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APOLLO PROGRAM

SOME EFFECTS OF RADAR ANTENNA POSITION ON LM DESCENT PERFORMANCE

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SUMMARY

A hybrid simulation study has been conducted in which LM descent performance is compared for three altitudes (33, 24, and 15,000) which are functions of the antenna position at which the radar starts to update the LGC altitude. The radar altitude measurements are made over a realistic lunar terrain model. The LM velocity is assumed to be exact, i.e., no velocity updates required. The altitude measurement to the terrain is assumed to be an exact measurement, and is either (1) independent of the radar antenna position, or (2) dependent in that the measurement is not available if the range beam is within 5° of zero doppler. Additional parameters of variation include an LGC altitude error of ± 3500 ft and a constant throttle thrust output variation of $\pm 2\%$.

The performance characteristics considered in the comparison were (1) characteristic velocity, (2) the vehicle pitch attitude excursions prior to high gate, and (3) the visibility time after high gate.

An analysis is made that relates the critical radar conditions of zero doppler and beam incidence for various antenna positions to the simulation results obtained with a perfect radar.

The results of this study revealed: (1) the radar should provide continuous updating of altitude from at least a time-to-go to high gate of 125 seconds; (2) the radar antenna position of 40 degrees that was designed for reception of both radar altitude and velocity measurements prior to high gate does not provide satisfactory altitude data due to zero doppler. For reception of radar altitude only prior to high gate, an optimum antenna position should exist between 20 and 40 degrees. With an antenna position of 24° prior to high gate (present evaluation by GAEC as best position) a loss of altitude data due to zero doppler could occur if the following three conditions are encountered:

a. Altitude updating is restricted to a starting time-to-go to high gate of about 120 sec due to terrain uncertainty at the ranges for Tgo > 120.

b. The throttle down time occurs at about the same time (110).

c. A navigation error of 3 - 4000 ft which produces a vehicle low condition.

(3) A minimum throttle down (from constant throttle to throttleable region) time of about 40 seconds (Tgo to high gate) may be required to prevent loss of radar altitude data due to high beam incidence angle.

INTRODUCTION

For LM descent to a lunar landing site an aim point called high gate is used which is approximately 6 n mi from the landing site. The LM guidance system flies the vehicle to that point in a near fuel optimum manner by applying the thrust vector approximately against the LM velocity vector. After reaching high gate a non-optimum type approach then provides pilot visibility of the landing site. To obtain the proper visibility profile from high gate to the landing site, the aim point conditions of altitude and velocity at high gate must be achieved. This requires then that the landing radar update the LGC computed state vector (upon which the guidance system is operating) prior to high gate. To investigate the effects of the starting point (time or altitude) in the descent at which the landing radar starts to update the LGC altitude, a study was conducted using the Guidance and Control Division hybrid landing simulation. This starting point is a function of antenna position. An analysis is made that relates the critical radar conditions of zero doppler and beam incidence at which radar data might be lost for various antenna positions to the simulation results obtained with a perfect radar.

DESCRIPTION OF SIMULATION

A detailed description of the hybrid simulation with quadratic LGC command logic is contained in references 1 and 2. Only the radar model characteristics will be presented in this report because a detailed radar math model was not simulated.

Lunar Terrain - The simulated terrain is shown on figure 2. This is equivalent to the terrain model T-7 of reference 3. The terrain altitude is the deviation of the surface about a sphere that contains the landing site. The magnitude of simulated radar altitude measurement was the distance from the LM vehicle at any time to the surface along the local vertical. The landing site, at 0,0 on figure 2, was at the same point on the terrain for all runs investigated.

Navigation Error - The effects of altitude error only were considered in this study. The LGC computed velocity was assumed to be exact, and did not require radar updating. An altitude error of ± 3500 ft was investigated. This error was inserted into the simulation by a shift of the whole terrain profile (fig 2) either up or down by 3500 ft. This shift is referred to as an (h-bias) - note that a +(h-bias) produces a vehicle low condition. The magnitude of 3500 ft is in the neighborhood of a two to three sigma navigation error.

Radar Altitude Updating - The point in the powered descent at which the radar signal becomes strong enough to lock on and provide altitude data for updating the LGC computed altitude is dependent on the radar antenna position. The estimates of the radar acquisition altitude as a function of the antenna position from reference 4 that was assumed in this study is shown on the table of figure 1. The logic used was that the radar updates ($h_{LGC} = W(h_{RADAR} - h_{LGC})$ started when the LGC altitude reached a specified value. The sampling and updating rate was every two seconds with the weighting function (W) as indicated in the note of table I. Besides the acquisition altitude, the only other dependence of radar altitude on antenna position was that the updating was inhibited whenever the altimeter beam was within 5^{o} of zero doppler, where zero doppler occurs when the beam is perpendicular to the velocity vector.

Thrust Profiles - From the start of powered descent at t=0 the guidance system operates with a constant throttle setting ($92\frac{1}{2}\%$) until the LGC command thrust gets less than 58%, at which point the engine can then be throttled. The thrust variation that can occur for the constant throttle setting can have a significant effect on the descent trajectory and on the time at which throttling occurs. A nominal thrust profile of (9700 + 1.2t) was assumed, and high (+2%) and low (-2%) thrust profiles were investigated. The high profile was the nominal $+1\frac{1}{2}\%$ at t=0 and nominal $+2\frac{1}{2}\%$ at t=400 sec. The low was $-1\frac{1}{2}$ to $-2\frac{1}{2}\%$. For the initial and target conditions used in this study, and for zero terrain and altitude error, the throttle down times for the high and low thrust profiles were t=110 and 20 seconds before high gate respectively.

TEST PROGRAM

Test runs with radar updating of altitude over a terrain model were flown from the start of powered descent at pericynthion to a hover altitude of 110 ft over the landing site. The initial conditions at pericynthion for each run were identical relative to the LGC state vector, i.e., the LGC computed trajectory between pericynthion and the radar acquisition altitude was dependent only on the thrust profile. From radar acquisition to hover the trajectory was then dependent on the conditions viewed by the radar. A series of 24 runs were made from all combinations of the following parameters of variation:

Radar acquisition altitudes - start of LGC altitude updates.

1. 33,000 ft
2. 24,000
3. 15,000

Thrust profiles

1. TH - thrust high an average of +2%
2. TL - thrust low an average of -2%

Navigation altitude errors - landing site altitude uncertainty

1. VH - vehicle high 3500 ft, $h_{BIAS} = -3500$
2. VL - vehicle low 3500 ft, $h_{BIAS} = +3500$

Radar lock-on logic

1. Inhibit update when altimeter beam within 5° of zero doppler, i.e., inhibit when $|\theta - \gamma - p| < 5^\circ$ (see fig 1). The antenna position is zero ($\alpha = 0$, $\rho = 20$) after high gate for all cases.
2. Perfect radar - no loss of data.

In addition, two runs were made for each thrust profile, TH & TL, for zero terrain deviation and navigation error.

DISCUSSION OF RESULTS

General

The performance data of the simulated runs are presented on table I. Of the set of twelve runs performed with a perfect radar (no loss of data), only one of the runs when repeated with the zero doppler drop out logic was affected by the logic. Therefore, the 12 rows of data on table I represent 23 runs. The run which lost radar data after acquisition is shown on the 13th row of the table.

The simulated runs were performed on the basis of three different altitudes (function of antenna position) at which radar altitude updating were to start. The significant parameter of interest, though, is the time-to-go (Tgo) to high gate at which the updating starts. The reason is that the nominal descent trajectory (h vs t) can be redesigned, as it has been since this study was performed, such that a given altitude can occur at a larger Tgo. This can be seen on figure 5 (#42318 used in this study). The larger the time that the system has to take out an altitude error, the smaller effect a given altitude error will have on the vehicle pitch attitude profile (θ vs t). This implies then that if the start of updating is satisfactory at 24,000 ft (or 125 sec) based on trajectory 42318, then the start of updating should be satisfactory at 20,000 ft (or 125 sec) based on trajectory 472285. The updating time (2nd column of table I) will then be referred to in the discussion of performance.

The performance characteristics presented on table I are (1) a characteristic velocity (ΔV) comparison which is a measure of the effect on the whole trajectory. Note that the ΔV difference due to thrust profile is not included on the table; i.e., the ΔV for each radar updating condition is compared with the ΔV for the no terrain, no navigation error with the same thrust profile. (2) The pilot visibility time of the landing site, which is a measure of effect after high gate. Note that ideally the high gate aim conditions will always be achieved so that the pilot would have 130 sec (for this trajectory) of visibility time. And (3), the pitch attitude variation prior to high gate. Large variations might cause loss of radar data.

START OF RADAR ALTITUDE UPDATING

Performance Comparison (perfect radar) - The obvious expectation of performance would be that the sooner the altitude updating starts the lower the effect would be on pitch attitude and characteristic velocity, because the system would have more time to take out altitude error. This expectation proves to be true on table I for $\Delta\theta$ for all cases. The ΔV is also smaller for larger update times in the region Tgo = 120 to 180 seconds. But note that for both THVL (thrust high, vehicle low) and TLVL, the ΔV is smaller for the 50-65 sec cases than the 120-124 sec cases. For THVL, 50 seconds of visibility was lost after high gate. This suggests that the high gate velocity condition was not met, and the higher velocity produced a more efficient trajectory, but degraded visibility. Because of this loss of visibility, and because of the excessive ΔV penalty of 121-180 ft/sec for the vehicle high condition, the updating time from 50-65 sec is deemed as unacceptable.

For the start of updating times of 120-125 sec, an improvement of visibility time from 2 to 15 sec was obtained for all cases. But because of the tendency of increased ΔV (about 40 ft/sec), this time period might be considered as near minimum for the start of radar altitude updating.

MAXIMUM UPDATE TIME - TERRAIN UNCERTAINTY

The question of whether or not a maximum update time should exist cannot be answered in this report, but the problem will be presented. The performance data of table I shows that the start of updating at 180 sec from high gate is better than the lower times. This is an obvious solution if terrain uncertainty is not considered. At 180 sec from high gate, the range from the target for either trajectory on figure 5 would be about 50 n mi. But note that for the terrain model used in this study (fig 2), the terrain was known to only 25 n mi, and was therefore programed to be a level 1650 ft at range greater than 25 n mi. If for an actual LM landing site the orbiter data can provide terrain profiles to 50 or 60 n mi, then a study of that site could be made to determine if a maximum update time would exist. In such a study though, the general terrain slope uncertainty of the orbiter data (rotation of a given terrain profile about the landing site) must be considered.

ANALYSIS OF RADAR ANTENNA POSITION

The performance data discussed so far has been related to antenna position only through the time at which radar altitude acquisition occurs. Once the updating started the radar measurement to the terrain was a perfect measurement, except for just one run that lost data due to zero doppler. For these runs the proximity of the radar altimeter beam (prior to high gate) to the conditions of zero doppler and maximum incidence angles will be investigated for two antenna positions.

The pitch attitude and altitude profiles versus Tgo to high gate for the 40° and 20° antenna positions are shown on figures 3 and 4. The 0° antenna position will not be discussed, for the perfect radar performance (50-65 sec) has shown this position to be unacceptable. In addition, the profiles for the runs made with zero terrain and navigation error (THVO & TLVO) are included on the figures.

Zero Doppler Effect - Zero doppler (no frequency shift of radar return signal - or a zero velocity measurement of velocity radar beam) occurs on a radar beam when the beam is perpendicular to the vehicle velocity vector. The type of radar altimeter being used for LM requires a compensation of the range measurement due to velocity along the range beam. A zero doppler problem results then, not from the h-beam being at zero doppler for zero compensation would be required there, but from the loss of track of the rear velocity radar beams (which would be used for compensation) as zero doppler is approached (low signal to noise ratio due to low velocity measurement). This loss of compensation would result in a large range measurement error, and therefore would probably require a program logic which prevents updating when the beam is near zero doppler. A proximity of 5° was assumed in this simulation, but data from GAEC (detailed radar model) indicates it may be as large as 10 to 15°. The zero doppler altimeter problem may possibly be eliminated by performing the compensation within the LGC rather than at the radar, but this analysis will assume the problem still exists.

The vehicle pitch attitude at any time at which the altimeter beam would be at zero doppler can be found as $\theta_{ZD} = \gamma + \rho$ (reference fig. 1). For each run shown on figure 3 the bottom zero doppler dashed line is drawn. On figures 3a to c it is evident that a 40° antenna position ($\rho = 60^\circ$) would not be satisfactory due to zero doppler. Even the condition of zero error (fig 3a) for TH reached zero doppler. The THVH on fig. 3b was the run of line 13 on table I. This run lost 80 seconds worth of update due to being within 5° of zero doppler (note that ΔV increased to 165). It is the dip in θ at about Tgo = 110 sec for TH (throttle down point) that forced THVH into zero doppler region. The curves of fig c. got close, but not quite, to 5° of zero doppler, and therefore did not lose data in the simulation, but they would have with the band at 10° instead of 5°. The closest approach to zero doppler for the 20° antenna position was about 10° for the THVL (fig 3e).

GAEC has recently evaluated and given a preliminary recommendation of a 24^o antenna position. Their evaluation was based on a trajectory similar to #472285 of fig 5, which (with radar acquisition of 26,000 ft = h) would provide θ profiles more like fig 3c due to a longer update time. If the zero doppler curves of fig 3e are shifted up 4^o (to 24^o) and compared with θ of fig 3c, a margin of about 20^o from zero doppler is found. The 24^o position, therefore, looks good if the updating can start at T_{go}= 180 sec. But as suggested in this report, a maximum update time may be necessary due to terrain uncertainty. If this maximum time were 125 seconds, the θ profile of fig 3e would be expected. THVL would then be within 5^o of zero doppler. The point being made is that a maximum update time, if it exists, can have an effect on the design of antenna position.

Maximum Incidence Angle - The maximum angle of the radar altitude beam from the local vertical is defined by the minimum signal to noise (S/N) ratio for maintaining both of the rear radar beams. The S/N is a very complex function of vehicle attitude, altitude, and velocity. For the purpose of analysis, a simplifying assumption will be made that the maximum radar beam incidence angle (Bmax) or max vehicle attitude is a function of altitude only. Some data obtained from GAEC with their detailed radar math model on Bmax for a specific run will be shown for comparison.

For a given trajectory a Bmax vs h curve can be constructed from the acquisition data tabulated in figure 1, because acquisition occurs when the Bmax curve is crossed. For a given trajectory where θ and h are known, Bmax can be found as $B\max = \theta - \rho$. For this analysis the trajectory described as THVO will be assumed for the construction of the figure 4f (solid line) curve. Now based on the assumption that figure 4f is valid for all the trajectories investigated, the maximum θ at any time (top dashed line plots on figures 3) can be found as $\theta_{max}(t) = B_{max}(h) + \rho$. These plots of θ_{max}, although not exact in magnitude, provide an indication of the shape of θ_{max} vs time, and an indication of the effect that terrain and navigation error have on the θ_{max} curve. The most recent data from GAEC's detail radar math model shows B_{max} curves as indicated by the dotted lines on figure 4f. The dotted line θ_{max} curves on figures 3d & e, constructed from the GAEC B_{max} curve, show about a 20^o wider margin for maximum pitch attitude.

Lowering the antenna position improves the zero doppler margin, but degrades the maximum incidence margin. The TLVL was the worst condition encountered, figure 3e, on incidence angle for the 20^o antenna position. The assumed θ_{max} curve shows that data would be lost at about T_{go} = 40 sec, whereas the GAEC curve shows the TLVL to be marginal. Relating the results of this study to a 24^o antenna position two factors are considered. As discussed under the zero doppler effect, with the 24^o antenna position and updating starting at 180 sec from high gate, the expected θ profile for TLVL would be more in line with that of figure 3c than 3e. For this case a 15^o margin from maximum incidence would exist. But if a maximum update time of about 125 sec due to terrain uncertainty is required, then the marginal condition of figure 3e could exist for TLVL. A possible solution to this condition would be to increase (by aim point design) the minimum Tgo at which throttling can occur. Note on figure 3a the θ peak at Tgo = 25 was caused by throttling down at that time for TL. If a minimum throttle down of, say, Tgo = 40 were used, then the θ peak on figure 3c would be lowered away from the maximum incidence curve.

CONCLUDING REMARKS

Radar Altitude Update Start Time

Updates starting at 50-65 sec from high gate are unacceptable due to either a ΔV penalty as high as 180 ft/sec, or a visibility time loss of 50 sec after high gate. Updates starting at 120-125 sec are satisfactory for visibility, but require about 40 ft/sec more ΔV than updates starting at 180 sec.

An antenna position of 24°, with estimated radar altitude acquisition at h = 26,000 ft, could provide a start of updating at about 200 sec from high gate or 60 n mi from the landing site. A specification for a maximum time to start updating might be required because of terrain uncertainty at this large range of 60 n mi.

Antenna Position

If the zero doppler problem can be eliminated from the radar altitude measurement by compensation of h in the LGC based on computed velocity, then a large antenna position, i.e., 40°, prior to high gate would be desirable for radar velocity acquisition prior to high gate. The following remarks assume, though, that compensation of h will be based on radar measured velocity (rear beams).

A 40° antenna position prior to high gate is unsatisfactory due to loss of rear beam velocity data due to zero doppler.

A 24° antenna position would be satisfactory if the updating of h starts at 180-200 sec from high gate. But, if the maximum update time requires limiting to about 125 sec, due to terrain uncertainty, then further evaluation of this 24° antenna position should be made for (1) zero doppler loss of data for a THVL (thrust high and vehicle low due to navigation error) condition, and (2) maximum incidence loss of data for a TLVL condition - any problem encountered here could be alleviated by restricting the minimum throttle down time for TL to about 40 sec from high gate.

REFERENCES

1. Thomas E. Moore, Presimulation report, "Piloted Lunar Landing Simulation Using a Math Model LM Guidance Computer," Memorandum EG27-3-66, January 11, 1966.

2. Thomas E. Moore, "Description of Conditions Investigated for LM Powered Descent on MSC/G&CD Hybrid Simulation," Memorandum EG27-66-131, November 4, 1966.

3. B. Kriegsman and N. Sears, "LM PGNCS and Landing Radar Operations During the Powered Lunar Landing Maneuver," MIT Report E-1982, August 1966.

4. M. Craig, "LR Single Position Antenna Study," Memorandum EG26-66-265, August 22, 1966.

	ACQUISITION ALTITUDE (Ft)	RADAR UPDATING TIME PRIOR TO HIGH GATE (Sec)	h BIAS (Ft)	THRUST PROFILE (%)	TYPE OF RUN	V PENALTY TO HOVER (NO TERR. OR ERROR = 0) (ft/sec)	VISIBILITY TIME (NOMINAL 130 SEC) (LPD 65°)	PITCH ATTIT. (θ) VARIATION BETWEEN ACQ. & HIGH GATE (DEG) (Δθ)
PERFECT RADAR ALTITUDE MEASUREMENTS TO SURFACE	33000	180	3500	+2	THVL	2	135	54-74 (20)
	24000	125	3500	+2	THVL	40	145	48-76 (28)
	15000	50	3500	+2	THVL	25	80	34-78 (44)
	33000	180	-3500	+2	THVH	-3	138	68-52 (16)
	24000	125	-3500	+2	THVH	40	132	68-48 (20)
	15000	50	-3500	+2	THVH	180	140	108-60 (48)
	33000	165	3500	-2	TLVL	10	135	60-86 (26)
	24000	120	3500	-2	TLVL	41	135	54-100 (46)
	15000	65	3500	-2	TLVL	25	120	52-112 (60)
	33000	165	-3500	-2	TLVH	18	137	74-54 (20)
	24000	120	-3500	-2	TLVH	30	138	74-50 (24)
	15000	65	-3500	-2	TLVH	121	140	108-54 (54)
DROP OUT DATA WHEN $\leq 5^{\circ}$ FOR $40^{\circ} \rightarrow 0^{\circ}$ ANTENNA POSITIONS	33000	100	-3500	+2	THVH	165	143	130-40

NOTE: 1. For +h BIAS, LM is closer to surface than LGC indicates, i.e., vehicle low.
2. Weighting Function: $W = .55 \left(\frac{ACQ.(h)-h}{ACQ.(h)} \right)$

TABLE I - Performance Data

ANT. POS. (℄ OF BEAMS W/R THRUST AXIS) α	ALT. BEAM ANGLE (W/R THRUST AXIS) ρ	ACQ. ALT.
40°	60°	33,000
20°	40°	24,000
0°	20°	15,000

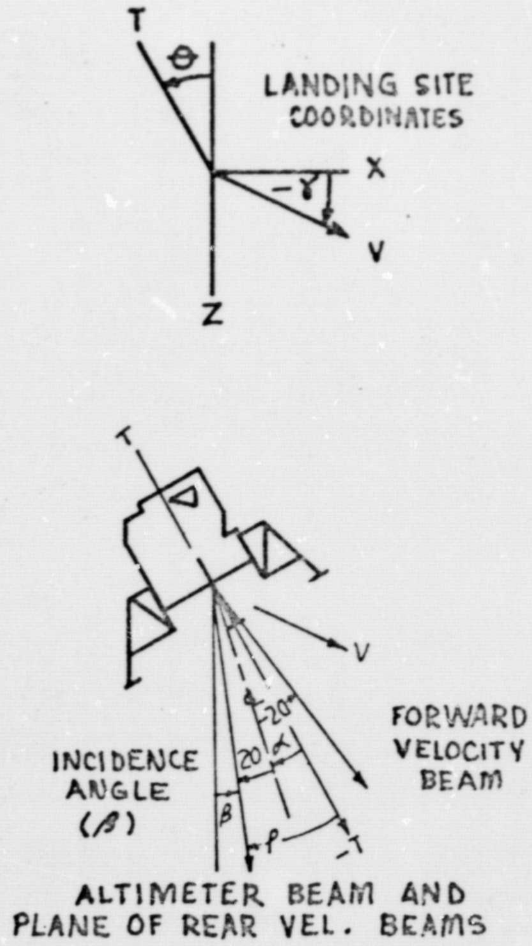

FIGURE 1. LM LR ANTENNA POSITION REFERENCE

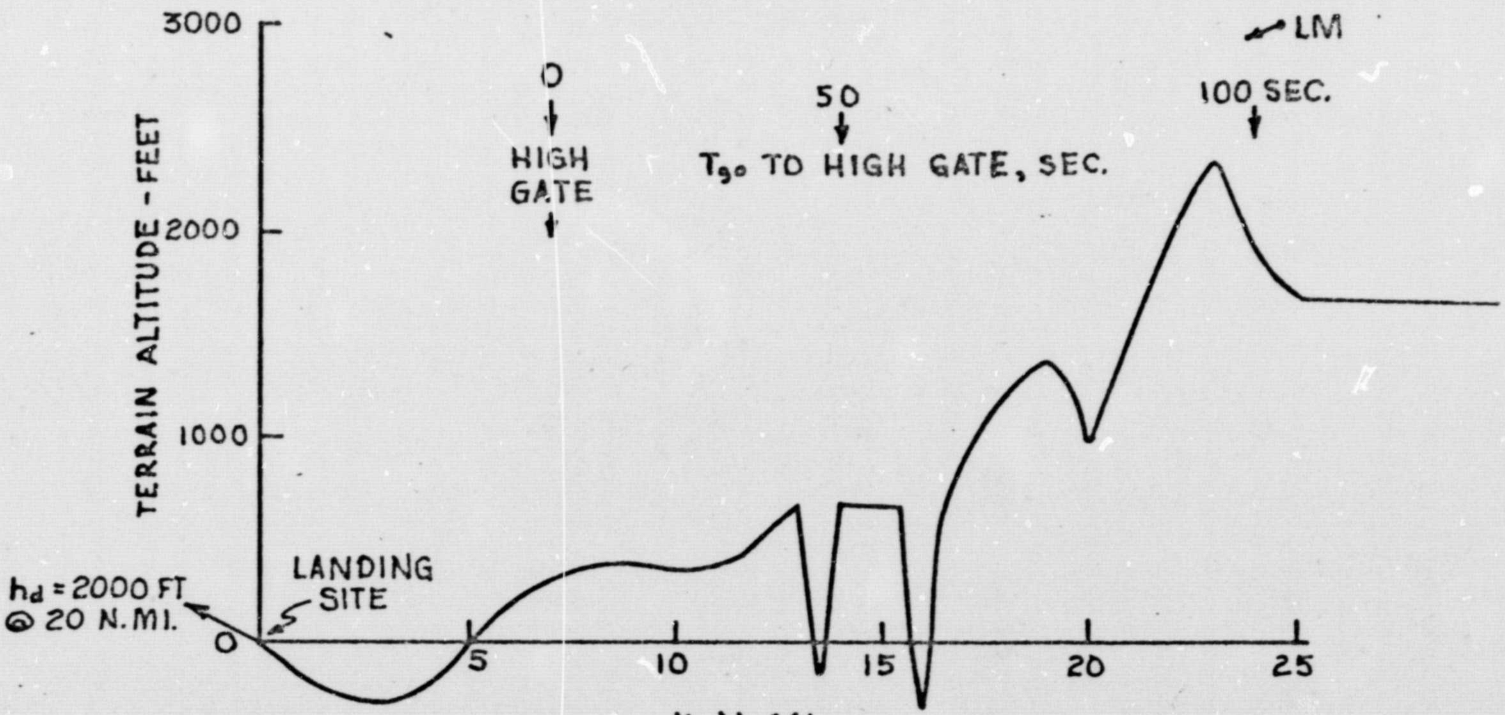

FIGURE 2. LANDING AREA

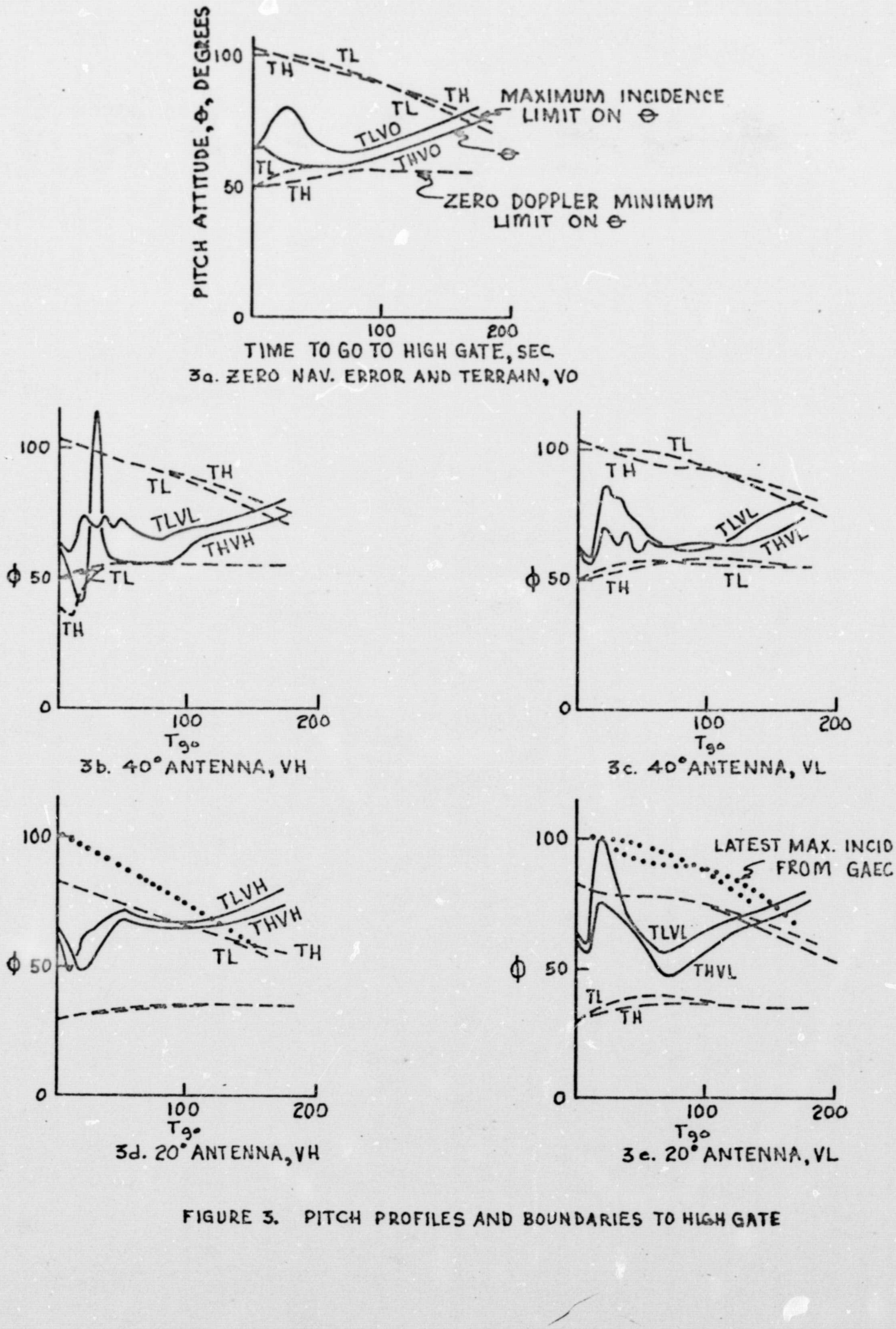

FIGURE 3. PITCH PROFILES AND BOUNDARIES TO HIGH GATE

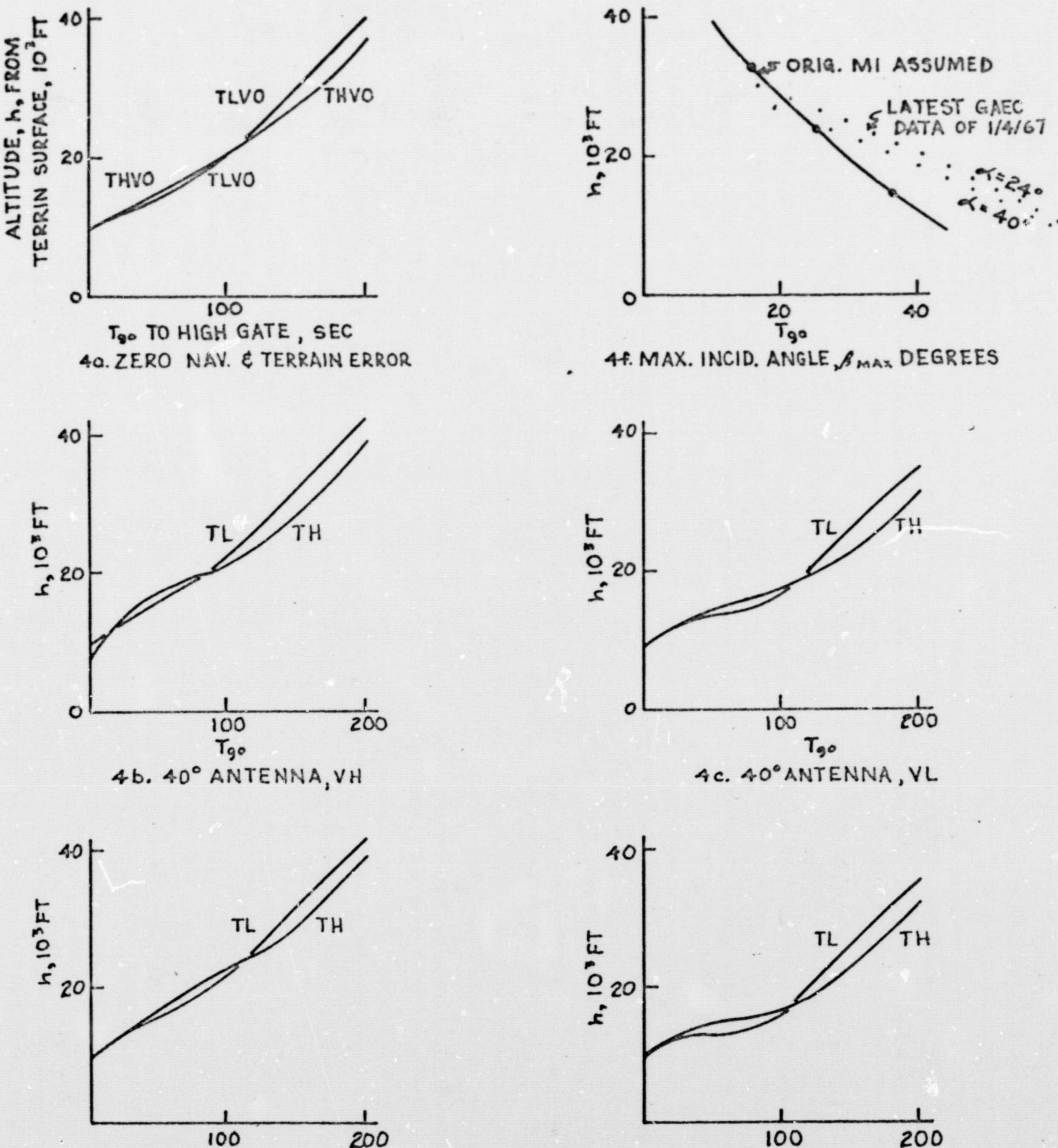

FIGURE 4. ALTITUDE PROFILES AND MAXIMUM INCIDENCE TO HIGH GATE

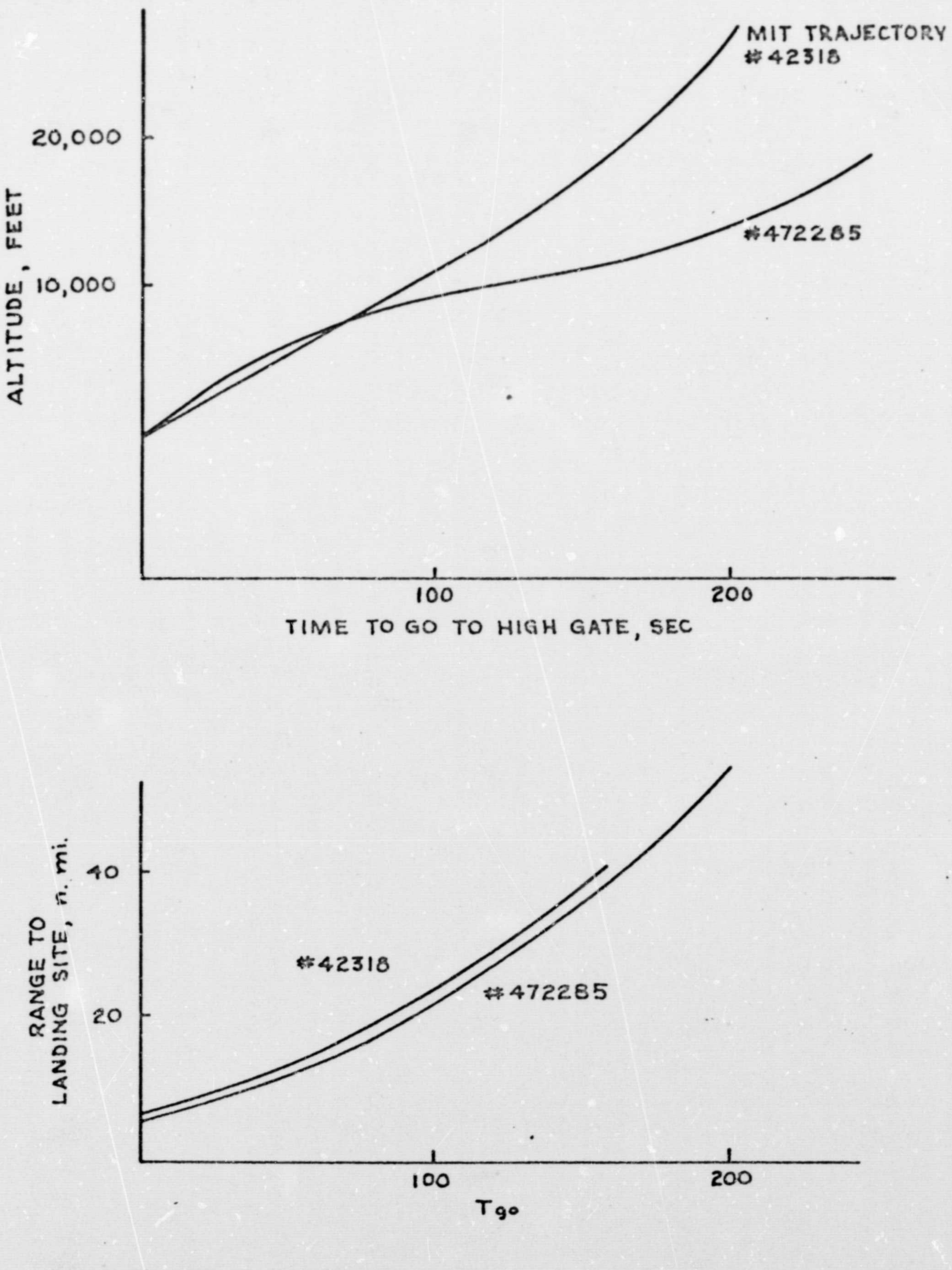

FIGURE 5. COMPARISON OF TWO NOMINAL LM DESCENT TRAJECTORIES