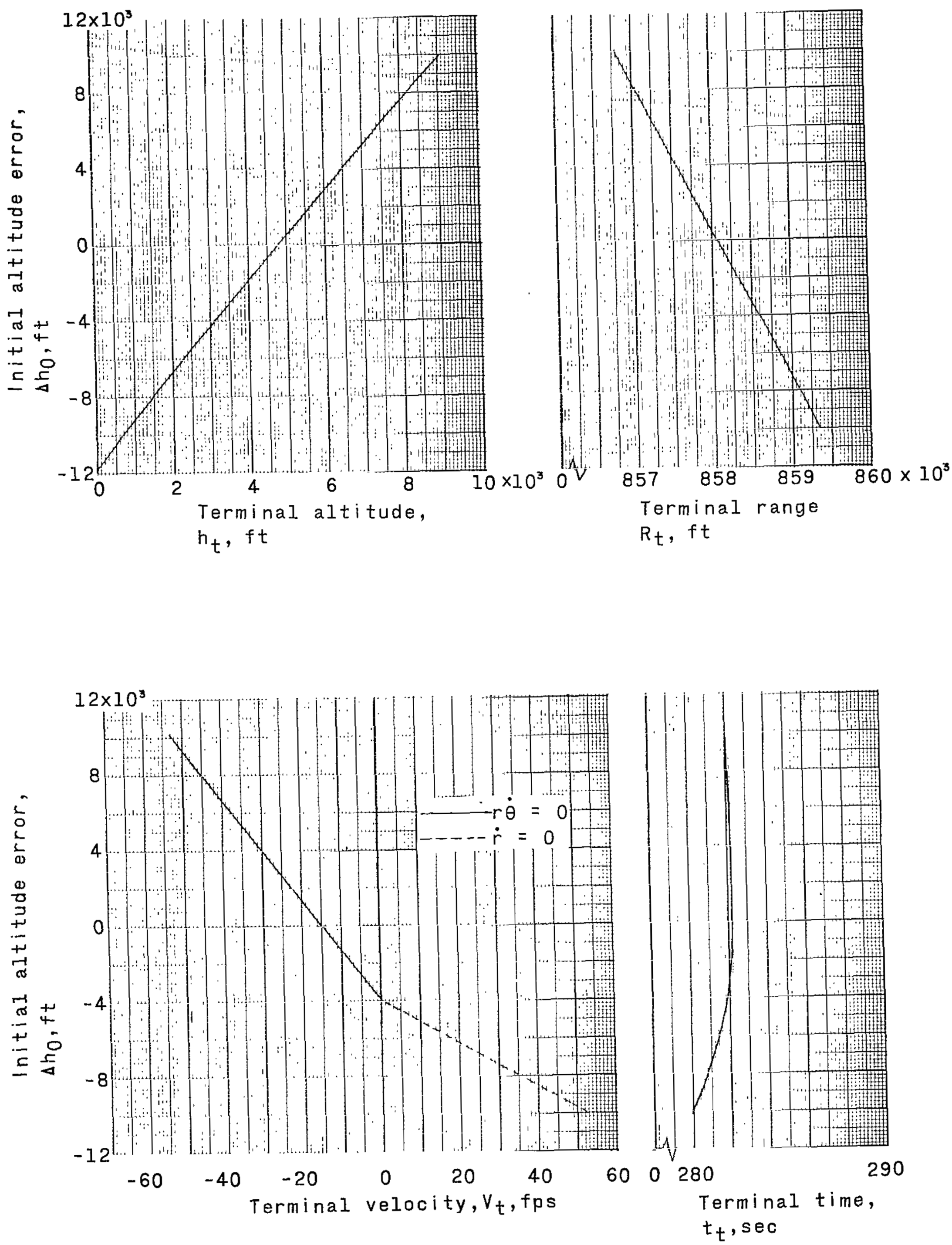


Figure 15.- Variation of terminal conditions with initial altitude when orbiting spacecraft is used as thrust-orientation reference. $K_S = 23^{\circ}$.

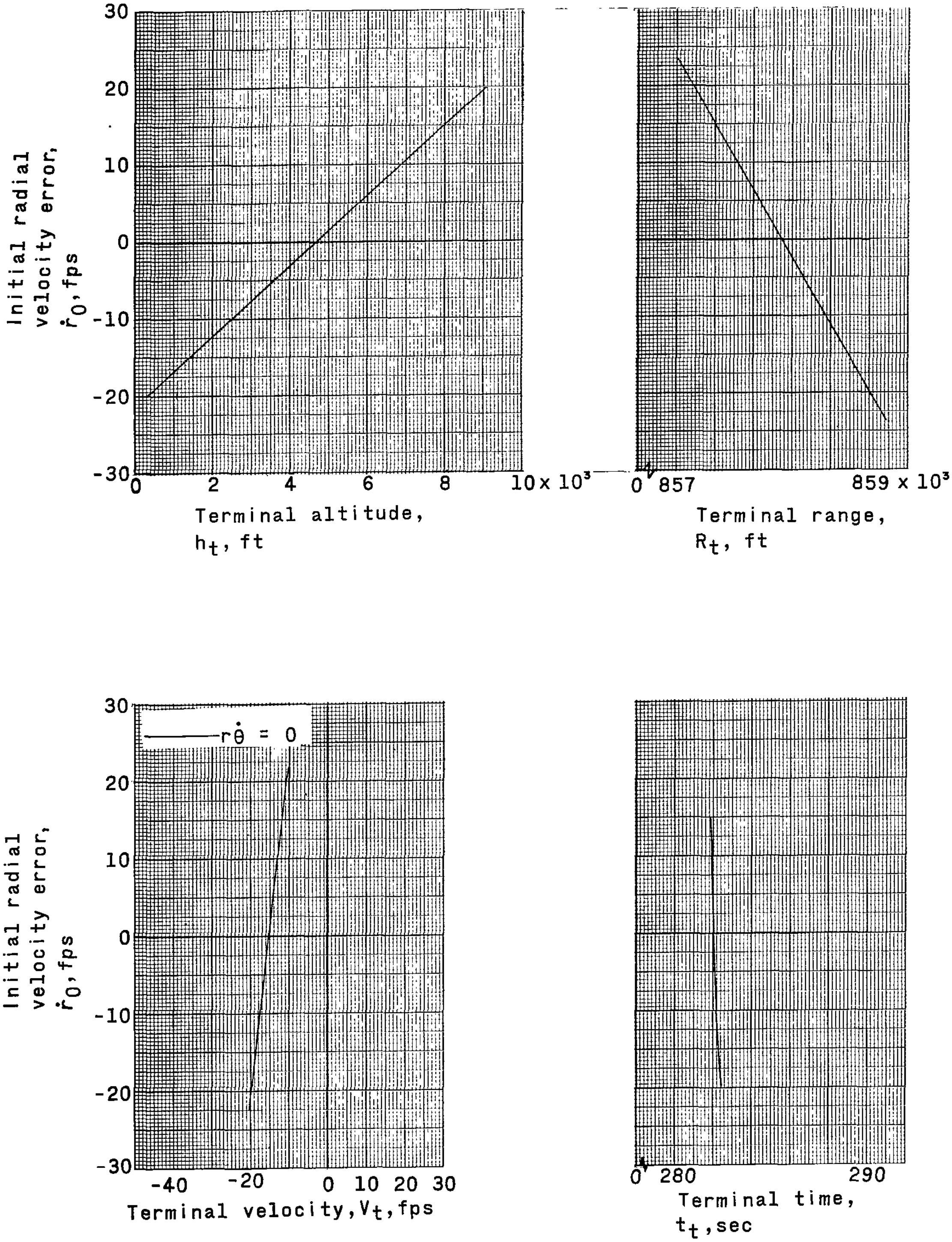


Figure 16.- Variation of terminal conditions with initial rate of descent when orbiting spacecraft is used as thrust-orientation reference. $K_S = 23^{\circ}$.

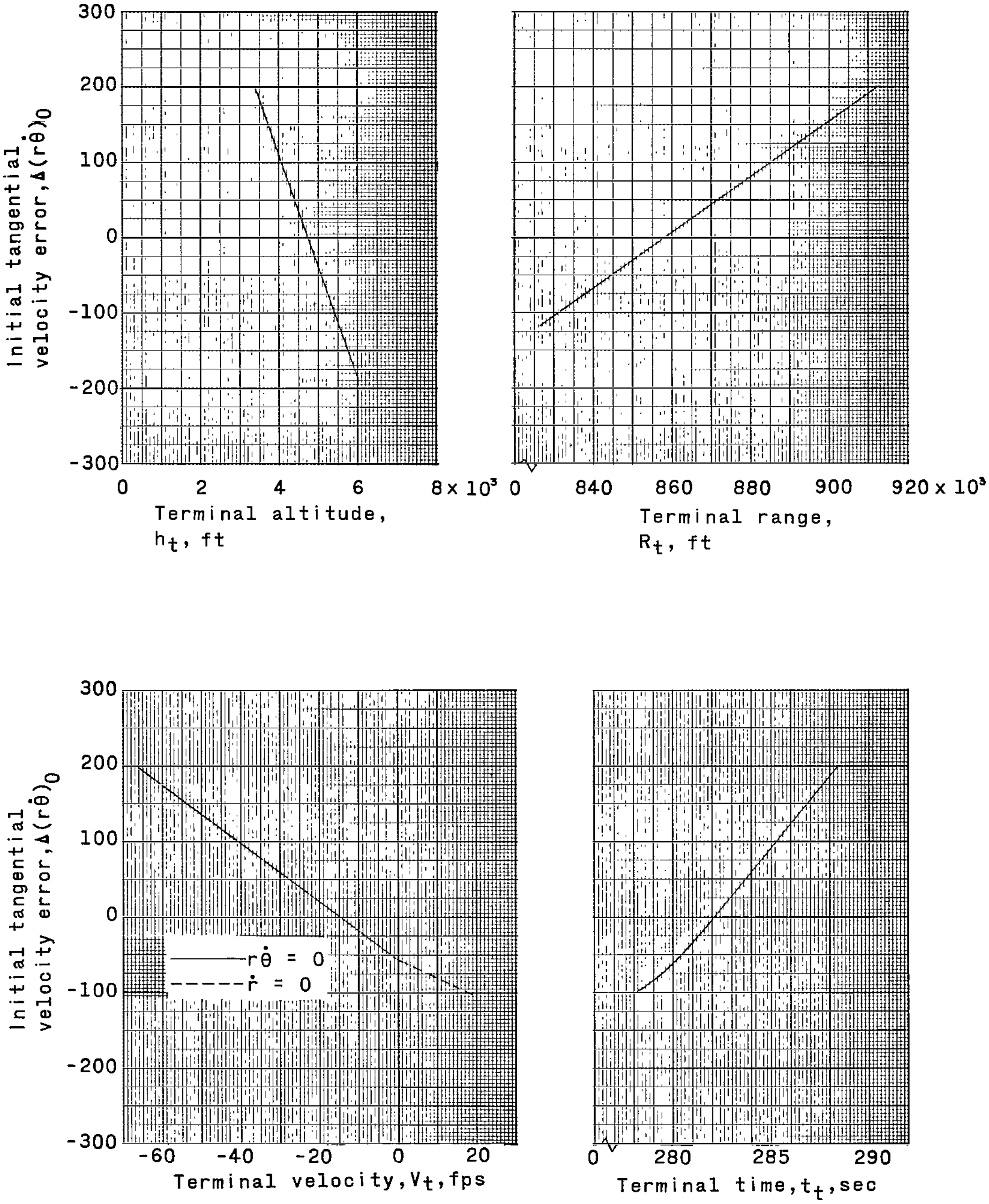


Figure 17.- Variation of terminal conditions with initial tangential velocity when orbiting vehicle is used as thrust-orientation reference. $K_S = 23^{\circ}$.

2/17/25

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