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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 68-EG[redacted]-03

APOLLO PROGRAM

EVALUATION OF THE LM GUIDANCE SYSTEM PERFORMANCE OVER THE APPROACH TERRAIN OF FIVE OF THE PROPOSED APOLLO LANDING SITES

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Prepared by: David A. Dyer
David A. Dyer
Systems Analysis Branch

Approved by: Kenneth J. Cox
K. J. Cox, Chief
Systems Analysis Branch

Approved by: R. A. Chilton for
Robert A. Gardiner, Chief
Guidance and Control Division

MANNED SPACECRAFT CENTER
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1. SUMMARY

A review of the evaluation status of the LM guidance system performance over approach terrain variations as of the March 1967 Apollo Site Selection Board briefing is presented. The development progress since the March briefing and a summary of the results of an evaluation of sites II-P-2, II-P-6, II-P-8, II-P-11, and II-P-13 are presented. A brief outline of the continuing activity is also presented.

2. INTRODUCTION

During the LM lunar descent, there is a requirement to remove errors in the guidance system's estimate of the state. This is accomplished by updating the system's estimate with landing radar information. The landing radar information is used to update the system's estimate of velocity and altitude. Since the landing radar measures the altitude of the LM vehicle above the local terrain, any large terrain variations will cause large fluctuations in the landing radar altitude data. When the guidance system is updated with these large fluctuations in altitude information attitude and thrust commands can be generated which could cause loss of radar tracking, waste of descent engine fuel, and loss of pilot viewing time during the approach phase of descent. Because of this interaction of terrain and the guidance system, there is a need to evaluate proposed landing sites to determine the acceptability of the possible approach paths to these sites. The study that is explained here considered five sites, II-P-2, II-P-6, II-P-8, II-P-11, and II-P-13. There are two more sites to be evaluated: III-P-11 and I-P-1.

The method used to evaluate these sites was to fly simulated LM descents over the approach paths to the various sites and determine the effect of the terrain/guidance interaction on such parameters as attitude, delta-V, and viewing angle. The variation of these parameters were compared with the appropriate constraints and the general conclusion was reached that with the present definition of the LM systems the LM guidance system is able to fly to the recommended Apollo landing sites within satisfactory LM systems operating conditions and with satisfactory pilot visibility of the landing site after hi-gate.

3. STATEMENT OF THE PROBLEM

The nominal LM powered descent begins at approximately 260 n.m. range to go to the landing area. The altitude at DPS start-up is 50,000 feet. This is the beginning of a three phase descent to the lunar surface. The first phase or braking phase is designed to reduce orbital velocity and terminates at a point called hi-gate which occurs at an altitude of approximately 9000 feet. Hi-gate is actually a state vector which is aimed for during the braking phase and it will be explained later that hi-gate is the key point during the LM descent. Hi-gate is the beginning of the second or approach phase and this phase is designed to allow out-the-window viewing of the landing area by the pilot. This phase terminates at a position called lo-gate (500 feet altitude).

The third, or landing phase, begins at lo-gate and terminates at touchdown on the lunar surface. This phase is designed to allow final visual assessment of the landing area by the crew and also manual takeover from the automatic guidance system. The terminal part of this phase is a vertical descent which terminates with a soft landing on the surface. Figure 1 presents a sketch of the LM descent trajectory with the significant points indicated.

As mentioned previously, hi-gate is the key point during descent. If this desired state vector is not obtained with sufficient accuracy, the approach trajectory could be such that the pilot does not have adequate time to visually assess the landing area. The two primary parameters that can significantly affect the LM guidance system's ability to attain hi-gate are navigation uncertainty and lunar terrain evaluation fluctuations. The navigation uncertainty accumulates during lunar orbit, descent orbit transfer, and powered descent and if this uncertainty is not removed, the hi-gate aim point will probably not be obtained within satisfactory limits. The principal component of the navigation uncertainty that has to do with how well the guidance system obtains hi-gate is the altitude uncertainty. The trajectory is now designed such that the landing radar altitude data is utilized, starting at an LGC estimated altitude of 25,000 feet, to update the LGC's estimate of altitude. The update scheme involves sampling the radar altitude information every two seconds and comparing it with the guidance system's estimate. The difference is then weighted and added to the guidance system's altitude estimate. The result is then used in the guidance system to derive the descent engine throttle commands and attitude commands for the RCS.

When this updating begins, the guidance system becomes susceptible to elevation fluctuations of the lunar terrain because the landing radar measures the altitude of the vehicle above the surface. The guidance system assumes the landing radar is measuring the altitude of the vehicle above the landing site. So, for example, if the vehicle flies over a crater, and if a radar measurement to the bottom of that crater is used to update the guidance system, new throttle and attitude commands will be

generated which will tend to lower the vehicle's altitude. In other words, the guidance system "thinks" the vehicle is too high when the radar measurement is taken to the bottom of the crater and generates commands accordingly, but just as soon as a radar measurement is taken outside the crater, the guidance system will find out that now the vehicle's altitude is too low and will generate commands accordingly. Therefore, as the LM descends toward the landing area, the descent engine throttle and the vehicle attitude will vary as the guidance system attempts to "fly" the lunar terrain. A crater has been used here as an example but a similar type of variation in throttle and attitude commands occurs when the vehicle flies over a terrain which has an uphill or downhill slope. The magnitude of the variation of throttle and attitude commands depends on the height and location of terrain features and the degree of slope. Figure 2 indicates that the guidance pitch attitude command becomes more sensitive to terrain variations, as sensed by the radar, as the vehicle approaches hi-gate and lo-gate.

When the throttle and attitude commands vary due to interaction of the terrain with the guidance system descent engine fuel can be wasted, pilot viewing time could be lost, and the radar could lose track. The constraints on fuel usage and pilot viewing time are 7180 ft/sec (reference 1), and 75 sec (reference 2), respectively. The 7180 ft/sec number is the total delta-V budget while approximately 40 ft/sec is allotted for navigation and terrain uncertainties. Approximately 60 ft/sec is allotted for navigation, terrain, and thrust uncertainties. The landing radar dropout boundaries are shown in figure 3. The upper boundary is determined by the maximum allowable beam incidence angle. That is, at some pitch angle between the radar beam and the local vertical, at the point of beam intersection with the surface, will become so large that the reflected signal power will be below the threshold of the radar trackers, and radar dropout will occur. The lower boundary can be termed the zero doppler boundary. When the zero doppler condition occurs, a velocity beam is normal to the velocity vector and the reflected signal power is below the tracker threshold and dropout occurs. Also shown in figure 3 is the variation of these boundaries when the radar is degraded by -2 and -4 decibels (db) in the power return signal. When dropout occurs there is not any radar information available for updating the LGC's estimate of the state and also there is a time delay in reacquisition of the signal after the vehicle has returned to favorable trajectory conditions. This time delay could be as much as 12 seconds. Although radar dropout does not necessarily lead to an unsafe landing, it could cause variations in the trajectory which could be unacceptable to the crew. In summary, there are three criteria used in this study to judge the acceptability of the various sites:

1. Fuel usage
2. Pilot viewing time
3. Radar dropout

4. DISCUSSION AND RESULTS

Before discussing the results of the evaluation of sites II-P-2, II-P-6, II-P-8, II-P-11, and II-P-13, a brief review of previous site selection work might be in order. Using preliminary definitions of fuel usage, radar, and viewing time constraints, a terrain criteria was developed. This criteria defined the allowable general terrain slopes and the allowable terrain elevation deviations from that general slope. The criteria are presented in figures 4 and 5. This criteria was presented at the March 1967 briefing of the Apollo Site Selection Board and was used by the Lunar and Earth Science Division (LESD) in screening the proposed landing sites.

Since the March briefing, the capability of making a closed loop evaluation of terrain profiles has been developed. This capability involves programming the descent guidance, radar model, terrain model, descent engine model, and trajectory dynamics. The radar model used is the one shown in figure 3. Also terrain data on the five previously mentioned sites was made available by LESD. Using this closed loop simulation capability, the approach terrain to the five sites was evaluated; the results will now be discussed.

First, consider site II-P-13. Figure 6 is a pictorial view of site II-P-13 as taken from Orbiter II. Superimposed on this picture are latitude and longitude lines and the landing area defined by the ellipse. Depending on the time of year of launch, the approach azimuth can vary about 10 degrees (reference 3) for the site in question. This 10 degree range of azimuths is labeled "expected" in figure 6. Since this study was begun before the expected range of azimuths was defined, a conservative estimate of 25 degrees was used and this range is labeled "considered" in figure 6. Also indicated on the figure are the approximate ranges back from the landing site where high gate, limits of Orbiter II data, and initiation of radar updating occurs over the range of azimuths. Using the 25 degree azimuth range and the terrain criteria previously mentioned, LESD screened the approach terrain to the various sites and determined what approach paths might be a problem to fly over. A number of terrain profiles were furnished by LESD for each site. For site II-P-13, for instance, three profiles were provided.

The method used in evaluating these terrain profiles is documented in reference 4. Briefly, the method is as follows: The worst approach terrain profile for each site was determined by making nominal (no system errors) trajectory (reference 5 defines the nominal trajectory used in this study) runs over all the profiles provided, and observing the pitch angle variation, viewing time variation, delta-V variation, et cetera. After the worst profile was determined, a matrix of runs was made over that profile. The matrix runs included combinations of initial condition errors, IMU errors, descent engine thrust variations, and terrain slope.

The combinations chosen resulted in trajectory variations which bounded the conditions that the guidance system is required to operate over. The results of flying over the worst case terrain combined with worst case system errors were compared with the previously mentioned criteria to determine the site acceptability.

For site II-P-13, the worst case approach is shown in figure 6. The terrain profile for that azimuth is shown in figure 7. The limits of the Orbiter II coverage is indicated in figure 7. The terrain data outside Orbiter II coverage was derived from earth based information and, therefore, is not as accurate. But, it was shown in the study that terrain features more than 130,000 feet from the landing site had very little effect on the trajectory.

Figure 8 is a comparison of the pitch angle profile resulting from flying over the worst case terrain for II-P-13 (no system errors) with the nominal pitch profile. The plot extends from radar acquisition down to hi-gate. Also on the plot are the terrain and the nominal radar dropout boundaries. For terrain only, the pitch angle deviations are only about ± 5 degrees from nominal and well within the dropout boundaries. Figure 9 is an extension of figure 8, from hi-gate to touchdown. Again, there is little deviation from the nominal pitch angle. The upper plot on figure 9 is a comparison with the nominal visibility margin profile. Visibility margin is defined as the angle between the lower edge of LM window and the pilot's line-of-sight. On figure 9, the zero degree line can be thought of as the lower edge of the window.

Figures 8 and 9 present the effects of flying on the worst case terrain profile for site II-P-13 with nominal system performance. But, the guidance system must be able to function in the presence of off-nominal system performance. A series of off-nominal cases were flown over the terrain and the bounds of the variations in pitch angle and visibility margin are shown in figures 10 and 11. As shown, the pitch angle bounds are within the radar dropout boundaries with several degrees of margin.

Also shown on figure 10 are the radar dropout boundaries when the radar is degraded by -2 db. For this radar model, the margin is reduced considerably. Below hi-gate (figure 11) the -2 db radar boundaries are practically coincident with the nominal boundaries so they are not shown. The visibility margin is quite adequate; well over the 75 second constraint.

The fuel usage on site II-P-13 was higher than any of the sites considered. As explained in reference 6, this is due to a 11.5 degree slope over the last 300 feet of the approach. The nominal flight over the terrain used 39.6 ft/sec. When the terrain and off-nominal system performance are combined in the same run, the fuel usage is actually less than the nominal over the terrain. The reason is that depending on the sign of the errors the vehicle lands either short of or past the area where the 11.5 degree

slope occurs. The fuel usage for the error cases are in the range of -32.7 to 26 ft/sec. The minus sign indicates the run used less fuel than the nominal run over a flat terrain.

While the approach terrain to site II-P-13 is the roughest of the prime sites evaluated (II-P-2, II-P-6, II-P-8, and II-P-13) the approach terrain to site II-P-11 was also evaluated. Although site II-P-11 is not one of the prime sites, the results of the evaluation are presented because they indicate that this site is acceptable. Previous screening of the approach terrain to this site with the terrain criteria (figure 5) indicated that it would be unacceptable. The reason that site II-P-11 is now acceptable is that the constraints (in particular the radar constraint) used in defining the terrain criteria were too conservative. (The terrain criteria will be redefined in future studies). Figures 12 and 13 present an oblique view of site II-P-11 and the worst case terrain profile, respectively. Figures 14 and 15 present a summary of the results of the evaluation on site II-P-11. The pitch angle bounds are within the nominal radar bounds although the margins are less than those on site II-P-13. The fuel usage is less on this site; the most ever used in all the runs was 31.6 ft/sec.

The results of the evaluation on sites II-P-13 and II-P-11 were selected to be presented here because of their relative roughness. Worst case terrains for sites II-P-2, II-P-6, and II-P-8 are presented in figures 16 through 21.

As shown, these terrain profiles are much smoother when compared with sites II-P-13 and II-P-11. The pitch angle and visibility margin variations are much smaller for these sites and the fuel usage is well within the budget. For detailed information on all the sites evaluated refer to reference 6.

5. FUTURE STUDIES

The results of this evaluation were presented to the Apollo Site Selection Board on December 15, 1967 (reference 7) and it was reported that all five sites were considered acceptable from the LM guidance standpoint. Based on all the site selection considerations (terrain data availability, lunar surface properties, and operational) five sites were recommended in set C for Mission I. These sites are II-P-2, II-P-6, II-P-8, III-P-11, and II-P-13. Six sites were recommended in set C for Mission II: I-P-1, II-P-2, II-P-6, II-P-8, III-P-11, and II-P-13. These recommendations were accepted by the Board (reference 8). Sites I-P-1 and III-P-11 will be evaluated in the near future. Some of the future work will be in the area of upgrading the LM descent simulation and determining the effect of system simplifications assumed in this evaluation. These simplifications were assumed to have a second order effect on the results of this evaluation. Radar errors and control system dynamics were not included in this study.

6. CONCLUSION

The conclusion of this evaluation is that the LM guidance system is able to fly to five sites within satisfactory landing radar operating conditions, within the delta-V budget, and with satisfactory pilot visibility of the landing site after hi-gate.

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(3) Fariss, J. B.: Maximum Variations in Optimum Approach Azimuths for Nominal Free Return Missions. TRW IOC 3423.8-55, October 11, 1967.

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(5) Bolt, Willis M. and Bennett, Floyd V.: Proposed IM Powered Descent Trajectory for the Apollo Lunar Landing Mission. MSC Internal Note 67-FM-117, August 15, 1967.

(6) McGee, C.: Approach Terrain Evaluation: Sites II-P-2, II-P-6, II-P-8, II-P-11, and II-P-13. TRW PTN 05952-4381-RO-00, January 15, 1968.

(7) Cheatham, D. C.: Apollo Site Selection Board Briefing. MSC compilation of presentation material, December 15, 1967.

(8) Maynard, Owen E.: Apollo Site Selection Board Meeting. MSC memorandum PD12/M352, January 16, 1968.

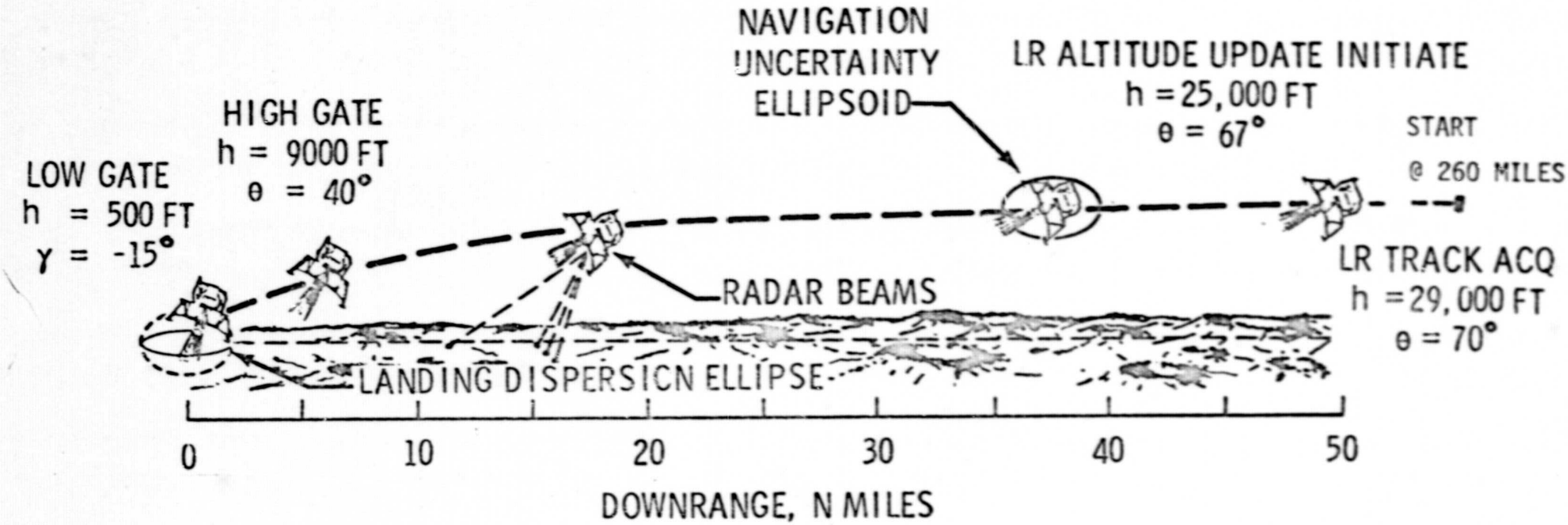

Figure 1.- LM Powered Descent Landing Approach

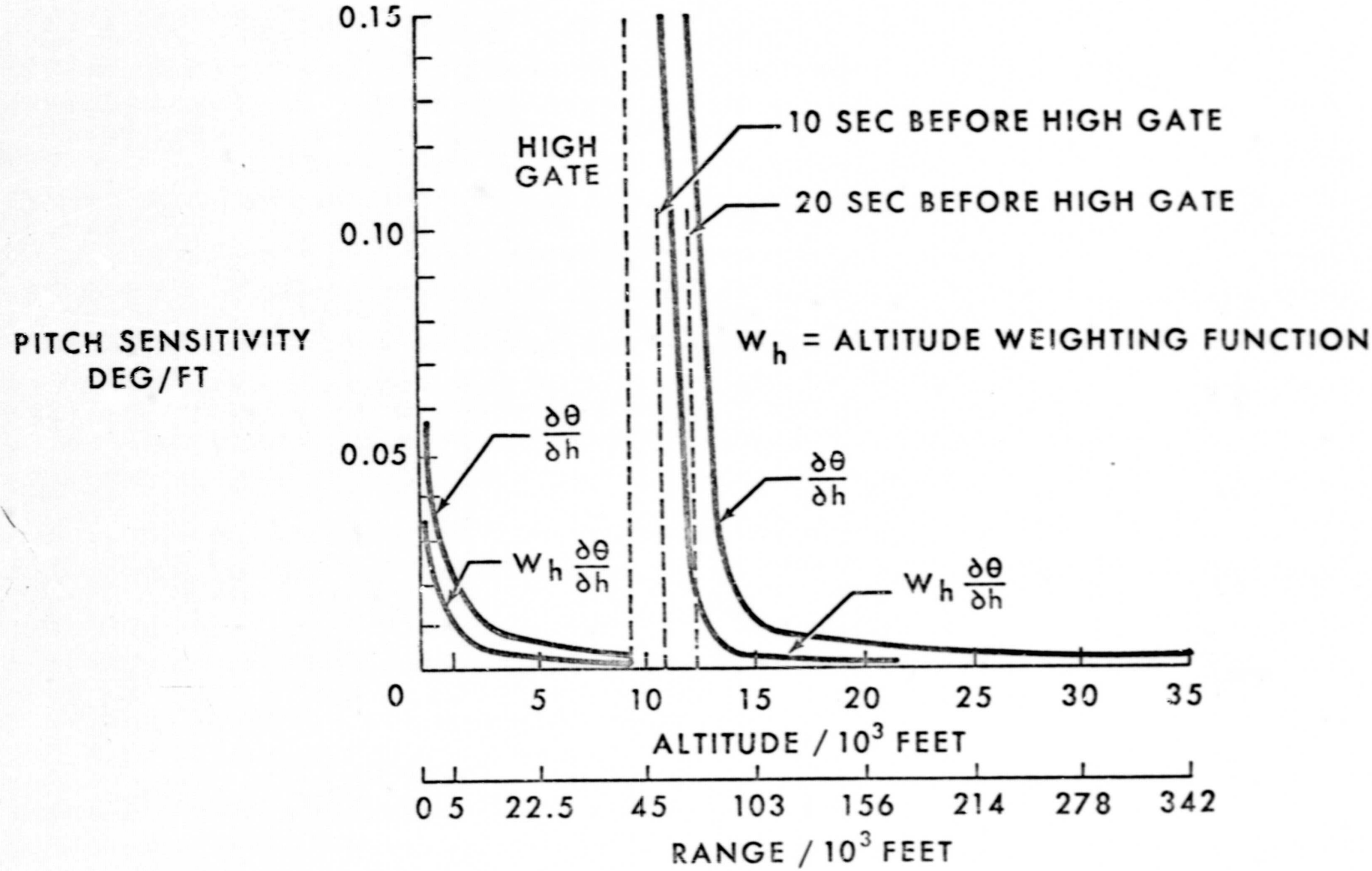

Figure 2.- Guidance Pitch-Command Sensitivity to Altitude Update for a Nominal Trajectory

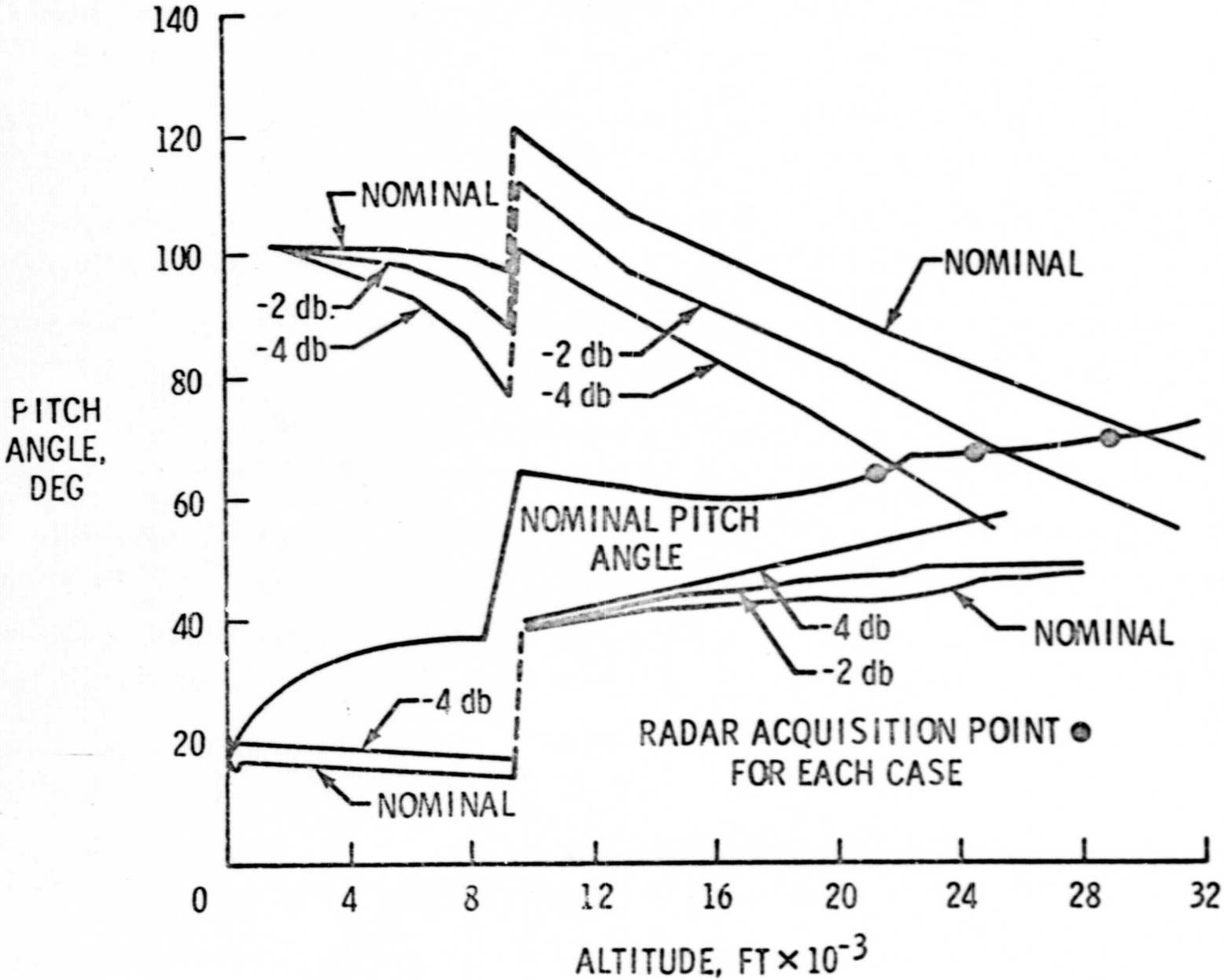

Figure 3.- Change in Radar Dropout Boundaries Due to Reduction in Power Return

ABOVE HI-GATE

- GENERAL UPHILL SLOPES OF 1° CAN BE TOLERATED
- GENERAL DOWNHILL SLOPES OF 2° CAN BE TOLERATED

AFTER HI-GATE

- SLOPES SHOULD BE LIMITED TO ± 1° TO MAINTAIN LANDING POINT DESIGNATION ACCURACY

Figure 4.- March 1967 Preliminary Results of Terrain-Slope Guidance System Interface Evaluation

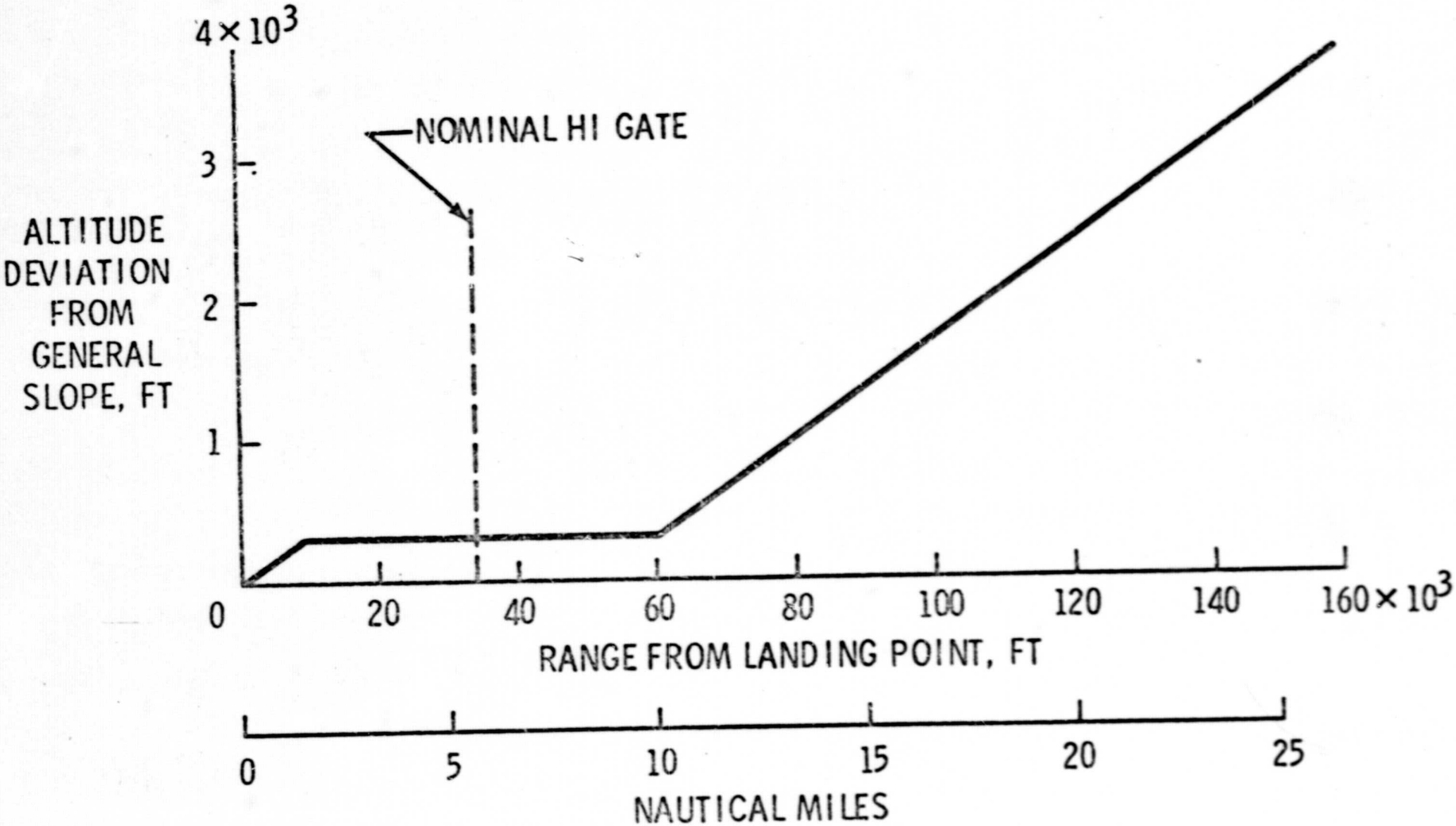

Figure 5.- Preliminary Site Selection Terrain Criteria

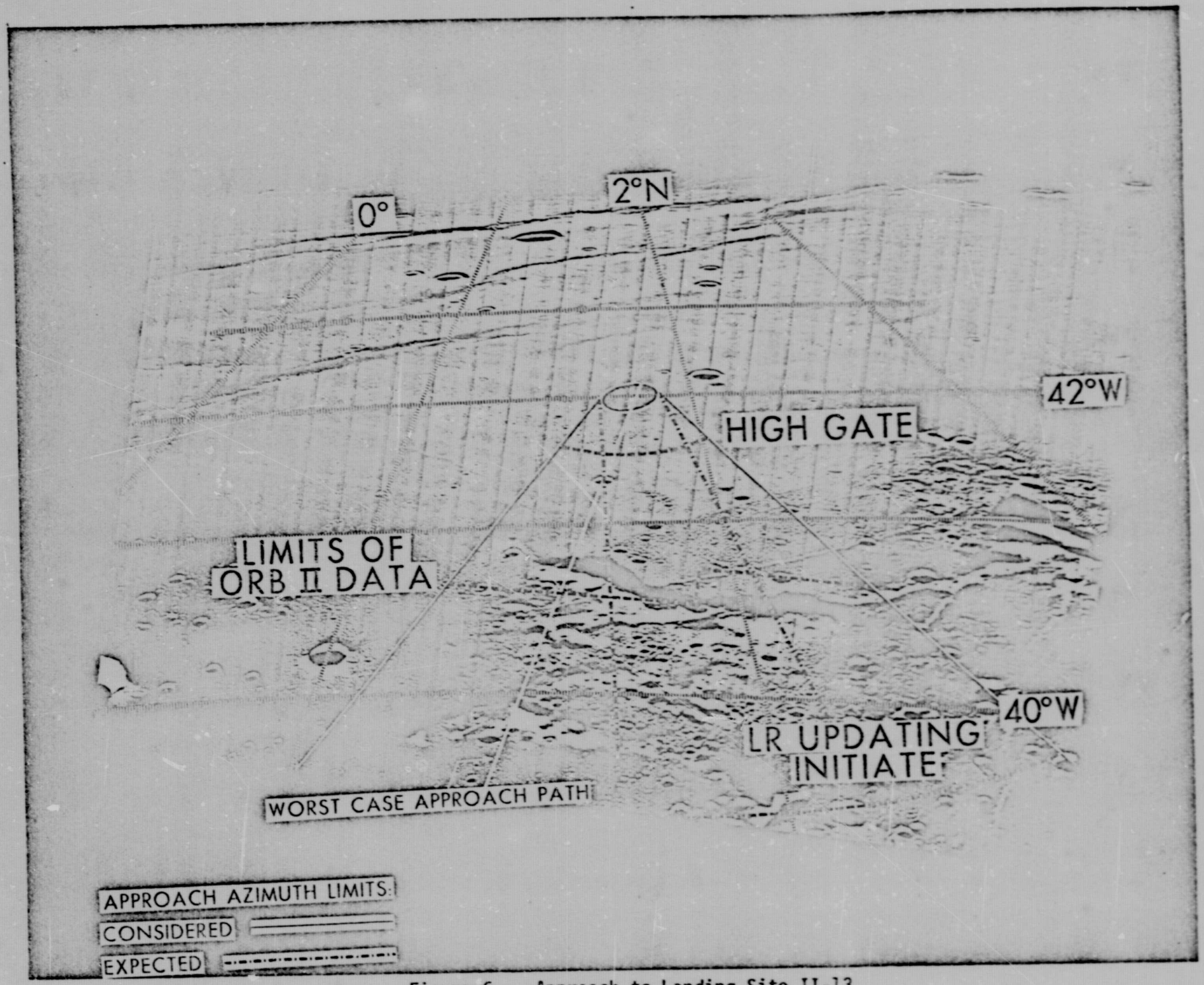

Figure 6.- Approach to Landing Site II-13

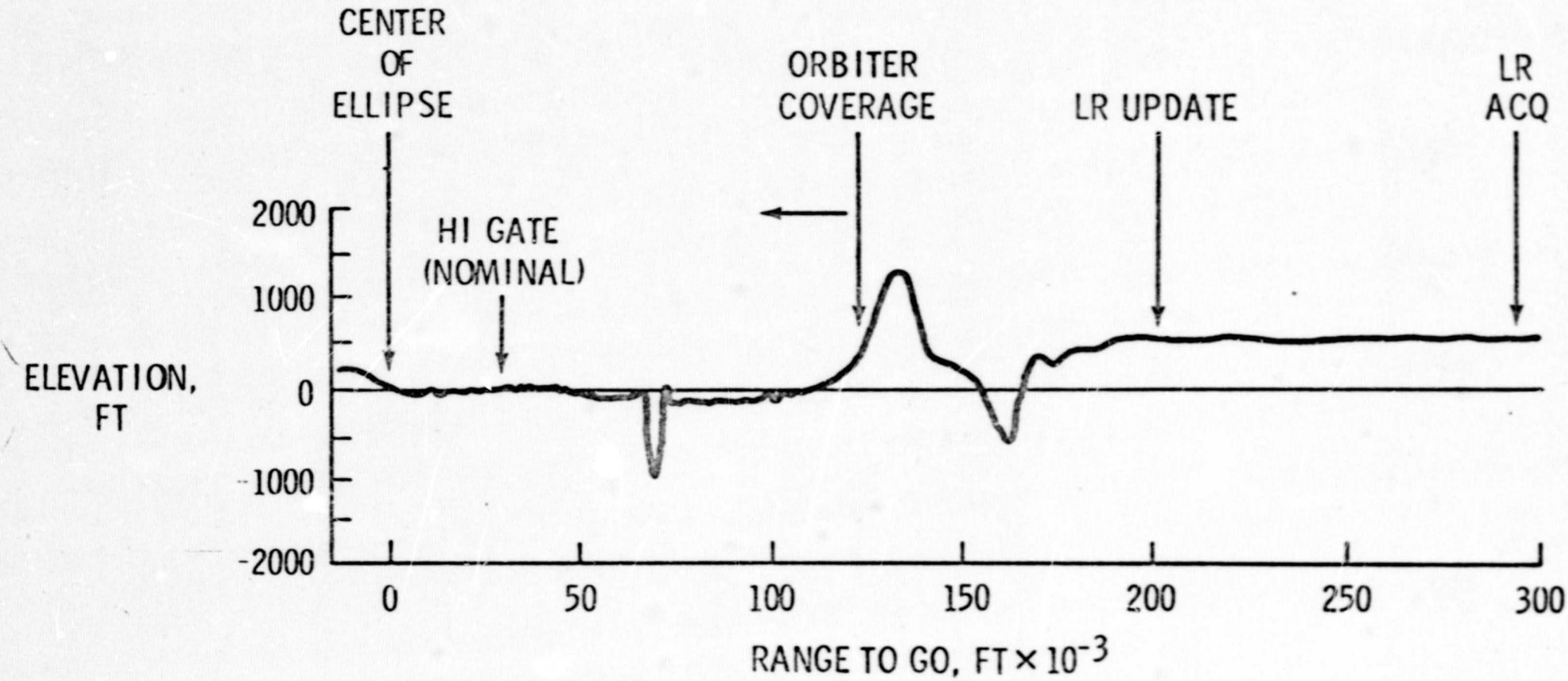

Figure 7.- Worst Case Approach Path Terrain Profile from II-P-13, Elevation Ratio 25:1

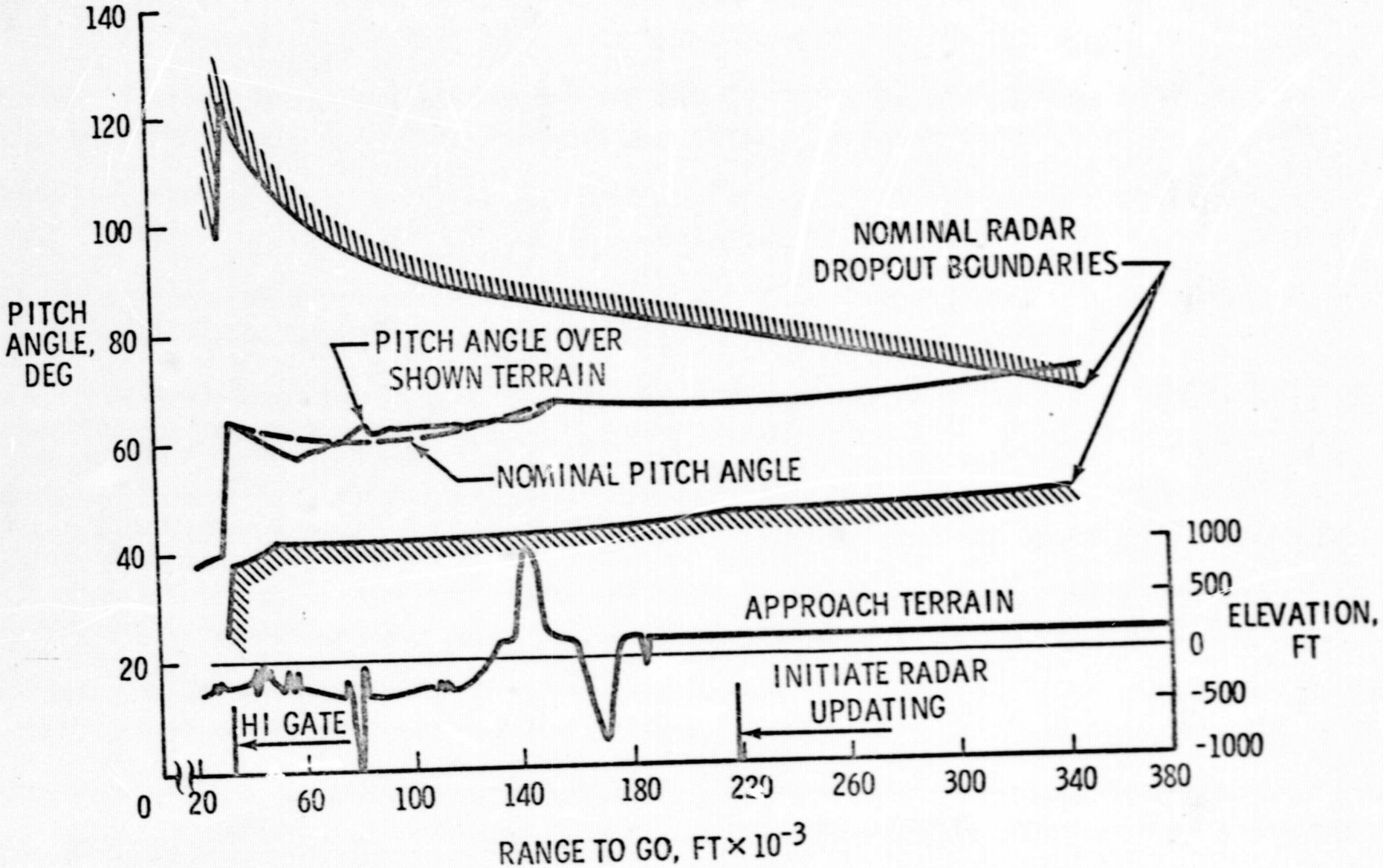

Figure 8.- Pitch Angle Variation Above Hi-gate Due to Site II-P-13 Terrain

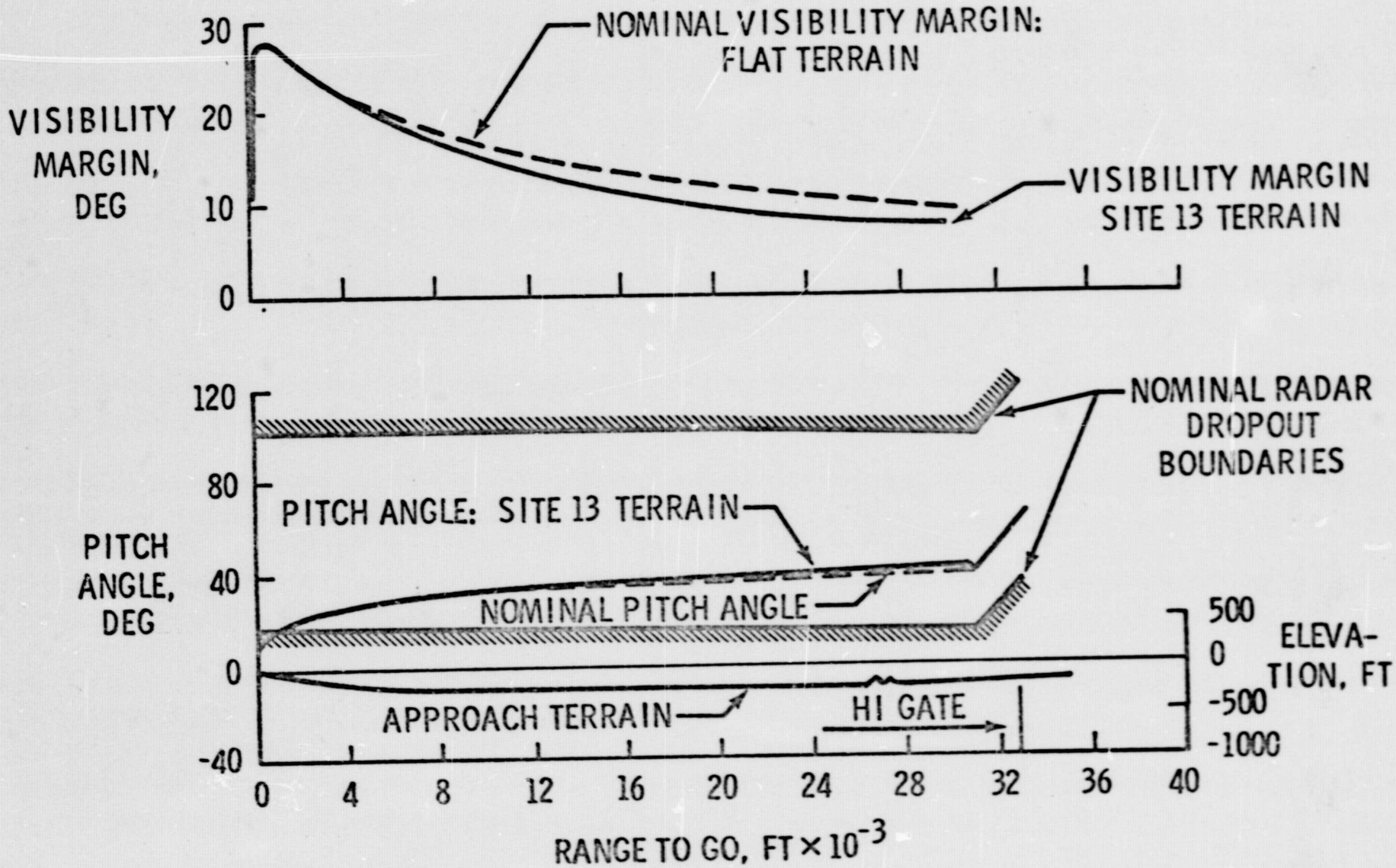

Figure 9.- Pitch Angle and Visibility Margin Variation Due to Site II-P-13 Terrain

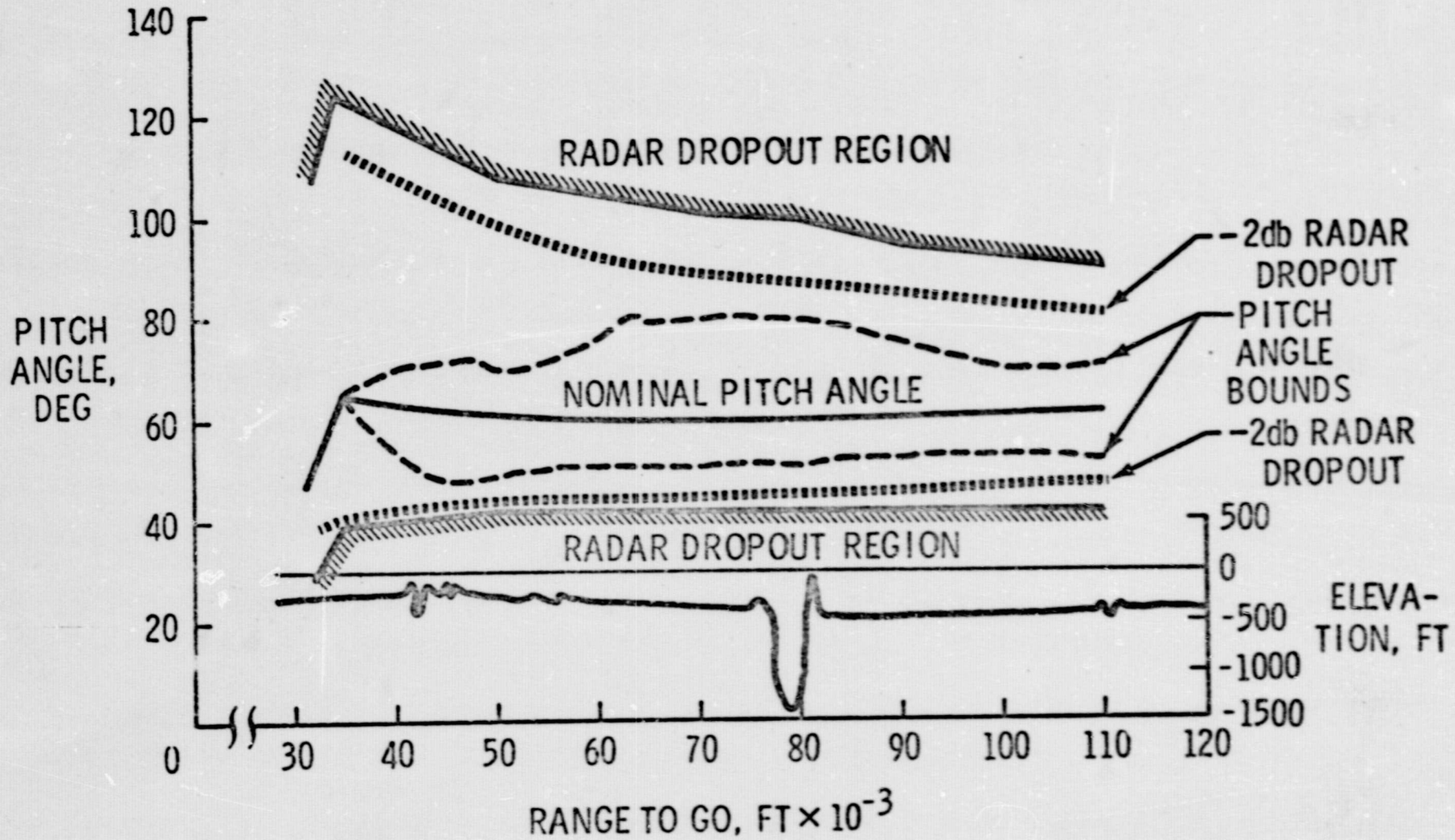

Figure 10.- Pitch Angle Bounds Above Hi-gate Due to Site II-P-13 Terrain Combined with Off-Nominal Performance

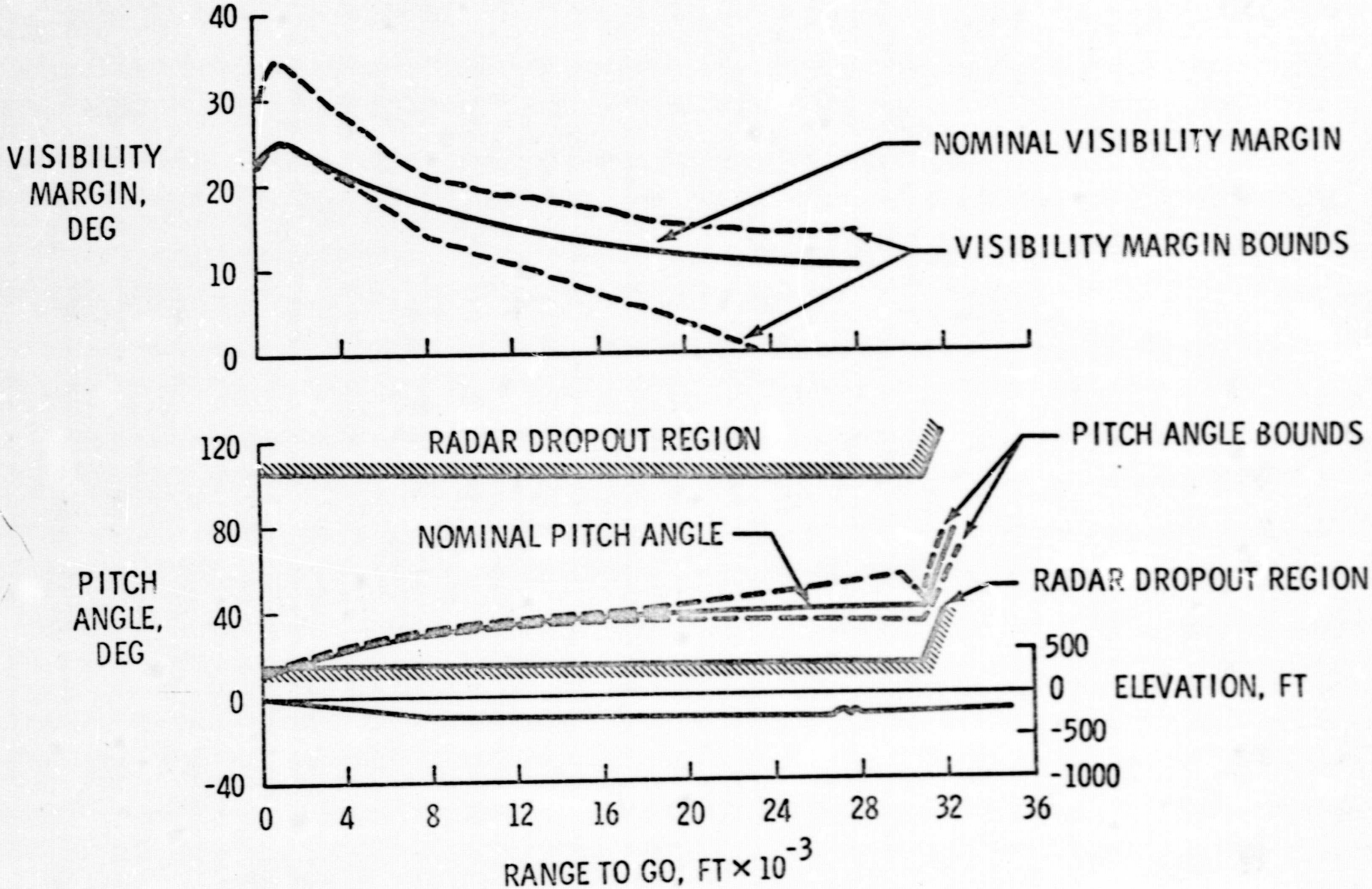

Figure 11.- Pitch Angle and Visibility Margin Bounds Due to Site II-P-13 Terrain Combined with Off-Nominal System Performance

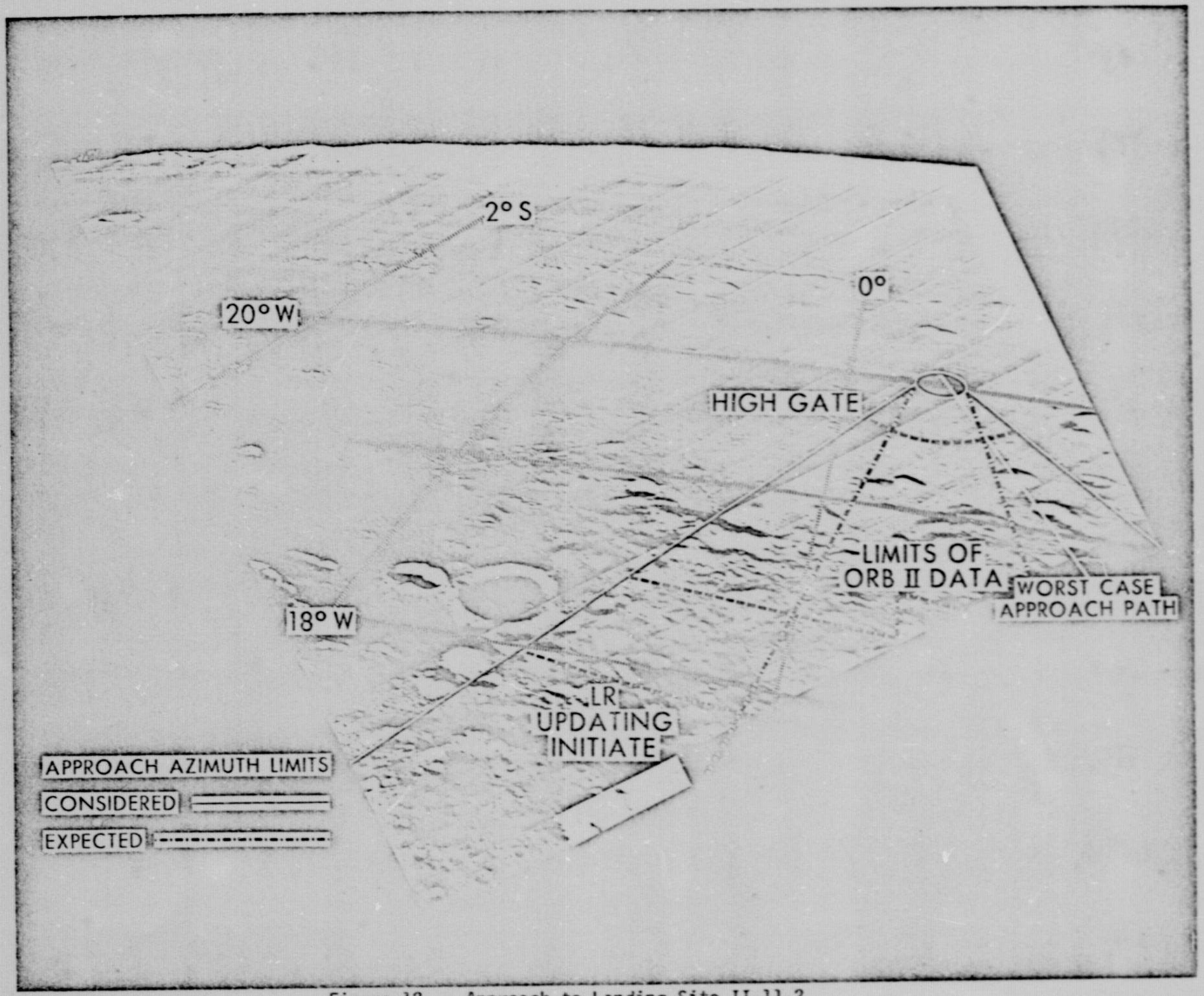

Figure 12.- Approach to Landing Site II-11-2

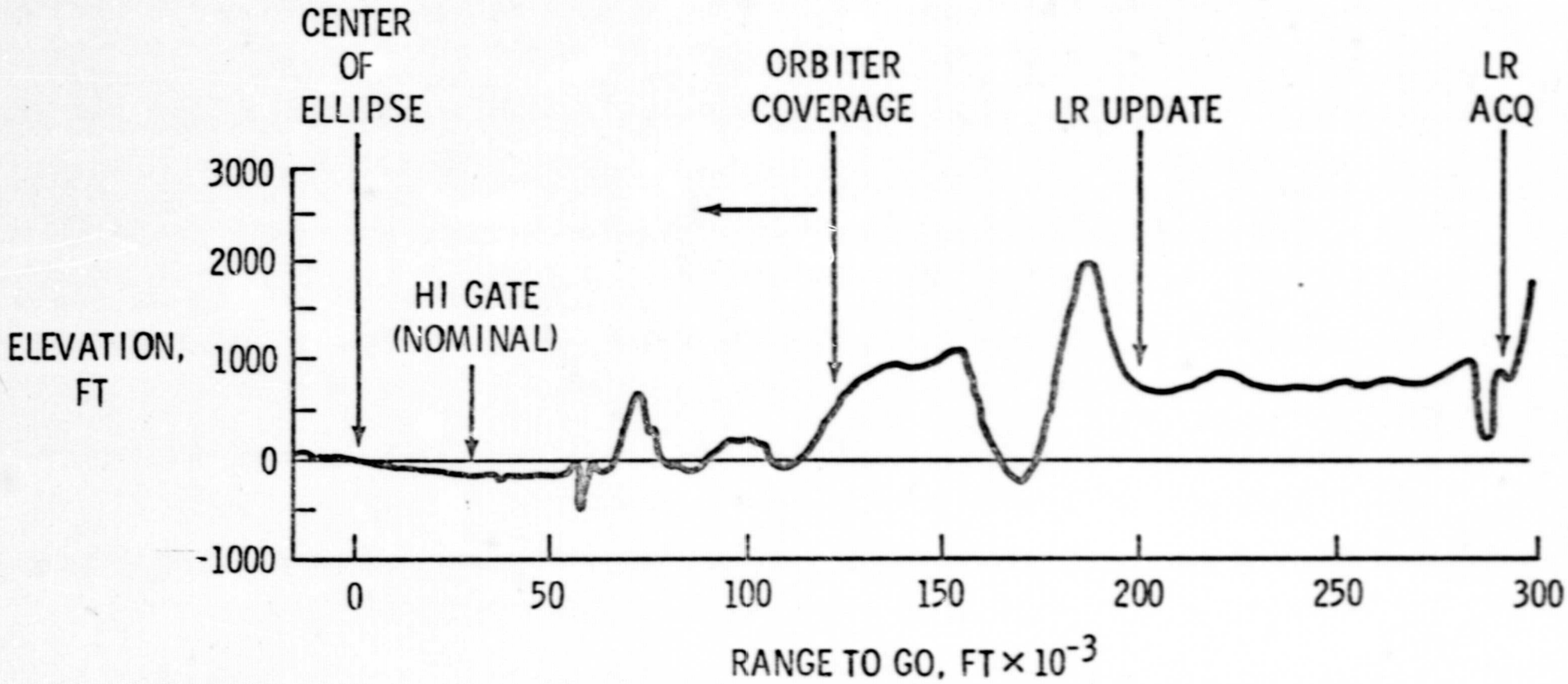

Figure 13.- Worst Case Approach Path Terrain Profile from II-P-11, Elevation Ratio 25:1

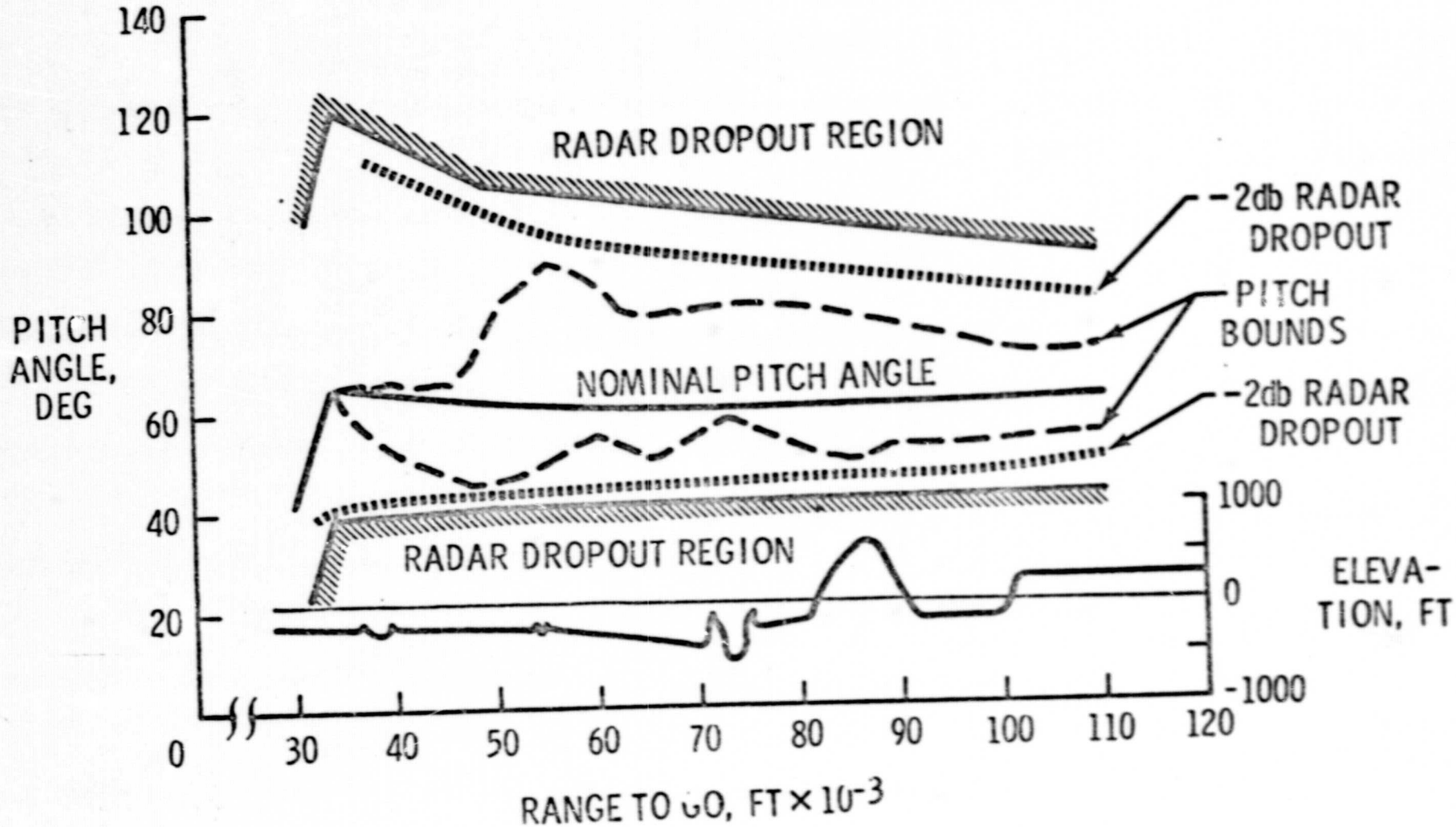

Figure 14.- Pitch Angle Bounds Above Hi-gate Due to Site II-P-11 Terrain Combined with Off-Nominal System Performance

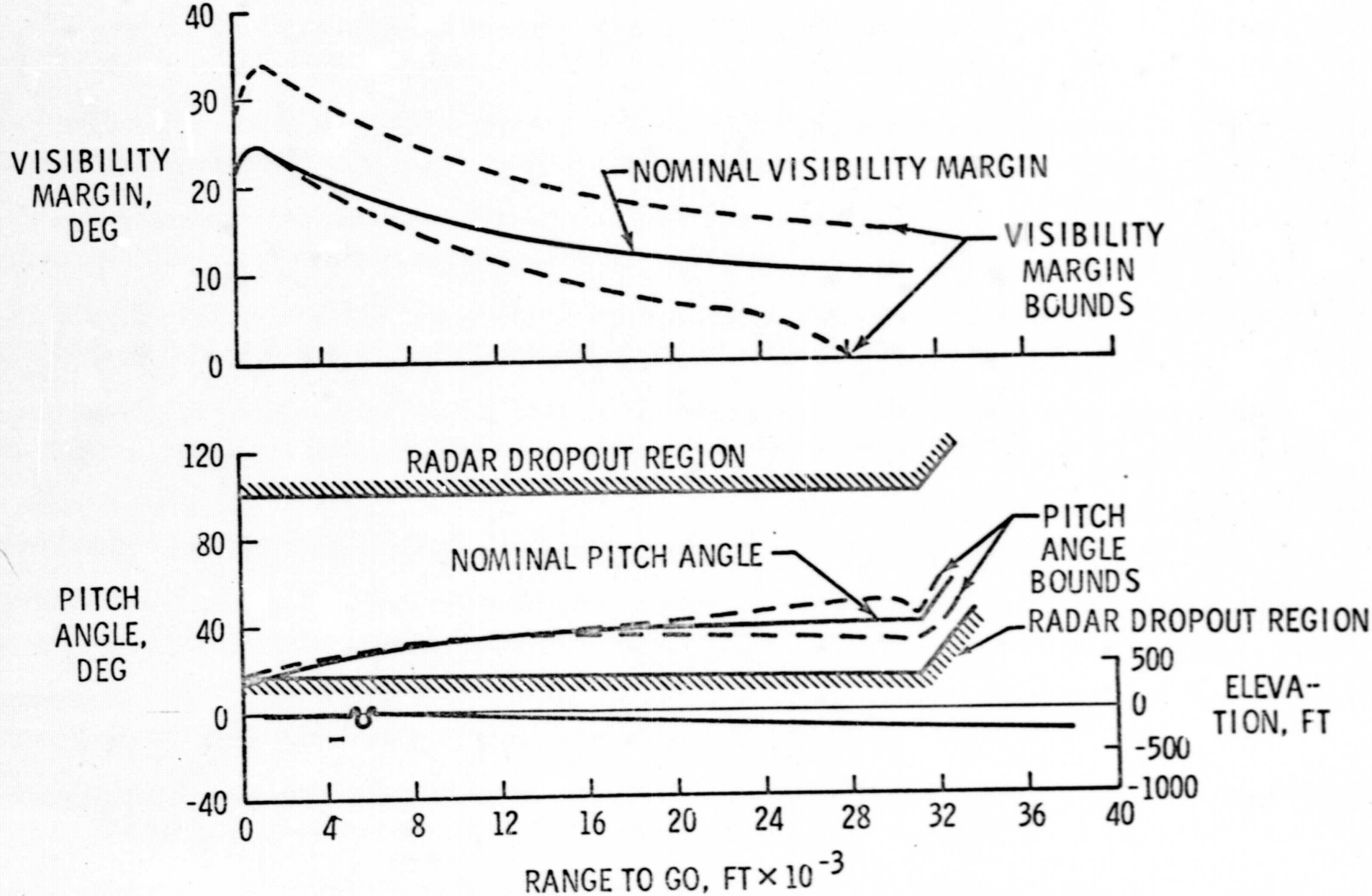

Figure 15.- Pitch Angle and Visibility Margin Bounds Due to Site II-P-11 Terrain Combined with Off-Nominal System Performance

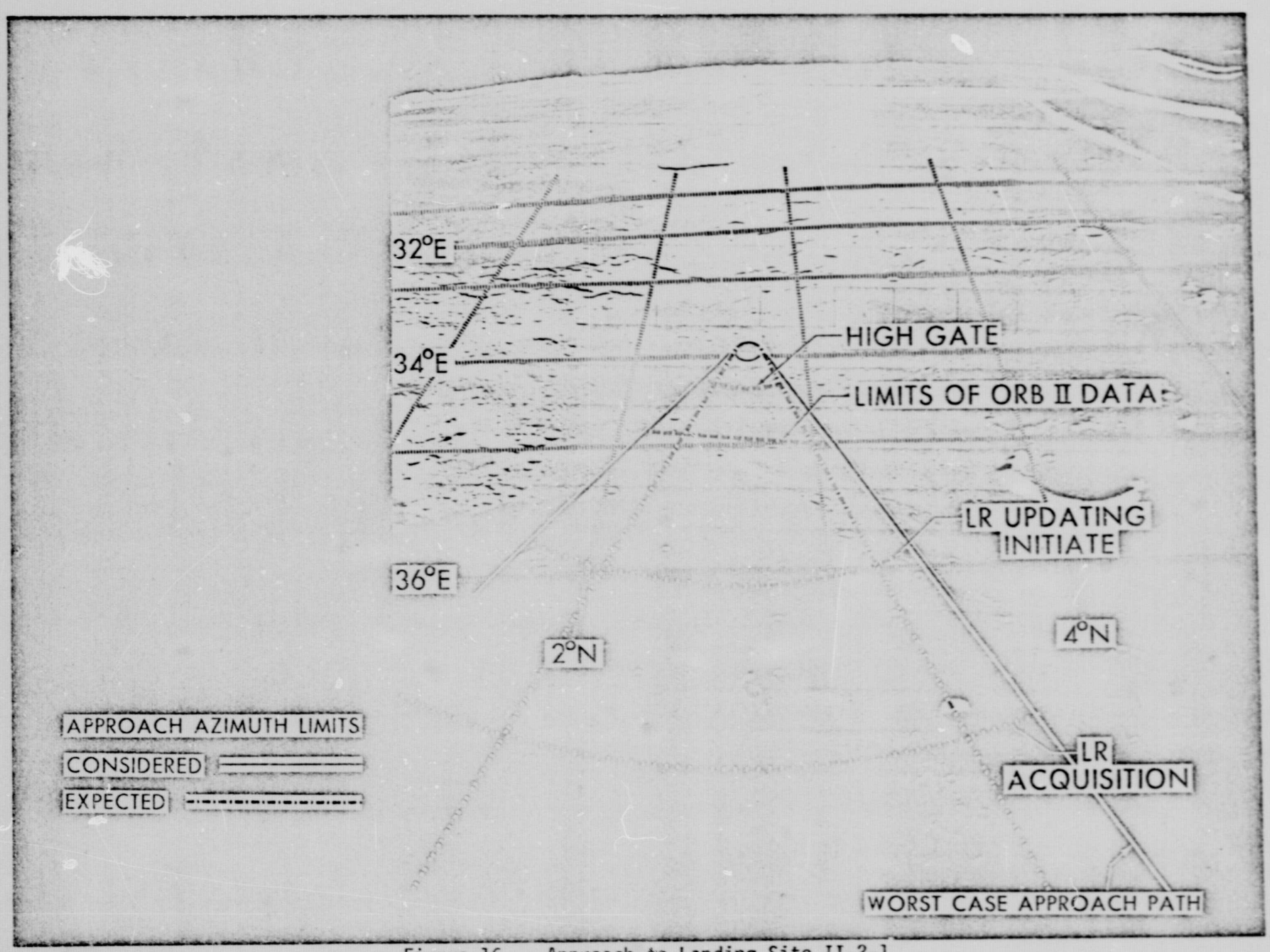

Figure 16.- Approach to Landing Site II-2-1

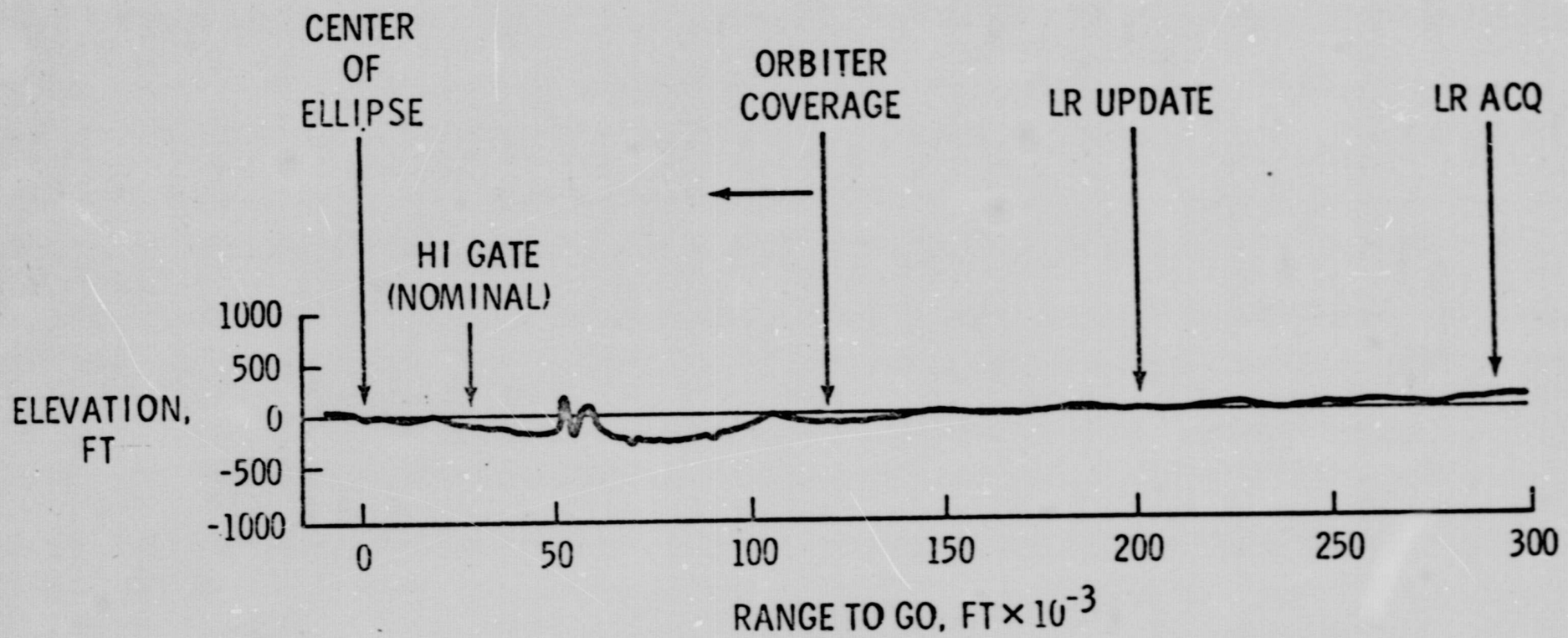

Figure 17.- Worst Case Approach Path Terrain Profile from II-P-2, Elevation Ratio 25:1

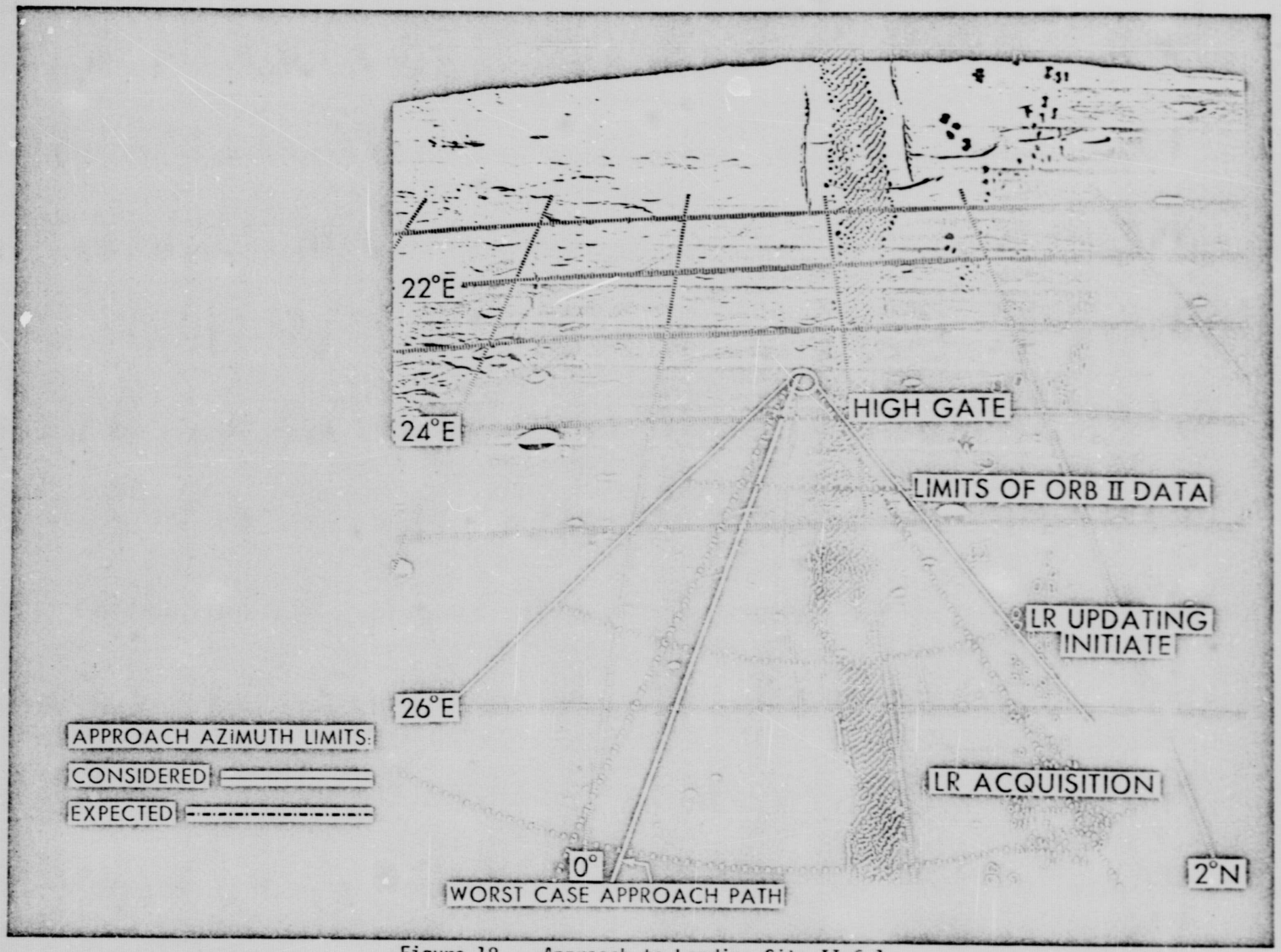

Figure 18.- Approach to Landing Site II-6-1

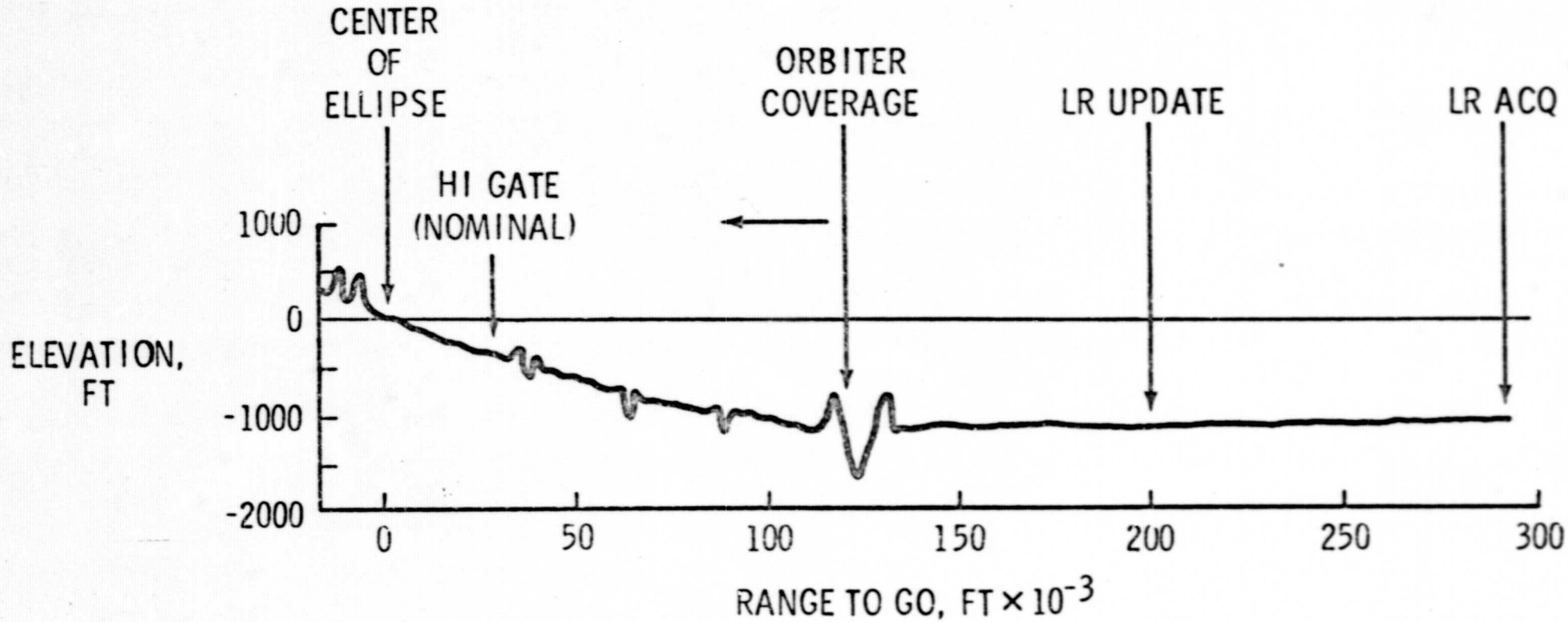

Figure 19.- Worst Case Approach Path Terrain Profile from II-P-6, Elevation Ratio 25:1

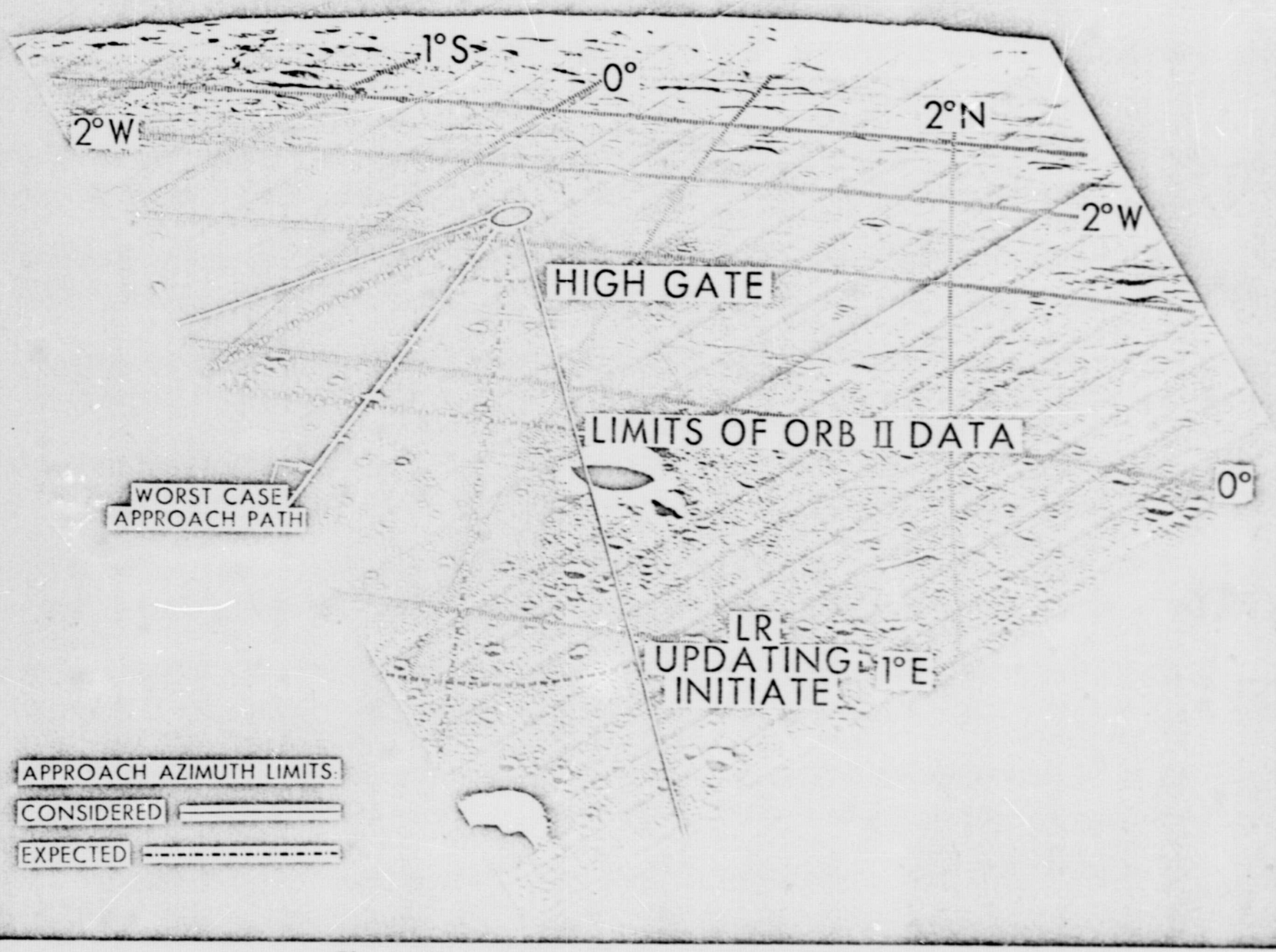

Figure 20.- Approach to Landing Site II-8-

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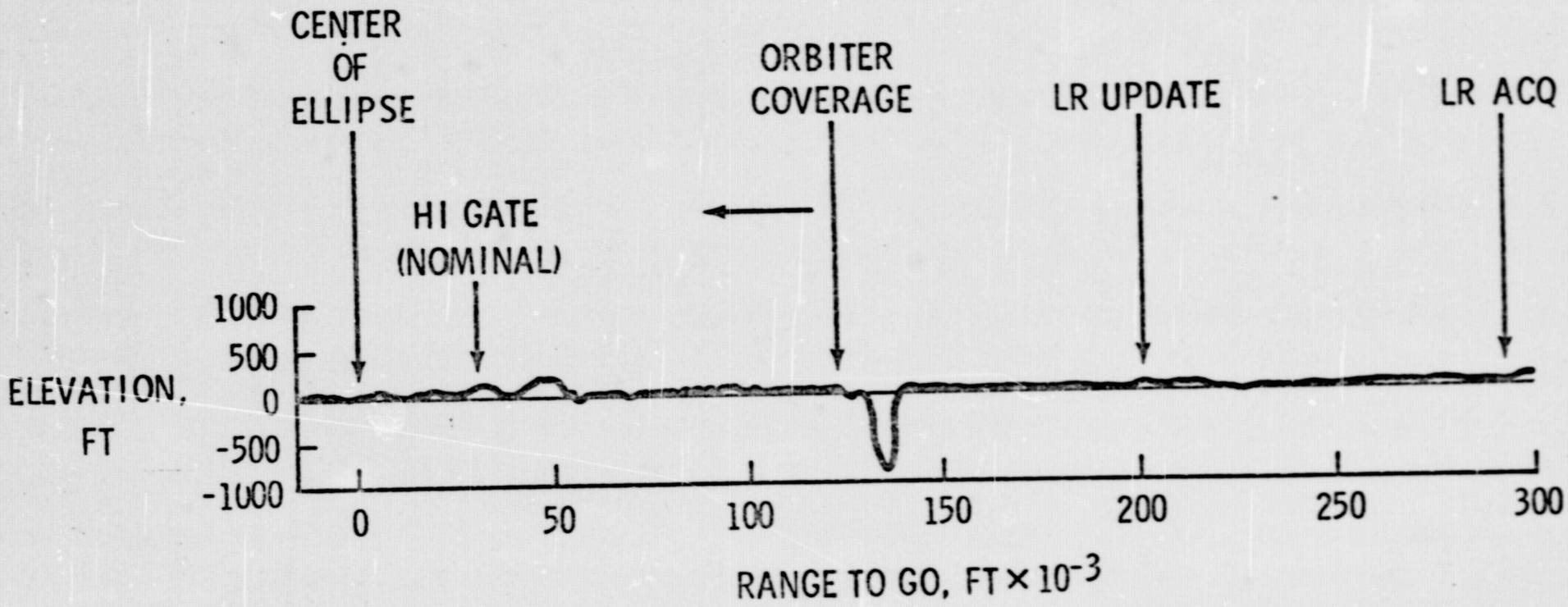

Figure 21.- Worst Case Approach Path Terrain Profile from II-P-8, Elevation Ratio 25:1