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A SIMPLIFIED GUIDANCE SCHEME FOR ABORTING LUNAR LANDINGS

by G. Kimball Miller, Jr.

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SUMMARY

An analytical investigation has been made of a technique to abort the landing phase of the lunar mission. The abort technique requires only a stopwatch and an optical device for measuring the angle between the vehicle thrust axis and the line of sight to the orbiting command module. The results of the investigation indicated that the abort maneuver placed the ferry vehicle in a safe orbit that would provide rendezvous capability during the first orbital period. Thrust-angle errors of $\pm 0.5^{\circ}$ were permissible if the landing trajectory was chosen so that the lunar surface in the region of the landing site contained no features that exceeded an altitude of 20,000 feet.

INTRODUCTION

The capability of aborting the landing phase of the lunar mission is a necessary requirement for insuring the astronauts' safety. Onboard automatic systems may be used to provide control during the abort mode. Alternately, simplified guidance techniques can be used to develop a manual procedure that is independent of automatic systems. These manual procedures can serve as a backup guidance mode or if sufficiently precise might be considered as primary control modes. Such abort procedures should be simple and require a minimum of equipment. The procedure investigated in the present paper uses the orbiting command module as a reference for thrust vector orientation and requires the pilots' use of line-of-sight measurements and a timing device.

SYMBOLS

Any consistent set of units may be used. In this report it is assumed that

1 international foot = 0.3048 meter

1 international mile = 1.852 kilometers

F thrust, lb

g_e acceleration at surface of earth due to gravitational attraction, 32.2 ft/sec^2

g_m acceleration at lunar surface due to gravitational attraction, 5.32 ft/sec^2

h altitude above lunar surface, ft

h_{min} minimum altitude reached during thrusting phase of abort maneuver, ft

I_{sp} specific impulse, 303 sec

K angle between thrust vector and line of sight to orbiting command module (fig. 1), deg

m mass of ferry vehicle, slugs

P period of orbit established by abort maneuver, sec

r radial distance from center of moon, ft

r_m radius of moon, 5,702,000 ft

t time, sec

t_A elapsed time between abort initiation and abort termination, sec

t_L elapsed time between landing initiation and abort initiation, sec

V characteristic velocity, $g_e I_{sp} \log_e \frac{m_o}{m}$, ft/sec

W weight of ferry vehicle on earth, lb

ω angular velocity of command module about moon, 0.048947, deg/sec

β angle between local vertical of command module and line of sight from ferry vehicle to orbiting command module, radians or deg

θ range angle between pericynthion of orbit established by abort maneuver and nominal landing site (positive values indicate a pericynthion located downrange from the nominal landing site), radians or deg

θ_l range angle by which the ferry vehicle leads the command module, radians or deg

θ_{min} range angle between minimum altitude reached during thrusting and the nominal landing site (positive values correspond to a minimum altitude that is located downrange from nominal landing site), radians or deg

$\bar{\theta}$ angular travel over lunar surface, radians

Subscripts:

a apocynthion conditions

n nominal abort conditions

o initial conditions

p pericynthion conditions

1 conditions during initial phase of abort maneuver

2 conditions during second phase of abort maneuver

I conditions at first intersection of orbit established by abort maneuver with orbit of command module

II conditions at second intersection of orbit established by abort maneuver with orbit of command module

Dots over symbols denote differentiation with respect to time.

A Δ preceding a parameter indicates a change in that parameter from the nominal; for example, $\Delta h = h - h_n$.

ANALYSIS

For the purpose of this investigation, the command module and ferry vehicle combination is assumed to have been injected into a circular orbit about the moon at an altitude of 80 nautical miles. The ferry vehicle is subsequently detached from the command module and placed in a synchronous orbit with a pericynthion altitude of 50,000 feet located approximately 90° downrange from injection. The nominal landing trajectory used in this study consists of applying constant thrust at the pericynthion of the synchronous orbit and performing a gravity-turn descent to a point about 5,500 feet above the lunar surface. At this point the ferry vehicle has approximately zero velocity. The trajectory characteristics of the nominal gravity-turn maneuver are presented in figure 2. The remainder of the descent is not considered in the present study.

Preliminary investigation indicated that after about the first 60 seconds of a gravity-turn lunar take-off, the angle between the thrust vector and the line of sight to the orbiting command module (fig. 1) remained very nearly constant. In addition, the end conditions of the initial 60-second segment of the lunar take-off could be approximated by maintaining a constant thrust angle with respect to the command module. Since the launch phase is about the same as an abort from the final portion of the landing maneuver, it appeared possible to develop an abort procedure for the entire landing maneuver, based on using two constant thrust angles with respect to the command module.

Equations of Motion

The computations for this investigation were made for a point mass moving in a plane about a spherical moon. The general equations of motion of a point mass in spherical coordinates are derived in a straightforward manner in reference 1. The equations of motion used in this study may be obtained by substituting the appropriate angles of figure 1 into the general spherical equations. The resulting equations are presented for reference as follows:

$$\ddot{r} - r\dot{\theta}^2 = \frac{F}{m}\sin(90^\circ + \theta_l + \beta - K) - g_m\left(\frac{r_m}{r}\right)^2 \tag{1}$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = \frac{F}{m}\cos(90^\circ + \theta_l + \beta - K) \tag{2}$$

where

$$m = m_o + \dot{m}\int dt \tag{3}$$

$$\dot{m} = -\frac{F}{g_e I_{sp}} \tag{4}$$

$$\theta_l = \theta_{l_o} + \bar{\theta} - \omega t \tag{5}$$

and

$$\beta = \tan^{-1}\frac{\sin\theta_l}{\frac{6.188 \times 10^6}{r} - \cos\theta_l} \tag{6}$$

Assumed Vehicle Parameters

It was assumed that the vehicle was fully staged at abort initiation and that the abort maneuver was made by using the ferry-vehicle ascent engine. It was also assumed that the rotation of the vehicle from landing-trajectory orientation to abort orientation occurred instantaneously. The values of F/W_o used for the descent and ascent stages were 0.485 and 0.436, respectively.

Abort Maneuver

The equations of motion were solved on an electronic digital computer to develop an abort procedure based upon two periods of constant thrust angle with respect to the orbiting command module. The initial thrust angle and time of thrusting at that angle were determined by an iteration process, the only criteria being that the pericynthion altitudes resulting from the abort maneuver be greater than 20,000 feet. Pericynthion altitudes of this magnitude were considered safe provided that pericynthion occurs within close proximity of the nominal landing site. The initial thrust angle and the time it is to be maintained are presented in figure 3 and are given in the following equations as linear functions of the elapsed time between landing initiation and abort initiation:

$$K_1 = 160 - 0.33t_L \tag{7}$$

$$t_{A,1} = 0.30t_L \tag{8}$$

where K_1 is expressed in degrees and $t_{A,1}$ in seconds.

The second thrust angle was chosen so that the radial velocity component was zero when the tangential velocity component became equal to that at pericynthion of the synchronous orbit at which time thrust was terminated. This procedure should result in the establishment of safe orbits that are very similar to the synchronous orbit used during landing. It was necessary to change the thrusting time given by this method for aborts that are initiated later than about 204 seconds after landing initiation. This change was made in order to formulate an abort procedure which, in addition to establishing safe orbits, provided the capability of rendezvousing with the command module during the first orbital period. The second thrust angle and the time of thrusting at that angle are given in figure 4 as functions of the elapsed time between landing initiation and abort initiation. It should be noted that the discontinuity in $t_{A,2}$ at a t_L of 204 seconds produced similar discontinuities in the orbital parameters of the orbits established by the abort maneuver.

The abort maneuver is predicated on the assumption that the pilot has available a timing device and an optical device for measuring the angle between ferry vehicle thrust axis and the line of sight to the command module. The pilot would also have available a family of charts corresponding to figures 3 and 4. The piloting procedure for the abort maneuver is given as follows for reference.

The timing device is started at landing initiation and is stopped at that point during the landing where an abort is deemed necessary. The pilot then enters a chart similar to figure 3 (instantaneous staging and rotation to abort attitude is assumed in the present study) and obtains the value of K_1 and $t_{A,1}$ that is appropriate for the time of abort initiation. The vehicle is then staged, releasing that portion that is necessary only for landing, and is rotated to the proper thrust angle K_1. Thrust is then applied and maintained for the proper time $t_{A,1}$. The pilot then enters a chart similar to figure 4 and obtains those values of K_2 and $t_{A,2}$ corresponding to the time of abort initiation. The ferry vehicle is then rotated to K_2 which is maintained until thrust termination at $t_{A,2}$. This procedure should result in a safe orbit which places the ferry vehicle in close proximity to the command module during the first orbital period.

DISCUSSION OF RESULTS

The abort maneuver results in the establishment of orbits with pericynthion altitudes that exceed 24,000 feet and are located within approximately ±8° of the nominal landing site (fig. 5) for aborts from any point along the nominal landing trajectory. Thus, pericynthion exceeds all but the highest lunar features (ref. 2) which are located primarily in the polar regions of the moon. The choice of the nominal landing site is virtually unrestricted for near equatorial orbits.

The altitude at pericynthion of the resulting orbit is not the minimum altitude reached during the abort maneuver. The minimum altitude, which occurs during the initial phase of the abort at K_1, is in general located between the point of landing initiation and the nominal landing site (fig. 6) and thus should not constitute a problem.

The elliptic orbits established by the abort maneuver exceed 486,000 feet at apocynthion (fig. 7) and thus intersect the circular orbit of the command module. At the first intersection the ferry vehicle leads the command module by 3° to 17°, but at the second intersection the ferry vehicle lead angle is between 2° and -2°. (See fig. 8.) Thus, the ferry vehicle is within ±36 nautical miles of the command module at the second orbital intersection which should be close enough to permit rendezvous. (See refs. 3 and 4.) The orbital period of the ferry vehicle is less than that of the command module (fig. 9) and the lead angle of the ferry vehicle increases with each revolution by as much as 13.5°. The characteristic velocity required to perform the abort maneuver is 6,000 feet per second or less. (See fig. 10.)

An error analysis is included in the appendix which considers the effect of various errors on the orbits established by the abort maneuver. The error analysis indicated that thrust angle errors of ±0.5° are permissible and that abort thrusting time must be maintained very accurately if the abort maneuver is to provide rendezvous capability during the first orbit.

CONCLUDING REMARKS

An analytical investigation has been made of an abort technique which requires only a timing device to measure the elapsed time between landing initiation and abort initiation and an optical device to measure the angle between the thrust axis of the ferry vehicle and the line of sight to the orbiting command module. The landing trajectory from which aborts were considered was a gravity-turn descent to 5,500 feet from the 50,000-foot pericynthion altitude of an equiperiod transfer orbit from the command module.

The abort maneuver was initiated by applying thrust at some angle with respect to the line of sight to the command module for a given time where both the thrust angle and the thrusting time are linear functions of the elapsed time between landing initiation and abort initiation. The ferry vehicle was then rotated to a second thrust angle with respect to the command module, and this angle was maintained until thrust termination at a given time. Both the thrust angle and thrusting time are functions of the elapsed time between landing initiation and abort initiation. It was found that the abort maneuver resulted in the establishment of nonimpacting orbits for aborts from any point along the landing trajectory. In addition, the orbits established by the abort maneuver resulted in placing the ferry vehicle within rendezvous range of the command module. Thrust-angle errors of $\pm 0.5^{\circ}$ are permissible, the resulting orbits having altitudes at pericynthion that are greater than 20,000 feet.

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

APPENDIX

ERROR ANALYSIS

The effect of errors in ferry vehicle thrust angle on several pertinent orbital parameters is presented in figure 11. In order to avoid the establishment of orbits with pericynthion altitudes that are too low to be considered safe, the nominal thrust angle of the abort maneuver must be maintained to within 0.5°. In addition, the ferry vehicle lead angle at the second orbital intersection can change by as much as about 3° per degree error in thrust angle. (See fig. 11(c).) The effect of thrust angle errors on the other orbital parameters considered are relatively insignificant.

Several additional errors including errors in total abort thrusting time and errors in velocity and altitude at abort initiation were considered. For the sake of brevity, only a single time of abort initiation along the landing trajectory was considered for this portion of the error analysis. The time chosen, 204^{+} seconds after landing initiation very nearly corresponds to that point along the landing trajectory for which the pericynthion altitude of the orbits established by the abort maneuver is a minimum. (See fig. 5.)

The effect of failing to terminate abort thrust at the proper time is presented in figure 12. Errors in time of thrust termination have little effect on pericynthion altitude and location. (See figs. 12(a) and 12(b).) However, there is a significant effect on apocynthion altitude (fig. 12(c)) and, consequently, on the ferry vehicle lead angle at the second orbital intersection (fig. 12(e)). The ferry vehicle lead angle changes by about 4° per second error in time of thrust termination. Thus, abort thrusting time should be maintained very accurately if the abort maneuver is to provide rendezvous capability during the first orbital period.

The abort maneuver assumes that the landing vehicle has a specific velocity-altitude combination at a given point along the landing trajectory. Consequently, errors in velocity and altitude at abort initiation result in the establishment of orbits that differ from those nominally expected. The effects of such errors on several pertinent orbital parameters are presented in figures 13 to 15. Errors in radial velocity primarily affect pericynthion altitude and location (figs. 13(a) and 13(b)), with little effect on apocynthion altitude (fig. 13(c)) and ferry vehicle lead angle at the second orbital intersection (fig. 13(e)). Errors in tangential velocity have some effect on pericynthion altitude and location (figs. 14(a) and 14(b)) but primarily affect apocynthion altitude (fig. 14(c)) and hence the ferry vehicle lead angle at the second orbital intersection (fig. 14(e)). Errors in altitude have some effect on pericynthion altitude (fig. 15(a)) and practically no effect on apocynthion altitude (fig. 15(c)) and ferry vehicle lead angle at the second orbital intersection.

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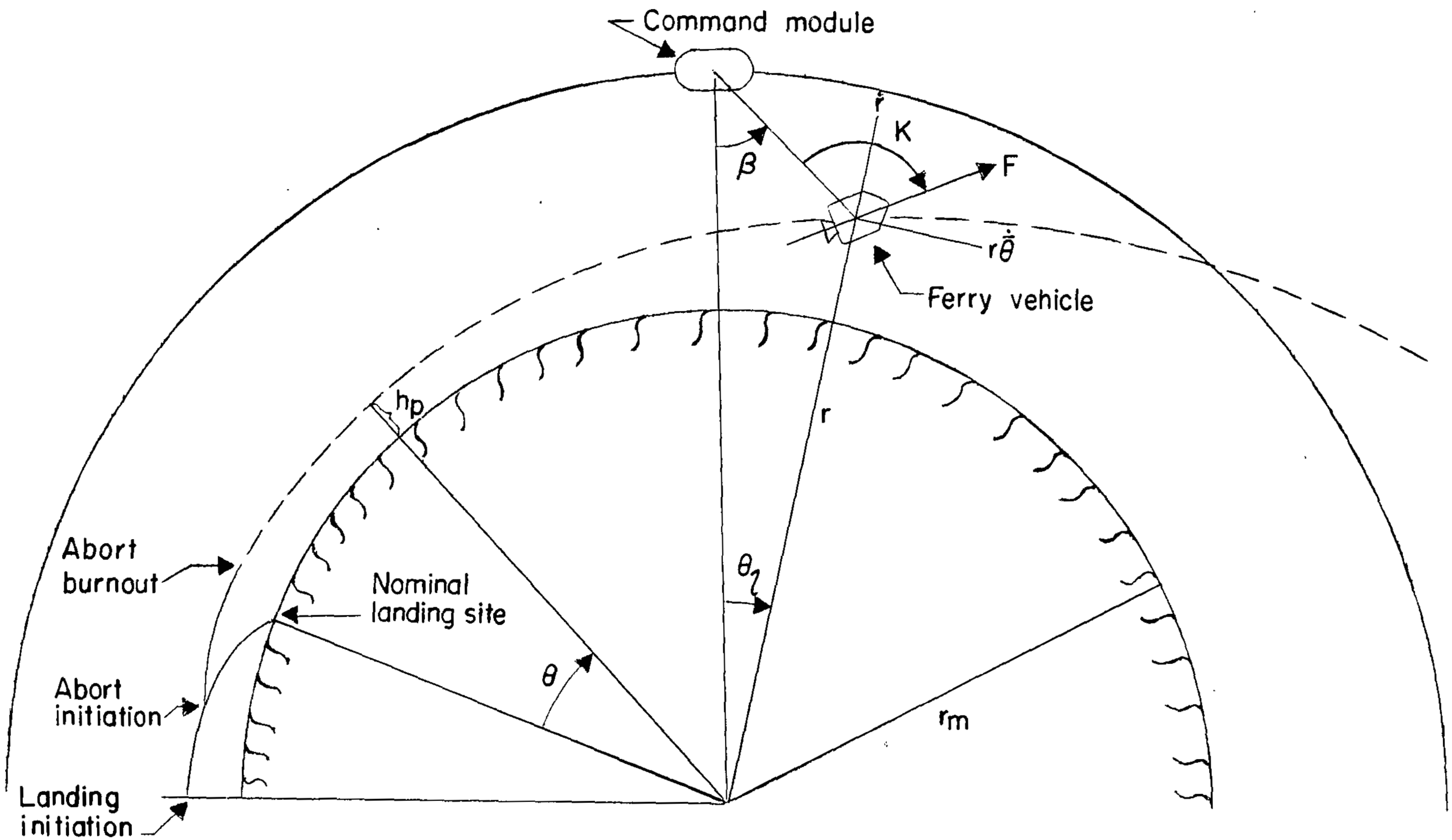
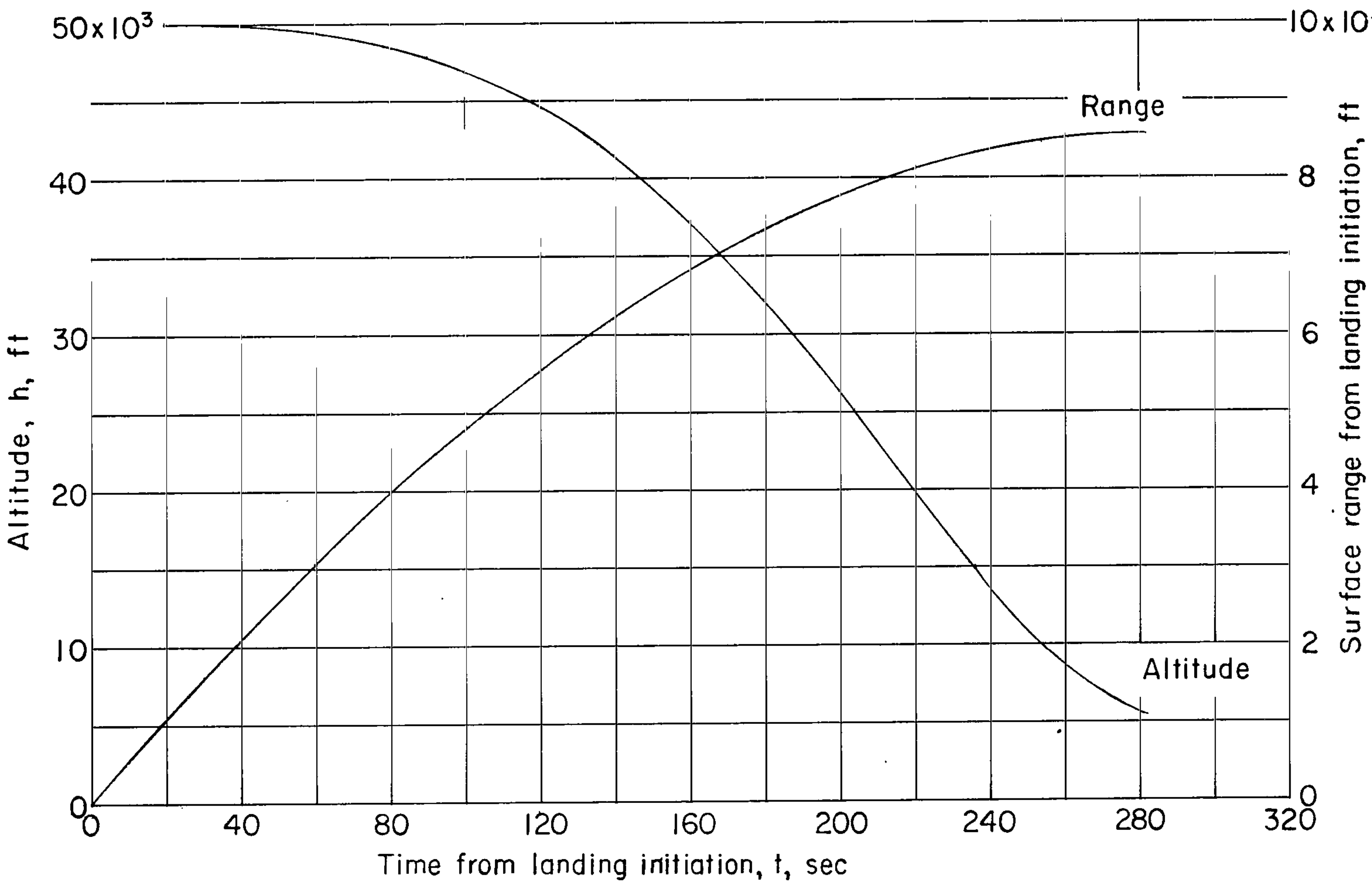
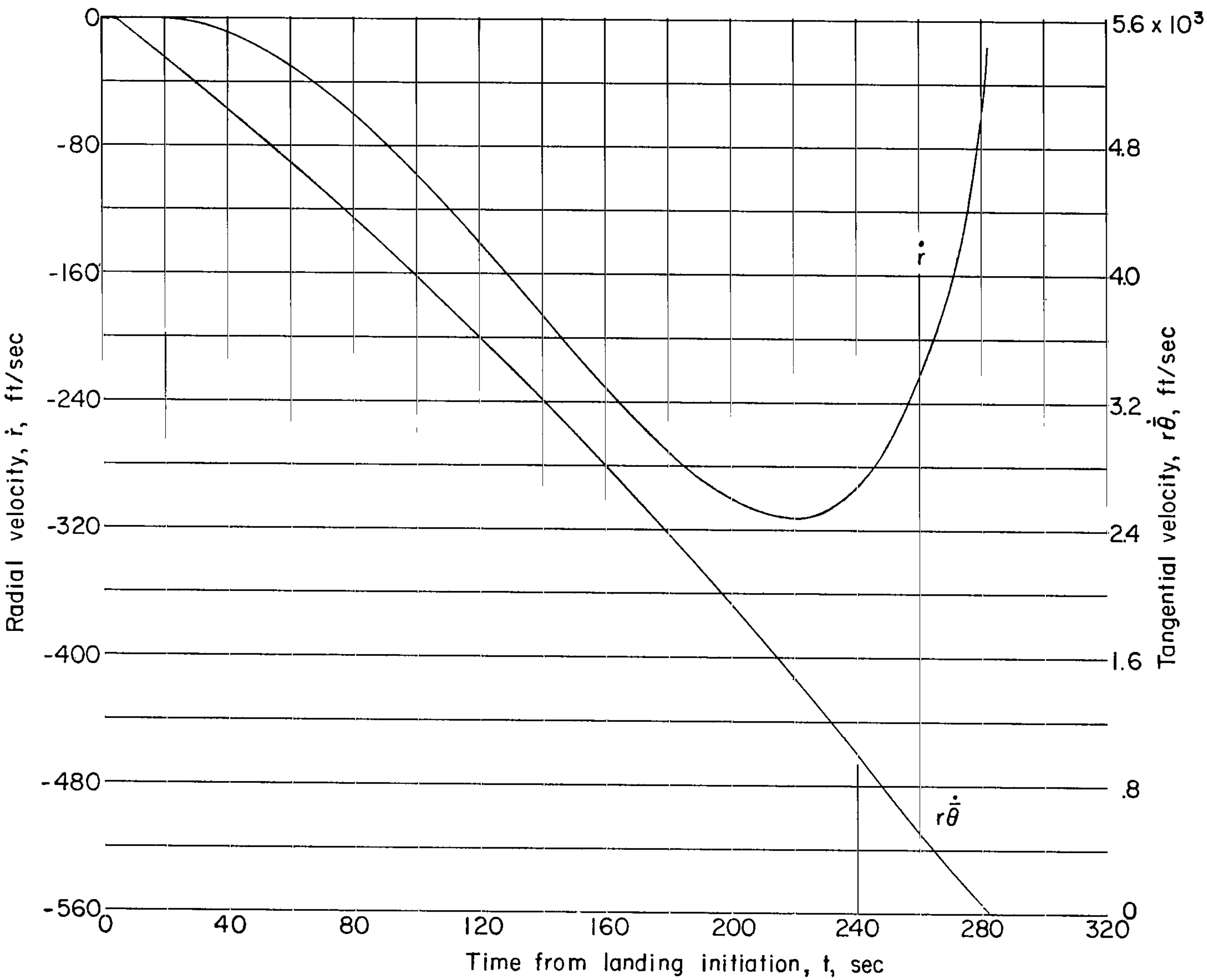


Figure 1.- Illustration of abort maneuver.



(a) Altitude and range.

Figure 2.- Trajectory characteristics of nominal gravity-turn landing trajectory.



(b) Velocity components.

Figure 2.- Concluded.

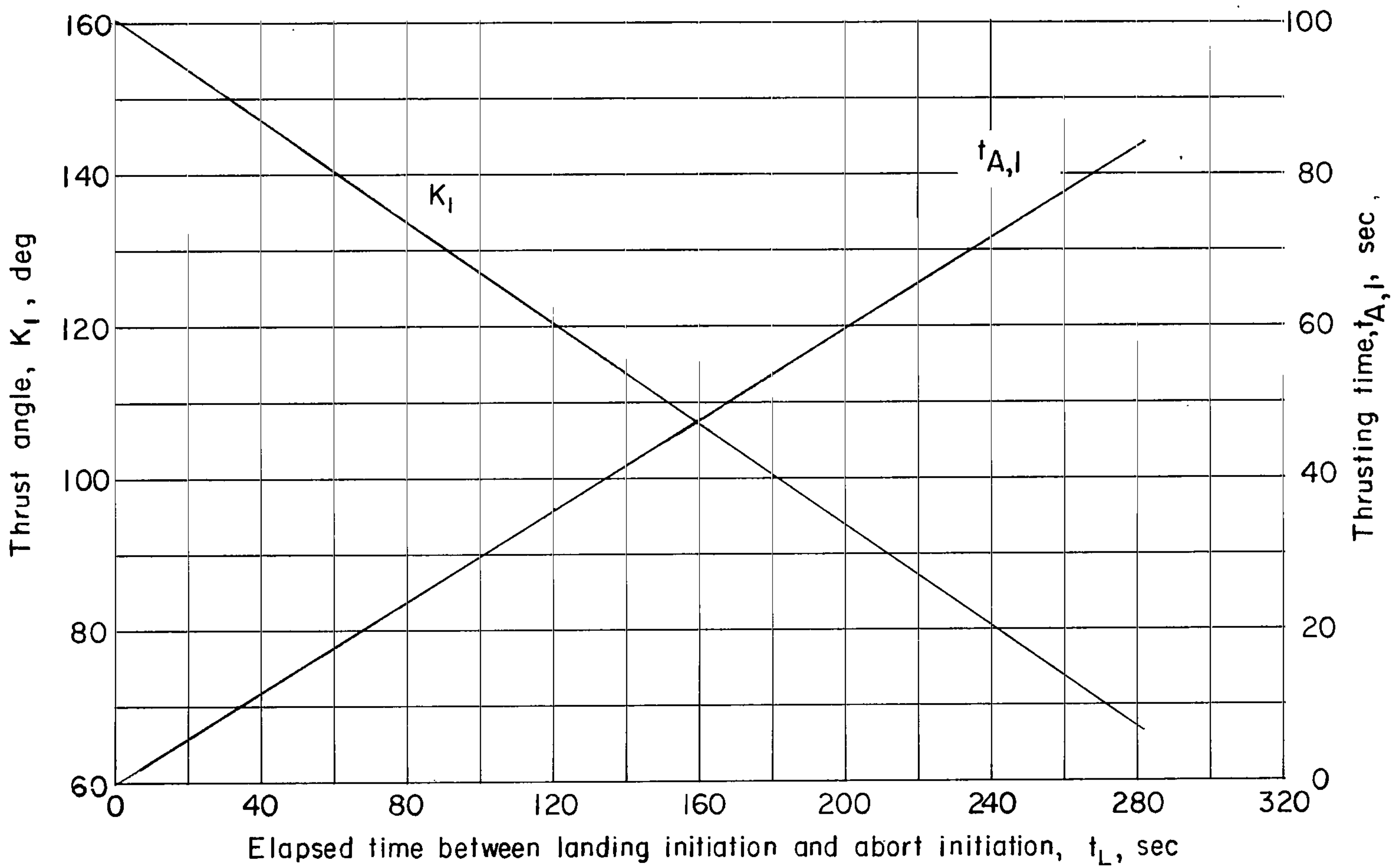


Figure 3.- Thrust angle and thrusting time used during initial phase of the abort maneuver as functions of elapsed time between landing initiation and abort initiation.

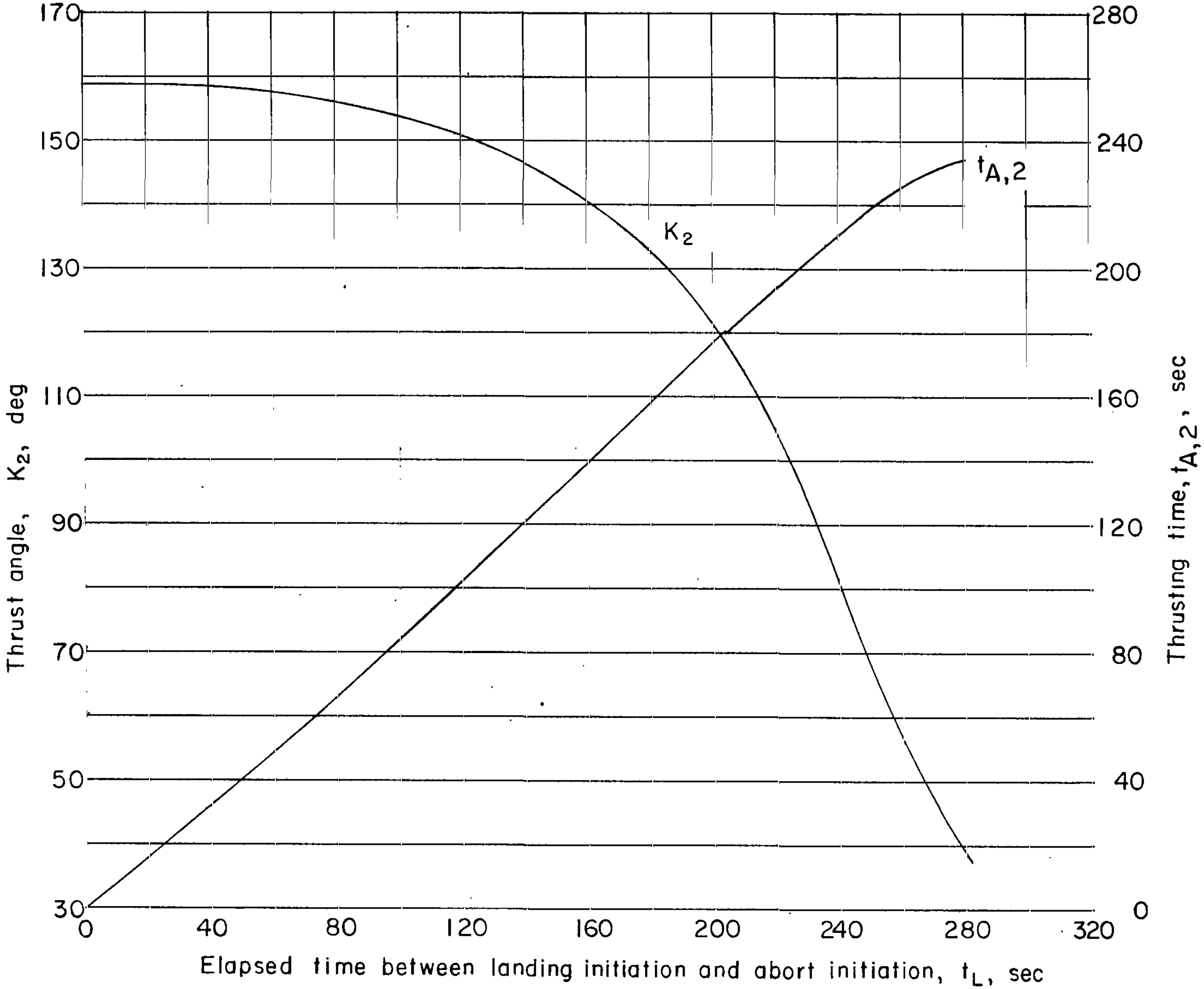


Figure 4.- Thrust angle and thrusting time used during second phase of the abort maneuver as functions of elapsed time between landing initiation and abort initiation.

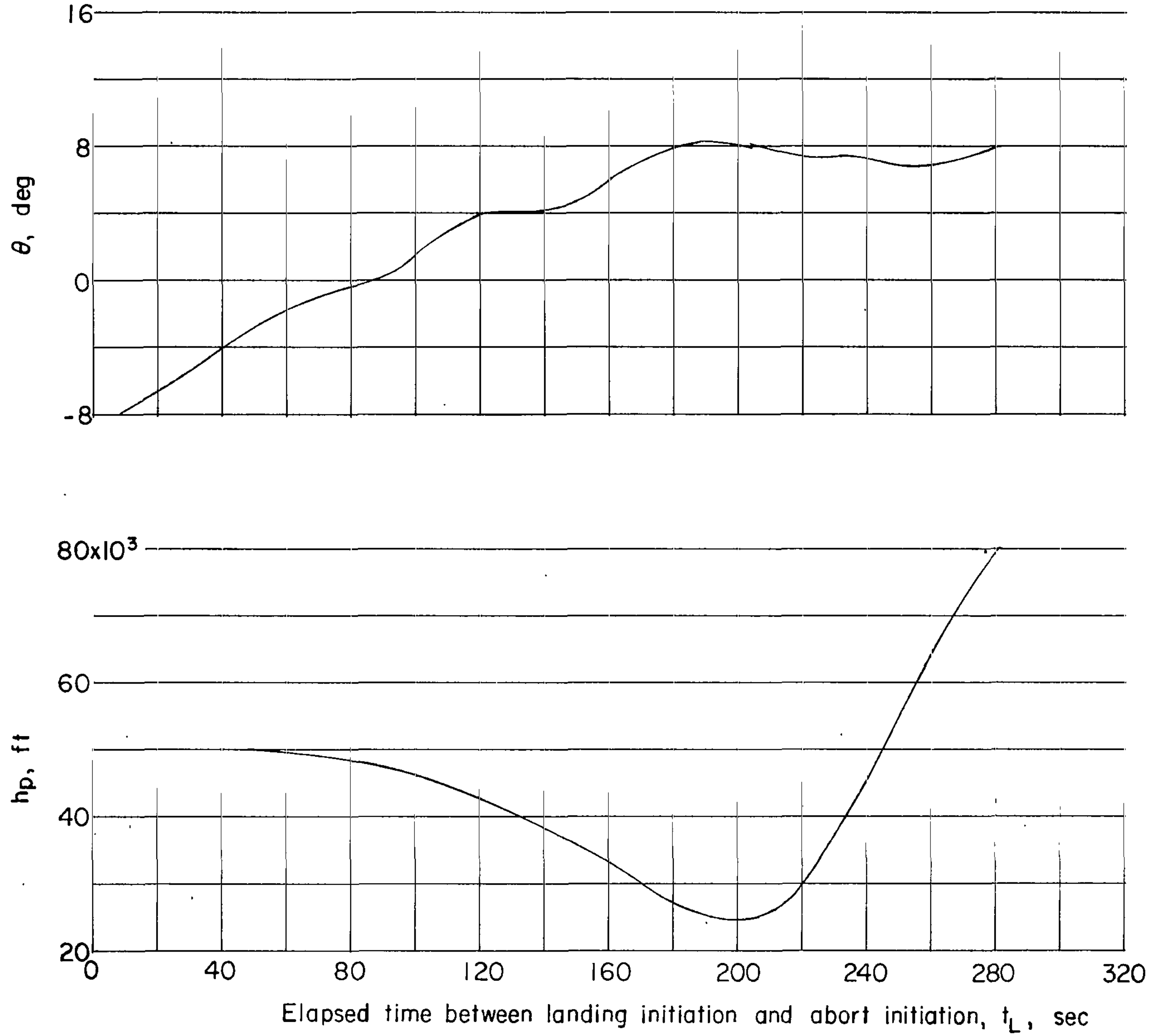


Figure 5.- Pericynthion altitude and location of pericynthion of orbits established by abort maneuver.

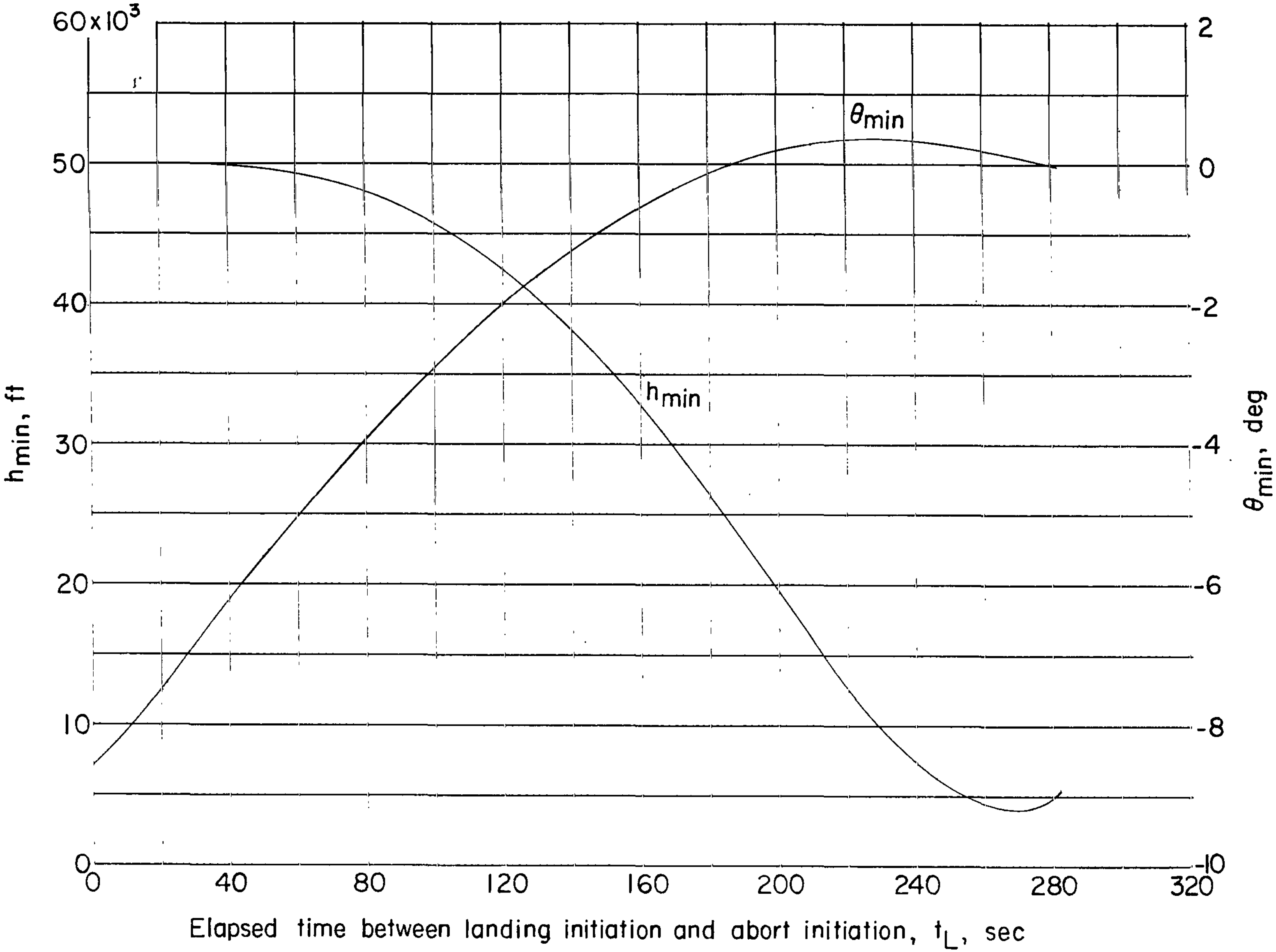


Figure 6.- Minimum altitude reached during thrusting phase of abort maneuver and its location with respect to nominal landing site.

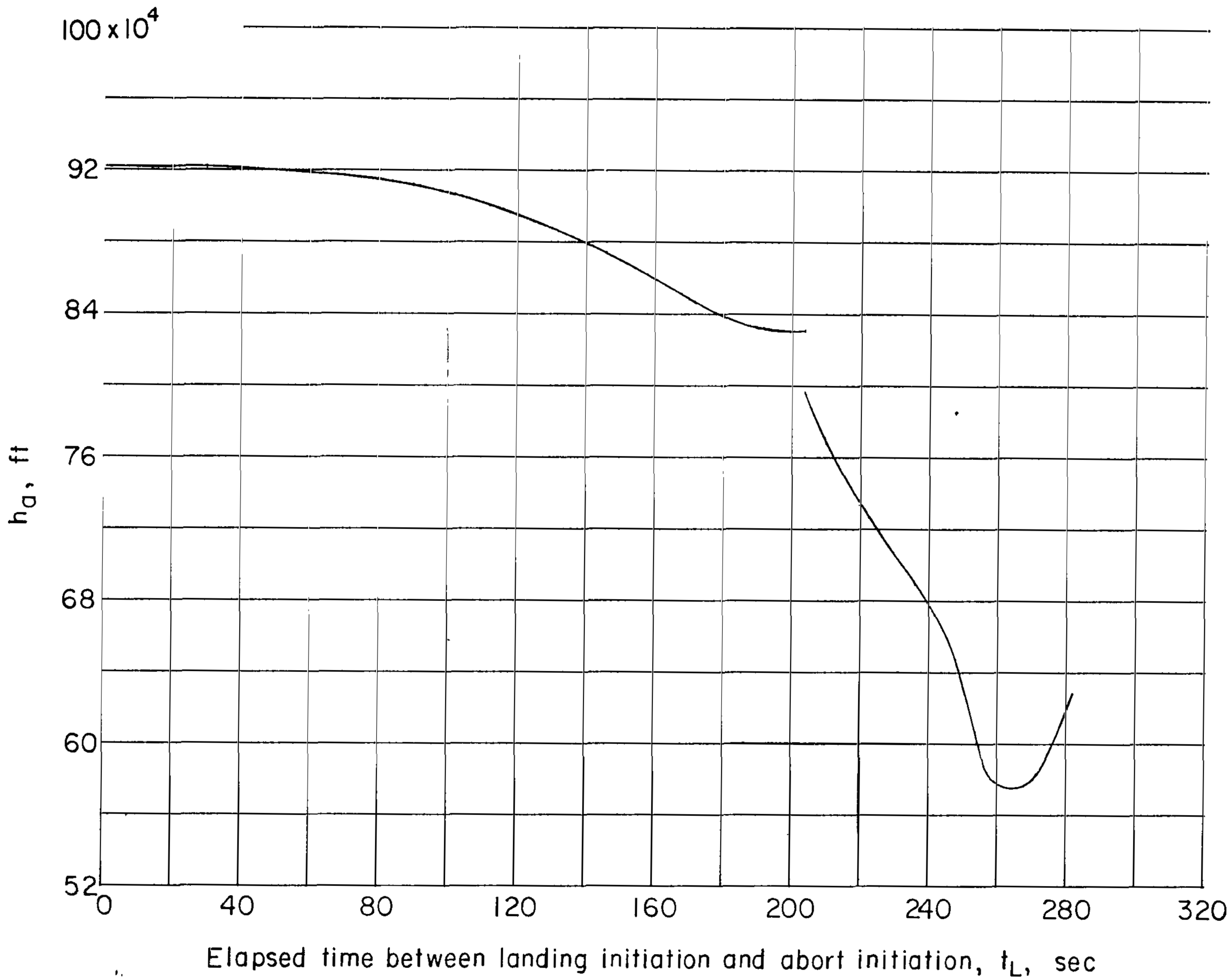


Figure 7.- Apocynthion altitude of orbits established by abort maneuver.

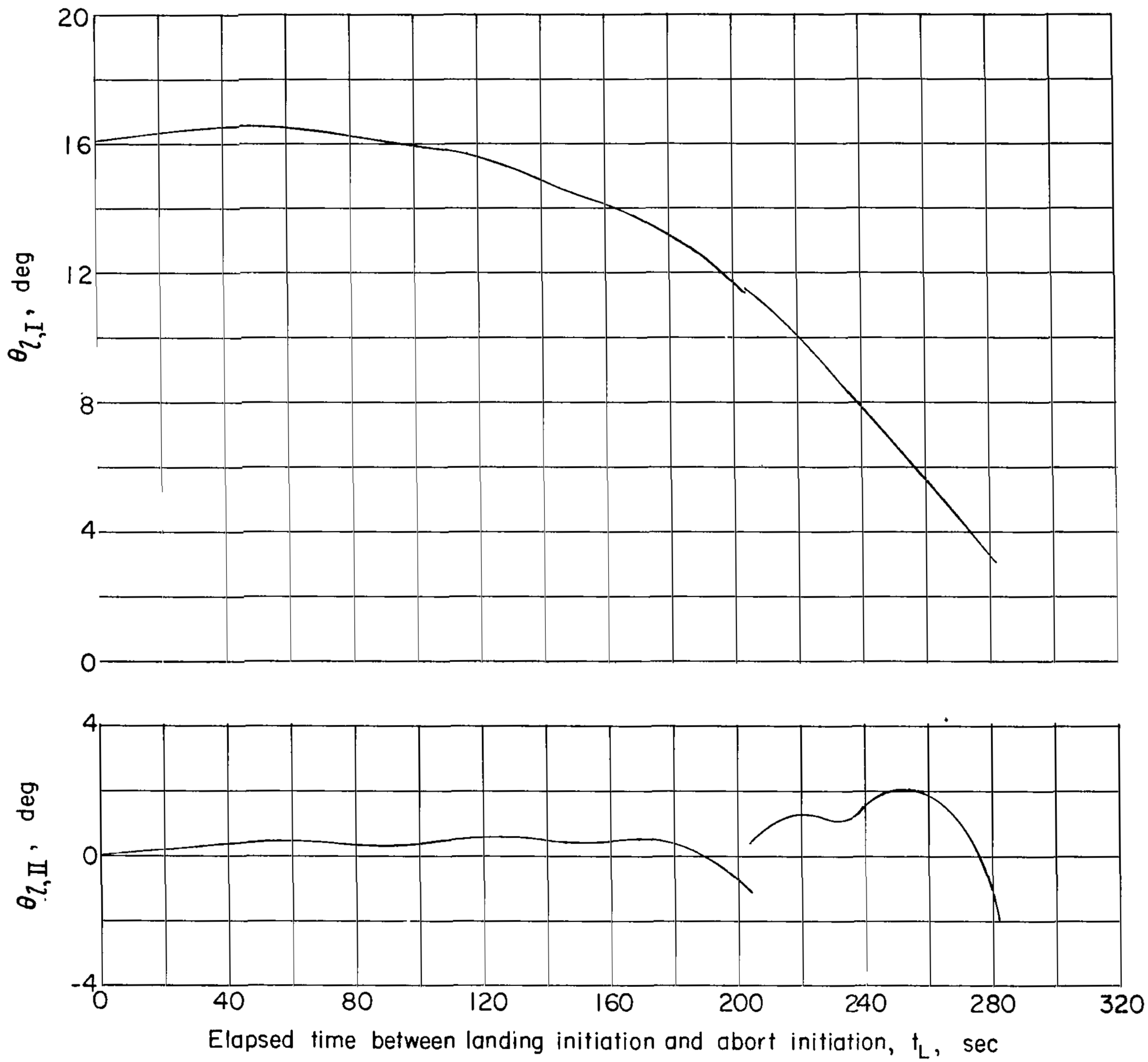


Figure 8.- Angle by which the ferry vehicle leads the command module at the two intersections of the orbit established by the abort maneuver with the orbit of the command module.

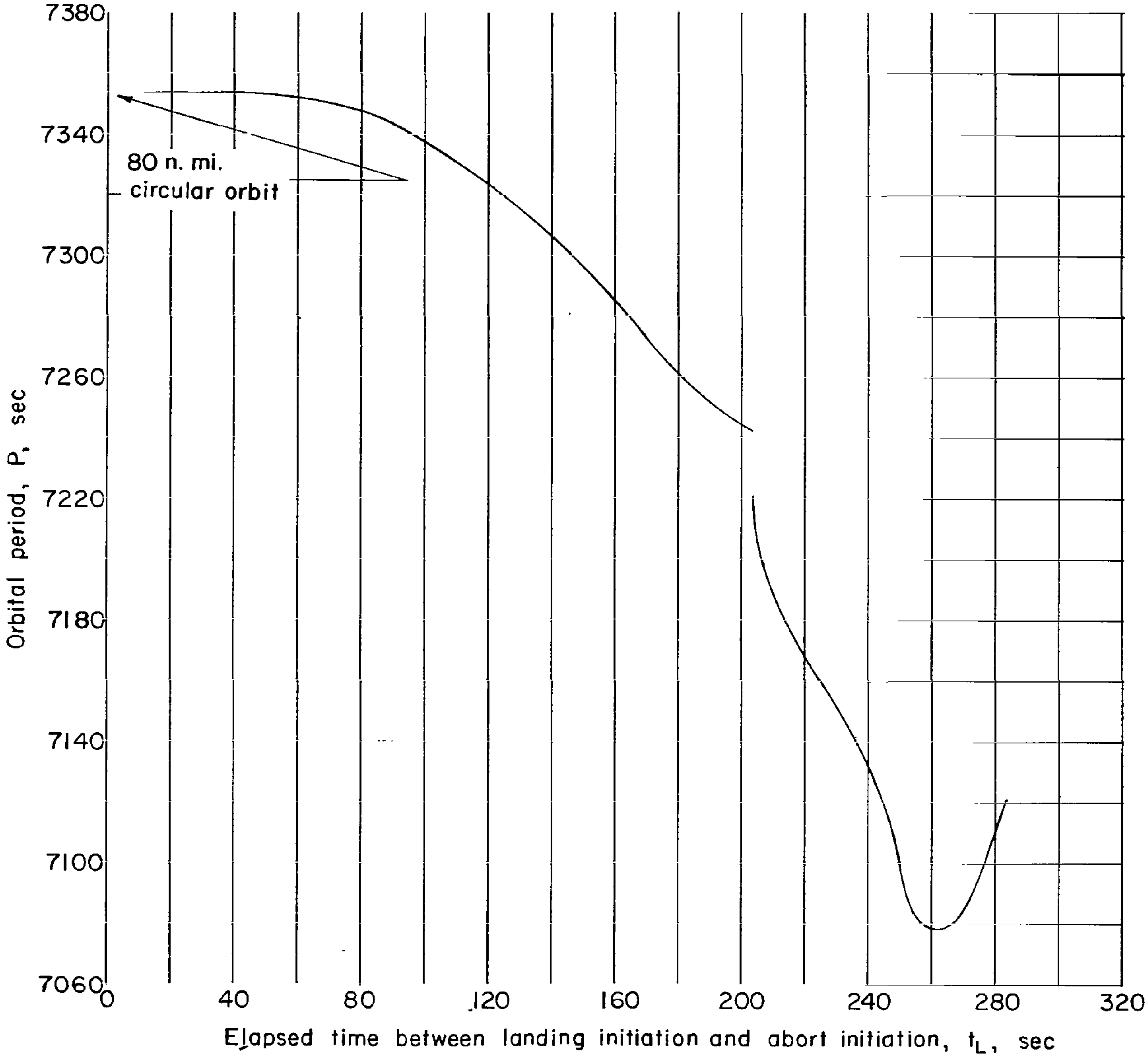


Figure 9.- Period of orbits established by abort maneuver.

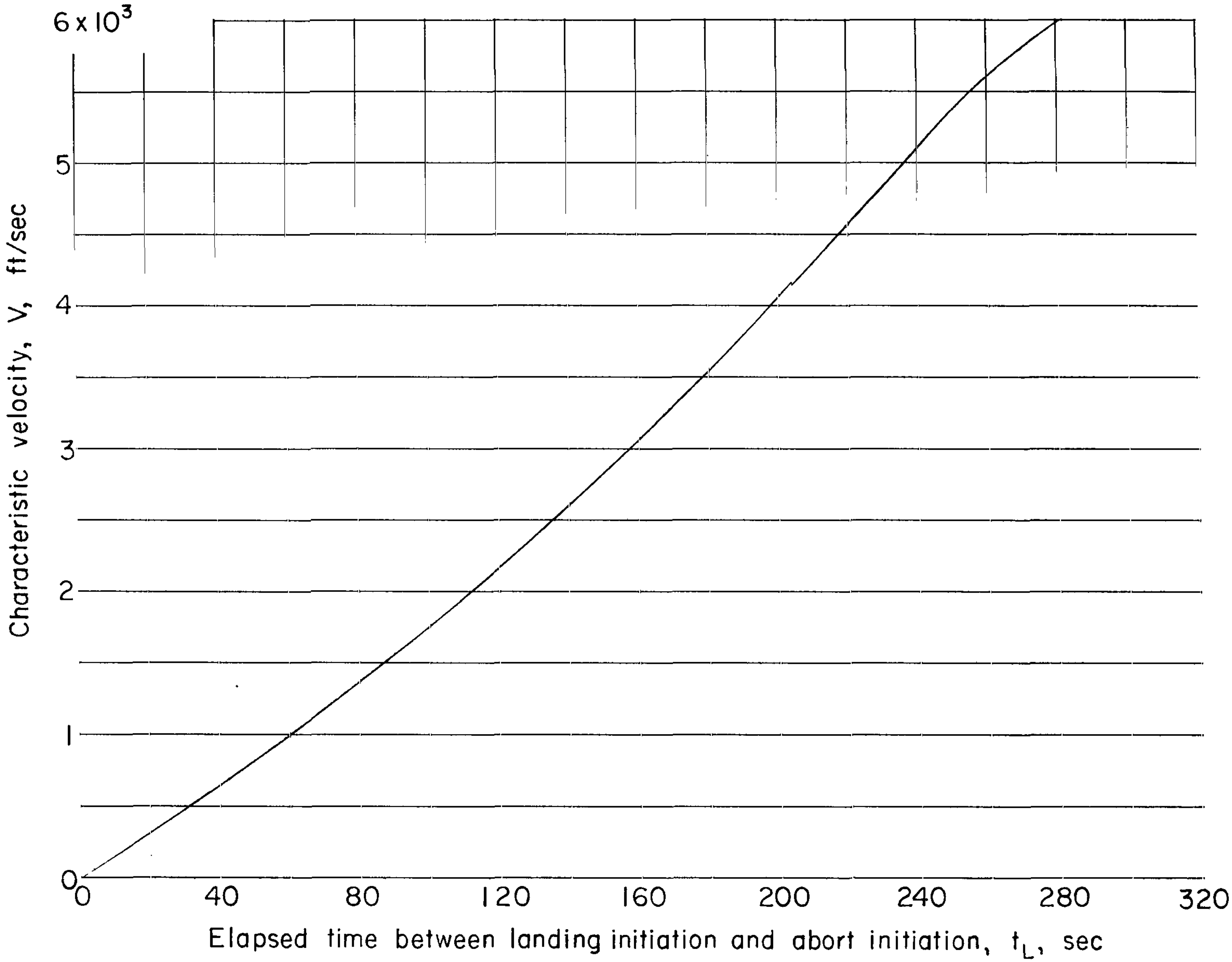
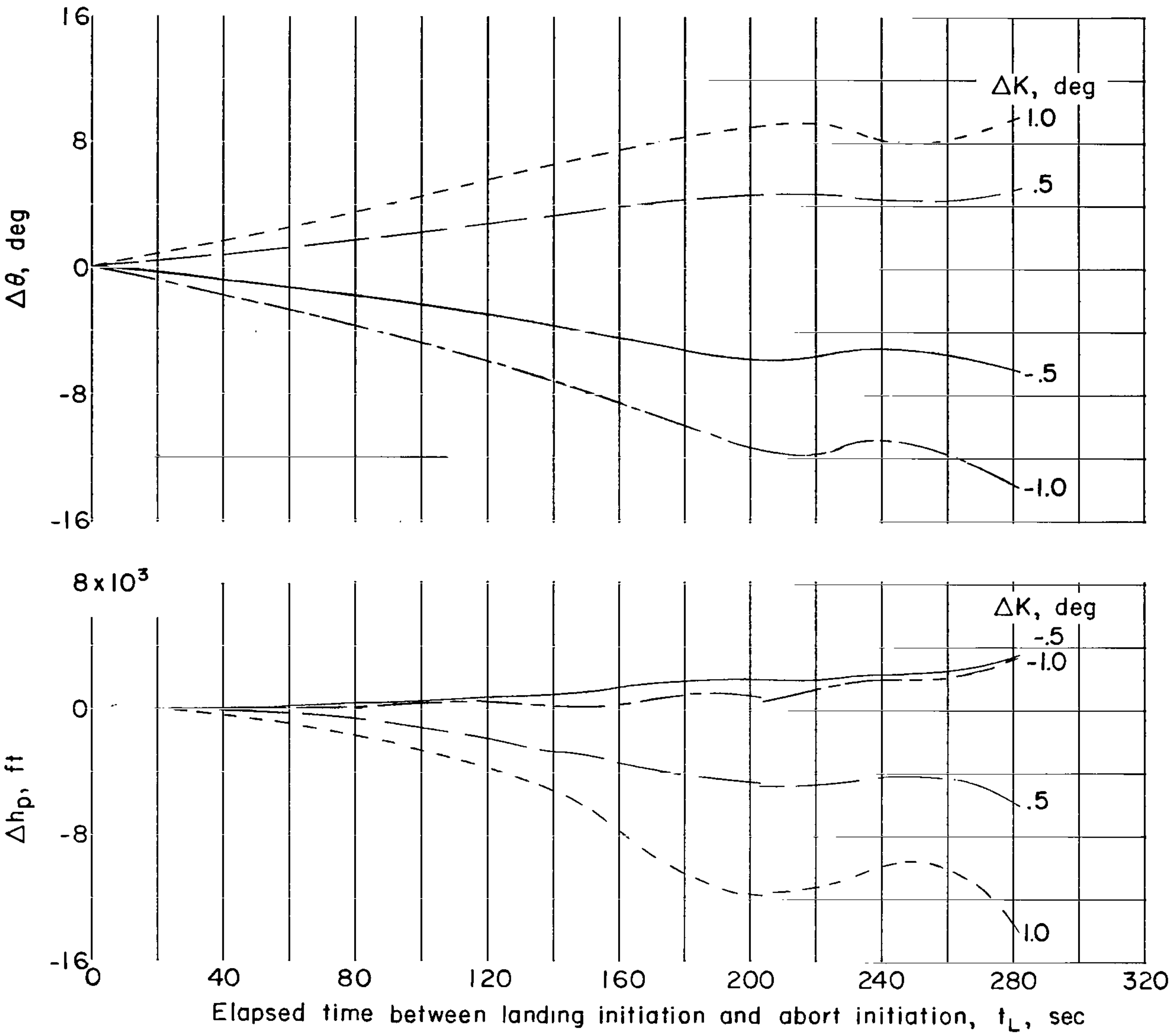
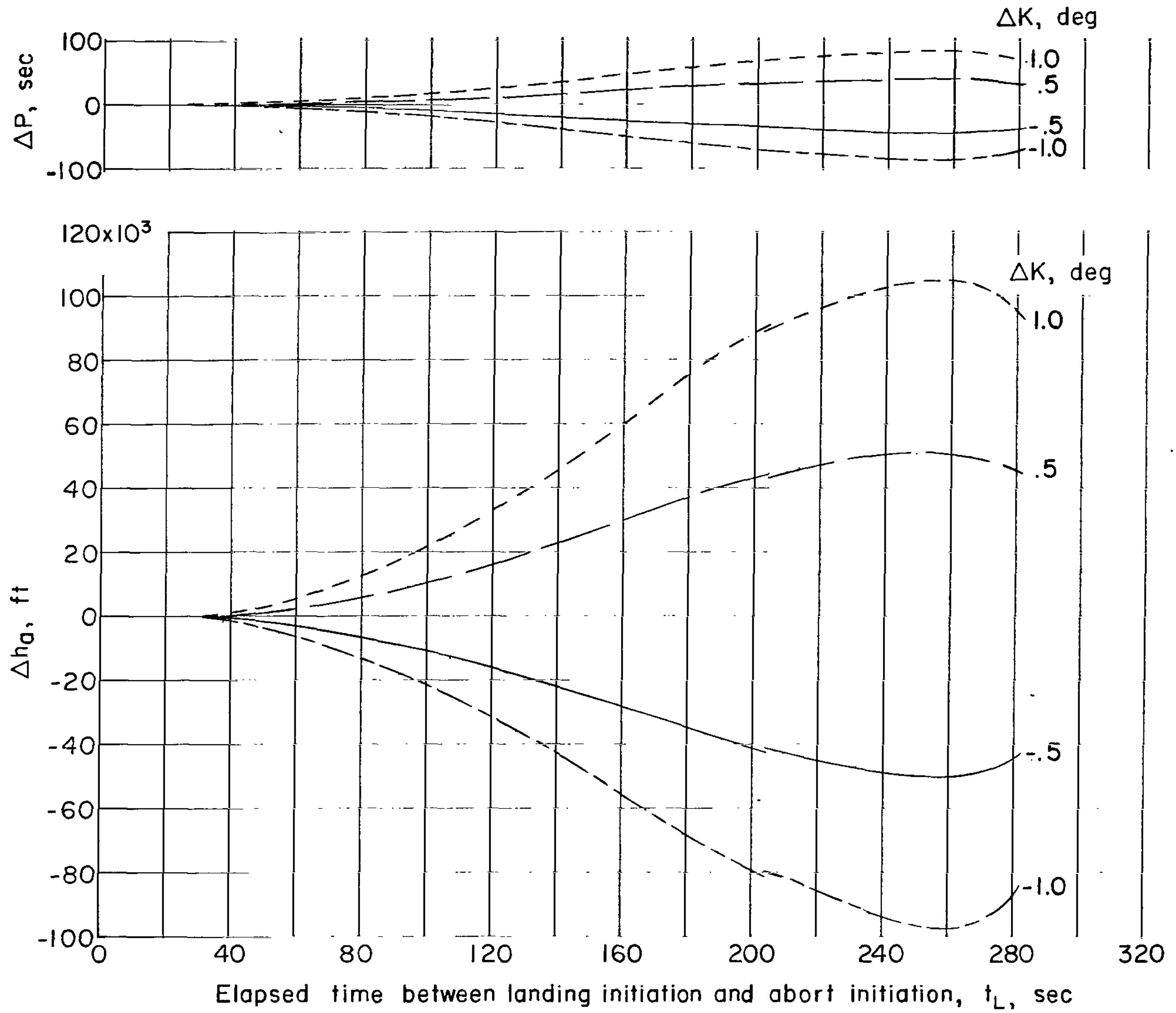


Figure 10.- Characteristic velocity required by abort maneuver.



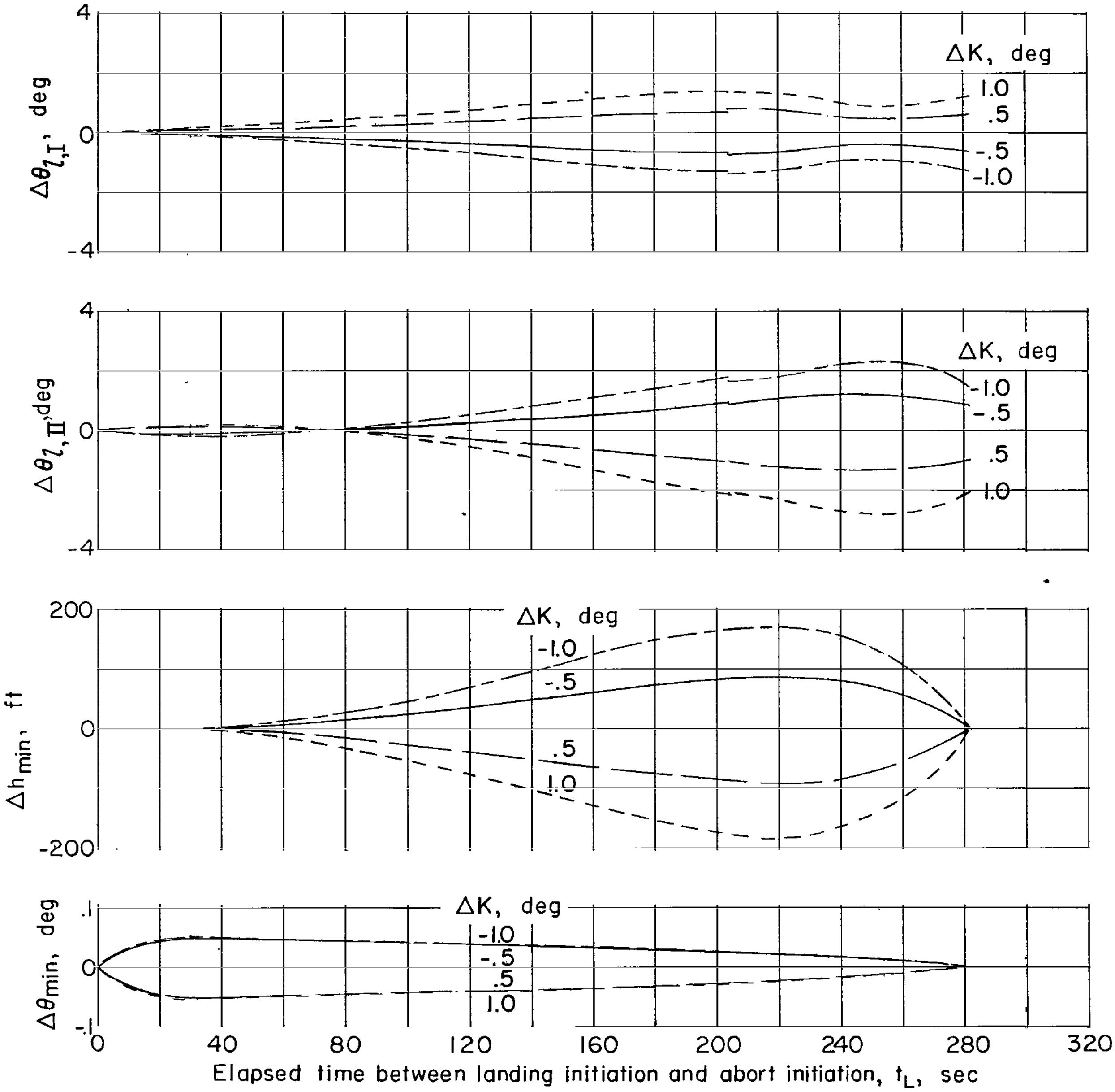
(a) Effect on pericynthion altitude and location.

Figure 11.- Effect of errors in thrust angle on orbits established by abort maneuver.



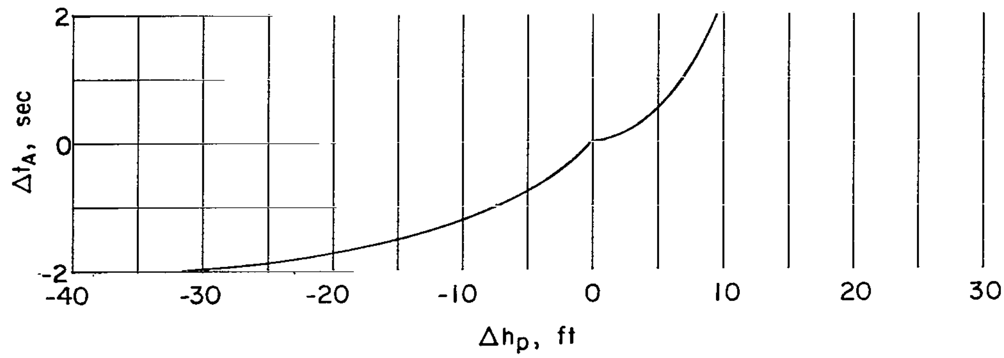
(b) Effect on apocynthion altitude and orbital period.

Figure 11.- Continued.

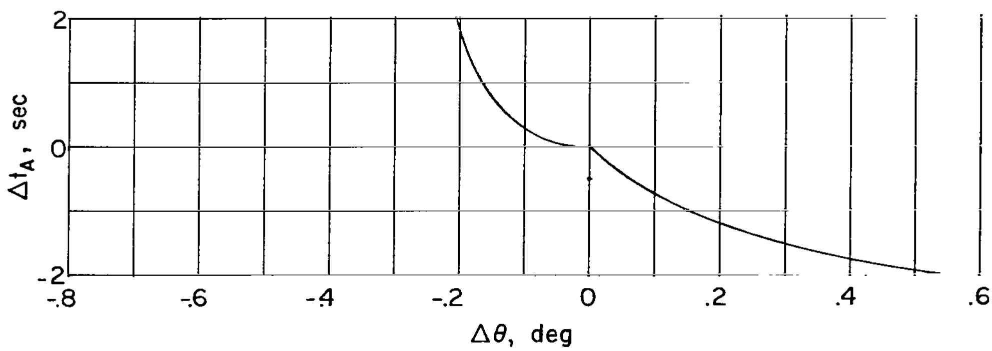


(c) Effect on minimum altitude reached during thrusting and its location, and on the ferry vehicle lead angle at the two orbital intersections.

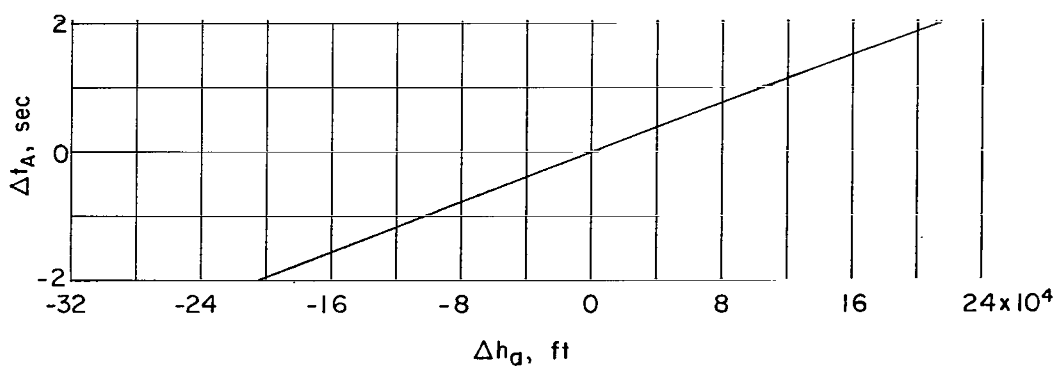
Figure 11.- Concluded.



(a) Effect on pericynthion altitude.

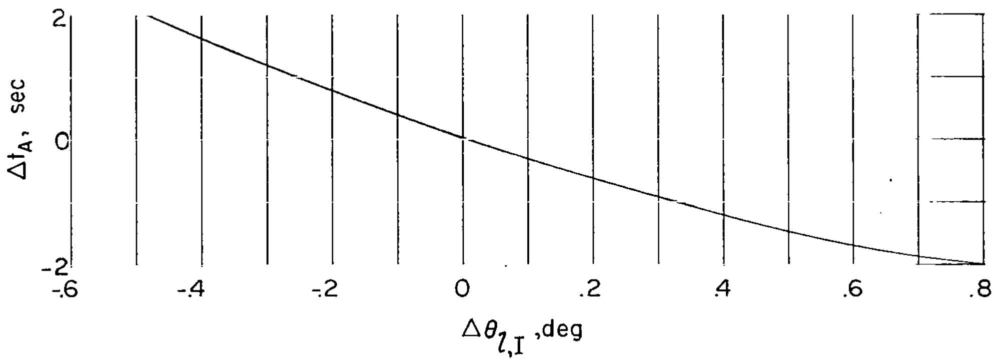


(b) Effect on pericynthion location.

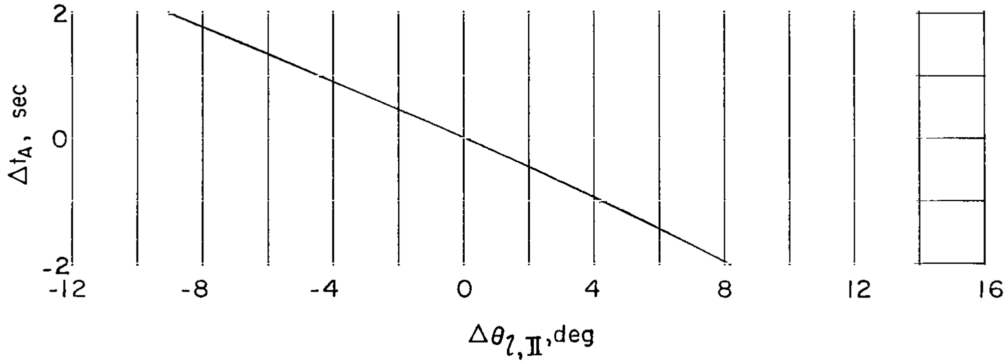


(c) Effect on apocynthion altitude.

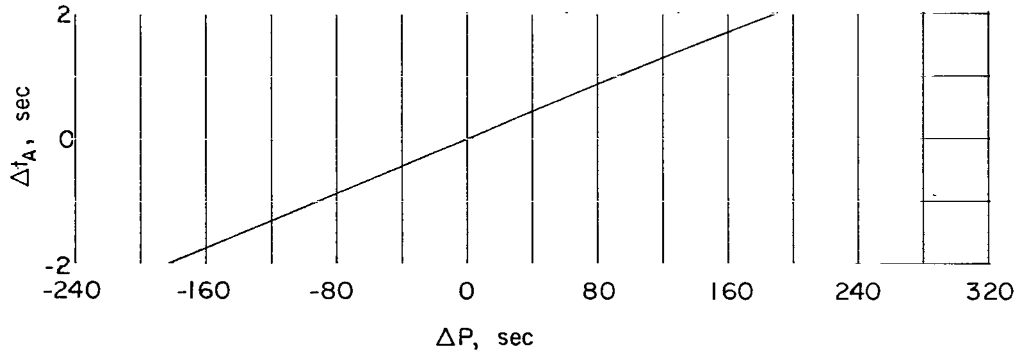
Figure 12.- Effect of errors in abort thrusting time on orbits established by abort maneuver.



(d) Effect on ferry vehicle lead angle at first orbital intersection.

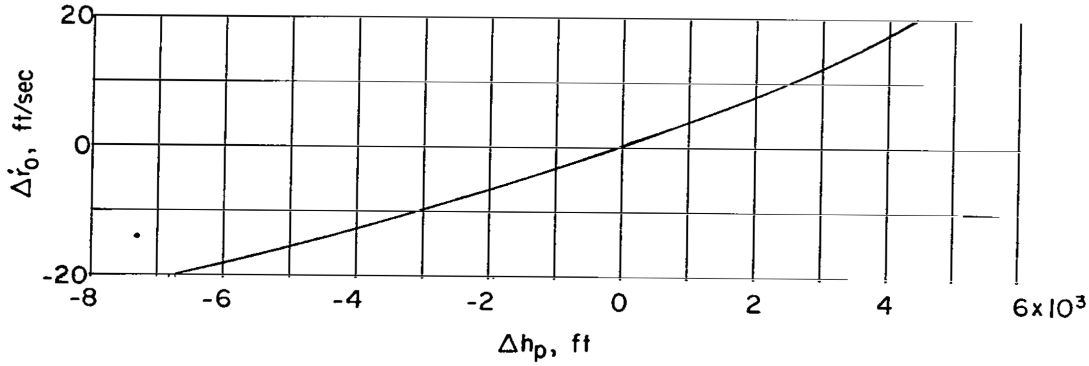


(e) Effect on ferry vehicle lead angle at second orbital intersection.

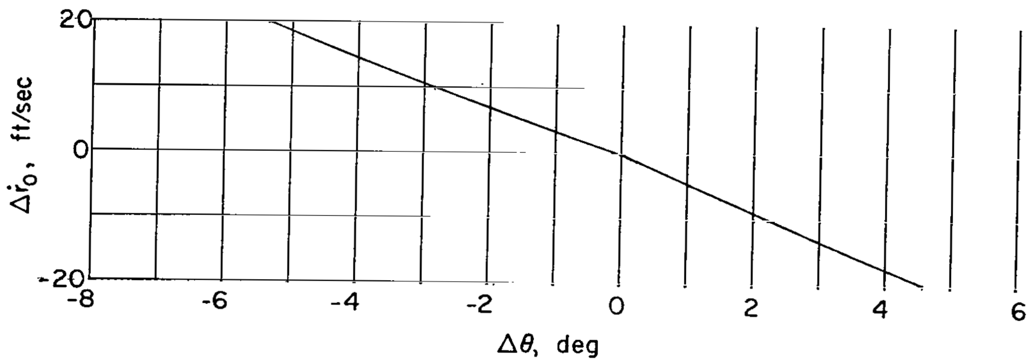


(f) Effect on orbital period.

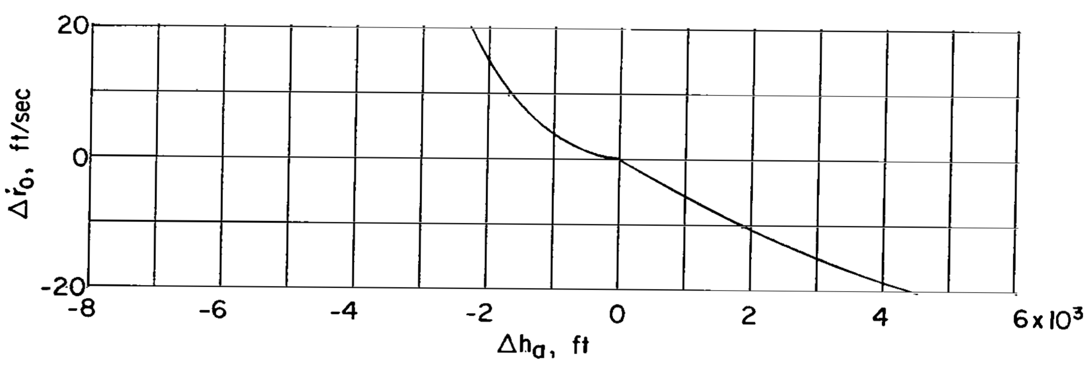
Figure 12.- Concluded.



(a) Effect on pericynthion altitude.

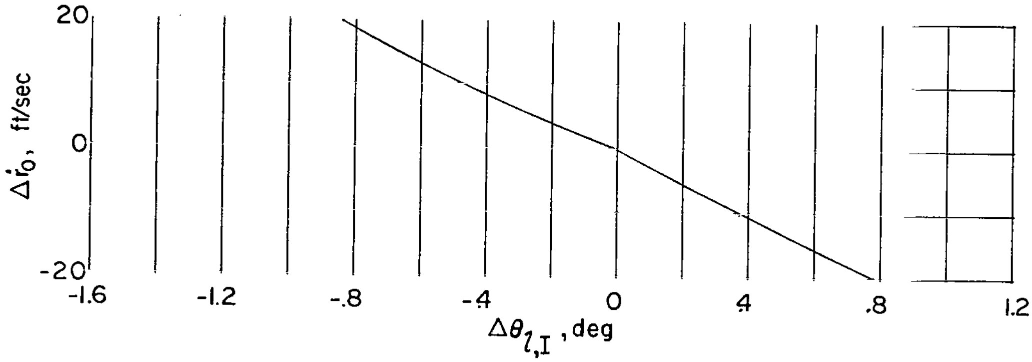


(b) Effect on pericynthion location.

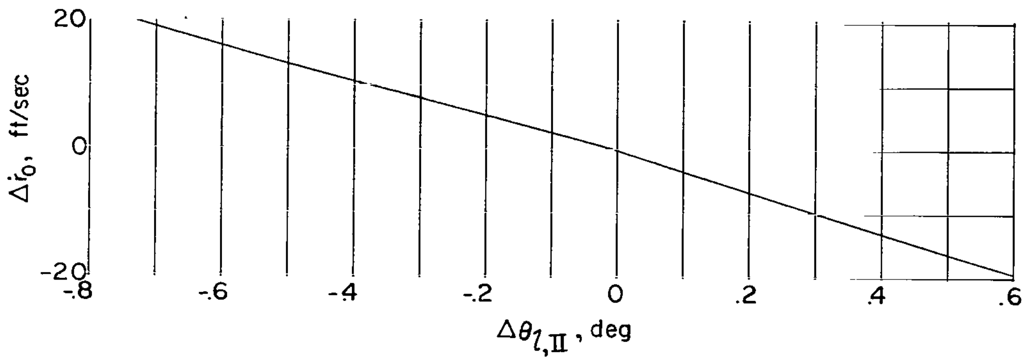


(c) Effect on apocynthion location.

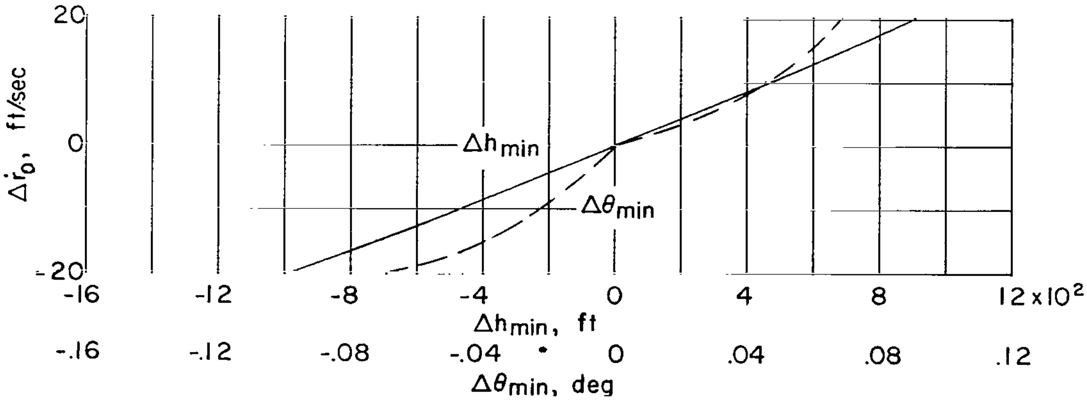
Figure 13.- Effect of errors in radial velocity at abort initiation on orbits established by abort maneuver.



(d) Effect on ferry vehicle lead angle at first orbital intersection.

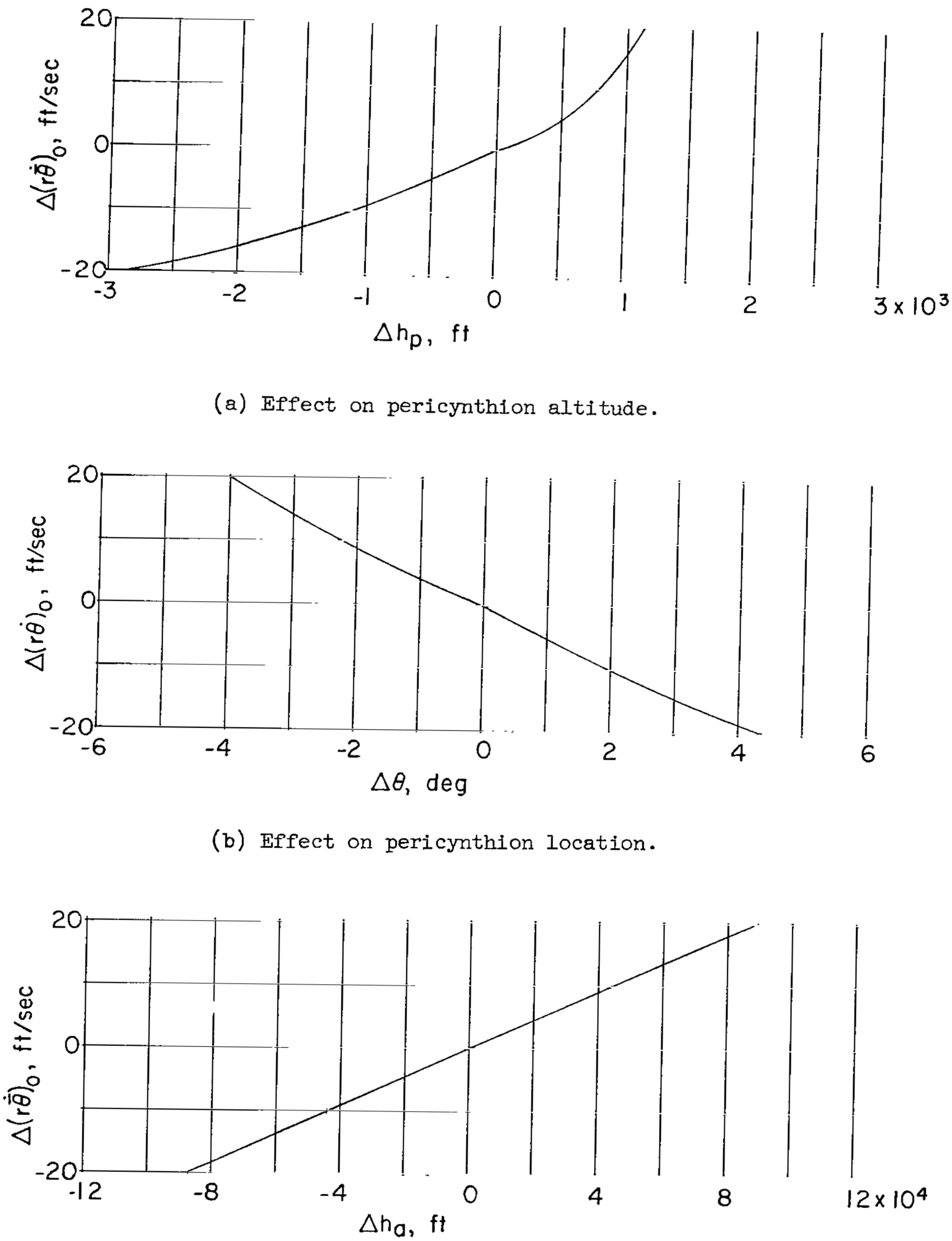


(e) Effect on ferry vehicle lead angle at second orbital intersection.



(f) Effect on minimum altitude reached during thrusting and on its location.

Figure 13.- Concluded.

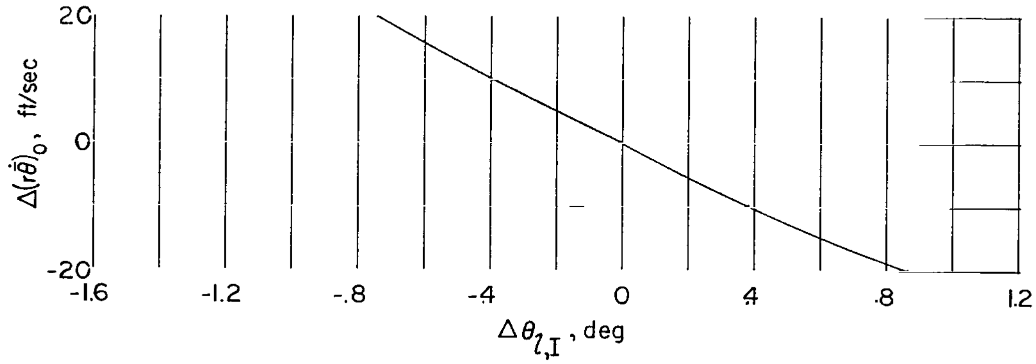


(a) Effect on pericynthion altitude.

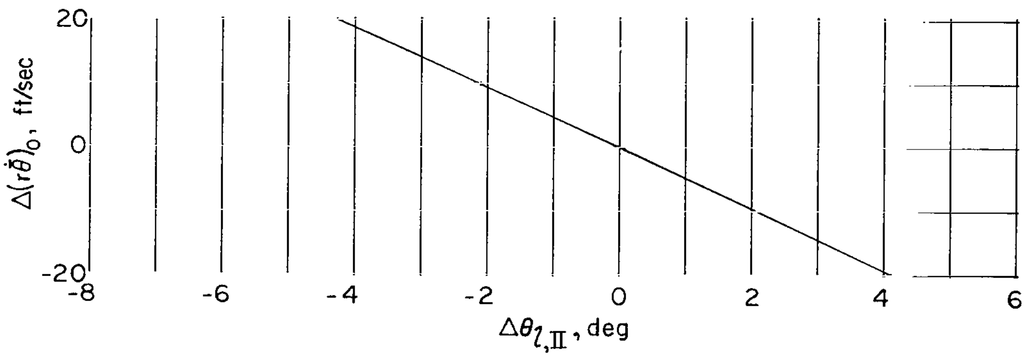
(b) Effect on pericynthion location.

(c) Effect on apocynthion altitude.

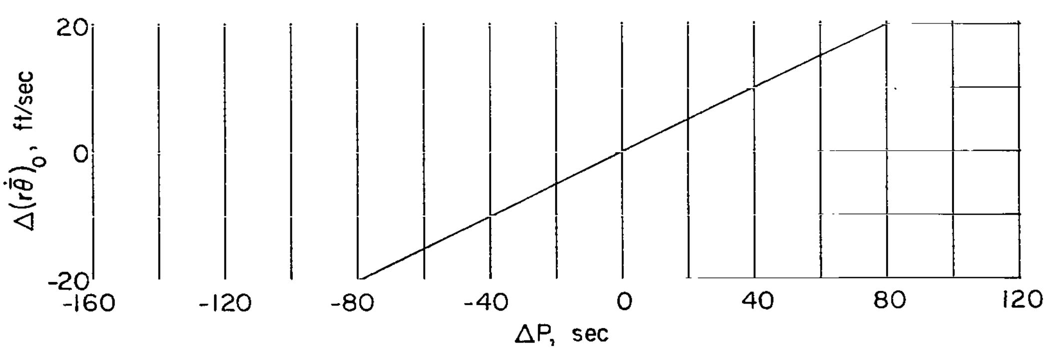
Figure 14.- Effect of errors in velocity at abort initiation on orbits established by abort maneuver.



(d) Effect on ferry vehicle lead angle at first orbital intersection.

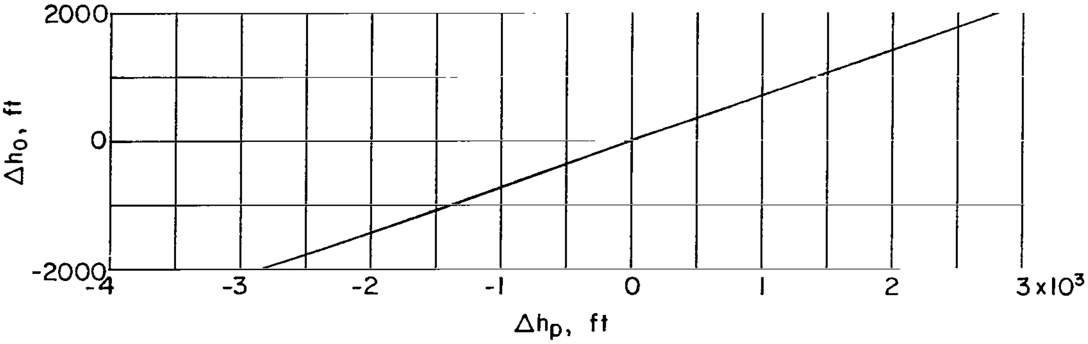


(e) Effect on ferry vehicle lead angle at second orbital intersection.

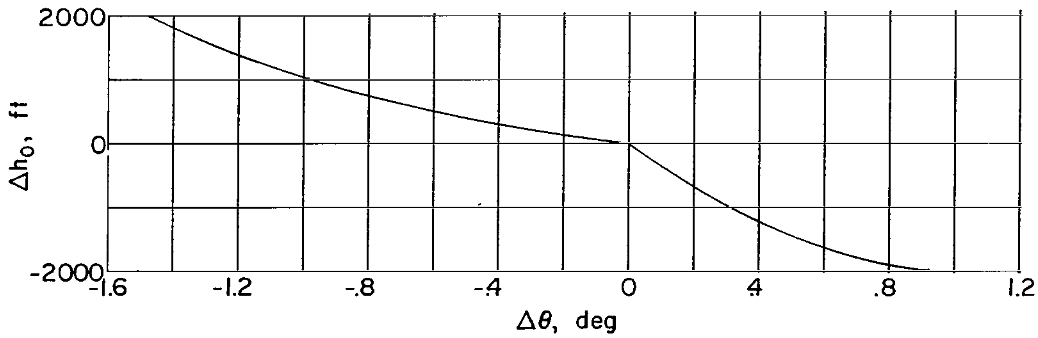


(f) Effect on orbital period.

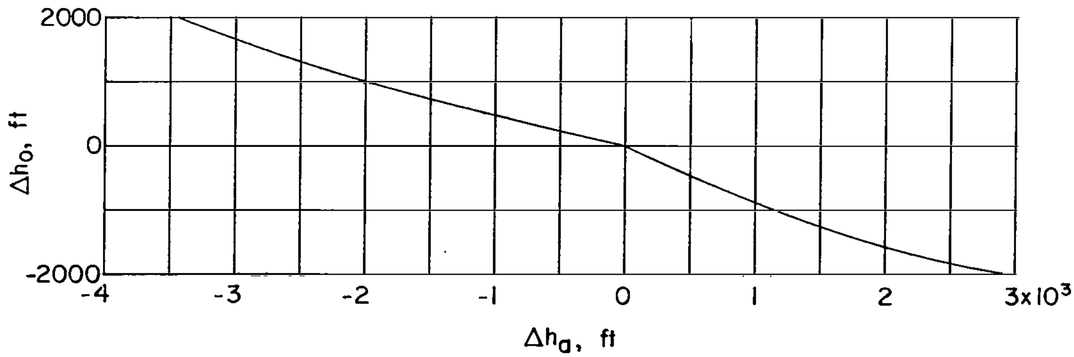
Figure 14.- Concluded.



(a) Effect on pericynthion altitude.

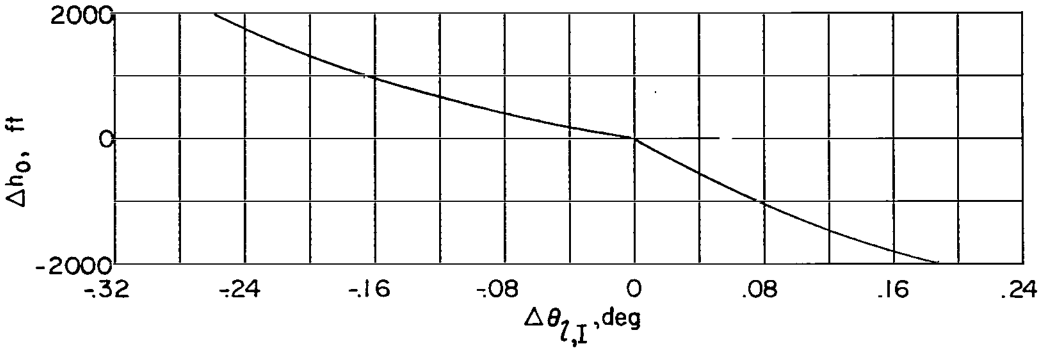


(b) Effect on pericynthion location.

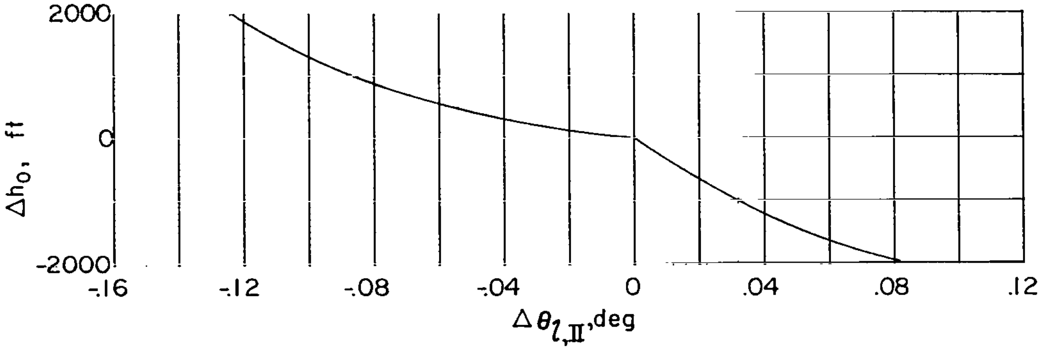


(c) Effect on apocynthion altitude.

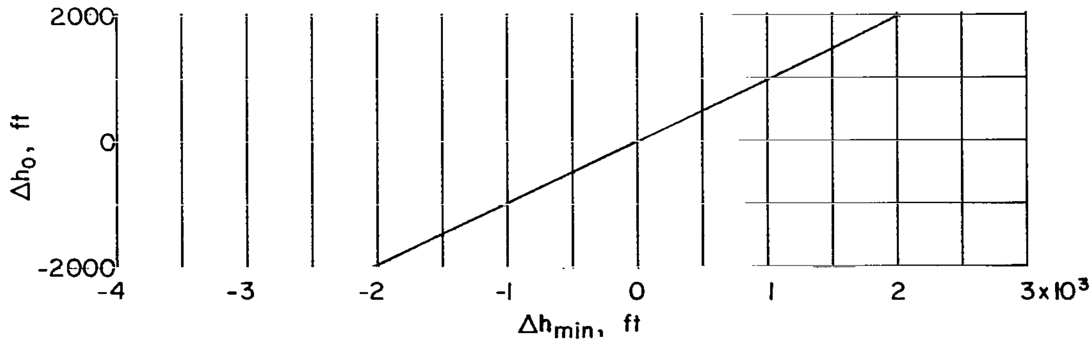
Figure 15.- Effect of errors in altitude at abort initiation on orbits established by abort maneuver.



(d) Effect on ferry vehicle lead angle at first orbital intersection.



(e) Effect on ferry vehicle lead angle at second orbital intersection.



(f) Effect on minimum altitude reached during thrusting.

Figure 15.- Concluded.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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