IMI6/M.A. Goodwin

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 67-FM-173

November 15, 1967

FEASIBILITY OF MANUAL COMPLETION OF A LOI BURN

VOLUME I - IMU DRIFT ABOUT THE PITCH AXIS

By Alexander H. Treadway
Flight Analysis Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

MSC INTERNAL NOTE NO. 67-FM-173

FEASIBILITY OF MANUAL COMPLETION OF A LOI BURN
VOLUME I - IMU DRIFT ABOUT THE PITCH AXIS

By Alexander H. Treadway
Flight Analysis Branch

November 15, 1967

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Approved: C. R. Hicks Jr.
C. R. Hicks, Jr., Chief
Flight Analysis Branch

Approved: ______________________
John P. Mayer, Chief
Mission Planning and Analysis Division

PRECEDING PAGE BLANK NOT FILMED.

FIGURES

Figure | Page

FEASIBILITY OF MANUAL COMPLETION OF A LOI BURN

VOLUME I - IMU DRIFT ABOUT THE PITCH AXIS

By Alexander H. Treadway

SUMMARY

This volume is the first of two studies investigating the feasibility of manual completion of the LOI burn. Manual completion in the investigation is a non-G&N-controlled burn at a constant inertial attitude. A manual completion procedure is desirable in order to avoid terminating the burn prematurely, which could result in an aborted nominal mission and a trajectory with undesirable characteristics requiring large abort delta velocity. Manual completion would most likely be required for a drifting or failed IMU. It is shown in Volume I that manual completion is feasible for an IMU drifting about its pitch axis. This type of drift is the only one considered since it is the one most likely to result in a lunar impact. Volume II will investigate completion if the BMAG subsystem is drifting about its pitch axis. This subsystem is used as the reference for the constant inertial attitude during completion.

Volume I presents data for two possible procedures for improving the resulting orbit at the end of manual completion if pericynthion altitude is too low. These are: (1) reducing the total length of the burn, i.e., the guided portion plus the manual completion portion, and (2) reorientating the vehicle to a new inertial attitude before the manual completion burn is initiated. The new inertial attitude used in the investigation is that one which gives 0° pitch on the BMAG FDAI. At this time procedure 1 appears to be more effective. Using a positive inertial pitch for the new attitude would probably improve the comparison. This is being studied. For a total burn-time of 383 seconds and an h_{pc} of 30 n. mi., $\Delta\alpha$ will have to be kept smaller than -2.0° due to the possibility of a takeover early in the burn. Reducing the burn-time will increase the limit on the attitude error, -10° at 300 seconds. A burn of at least 260 seconds will be necessary in order to have a stable nonimpacting ellipse. Volume I also presents data of pericynthion and apocynthion altitude at the end of a guided burn for an IMU misaligned abort about its pitch axis.

INTRODUCTION

During the LOI burn for a manned lunar mission, it will be necessary for the flight crew to decide whether to terminate the burn or use an alternate procedure if a problem should arise in the PGNCS that might result in a lunar impact. The decision must be made without ground support since the LOI burn is performed behind the moon and, consequently, out of contact with the ground. Terminating the burn prematurely can result in an aborted nominal mission and a trajectory with undesirable characteristics requiring large abort delta velocity. For this reason it is desirable that a manual takeover procedure for the LOI burn be possible. The procedure must be simple and yet guarantee crew safety. The PGNCS problem most likely to require the manual takeover is a drifting or failed IMU.

The purpose of Volume I is to determine the feasibility of manually completing the LOI burn if the IMU is drifting about its pitch axis. The manual procedure being considered in the study is a non-G&N-controlled burn at a constant inertial attitude. If a stable, non-impacting ellipse can be obtained after such a burn, then the return-to-earth procedures will be similar to those planned for a nominal transearth injection. A brief examination of the effect of an IMU misaligned about its pitch axis on the orbit at the end of a LOI burn is also included.

The results of these investigations are presented parametrically, which allows flexibility in defining the minimum pericynthion altitude acceptable. The parameters considered are pericyntyion altitude, apocynthion altitude, delta pitch, drift rate, pitch misalignment, and LOI burn time.

SYMBOLS

BMAGS	body mounted attitude gyro subsystems
CSM	command and service modules
FDAI	flight director's attitude indicator
h_{pc}	pericynthion altitude
h_{ac}	apocynthion altitude
IMU	inertial measurement unit
LOI	lunar orbit insertion
LM	lunar module
PGNCS	primary guidance, navigation, and control subsystem
SPS	service propulsion system

METHOD

The nominal LOI maneuver of the preliminary spacecraft reference trajectory (ref. 1) which is used for the study, consists of a 383-second SPS burn that reduces the incoming escape hyperbola to an 80-n. mi. circular orbit. The inertial plane containing the landing site at the time of LM landing (approximately 9 hours after LOI) provides the targeting condition for the LOI guidance. At the beginning of this burn the CSM/LM is orientated with respect to the local horizontal, as illustrated in figures 1 and 2. The X axis of the vehicle is along the initial-guidance-computed thrust direction, $\bar{a}_{TD}$, which is opposite to and above the velocity vector. It has a pitch angle, θ, of approximately 165° and a yaw angle of 18° (fig. 2). In addition, figure 2 also shows the alignment of the IMU at burn initiation. Its X axis, $\bar{X}_B$, is aligned along $\bar{a}_{TD}$; Y axis, $\bar{Y}_B$, is perpendicular to the plane of $\bar{a}_{TD}$ and the radius vector in the direction shown; and Z axis, $\bar{Z}_B$, completes a right-handed coordinate system. Since a heads-up burn is arbitrarily assumed, the vehicle Z axis is aligned collinear with $\bar{Z}_B$, which points toward the moon. For the local horizontal coordinate system, the X axis is along the local horizontal in the direction of velocity, Z axis points down the radius vector, and Y axis completes the right-handed coordinate system. The sequence for determining the attitude in any coordinate system is pitch, yaw, and roll, where a positive maneuver obeys the right-hand rule. The attitude time history of the burn in presented in figures 3 and 4 with respect to the local horizontal and IMU coordinate system, respectively.

During the LOI burn the flight crew can monitor the attitude time history on the FDAI driven by the PGNCS. It is also possible for them to monitor the attitudes on the second FDAI driven by the BMAGS. If the BMAG and IMU X, Y, and Z axes are collinear at burn initiation and if neither system is drifting, the attitudes on both FDAI's will be the same. However, if drift rates are present this is no longer the case. For this study only the IMU will be drifting and the rates will begin at burn initiation. The effect of rates beginning later in the burn is presently being studied. The feasibility of manual completion with the BMAGS drifting instead of the IMU will be presented in Volume II.

The pitch attitude time history with respect to the BMAGS and IMU coordinate system is shown in figure 5 for drift rates of ± 0.05 deg/sec. It can be seen that the IMU attitude history is nominal while BMAG pitch attitude diverges significantly. The IMU attitudes are nominal because the guidance computer thinks the IMU is correct and computes steering commands for the target in that system. The parameter delta pitch, $\Delta\alpha$, is the algebraic difference between BMAG pitch and the IMU pitch at a given instant in the burn. From the plot, at an LOI burn time of 100 seconds, the BMAG pitch for +0.05 deg/sec is 7.0° and the IMU pitch is 2.0°; therefore, $\Delta\alpha$ is 5.0°. It is also equal to the drift rate times the LOI burn time, since it is the angle through which the IMU drifts with the rate beginning at burn initiation. It is therefore possible to fix $\Delta\alpha$ and calculate the drift rates (D.R.) from the equation $\text{D.R.} = \frac{\Delta\alpha}{\text{LOI burn time}}$ as a function of LOI burn time. As an example let $\Delta\alpha$ equal 5.0° and LOI burn time be 100 and 200 seconds, then the drift rates are 5°/100 sec = .05 deg/sec and 5°/200 sec = .025 deg/sec., respectively. To study the feasibility of manual completion, the IMU is allowed to drift to preselected LOI burn-times with rates calculated in the above manner for these times and selected $\Delta\alpha$'s. At the end of these times (takeover times), the BMAG attitude is held during the manual completion. The total length of the burn, i.e., the guided portion plus the manual portion, is a constant.

Most of the manual completion data was computed with this constant equal to the nominal LOI burn-time, 383 seconds. However, data was also computed for other values of this constant. The cases selected to show this data are $\Delta\alpha$ equal to $\pm 5°$ and $\pm 10°$. In both guided and manual burns nominal thrust was used.

All data has been generated using the Apollo Reference Mission Program, version IV.

RESULTS

The effect of pitch and subsequently the effect of $\Delta\alpha$, or pitch misalignment, is illustrated in figure 6. If the velocity is $\bar{V}$ and thrust direction $\bar{T}_+$, corresponding to a positive pitch, $+\alpha$, the instantaneous change in velocity, $\Delta\bar{V}_+$, will be in the direction shown in 6(a). This will cause the magnitude and flight-path angle of the new velocity, $\bar{V}_+$, to be less than that of $\bar{V}$. At the end of the nominal LOI burn, $\bar{V}_+$ will be equal to circular velocity at 80 n. mi. and the flight-path angle will be 0°. With a positive IMU drift or misalignment, the true pitch will be greater than the nominal. The flight-path angle at the end of the burn will therefore be positive, and the vehicle will be headed toward apocynthion. For negative drifts and misalignments, the thrust will be in the direction $\bar{T}_-$, shown in 6(b). At the end of the burn the flight-path angle will be negative and the vehicle will be headed toward pericynthion. A similar effect occurs for manual completion. However, since an inertial attitude is being held, a positive $\Delta\alpha$ will not necessarily guarantee the vehicle to be postpericynthion.

The osculating h_{pc} and h_{ac} are shown in figure 7 as a function of LOI burn-time at manual takeover for the selected $\Delta\alpha$'s. Data for osculating h_{ac} is shown only for $\Delta\alpha$'s of 0° and 10° since the remaining $\Delta\alpha$'s fall between them and is not presented prior to 200 seconds since the orbit is either hyperbolic or unstable. If the guided burn is terminated and no manual completion is attempted, then the figure shows the osculating orbit. The abort procedures will then be similar to those presented in reference 2. However, if the guided burn is not terminated, the resulting h_{pc} and h_{ac} at the end of the burn will be similar to those shown in figure 8 for various drift rates. To determine the $\Delta\alpha$ associated with a given h_{pc} in the figure, multiply the drift rate times the nominal LOI burn-time.

The data for a manual completion of the LOI burn is presented in figures 9, 10 and 11 for a constant burn length of 383 seconds and figures 12 and 13 for various burn lengths.

Figure 9 shows, for various drift rates, h_{pc} at the end of manual completion as a function of the LOI burn-time at which the manual completion begins (takeover time). Note that the positive drift rate curves have a positive slope, zero slope at the maximum point and then a negative slope. The sign of the slope can be correlated with the vehicle's position relative to pericynthion. Zero slope corresponds to pericynthion, while positive corresponds to prepericynthion and negative to postpericynthion. The vehicle is always prepericynthion for negative drift rates.

Figure 10 shows h_{pc} and h_{ac} at the end of manual completion as a function of the takeover time for the selected $\Delta\alpha$'s. A curve of figure 9 can be obtained from figure 10(a) in the following manner:

1. Obtain the time on the abscissa by dividing the $\Delta\alpha$'s by the drift rate for the curve, i.e.,

$$t = \left| \frac{\Delta\alpha}{\text{drift rate}} \right|$$

2. Use the corresponding $\Delta\alpha$'s and times to determine h_{pc}'s in figure 10(a).

The locus of the resulting h_{pc}'s is the desired curve. Since this is true, zero slope at a maximum h_{pc} for a $\Delta\alpha$ will also correspond to pericynthion at the end of manual completion. To the left of these points the vehicle will be prepericynthion and to the right postpericynthion. The zero slope point occurs for a $\Delta\alpha$ of 5° at a takeover time of 100 seconds, 2.5° at 210 seconds, and 0° at 383 seconds. There are none for 7.5° and higher, and hence the vehicle is postpericynthion. Negative $\Delta\alpha$'s will result in the vehicle being prepericynthion at the end of manual completion.

Figure 11 shows $\Delta\alpha$ as a function of LOI burn-time at crew takeover for various h_{pc}'s at the end of manual completion. If a straight line is drawn for a constant h_{pc} in figure 10(a) and the $\Delta\alpha$ it intersects is plotted against the time at the intersection, the curves of figure 11 will be the result. Given a minimum allowable h_{pc}, the figure shows the limits on $\Delta\alpha$ to maintain this minimum h_{pc} or higher. For each h_{pc} there is a curve above the 80-n. mi. curve and one below it. The vehicle will be postpericynthion at the end of manual completion for the upper curve and prepericynthion for the lower one. For a minimum h_{pc} of 40 n. mi., the lower limit on $\Delta\alpha$ runs from -1.0° to -7.5°, while the upper limit runs from 13.5° to 9°. Values of $\Delta\alpha$ between the curves will give an h_{pc} of greater than 40 n. mi.

By reducing the total length of the LOI burn, guided portion plus manual portion, a reduction in the effect of IMU drift on the orbit at the end of manual completion might be possible. The effect of various total burn lengths on h_{pc} and h_{ac} at the end of manual completion is shown in figures 12 and 13, respectively, as a function of LOI burn-time at crew takeover.

The $\Delta\alpha$ cases for which the data is presented, $\pm 5°$ and $\pm 10°$, were chosen since the first represents a reasonable deviation and the second, the largest deviation considered. The figures show that as the burn-time decreases h_{pc} and h_{ac} both increase. Pericynthion altitude increases significantly between 383- and 360-seconds total burn-time; the h_{pc} differences between consecutive curves decreases with a decrease in total burn-time. The large increase in h_{pc} between 383 and 360 seconds is a result of most of the $\Delta\alpha$ being applied horizontally causing a decrease in h_{ac} and large rotation of the line of apsides. Half of the rotation of the line of apsides between 260- and 383-seconds burn length occurs in the last 20 seconds. Apocynthion altitude increases in just the opposite manner as h_{pc}. Between 383 and 360 seconds the h_{ac} differences are smaller but increase with decreasing burn length. This trend is exactly the same for either positive or negative $\Delta\alpha$'s. Reducing the burn length to as low as 260 seconds will still result in a stable orbit. For $\Delta\alpha$'s as large as $\pm 10°$, the figure shows that a safe orbit can be obtained by reducing the total burn-time.

Instead of holding the inertial attitude during manual completion of the burn, which corresponds to a given $\Delta\alpha$ and LOI burn-time, the crew might be able to improve h_{pc} at the end the burn by reorientating the vehicle to another inertial attitude. A brief study is included to show the effect of a reorientation prior to manual completion. The inertial attitude to be reorientated to will be the one that gives a zero pitch on the BMAG FDAI. The procedure used to generate the data is the same as for the manual completions using a constant burn length of 383 seconds except the vehicle is instantaneously orientated to the new attitude before manual completion begins.

Figure 14 shows h_{pc} at the end of manual completion with and without reorientation for the $\Delta\alpha$'s of $\pm 10°$ as a function of LOI burn-time at crew takeover. These $\Delta\alpha$'s result in the lowest h_{pc} at the end of manual completion. The h_{pc} at the end of manual completion after reorientating from the attitude for $\Delta\alpha$ of 10° is R_{10} and R_{-10} for reorientating from a $\Delta\alpha$ of -10°. It can be seen from the figure that reorientation improves h_{pc} for -10° for a large part of the burn, but then lowers it slightly. However, the vehicle is still prepericynthion. Reorientating for 10° will lower h_{pc} for the first 110 seconds of LOI burn-time after this time h_{pc} is raised. The sign of the slope can again be used to determine the vehicle's position at the end of manual completion relative to pericynthion for the reorientated attitude. The zero slope occurs at approximately 280 seconds; prior to this time the vehicle is prepericynthion and afterwards it is postpericynthion. Reorientating to the inertial attitude that gives a 0° pitch reading on the BMAG FDAI before manual completion improves h_{pc} at the end of manual completion, but tends to complicate the manual procedure. Reorientating to other inertial attitudes is being studied.

When the crew aligns the IMU platform prior to LOI, they might accidentally introduce an error in the alignment. The effect of this misalignment will be to change the resulting orbit after a guided LOI maneuver. The thrust will be terminated by the guidance even with misalignment. A brief examination is presented for the IMU being misaligned about its pitch axis. Figure 15 shows h_{pc} and h_{ac} at the end of the guided LOI burn as a function of IMU pitch misalignment. The increase in h_{ac} and decrease in h_{pc} is almost a linear function of the misalignment angle. By comparing this figure with figure 8, it can be seen that the effect of pitch misalignment on the orbit at the end of the guided LOI burn is very similar to the effect of a pitch drift rate on the orbit at the end of the burn. Roughly it requires a misalignment of one-half the angle ($\Delta\alpha$) the IMU has drifted by end of the burn to obtain the same orbit for rates initiated at burn initiation. However, a misalignment of the IMU cannot be detected by monitoring the instruments. If 80 n. mi. is the target altitude, a reasonable error could be tolerated when aligning the platform for the LOI burn depending on the lowest h_{pc} acceptable.

CONCLUSIONS

Under the assumptions of Volume I, manual completion of the LOI burn is feasible for an IMU drift about its pitch axis. The assumptions are (1) manual completion is a non-G&N-controlled burn at a constant inertial attitude, (2) IMU drift begins at LOI burn initiation, (3) BMAG's are not drifting, (4) LOI circularization guidance is targeted for 80 n. mi., and (5) weights and SPS performance are nominal. Since a negative $\Delta\alpha$ results in the vehicle being prepericynthion at the end of manual completion, $\Delta\alpha$ should be monitored closely. The limit on $\Delta\alpha$ will depend upon the minimum h_{pc} acceptable and the total burn-time. (For a total burn-time of 383 seconds and an h_{pc} of 30 n. mi., $\Delta\alpha$ will have to be kept smaller than $-2.0°$ due to the possibility of a takeover early in the burn.) However, reducing the total burn-time to 330 seconds, the limit is expanded to $-10°$. Reducing the total burn-time to 300 seconds insures an h_{pc} of greater than 40 n. mi. for $-10°$ and an h_{pc} of greater than 80 n. mi. for $+10°$. A burn of at least 260 seconds will be necessary in order to have a stable nonimpacting ellipse.

Reorientating the vehicle to the attitude that gives 0° pitch on the BMAG FDAI prior to manual completion and using 383 seconds for total burn-time is not as effective as reducing the total burn-time. Since for negative $\Delta\alpha$'s, the vehicle is pitched in the positive direction in order to have a 0° pitch on the BMAG FDAI, pitching it more positive will improve h_{pc} at the end of manual completion. However, reducing the total burn-time appears more advantageous due to its simplicity at this time.

Finally, Volume I shows that the IMU could be misaligned about its pitch axis roughly $\pm 5°$ before an h_{pc} of less than 30 n. mi. would occur. Since considerable effort will be made to align the platform correctly and to verify the alignment prior to LOI ignition, this magnitude of misalignment is highly unlikely.

The effect on manual completion of the BMAG's drifting about its pitch axis will be forthcoming in Volume II. More study in the following areas are planned: (1) Reorientation of the vehicle prior to manual completion, (2) what the effect on manual completion will be when a drift rate begins later than LOI burn initiation, and (3) determining which system is drifting, i.e., IMU or BMAG, by monitoring the onboard displays.

$\bar{1}_H$ - UNIT VECTOR IN DIRECTION OF LOCAL HORIZONTAL
$\bar{V}$ - VELOCITY VECTOR
θ - ORIENTATION ATTITUDE ANGLE MEASURED POSITIVE FROM LOCAL HORIZONTAL
$\bar{1}_R$ - UNIT VECTOR IN DIRECTION OF RADIUS VECTOR
$\bar{a}_{TD}$ - GUIDANCE -COMPUTED DESIRED THRUST DIRECTION

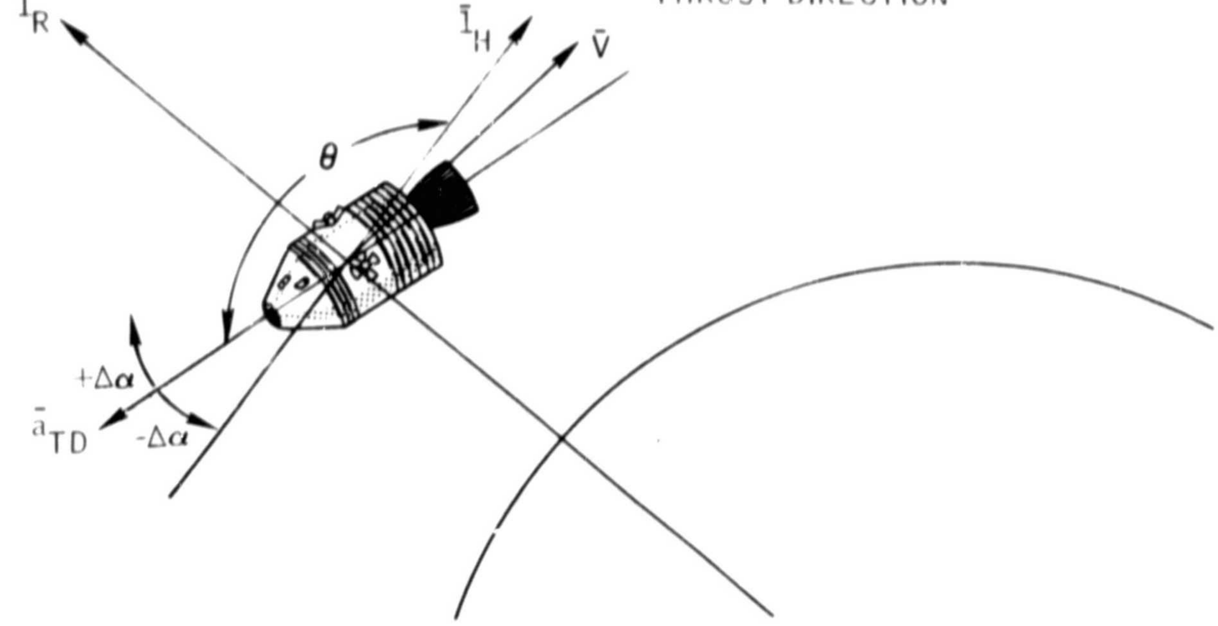
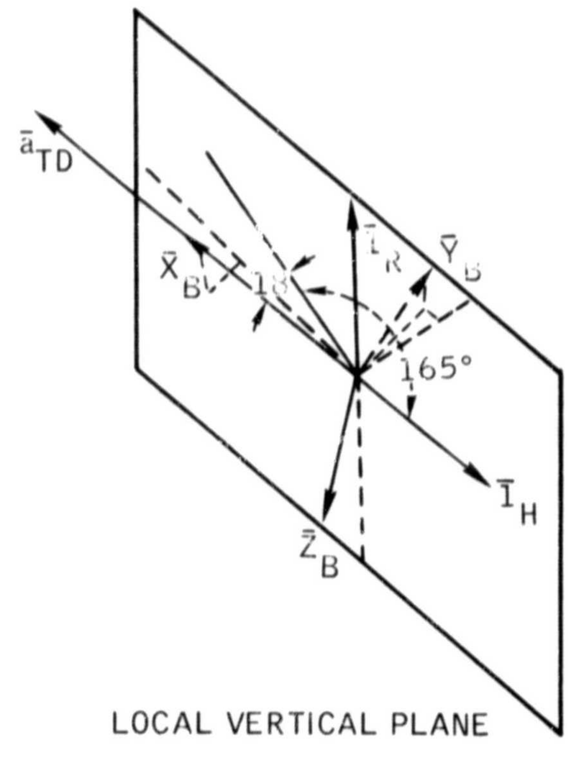


Figure 1.- Vehicle attitude relative to local horizontal at LOI burn initiation.



$\bar{a}_{TD}$ - GUIDANCE-COMPUTED DESIRED THRUST DIRECTION
$\bar{1}_R$ - UNIT VECTOR IN DIRECTION OF RADIUS VECTOR
$\bar{1}_H$ - UNIT VECTOR IN DIRECTION OF LOCAL HORIZONTAL
$\bar{X}_B$ - VEHICLE AND IMU X AXIS
$\bar{Y}_B$ - VEHICLE AND IMU Y AXIS
$\bar{Z}_B$ - VEHICLE AND IMU Z AXIS

Figure 2.- IMU guidance alinement at LOI burn initiation.

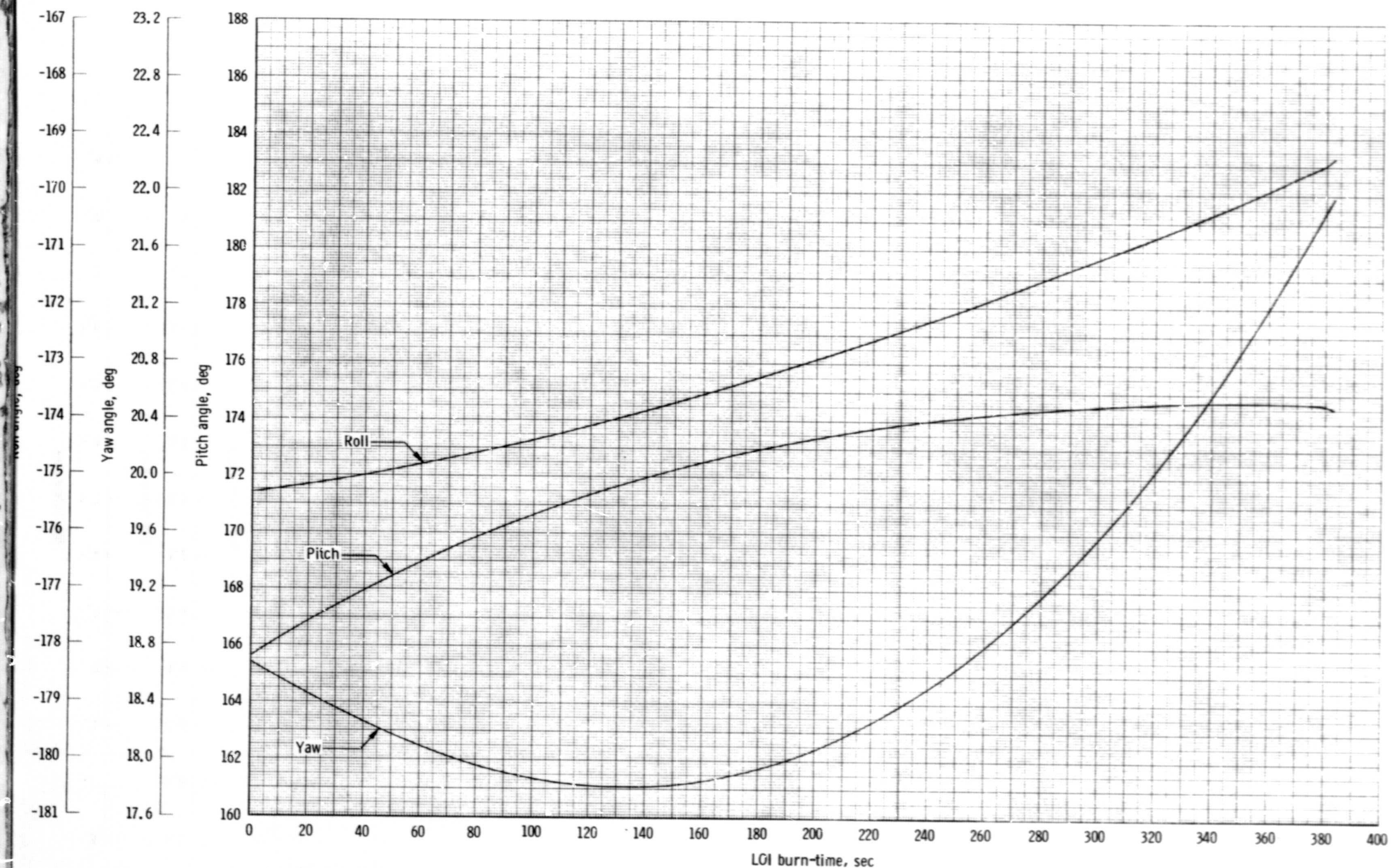


Figure 3. - Attitude time history of LOI burn with respect to the local horizontal coordinate system.

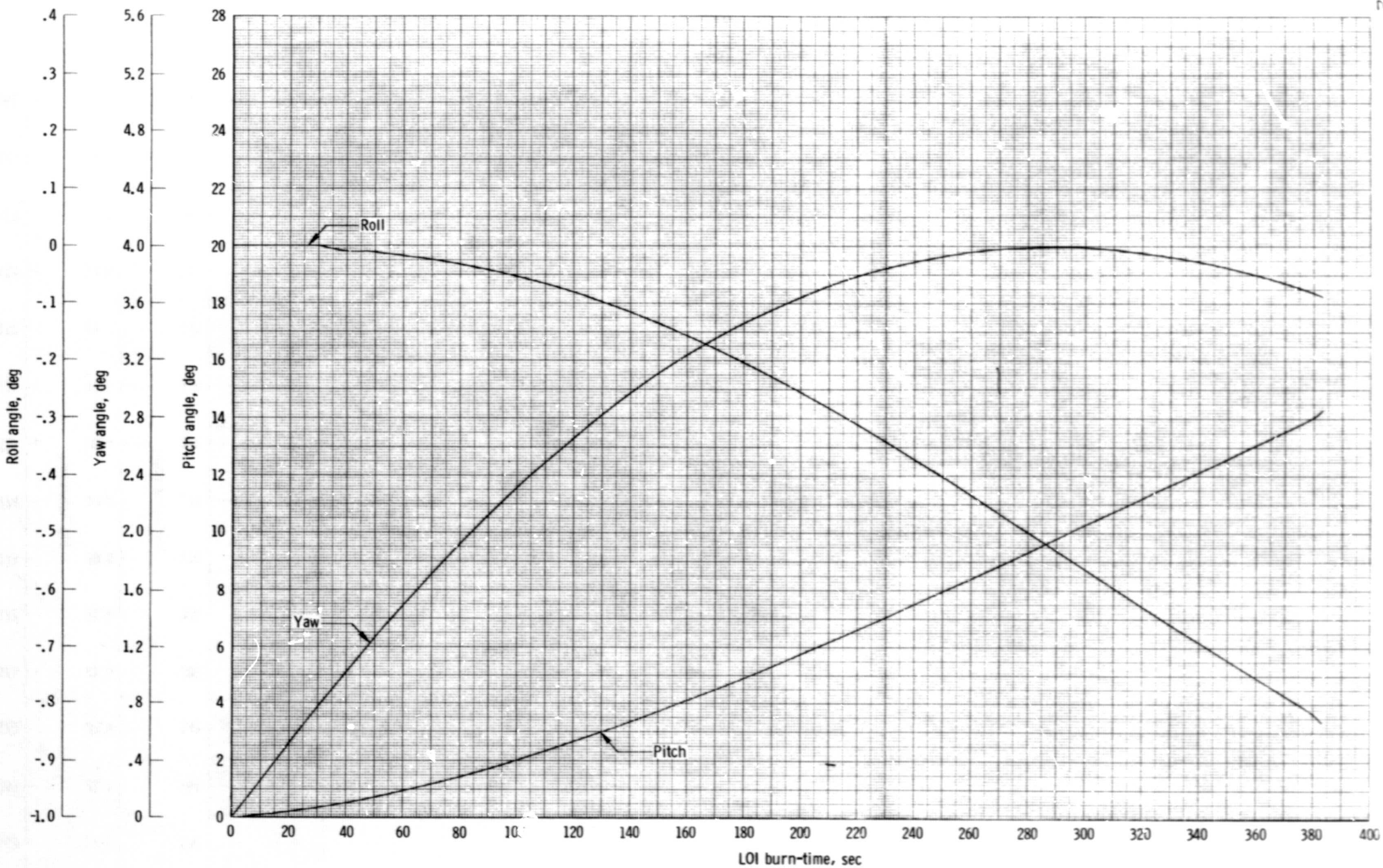


Figure 4.- Attitude time history of LOI burn with respect to IMU coordinate system.

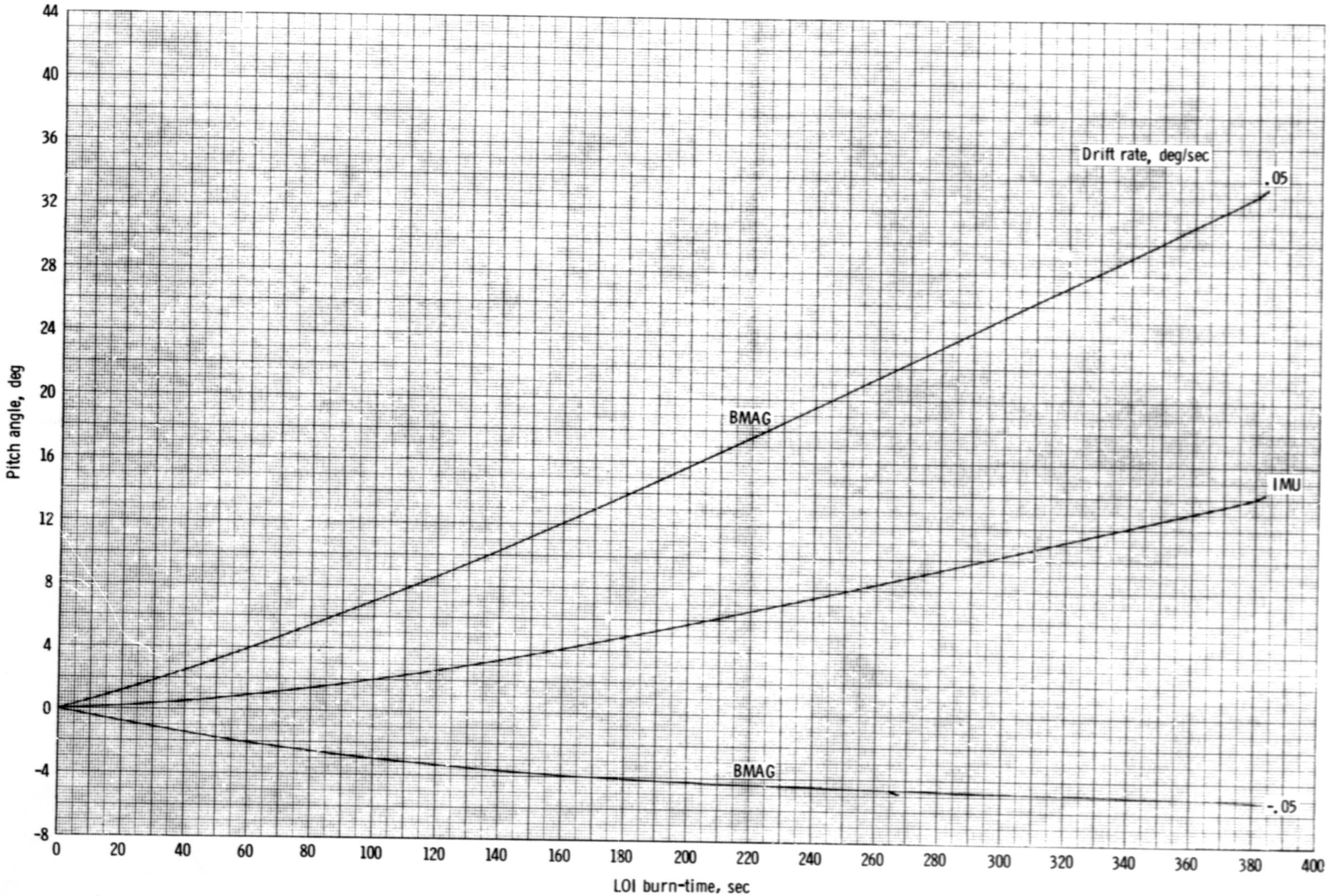
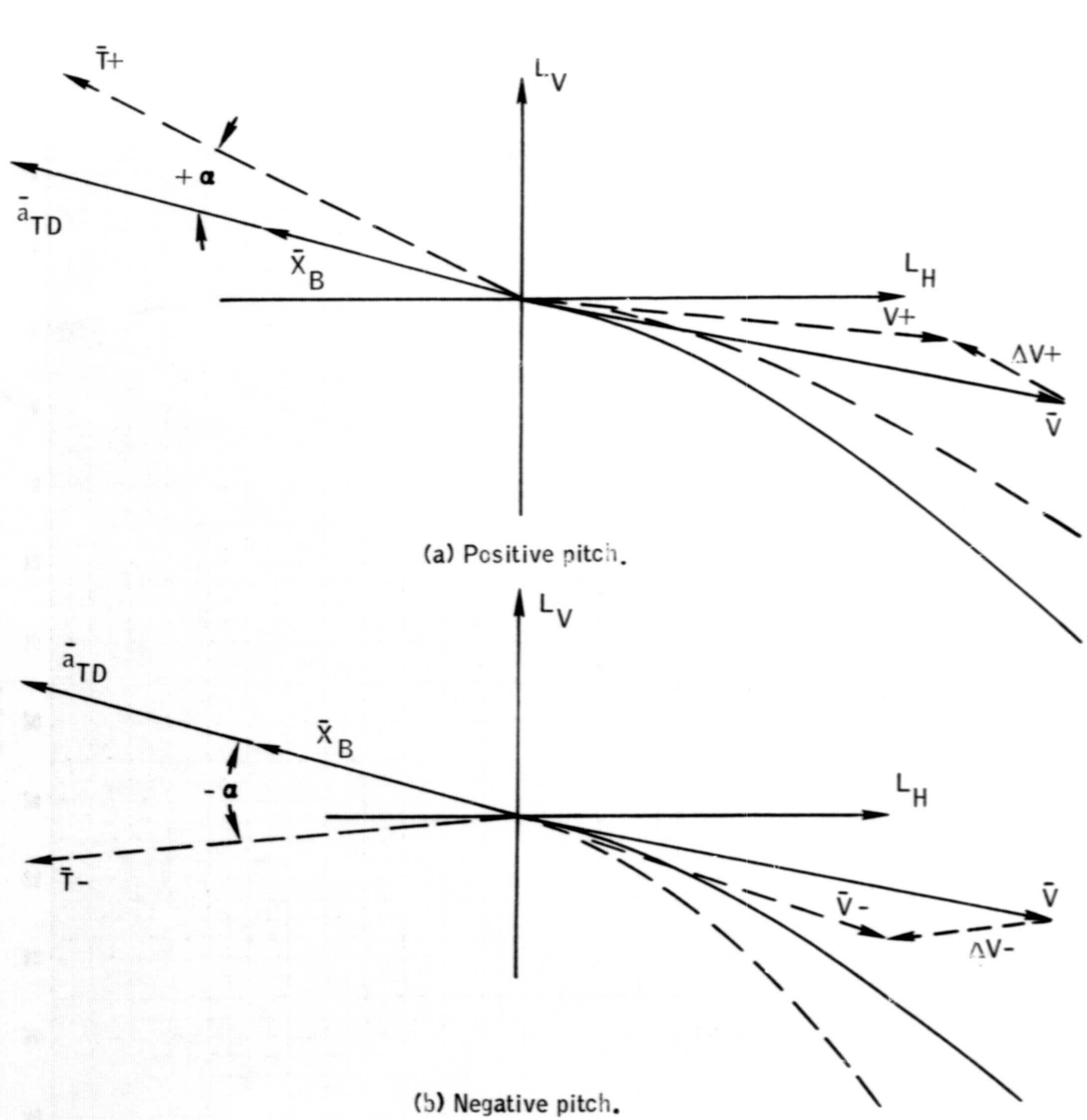


Figure 5. - Pitch attitude time history for an IMU drifting about its pitch axis.

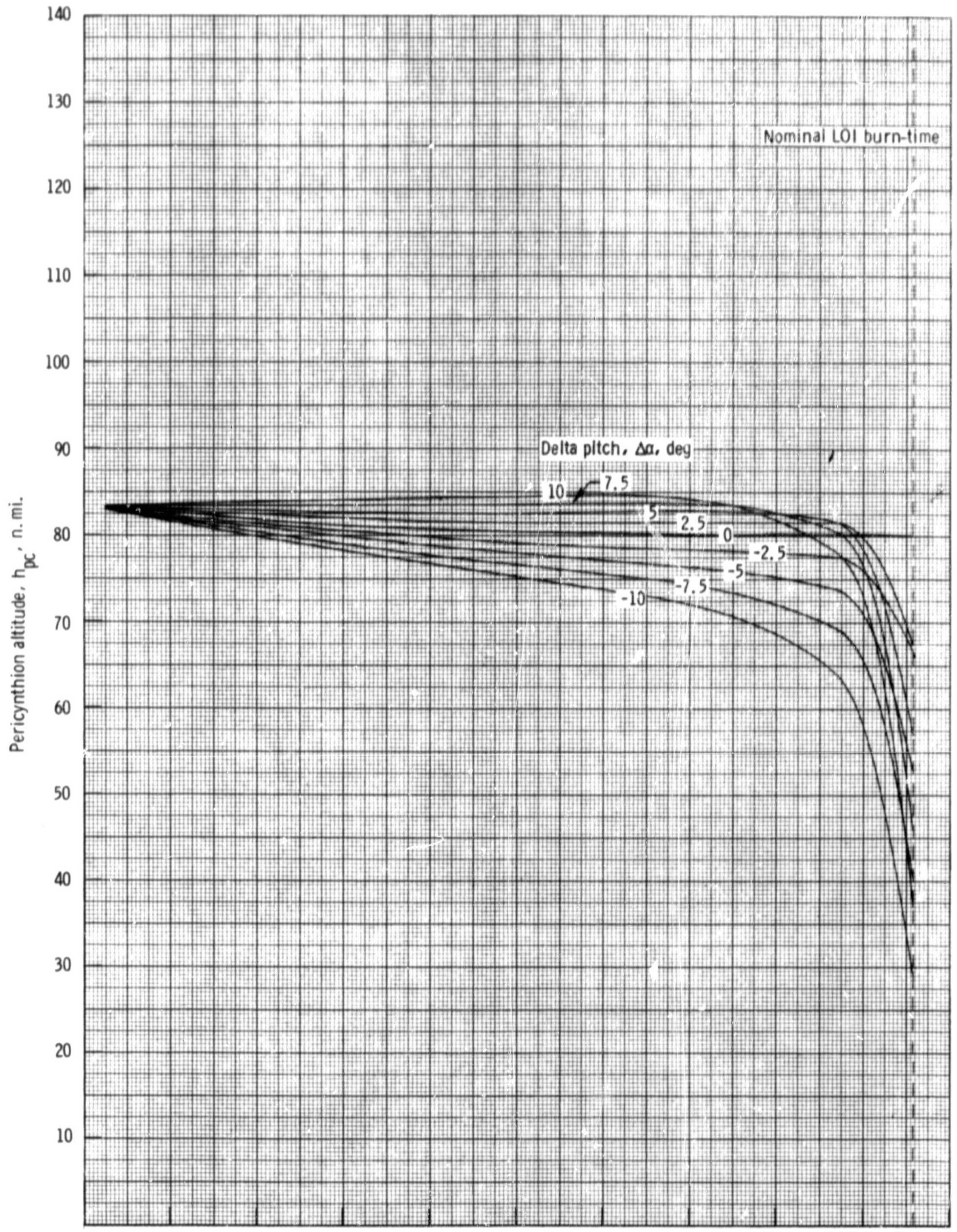


(a) Positive pitch.

(b) Negative pitch.

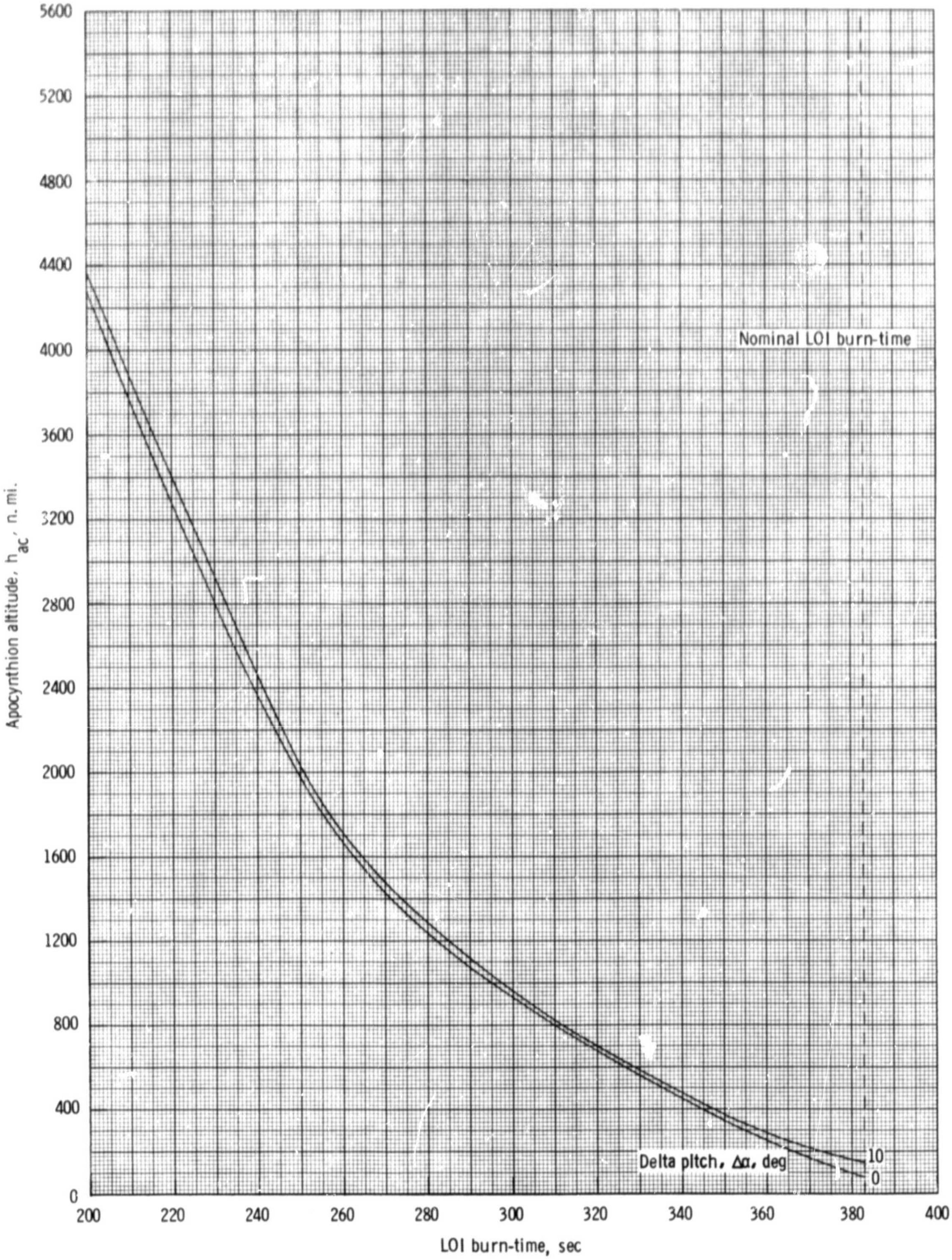
L_V	LOCAL VERTICAL
L_H	LOCAL HORIZONTAL
$\bar{a}_{TD}$	INITIAL GUIDANCE COMPUTED THRUST DIRECTION
$\bar{V}$	VELOCITY VECTOR
α	PITCH ANGLE
$\bar{X}_B$	IMU X-AXIS
$\bar{V}\pm$	VELOCITY AFTER IMPULSE
$\bar{T}\pm$	THRUST DIRECTION
$\Delta V\pm$	IMPULSE OF DELTA VELOCITY

Figure 6.- Instantaneous effect of pitch on the LOI burn.



(a) Pericynthion.

Figure 7. - Osculating pericynthion and apocynthion altitudes at crew takeover of a drifted LOI burn.



(b) Apocynthion.

Figure 7. - Concluded.

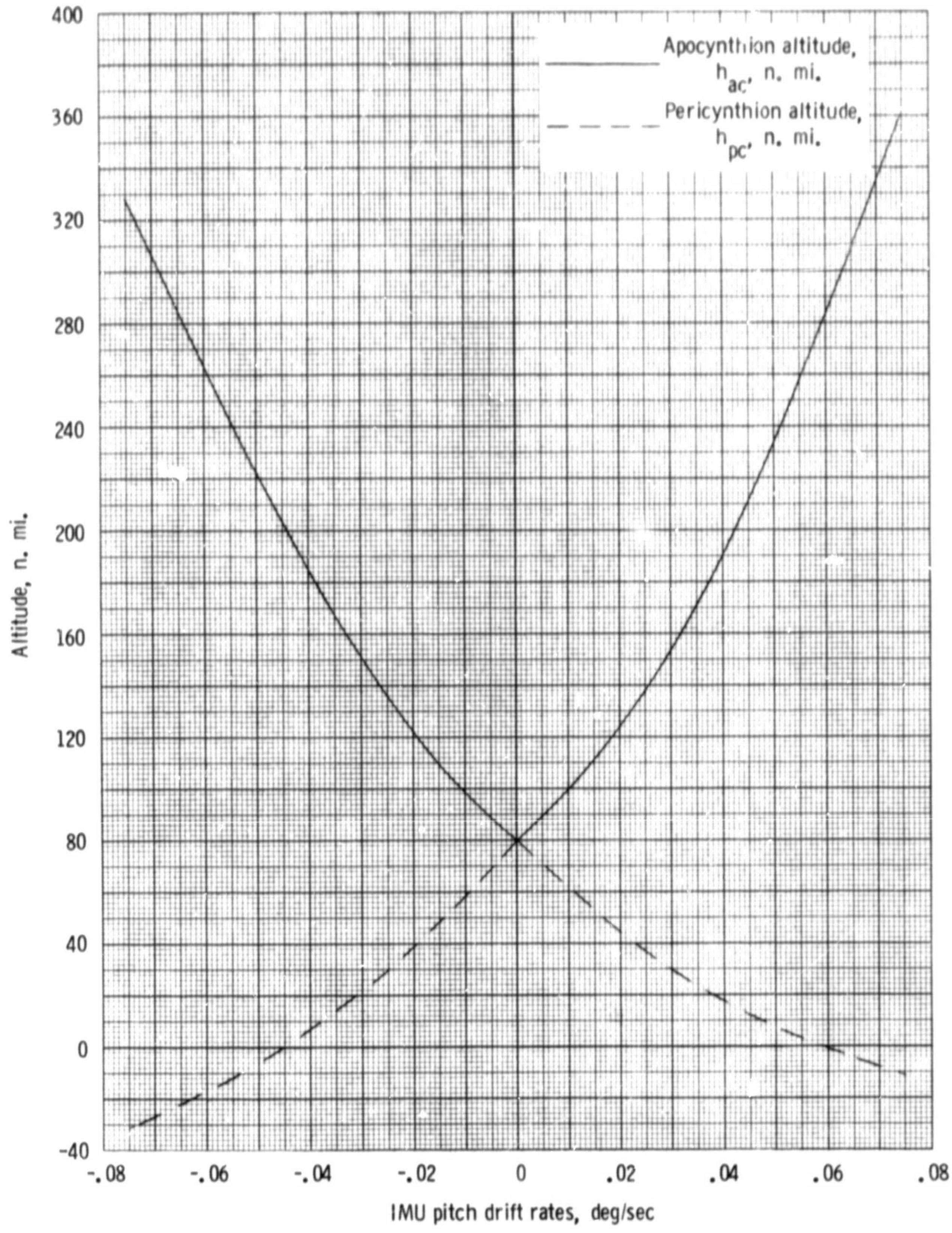


Figure 8. - Resulting pericynthion and apocynthion altitudes for various IMU pitch drift rates.

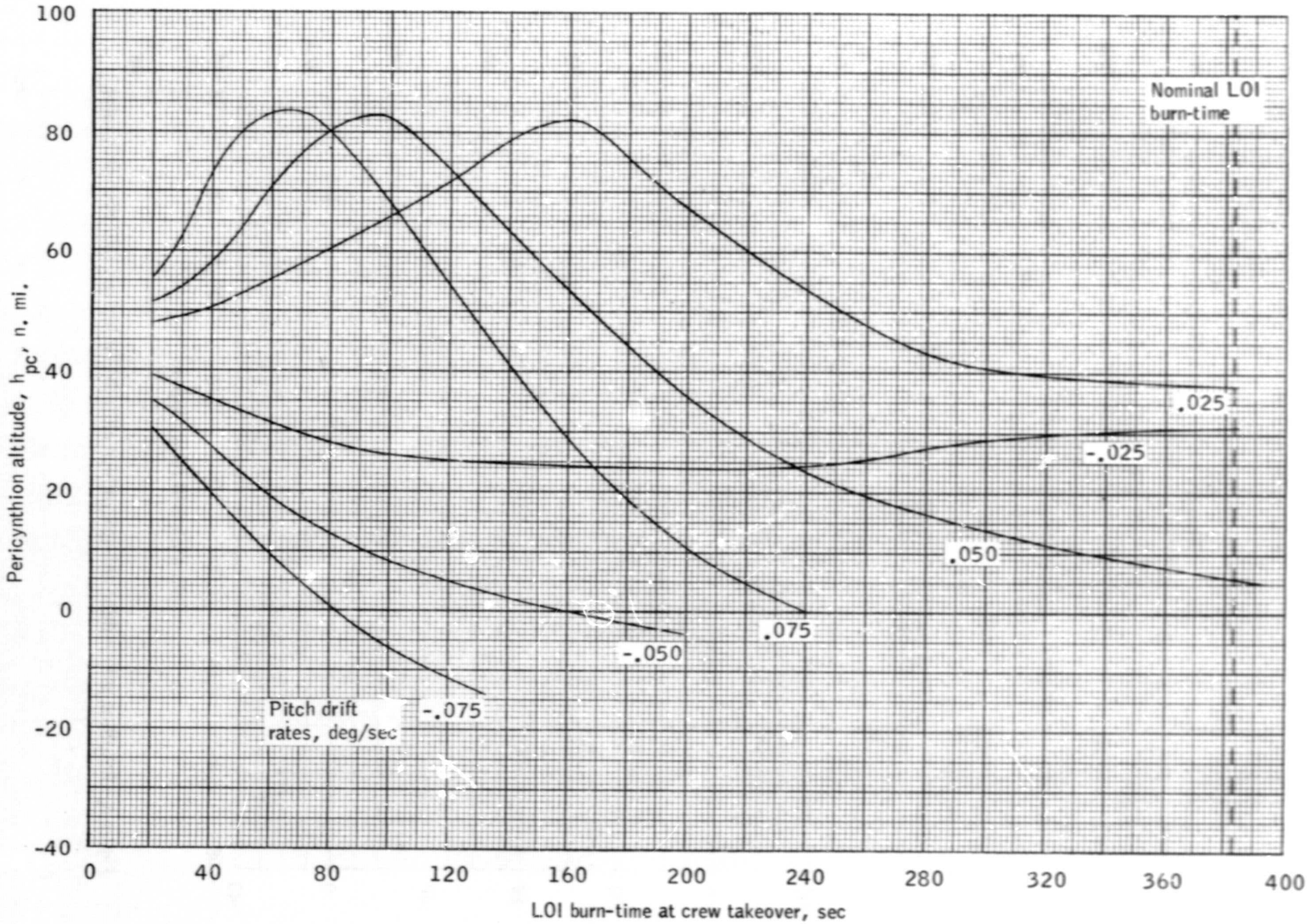
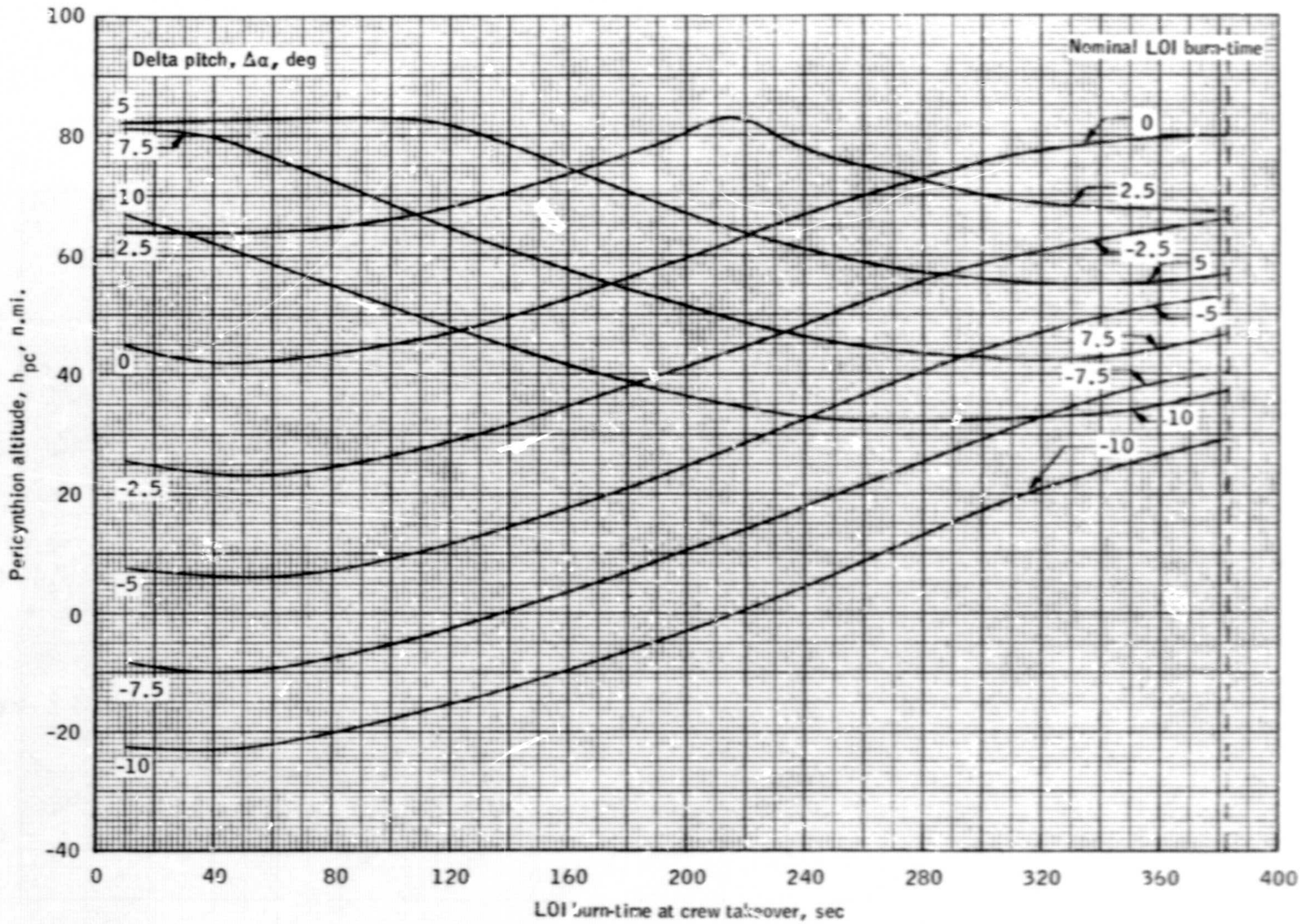
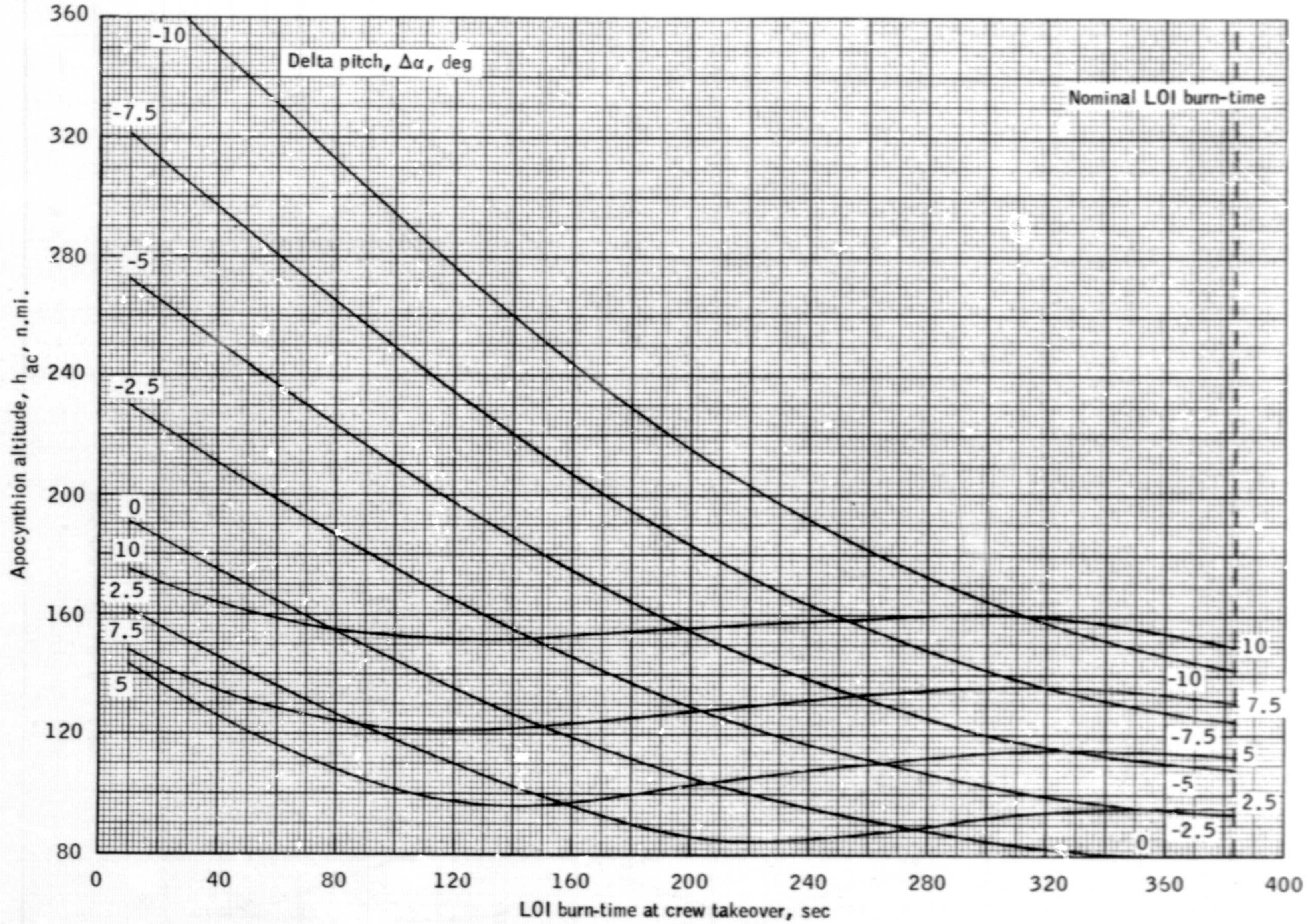


Figure 9.- Pericynthion altitude at the end of a manual completion of an LOI burn for various drift rates.



(a) Pericynthion altitude.

Figure 10.- Pitch error contours for manual completion of LOI burn.



(b) Apocynthion altitude.

Figure 10.- Concluded.

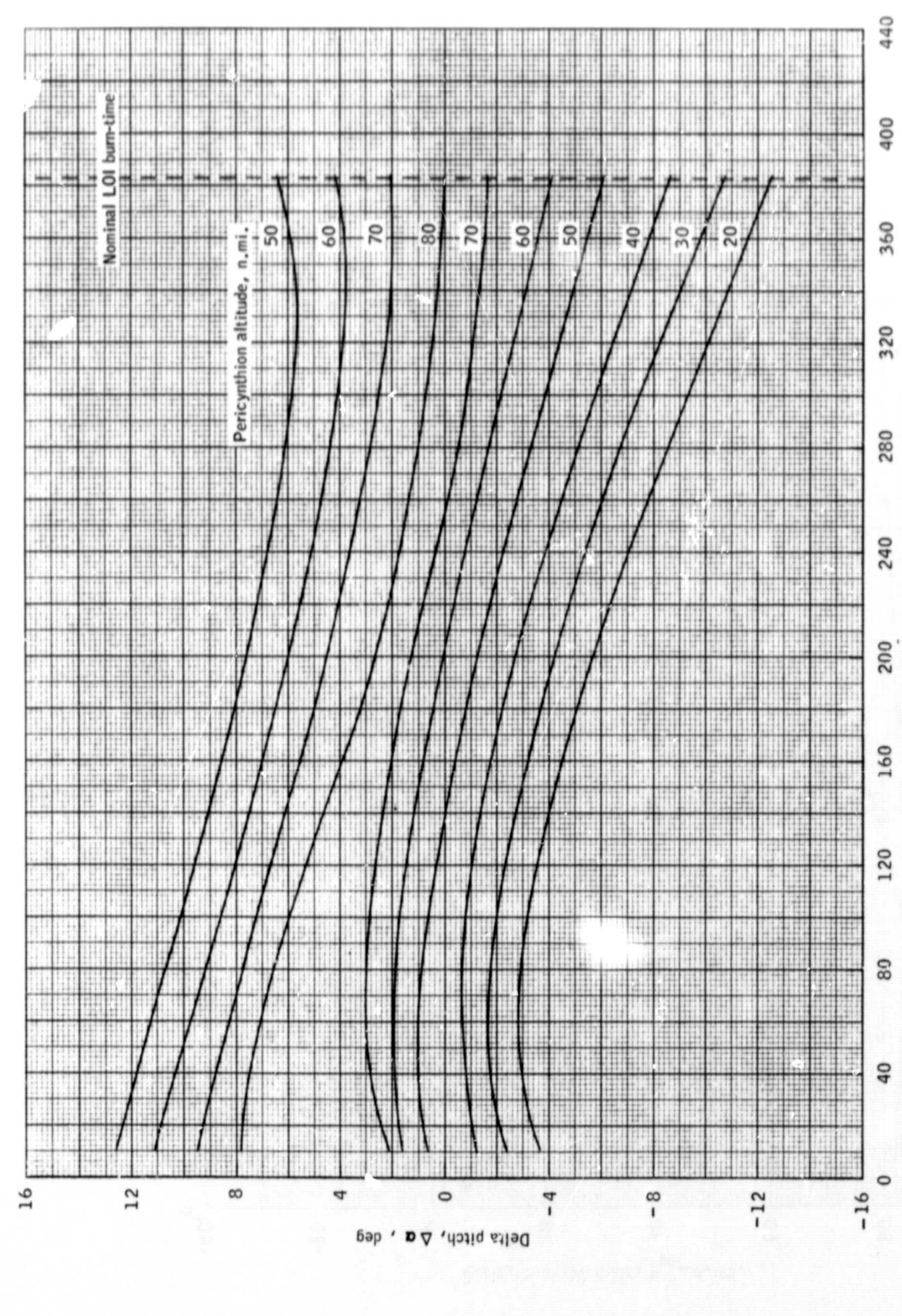
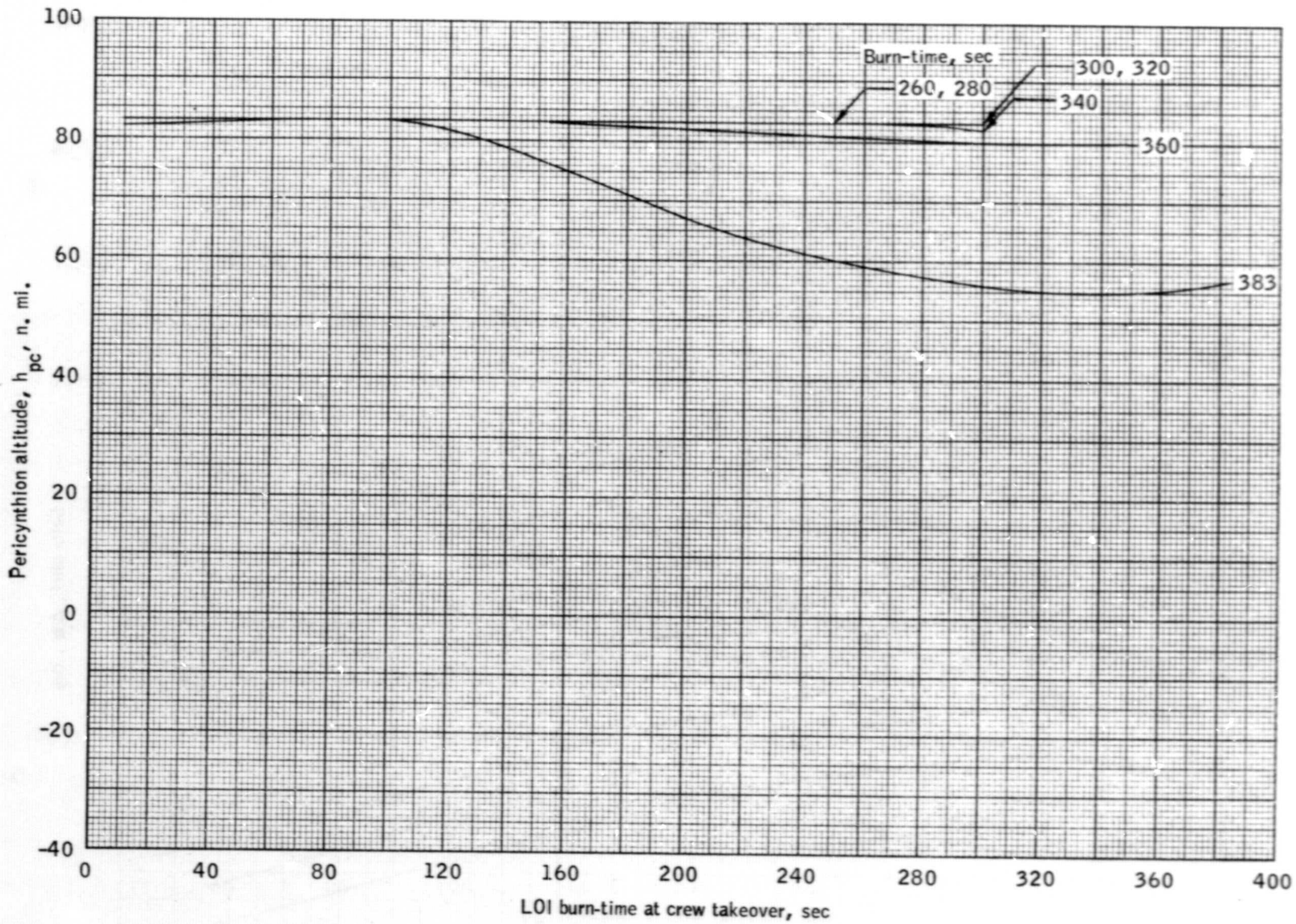
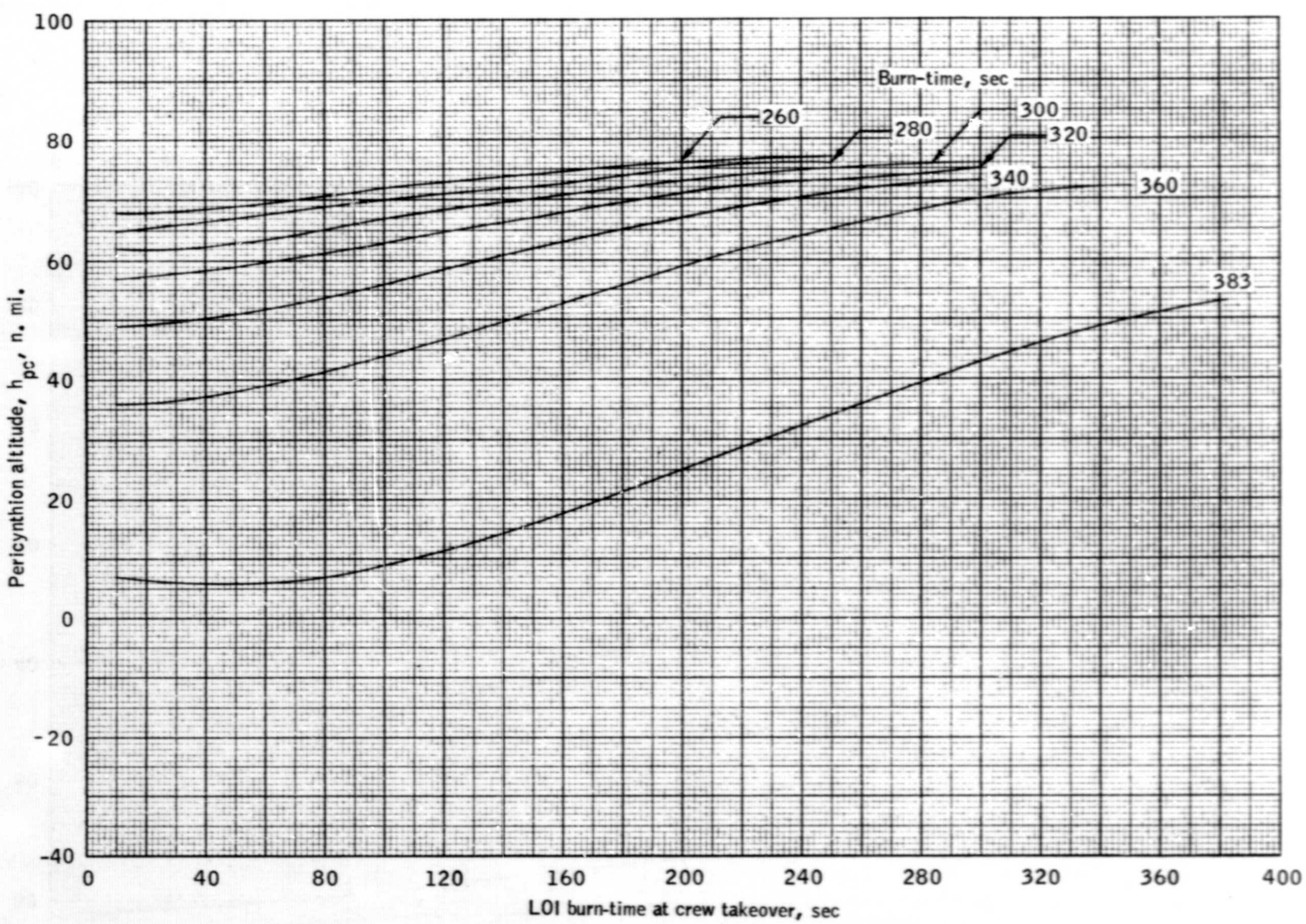


Figure 11.- Pericynthion altitude contours for manual completion of LOI burn.



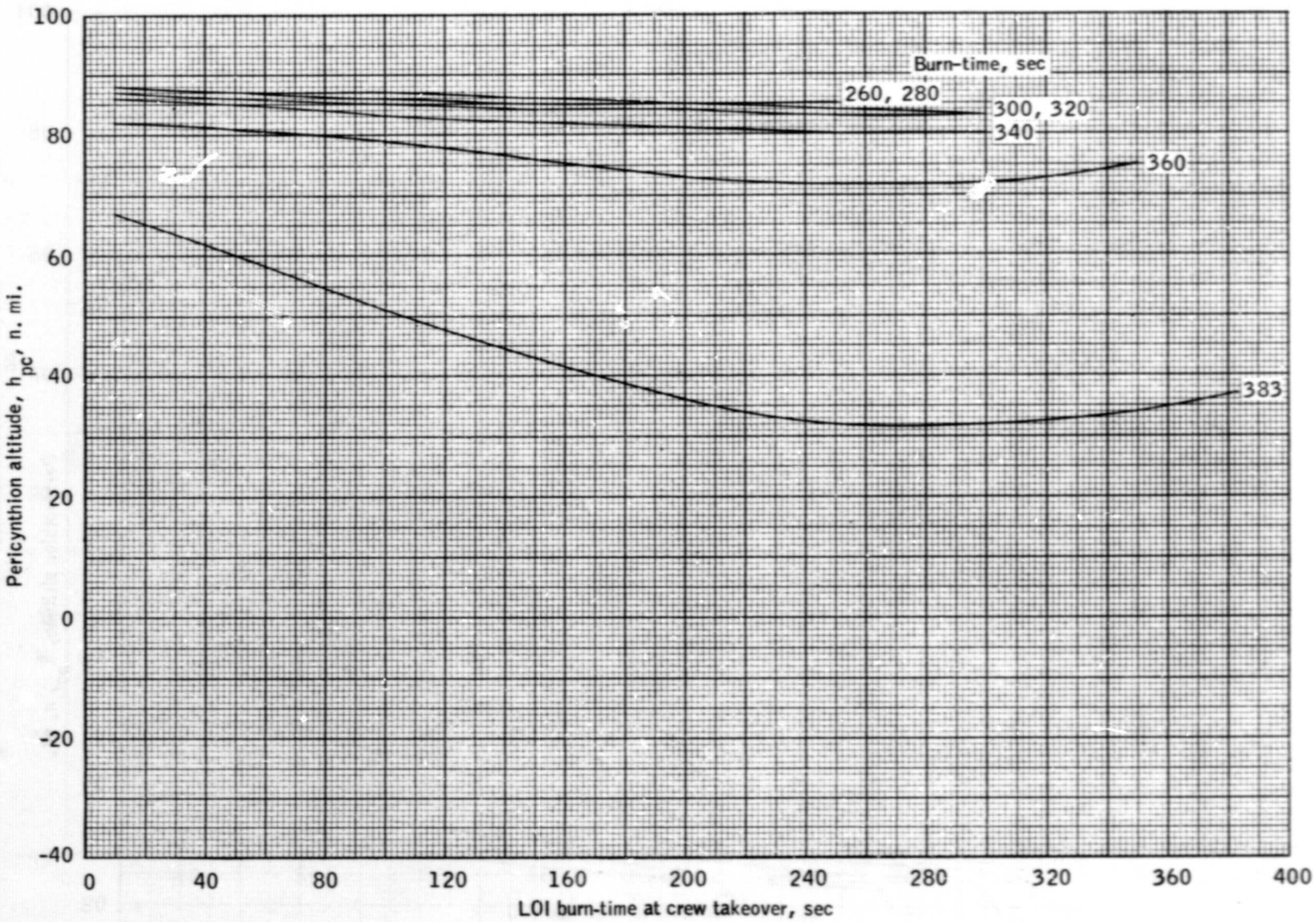
(a) $\Delta\alpha = +5$ deg

Figure 12.- Pericynthion altitude at the end of a manual completion for various total LOI burn-times.



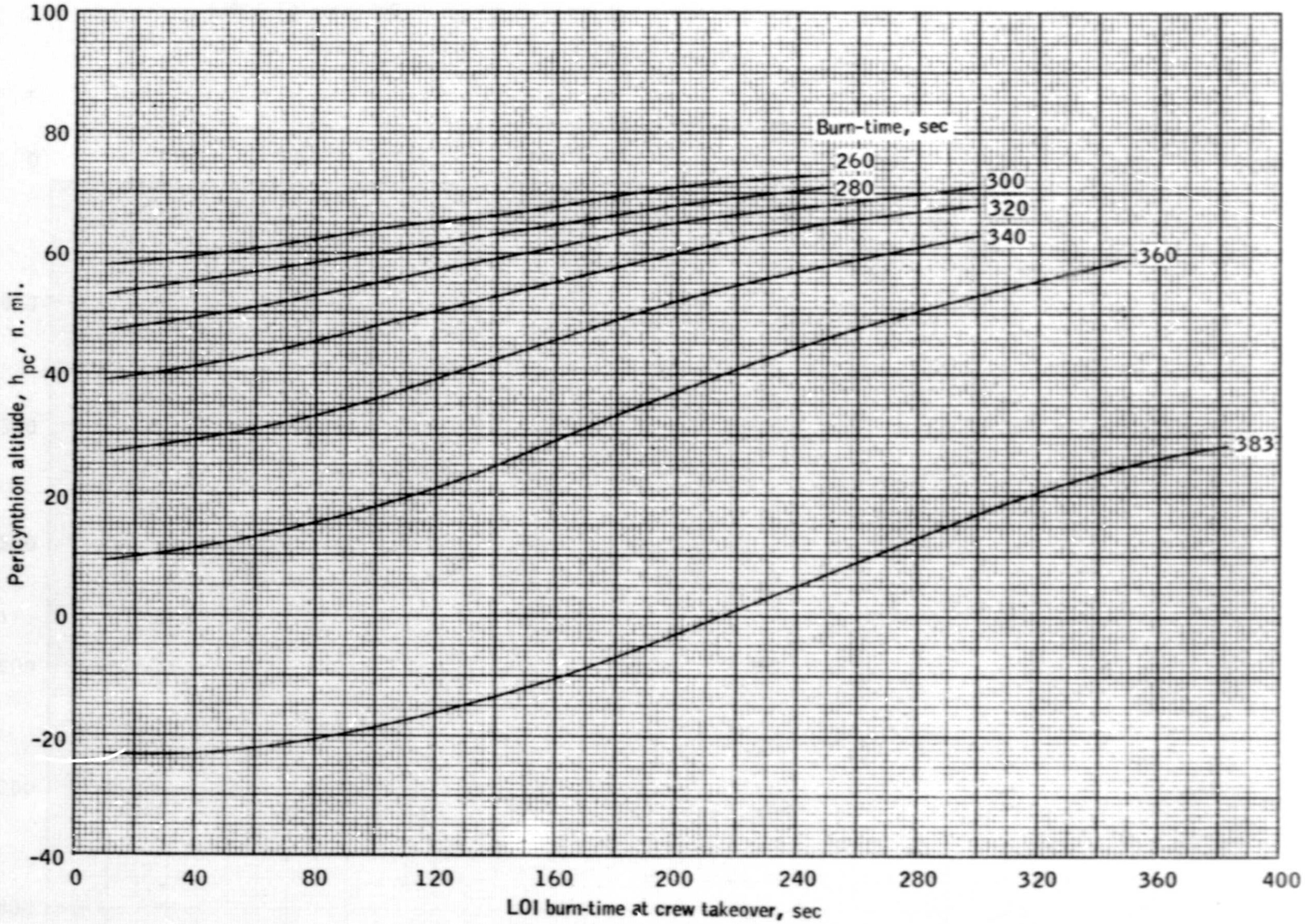
(b) $\Delta\alpha = -5$ deg

Figure 12.- Continued.



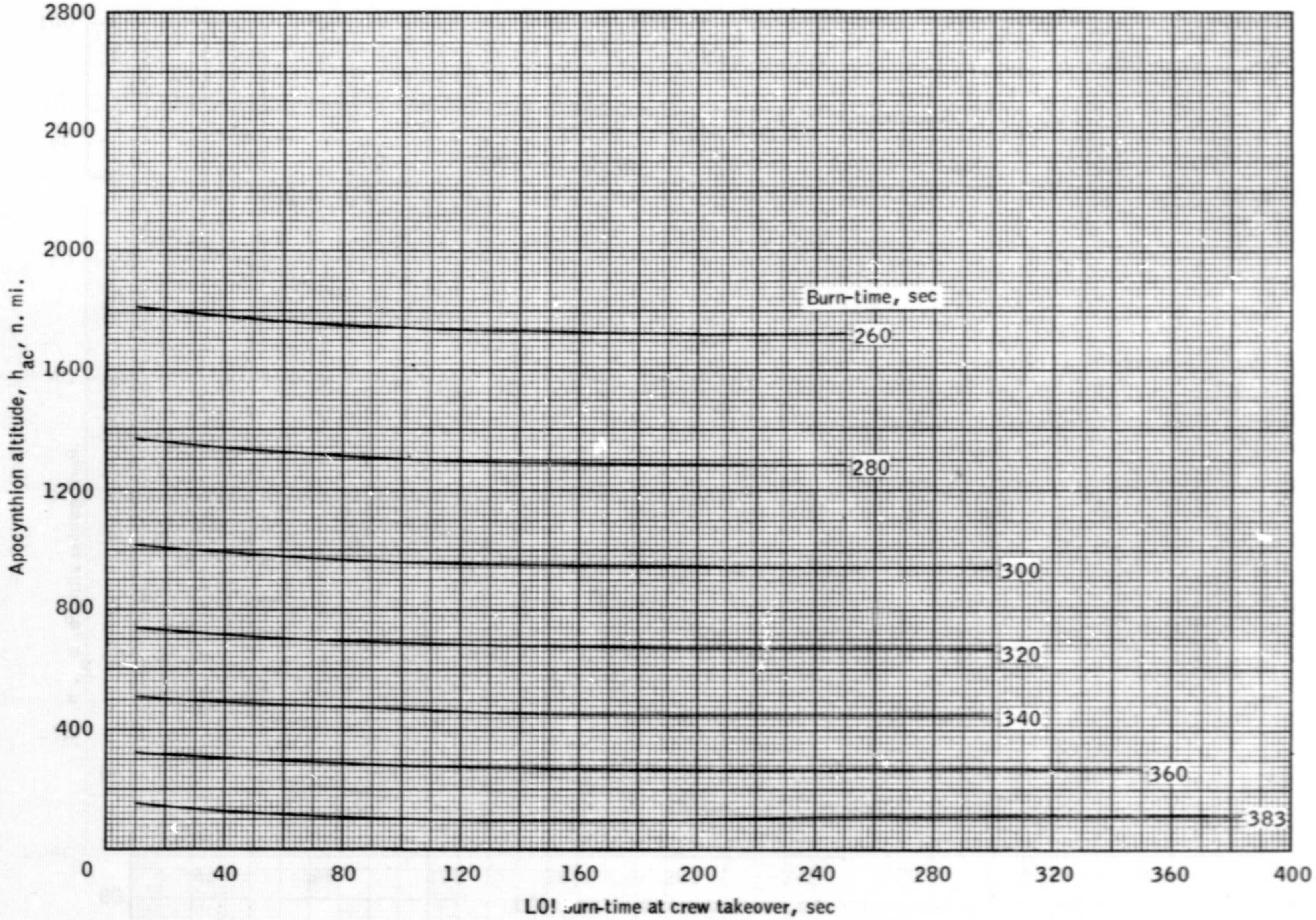
(c) $\Delta\alpha = +10$ deg

Figure 12.- Continued.



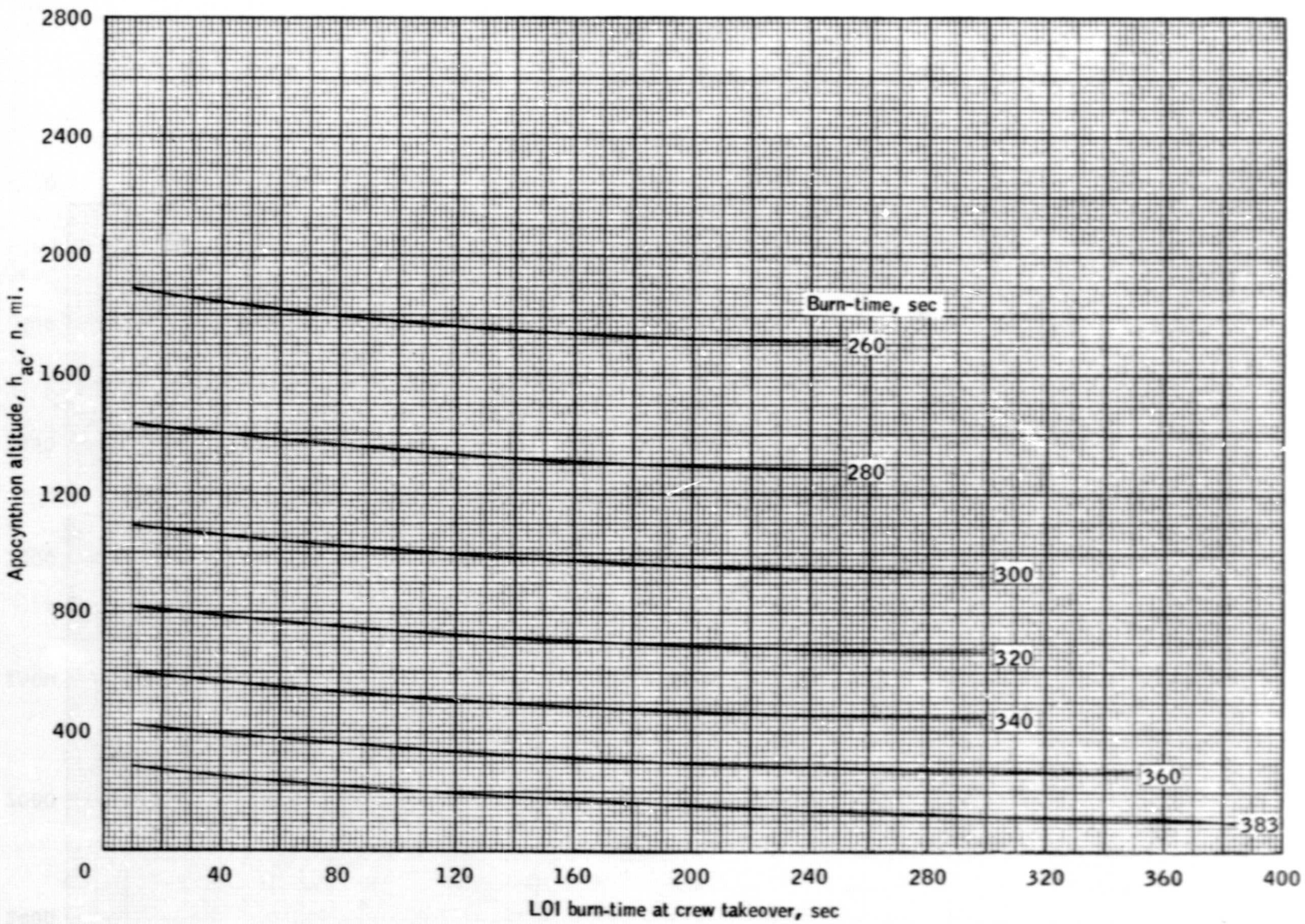
(d) $\Delta\alpha = -10$ deg

Figure 12. - Concluded.



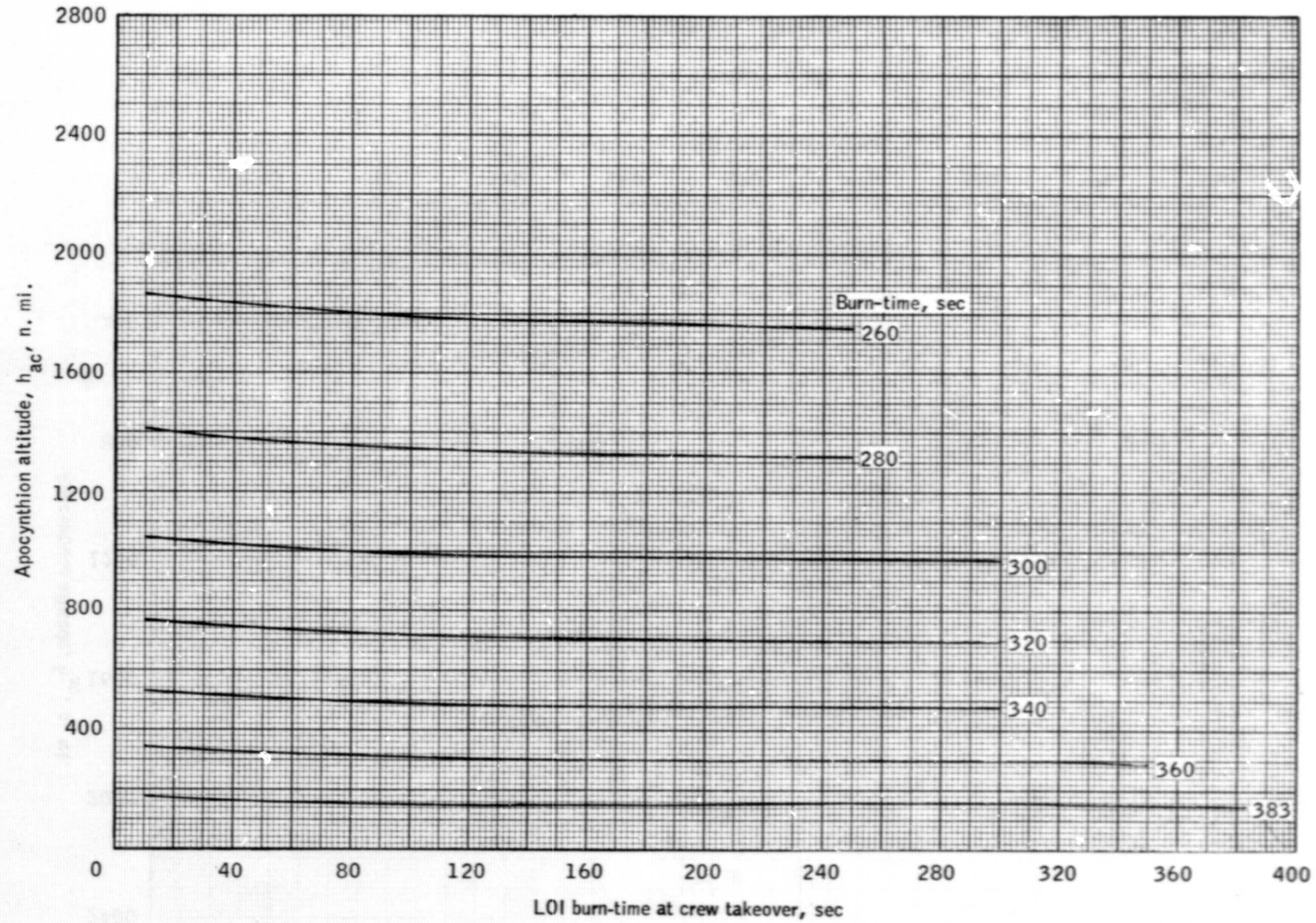
(a) $\Delta\alpha = +5$ deg

Figure 13.- Apocynthion altitude at the end of a manual completion for various total LOI burn-times.



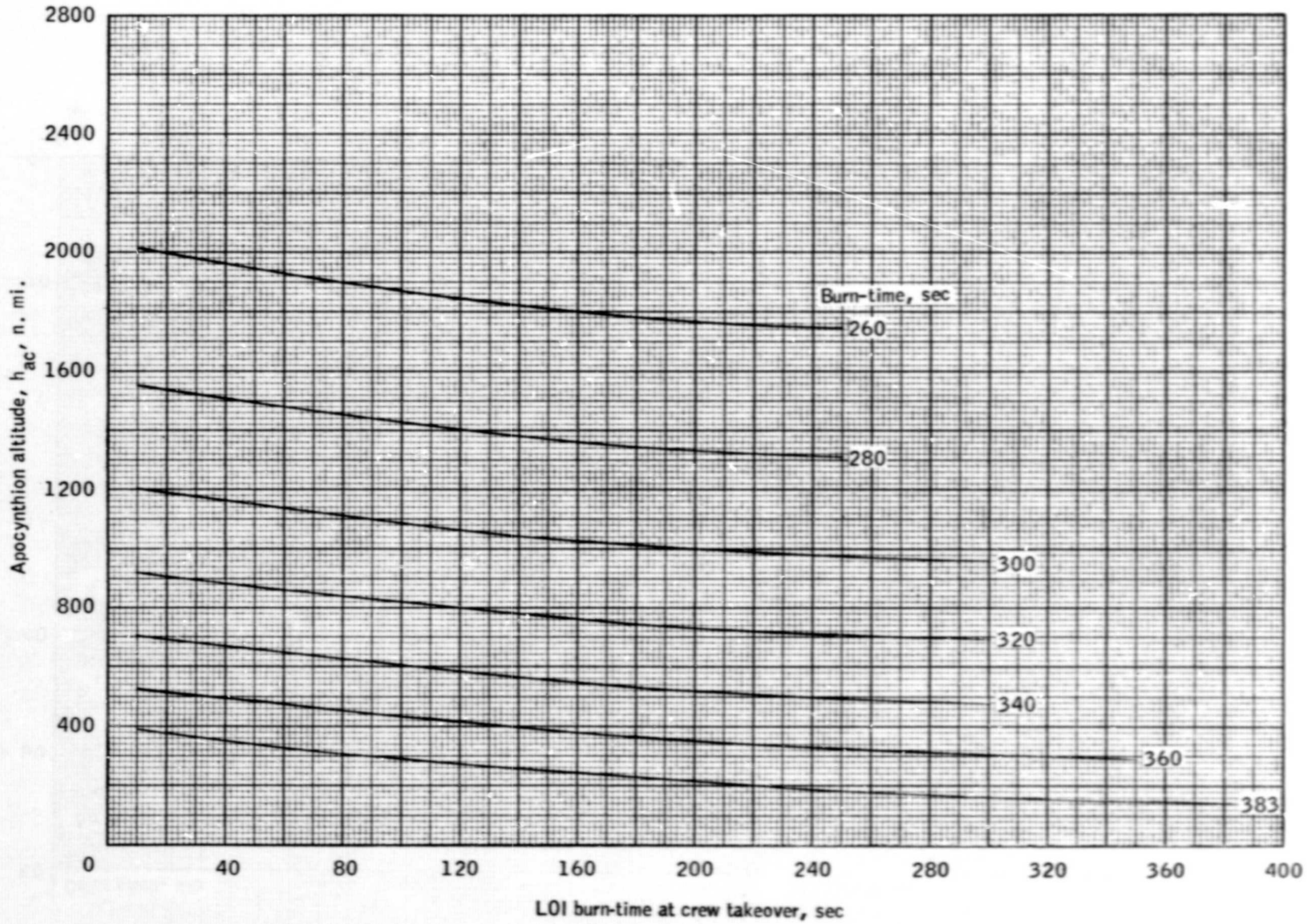
(b) $\Delta\alpha = -5$ deg

Figure 13.- Continued.



(c) $\Delta\alpha = +10$ deg

Figure 13.- Continued.



(d) $\Delta\alpha = -10$ deg

Figure 13.- Concluded.

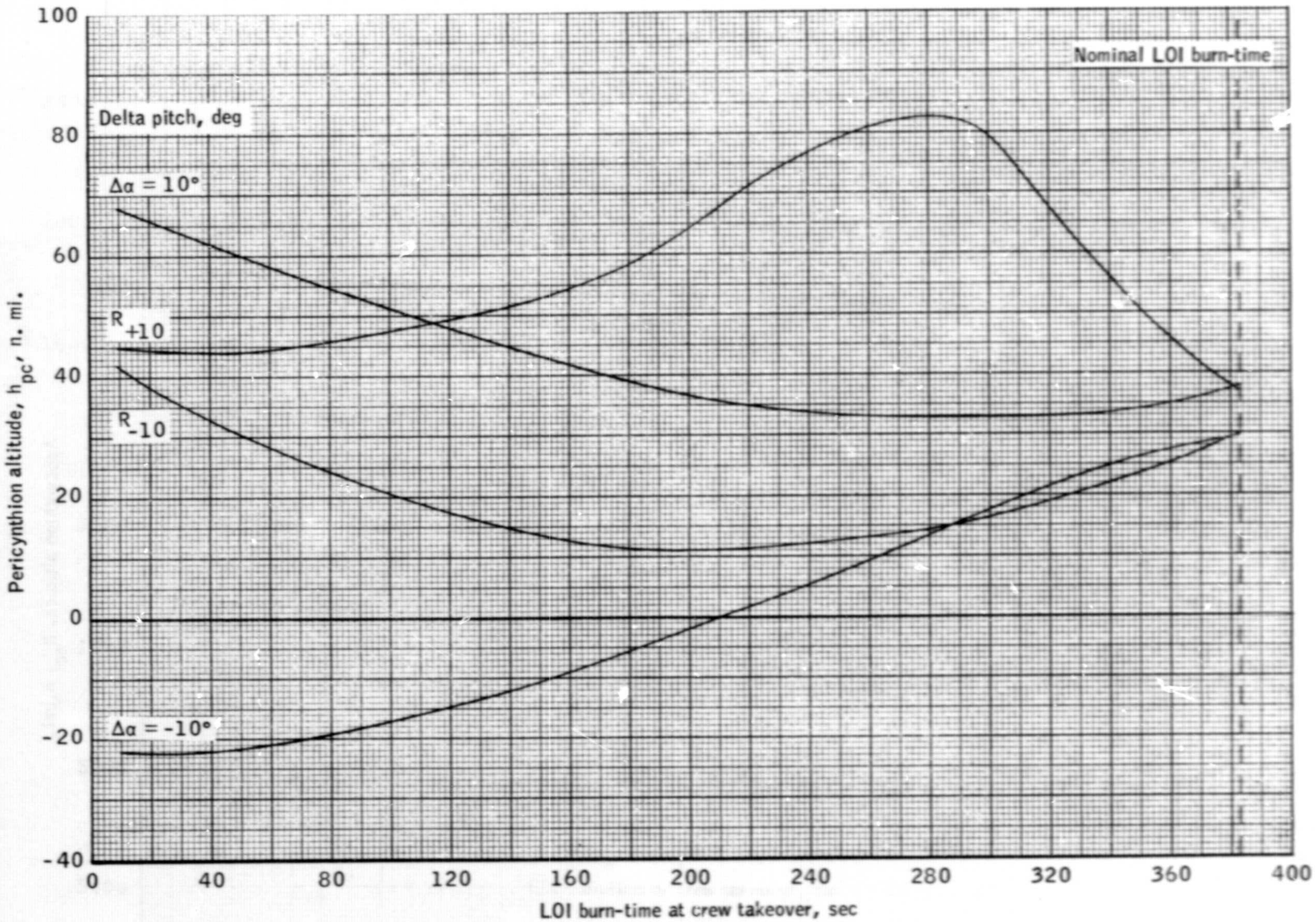


Figure 14.- Comparison of pericynthion altitude for manual completion of LOI burn with and without vehicle reorientation.

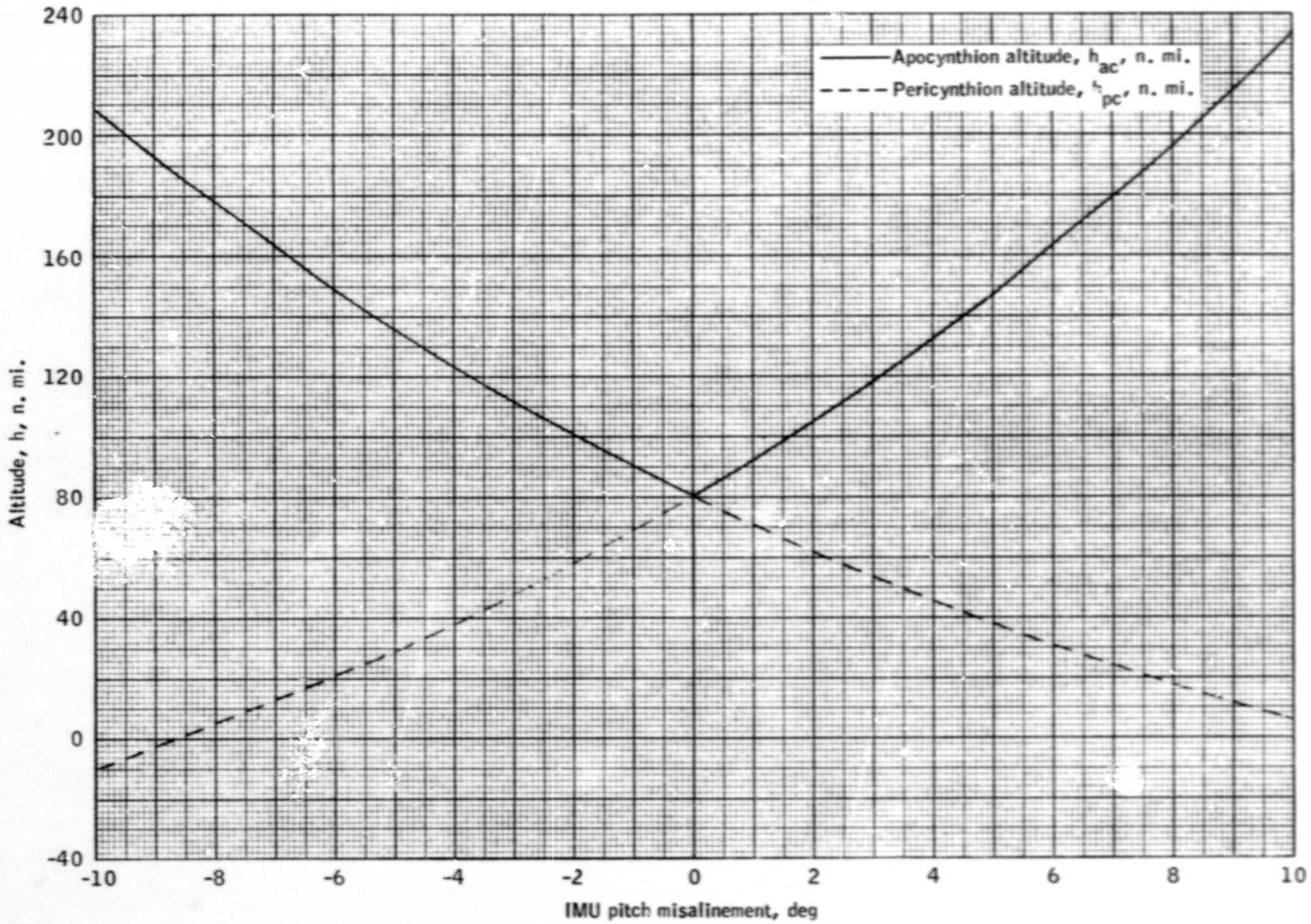


Figure [illegible].- Resulting pericynthion and apocynthion altitude for various IMU pitch misalignments.

REFERENCES

1. Mission Analysis Branch: AS-504A Preliminary Spacecraft Reference Trajectory. MSC Internal Note No. 66-FM-70, July 1, 1966. (C)

2. Foggatt, Charles E.; Lunde, Alfred N.; Newman, Samuel R.; Pace, Charles W.; Treadway, Alexander H.; Weber, Bobbie D., Flight Analysis Branch; and Gonzales, Lazarus, Jr., Mission Analysis Branch: AS-504A Preliminary Abort and Alternate Mission Studies, Volume II, Return to Earth Abort Studies. MSC Internal Note No. 67-FM-91, June 30, 1967.