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PROJECT APOLLO

UTILIZATION AND CHARACTERISTIC VELOCITY SAVING WITH A SMALL THROTTLEABLE REGION ABOUT 92.5% THRUST FOR LM POWERED DESCENT

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SUMMARY

The possibilities of utilizing a small throttling capability about the high thrust region of $92\frac{1}{2}\%$ for LM powered descent, and the studies required to determine the ΔV saving and overall system performance with these possibilities are presented. Some preliminary data has been obtained on the required studies and is also presented.

The utilization possibilities are:

Throttling - T1 - Command a specific thrust-time profile to eliminate DPS uncertainty.

T2 - Adjust trajectory and guidance aim point targeting such that guidance system commands a nearly constant $92\frac{1}{2}\%$ thrust-thrust controlled to the command within the limits of throttle capability.

Guidance Targeting -

G1 - Present concept of high gate targeting.

G2 - False high gate targeting (presently not documented).

A total of four possibilities result from combining the two throttling and two targeting possibilities. With each possibility a ΔV saving can be obtained independent of the small throttle capability, plus a ΔV saving resulting from the throttle capability. The system performance with terrain and navigation error for each of these possibilities will be investigated on both an all-digital LM descent program, and hybrid simulation for cases where pilot opinion is required. A search is being conducted for a trajectory which will produce the nearly constant thrust command of $92\frac{1}{2}\%$ (overall or just latter part of descent to high gate) required for item T2.

The maximum ΔV saving that can be obtained with any of the above possibilities has been estimated as 140 ft/sec. This saving is the difference between the present system and a fully throttleable system. The maximum saving that will result from the above studies can only be estimated at this time as being between 100 and 140 ft/sec (probably 120). The minimum ΔV saving that can be attributed to a high thrust throttle capability (sufficient to produce (T1) with a DPS uncertainty of +1% to -2%) can be specified from data presented at 46 ft/sec. This results from the minimum

change to the present system of (T1G1), with the commanded nominal thrust profile (assumed to be 9710 + .47t) producing a throttle-down (thrust = guidance command < 5250 lbs) at a time-to-go-to-higate of 76 sec, which is the time produced by a three-sigma low engine with the present system. An additional saving might be obtained by delaying this throttle-down time, but the additional saving could not be attributed to the throttle capability. *

If the possibility (T2G1) can be perfected with satisfactory performance in the presence of terrain and navigation errors, then a ΔV saving near maximum (100 to 140) might be obtained, and all of the saving would be attributed to the throttle capability. The possibility (T1G2), which has greatly improved radar-terrain interface characteristics (to be shown in future documentation), might also produce a near maximum ΔV saving, but only 55 ft/sec of the saving could be attributed to the throttle capability.

A high thrust throttle capability is desirable based only on the minimum ΔV saving of 46 ft/sec, and the elimination of the effect of thrust uncertainty on trajectory monitoring parameters.

INTRODUCTION

The present LM descent engine is limited to throttle operation over the interval of approximately 10 to 60% of maximum thrust, and at a fixed throttle position (FTP) of 92½% thrust. The thrust output, when the engine is operated at FTP, is variable but bounded by the limits as specified in reference 1. * The uncertainty of thrust output is approximately +1 to -2% about a nominal thrust-time profile.

With the present guidance concept the guidance thrust command at FTP ignition is large but eventually reduces to the throttleable region (5250 lbs), at which point throttle-down from FTP to the guidance thrust command occurs. The time at which this throttle-down occurs is dependent on the thrust profile encountered. The variation of throttle-down time due to the FTP thrust uncertainty requires a bias in the design of the trajectory such that throttle-down would occur prior to high gate, if a low thrust profile were encountered. Ideally, the lowest ΔV to high gate would be obtained if throttle-down were to occur at high gate, but the linear guidance mode which is entered at 20 sec prior to high gate requires that throttle-down occur prior to this time. The minimum

*See note on reference page.

throttle-down time is itself a subject of study. It is estimated to be between 30 and 50 sec. The trajectory must therefore be designed such that a low thrust profile would throttle at the minimum time. Higher thrust profiles throttle down at larger times from high gate with resulting ΔV penalties.

If a small throttling capability of the engine (say 5%) were provided in the high thrust region of $92\frac{1}{2}\%$, it may be possible to save ΔV by forcing the throttle-down time to the minimum, or by changing the guidance concept and forcing throttle-down to occur at high gate for the maximum ΔV saving. This paper presents a discussion of possibilities of using a small throttle capability and results of studies that have been completed to date.

UTILIZATION

Two methods of utilizing a small throttleable region about the $92\frac{1}{2}\%$ thrust level, and two methods of guidance targeting are presented. A combined total of four possibilities should be studied.

Throttling

T1 - Command a specific thrust acceleration-time profile to eliminate DPS uncertainty. The thrust uncertainty is presently approximately +1% to -2%, and, therefore, with a $\pm2.5\%$ throttle control, a specific profile could be commanded. The throttle-down time could then be a fixed quantity, at least for a nominal case. The minimum value of throttle-down time must be studied with terrain and navigation error.

T2 - Adjust trajectory and guidance aim point targeting such that guidance system commands a nearly constant 92.5% thrust-control thrust to the command within the limits of throttle capability. This method may involve a nearly constant command over the entire descent to high gate (which may not be possible), or a thrust command which starts high and later reduces to, and remains in, the throttleable region about 92.5%. A special throttle logic for the condition of thrust command going less than the high thrust throttleable region may be required. Work is being done to establish a nominal trajectory with this method. Once a nominal is established, the required size of throttleable region will have to be studied with terrain and navigation error.

Guidance Targeting

G1 - Present concept of high gate targeting. The guidance system guides the vehicle all the way to the high gate aim point; i.e., to Tgo = 0, and supposedly achieves the desired position and velocity. A problem with this method is the effect, mainly on the desired velocity condition at high gate, of a radar update of altitude over a rough terrain near the Tgo = 20 to high gate, which is the time when the system switches to a linear guidance routine. The resulting high gate miss can have a degraded effect on the visibility phase that follows high gate.

G2 - False high gate targeting. There are two general types of error that can occur at high gate. (1) Referenced to the given knowledge that the guidance has of the vehicle state vector, the desired conditions may not be achieved, because of the problem mentioned above, and (2) an error in the knowledge of state vector; i.e., navigation error. One method of alleviating the aforementioned problem would be to reduce the radar weighting function; i.e., pay less attention to radar near high gate, but this would be at the expense of navigation accuracy. The false high gate targeting method, though, achieves a reduction of sensitivity to radar-terrain updates and also maintains navigation accuracy.

The false high gate aim point that has been studied is located 60 seconds beyond the real high gate. High gate is achieved with this method when Tgo reduces to 60 seconds, at which point the guidance system then aims for the next, or hover aim point. Because Tgo never gets lower than 60 seconds, the system does not respond as markedly (sensitivity reduced) to a given terrain feature as viewed by the radar, but navigation error is extracted just as readily as with high gate targeting. An example of this reduced sensitivity is shown on figure 1 for a landing in the crater Copernicus. Each run was made with a perfect radar; i.e., no radar loss after updating started. From a comparison of radar data which specifies the beam velocities and maximum incidence angles of the radar beams for radar lock, and the printout of beam velocities and incidence angles of the false high gate run over Copernicus, it was found that the radar would not have dropped out. The crash and near crash conditions obtained with high gate targeting over Copernicus, when the radar was allowed to drop out was reported in reference two.

The reduced sensitivity of the false targeting results because the guidance system does not try to force the vehicle to the high gate point, but to a point 60 sec beyond high gate. This can result in a miss of the high gate point, but it has been determined that with ± 3 sigma navigation errors, satisfactory visibility phases were obtained. These cases were reviewed by a pilot on a hybrid simulation. The three-sigma altitude misses were ± 1500 ft (high gate altitude of 8000 to 11000 ft). Associated with these altitude misses were nearly compensating velocity misses which produced a nearly uniform visibility profile after high gate; i.e., when vehicle low, rate of descent low and vice versa. With high gate targeting, the linear guidance mode at Tgo = 20 (which is not entered for false targeting) can cause degrading high gate misses of vehicle low, rate of descent high, and vice versa.

DESCRIPTION OF STUDIES PERFORMED

Simulated LM descents have been performed for the system (T1G1) on an all-digital LM descent program (reference 3) to obtain characteristic velocity as a function of thrust profile and throttle-down time. Overall performance in the presence of terrain and navigation error is yet to be performed. The trajectory conditions used are shown on Table I. A variation of throttle-down time for a given thrust profile was obtained by delaying FTP ignition by td sec, i.e., thrust = 0 for td seconds. Nominally, FTP ignition occurs at the indicated initial conditions; i.e., td = 0.

Reason for Trajectory Used

The nominal trajectory is basically that described in reference 4, with the exception of the desired vertical acceleration (or pitch attitude) at high gate. This change was made to lower the shape of the trajectory to high gate, as shown on figure 2, to provide a higher probability of radar acquisition when LM high navigation errors are encountered. This subject of trajectory shaping is a study within itself, but the study requires a radar math model which is presently being prepared. The following discussion is presented, based on preliminary radar data, to show the importance of trajectory shaping.

For each nominal trajectory (65 and 69°), the digital program provides a printout of the four radar beam conditions of incidence angle and velocity along the beam. A comparison of this data with the preliminary radar data enabled the construction of figure 3, which shows the time of radar altitude acquisition as a function of various navigation altitude errors. Also shown on the plot is the overall probability of navigation error as a function of Tgo to high gate. The step change on the acquisition curves is caused by more restrictive conditions for acquisition of beams one and two because of the lower velocity as Tgo decreases. For Tgo > 150, beam four acquisition is more restrictive than beams one and two.

The data on figure 3 shows that a five-sigma navigation error if encountered with the 65° trajectory would not acquire radar at all prior to high gate, whereas, for the 69° trajectory acquisition would occur at Tgo = 200 sec. Five-sigma might seem an unreasonable number to be designing for, but even though figure 3 shows acquisition at 165 sec for three-sigma (65° trajectory) there is no guarantee that the radar would stay locked after acquisition, because figure 3 is not based on a closed loop radar simulation. The tendency would actually be toward radar loss after acquisition because the beam incidence angles would increase when removal of the vehicle high navigation error is attempted. The point of this discussion is to suggest that with the present lack of closed loop LM descent radar studies, that the trajectory be conservatively designed for a lower approach, such as the 69° trajectory. This applies to either high gate or false high gate targeting. In addition, the resulting high probability of radar acquisition at Tgo > 200 sec (54 n mi of range from landing site, and even greater for LM low navigation error) for the 69° trajectory might require an updating inhibit until Tgo = 160 sec (43 n mi) due to terrain slope uncertainty (another area requiring further study).

DISCUSSION OF RESULTS

The variation of throttle-down time for thrust high, nominal and low (three-sigma) profiles obtained by delaying FTP ignition is shown on figure 4. Approximately a 10sec change of throttle-down time is obtained per second of ignition-delay.

The variation of ΔV and throttle-down time as a function of thrust profile for three ignition delays (1, 2.65, and 4.35) is shown on figure 5. For example, a comparison with the nominal trajectory (td = 0) of throttle-down time and ΔV between TL and TH shows 76sec, 5283 ft/sec and 141sec, 5334 ft/sec, respectively. The ΔV difference of 51 ft/sec between these numbers is really of no significance, because the ΔV budget (ref 5) states the nominal ΔV requirement for TN; the ΔV difference between TH and TN (17 ft/sec) is RSS'd with other numbers. When the ΔV budget is updated to the present thrust uncertainty of +1 to -2% (presently based on ±3%), the ΔV requirement for DPS uncertainty would only be about 1 ft/sec. (RSS contribution of 17 ft/sec). The dashed line which connects the TN points on figure 5 represents the ΔV for various throttle-down times of a nominal (TN) thrust profile. The minimum ΔV saving for a T1G1 system that can be obtained with a small throttleable region about 92.5% thrust is obtained as the difference between ΔV for the present TN (td = 0) and the ΔV for TN along the dashed line with throttle-down time adjusted to 76 sec (present throttle time for TL). This difference is 46 ft/sec.

MIT has previously stated that the ΔV penalty as a function of throttle-down time is approximately 1 ft/sec/sec. Notice that the slope of a straight line projection of the dashed curve on figure 5 going through the TN points is approximately 1 ft/sec/sec and contains the dotted line which intersects 5200 ft/sec at Tgo = 0. It is suspected that this straight line represents the ΔV function for an optimized system, probably attainable for T2G1 or T1G2. If true, the maximum ΔV saving would then be the difference 5320-5200 = 120 ft/sec. The curves on figure 5 do not follow that straight line projection, but are concave upwards. The reason for this is that the T1G1 system is not very efficient for low throttle-down times (ΔV less than high throttle times, but not optimum), because the pitch attitude gets large as shown on figure 6 for three throttle-down times of TN.

The minimum throttle time must be studied with the presence of terrain and navigation error, and with a radar model--not only to assure throttle-down at Tgo > 20, but to determine the effect of possible radar loss near high gate because of the high θ tendency as shown on figure 6. Note also on figure 6 that radar acquisition could be a problem because of the higher altitude profiles for low throttle-down times.

The effect of thrust uncertainty for the present system on trajectory monitoring parameters such as $\dot{h}$ vs h is shown on figure 7. The T1G1 system which would use the throttle region to produce TN would then eliminate this variation of the $\dot{h}$ vs h profile.

CONCLUDING REMARKS

There are four possibilities, (combined throttling and targeting possibilities) of utilizing a small throttling capability about the high thrust region of 92½%.

Throttling - T1 - Command a specific thrust-time profile to eliminate DPS uncertainty.

T2 - Adjust trajectory and guidance aim point targeting such that guidance system commands a nearly constant 92½% thrust-thrust controlled to the command within the limits of throttle capability.

Guidance Targeting -

G1 - Present concept of high gate targeting.

G2 - False high gate targeting.

T1 - A throttle range of ±2.5% would suffice based on the present engine uncertainties. The variation of trajectory monitoring parameters caused by thrust uncertainty would be eliminated.

T2 - The time over which the thrust command is a nearly constant 92½% for a nominal case is a subject of study; i.e., the thrust command could start higher than would be controllable, but eventually would reduce to the throttleable region about 92.5%. The required throttle range about 92.5% requires study with terrain and navigation error, once a nominal trajectory is established. The variation of trajectory monitoring parameters caused by thrust uncertainty may not be completely eliminated.

T1G1 - Would be the minimum change to the present system. A minimum ΔV saving of 46 ft/sec would be obtained by adjusting TN (thrust nominal) throttle-down time to the down time of TL (Tgo = 76) for the present trajectory. A ΔV saving of 76 ft/sec would be obtained for throttle-down at Tgo = 30, but the resulting system performance would have to be studied.

T1G2 - In addition to the reduced sensitivity of radar-terrain deviation offered by the G2 system, the throttle-down for TN could occur at high gate (for maximum ΔV saving of 100 to 140 ft/sec), because the system does not contain the linear guidance mode at Tgo = 20. This system has been studied for TL throttle-down at Tgo = 76sec, but requires further studies for TN throttle-down at Tgo = 0.

T2G1 and T2G2 - Both systems have potential of maximum ΔV saving. The performance in the presence of terrain and navigation error require study. A high thrust throttle capability would be desirable based only on the minimum ΔV saving of 46 ft/sec, and the elimination of the effect of thrust uncertainty on trajectory monitoring parameters.

REFERENCES

*1. Delaney, F. and Khun, A., "Predicted Thrust Tolerance for the Descent Propulsion Subsystem," GAEC Memorandum LMO-271-356, Jan. 23, 1967.

2. Moore, Thomas E. and McSwain, Gene, "Feasibility Study of a LM Landing in the Crater Copernicus," MSC Internal Note 67-EG-25, Aug. 25, 1967.

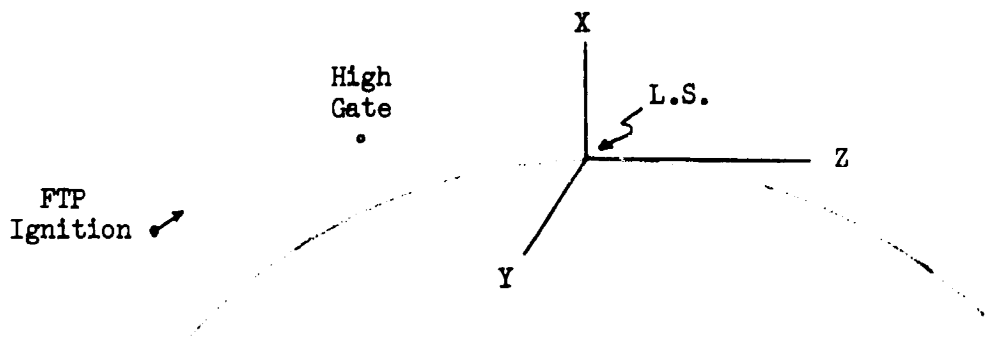
3. EG27/Control Requirements Branch, "General Purpose Digital Program for LM Powered Descent - Presimulation Report," EG27-61-67, April 17, 1967.

4. Bolt, Willis M. and Bennett, Floyd V., "Proposed LM Powered Descent Trajectory for the Apollo Lunar Landing Mission," MSC Internal Note 67-FM-117, August 15, 1967.

5. Mayer, John P., "Operational Budget Presentation," MPAD Memorandum 67-FM-J-10, May 16, 1967.

*At a DPS meeting (11/7/67) held at MSC, after this report was written, GAEC indicated the DPS uncertainties are not those of reference 1, but are more nearly +1½% to -3½% (average thrust over 370sec). A ΔV saving can therefore not be obtained by delaying the present throttle-down time, but may actually require a higher bias time with this uncertainty. This uncertainty of uncertainty appears to make a throttle capability even more desirable.

TABLE I. - DESCRIPTION OF TRAJECTORY CONDITIONS



Landing Site Coordinate System

Initial Conditions

(Ignition Delay, td = 0)

$X = -130,800$

$\dot{X} = 1,387.6$

$Z = -1,432,337$

$\dot{Z} = 5,396.8$

For td > 0 LM starts at indicated IC's and remains in orbit. At td, FULL THROTTLE (FTP) ignition occurs.

High Gate Aim Conditions

$X_D = 9592$

$\dot{X}_D = -159.2$

$\ddot{X}_D = -2.174$ *

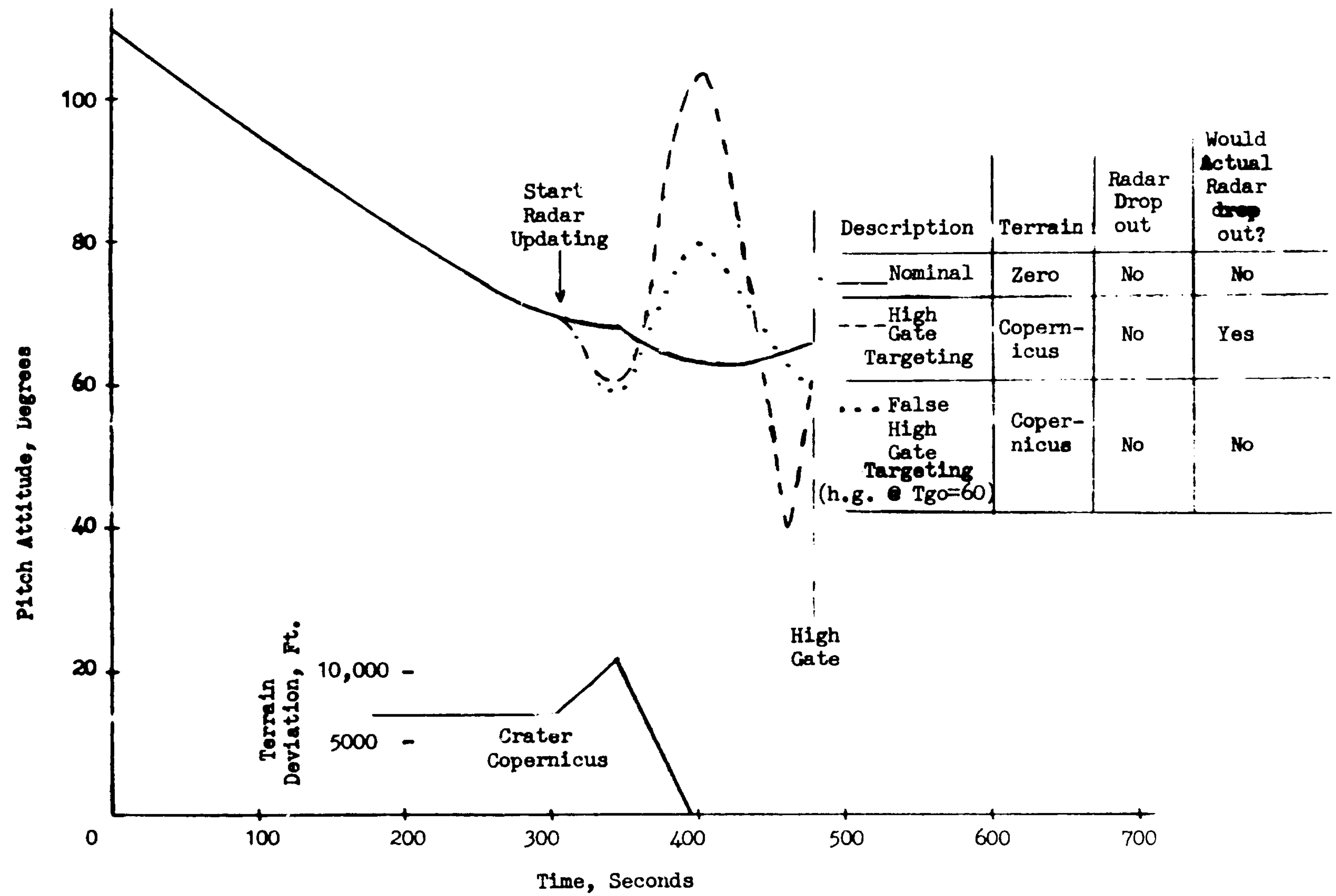
$Z_D = -33077$

$\dot{Z}_D = 561$

$\ddot{Z}_D = -8.2$

$\dddot{Z}_D = -.00918$

*X_D changed from MPAD trajectory to produce $\theta = 69^\circ$ @ High Gate - This provides a better altitude profile for radar acquisition.



Description	Terrain	Radar Drop out	Would Actual Radar drop out?
____ Nominal	Zero	No	No
- - - High Gate Targeting	Copernicus	No	Yes
. . . False High Gate Targeting (h.g. @ Tgo=60)	Copernicus	No	No

Figure 1. - Effect of Terrain Deviation Prior to High Gate on Pitch Attitude for High Gate and False High Gate Targeting (Perfect Radar)

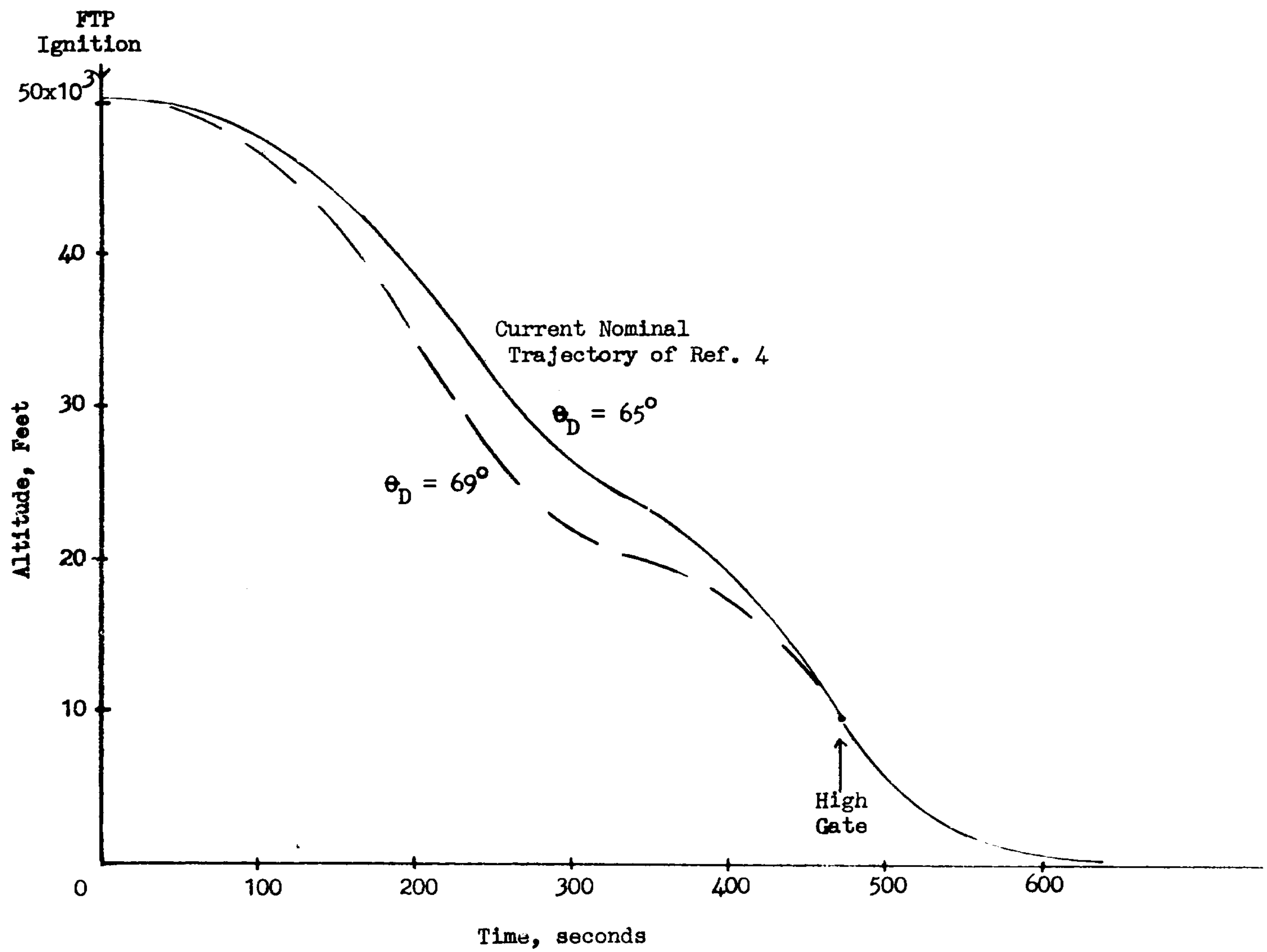


Figure 2. - Effect of desired Pitch Attitude at High Gate (Function of desired Vertical Acceleration) on Trajectory shaping

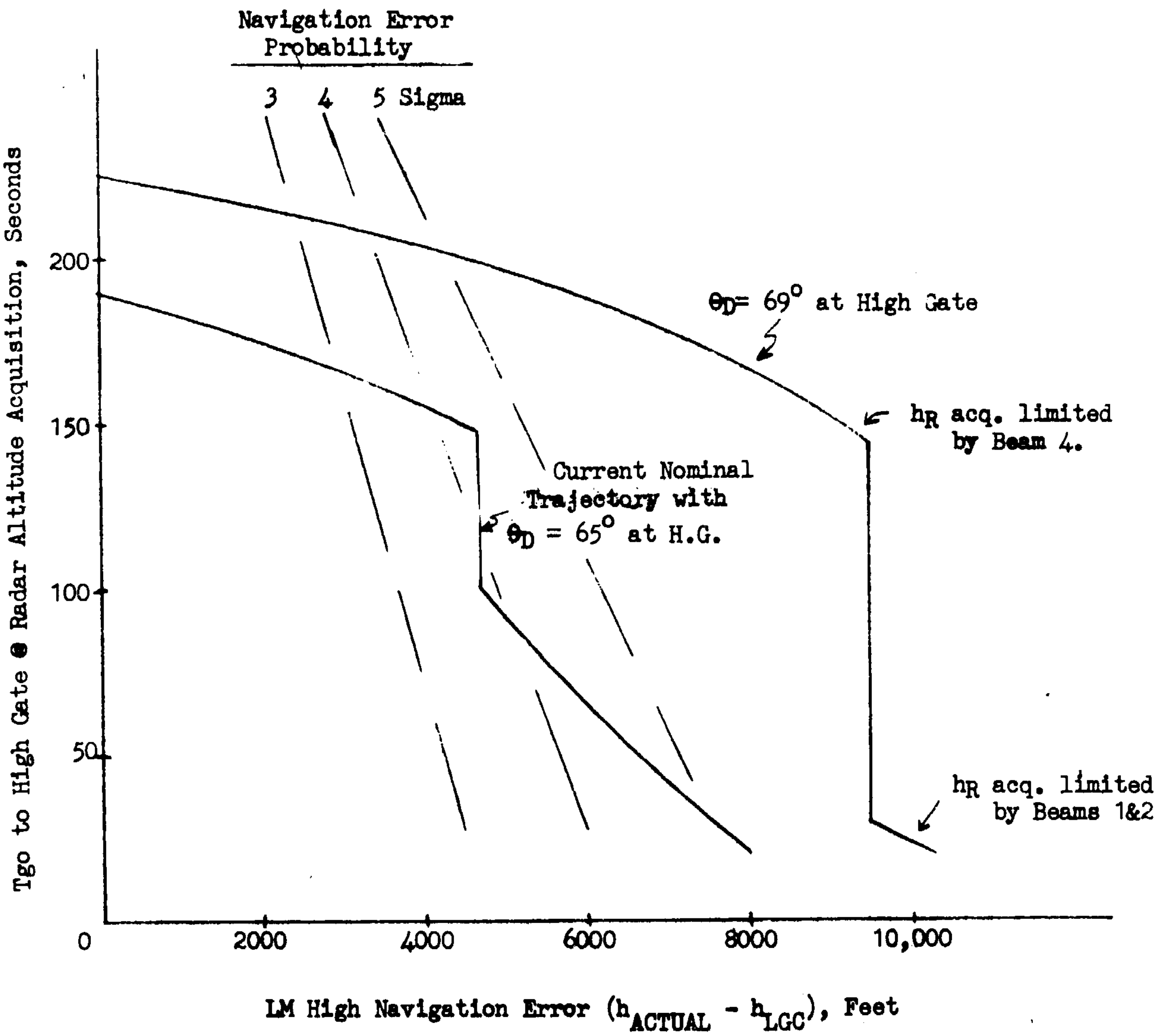


Figure 3. - Effect of altitude navigation error and trajectory shaping (by varying desired pitch attitude @ h.g.) on the time of radar altitude acquisition.

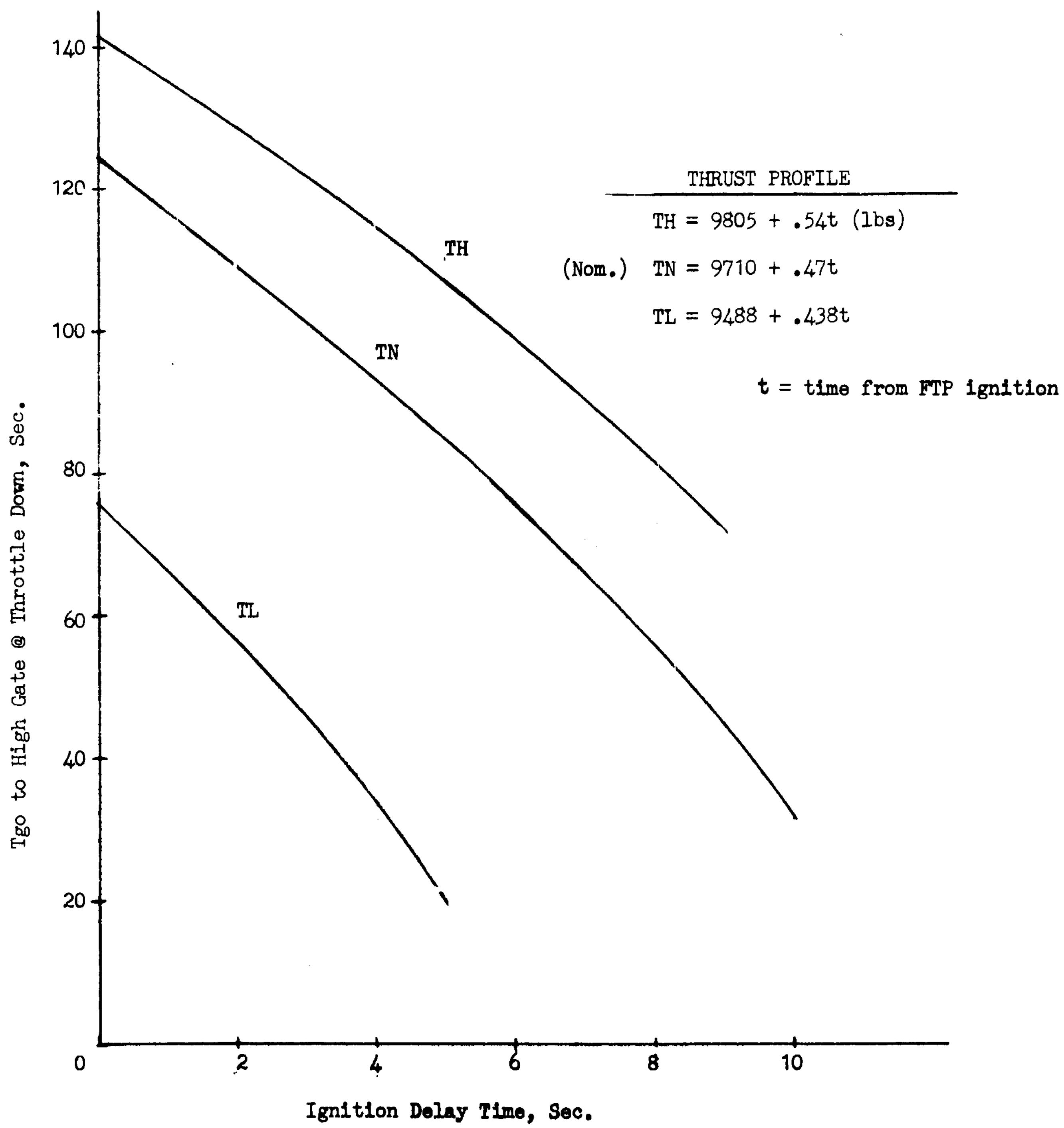


Figure 4. - Variation of throttle down time resulting from delayed ignition.

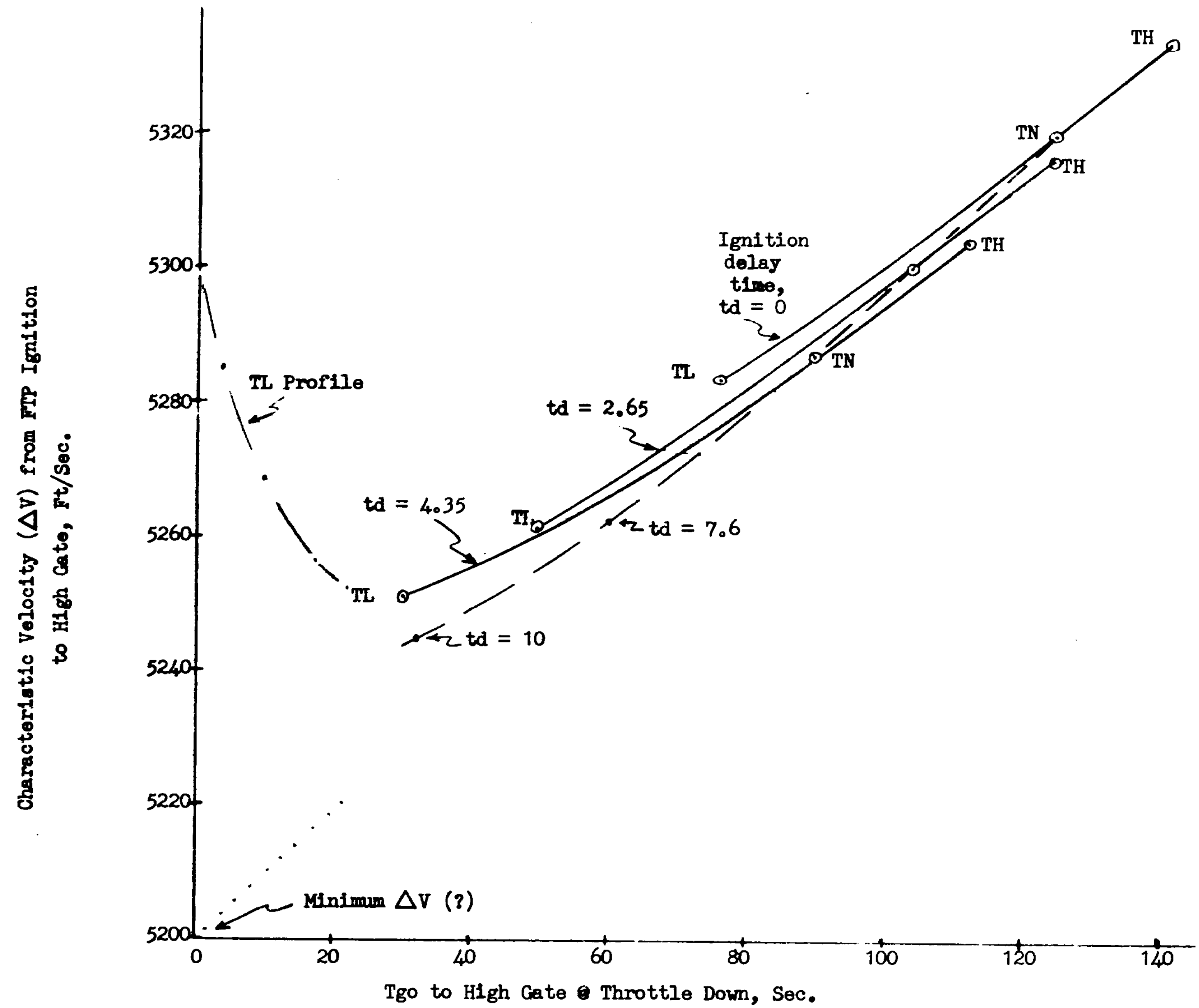


Figure 5.-Effect of Thrust Profile and Throttle Down Time on ΔV.

	Thrust Profile	Ignition Delay Time	Tgo ● Throttle Down	Time from * Ignition (FTP) to High Gate
———	Nom.	0	124.4	474
— — —	Nom.	5	84.76	454
· · · · · ·	Nom.	10	31.72	428

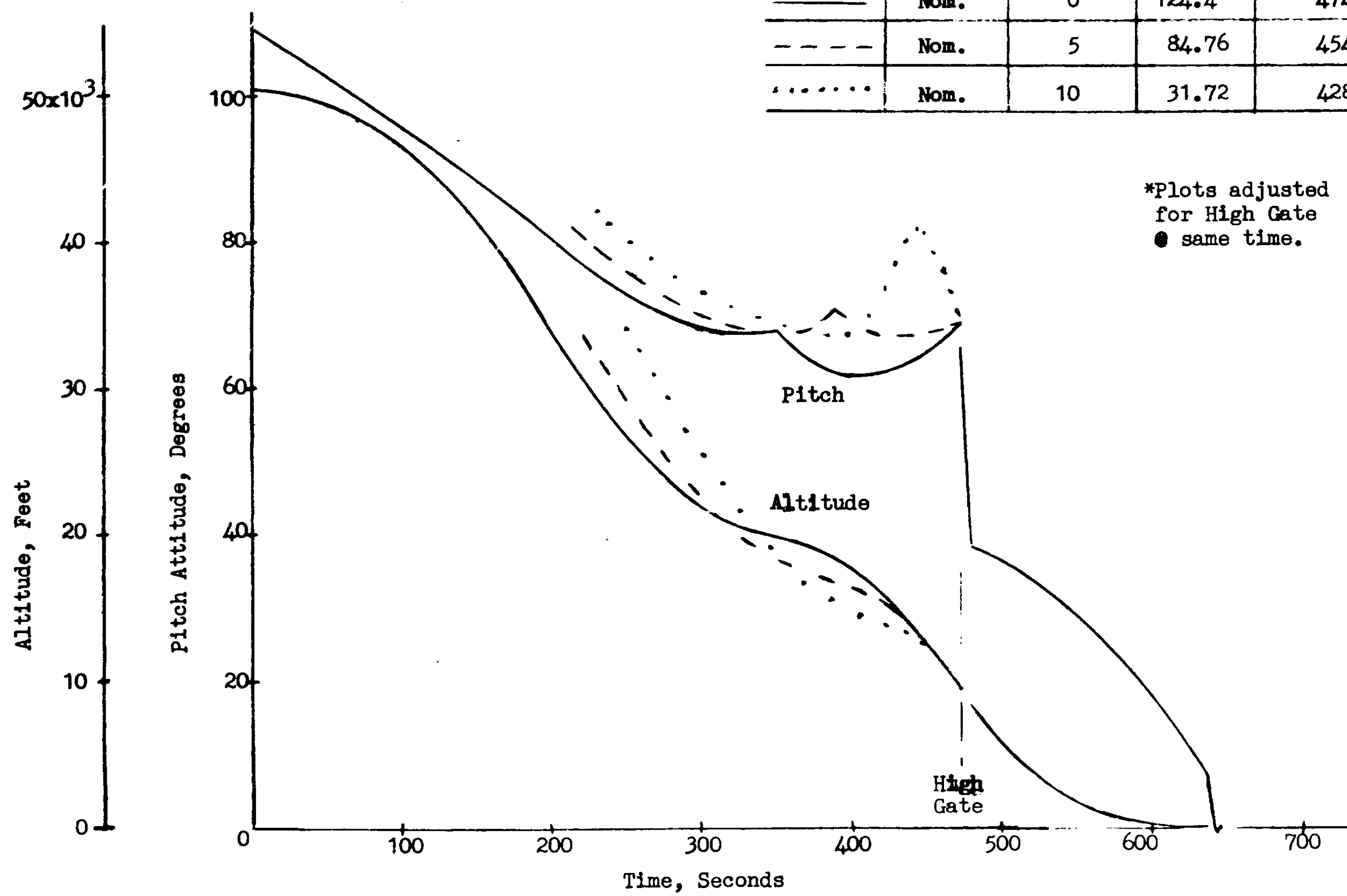


Figure 6. Effect of Throttle Down Time of Nominal Thrust Profile on LM attitude and altitude.

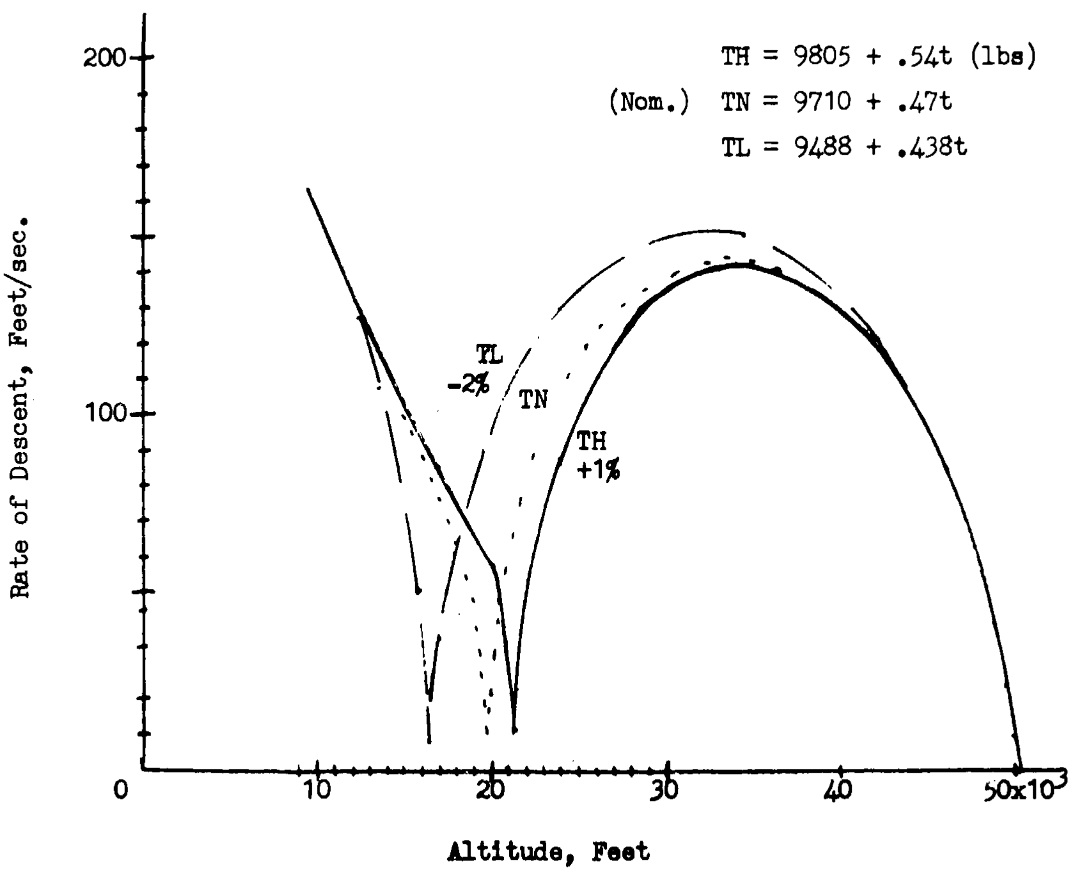


Figure 7. - Effect of Thrust Uncertainty on Trajectory Monitoring Profile of ($-\dot{h}$ vs h).