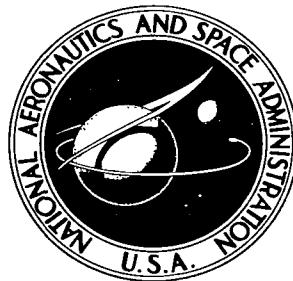


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A MANUAL ABORT GUIDANCE TECHNIQUE WITH CONCENTRIC-FLIGHT-PLAN RENDEZVOUS

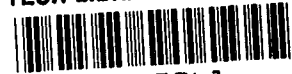
by G. Kimball Miller, Jr., and L. Keith Barker

Langley Research Center

Langley Station, Hampton, Va.

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SUMMARY

An analytical investigation has been made of a manual technique based on two periods of constant thrust-angle thrusting to abort the landing phase of the manned lunar mission. The abort initiation technique requires only an optical device for measuring the angle between the landing module thrust axis and the line of sight to the orbiting command module and a stopwatch. The results of the investigation indicated that standard abort orbits with pericynthion altitudes of approximately 50 000 feet (15 240 meters) and apocynthion altitudes of about 770 000 feet (234 696 meters) could be established for aborts from any point along the landing trajectory when the field of view in the pitch plane was unobstructed. To comply with window constraints typical of the Apollo landing module, it was necessary to accept nonstandard orbits for a range of abort initiation points. Although a fuel penalty is involved, the characteristic velocity capability remaining after abort-orbit insertion in all cases exceeded 2000 ft/sec (609.6 m/sec). Thrust-angle errors of $\pm 1.0^\circ$ do not compromise the safety of the maneuver, the resulting orbits having pericynthion altitudes that exceed 30 000 feet (9144 meters). The established orbits are compatible with concentric-flight-plan rendezvous. Inherent in the technique, however, is the capability of performing a direct rendezvous from the first 383 seconds of the landing trajectory in the event that the time of abort initiation is not critical.

INTRODUCTION

The capability of aborting the powered descent phase of the manned lunar landing mission is a necessary requirement for insuring the astronauts' safety. Automatic onboard equipment will normally be used to control the landing module during an abort maneuver. Alternately, simplified guidance techniques can be used to develop manual abort procedures that are independent of automatic onboard systems. Such techniques should be simple and require a minimum of equipment. Moreover, these techniques should be compatible with the automatic abort trajectories. The procedure investigated in the present paper uses the orbiting command module as a reference for thrust-vector orientation and involves rendezvous on the front side of the moon. The abort technique

which is compatible with the concentric-flight-plan approach to rendezvous requires the landing-module pilots' use of line-of-sight angle measurements, a timing device, and two guidance charts.

SYMBOLS

Measurements for this investigation were made in U.S. Customary Units, but are also given parenthetically in the International System of Units (SI). (See ref. 1.)

C	angle between thrust vector and line of sight to orbiting command module, deg
F	rocket thrust, lbf (newtons)
g_e	acceleration at surface of earth due to gravitational attraction, 32.2 ft/sec ² (9.814 m/sec ²)
g_m	acceleration at lunar surface due to gravitational attraction, 5.32 ft/sec ² (1.621 m/sec ²)
h	altitude above lunar surface, ft (m) or nautical miles (km)
h_{min}	minimum altitude reached during thrusting phase of abort maneuver, ft (m)
I_{sp}	specific impulse, sec
m	mass of landing module, slugs (kg)
r	radial distance from center of moon, ft (m)
r_m	radius of moon, 5 702 000 ft (1 737 969.6 m)
t	time, sec
t_A	elapsed time during abort thrusting, sec
t_L	elapsed time between landing initiation and abort initiation, sec
V_c	characteristic velocity, $g_e I_{sp} \log_e m_0/m$, ft/sec (m/sec)

α	angle between thrust vector and local horizontal, radians or deg
β	angle between command module local vertical and the line of sight to the landing module, radians or deg
ω	angular velocity of command module about moon 0.048947, deg/sec
λ	longitudinal location of rendezvous initiation (fig. 2), deg
θ	angular travel of landing module over lunar surface, radians
θ_l	range angle by which landing module leads command module, radians or deg
$\theta_{\min}$	range angle between minimum altitude reached during abort thrusting and nominal landing site (positive values correspond to a minimum altitude located down range from the point of landing initiation, but up range from the nominal landing site), radians or deg
$\bar{\theta}$	range angle between pericynthion of trajectory established by abort maneuver and nominal landing site (positive values indicate a pericynthion located down range from the nominal landing site), radians or deg

Subscripts:

a	apocynthion conditions
n	nominal conditions
o	initial conditions
p	pericynthion conditions
1	conditions during initial phase of abort maneuver
2	conditions during second phase of abort maneuver

Dots over symbols denote differentiation with respect to time. A delta (Δ) preceding a parameter indicates a change in that parameter from the nominal; for example, $\Delta h = h - h_n$.

PRELIMINARY CONSIDERATIONS

Descent Trajectory

In the present investigation, the landing-module and command-module combination is assumed to have been injected into a circular orbit about the moon at an altitude of 80 nautical miles (148.16 km). The landing module is subsequently detached from the command module and placed in an elliptic descent orbit with a pericyynthion of 50 000 feet (15 240.0 meters), located approximately 180° down range from injection (at about 0° longitude). The nominal landing trajectory used in this study results from applying thrust at the pericynthion of the descent orbit and flying a near fuel-optimum descent to an altitude of approximately 10 000 feet (3 048.0 meters). The landing approach is made with the landing module maintained at a nearly constant attitude to facilitate landing-site evaluation. The landing approach ends at an altitude of approximately 200 feet (60.96 meters) with nearly zero velocity. The characteristics of the nominal landing trajectory are presented in figure 1. The present study is concerned with abort from the powered phase of the landing in the altitude range from 50 000 feet (15 240.0 meters) to 200 feet (60.96 meters). The aborts are to be compatible with the concentric flight plan, which is being considered for normal automatic lunar ascent and for aborts using automatic systems.

Concentric Flight Plan

The abort procedure is depicted in figure 2 and follows a course that is generally referred to as the concentric flight plan. The abort is initiated during the braking phase of the landing maneuver. At abort initiation, the landing module is rotated to the abort attitude and thrust is applied so that the landing module follows a fuel-optimum path to an altitude of 50 000 feet (15 240 meters) and attains a tangential velocity at insertion of approximately 5640 ft/sec (1719 m/sec). The landing module then coasts for 30 minutes after orbit insertion, at which time thrust is again applied to adjust apocynthion altitude to a desired value associated with the particular point of abort initiation. The orbit is made circular by thrusting at apocynthion and the landing module coasts in its circular orbit until the phase angle with respect to the command module reaches a prescribed value, at which time thrust is again applied to initiate the rendezvous maneuver.

The primary constraint imposed on the abort-rendezvous procedure is that the landing module be visible to the earth-based tracking system for a sufficient time prior to each thrusting maneuver so that the earth-based system can relay to the pilot the updated information necessary for proper thrust application. Data obtained at NASA Manned Spacecraft Center (not generally available) indicate that 15 minutes tracking time is adequate. In addition, it was required that the terminal rendezvous braking maneuver be

performed no more than 90° west of the earth-moon line. The earth-based system can acquire the landing module as it emerges from behind the moon at approximately 100° east longitude. Consequently, because the landing module is moving around the moon at about 3° per minute and 15 minutes of tracking time are required prior to thrusting, the location of rendezvous initiation is fixed at approximately 55° east longitude ($\lambda = 55^\circ$). Thus, 145° are available between 55° east and 90° west longitude for performing the rendezvous. The nominal concentric flight plan specifies a standard transfer angle of 140° be used for all orbits and, in addition, requires that the angle between the landing-module local horizontal and the line of sight to the command module be 28° at rendezvous initiation, irrespective of landing-module altitude.

An insight into why the angle between the landing-module local horizontal and the line of sight to the command module can be considered constant for a range of landing-module altitudes at transfer initiation may be obtained by considering 180° Hohmann transfer orbits. In this simplified case, the angle can be shown to remain very nearly constant at approximately 23° for a wide range of landing-module altitudes, the angle changing by about 0.1° per 10 000-foot (3048-meter) change in landing-module altitude.

ANALYSIS

The purpose of this investigation is to examine simplified techniques for possible manual control in abort situations during the braking phase of the landing maneuver. The problem was studied in various steps to answer the following questions. Can a reasonably efficient procedure be developed to inject into an orbit with a 50 000-foot (15 240-meter) pericynthion and 770 000-foot (234 696-meter) apocynthion with the use of only visual cues for thrust-vector orientation? (In subsequent sections this orbit will be referred to as the standard orbit.) Is the manual procedure compatible with existing window constraints of the landing module? With the existing constraints is it possible to inject directly into an orbit which, when circularized, will be properly phased to meet the rendezvous initiation constraints of the concentric flight plan? A basic assumption of this study was that staging and rotation from one abort attitude to another were instantaneous.

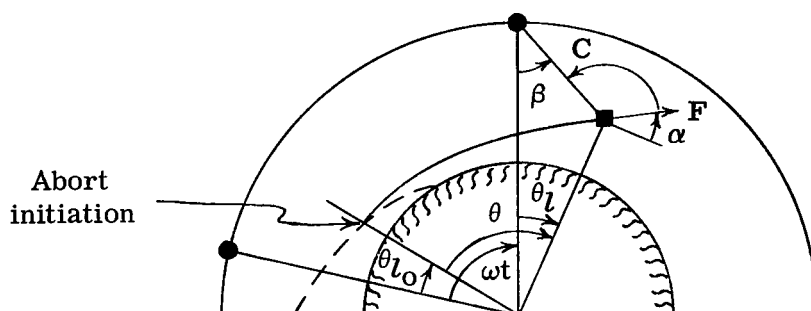
Optimum Abort Trajectories to Standard Orbit

Fuel-optimum abort trajectories were computed from various points along the landing trajectory to thrust termination at an altitude of 50 000 feet (15 240 meters) with a tangential velocity of approximately 5640 ft/sec (1719 m/sec) and a radial velocity of approximately zero. The orientation of the thrust vector with respect to the lunar horizon and the orbiting command module was then examined for the various abort trajectories. It appeared that two periods of constant thrust angle, thrusting with respect to either the lunar horizon or the command module, could be used to approximate a given fuel-optimum

abort trajectory. The lunar horizon was discarded as a visual reference for thrust-vector orientation because of the possibility of large errors in thrust angle at low altitudes due to lunar surface irregularities. For example, a surface formation 5000 feet (1524 meters) in altitude located at the horizon would cause a thrust-angle error of 2.68° (ref. 2) when the landing module is at an altitude of 1000 feet (304.8 meters). The orbiting command module is not subject to such errors and was chosen as a visual reference for thrust-vector orientation during the abort initiation maneuver.

Two-Angle Approximation to Fuel-Optimum Aborts

The axis system and pertinent angles used in this part of the investigation are illustrated in the following sketch:



The computations were made for a point mass moving in a plane about a spherical moon. A derivation of the general equations of motion of a point mass in spherical coordinates is presented in reference 3. The equations of motion used in this study may be obtained by substituting the appropriate angles of this sketch into the general spherical equations of motion. The resulting equations are presented for reference:

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

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = \frac{F}{m} \cos \alpha \quad (2)$$

where

$$m = m_0 - \frac{F}{g_0 I_{sp}} \int dt \quad (3)$$

$$\theta_l = \theta_{l_0} + \theta - \omega t \quad (4)$$

$$\beta = \tan^{-1} \frac{\sin \theta_l}{\frac{6.188 \times 10^6}{r} - \cos \theta_l} \quad (5)$$

and

$$\alpha = 90^\circ + \theta_l + \beta - C \quad (6)$$

The aborts were initiated by using the descent stage of the landing module operating at maximum thrust. The maximum thrust level of the descent stage was capable of accelerating the fully loaded landing module at approximately $0.343g_e$. When the descent-stage fuel is exhausted, the vehicle is staged and the ascent stage thrusts until abort-orbit insertion. The thrust level of the ascent stage was capable of accelerating the fully loaded ascent stage of the landing module at approximately $0.333g_e$.

These equations of motion which were solved on an electronic digital computer were used to develop an abort procedure based on two periods of thrusting at constant angles with respect to the orbiting command module. The two constant thrust angles and the corresponding thrusting times were determined through an iteration process. The condition to be met was the attainment of zero radial velocity and a tangential velocity of approximately 5640 ft/sec (1719 m/sec) at an altitude of 50 000 feet (15 240 meters). These standard burnout conditions result in the establishment of an orbit with a pericynthion altitude of 50 000 feet (15 240 meters) and an apocynthion altitude of approximately 770 000 feet (234 696 meters). In general, the initial thrust angle C_1 and thrusting time $t_{A,1}$ were chosen to attain the 50 000-foot (15 240-meter) altitude. The second thrust angle C_2 was chosen so that the radial velocity component was zero at that altitude. The second thrusting time $t_{A,2}$ was chosen so that a burnout tangential velocity of about 5640 ft/sec (1719 m/sec) was attained. The two constant thrust angles and the two thrusting times are presented in figure 3 as functions of the elapsed time between landing initiation and abort initiation.

Piloting Procedure

The only equipment required by the pilot to perform the abort initiation maneuver is an optical device for measuring the angle between the landing-module thrust axis and the line of sight to the command module and a timing device. In addition, the pilot would be provided with charts corresponding to figure 3. The piloting procedure during the maneuver is described as follows.

The timing device is started at landing initiation and is subsequently halted when abort of the landing is necessary. The pilot enters a chart similar to figure 3 and obtains the values of C_1 and $t_{A,1}$ required for the particular time of abort initiation. Thrust is applied at the proper angle C_1 and is maintained for the proper time $t_{A,1}$. The pilot then reenters the charts and obtains the appropriate values of C_2 and $t_{A,2}$ for the abort initiation time. The landing module is then rotated to and maintained at C_2 until thrust termination at $t_{A,2}$. The earth-based system can be used to track the landing module immediately after orbit insertion and to relay to the pilot the information necessary for proper thrust application at the subsequent stages of the concentric flight plan. Because earth-based tracking can be used to track the landing module prior to rendezvous initiation, the proper information can be relayed to the pilot so that previous dispersion errors can be reduced during thrusting at rendezvous initiation.

DISCUSSION OF RESULTS

The results of this investigation are presented in three sections. The first section pertains to the constant-thrust-angle technique for insertion into the standard orbit. The second section considers the effect of various errors on the standard orbit established by this technique. The third section is concerned with the concentric circular orbit phasing maneuver. In the latter section the abort technique and the concentric flight plan are shown to be compatible.

Insertion Into Standard Orbit

By using the thrust angles and thrusting times presented in figure 3, the abort technique results in the establishment of trajectories with pericyynthion altitudes that generally lie within 1000 feet (304.8 meters) of the desired 50 000-foot (15 240.0-meter) altitude and apocynthion altitudes in the neighborhood of 770 000 feet (234 696.0 meters). (See fig. 4.) The pericynthion of the established orbits lies within about 12° of the nominal landing site (fig. 5).

The pilot's field of view through the landing-module windows has not been considered prior to this point. The field of view through the windows of the currently planned landing module is depicted in the sketch on page 9.

There is a blindspot for $40^\circ \leq C \leq 80^\circ$. Consequently, an optical device capable of eliminating the blindspot is required if the abort technique is to utilize the thrust angles presented in figure 3. To determine whether this complication could be avoided, computations were made by using thrust angles which avoid the blindspot in the field of view. Modified thrust angles and thrusting times which comply with the window constraints are presented in figure 6. In order to obtain this compliance, however, it was necessary to

location of the pericynthion of the resulting orbit is affected. (See fig. 11(c).) Thrust-angle errors of 0.5° can shift the pericynthion location by as much as 6° .

Several additional errors including errors in thrust magnitude and errors in velocity and altitude at abort initiation were considered. For the sake of brevity, only a single time of abort initiation was considered for this portion of the analysis. The time chosen, 305 seconds after landing initiation, very nearly corresponds to that point along the landing trajectory for which the rate of descent of the landing module is a maximum. (See fig. 1.)

The effect of errors in thrust magnitude is presented in figure 12. Thrust-magnitude errors have relatively little effect on pericynthion altitude but a considerable effect on apocynthion altitude. For example, a 0.5-percent error in thrust magnitude results in a 1100-foot (345.3-meter) change in pericynthion altitude and a 110 000-foot (34 528-meter) change in apocynthion altitude. The change in pericynthion location with respect to the nominal landing site is fairly small (fig. 12(b)), being approximately -1.6° for a 0.5-percent error in thrust magnitude. The errors in apocynthion altitude may, of course, be greatly reduced if the pilot has an integrating accelerometer which he can use to terminate thrust when the proper velocity change has been applied.

The abort initiation maneuver assumes that the landing module has a specific velocity-altitude combination at a given point along the landing trajectory. Consequently, errors in velocity or altitude at abort initiation result in the establishment of orbits that differ from those nominally expected. The effects of errors in velocity and altitude on several pertinent orbital parameters are presented in figures 13 to 15. Errors in radial velocity primarily affect pericynthion altitude (fig. 13(a)) and pericynthion location (fig. 13(b)) with little effect on apocynthion altitude (fig. 13(a)). However, a radial velocity error of -20 ft/sec (-6.1 m/sec) lowers the pericynthion altitude of the resulting abort orbit by less than 7000 feet (2133.6 meters) and thus should not compromise the safety of the maneuver. Errors in circumferential velocity have little effect on pericynthion altitude (fig. 14(a)) and location (fig. 14(b)) but primarily affect apocynthion altitude (fig. 14(a)). It is shown in figure 14(a) that a 20-ft/sec (6.1-m/sec) error in circumferential velocity results in an apocynthion altitude change of almost 100 000 feet (30 480 meters). Errors in altitude have very little effect on pericynthion altitude, apocynthion altitude, and pericynthion location. (See fig. 15.)

Circularization and Phasing

The results presented indicate that the abort initiation maneuver is capable of establishing safe orbits about the moon even with the landing-module window constraints. It is now necessary to demonstrate that resulting orbits can be made to meet the

requirements for circularization at apocynthion and subsequent phase-angle reduction prior to rendezvous initiation.

The apocynthion altitude of the standard orbits can be adjusted, to the proper altitudes for circularization and phasing for the particular abort initiation points, during the corrective thrusting period which occurs 30 minutes after orbit insertion. A similar, but somewhat more efficient, method is to adjust the orbit-insertion conditions so that the landing module is inserted directly into an orbit that has a specific apocynthion altitude for circularization for each point of abort initiation. The guidance parameters required for the specific apocynthion method differ from the values presented in figure 6 only in that the second thrusting time $t_{A,2}$ is varied about the values required for the establishment of the standard orbits. If no errors are made during abort-orbit insertion, the specific apocynthion method avoids the corrective thrusting period which occurs 30 minutes after insertion. Operationally, however, errors are present so that corrective thrusting is required in this method also. Thus, the two methods are simply variations of the same technique. The specific apocynthion method is used in this phase of the study because it is somewhat easier to handle analytically and because insertion into the standard orbits requires larger corrective thrusting to obtain the proper apocynthion altitudes for circularization.

For a given point of abort initiation the desired apocynthion altitude is a function of the location of rendezvous initiation which, in turn, is a function of the tracking time required by the earth-based system prior to rendezvous initiation. The location of rendezvous initiation, defined by the attainment of a 28° angle between the landing-module local horizontal and the line of sight to the command module, is presented in figure 16 as a function of elapsed time between landing initiation and abort initiation for 0, 5, 10, and 15 minutes of tracking after reacquisition at 100° east longitude. For a given tracking time, the angle between the landing-module local horizontal and the line of sight to the command module becomes 28° when the landing module reaches the indicated location for rendezvous initiation. The location of rendezvous varies with time of abort initiation by less than 3° for a given tracking time. The apocynthion altitudes required for circularization such that the desired 28° angle with respect to the command module will be attained at the proper rendezvous initiation location for a given tracking time are presented in figure 17. The required apocynthion altitudes range from approximately 460 000 feet (140 208 meters) to about 810 000 feet (246 888 meters) with a significant reduction in the region where it was necessary to modify the maneuver in order to comply with the window constraints. The second thrusting time $t_{A,2}$ required to inject directly into orbits which have these desired apocynthion altitudes is presented in figure 18 as a function of the elapsed time between landing initiation and abort initiation. The variation of the second thrusting time with tracking time is less than 1 second for all abort initiation points and is thus too small to be shown in figure 18. The small variation in $t_{A,2}$

emphasizes the necessity of a corrective velocity change to be applied 30 minutes after abort-orbit insertion on command from the earth-based system. The minimum available time for earth-based tracking of the landing module after insertion occurs for an abort from the hover point of the landing maneuver which is located 471 seconds after landing initiation. The available tracking time subsequent to insertion for this abort point is approximately 22 minutes which should be sufficient for obtaining the information necessary for applying the corrective velocity change.

The characteristic velocity required to circularize the abort trajectory at apocynthion is presented in figure 19. The required characteristic velocity V_c never exceeds 170 ft/sec (52 m/sec) which is a small part of the capability remaining at abort-orbit insertion. (See fig. 8.) The altitude and location of pericynthion of the abort orbits with proper apocynthion altitudes for circularization are presented in figure 20. (The variation with tracking time is too small to be shown.) Both altitude and location of pericynthion differ somewhat from those obtained when the landing module was inserted into the standard orbit. However, the pericynthion altitudes always exceed 30 000 feet (9144 meters) and are acceptable.

The results of this section indicate that the proposed manual technique for abort initiation is compatible with the requirements for circularization and phasing such that the rendezvous maneuver may be accomplished on the front side of the moon. The earth-based tracking information which is relayed to the landing module in order to permit accurate velocity changes to be made will contain small errors. However, the errors involved in applying the velocity change 30 minutes after abort-orbit insertion and the velocity change at apocynthion will be detected by the earth-based system during the period of tracking prior to rendezvous initiation and subsequently removed during thrust application at rendezvous initiation. The remaining errors can be further reduced after additional tracking through the application of a midcourse correction prior to interception.

Special Considerations

The current investigation is primarily concerned with manual abort trajectories from various points along the landing trajectory that are compatible with concentric flight-plan rendezvous. Inherent in the abort technique, however, is the capability of performing a direct rendezvous with the command module when the abort is initiated at a point approximately 383 seconds after landing initiation. It may be seen from figure 17 that when an abort is initiated 383 seconds after landing initiation, the resulting apocynthion altitude is 486 000 feet (148 132.8 meters) which is the altitude of the circular orbit of the command module. Because the two altitudes are the same and the separation angle at apocynthion is zero (fig. 21), terminal rendezvous may be accomplished on the back side of the moon in the event that rendezvous time is critical. Thus, if an abort is

required at any point along the landing trajectory prior to the 383-second point and it is not necessary to abort immediately, the pilot can delay abort initiation until 383 seconds and perform a direct rendezvous. The apocynthion altitude of the abort orbit is fairly sensitive to thrust-angle errors (fig. 11(b)) for an abort initiated 383 seconds after landing initiation. Consequently, the corrective thrusting maneuver 30 minutes after orbit insertion will be required for direct rendezvous.

CONCLUDING REMARKS

An analytical investigation has been made of a simplified guidance technique for aborting the landing phase of the manned lunar landing mission. A typical lunar landing trajectory beginning at the 50 000-foot (15 240-meter) pericynthion of a Hohmann transfer orbit from the command module was employed. Abort initiation from any point along the landing trajectory requires only an optical device to measure the angle between the landing-module thrust axis and the line of sight to the orbiting command module and a timing device. The abort-orbit insertion technique is initiated by applying thrust at a given angle with respect to the line of sight to the command module for a given time. The landing module is subsequently rotated to a second thrust angle with respect to the command module which is maintained until thrust is terminated at a given time. The two thrust angles and times of thrusting at those angles are all functions of the elapsed time between landing initiation and abort initiation.

It was found that standard abort orbits with pericynthion altitudes of approximately 50 000 feet (15 240 meters) and apocynthion altitudes of about 770 000 feet (234 696 meters) could be established for aborts from any point along the landing trajectory when the pilot was provided with a large field of view in the pitch plane. To avoid thrust angles which violate window constraints typical of the Apollo landing module, it was necessary to accept nonstandard orbits for aborting a part of the landing trajectory. The primary penalty is fuel consumption. In all cases, however, the characteristic velocity capability remaining after abort-orbit insertion exceeds 2000 ft/sec (609.6 m/sec). Thrust-angle errors of $\pm 1.0^\circ$ do not compromise the safety of the abort-orbit insertion maneuver, the resulting orbits having altitudes at pericynthion that exceed 30 000 feet (9144 meters).

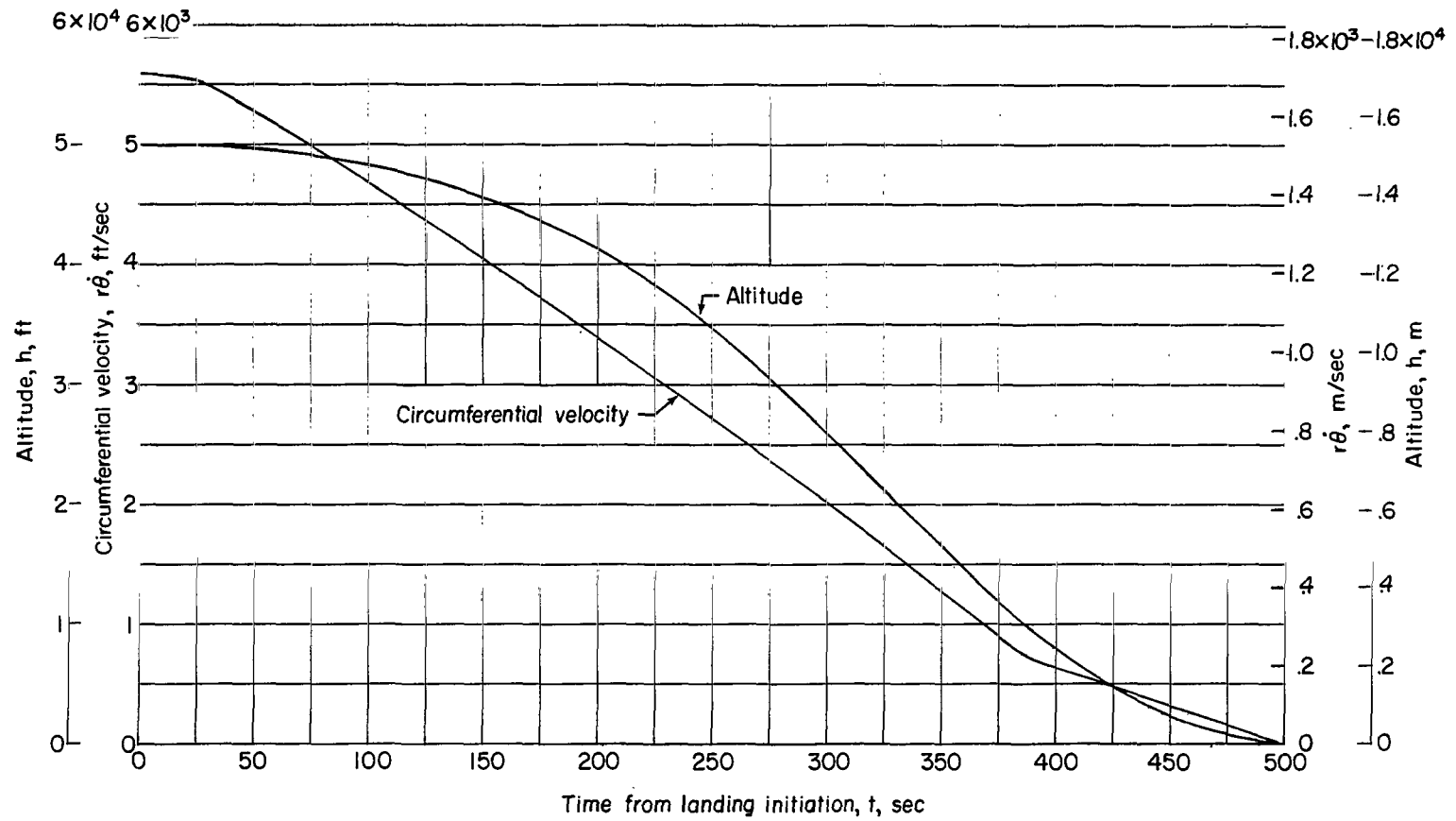
The orbits established by the abort-orbit insertion technique are compatible with concentric flight-plan rendezvous. To complete rendezvous, the technique relies upon an earth-based tracking system for the information required to perform those thrusting maneuvers of the concentric flight plan subsequent to abort-orbit insertion. Inherent in

the technique is the capability of performing a direct rendezvous from the first 383 seconds of the landing trajectory in the event that the time of abort initiation is not critical.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 31, 1967,
127-51-01-02-23.

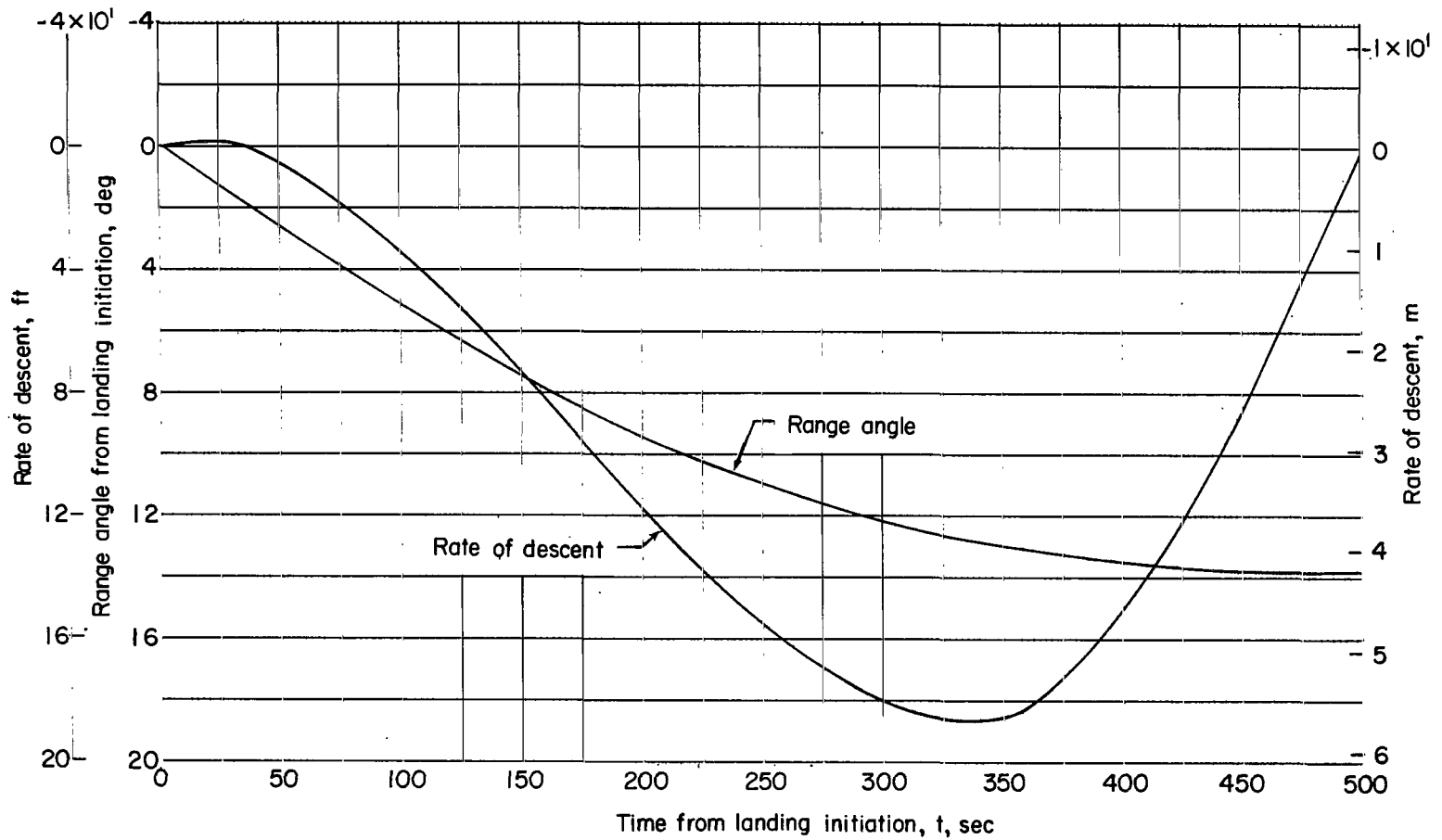
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3. Nelson, Richard D.: Effects of Flight Conditions at Booster Separation on Payload Weight in Orbit. NASA TN D-1069, 1961.



(a) Altitude and circumferential velocity.

Figure 1.- Trajectory characteristics of nominal landing trajectory.



(b) Rate of descent and range angle.

Figure 1.- Concluded.

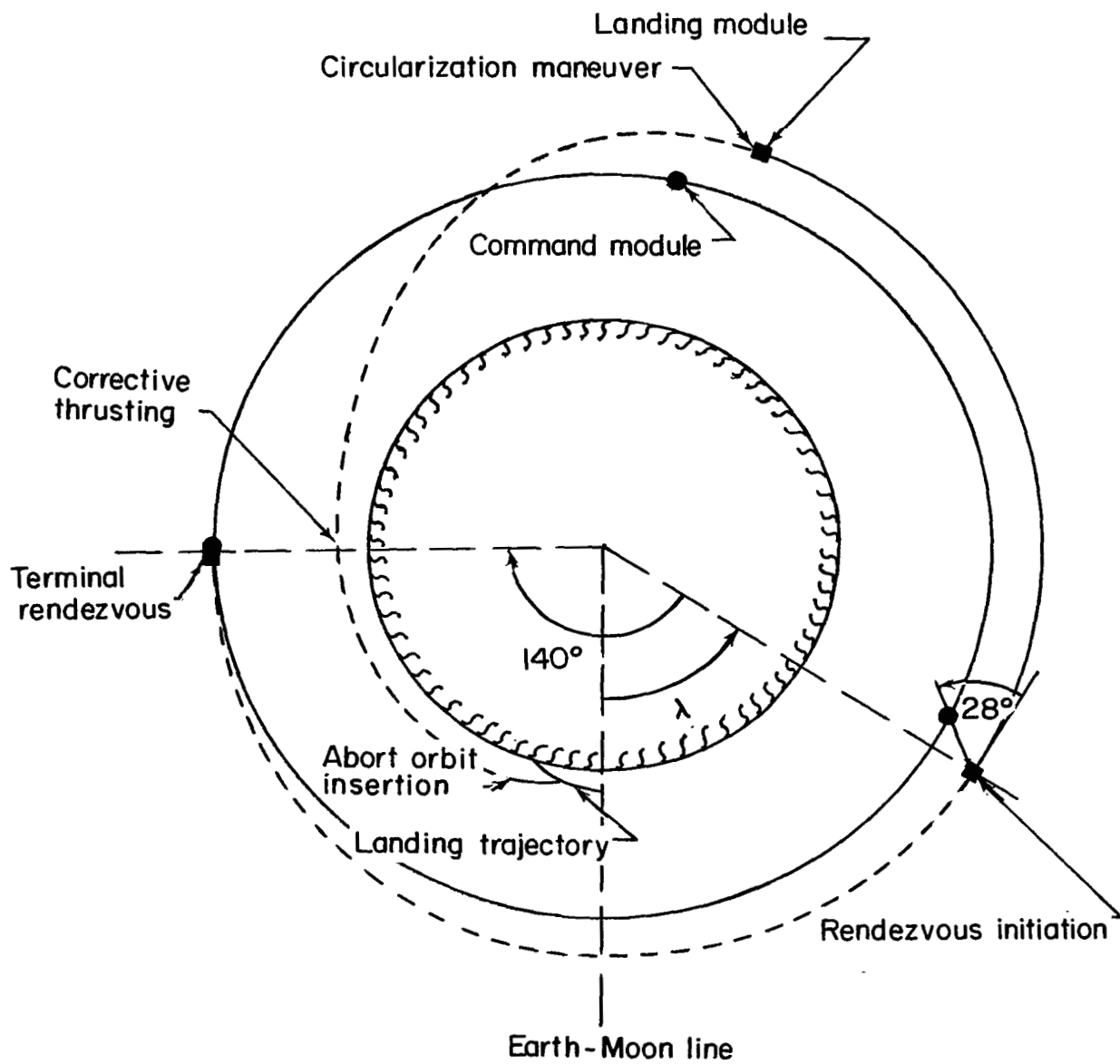
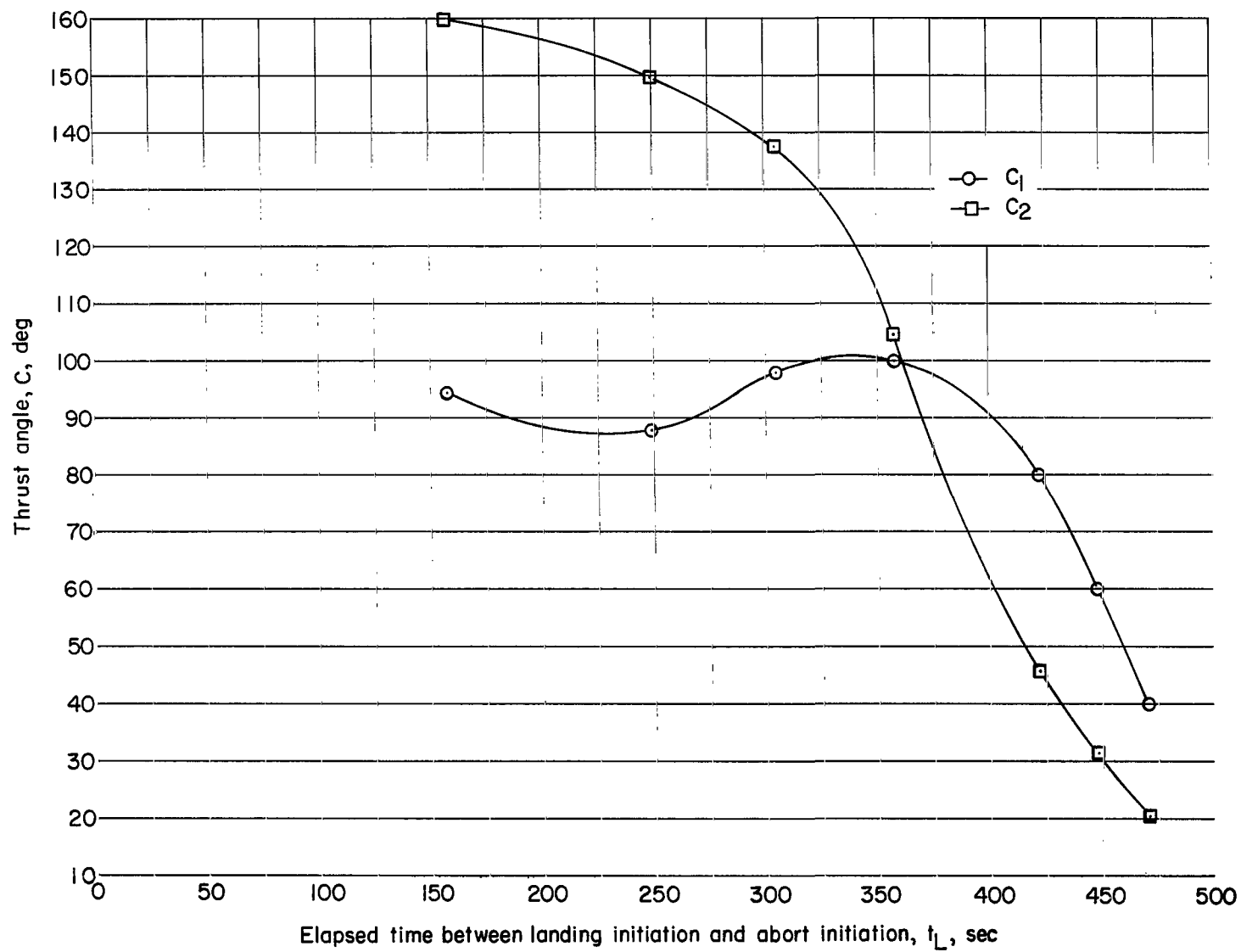
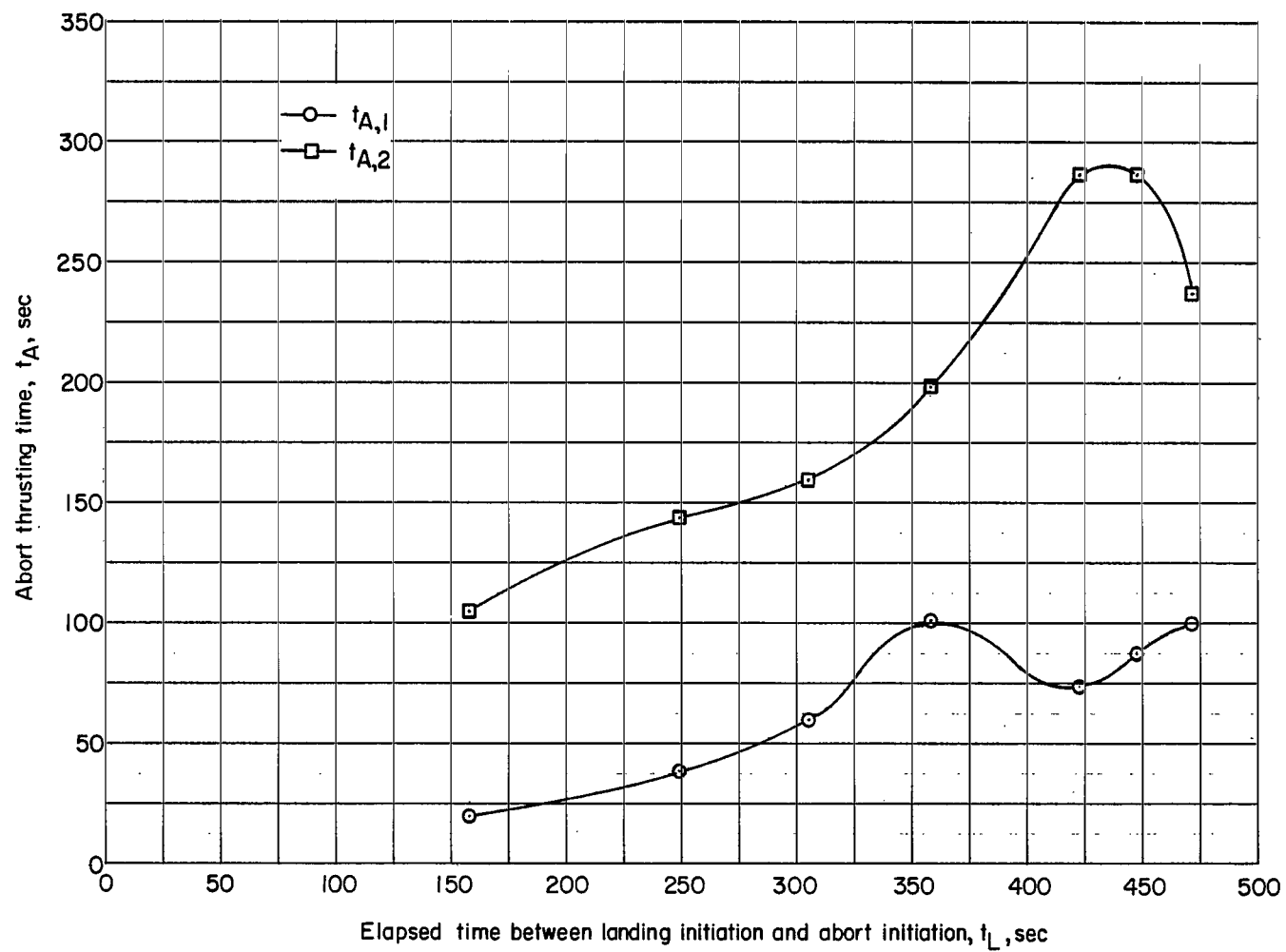


Figure 2.- Illustration of abort-rendezvous maneuver.



(a) Thrust angles.

Figure 3.- Thrust angles and thrusting times to be used during abort maneuver as functions of elapsed time between landing initiation and abort initiation.



(b) Thrusting times.

Figure 3.- Concluded.

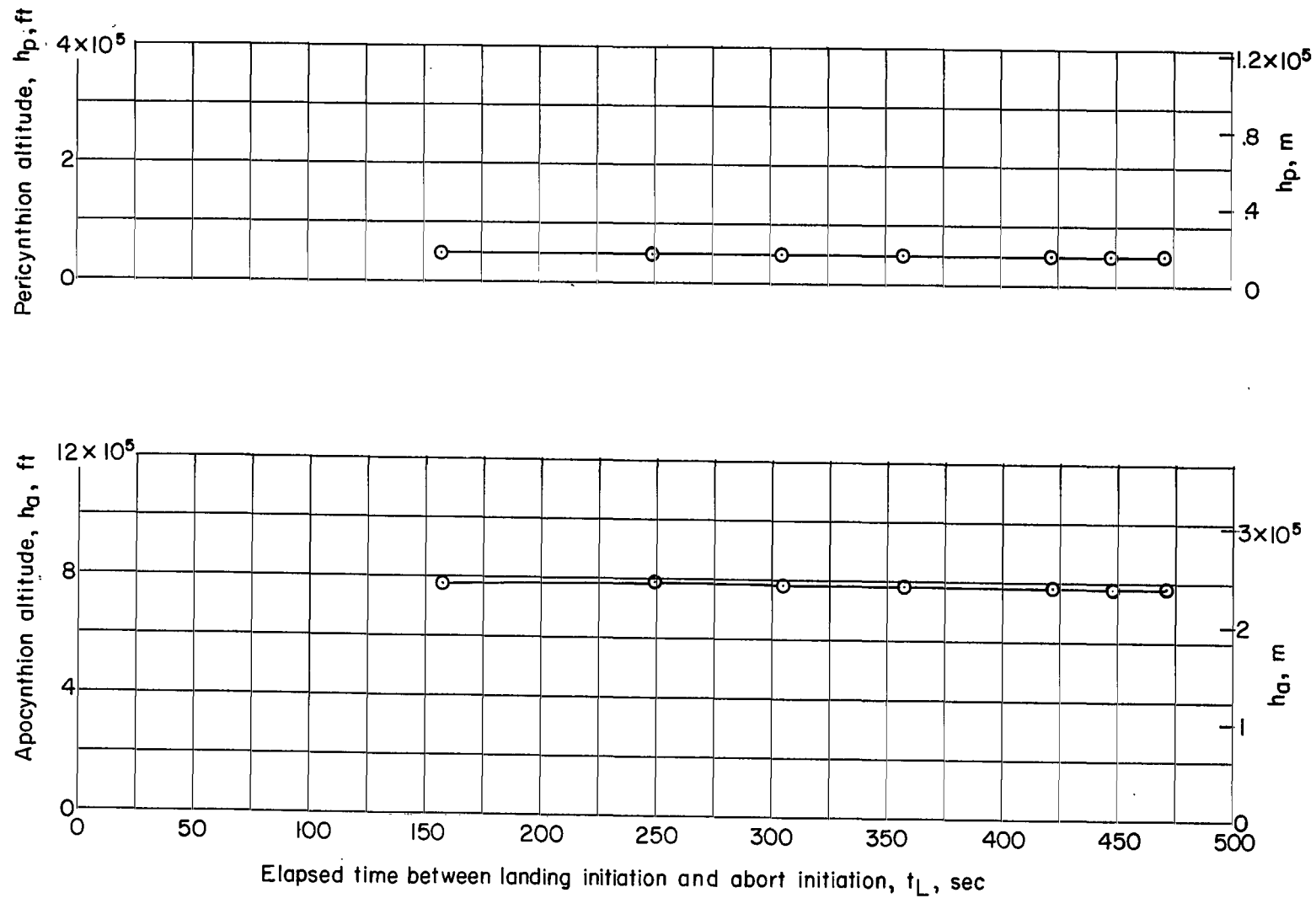


Figure 4.- Pericynthion and apocynthion altitudes of orbits established by abort maneuver.

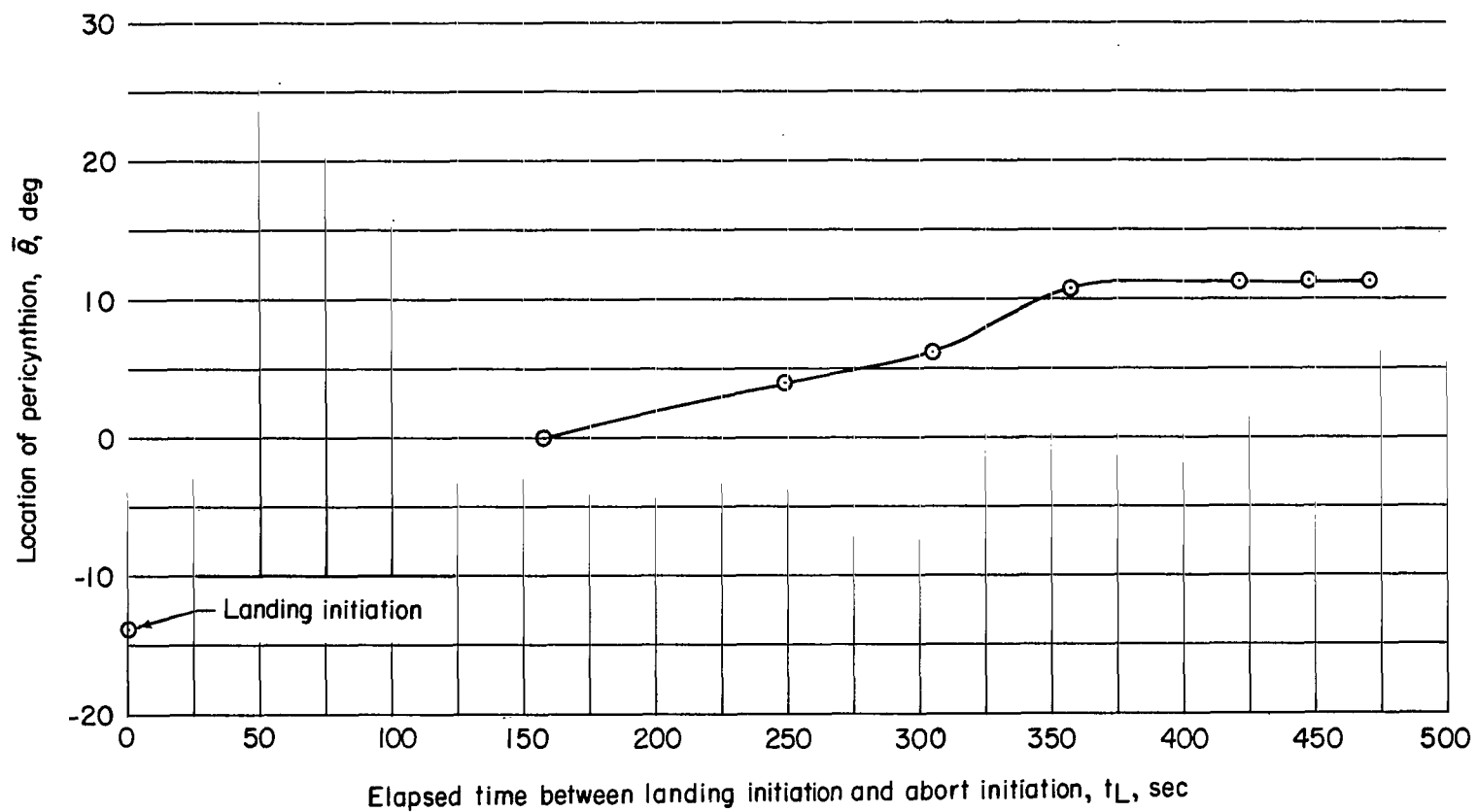
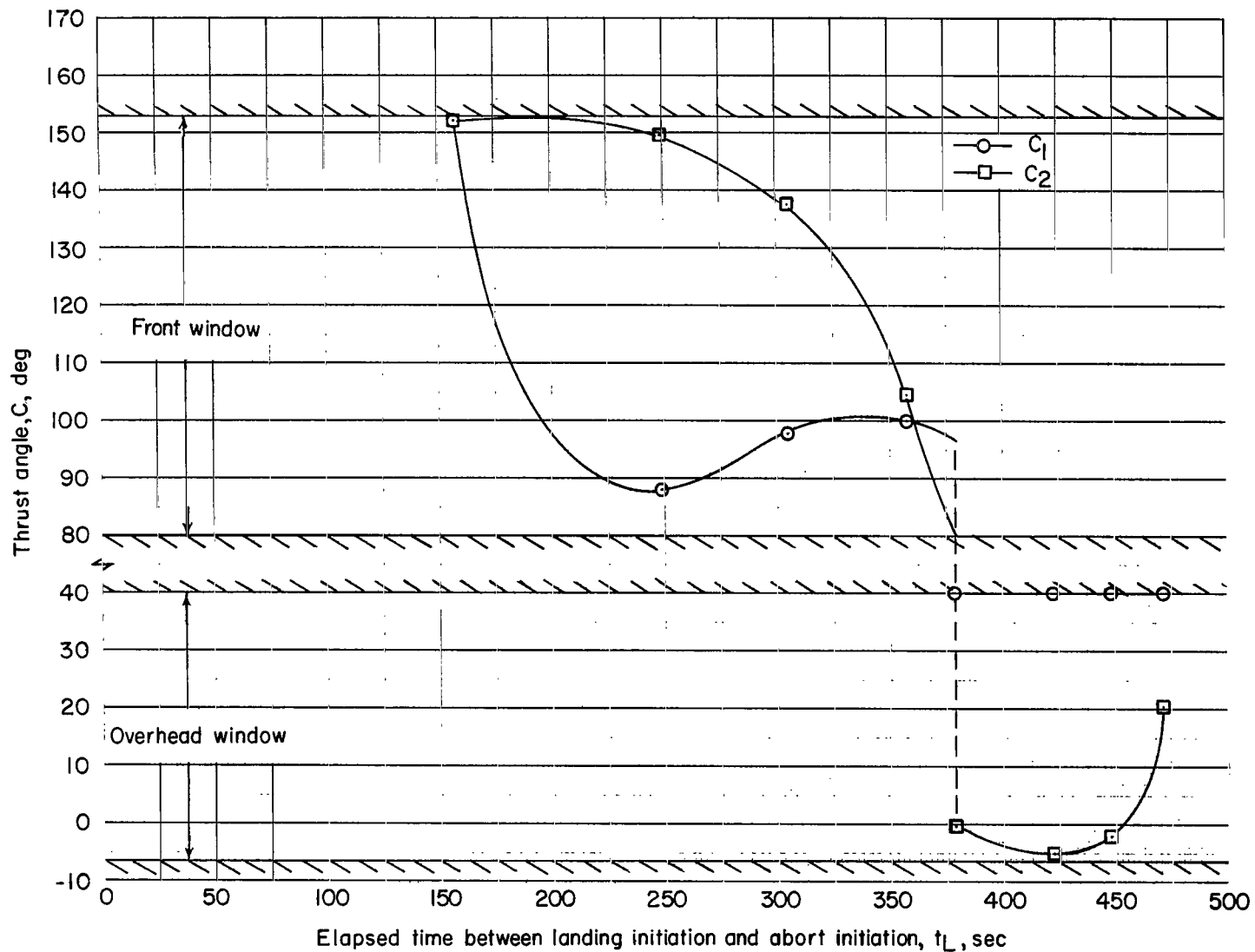
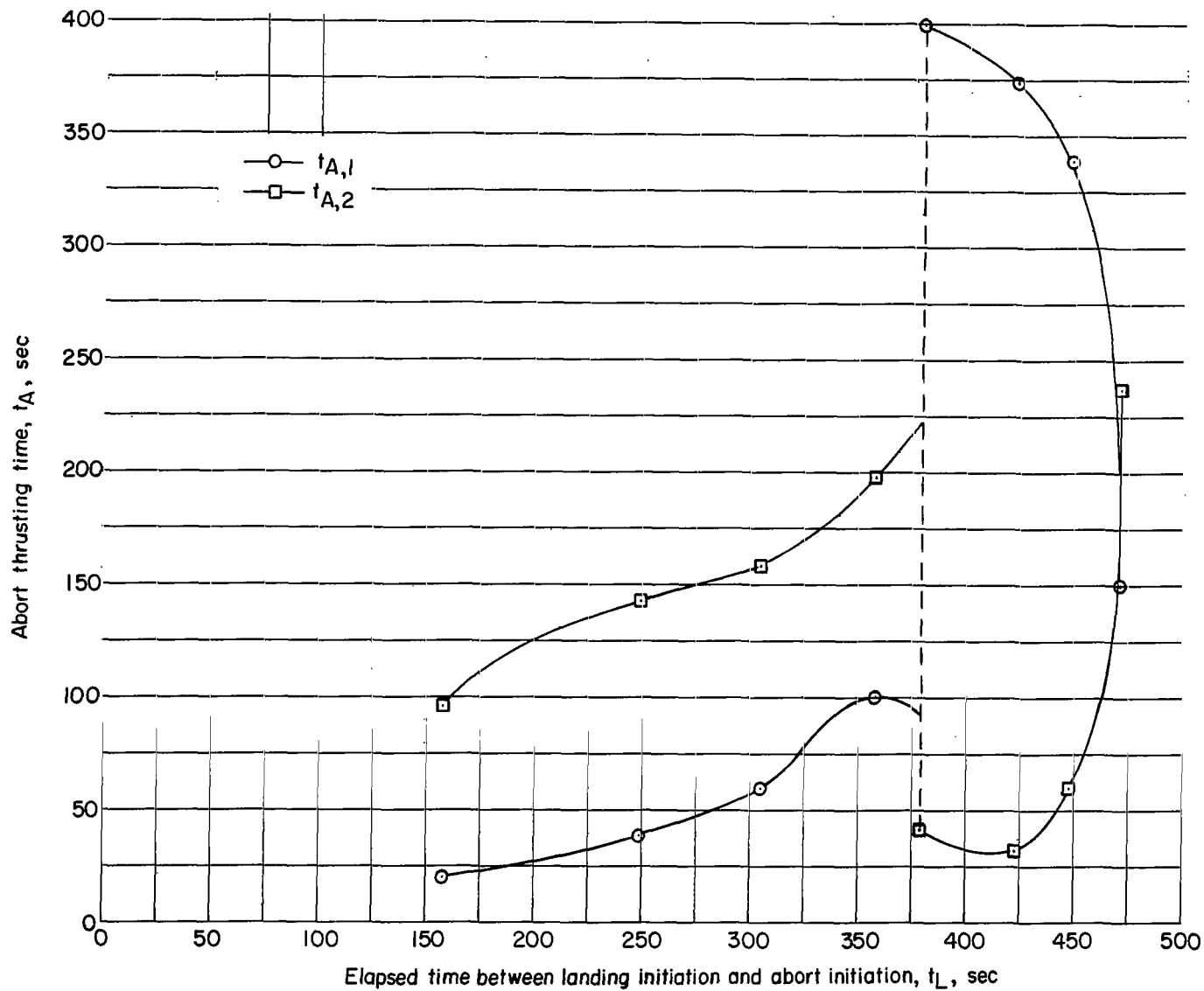


Figure 5.- Location of pericynthion with respect to nominal landing site of orbits established by abort maneuver.



(a) Thrust angles.

Figure 6.- Thrust angles required to avoid window constraints and thrusting times to be used during abort maneuver as functions of elapsed time between landing initiation and abort initiation.



(b) Thrusting times.

Figure 6.- Concluded.

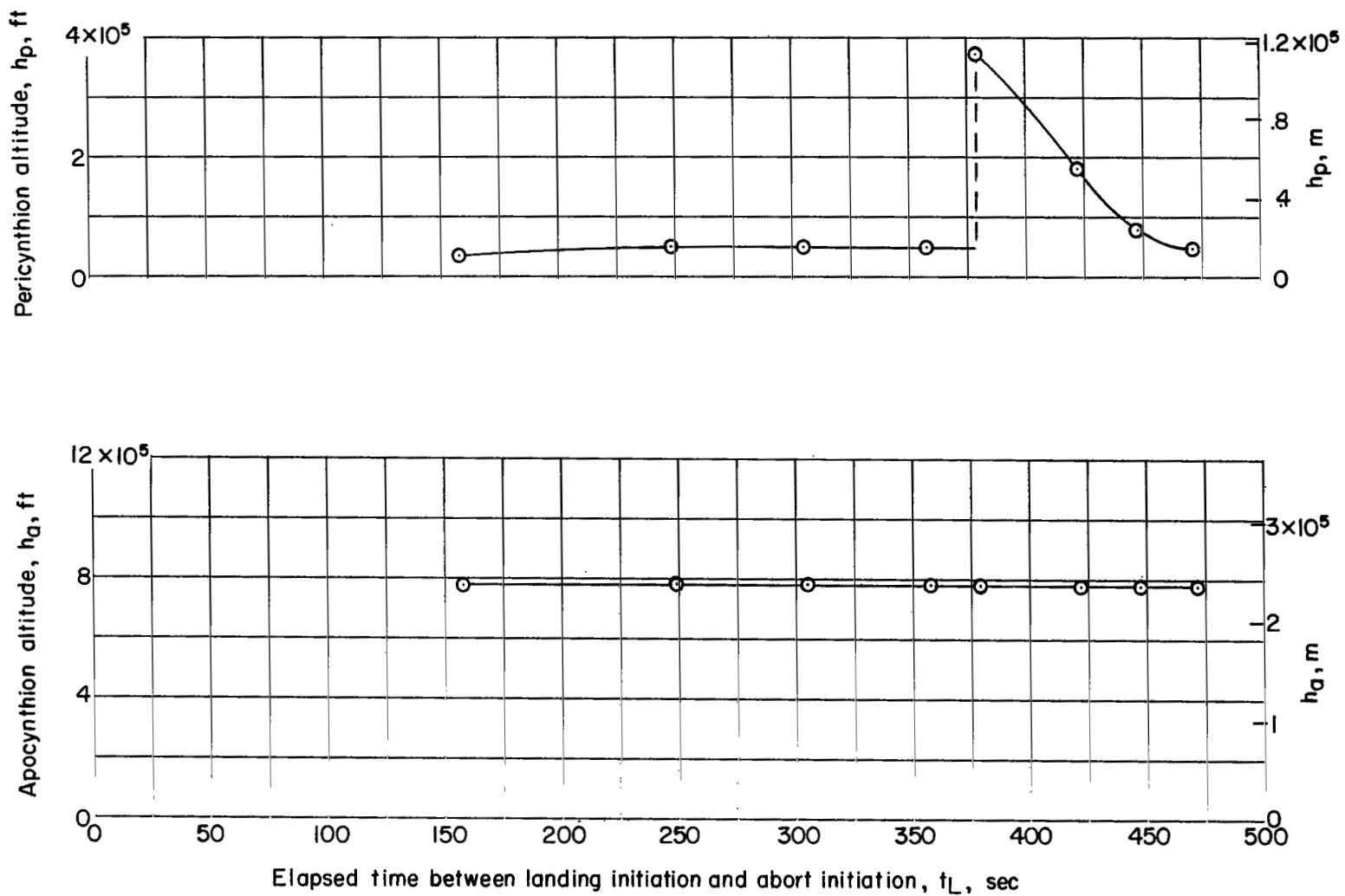


Figure 7.- Pericynthion and apocynthion altitudes of orbits established by abort maneuver with window constraints.

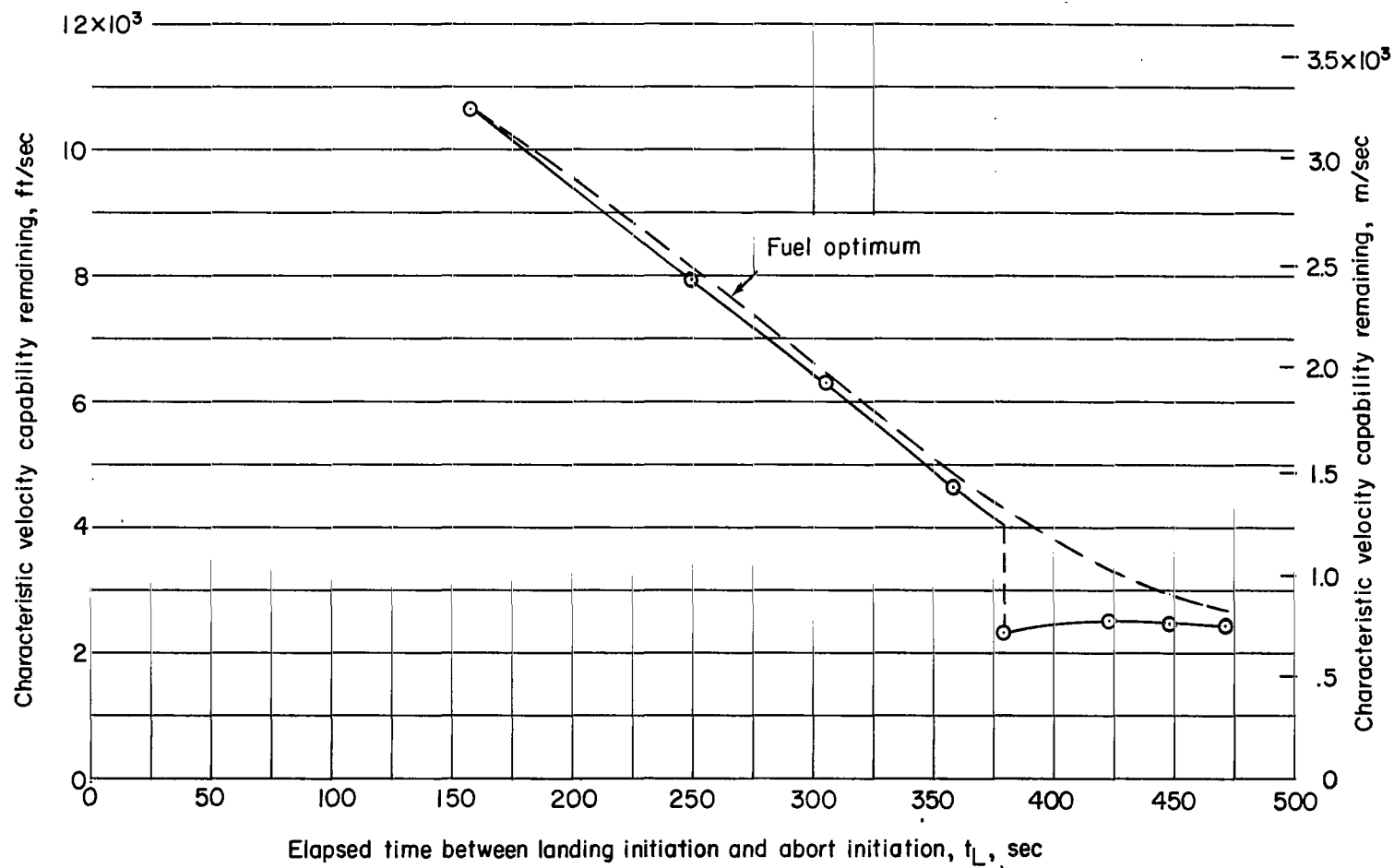


Figure 8.- Characteristic velocity capability remaining at end of abort maneuver with window constraints.

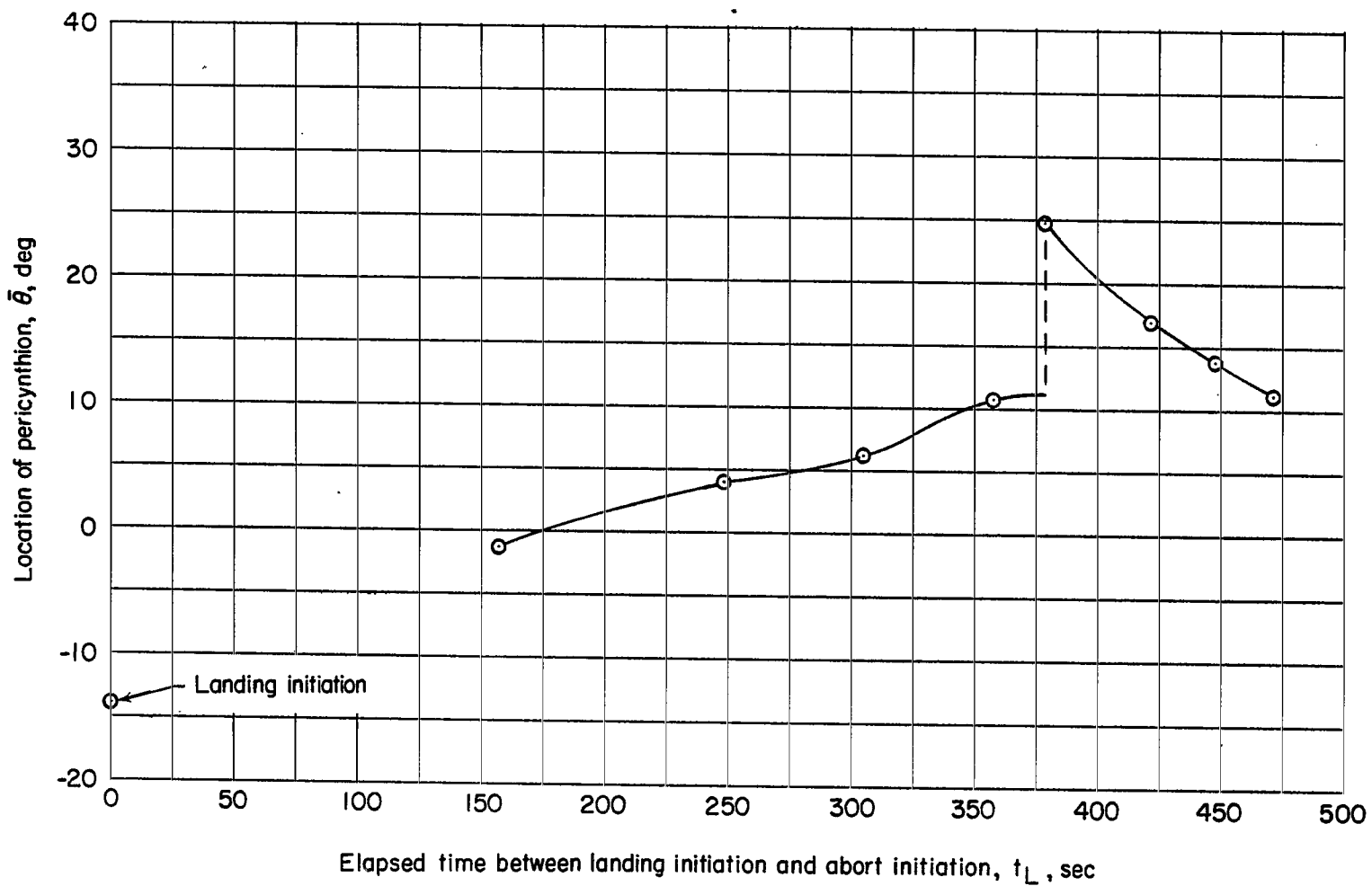


Figure 9.- Location of pericynthion with respect to nominal landing site of orbits established by abort maneuver with window constraints.

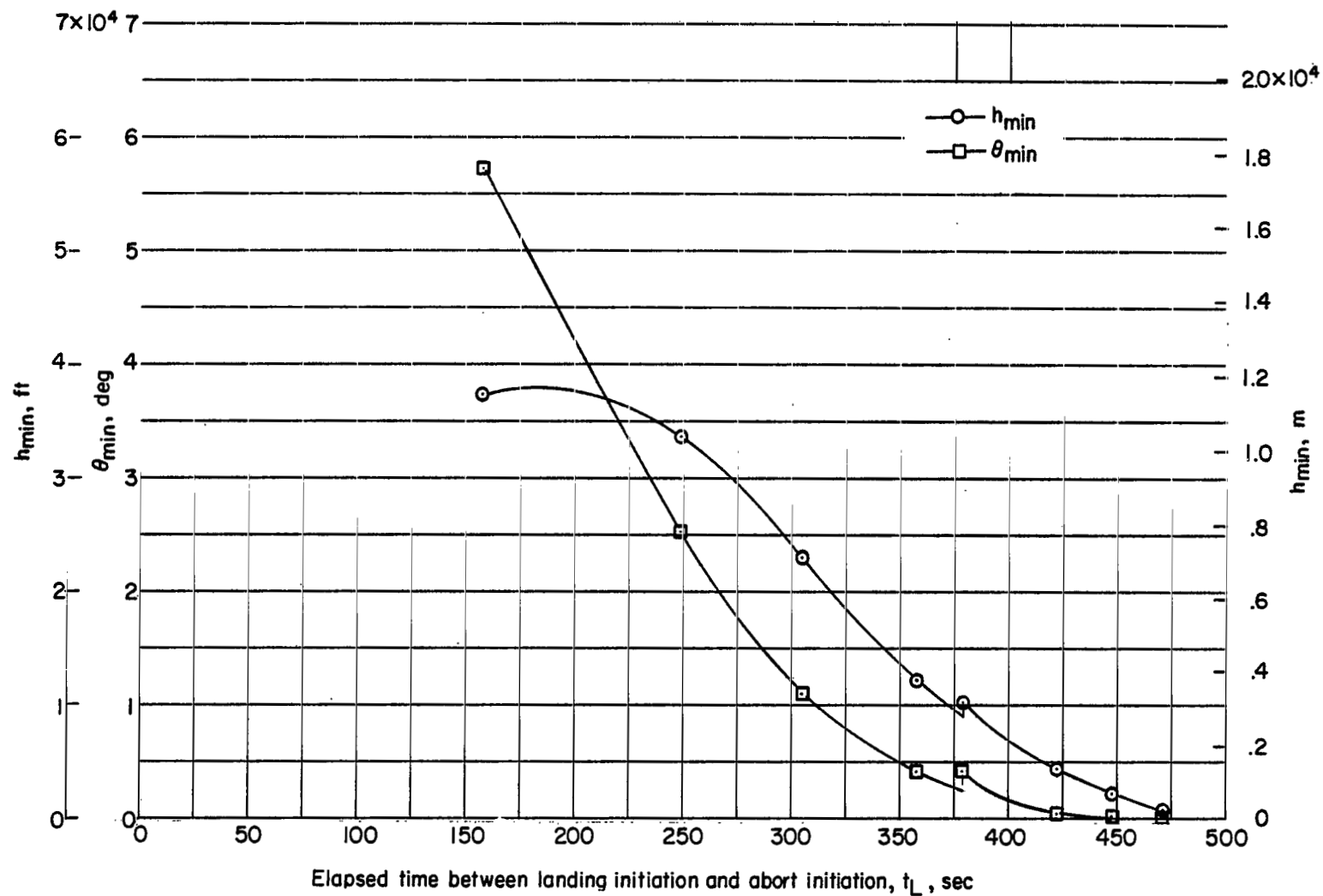
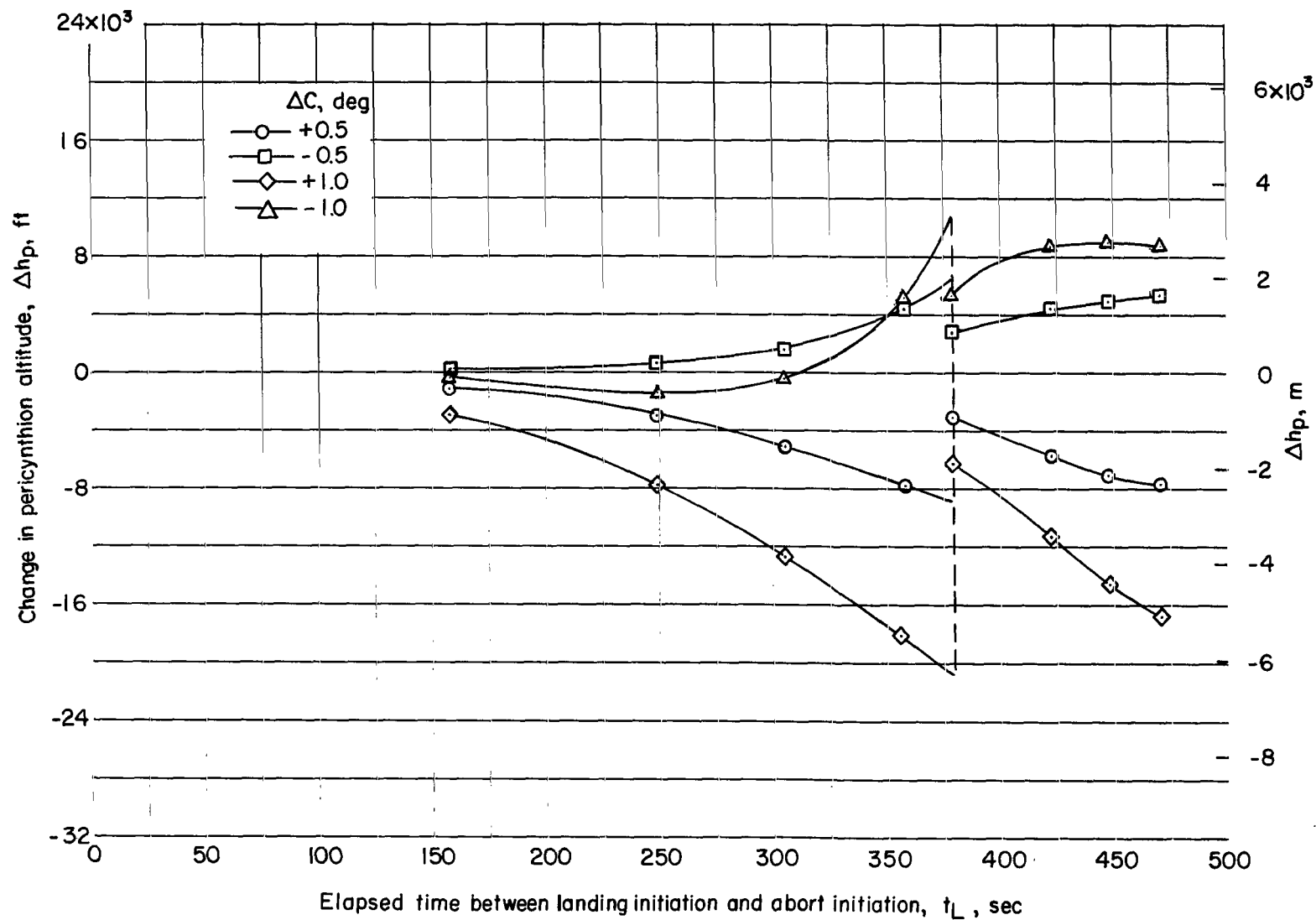
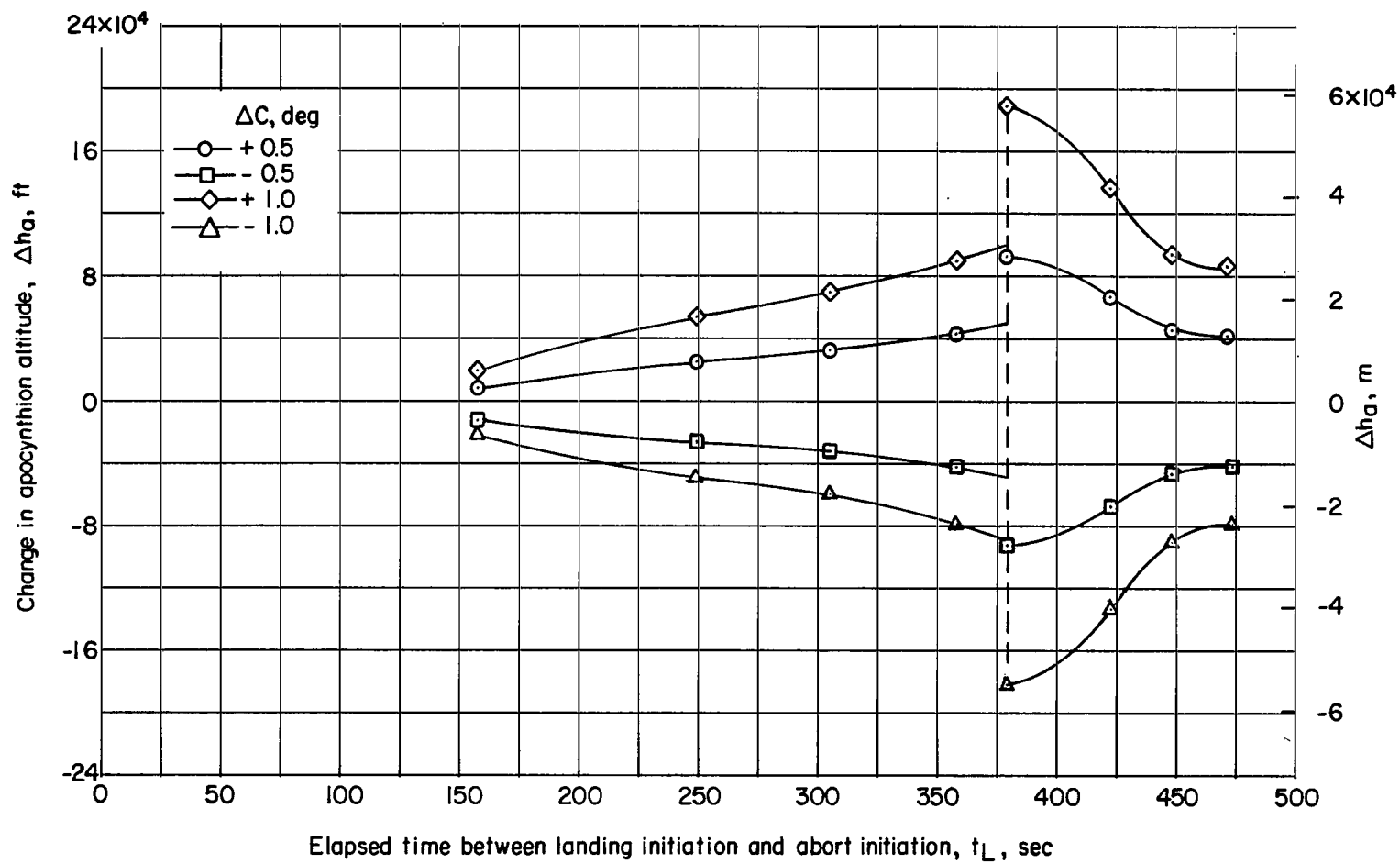


Figure 10.- Minimum altitude reached during abort maneuver with window constraints and abort maneuver location with respect to nominal landing site.



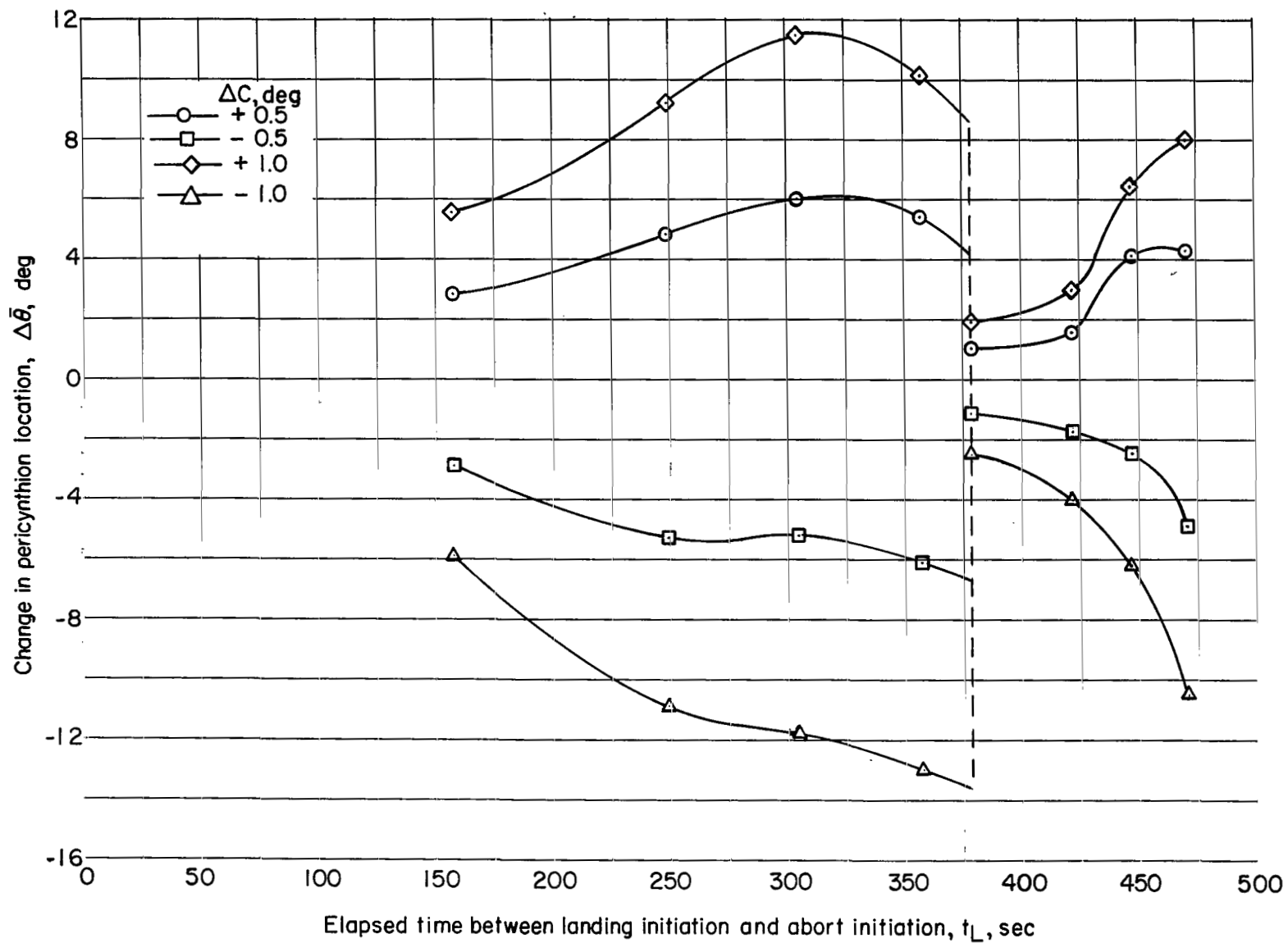
(a) Effect on pericynthion altitude.

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



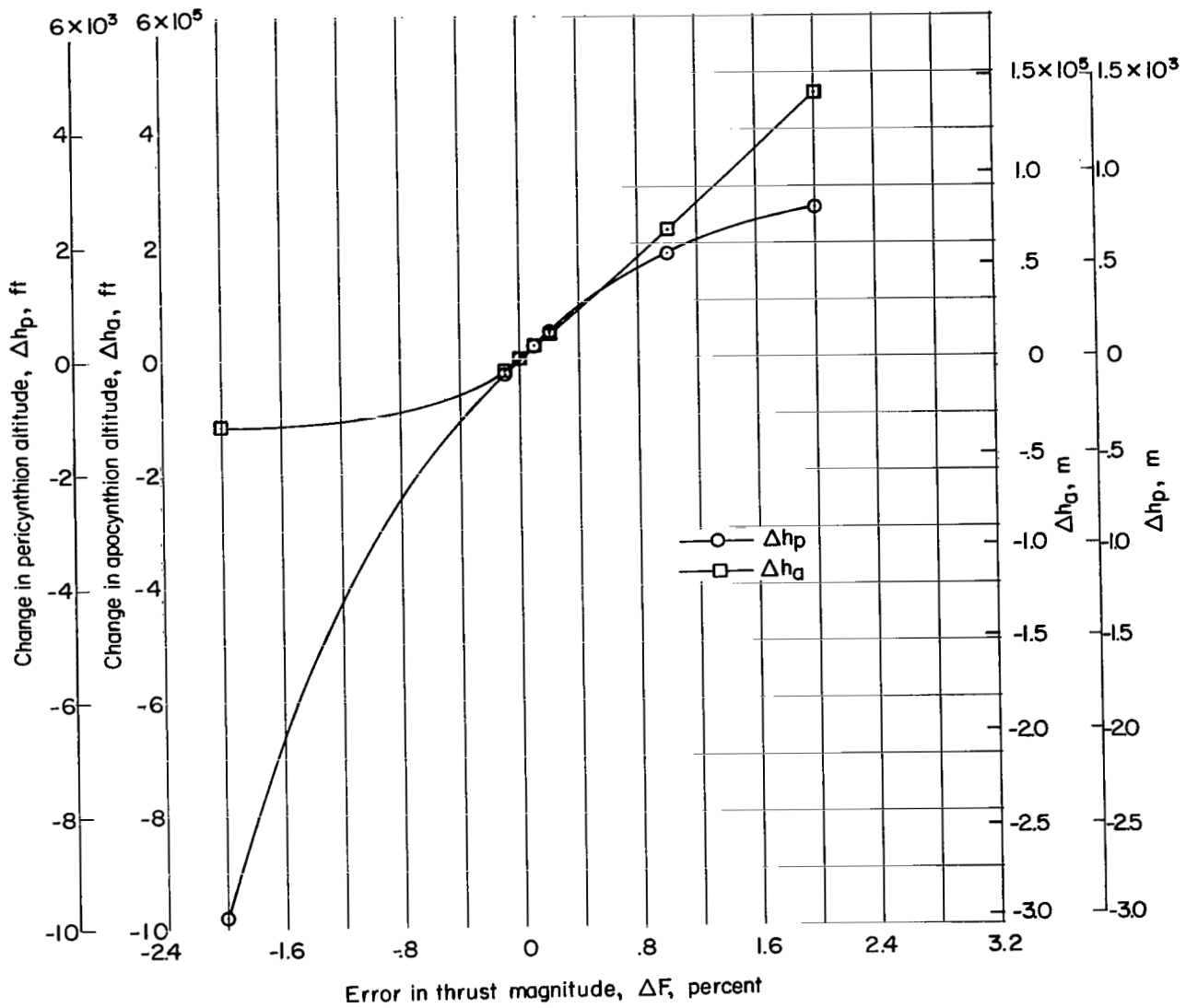
(b) Effect on apocynthion altitude.

Figure 11.- Continued.



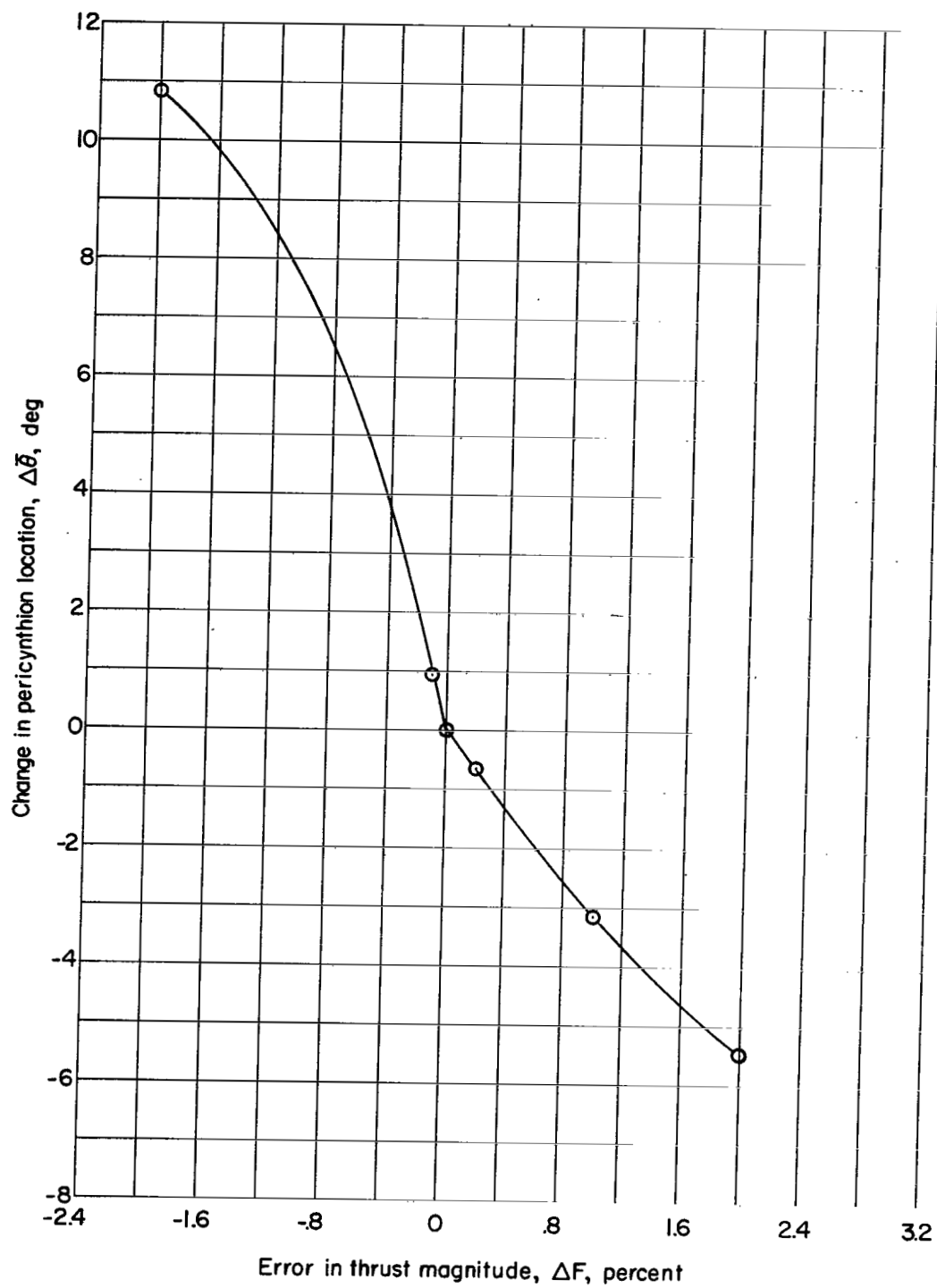
(c) Effect on location of pericynthion. (Positive values of $\Delta\bar{\theta}$ correspond to locations down range of nominal location.)

Figure 11.- Concluded.



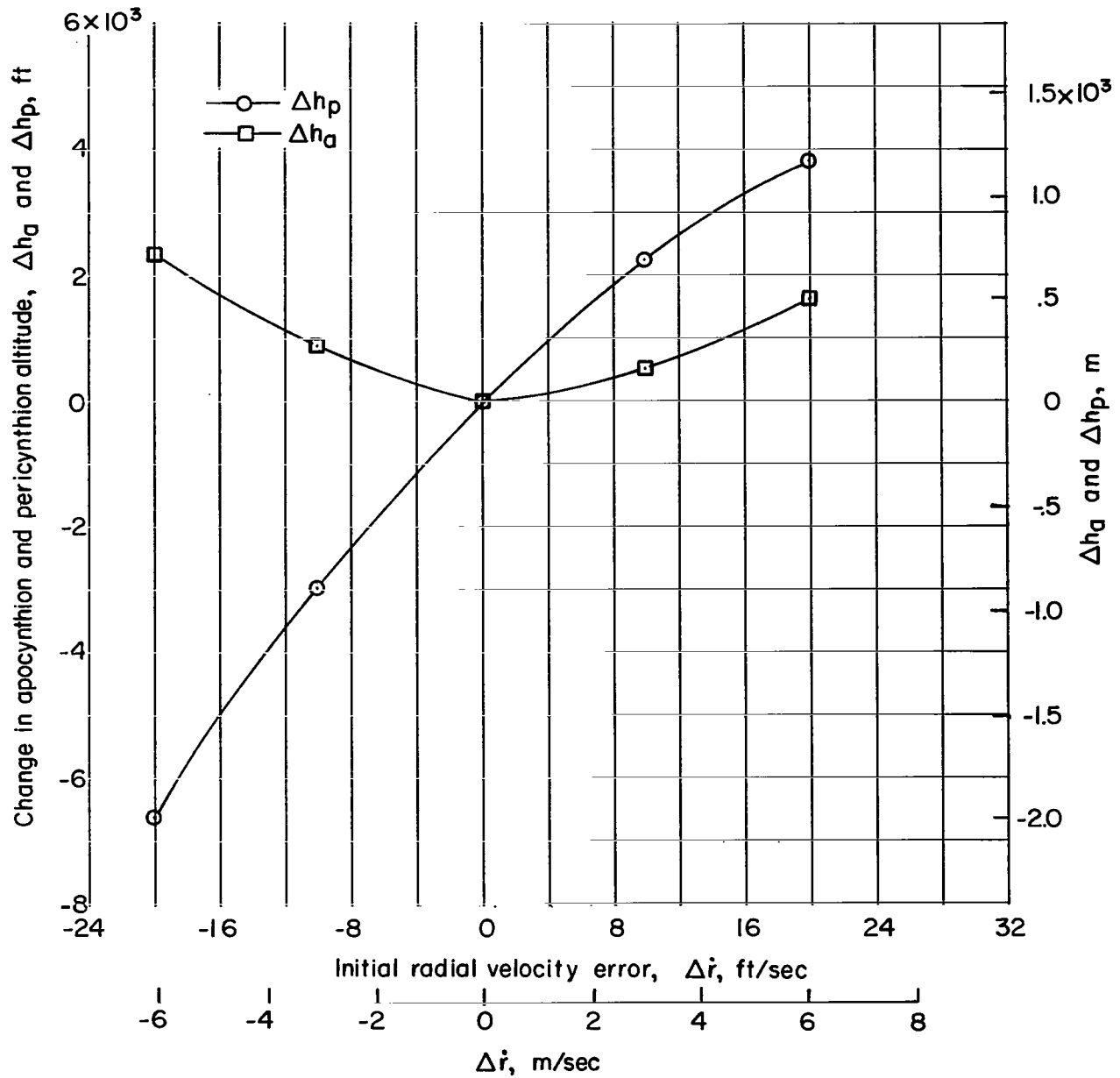
(a) Effect on apocynthion and pericynthion altitude.

Figure 12.- Effect of errors in thrust magnitude on orbits established by abort maneuver with window constraints.



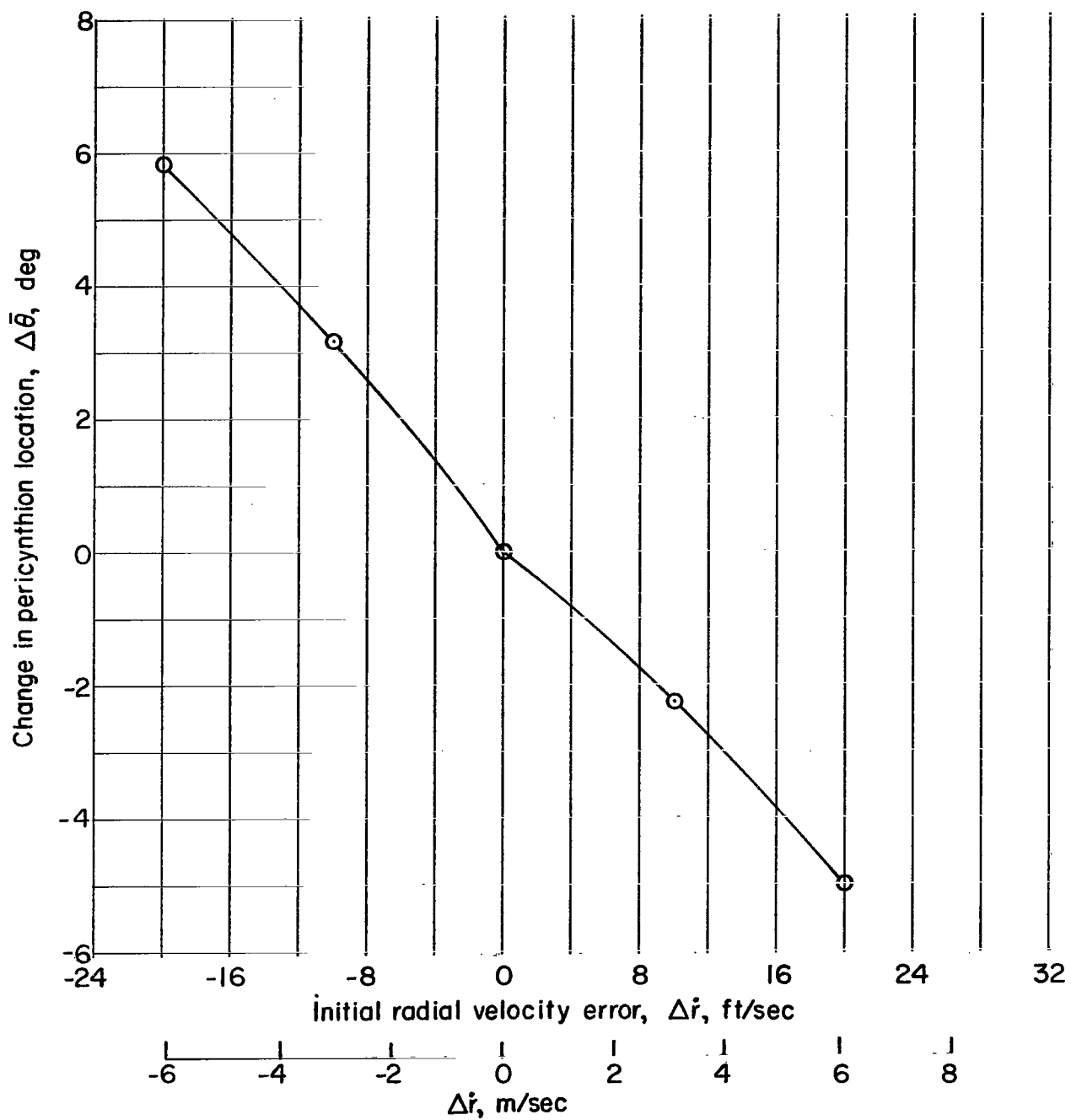
(b) Effect on location of pericynthion. (Positive values correspond to locations down range from nominal location.)

Figure 12.- Concluded.



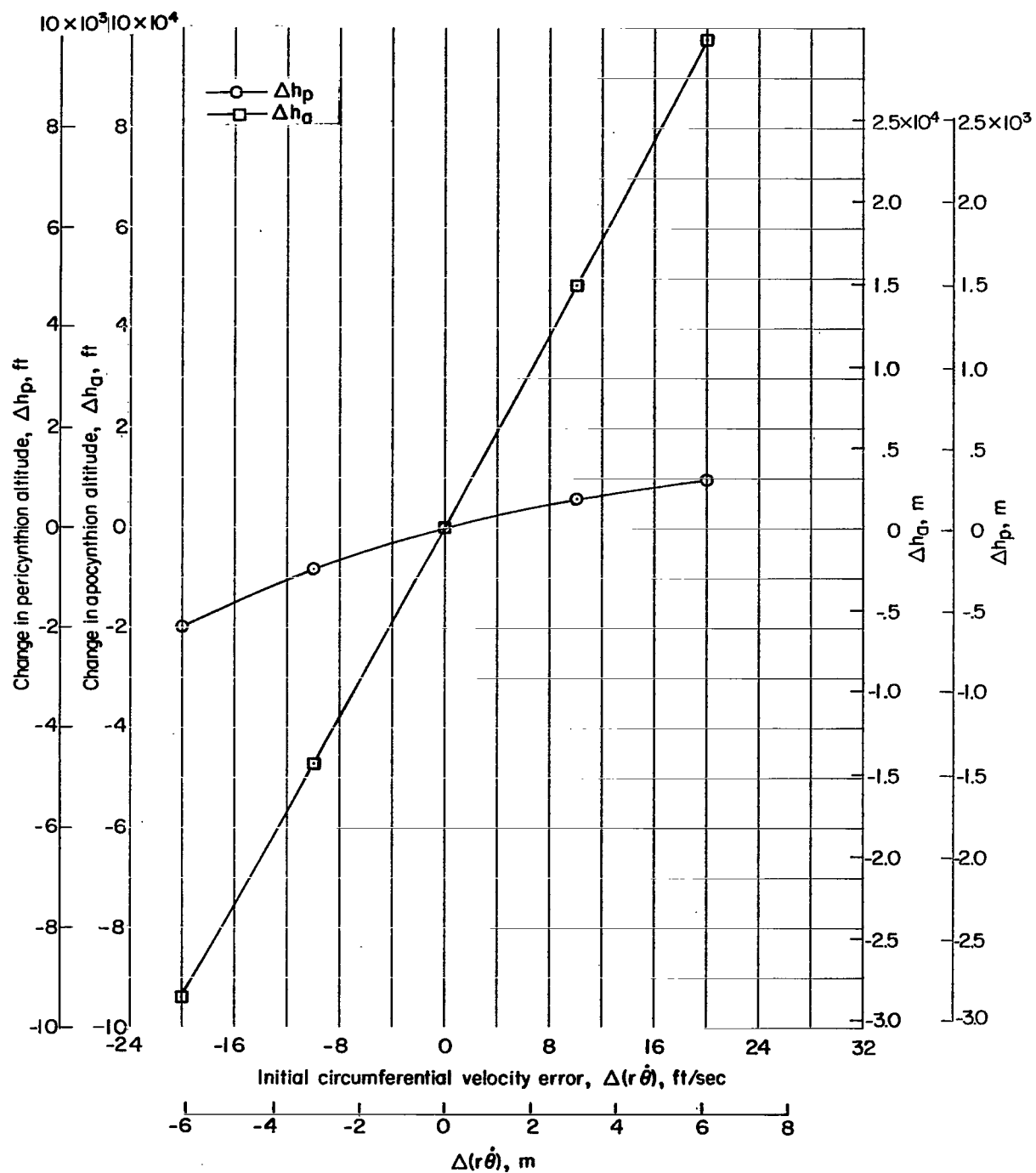
(a) Effect on apocynthion and pericynthion altitudes.

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



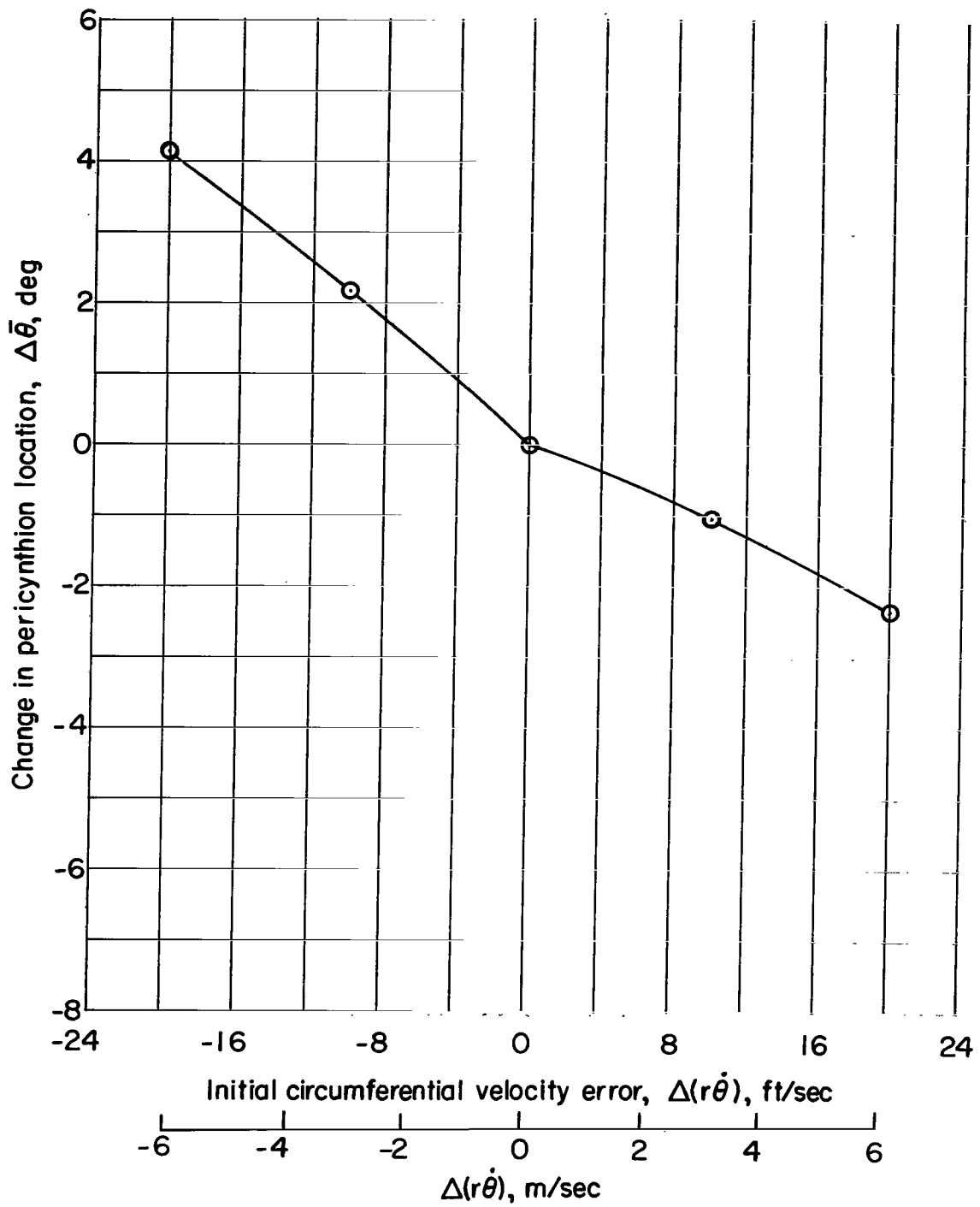
(b) Effect on pericynthion location.

Figure 13.- Concluded.



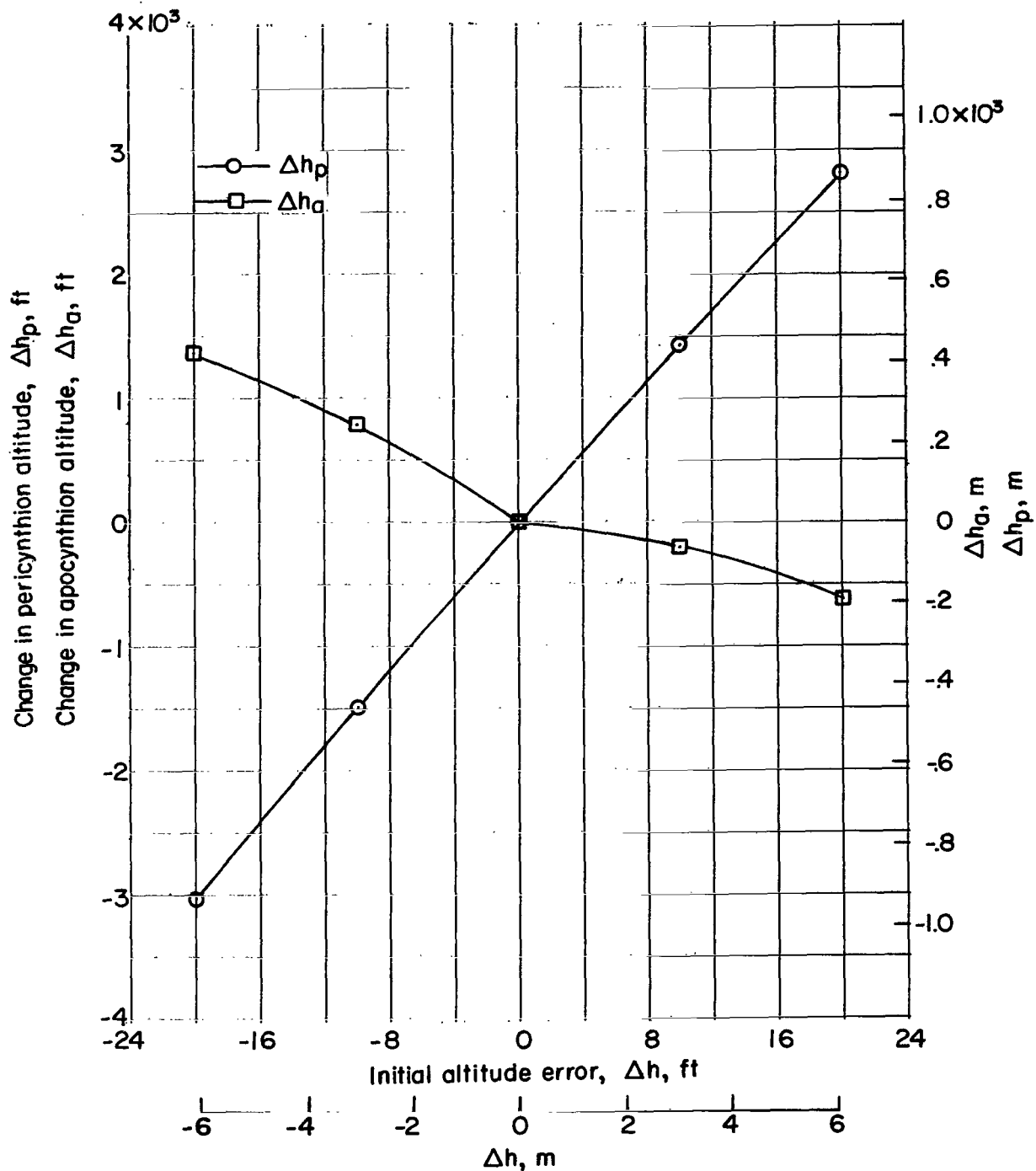
(a) Effect on apocynthion and pericynthion altitudes.

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



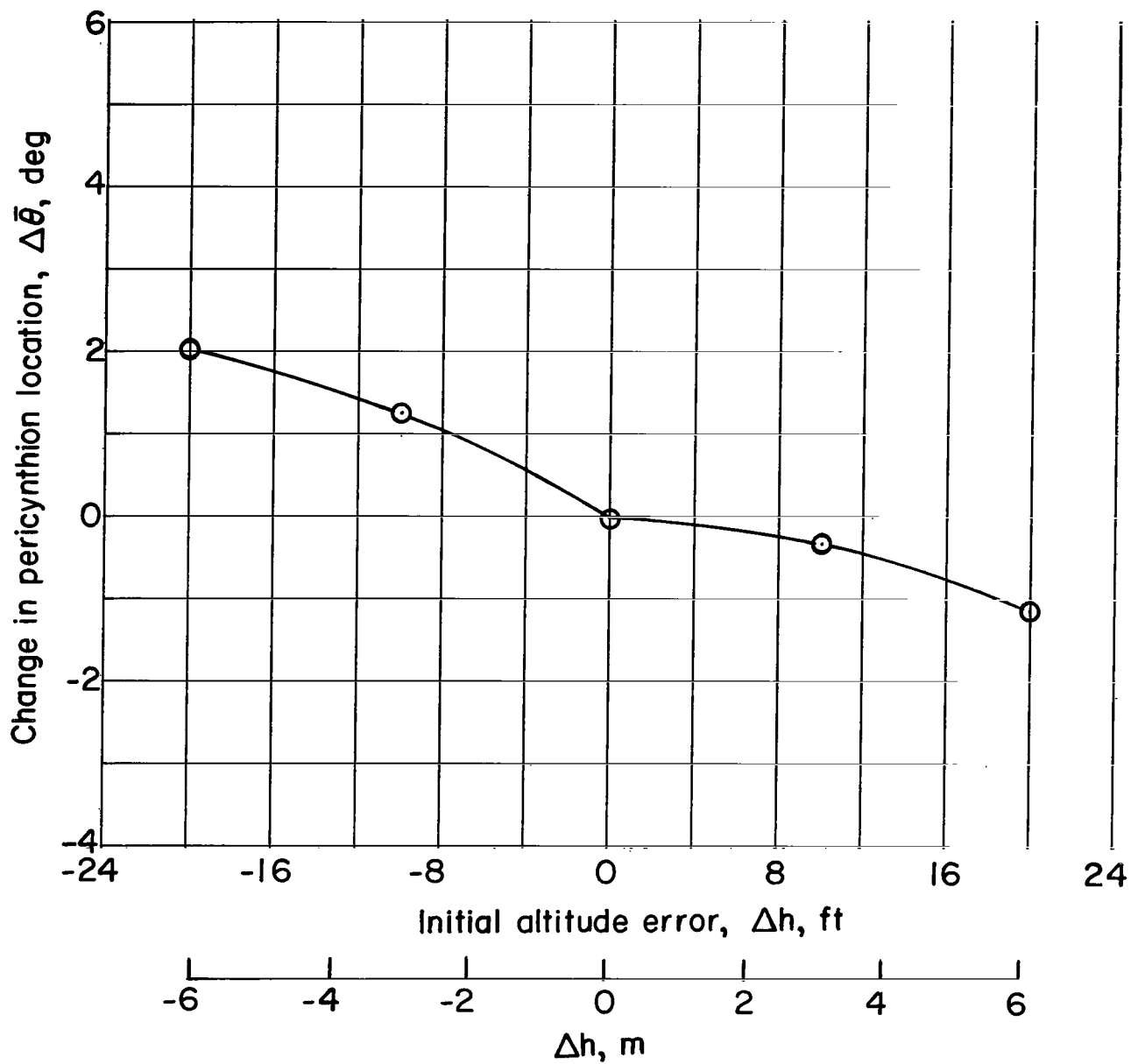
(b) Effect on pericynthion location.

Figure 14.- Concluded.



(a) Effect on apocynthion and pericynthion altitudes.

Figure 15.- Effect of errors in altitude at abort initiation on orbits established by abort maneuvers with window constraints.



(b) Effect on pericynthion location.

Figure 15.- Concluded.

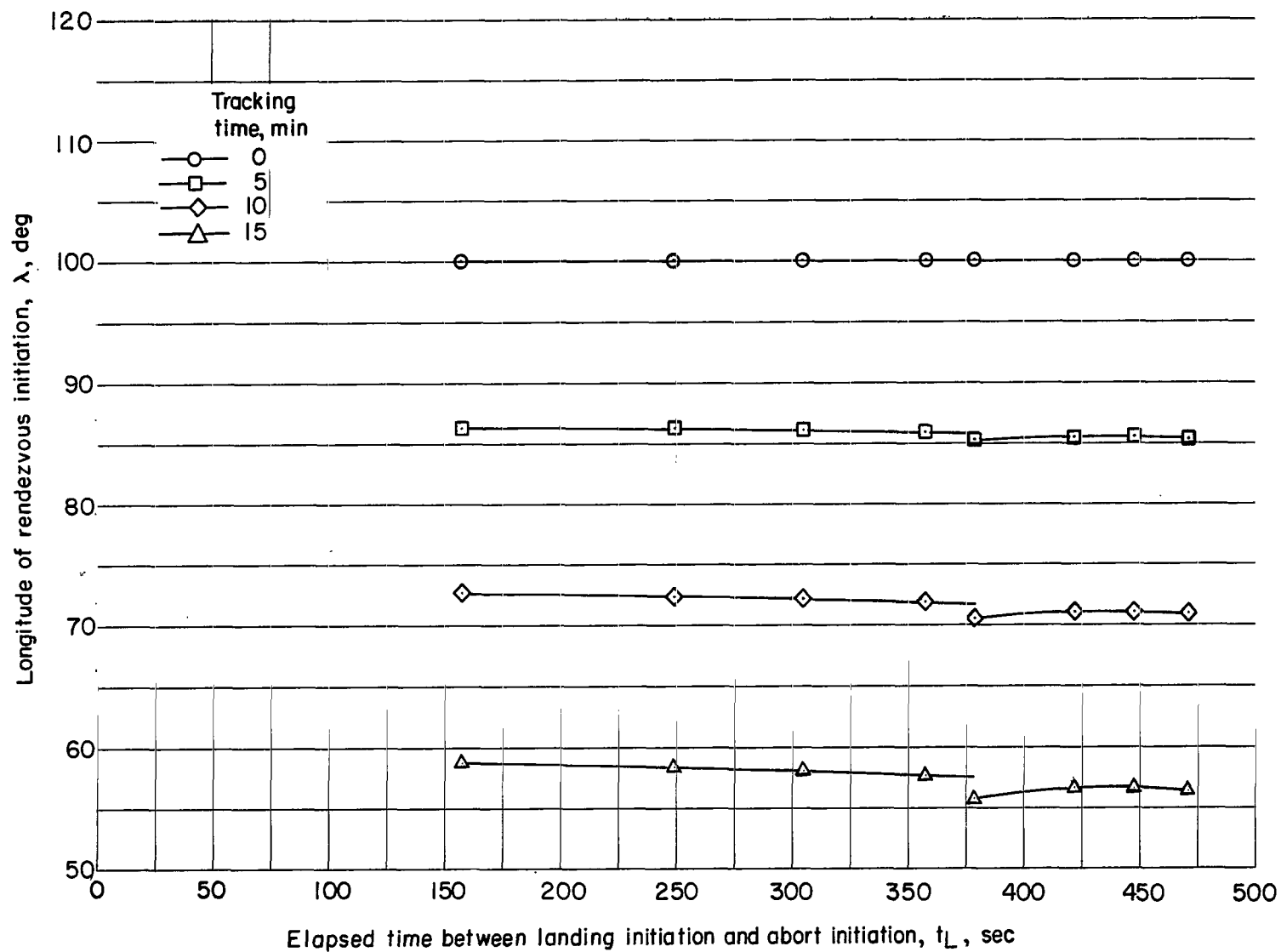


Figure 16.- Location of rendezvous initiation point as a function of tracking time required by earth-based system.

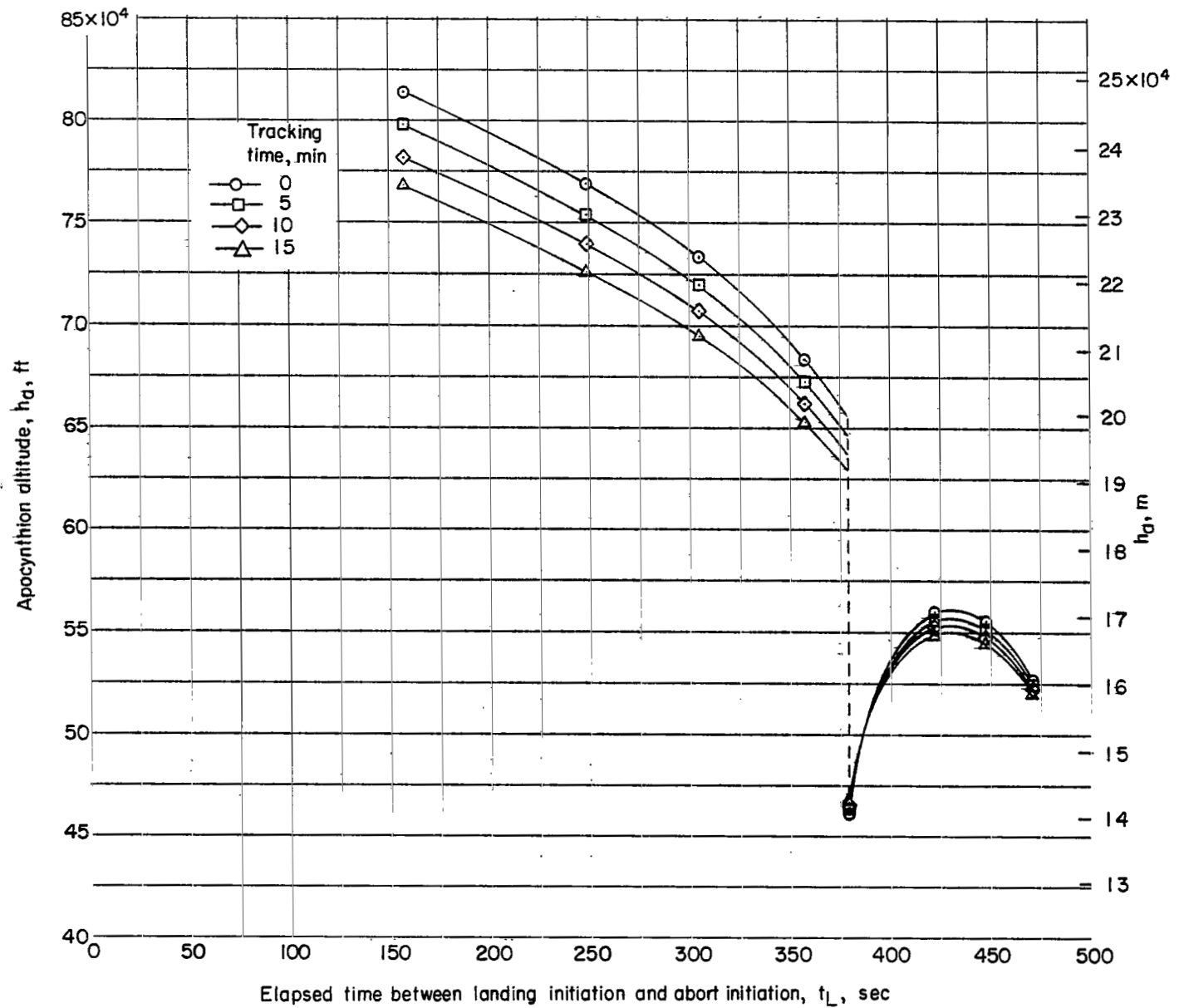


Figure 17.- Apocynthion altitude required to make orbit circular by thrusting function of tracking time.

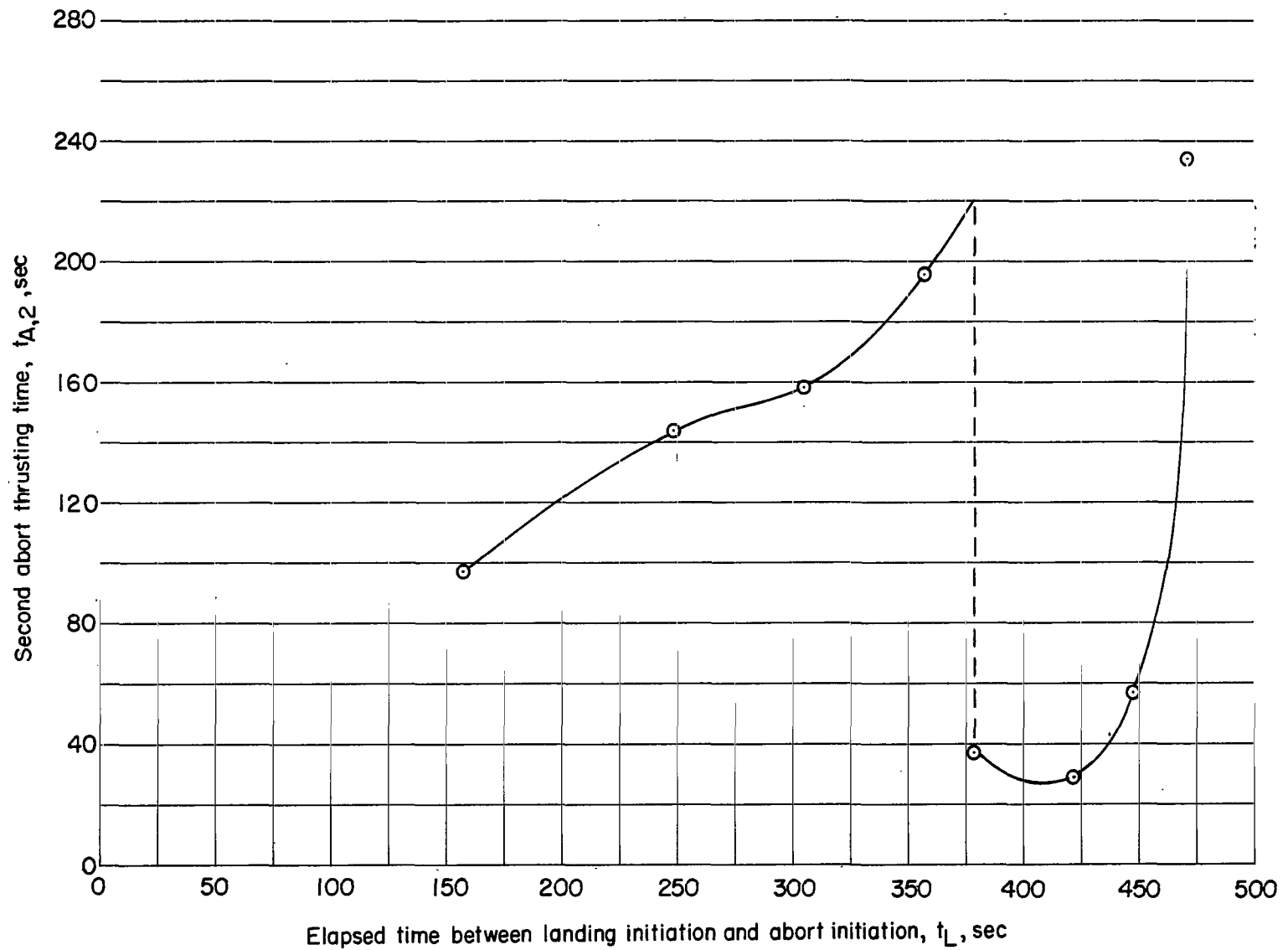


Figure 18.- Second thrusting time required to inject directly into orbits with apocynthion altitude required to make orbit circular.

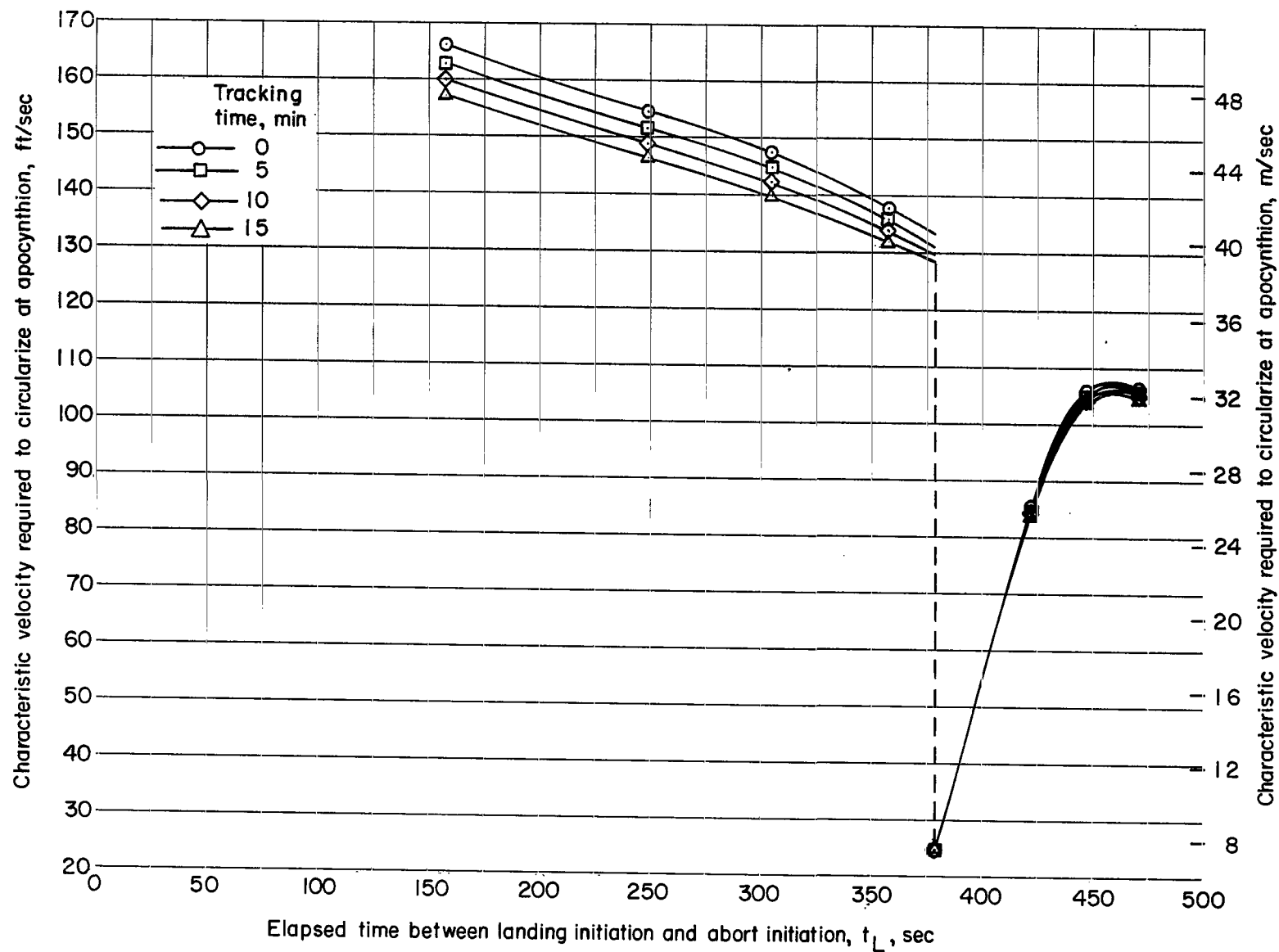
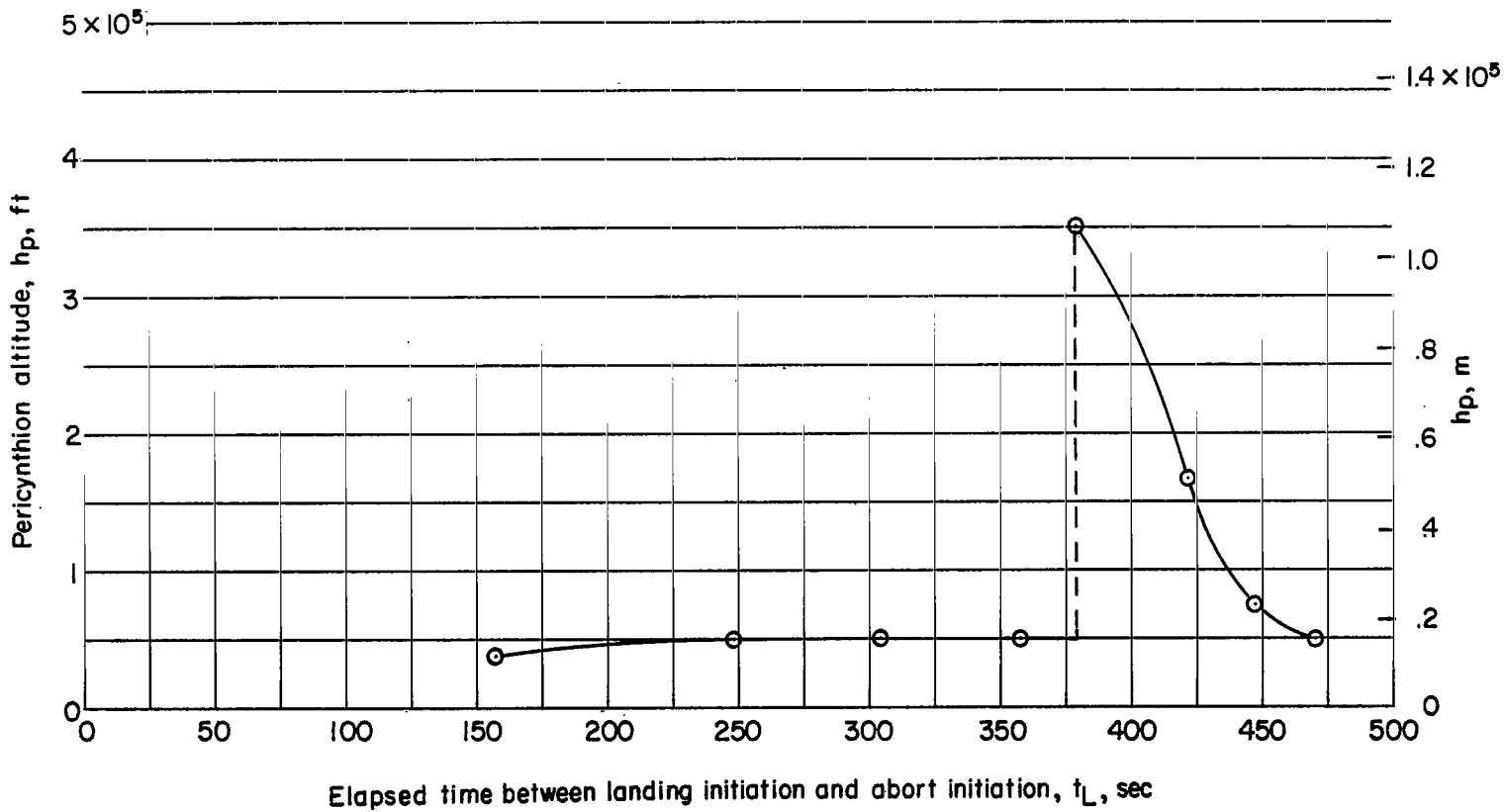
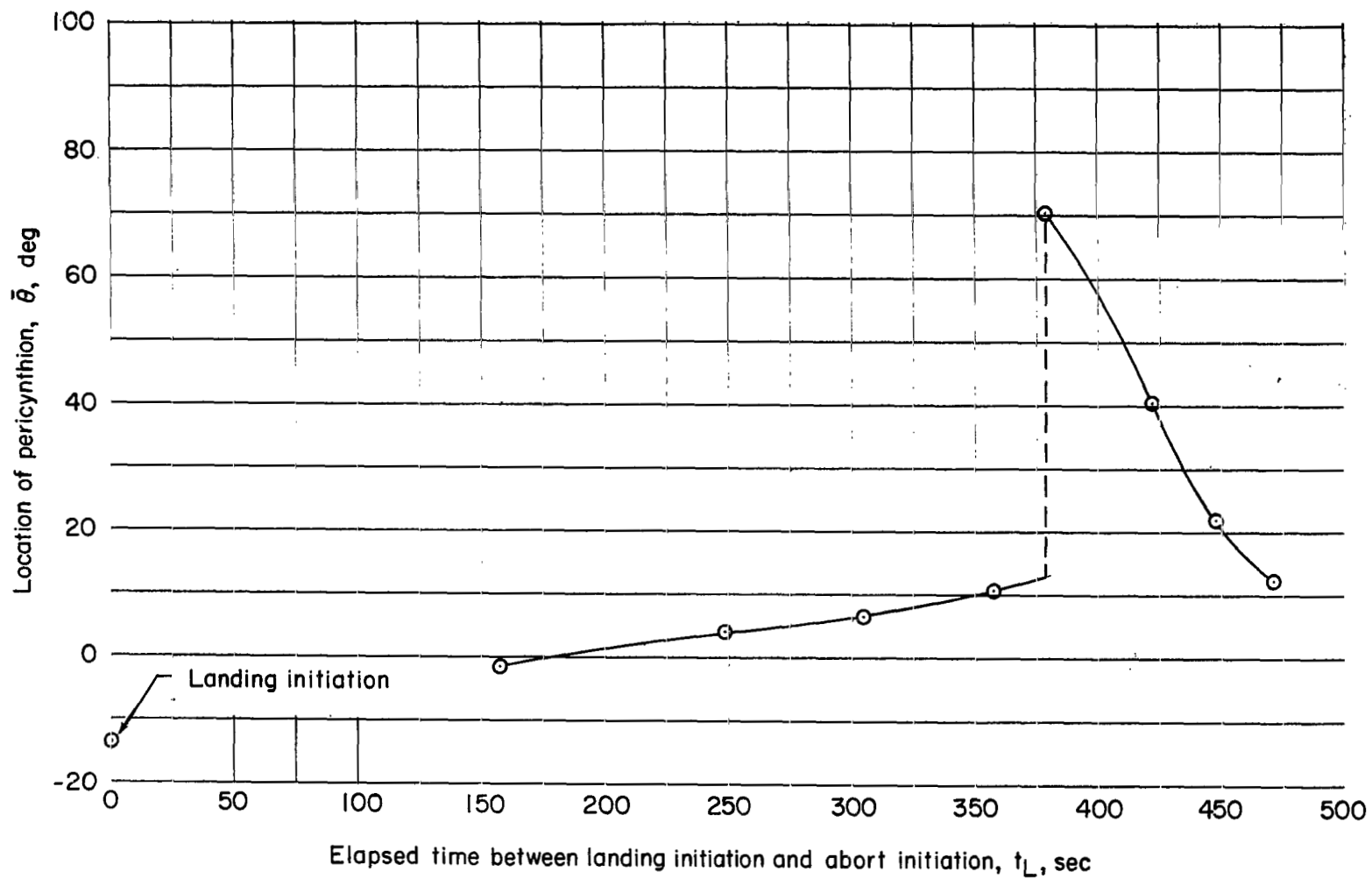


Figure 19.- Characteristic velocity at apocynthion required to make orbit circular by thrusting.



(a) Pericynthion altitude.

Figure 20.- Pericynthion altitude and location for orbits with apocynthion altitudes required to make orbit circular.



(b) Pericynthion location.

Figure 20.- Concluded.

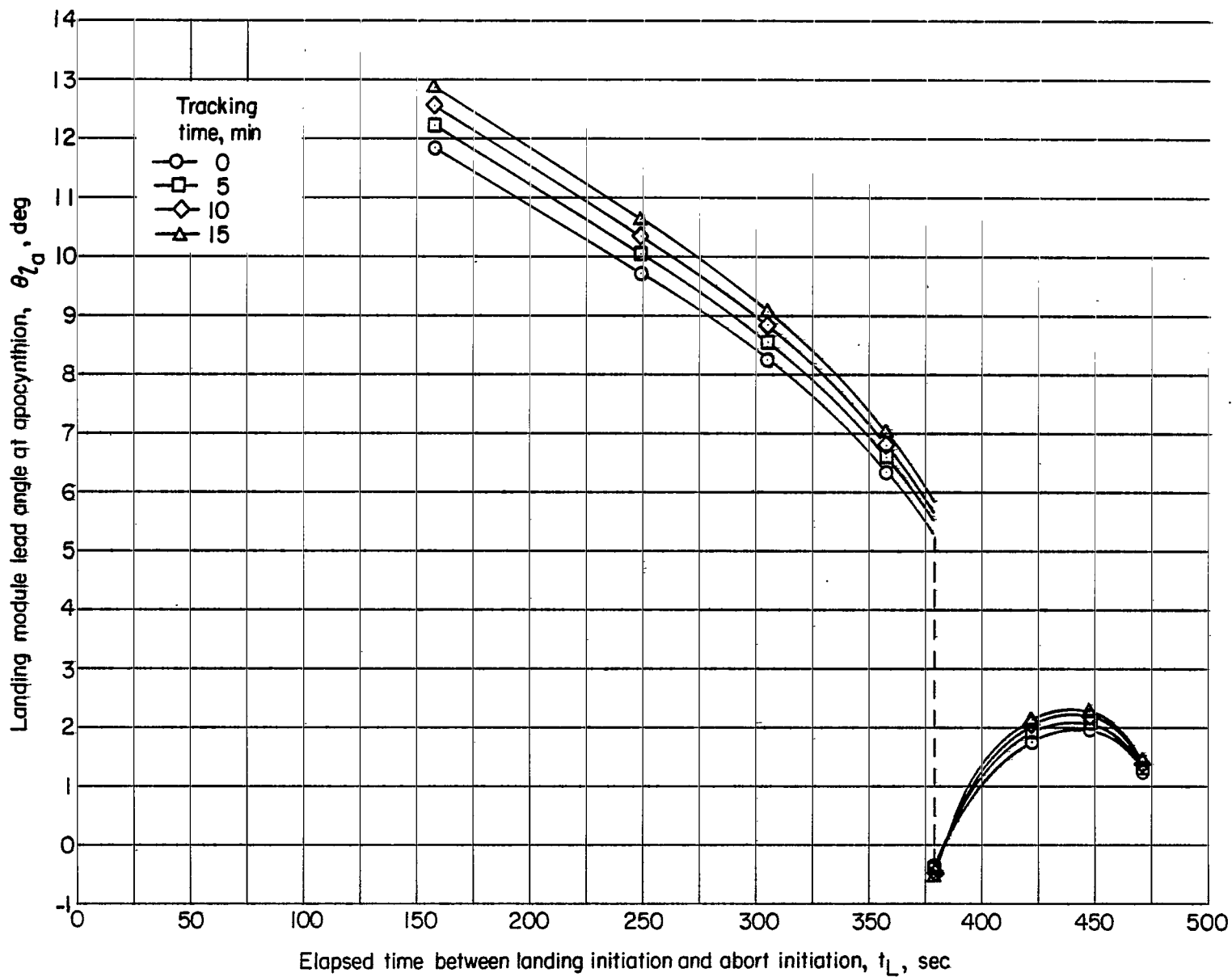


Figure 21.- Landing-module lead angle at apocynthion altitudes required to make orbit circular.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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