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SUMMARY

An analytical investigation has been made of a technique to abort the lunar mission during the landing phase. The piloted abort technique made use of a stopwatch and an optical device for measuring the angle between the vehicle thrust nozzle and a visual reference. If the landing is aborted during the first 75 percent of the landing trajectory, the abort maneuver consists of applying thrust along the line of sight to the lunar horizon for a time period proportional to the time along the landing trajectory at which abort is initiated. The proportionality constant is the ratio of the thrust-weight ratio used during landing to the thrust-weight ratio used during abort. Aborts initiated later in the landing trajectory require the use of an initial period of thrusting at a steep angle to avoid lunar impact followed by a more horizontal period of thrusting.

The results of the investigation showed that the abort maneuver could place the ferry vehicle in a safe orbit when the landing was aborted prior to the transition to vertical descent. Increasingly more accurate maintenance of the thrust angle was necessary as the range between landing initiation and abort initiation increased. Thrust-angle errors of ±1° were permissible for aborts from the first 75 percent of the landing trajectory. Later aborts permitted errors of only ±0.5°.

INTRODUCTION

One of the present concepts (ref. 1) for accomplishing the lunar landing mission involves establishing a circular orbit about the moon at an altitude of approximately 80 nautical miles. When the orbital characteristics of the vehicle have been established, the ferry vehicle is detached from the command module and placed in the desired elliptic orbit (i.e., with a period equal to that of the circular orbit and a properly positioned pericynthion at an altitude of 50,000 feet). The ferry vehicle coasts in the equiperiod (synchronous) orbit until reaching pericynthion, at which time thrust is applied to initiate the landing maneuver. In the event of a mission abort at this point, the ferry vehicle remains in the synchronous orbit, thus enabling rendezvous once each orbital period, or approximately every 2 hours. However, if the landing maneuver is started and an abort situation subsequently develops, the ferry vehicle must be placed in a safe orbit. The abort procedure to be used in establishing safe orbits should be simple and require a minimum of equipment. The present paper presents an analytical examination of a scheme which requires only a pilot and his use of line-of-sight measurements and time.

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 = 1.852000 kilometers

C	thrusting-time constant
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 above lunar surface, ft
I_{sp}	specific impulse, 305 sec
K	angle between thrust axis and line of sight to horizon, positive when above horizon, radians or deg
m	mass of ferry vehicle, slugs
P	orbital period of circular orbit at an altitude of 80 nautical miles, 7,354 sec
δP	difference between orbital periods, P - period of ferry vehicle, sec
R_L	surface range between landing initiation and abort initiation, ft
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
β	range angle between local vertical and point of tangency of line of sight to lunar horizon, radians or deg
γ	angle between flight path and local horizontal, radians or deg
θ	range angle between pericynthion of orbit established by abort maneuvers and nominal landing site, radians or deg
θ_l	range angle by which the ferry vehicle leads the command module, radians or deg
θ'	range angle between minimum altitude and nominal landing site, radians or deg
$\bar{\theta}$	angular travel over surface of moon, radians

Subscripts:

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

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

The nominal landing trajectory used in this study consists of applying constant thrust at pericynthion of the synchronous orbit and performing a gravity-turn descent (for which thrust is directed against the velocity vector) to a point about 6,000 feet above the lunar surface. At this point the ferry vehicle has approximately zero velocity. A vertical descent is then made to the surface. The trajectory characteristics of the gravity-turn phase of the landing are presented in figure 1. It is seen that the flight-path angle γ

changes very little during the first 90 percent of the range of the nominal gravity-turn landing trajectory. (See fig. 1(c).) In addition, K, the angle between the thrust axis and the line of sight to the lunar horizon changes only slightly throughout the same range. This small amount of variation indicates that the horizon is a convenient reference which might be useful in developing a simple abort maneuver.

Basic Abort Maneuver

At a given point along the landing trajectory the velocity has been reduced a given amount by applying thrust at an essentially constant value of K. It should therefore be possible to establish a safe orbit by applying the same velocity change using a constant thrust angle with respect to the other horizon. (See fig. 2.) In order that the velocity change during landing and abort be equal, it is necessary to thrust during abort for a time period given approximately by

$$t_A = \frac{(F/W_o)_{landing}}{(F/W_o)_{abort}} t_L = Ct_L \qquad (1)$$

where t_L is the elapsed time between landing initiation and abort initiation and C is a constant.

The abort maneuver used in the present investigation is predicated on the assumption that the pilot has available a stopwatch and an instrument that provides angular measurements between vehicle thrust axis and the horizon. The stopwatch is started when the landing is initiated and is stopped at that point along the landing trajectory where abort is deemed necessary. Staging is then accomplished, and that portion of the ferry vehicle necessary only for landing is released. The basic abort maneuver is then initiated by rotating the ferry vehicle to the thrust angle K that is appropriate for the particular time t_L of abort initiation. Thrust is then applied and maintained for the appropriate time. This procedure should result in placing the ferry vehicle in a safe orbit.

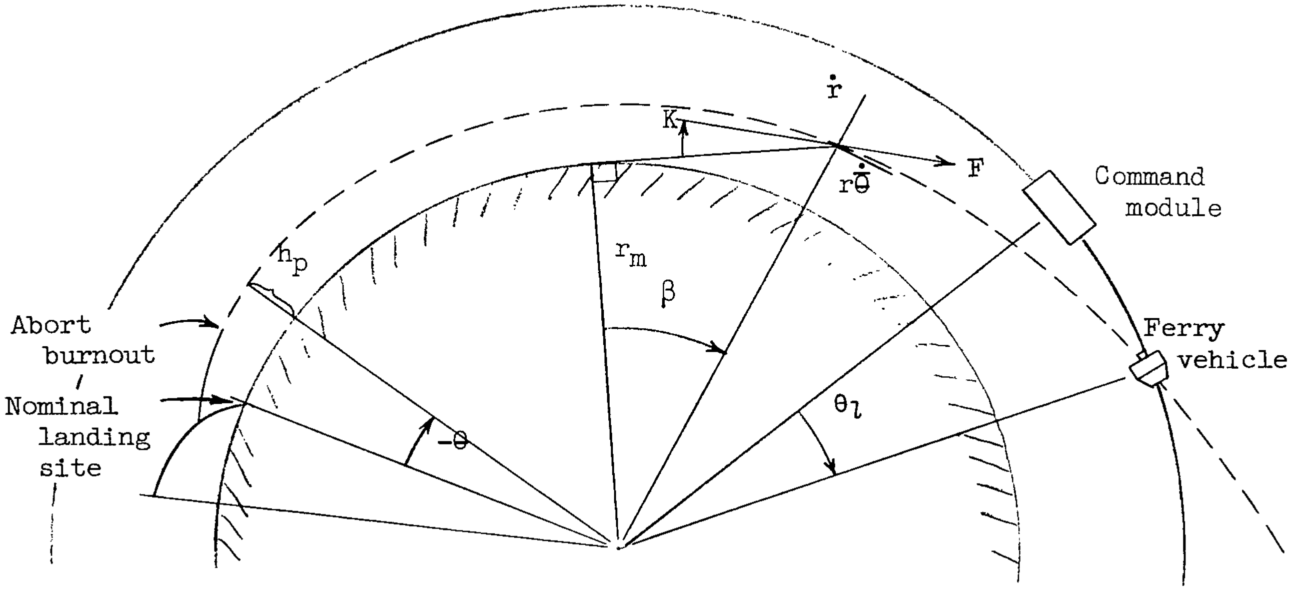
This procedure was found to be satisfactory for about the first 75 percent of the landing range (where K was nearly constant). However, the basic maneuver, if applied in the region where K varies rapidly (fig. 1(c)) proved to be unsatisfactory in that the abort trajectory would impact the lunar surface. This situation was remedied by use of a modified procedure which is described in the section "Modified Abort Maneuver."

Modified Abort Maneuver

If abort is initiated toward the end of the landing trajectory, a period of thrusting at fairly steep angles is required to avoid impacting the lunar surface. Therefore, a modifed abort maneuver was devised to utilize an initial thrusting period of $0.1t_L$ seconds during which the thrust is arbitrarily directed 50° below the line of sight to the horizon ($K_1 = -50°$), followed by a period during which the thrust is directed more nearly horizontally. The value of K_2 is chosen as that angle appropriate for the particular time at which abort is initiated. In addition, the total time constant for the modified abort technique is somewhat greater than the value which would be used for the basic abort technique.

Equations of Motion

The axis system and pertinent angles used in this investigation are illustrated in the following sketch. The computations were made for a point mass moving in a plane about a spherical moon. A straightforward derivation of the general equations of motion of a point mass in spherical coordinates is presented in reference 2. The equations of motion used in this study may be obtained by substituting the appropriate angles in the sketch into the general spherical equations of reference 2. For reference, the resulting equations are presented as follows:



$$\ddot{r} - r\dot{\theta}^2 = \frac{F}{m}\sin(\beta - K) - g_m\left(\frac{r_m}{r}\right)^2 \qquad (2)$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = \frac{F}{m}\cos(\beta - K) \qquad (3)$$

where

$$m = m_o + \int \dot{m}\, dt \tag{4}$$

$$\dot{m} = -\frac{F}{g_e I_{sp}} \tag{5}$$

and

$$\beta = \cos^{-1}\left(\frac{r_m}{r}\right) \tag{6}$$

These equations were solved on an electronic digital computer. An iteration process was used to obtain the value of K which would yield an acceptable orbit for a given abort condition.

Assumed Vehicle Parameters

It was assumed that the vehicle was fully staged at abort and that the abort maneuver was made using the lunar ascent engines. It was also assumed that rotation of the vehicle from its descent-trajectory orientation to its abort orientation occurred instantaneously. The values of F/W_o used for the descent and ascent stages were 0.485 and 1.20, respectively. These values specify the thrusting time for the basic abort maneuver through equation (1); that is,

$$t_A = \frac{(F/W_o)_{landing}}{(F/W_o)_{abort}} t_L = 0.404 t_L \tag{7}$$

For the modified abort maneuver, t_A was $0.424t_L$, of which $0.1t_L$ was used as the initial thrusting period at $K_1 = -50^\circ$. These values are empirical.

DISCUSSION OF RESULTS

Basic Abort Maneuver

For the range of the values of K studied, the basic abort maneuver results in the establishment of nonimpacting orbits when used over the majority of the landing range. (See figs. 3 and 4.) It may also be seen from figure 4 that the simple expedient of directing thrust along the line of sight to the lunar horizon, $K = 0^\circ$, results in a pericynthion altitude greater than or equal to 30,000 feet for aborts up to 650,000 feet from landing initiation. Thus, pericynthion exceeds the highest known lunar protuberances. (See ref. 3.)

However, it is not difficult to choose the nominal landing site to be in an area of the moon that contains no surface formations that exceed 20,000 feet. If $K = 0^{\circ}$ is used and if the landing site is chosen so that pericynthion altitudes of 20,000 feet or greater are permissible, safe orbits can be established by using the basic abort maneuver for the first 75 percent of the landing trajectory (650,000 feet downrange of landing initiation), with thrust-angle errors of $\pm 1^{\circ}$ about the desired orientation of $K = 0^{\circ}$. It can be seen from figure 5 that the pericynthions established by the basic abort maneuver are always located within 24° of the nominal landing site. If pericynthion altitudes lower than the highest lunar formations are to be allowed, the location of the nominal landing site must be chosen accordingly.

The elliptic orbit established by the basic abort maneuver using $K = 0^{\circ}$, $\pm 1^{\circ}$, and $\pm 2^{\circ}$ is a rough approximation of the synchronous orbit of the landing phase, the primary difference being a rotation of the line of apsides. The orbit of the ferry vehicle intersects the 80-nautical-mile-altitude circular orbit of the command module (fig. 6), and at the first intersection the ferry vehicle leads the command module by approximately 14° to 19° (fig. 7(a)). At the second intersection the lead angle is less than 4.5° for all cases (fig. 7(b)); for aborts prior to 650,000 feet after landing initiation, the lead angle is less than 3° and the two vehicles are less than 55 nautical miles apart. However, the orbital period of the ferry vehicle is somewhat less than that of the command module (fig. 8), and the lead angle of the ferry vehicle increases with each revolution by as much as 6°.

Modified Abort Maneuver

As previously defined, the modified abort maneuver consists of applying thrust at an initial thrust angle K_1 of -50° for $0.1t_L$ seconds, followed by a more horizontal thrust angle K_2. It was empirically determined that a firing time of $0.324t_L$ during the K_2 phase of the abort maneuver was sufficient to place the ferry vehicle in a safe orbit for the range of the values of K investigated.

The altitude at pericynthion is not the minimum altitude reached during the modified abort maneuver. The minimum altitude, which occurs during the initial phase of the abort at $K_1 = -50^{\circ}$, is in close proximity to the nominal landing site (fig. 9) and hence should not constitute a problem.

The modified abort maneuver results in the establishment of nonimpacting orbits when used over the final portion of the landing range. (See figs. 10 and 11.) The advantage of choosing the nominal landing site so that pericynthion altitudes may be reduced as much as possible is indicated in figure 11. For example, if it is assumed that a thrust-angle error of $\pm 0.5^{\circ}$ is allowable, it is possible to find a constant thrust angle K_2 so that the modified abort maneuver results in orbits that exceed 20,000 feet at pericynthion for aborts that are initiated prior to 840,000 feet downrange from landing initiation. However, if the pericynthion altitude is limited to those in excess of 30,000 feet, then the range at abort initiation is restricted to 780,000 feet.

The altitude at pericynthion is more sensitive to the abort initiation point in this region of the nominal landing trajectory than was the case for aborting during the first 75 percent of the landing. The use of a single value of K_2 for the entire region does not result in orbits with pericynthion altitudes in excess of 20,000 feet. However, pericynthion altitudes greater than 20,000 feet can be obtained by using a thrust-angle program of K_2 equal to 9.5° for aborting prior to 750,000 feet, 7.75° for aborting between 750,000 feet and 800,000 feet, and 7.0° for aborting between 800,000 feet and 840,000 feet. (See fig. 11.) The resulting pericynthions are located between -40° and 30° of the nominal landing site (fig. 12). Alternately, the constant thrust angle to be used can be specified as a linear function of the elapsed time between landing initiation and abort initiation. For example, the following function results in pericynthion altitudes greater than 20,000 feet for aborts up to 235 seconds or 830,000 feet from landing initiation (fig. 11) and also results in having the pericynthion position very near the nominal landing site (fig. 12).

$$K_2 = f\left(t_L\right) = 17.60 - 0.0476t_L \qquad \left(146 \leqq t_L \leqq 240\right)$$

where K_2 is expressed in degrees.

The increased complexity of the abort procedure due to the necessary modifications creates a display problem. One solution to the problem is to present the necessary abort information on a timing device as indicated in the appendix. The elliptic orbits established by the modified abort maneuver in general do not intersect the 80-nautical-mile-altitude circular orbit. (See fig. 13.) The angular distance by which the ferry vehicle leads the command module at ferry-vehicle apocynthion or, should the two orbits intersect, at the first intersection point is shown in figure 14. The lead angle varies from about 9° to about 22°, and therefore the two vehicles are approximately 160 to 350 nautical miles apart. The orbital period of the ferry vehicle is considerably less than that of the command module (fig. 15); consequently, the lead angle of the ferry vehicle increases by as much as 10° to 20° per revolution.

No attempt has been made to optimize the thrusting time used in the modified abort maneuver; $0.324t_L$ was used at the reference angle K_2 because it satisfied the requirements for establishing safe orbits. An indication of the effect of further increasing this time constant on the orbital parameters is shown in figure 16. The larger time constant, 0.334, resulted in higher pericynthion altitudes and reduced the angular separation of the pericynthion from the nominal landing site. Apocynthion altitude increased so that all orbits intersected the 80-nautical-mile-altitude circular orbit. The lead angle of the ferry vehicle is reduced slightly at the first intersection point, and at the second intersection the ferry vehicle trails the command module. The period of the ferry vehicle is increased to the point that it exceeds that of the command module, and the lead angle of the ferry vehicle decreases with each revolution.

Characteristic Velocity

The characteristic velocity required to perform the abort maneuver is less than 3,200 feet per second for the basic abort maneuver to a range of 650,000 feet and less than 6,000 feet per second for the modified abort (figs. 17 and 18, respectively). Increasing the thrusting-time constant from 0.304 to 0.324 required approximately 400 feet per second, and the increase from 0.324 to 0.334 requires about 200 feet per second.

Error Analysis

Various types of errors could be made in attempting to control the vehicle in a prescribed manner. For example, the abort maneuvers considered assume that the landing vehicle has a particular velocity-altitude combination corresponding to the given range from landing initiation along the nominal landing trajectory at which the abort is initiated. Consequently, errors in velocity or altitude at abort initiation result in the establishment of orbits that are different from those nominally expected. The effect on the altitude at pericynthion and apocynthion of initial errors in radial velocity, tangential velocity, and altitude at three ranges of abort initiation is shown in figure 19. Errors in radial velocity primarily influence pericynthion altitude, whereas errors in tangential velocity primarily affect apocynthion altitude. Errors in altitude have some effect on pericynthion altitude and practically no effect on apocynthion altitude.

It was assumed in this investigation that the transition of the ferry vehicle from landing attitude to the attitude at abort initiation occurred instantaneously. The effect of delaying abort thrust initiation until the ferry vehicle has been pitched to the proper abort attitude is indicated in figure 20, which presents the change in altitude at pericynthion and apocynthion as a function of delay time at three abort points. For the modified abort maneuver, one-half of the delay time is used to rotate to K_1 and one-half, to rotate to K_2. As can be seen, this effect can be appreciable. However, for known vehicle characteristics, this delay time could be anticipated and the abort maneuver could be adjusted accordingly.

An indication of the effect of errors in duration of abort thrusting time on the orbits established by the basic abort maneuver with $K = 0^{\circ}$ is shown in figure 21. For aborts that take place prior to 650,000 feet downrange from landing initiation, the resulting altitude at pericynthion is not affected appreciably for thrusting-time errors of ±2 seconds. However, the change at apocynthion is rather large, and the resulting orbits are no longer close approximations to the synchronous orbit of the landing maneuver. The range angle between the ferry vehicle and the command module at the second intersection of the two orbits is no longer small if thrusting time is terminated 2 seconds too late, and if thrusting time is terminated 2 seconds early the orbits fail to intersect. The difference between the periods of the two orbits is also changed considerably, and the lead angle of the ferry vehicle at orbital intersection or at its apocynthion should no intersection exist changes approximately three times as rapidly as when no thrusting-time error is present.

The vast majority of the lunar mountains fall between 0.5 and 1.5 nautical miles in altitude. (See ref. 3.) However, even these irregularities can introduce errors into the measurement of the thrust angle K. For example, a surface formation 6,000 feet in altitude can introduce uncertainties into K of approximately 0.5° to 1.2°, depending on the ferry vehicle altitude. These uncertainties can be minimized by sighting at the base of the distant mountains or by using an average horizon. In any event, the area around the nominal landing site should be as flat as possible.

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 longitudinal axis of the ferry vehicle and the line of sight to the lunar horizon. The landing trajectory from which aborts were considered was a gravity-turn descent to 5,000 feet from the 50,000-foot pericynthion altitude of an equiperiod transfer from the command module.

It was found that by thrusting for a period of time which is proportional to the elapsed time between landing initiation and abort initiation, nonimpacting orbits can be established by directing thrust along the line of sight to the lunar horizon if the abort takes place during the first 75 percent of the landing trajectory. Thrust-angle errors of ±1° are permissible with the resulting orbits having altitudes at pericynthion greater than or equal to 20,000 feet.

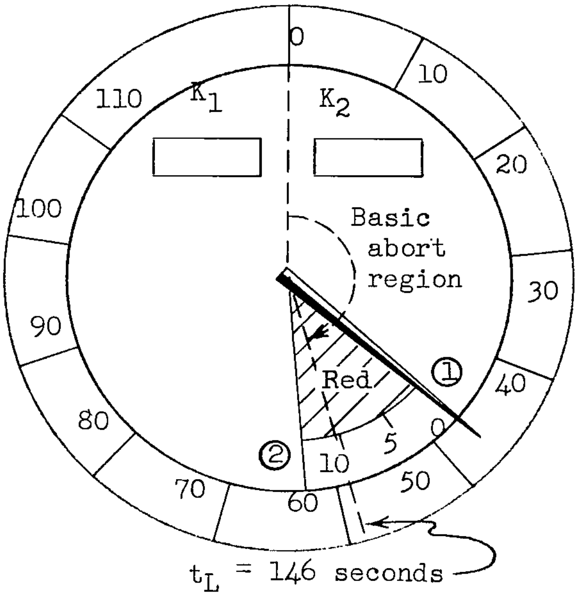
If an abort is deemed necessary during the latter part of the landing trajectory up to the transition to vertical descent, nonimpacting orbits can be established by directing thrust 50° below the lunar horizon for a short period of time followed by thrusting slightly above the lunar horizon for a period of time. Both thrusting times are functions of the elapsed time between landing initiation and abort initiation. The second thrust angle can also be represented as a linear function of the elapsed time between landing initiation and abort initiation. Thrust-angle errors of ±0.5° are permissible, with the resulting orbits having altitudes at pericynthion greater than or equal to 20,000 feet.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 17, 1964.

APPENDIX

MECHANICAL TIMING DEVICE

The principles of a mechanical timing device for displaying the information necessary for performing the abort maneuver are indicated in the following sketch. The device, which is essentially a sophisticated stopwatch, should be reliable, compact, and lightweight. The timing device is activated at landing initiation, and the pointer moves clockwise at $\frac{(F/W_o)_{landing}}{(F/W_o)_{aborting}}$ times real time ($0.404t_L$ for the present investigation) until it reaches the limit ($t_L = 146$ seconds) for the basic abort maneuver. During this time the digital readouts of the thrust angles K_1 and K_2 indicate 0°. When an abort is initiated in this region, a button on the device is pushed and the pointer reverses its direction and moves counterclockwise at real time. The pilot then thrusts at $K = 0^{\circ}$ until the pointer reaches zero, at which time thrust is terminated.



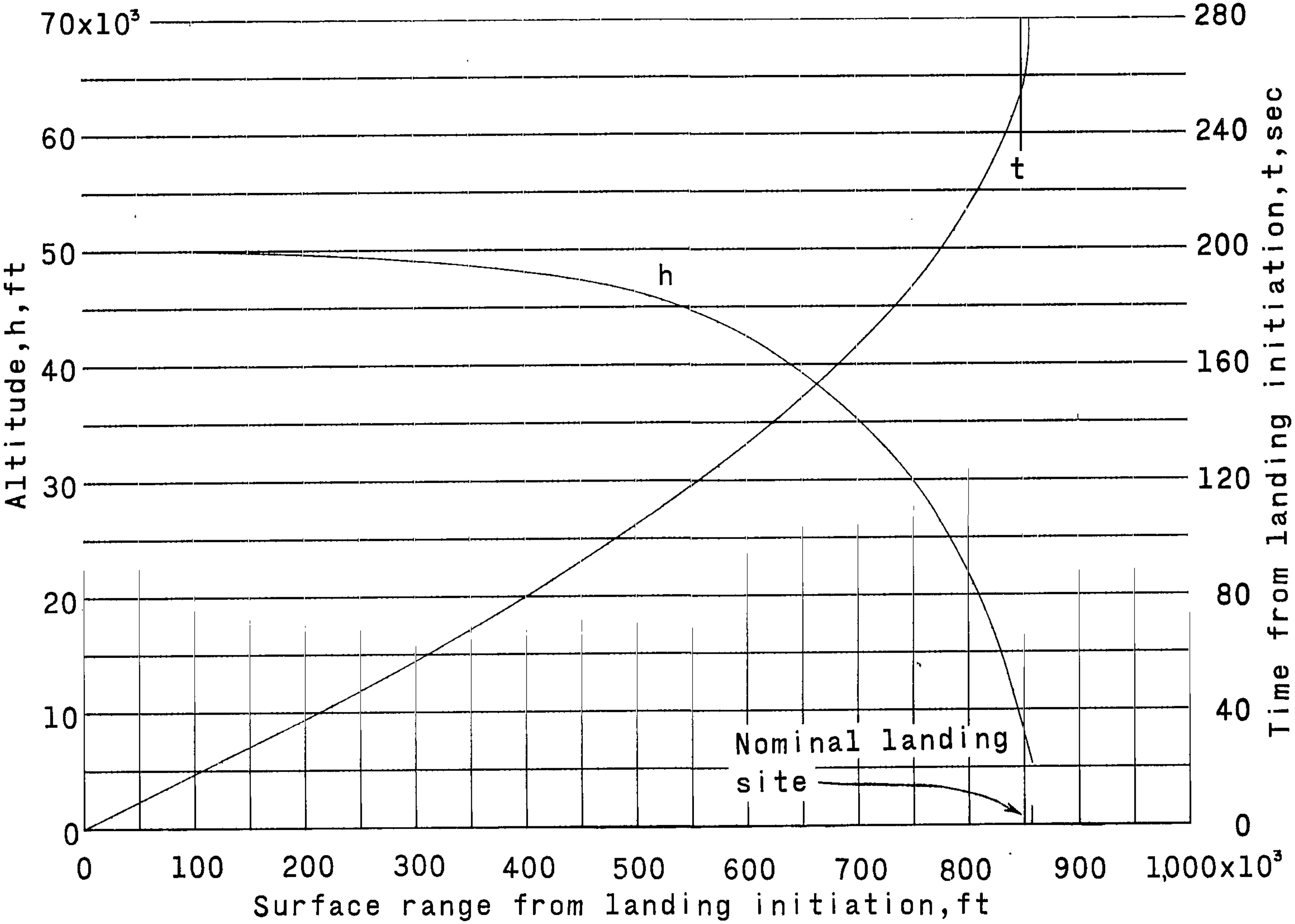
If no abort is necessary during the region when the basic abort maneuver is applicable, the pointer continues clockwise until the limiting value of time ($t_L = 146$ seconds) is reached. The pointer then jumps backwards, counterclockwise, to the position of 0.324 times the limiting value of $t_L = 146$ seconds (position ① in sketch). Simultaneously, a red sector opens up with its leading edge jumping clockwise to the position corresponding to 0.424 times the limiting value of time (position ② in sketch). The leading edge of the sector is then driven clockwise at 0.424 times real time while the pointer, the sector trailing edge, and the scale of the sector are driven clockwise at 0.324 times real time. The scale of the red sector indicates the time ($0.1t_L$) of firing at the initial thrust angle K_1 of the modified abort maneuver. The initial thrust angle is in general a function of time, but in the present investigation it is a constant equal to -50°. The second thrust angle K_2 is set at 10° when the pointer moves into the region of applicability of the modified abort procedure and decreases linearly with time thereafter. When an abort is initiated, a button on the timing device is pushed and K_2 remains fixed at its last value. The leading edge of the red sector reverses its direction and moves counterclockwise at real time. The pointer remains fixed until the sector is closed, at which time it moves counterclockwise at real time. Thus, the pilot holds K_1 at -50° until the red sector closes ($0.1t_L$) and then maintains K_2 at the indicated value until the pointer moves to zero and thrust is terminated.

REFERENCES

1. Houbolt, John C., Bird, John D., and Queijo, Manuel J.: Guidance and Navigation Aspects of Space Rendezvous. Proceedings of the NASA-University Conference on the Science and Technology of Space Exploration, vol. 1, NASA SP-11, 1962, pp. 353-366. (Also available as NASA SP-17.)

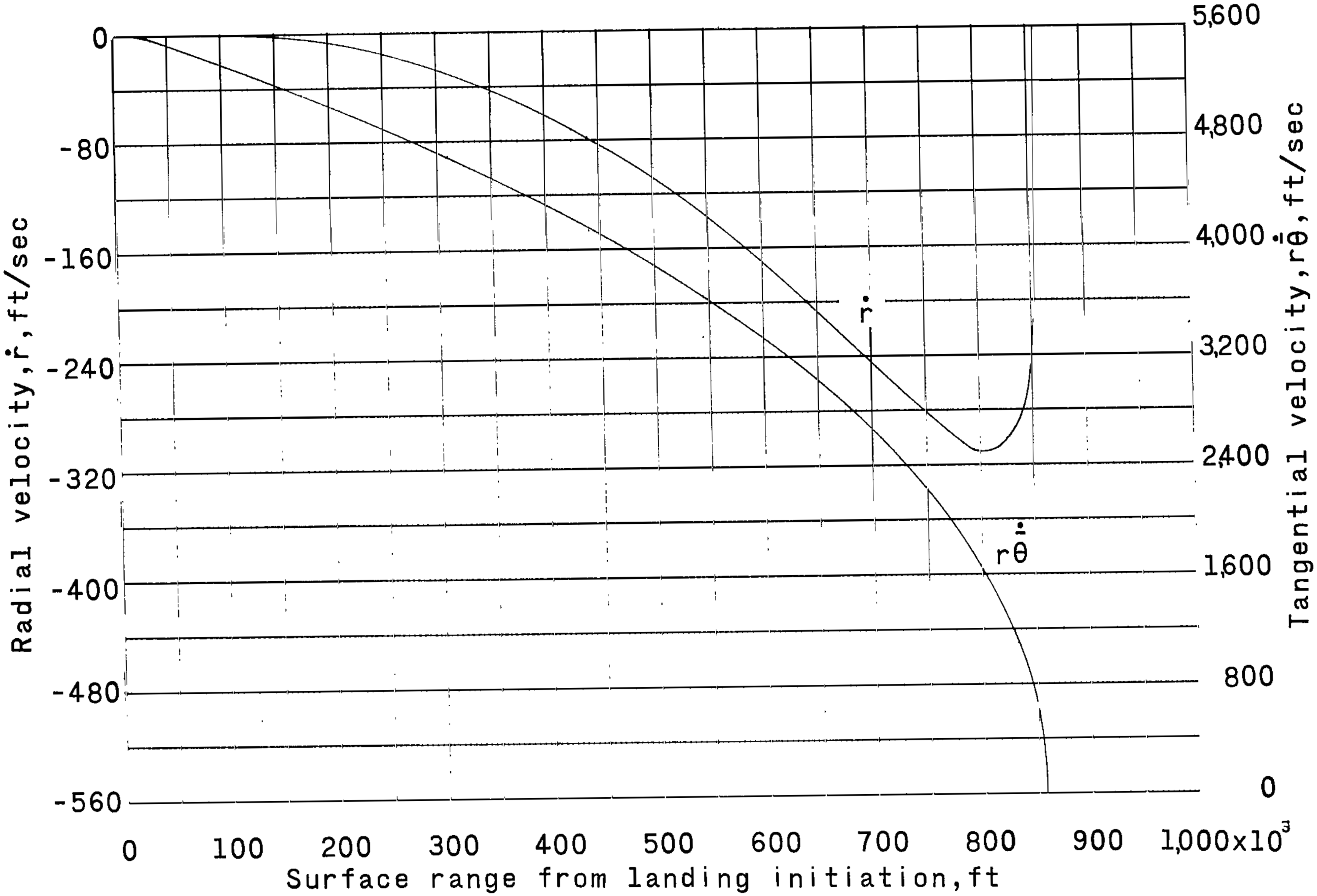
2. Nelson, Richard D.: Effects of Flight Conditions at Booster Separation on Payload Weight in Orbit. NASA TN D-1069, 1961.

3. Kopal, Zdeněk: Topography of the Moon. Physics and Astronomy of the Moon. Zdeněk Kopal, ed., Academic Press, 1962, pp. 231-282.



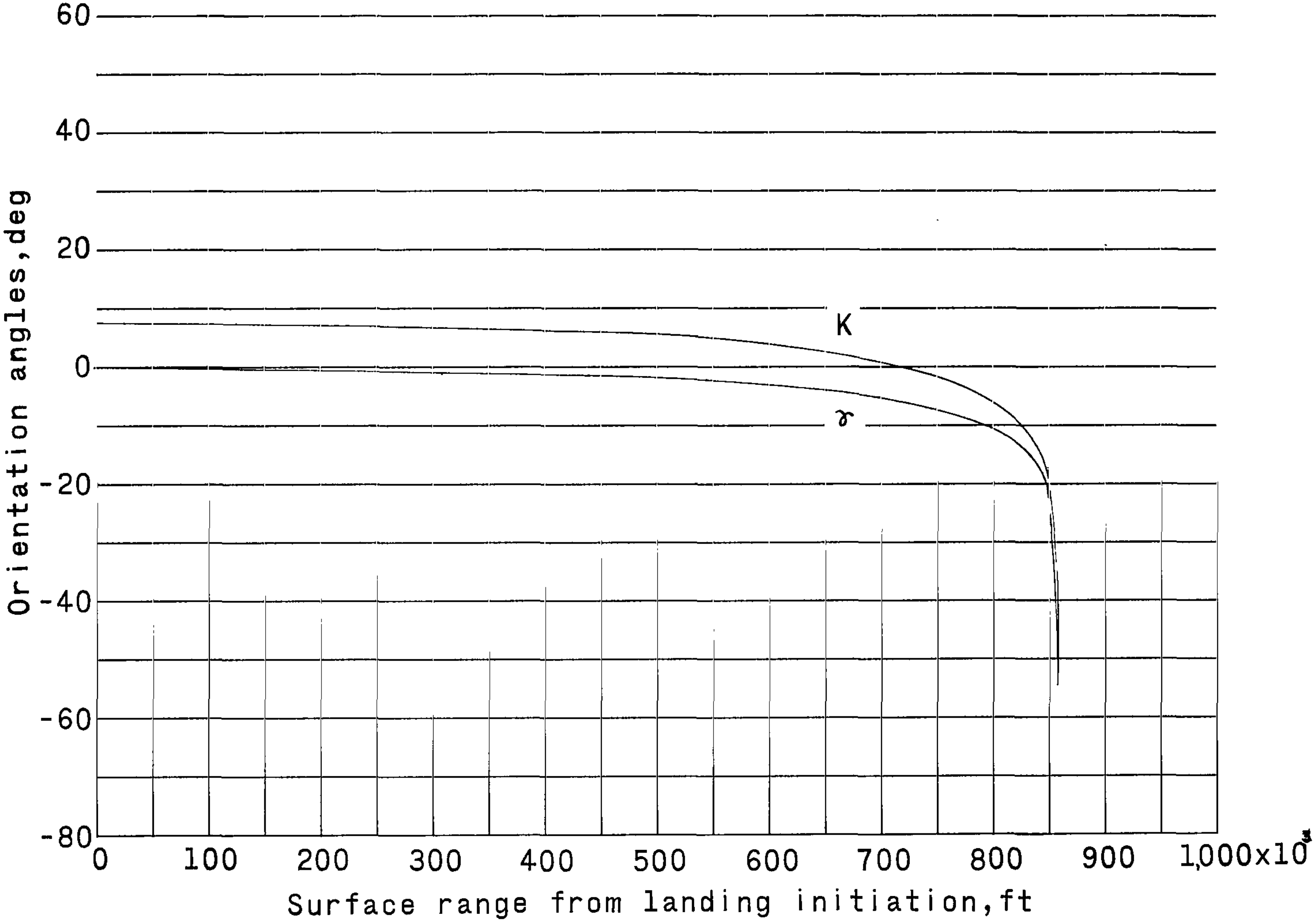
(a) Altitude and time.

Figure 1.- Trajectory characteristics of nominal gravity-turn landing trajectory.



(b) Velocity components.

Figure 1.- Continued.



(c) Flight-path angle γ and thrust angle K.

Figure 1.- Concluded.

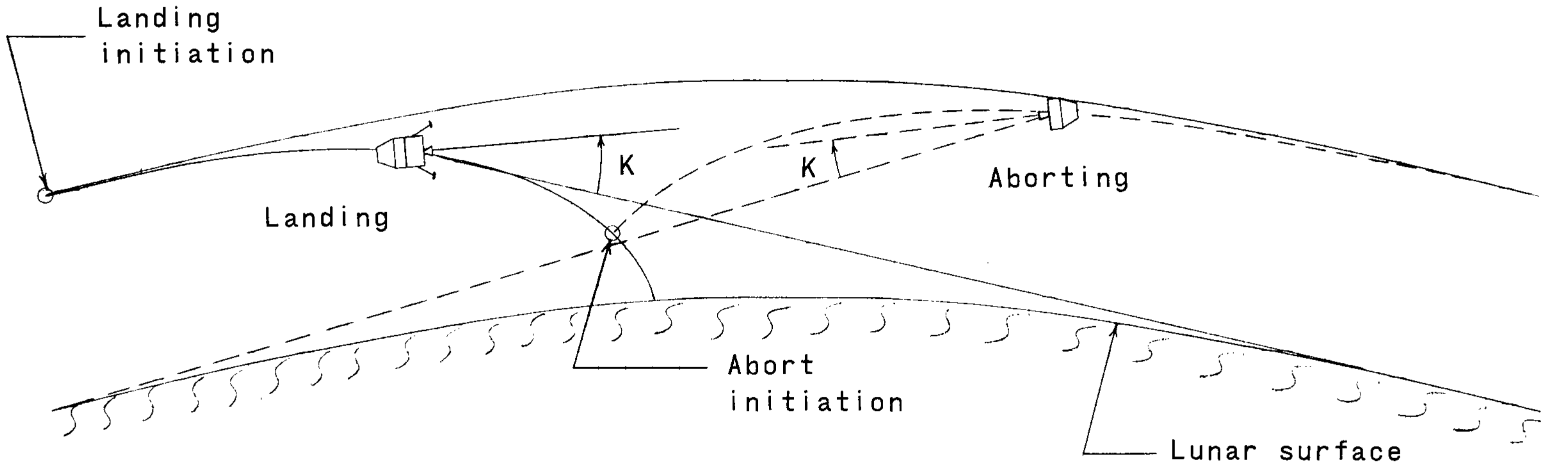


Figure 2.- Illustration of abort maneuver.

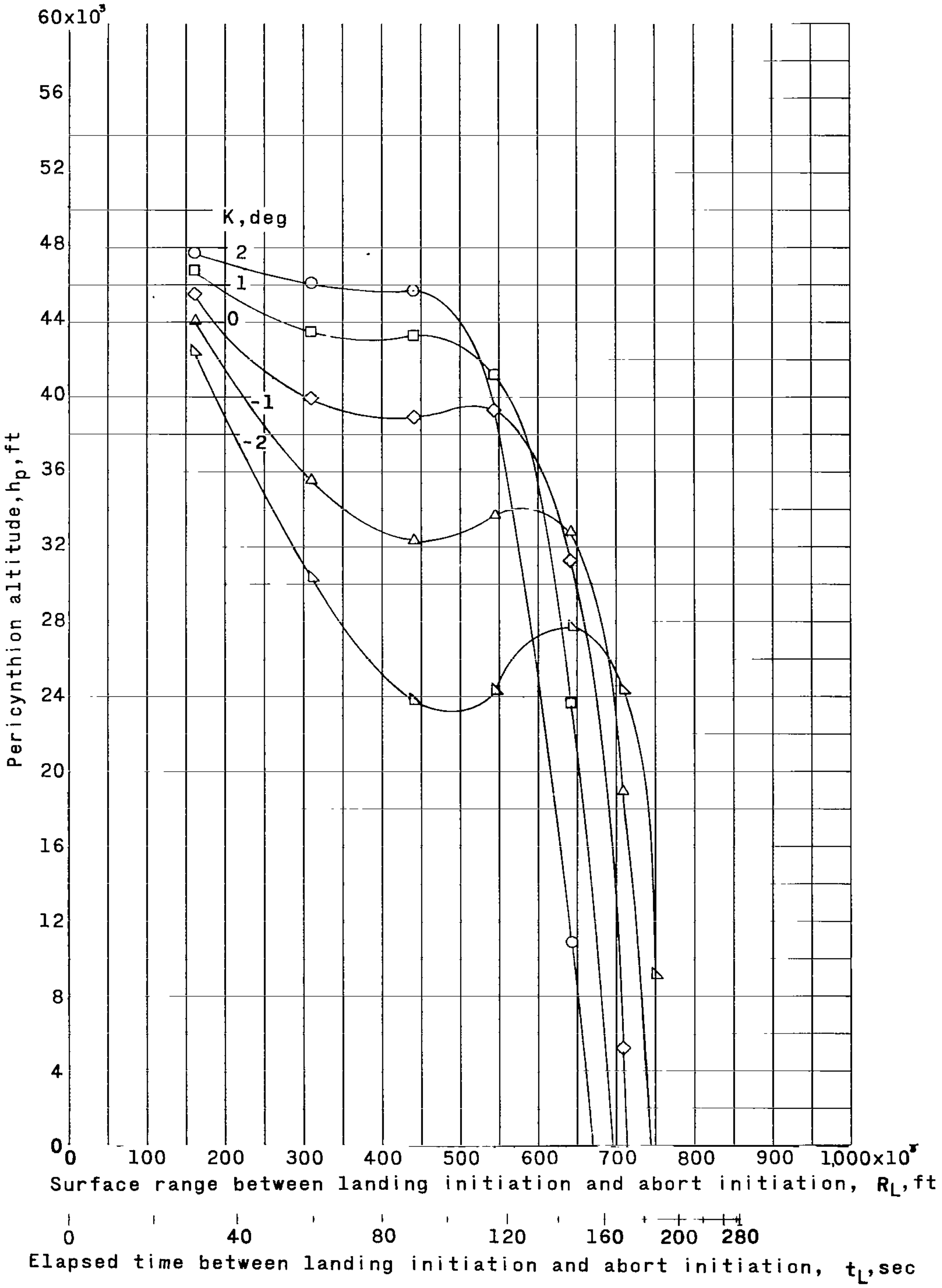


Figure 3.- Pericynthion altitude of orbits established by basic abort maneuver.

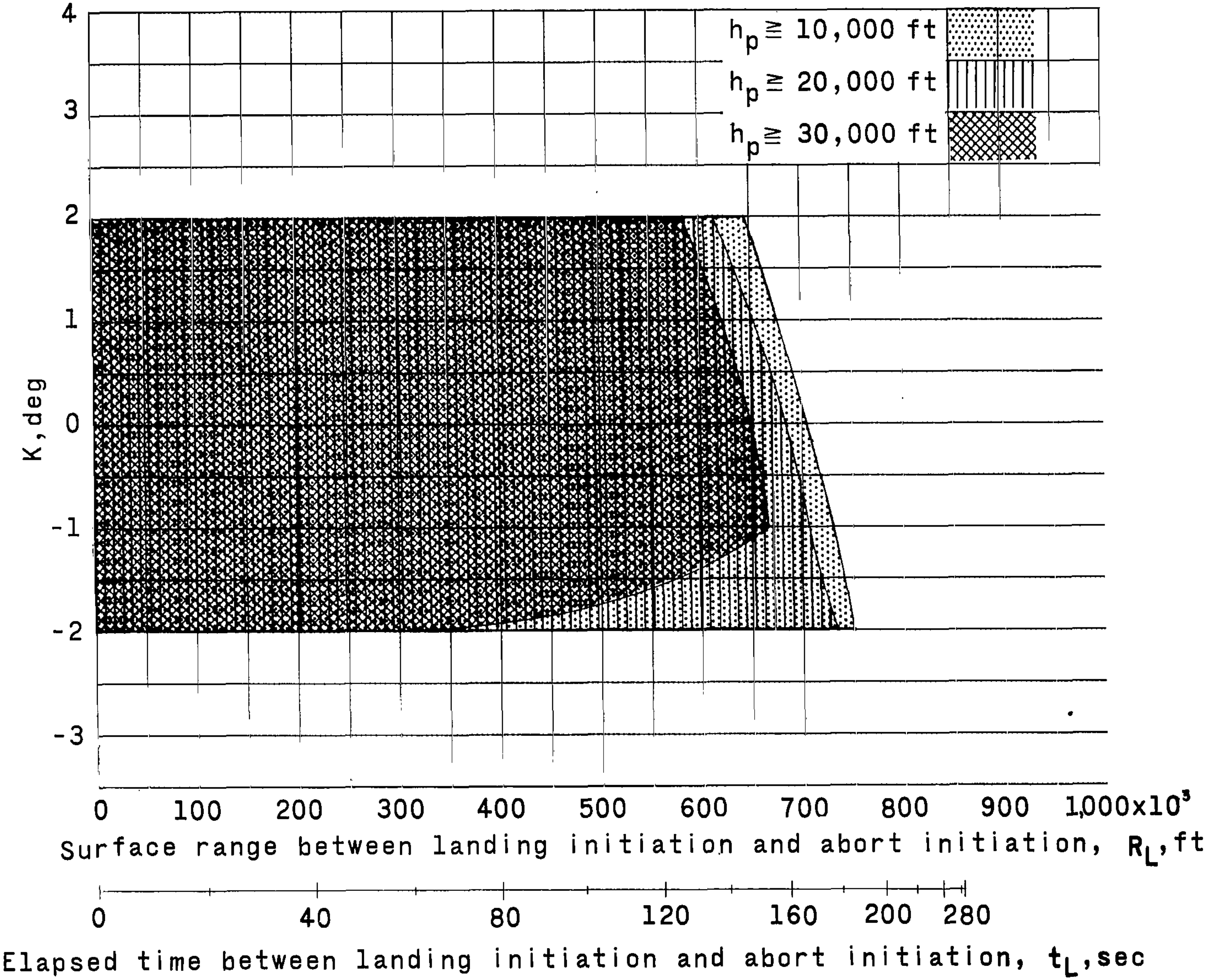


Figure 4.- Thrust-angle boundaries for basic abort maneuver formed by minimum pericynthion altitudes of 10,000, 20,000, and 30,000 feet.

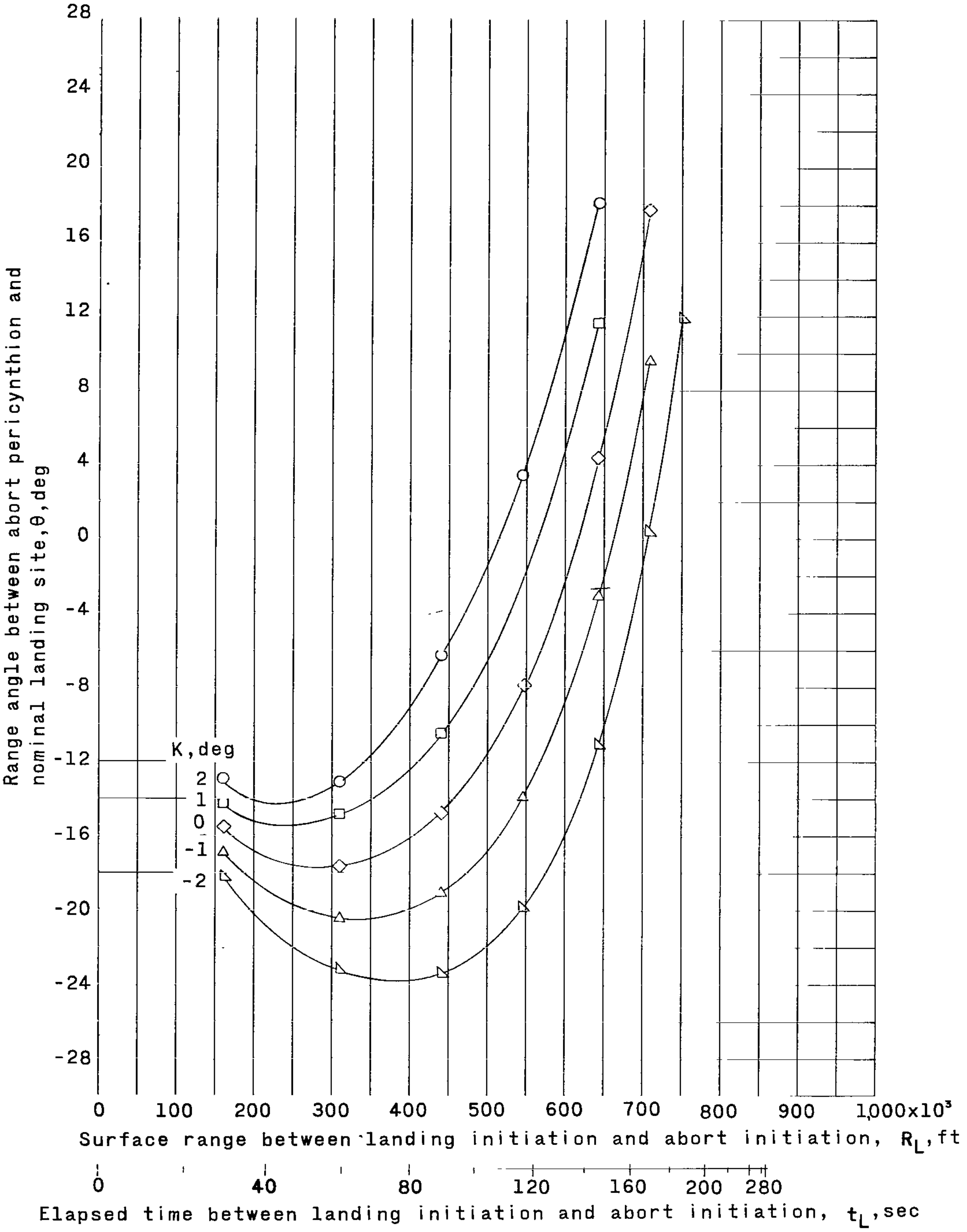


Figure 5.- Location of pericynthion of orbits established by basic abort maneuver. (Negative values of θ correspond to pericynthion that is downrange from nominal landing site.)

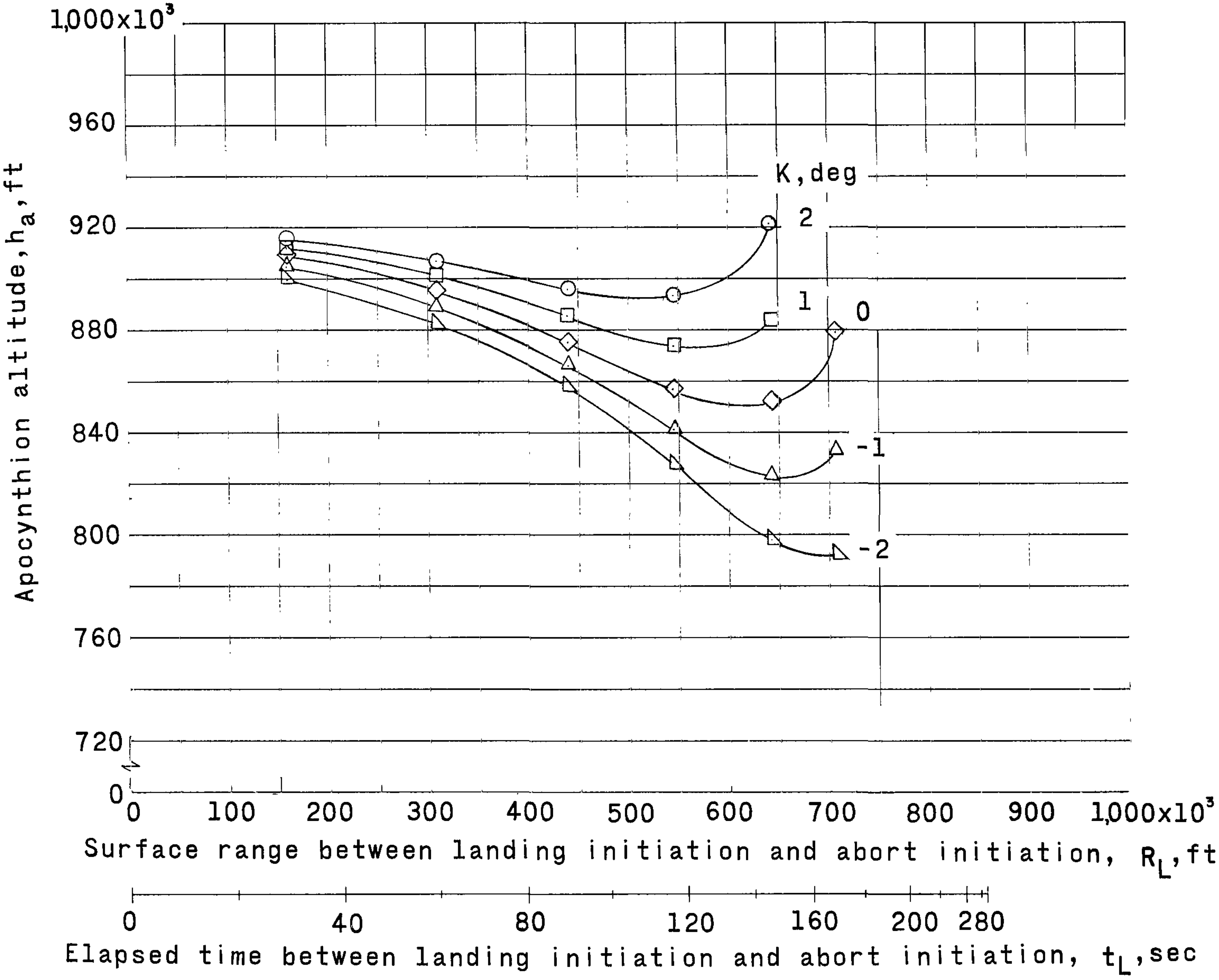
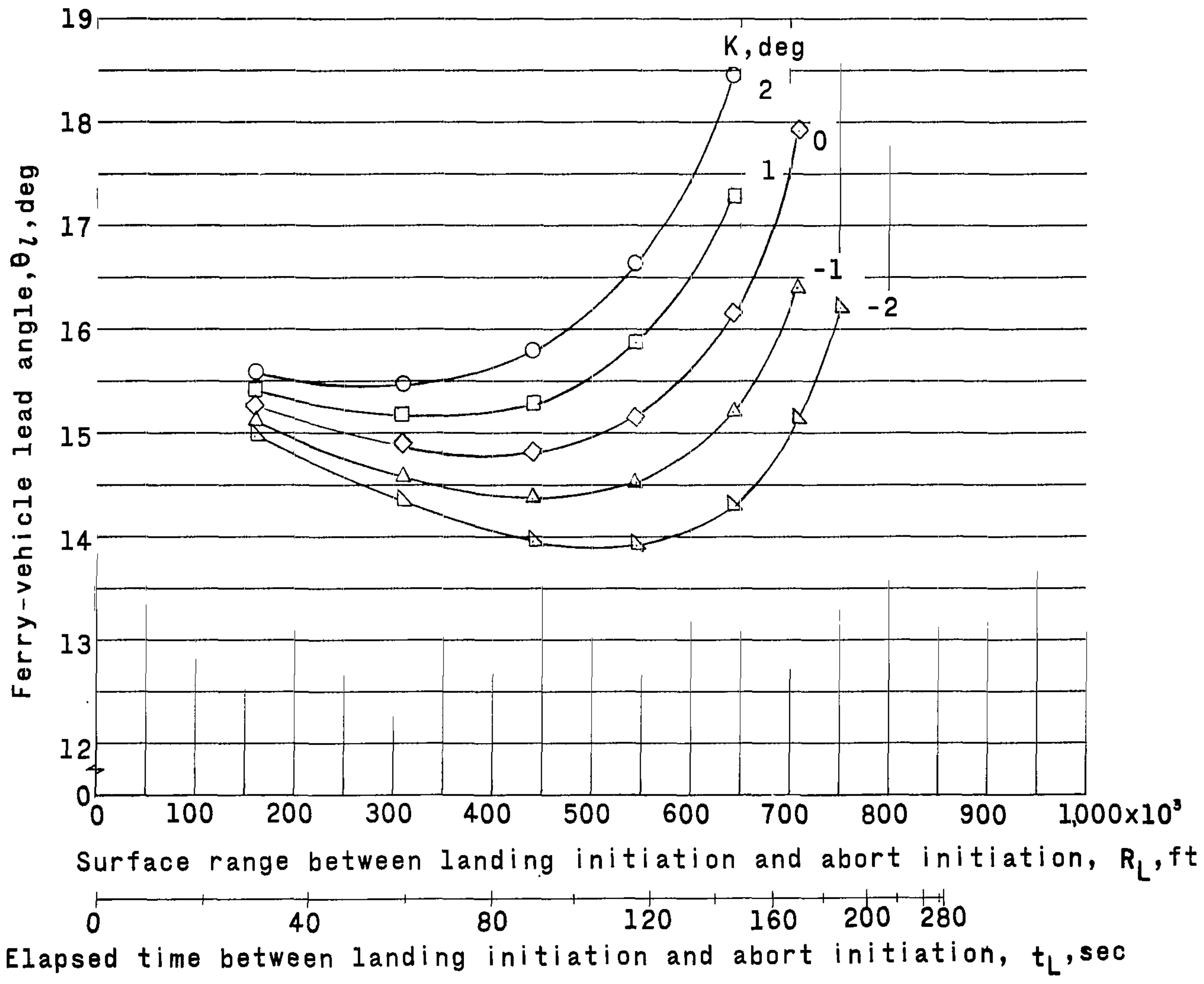
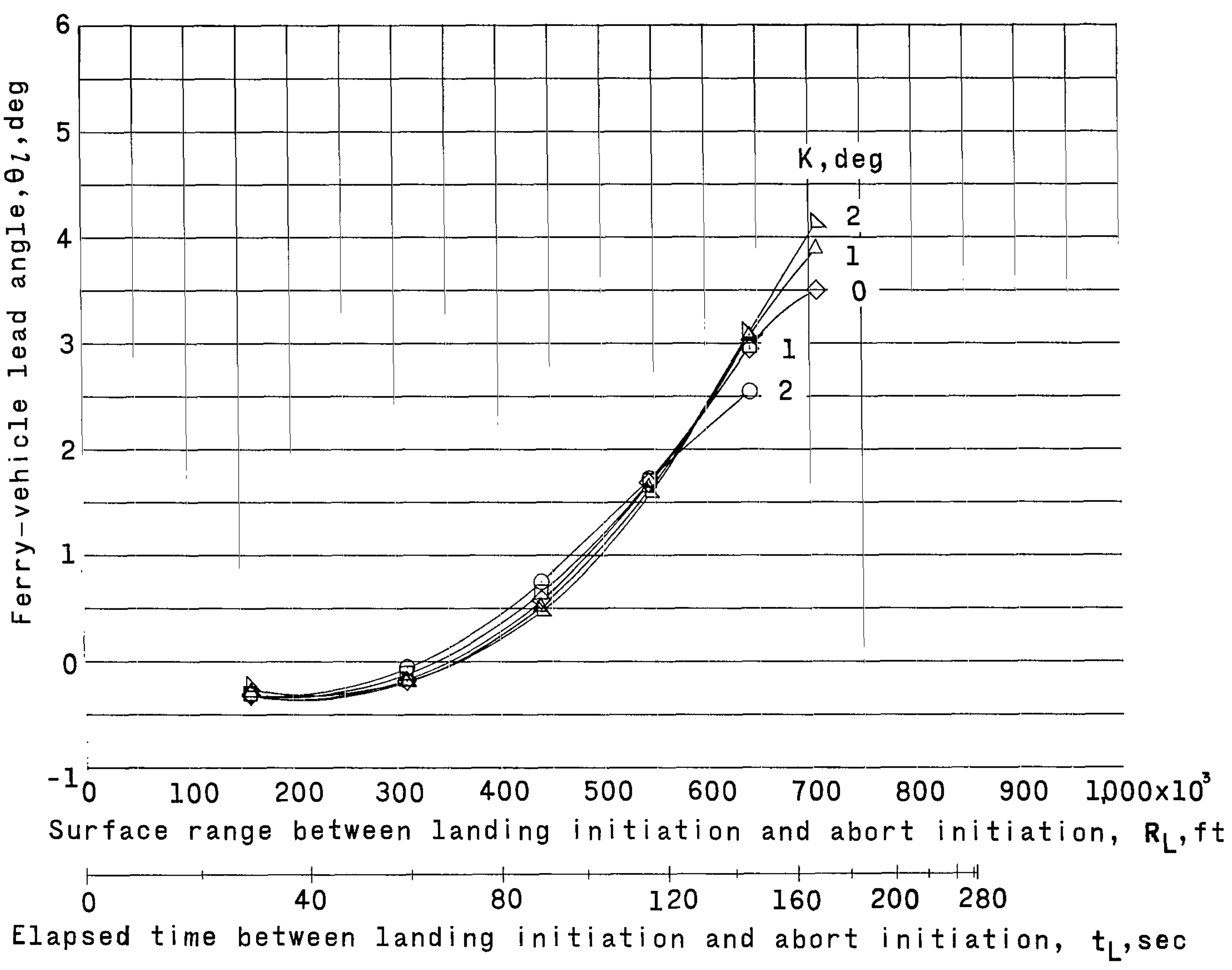


Figure 6.- Apocynthion altitude of orbits established by basic abort maneuver.



(a) First intersection point.

Figure 7.- Angle by which ferry vehicle leads command module when orbit established by basic abort maneuver intersects 80-nautical-mile-altitude circular orbit.



(b) Second intersection point.

Figure 7.- Concluded.

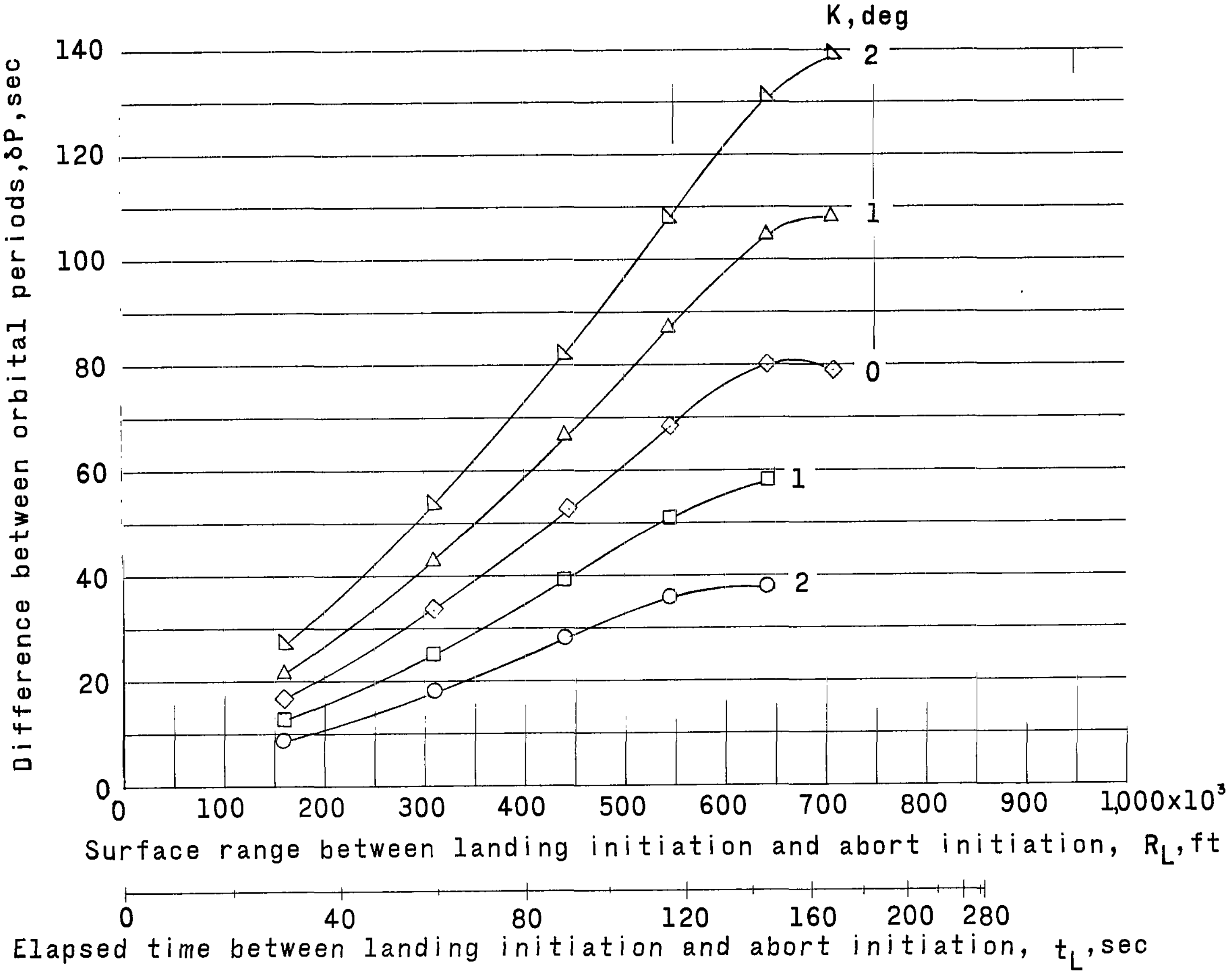


Figure 8.- Difference between period of 80-nautical-mile-altitude circular orbit and that of the orbit established by basic abort maneuver. (Period of ferry vehicle is less than period of circular orbit.)

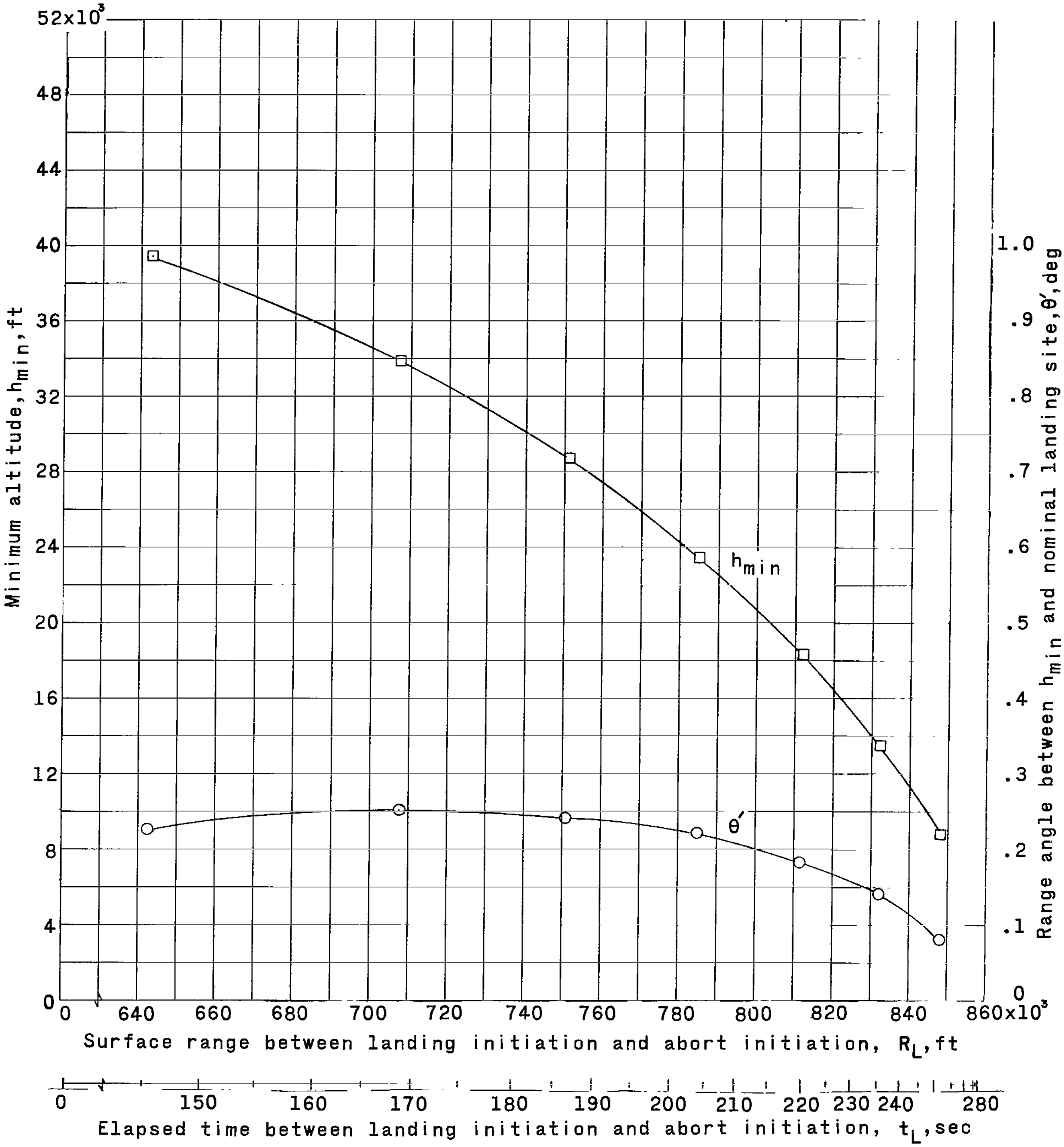


Figure 9.- Minimum altitude reached during initial phase of modified abort maneuver (K_1 = -50°) and its location with respect to nominal landing site.

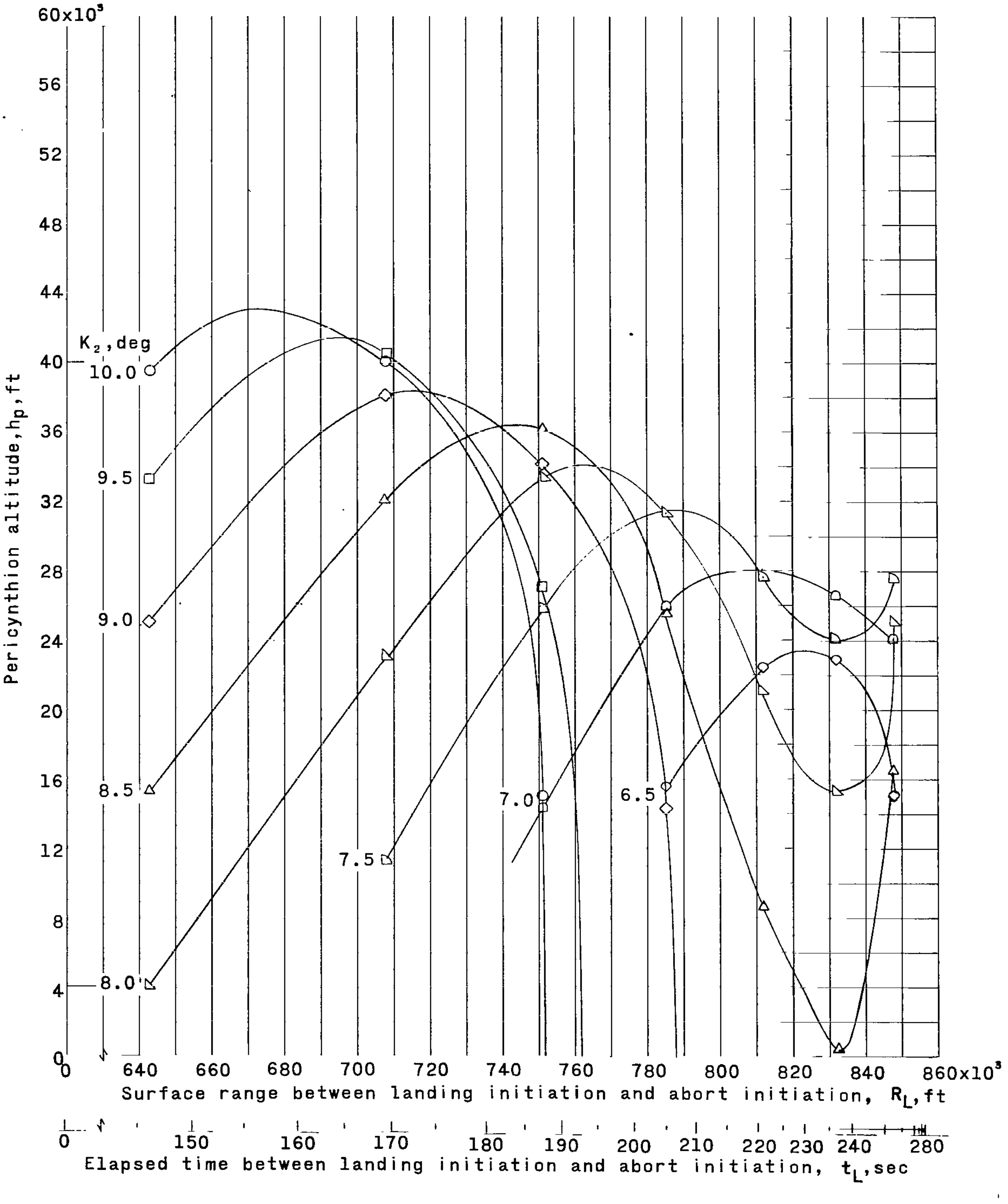


Figure 10.- Pericynthion altitude of orbits established by modified abort maneuver.

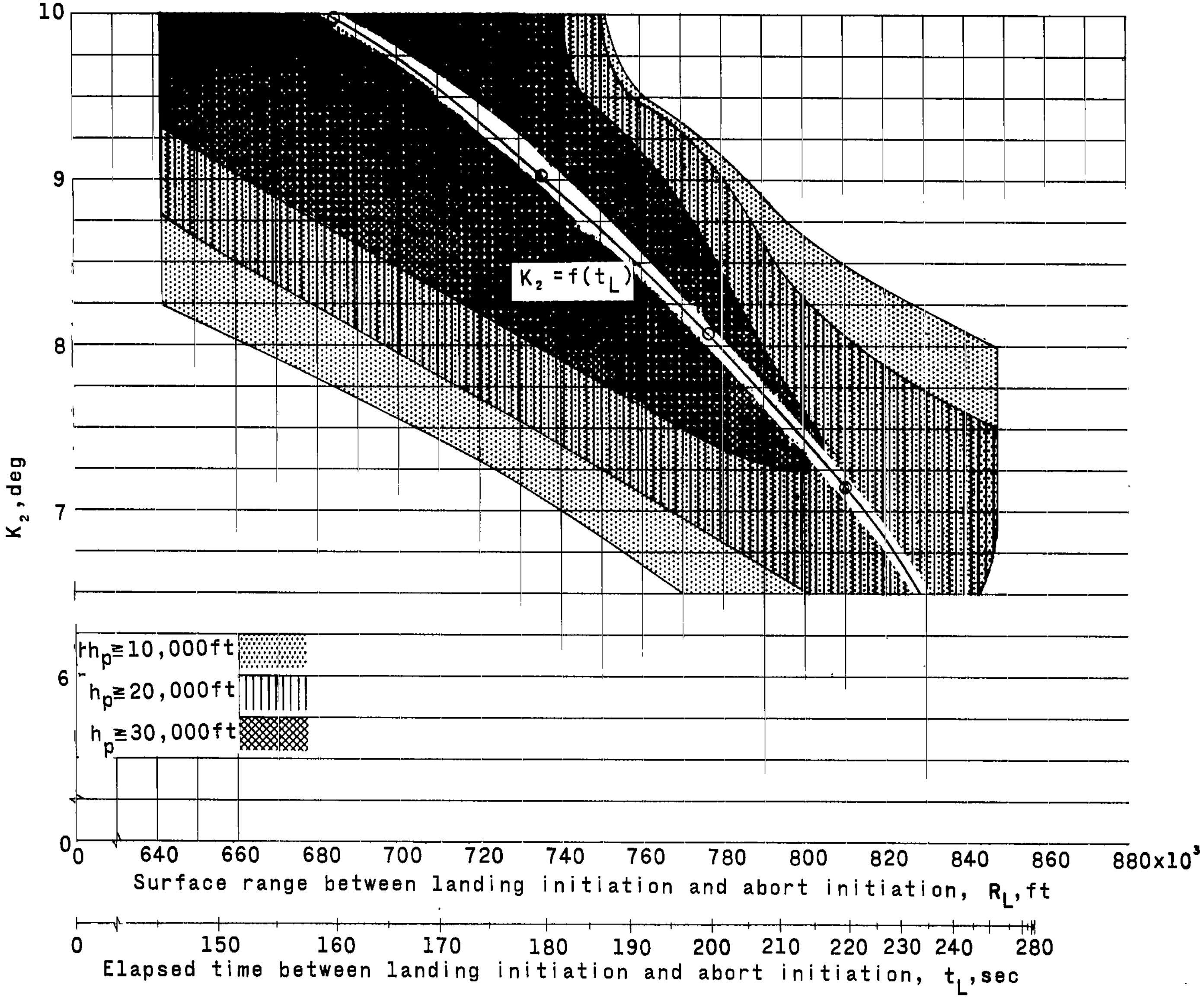


Figure 11.- Thrust-angle boundaries for modified abort maneuver formed by minimum pericynthion altitudes of 10,000, 20,000, and 30,000 feet.

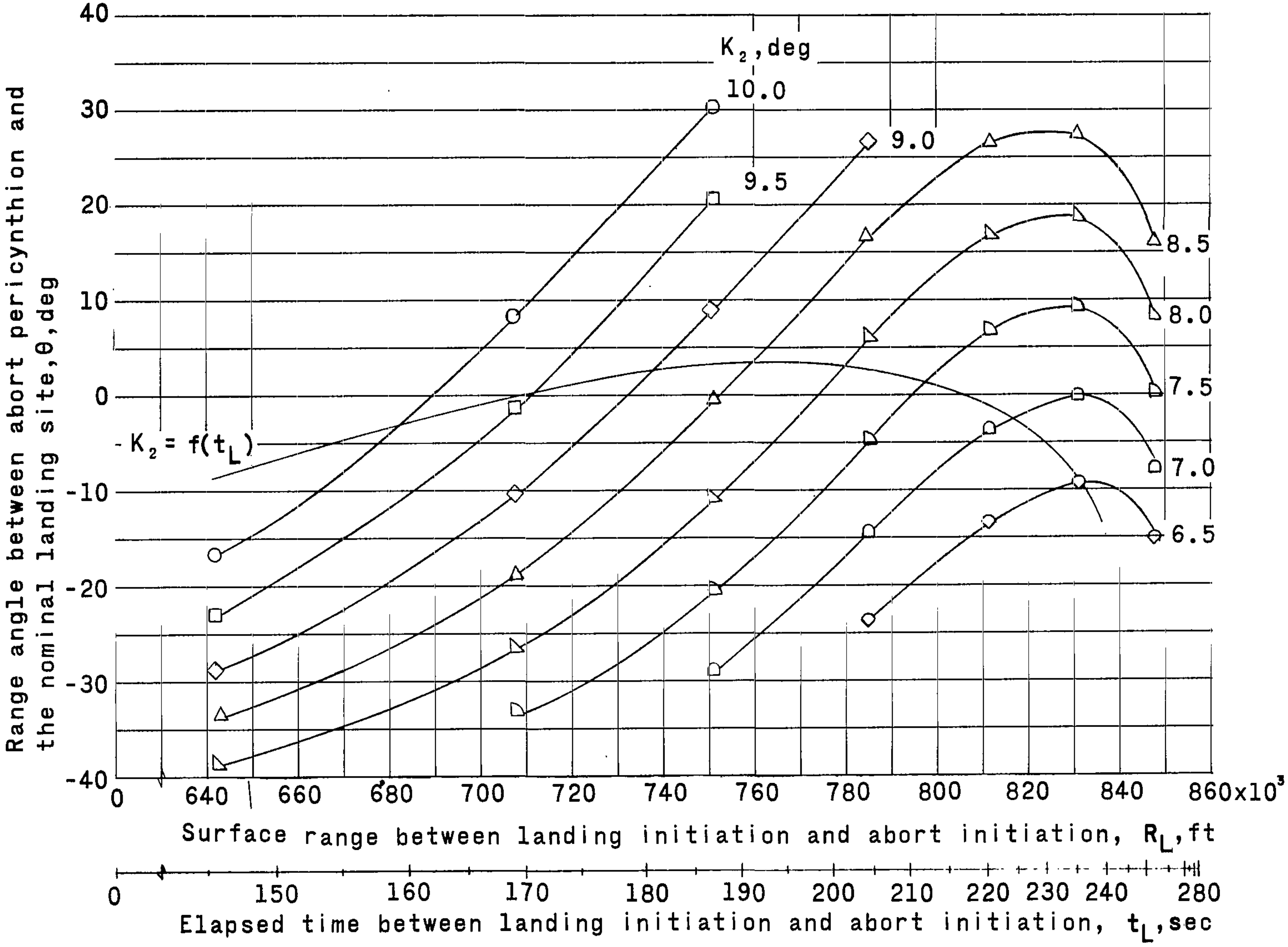


Figure 12.- Location of pericynthion of orbits established by modified abort maneuver. (Negative values of θ correspond to a pericynthion that is downrange from nominal landing site.)

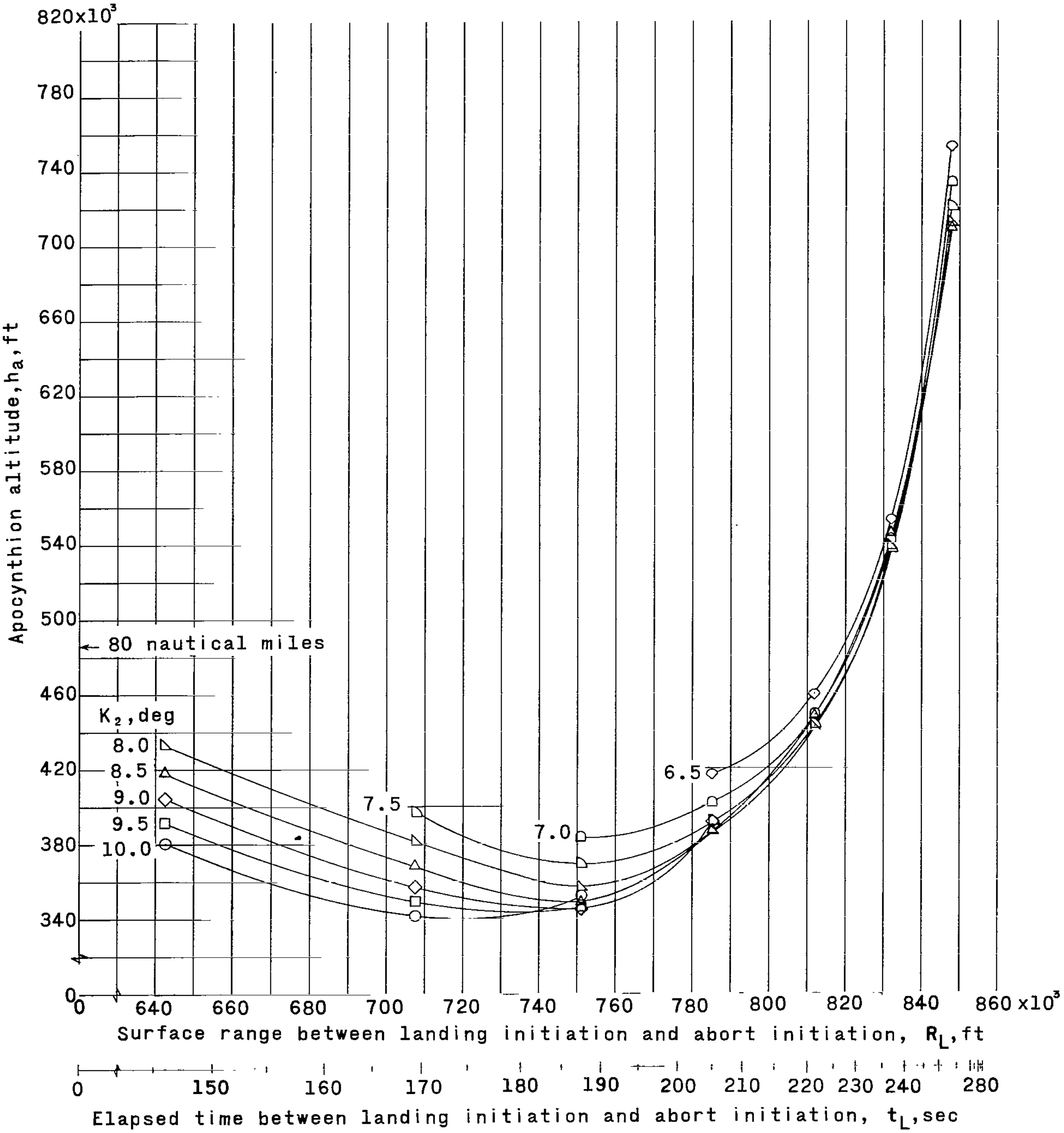
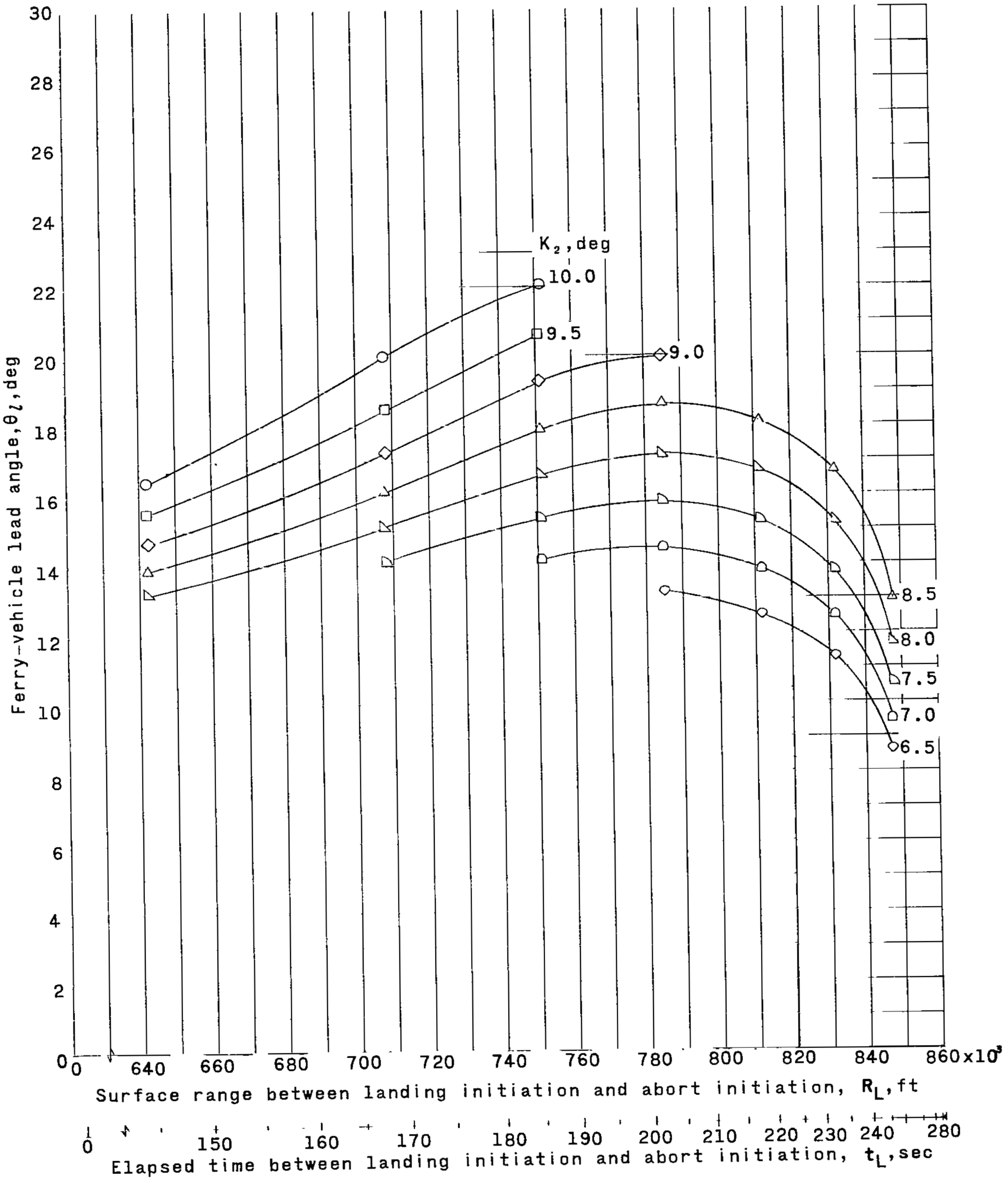
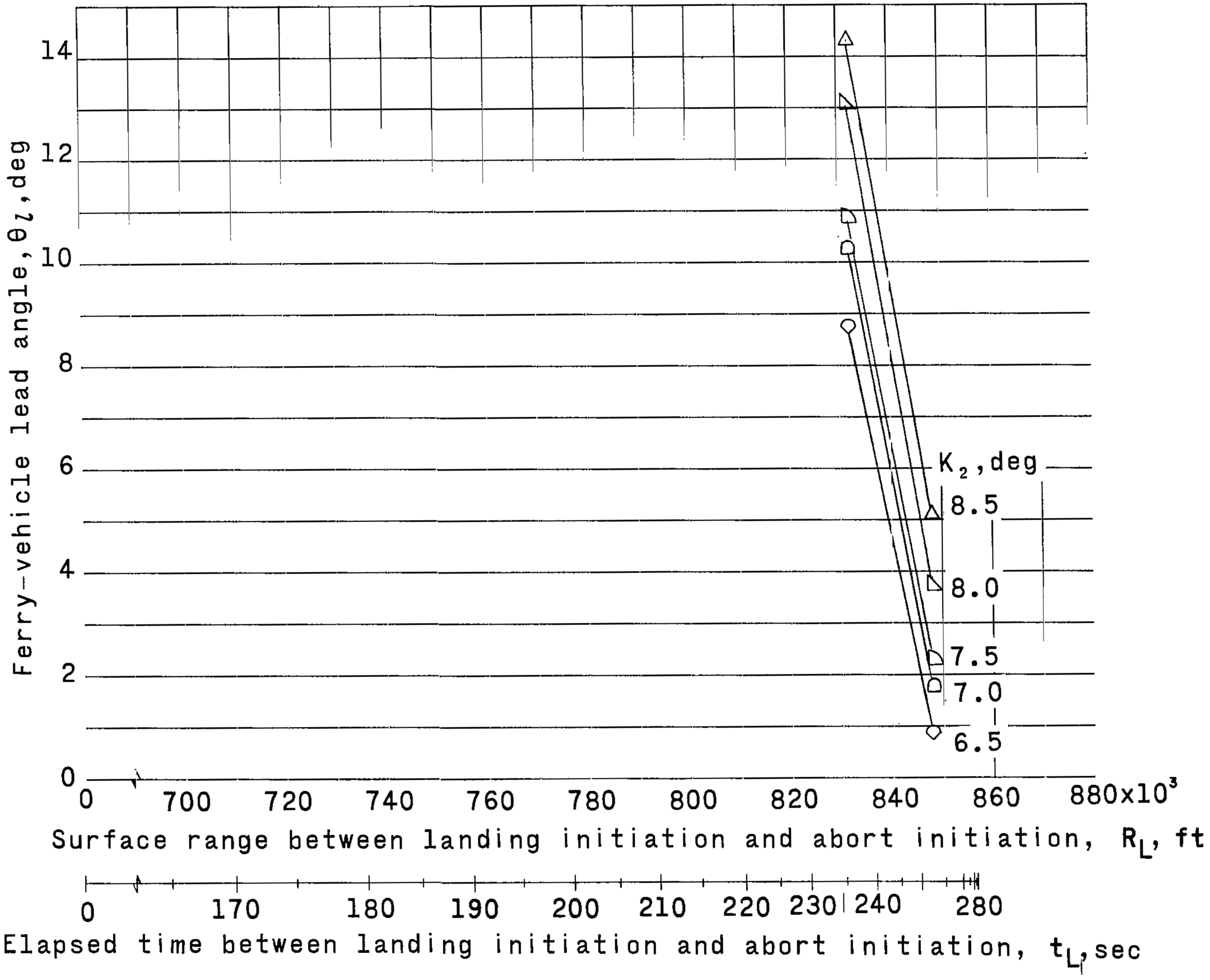


Figure 13.- Apocynthion altitude of orbits established by modified abort maneuver.



(a) First intersection point or, if no intersection occurs, ferry-vehicle apocynthion.

Figure 14.- Angle by which ferry vehicle leads command module when the orbit established by modified abort maneuver intersects the 80-nautical-mile-altitude circular orbit or, should no intersection occur, at ferry-vehicle apocynthion.



(b) Second intersection point.

Figure 14.- Concluded.

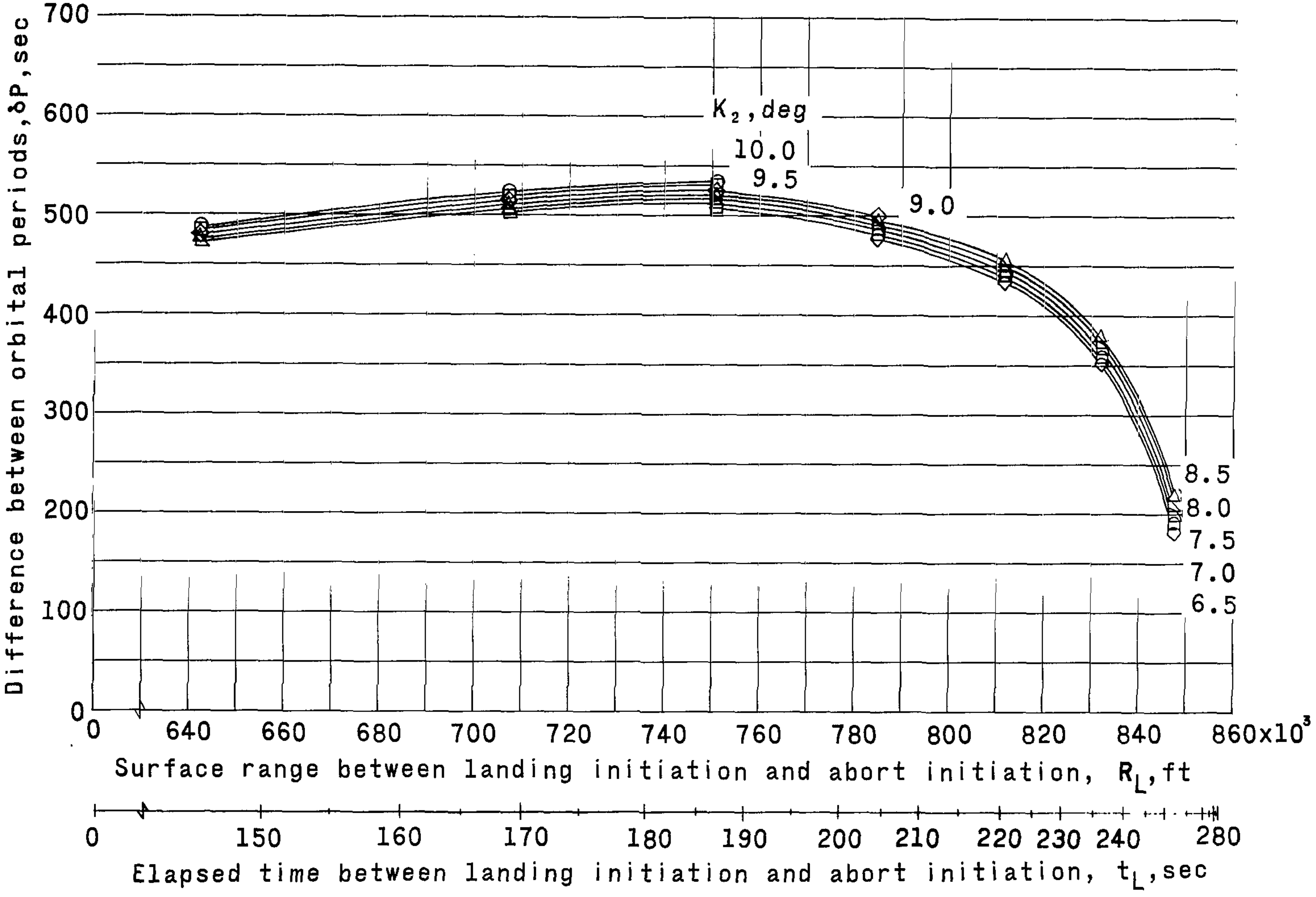
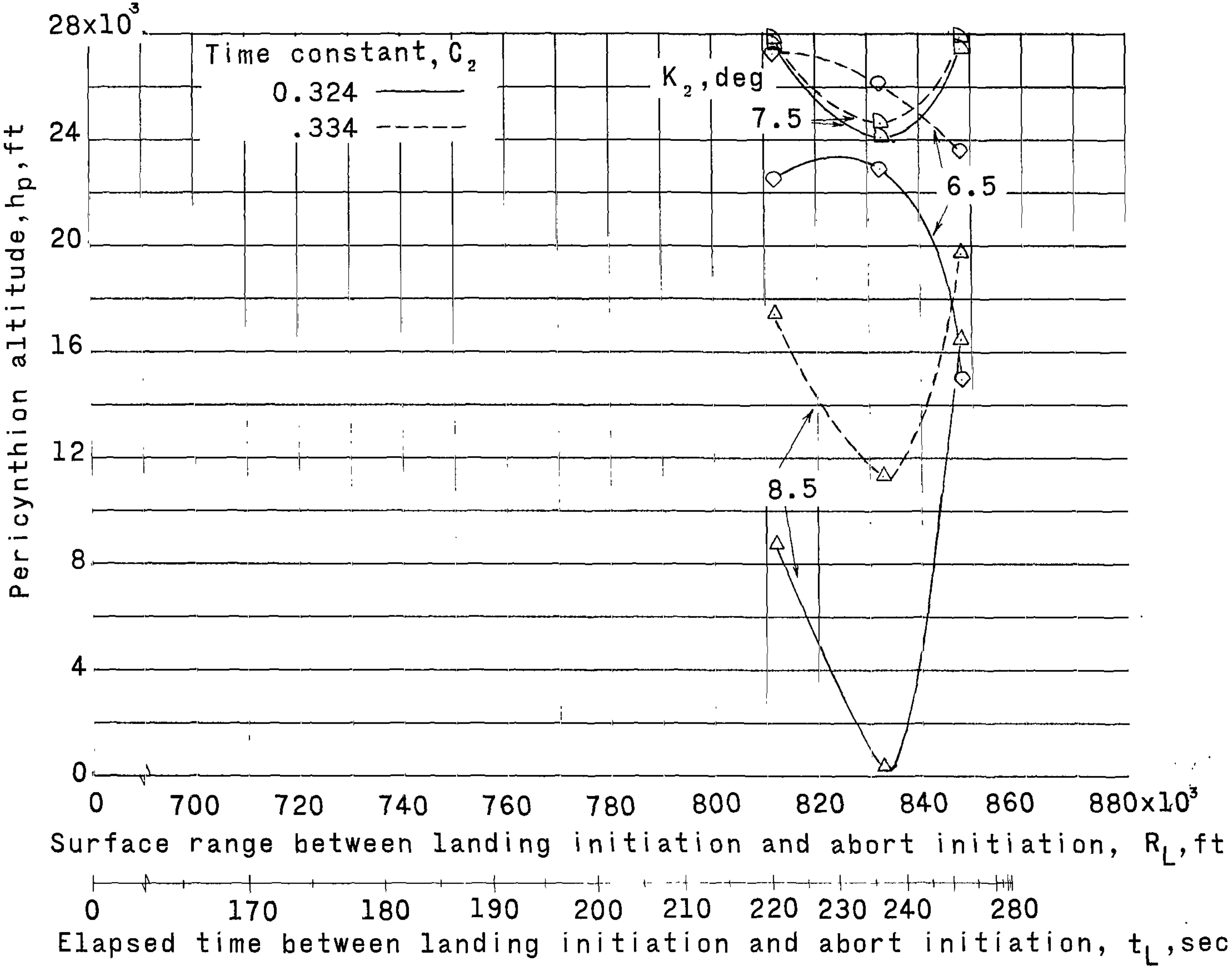
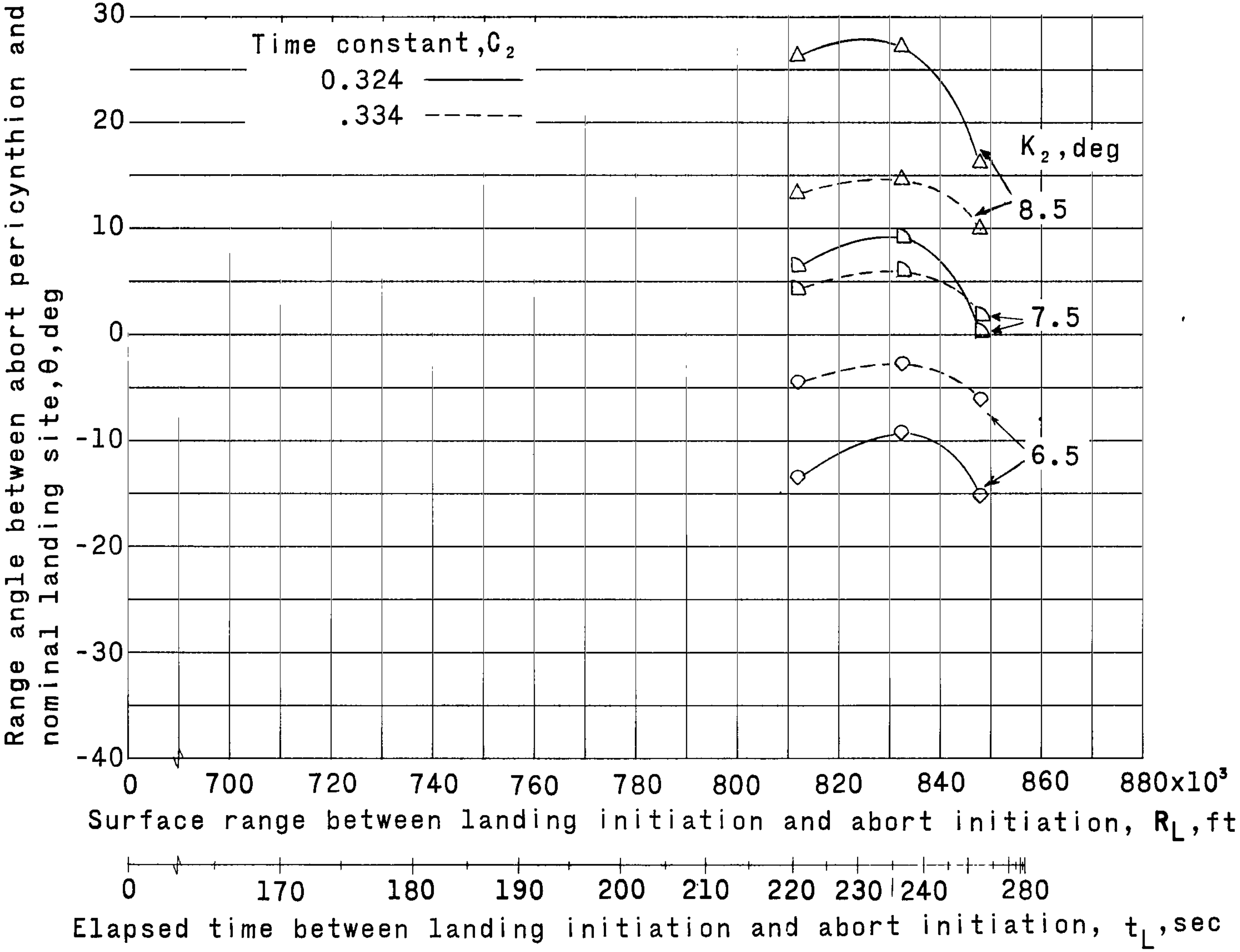


Figure 15.- Difference between period of the 80-nautical-mile-altitude circular orbit and that of the orbit established by modified abort maneuver. (Period of ferry vehicle is less than period of circular orbit.)



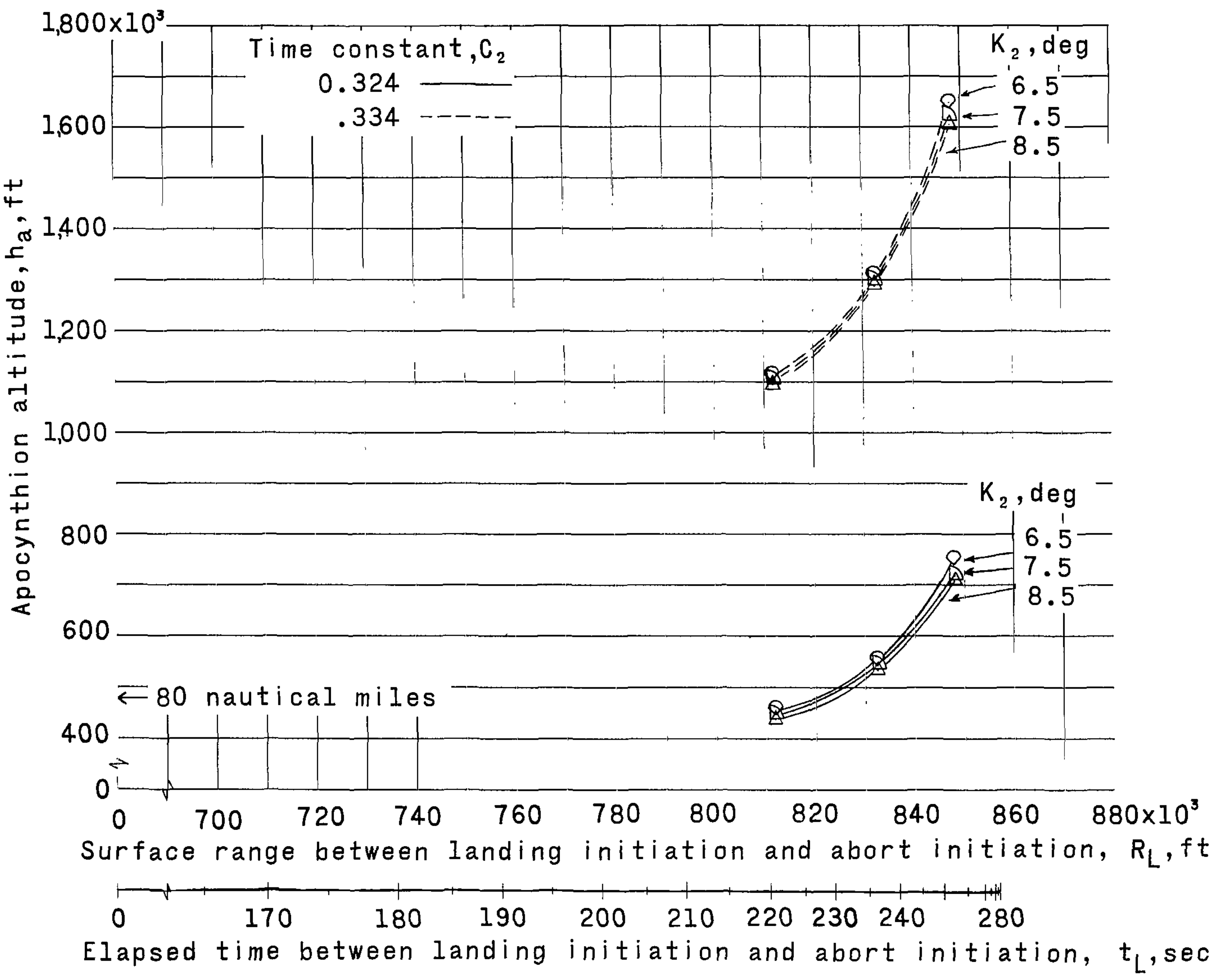
(a) Effect on pericynthion altitude.

Figure 16.- Effect of increasing thrusting-time constant on orbit established by modified abort maneuver.



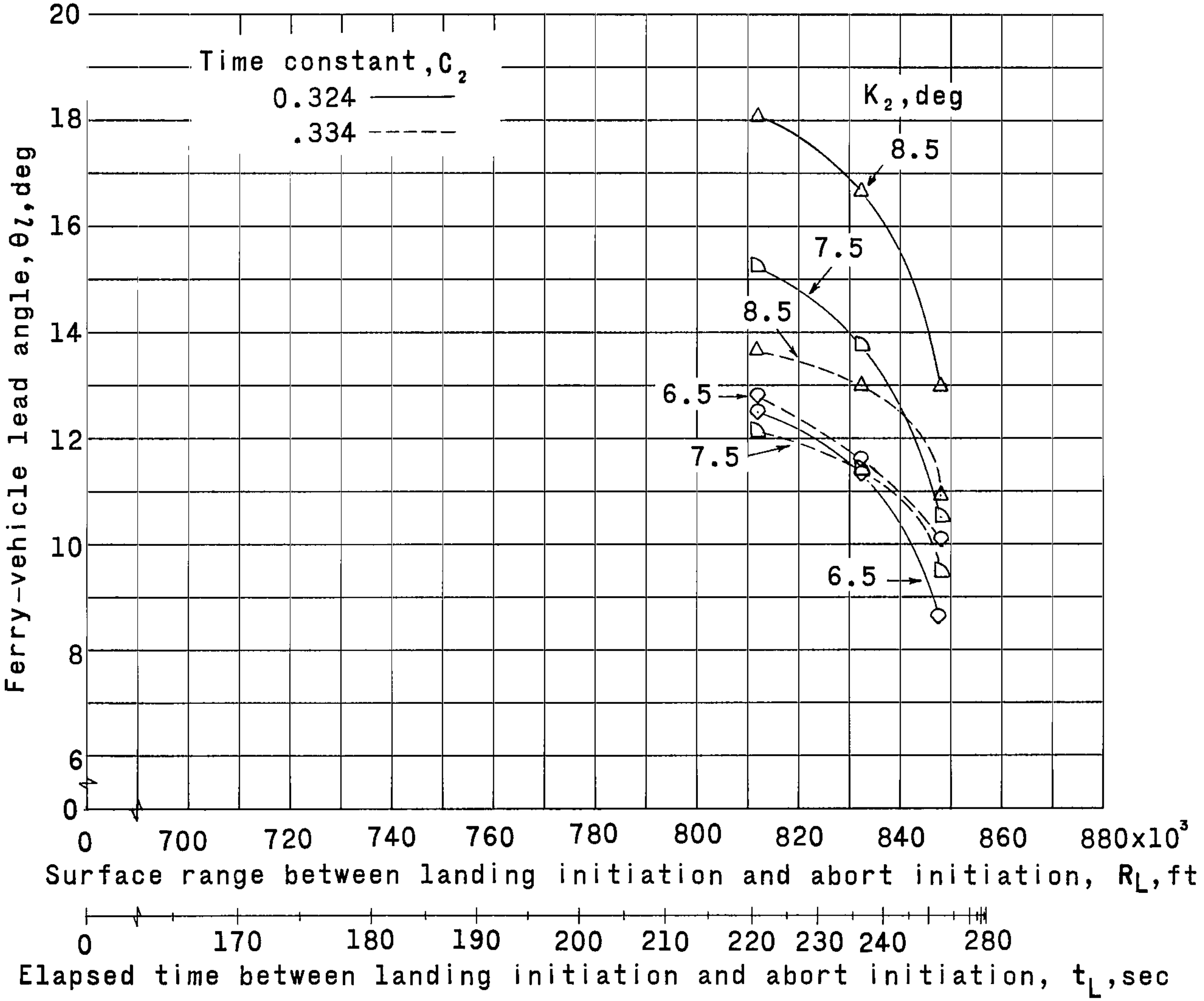
(b) Effect on location of pericynthion.

Figure 16.- Continued.



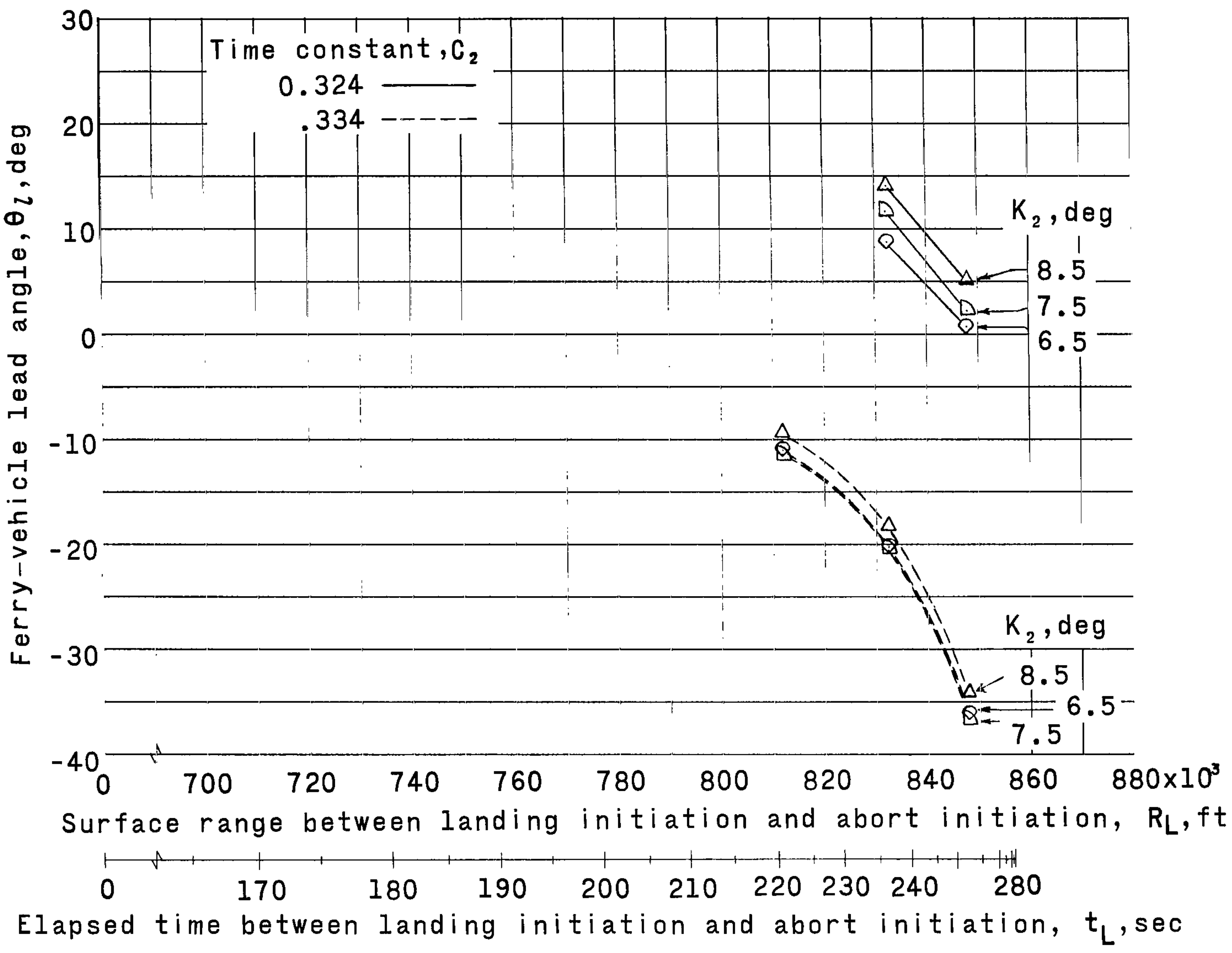
(c) Effect on apocynthion altitude.

Figure 16.- Continued.



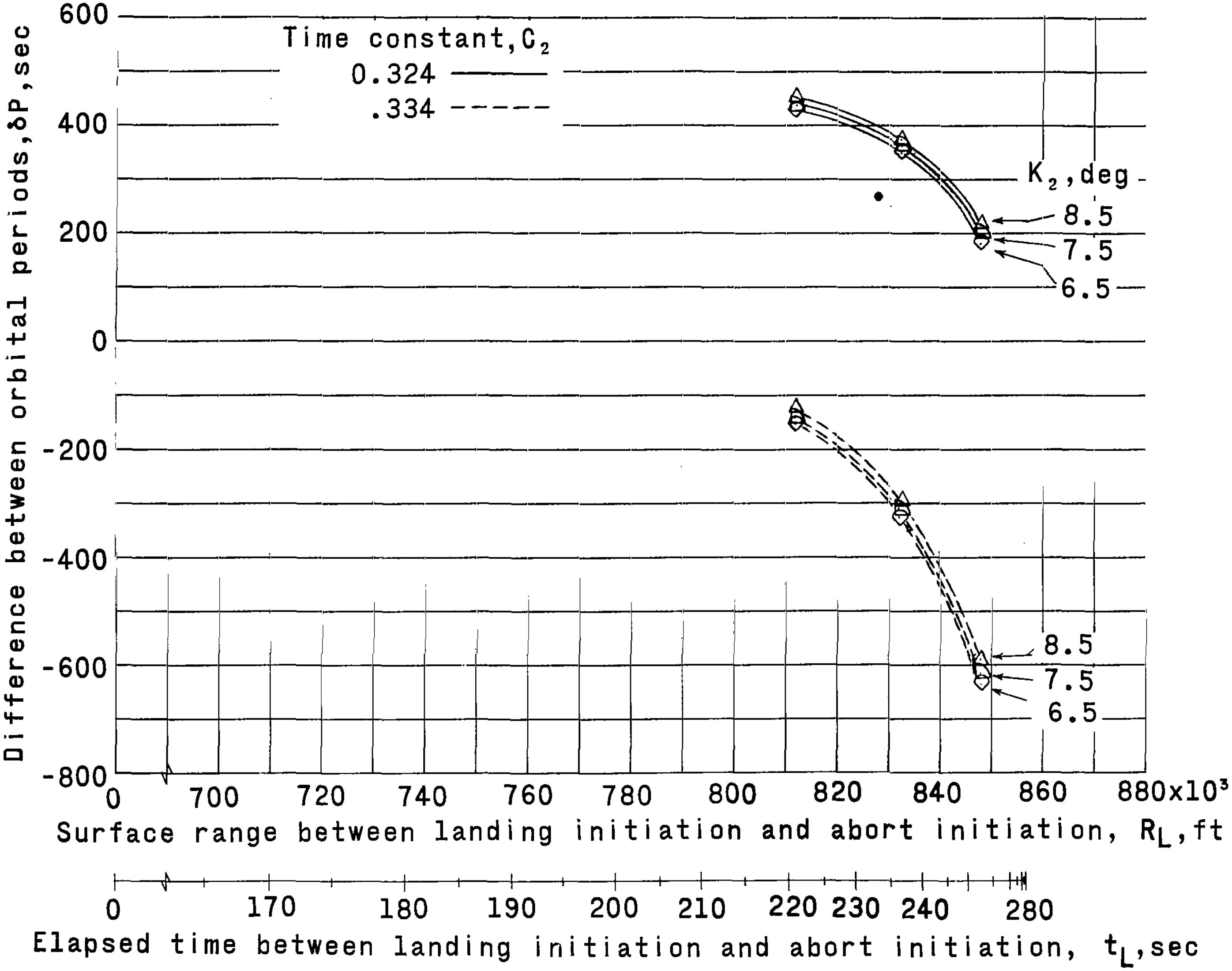
(d) Effect on lead angle of ferry vehicle at first orbital intersection or, should no intersection occur, at ferry-vehicle apocynthion.

Figure 16.- Continued.



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

Figure 16.- Continued.



(f) Effect on difference between orbital periods.

Figure 16.- Concluded.

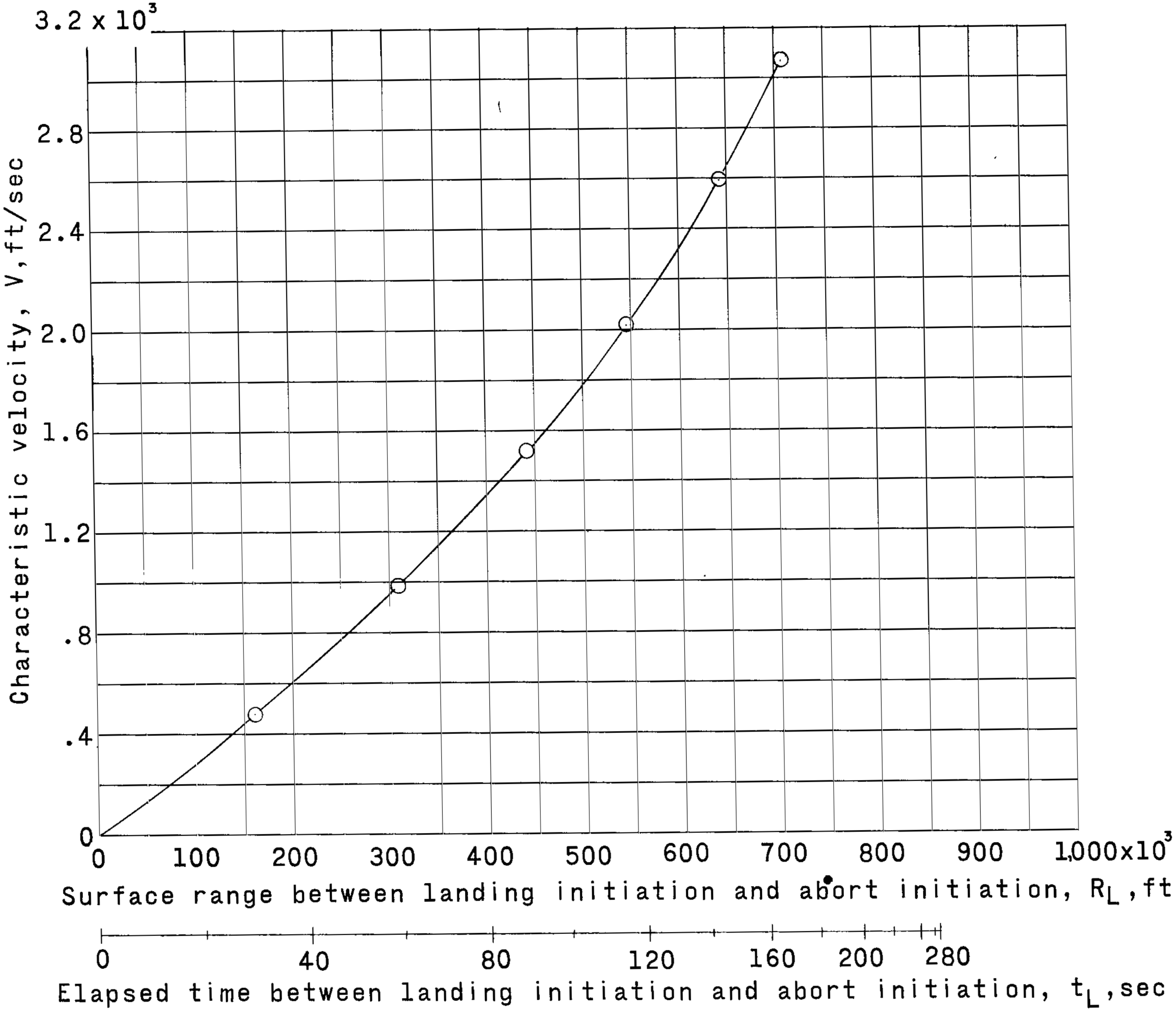


Figure 17.- Characteristic velocity required by basic abort maneuver.

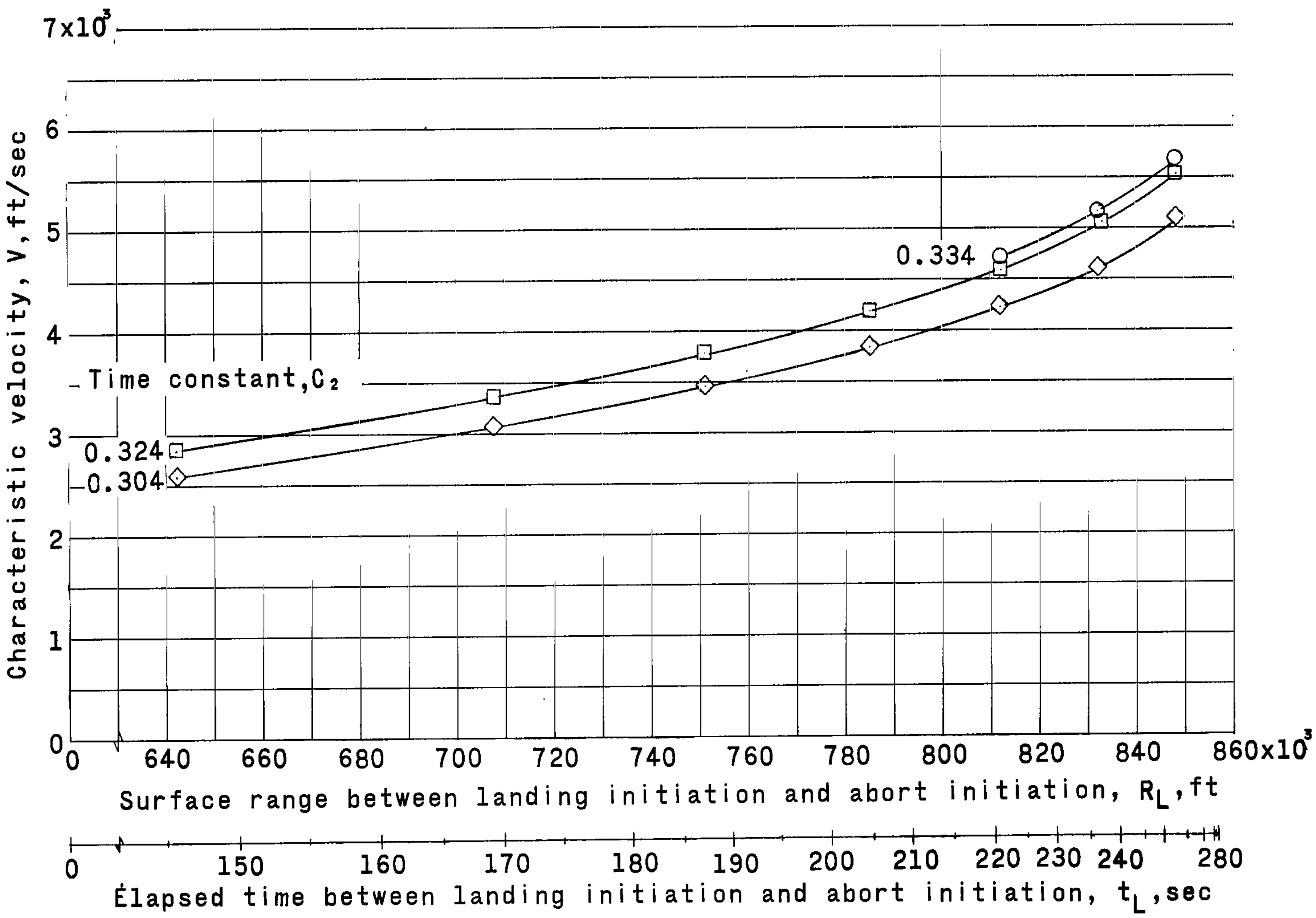
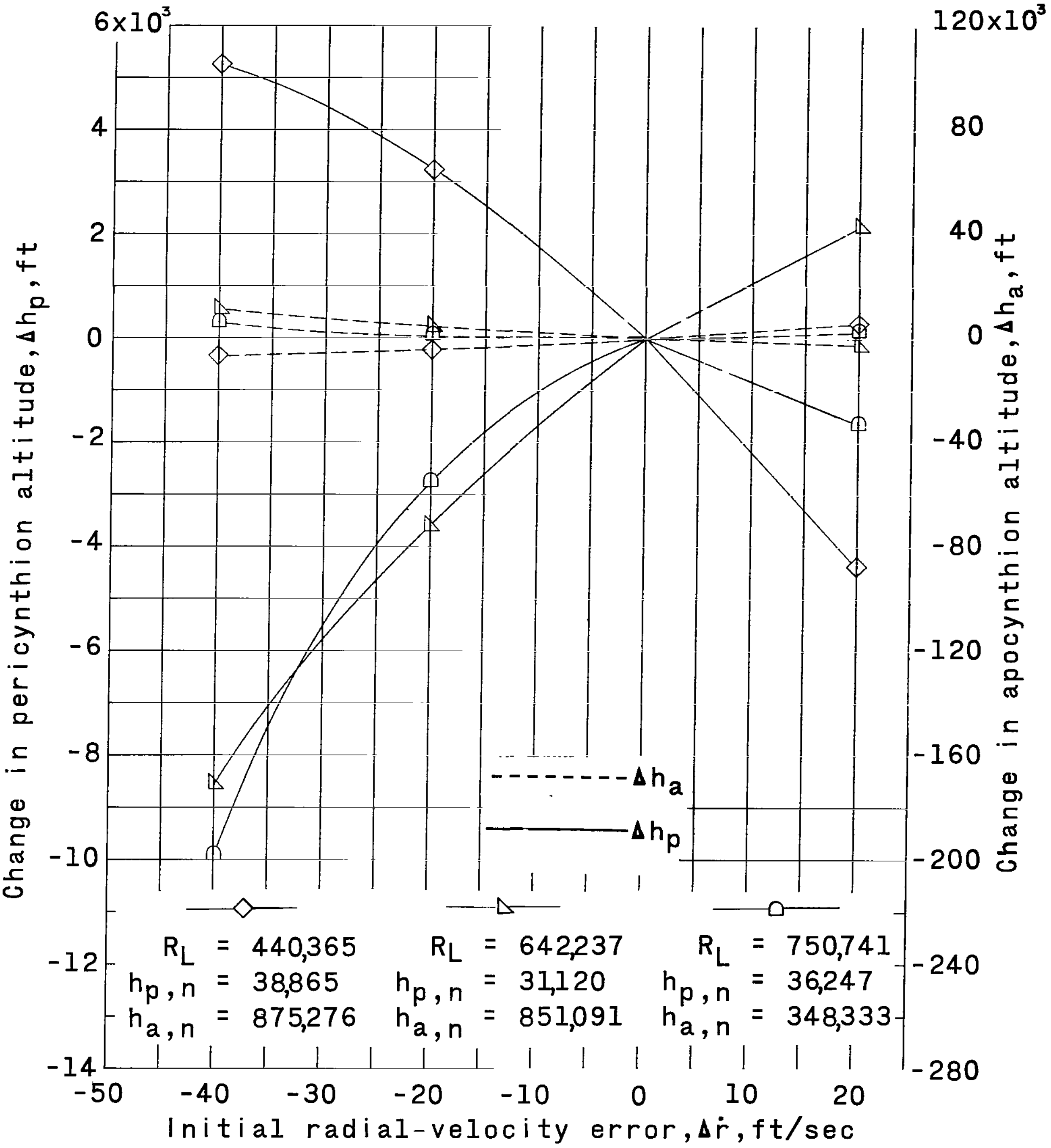
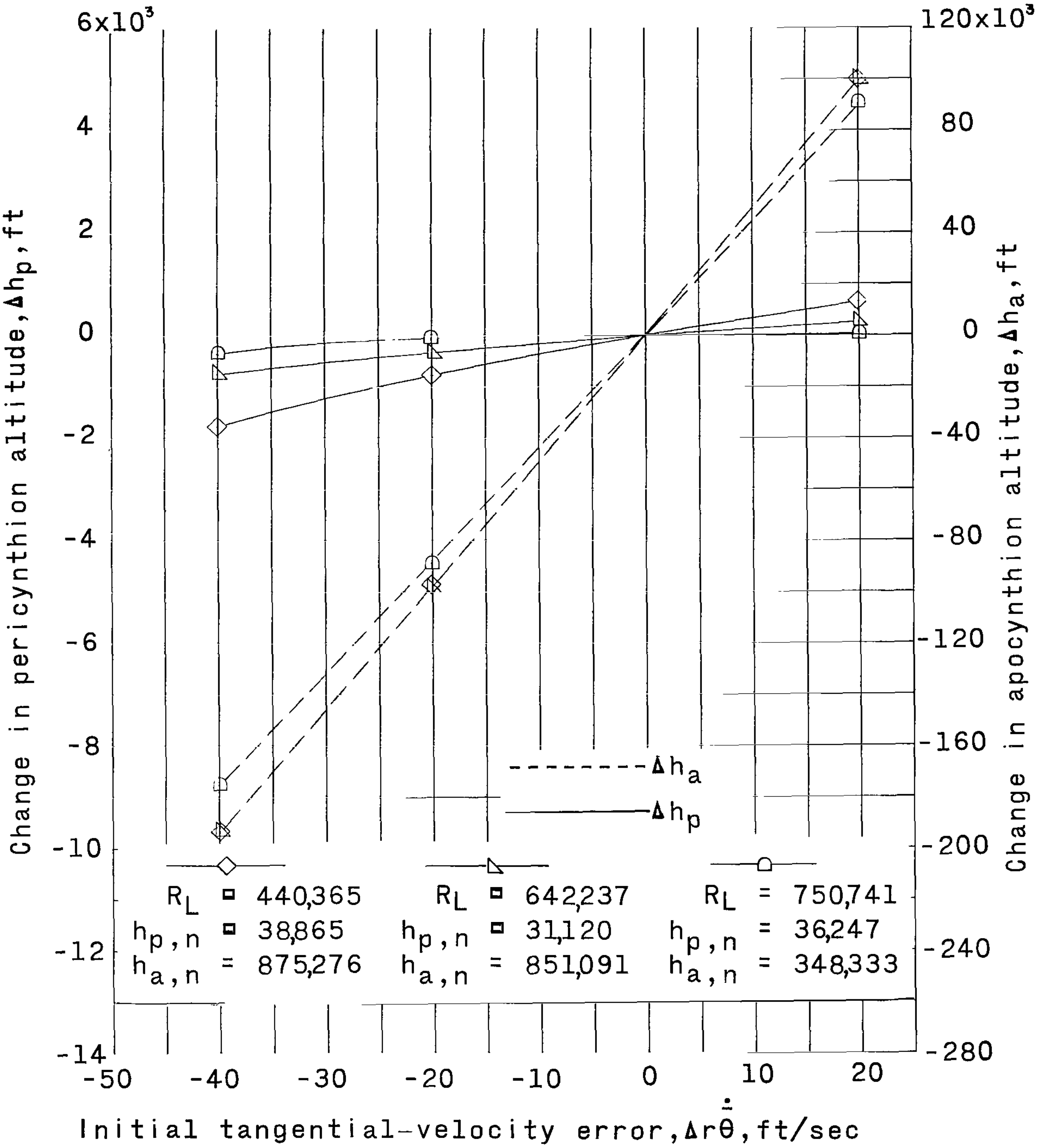


Figure 18.- Effect of increasing thrusting-time constant on characteristic velocity required by modified abort maneuver.



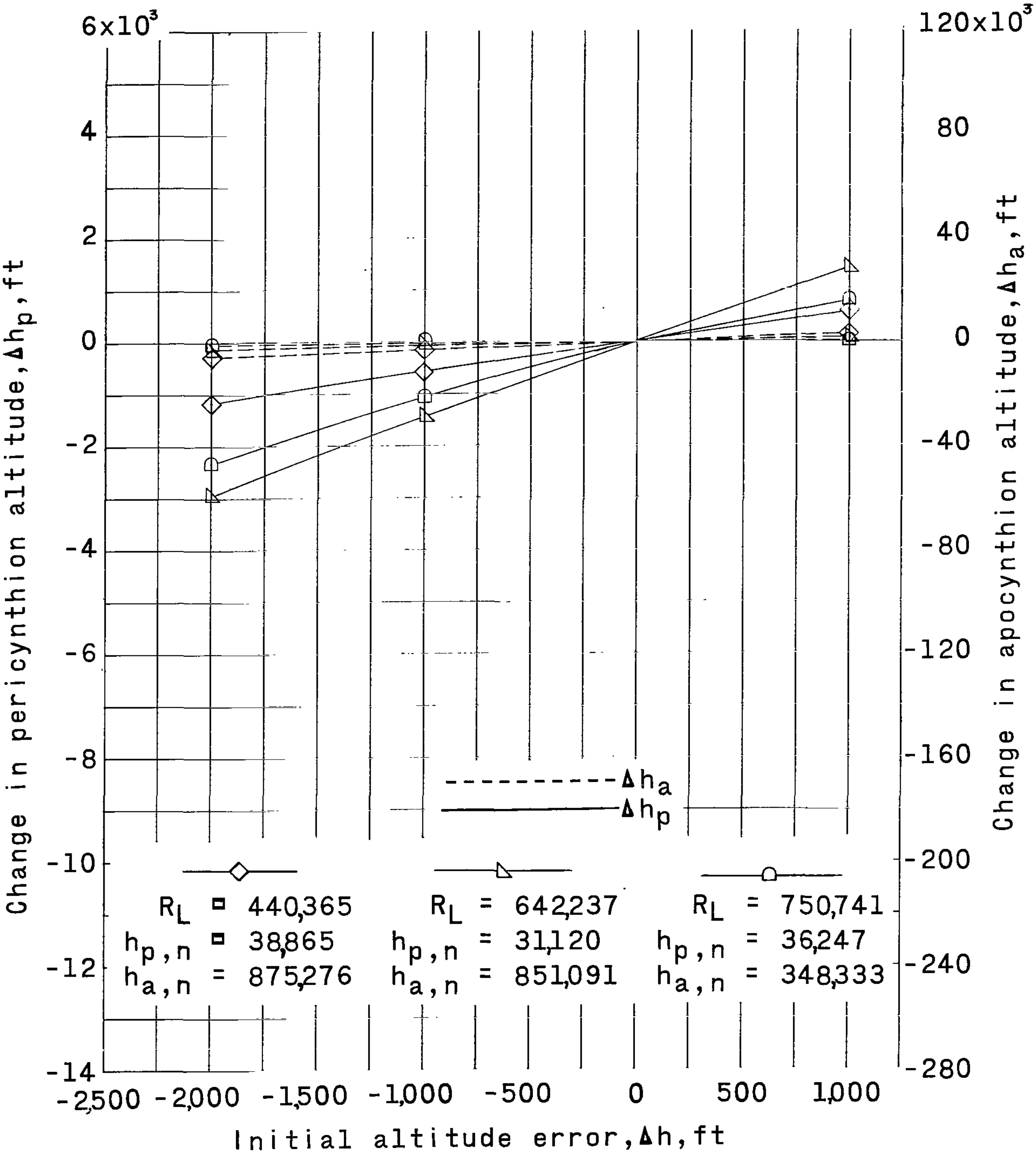
(a) Effect of radial-velocity errors.

Figure 19.- Change in pericynthion and apocynthion altitudes due to errors in altitude and velocity at abort initiation. ($\Delta h = h - h_n$.)



(b) Effect of tangential-velocity errors.

Figure 19.- Continued.



(c) Effect of altitude errors.

Figure 19.- Concluded.

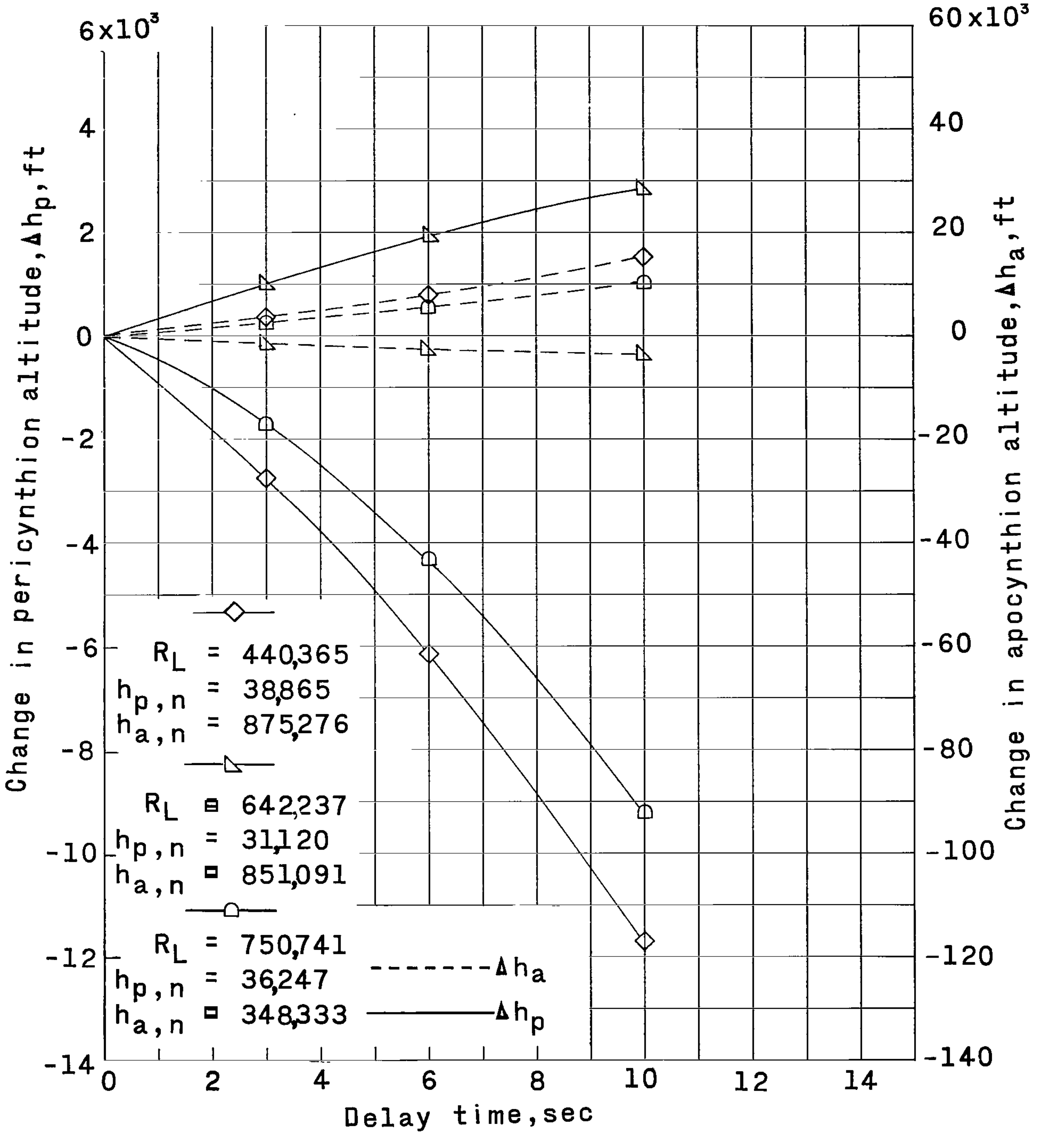
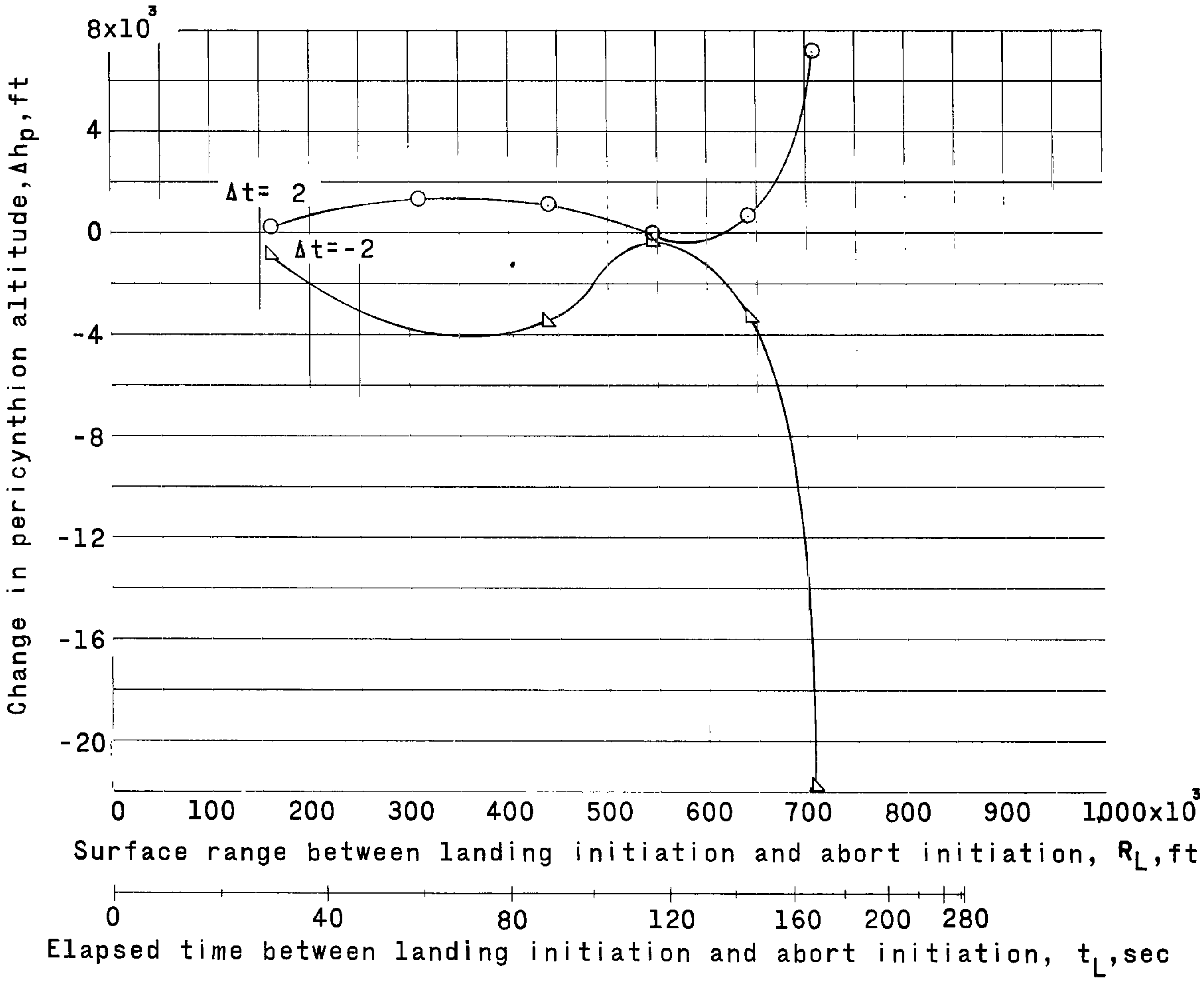
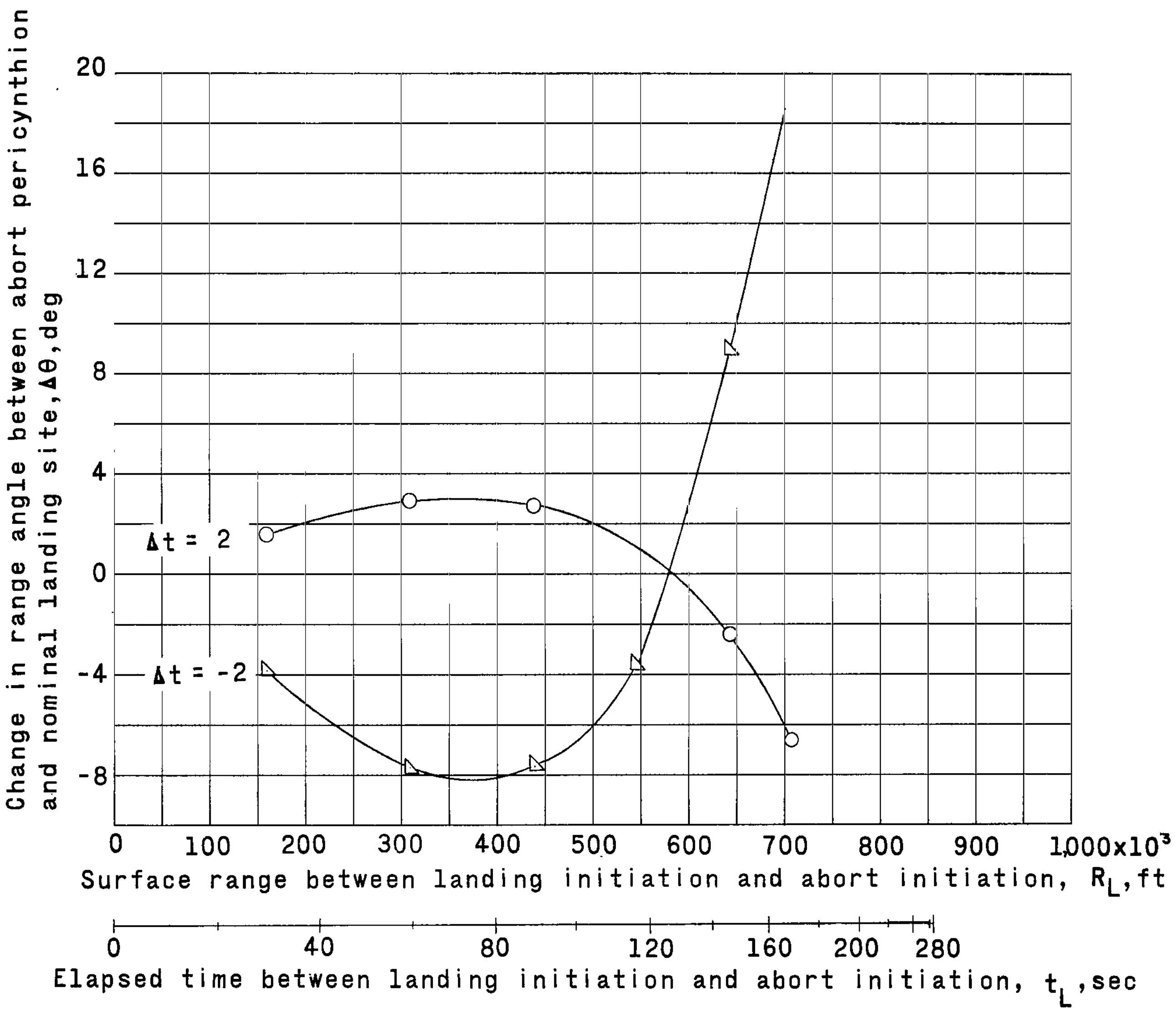


Figure 20.- Change in pericynthion and apocynthion altitudes due to a time delay in abort thrust initiation.



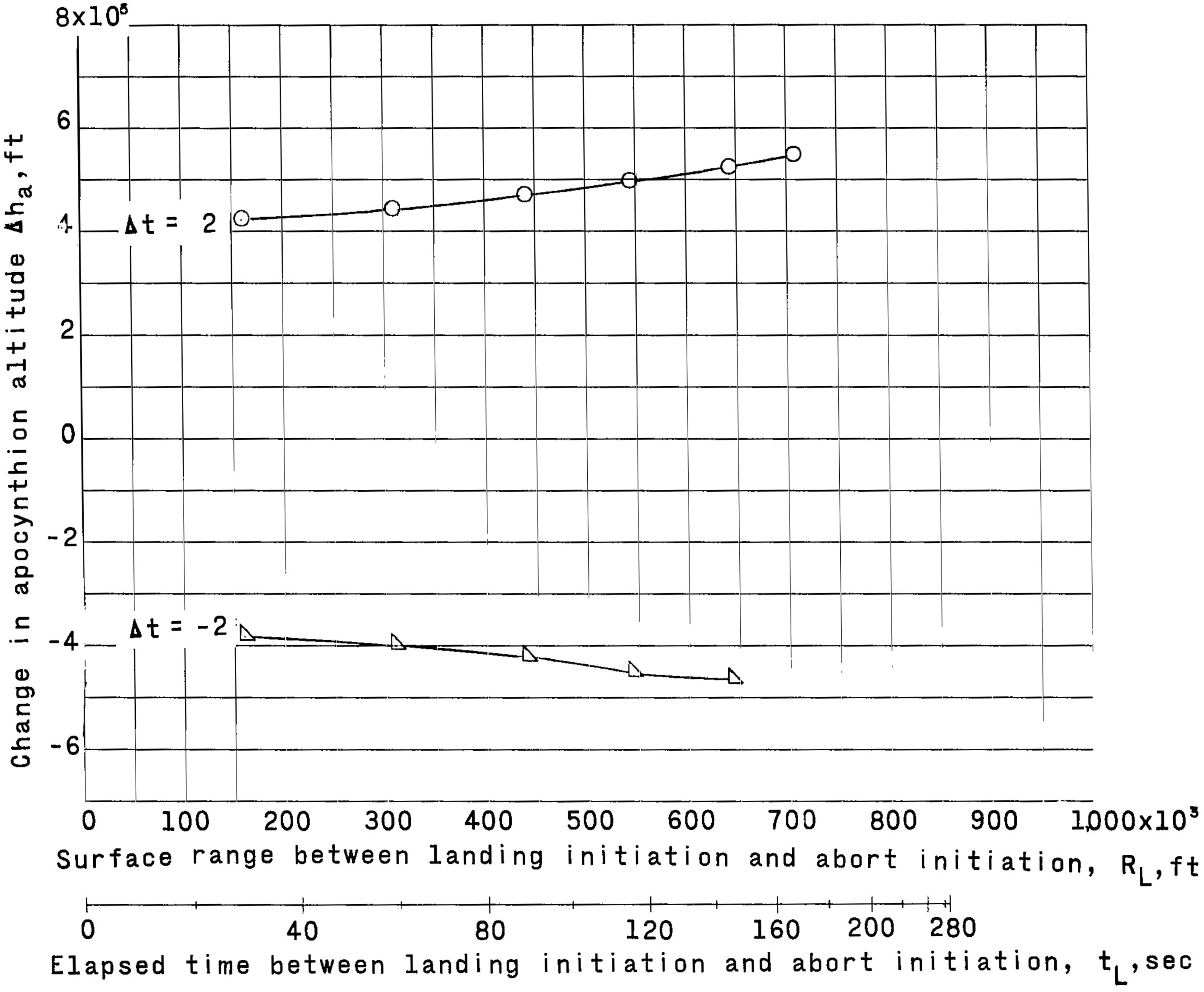
(a) Effect on pericynthion altitude.

Figure 21.- Effect of varying thrusting time by ±2 seconds on orbits established by basic abort maneuver. K = 0°.



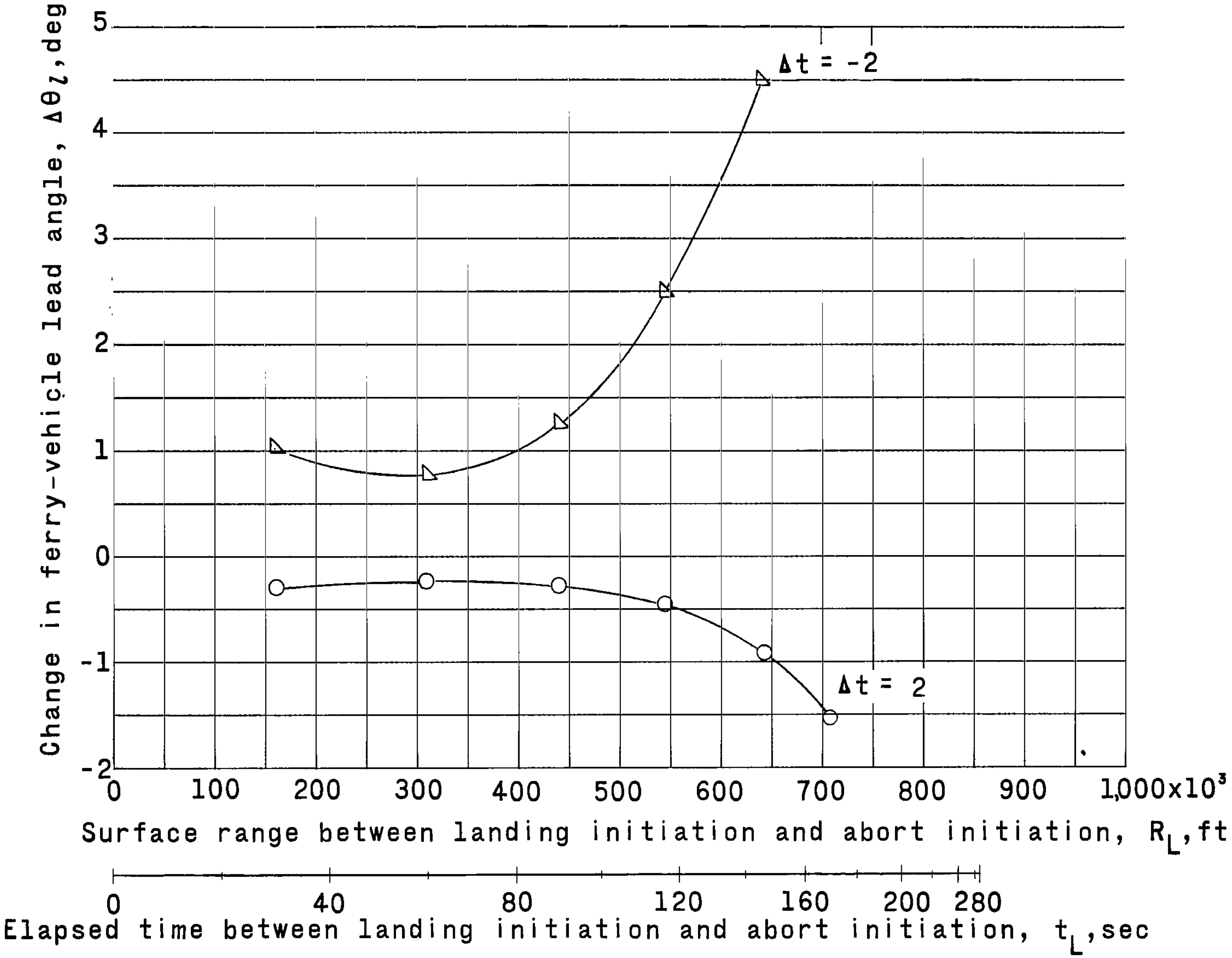
(b) Effect on location of pericynthion.

Figure 21.- Continued.



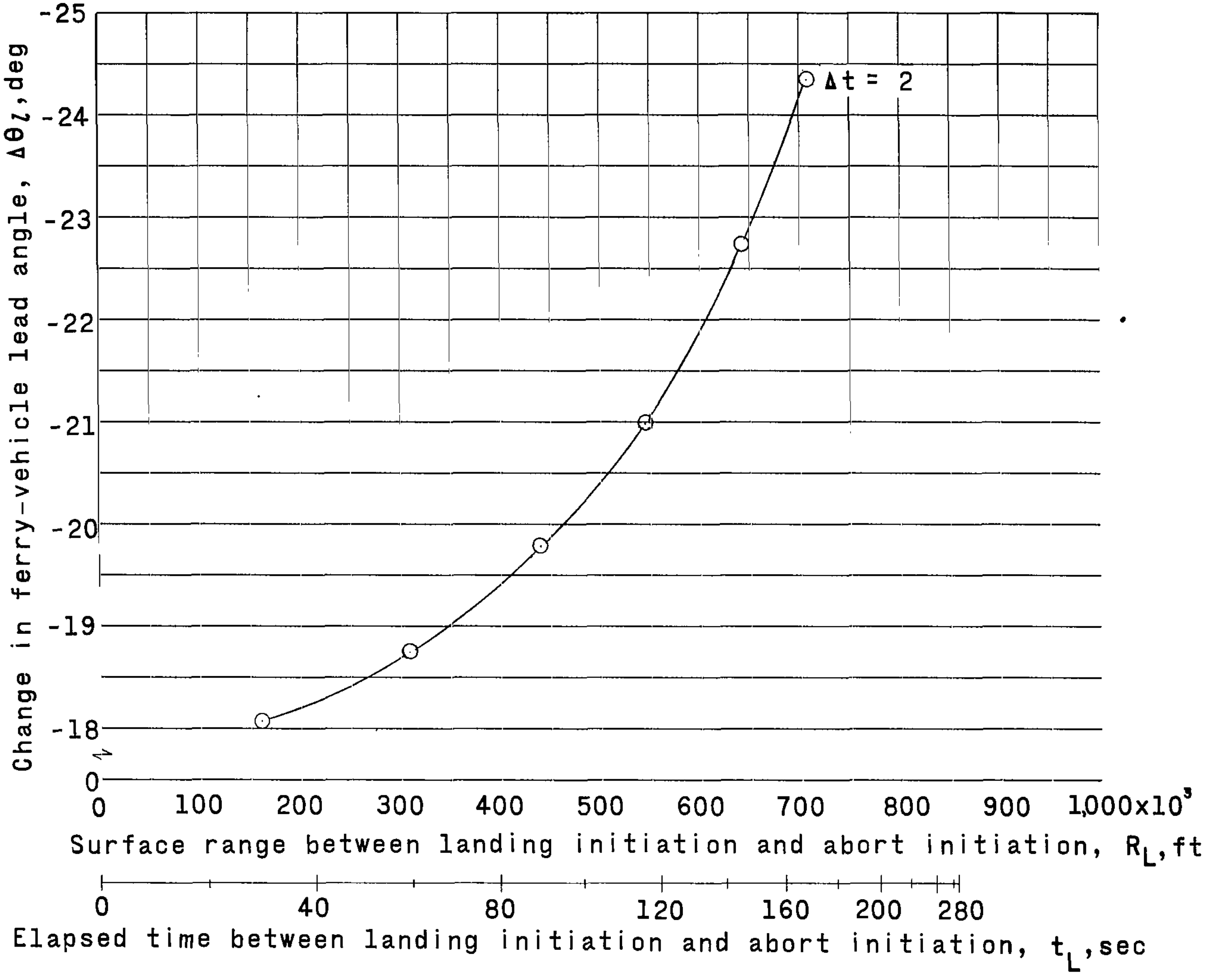
(c) Effect on apocynthion altitude.

Figure 21.- Continued.



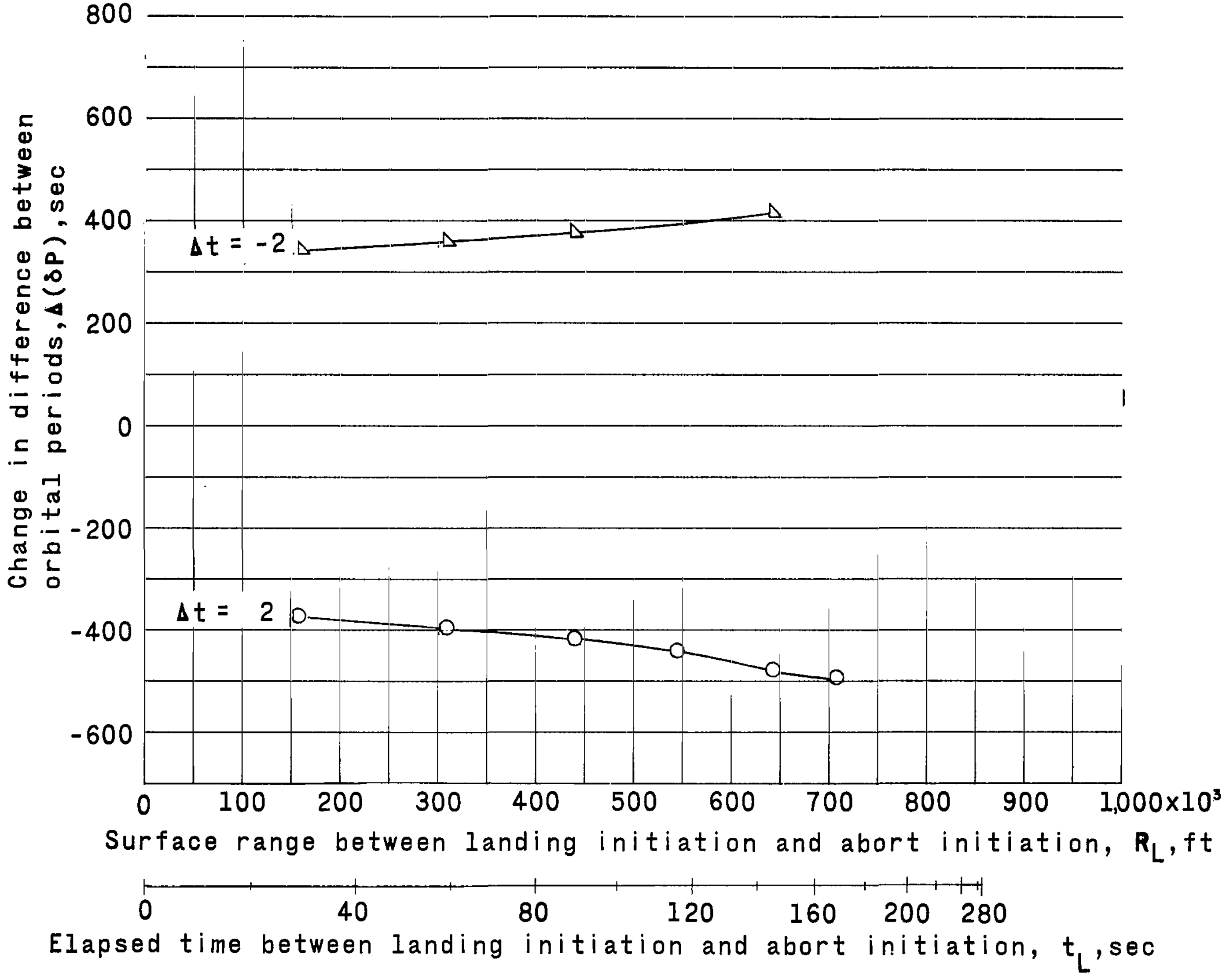
(d) Effect on ferry-vehicle lead angle at first orbital intersection.

Figure 21.- Continued.



(e) Effect on ferry-vehicle lead angle at second orbital intersection.
(Orbits do not intersect if $\Delta t = -2$ seconds.)

Figure 21.- Continued.



(f) Effect on difference between orbital periods.

Figure 21.- Concluded.

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>
> —NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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