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THE EFFECT OF RANGE CONSTRAINTS ON LM DESCENT GUIDANCE PERFORMANCE IN THE PRESENCE OF ENGINE THRUST UNCERTAINTIES

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SUMMARY

A hybrid simulation study has been conducted in which the performance of range-free and range-fixed LM descent guidance is compared for a descent engine thrust uncertainty of ±4%. The trajectory for the range-fixed guidance was designed for a ±2% thrust uncertainty (nominal throttling at 70 seconds). For the low thrust cases, the pilot used the LPD to adjust the trajectory after high gate.

The performance characteristics considered in the comparison were (1) the conditions achieved at high gate, (2) the characteristic velocity, (3) the visibility after high gate, and (4) the landing site range dispersion.

The results of this study revealed that the trajectory does not need to be designed for the full range of thrust uncertainty for range-fixed guidance. Instead, pilot procedures can be established for redesignations after high gate using the LPD to provide a satisfactory visibility phase for the low thrust cases. For a -4% thrust LPD increments were required to avoid crashing. The additional pilot workload and ΔV penalty of 125 ft/sec for either + or -4% thrust (with high gate designed for a nominal 70 seconds throttling time) leads to a recommendation for a range-free option in the LGC.

INTRODUCTION

A final approach phase during powered descent, which occurs after the high gate aim point, is required so that the pilot can visually evaluate the landing area. To obtain proper final approach visibility characteristics, a specific velocity at high gate must be achieved by the descent guidance. The descent guidance must also work with the descent engine limitation of not being able to throttle between 60 and 92.5% thrust. In this region the guidance must utilize the constant throttle setting of 92.5% because the ΔV required would be prohibitive if the entire descent occurred with the engine thrusting in the throttlable region. The guidance problem results from the uncertainty of the thrust output for a constant throttle setting which can be as large as ±4% when redundant paths for pressure regulators in the descent engine are considered.

The present MIT guidance achieves the high gate aim point conditions of position and velocity by having the thrust control system go from the constant throttle mode to the lower throttlable region at some time prior to high gate. The time at which throttling occurs depends on the actual thrust output of the engine; i.e., high thrust profiles throttle sooner than low thrust profiles. The position of the high gate aim point must be designed so that the lowest possible thrust profile produces throttling prior to high gate. If a lower thrust profile is encountered than high gate is designed for, then the required velocity conditions at high gate will not be achieved. This, in turn, affects the vehicle attitude and hence the visibility during the final approach. The disadvantage with this guidance scheme is that a ΔV penalty of the order of 200 ft/sec occurs if the high (+4%) thrust profile is encountered with the high gate aim point designed to accommodate the low (-4%) thrust profile.

There are at least two possible solutions to this problem. The first is add logic equations to the present MIT guidance to provide "range-free guidance" as discussed in the reference to this internal note. This technique varies the downrange component of both high gate and the landing site so that the velocity at high gate is achieved with a constant 92.5% throttle all the way to high gate regardless of thrust profile. Some changes to the logic proposed in the reference will be presented herein. The second possible solution is to use the MIT guidance as is and to design the high gate position for a low thrust profile that is not the lowest possible. This will lower the ΔV penalty if a high profile is encountered. But if lower thrust profiles are encountered which do not produce throttling prior to high gate, then pilot procedures can be established for correcting the trajectory using the landing point designator. To investigate the feasibility of these two possibilities, a study was conducted using the Guidance and Control Division hybrid landing simulation.

RANGE-FREE GUIDANCE

The range-free guidance investigated is actually an automatic adjustment of the range term in the range-fixed guidance law. The additional logic required for the automatic adjustment as proposed in the reference was:

$$\Delta X = k \int_0^t (T_c - T)\, dt$$

where ΔX = forward range change of both high gate and landing site

$t = 0$ is the start of the constant throttle mode

T_c = Thrust command from LGC

T = Actual engine thrust

$k = 1/2$, until 10 seconds before high gate

$k = 0$, thereafter

It was postulated in the reference that the ΔX calculation would tend to damp the effects of radar altitude updates on pitch attitude. Some preliminary terrain runs made with the radar updates have since indicated the reverse situation. These runs indicate the attitude and thrust commands actually go unstable when the above logic is used following an altitude correction. The reasons for this instability will not be discussed here, but the following logic corrects the instability.

Revised Range-Free Guidance

$$\Delta X = k \int_0^t (T_c - T)\, dt$$

$k = 4$, from pericynthion to radar acquisition altitude

$k = 0$, thereafter

Aim point change from high gate to low gate when the forward velocity $\doteq$ desired velocity (not when $T_{go} = 0$ or $X = X_D$). When $\dot{X} = \dot{X}_D$, ADD $(X - X_D)$ to the low gate aim point. Maintain constant throttle mode prior to high gate until $\dot{X} = \dot{X}_D$ even though T_c may go less than 58%.*

After $k = 0$, T_c can go less than T if a high thrust is encountered and can be greater than T if a low thrust is encountered. Because of the low thrust case, it may be necessary to provide limits on the acceleration commands from the LGC to prevent them from overflowing and giving erroneous attitude commands. A logic flow diagram is presented on figue 1.

RANGE-FIXED GUIDANCE WITH LANDING SITE REDESIGNATION TO COMPENSATE FOR OFF-NOMINAL HIGH GATE CONDITIONS

Two things can occur if the high gate aim point is not designed to produce throttling over the entire range of thrust uncertainty. The first is a low thrust profile that would cause the thrust command to approach 58% (throttle test) as the time-to-go approached 10 seconds (point at which the computation of acceleration commands cease).** If the T_{go} reaches 10 seconds before T_c gets to 58%, the guidance will not throttle the engine until high gate. The 40% high thrust for 10 additional seconds produces a lower than desired velocity at high gate. Pilot visibility of the landing area is enhanced in this case, but at the expense of increased ΔV expenditure. The pilot could correct this situation (reduce the ΔV penalty) by redesignating short to provide a normal visibility profile. The second is for an even lower thrust profile that would cause the thrust command to continue to increase as high gate is approached. The lower than required thrust results in a high forward velocity at high gate. This either degrades visibility or results in no visibility at all. In this case, the pilot might be able to provide visibility by redesignating long.

TEST PROGRAM

The runs made to test the redesignation hypothesis and to illustrate the range-free characteristics were made without radar updates or IMU errors.

*The engine was throttled by the LGC thrust command (T_c) when T_c was less than 58%, except as noted for range-free.

**Satisfactory results (with altitude errors and terrain uncertainties) have been obtained on the GCD hybrid simulation with this time test at 10 seconds. MIT is currently planning to use 20 seconds for this test.

Test runs started at the beginning of the constant throttle mode at pericynthion and ended at the hover altitude of 115 feet. A high gate altitude of 9800 feet (start of pitch-over for visibility) was employed. The constant throttle thrust profiles investigated were as follows:

Average Thrust Uncertainty	Constant Throttle Thrust Profile
-4%	9360 + .9t lbs.
-2.4	9505 + 1.0t
-2.0	9555 + .925t
0	9700 + 1.2t (Nominal)
+2.0	9845 + 1.48t
+2.9	9937 + 1.46t
+3.6	10100 + 1.0t

Unpiloted Studies

Range-Free - Three test runs with the revised range-free guidance were made for thrust uncertainties of 2.9, 2.0, and -2.0%

Range-Fixed - Four runs without a pilot were made for thrust uncertainties of 3.6, 2.0, 0, and -2%. The high gate aim point was designed to accommodate the -2% thrust and thus no redesignations were required for thrust greater than -2%. Preliminary runs were made to define the thrust uncertainty (-2.4%) at which the thrust command approaches 58% as the T_{go} approaches 10 seconds. Three runs with the -2.4% were made with automatic redesignations "short" of 0, 3, and 5 LPD increments applied immediately at high gate. Four runs with -4% were made with automatic redesignations "long" of 0, 5, 10, and 15 LPD increments, applied at a rate of approximately two increments per second. The assumption is that a pilot procedure could be established so that the pilot would know the number of increments to be applied as a function of the velocity error at high gate.

Piloted Studies

A series of piloted runs were made to examine techniques for compensating the high gate conditions for the -4% thrust case. The simulation was flown by a pilot who monitored the simulated lunar surface (flat plane) through the virtual image window display using the landing point designator (LPD) mounted on the LM window. The pilot controlled the vehicle in the automatic mode by monitoring the LPD angle on the DSKY and commanding LPD increments to the guidance computer through the attitude hand controller. The simulation was initialized at high gate with the conditions previously obtained for a -4% thrust uncertainty using the range-fixed guidance.

Assumptions - Two assumptions were made: (1) the pilot knew that high gate had been reached (possibly from monitoring T_{go} as high gate was approached) and (2) the pilot knew that the forward velocity was about 400 ft/sec high and that at least 15 LPD increments would be required to provide visibility.

Test Runs - Four runs were made by the pilot. The objectives were: (1) provide visibility as soon as possible or (2) control the LM attitude with LPD increments to maintain a high pitchback attitude until after a lower altitude and velocity are achieved and then apply additional increments so that vehicle pitches forward for visibility.

DISCUSSION OF RESULTS

From the test runs made, a plot was constructed of the parameters of interest versus the percentage throttle uncertainty. The data presented in Table I were obtained from these plots for the $\pm 4\%$ range of thrust. The ΔV to hover for range-free guidance with a 0% thrust (nominal) uncertainty is used as a zero base for the ΔV comparison for the various cases examined.

Range-Free Guidance

For range-free guidance, all of the high gate conditions (except for range) can be met with no throttling time prior to high gate. This assures the nominal visibility time of 130 seconds after high gate for the trajectory studied. The range dispersion for $\pm 4\%$ thrust uncertainty is over 100,000 feet, but the ΔV is practically independent of the throttle uncertainty, as is shown in Table I.

Range-Fixed Guidance

For range-fixed guidance, the first throttling problem occurs for a -2.4% thrust profile. At -2.39%, the engine command throttles at 10 seconds prior to high gate and therefore the high gate conditions are achieved successfully. At -2.4%, no throttling occurs which results in a high gate forward velocity that is 80 ft/sec low. In this case, the visibility following high gate is 5 seconds longer than nominal, but the characteristic velocity expended is 70 ft/sec greater than for the -2.39% thrust profile (Table I). Using the LPD to redesignate short reduces the penalty to almost zero at a modest reduction in visibility time. The forward velocity for the -4% thrust profile was 410 ft/sec high at high gate with essentially zero descent rate. Because of the low descent rate at high gate, the guidance was required to increase the descent rate to 250 ft/sec at an altitude of 5,000 feet in an attempt to regain the altitude profile which resulted in an early contact with the surface (crash). The crash can be avoided by redesignating long. Table I shows that 5 LPD increments applied at high gate salvaged the trajectory and gave a visibility time of 32 seconds. Incrementing 15 LPD inputs gives a range extension of the order of 30,000 feet and 60 seconds of visibility time. However, the landing site in the 15 LPD input case did not become visible until 100 seconds after the inputs were made. This condition would not be satisfactory, but note that the ΔV penalty compared to the baseline case was only 20 ft/sec. Thus, if the guidance had been targeted for a nominal 70 seconds throttling time to go, and if the ΔV budget contains 125 ft/sec to accommodate the +4% thrust profile, then an additional number of LPD increments would provide more visibility time.

Piloted Trajectory Adjustments

The last line of Table I is shown again on Table II. The additional four lines on Table 2 are the results of the piloted study.

At high gate the LM normally pitches up from 70° to 40°, but for the high velocity case (-4% engine profile), the LM actually pitches back further at high gate. For some of the runs, the pilot immediately applied LPD increments to force the vehicle to pitch up for visibility. For the other runs, the pilot put in just enough LPD increments to prevent pitchback attitudes greater than 90°. This high pitchback attitude was held until predetermined velocity conditions were reached at which time the trajectory was adjusted for visibility.

<u>Immediate LPD Inputs</u> - For line 2 of Table II, the pilot rapidly applied LPD increments until the landing site became visible. The 26 inputs were more than necessary and resulted in a ΔV penalty of 177 ft/sec compared to the range-free 0% thrust base line. However, the pilot achieved 200 seconds of visibility only 12 seconds after high gate. The range extension was approximately 70,000 feet. The technique was changed slightly by having the pilot input 15 increments at high gate and then gradually apply four more until the target was visible (line 3). The ΔV penalty for this technique was 124 ft/sec for 190 seconds of visibility starting 15 seconds after high gate. The range extension for this case was 55,000 feet. The resulting h, $\dot{h}$ trajectory profile and visibility were satisfactory for both cases.

<u>LPD Inputs to Correct Velocity</u> - For line 4 of Table II, the LM pitch attitude was maintained at 90° by applying LPD increments until h = 10,000 feet, $\dot{h}$ = -95 ft/sec, and $\dot{X}$ = 700 ft/sec. Further inputs were then made to achieve landing site visibility.

The total number of inputs made was 19; 11 to maintain the pitch attitude and 8 to acquire the landing site. The high gate conditions were attained 35 seconds after the normal high gate time, the visibility time was 145 seconds and the ΔV penalty 99 ft/sec. The range extension was approximately 40,000 feet. For line 5, the pitch attitude was held until h = 7,000 feet, $\dot{h}$ = -130 ft/sec, and $\dot{X}$ = 500 ft/sec. The twelve inputs provided 100 seconds of visibility 45 seconds later than nominal at a ΔV penalty of 32 ft/sec, and the range extension was 14,200 feet. Again, all trajectory characteristics following the LPD inputs were satisfactory.

<u>Summary</u> - The best case for the procedures investigated appears to be that of line 4 of Table II. The desired high gate conditions were achieved 35 seconds after nominal, but the trajectory from then on is almost the reference. The ΔV penalty is of the order of 100 ft/sec, which is of the same order of magnitude as the ΔV penalty associated with targeting for a +4% engine thrust profile. The line 3 case might be acceptable but uses a little more ΔV and range extension. Line 5 provides less visibility time than the nominal 130 seconds.

CONCLUDING REMARKS

The analysis of the range-free guidance technique presented herein indicates that the ΔV performance is essentially independent of descent engine thrust uncertainties as large as ±4%. However, while the range-free guidance technique has no ΔV or visibility penalties associated with it, the range uncertainties are of the order of 100,000 feet.

The studies also show that if the range-fixed guidance is designed for a nominal throttling time of 70 seconds prior to high gate, then it appears that pilot procedures can be developed for trajectory correction in the event of excessive velocities at high gate caused by a -4% descent engine thrust profile. These procedures, however, require that a ΔV of the order of 125 ft/sec be included in the descent fuel budget to accommodate descent engine thrust dispersions. Range uncertainties are of the order of 55,000 feet.

RECOMMENDATION

Because of the ΔV penalties for range-fixed guidance with the large descent engine thrust uncertainties that presently exist and the additional pilot workload if low thrust profiles are encountered, it is recommended that a range-free option be included in the LGC. At mission time, an evaluation of the current thrust uncertainty, ΔV budget, and landing areas available can dictate whether the option should be used.

REFERENCE

MSC Internal Note No. 66-EG-36, "Feasibility of Range-Free Guidance During LM Powered Descent," August 11, 1966

Guidance	Thrust Profile	Tgo to High Gate for Throttle	Approximate High Gate State			ΔV Comparison at Hover	Visibility Time After High Gate	Automatic Range Change	
			h	$\dot{h}$	$\dot{x}$				
	%	sec	ft	ft/sec	ft/sec	ft/sec	sec	ft	
Range Free	4	0	9800	-151	705	-4	130	-70,000	
	2	0	9800	-151	705	-2	130	-44,000	
	0	0	9800	-151	705	0	130	-17,000	
	-2	0	9800	-151	705	+2	130	+8,000	
	-4	0	9800	-151	705	+4	130	+34,000	
								Automatic Target Redesignation After High Gate	
								No. of LPD Increments	Range Extension
Range Fixed	4	145	9800	-151	705	125	130	0	0
	2	110	9800	-151	705	85	130	0	0
	0	70	9800	-151	705	65	130	0	0
	-2	23	9800	-151	705	25	130	0	0
	-2.39	10	9800	-151	705	20	130	0	0
	-2.4	0	9800	-130	625	90	135	0	0
	-2.4	0	9800	-130	625	25	125	3	-6750
	-2.4	0	9800	-130	625	10	120	5	-8135
	-4	0	11,000	-2	1115	"crash"	0	0	0
	-4	0	11,000	-2	1115	-5	32	5	9186
	-4	0	11,000	-2	1115	+10	37	10	13,900
	-4	0	11,000	-2	1115	+20	60	15	29,400

Table I - Descent Guidance Performance in the Presence of Large Engine Thrust Uncertainties

	Approximate High Gate State			After High Gate				
	h	$\dot{h}$	$\dot{x}$	Number of LPD Increments	Range Extension	Time Elapsed for Start of Visibility	Visibility Time	ΔV Comparison at Hover
	ft	ft/sec	ft/sec		ft	sec	sec	sec
Line 1	11,000	-2	1115	15	29,000	100	60	20
Line 2	11,000	-2	1115	26	70,000 (Approx.)	12	200	177
Line 3	11,000	-2	1115	19(15+4)	55,000	15	190	124
Line 4	11,000	-2	1115	19(11+8)	40,000 (Approx.)	35	145	99
Line 5	11,000	-2	1115	12	14,200	45	100	39

Table II - Range-fixed Guidance Performance with Pilot LPD Increments After High-gate (-4% Thrust Profile)

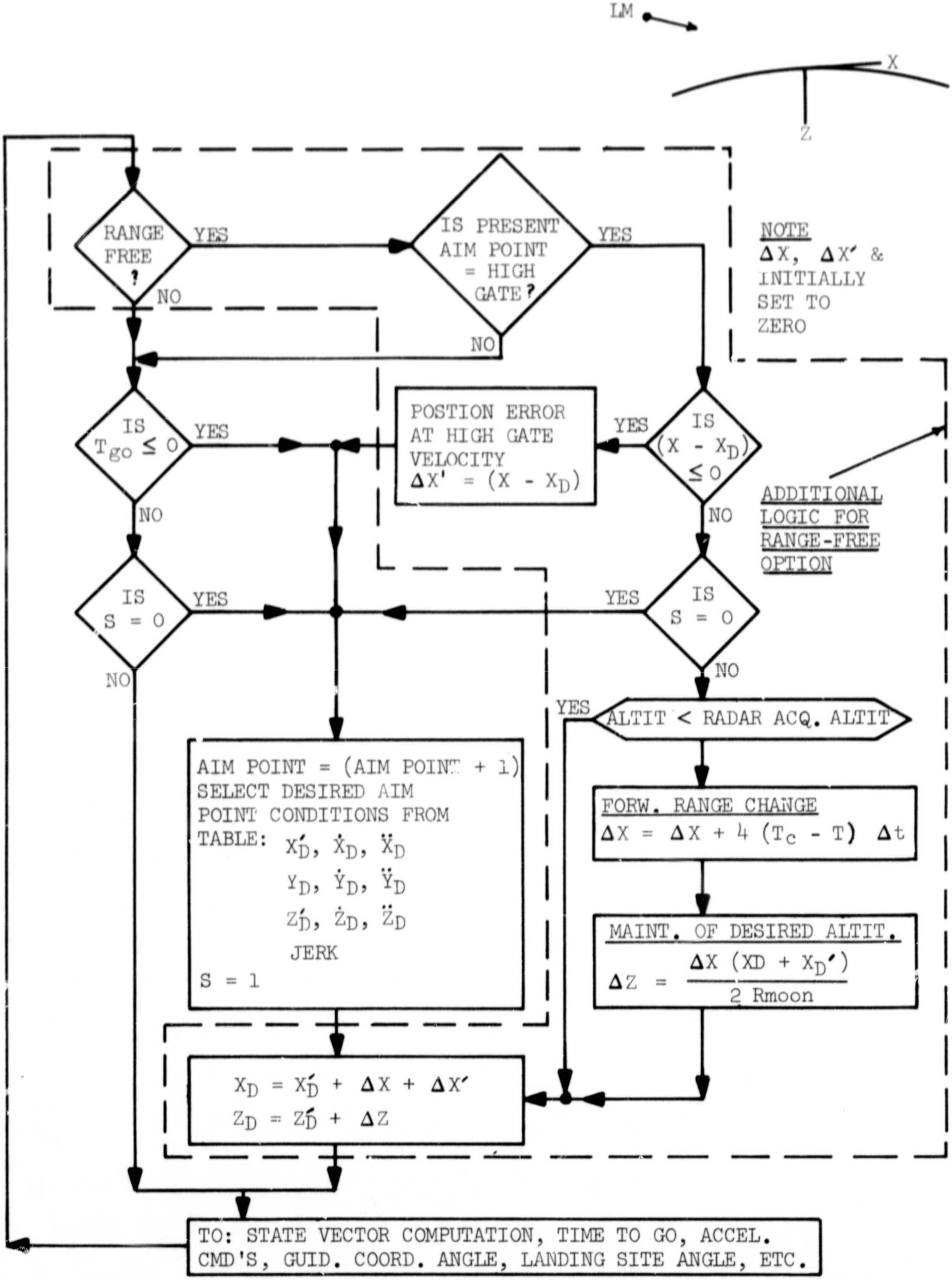

FIGURE 1. - POSSILLE LGC GUIDANCE LOGIC WITH RANGE-FREE OPTION