TM-70-2014-6

TECHNICAL MEMORANDUM

THE USE OF DELTA GUIDANCE FOR IMPROVED TRAJECTORY CONTROL AND FUEL COST DURING LM DESCENT

Bellcomm

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TITLE- The Use of Delta Guidance for Improved Trajectory Control and Fuel Cost During LM Descent

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AUTHOR(S)- J. A. Sorensen

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ABSTRACT

"Delta guidance" consists of a group of changes suggested for incorporation into the existing LM descent guidance equations. The objectives of these changes are to produce a trajectory which costs less in terms of propellant to land the LM, and to provide a means of steering the vehicle back to a nominal landing approach from a perturbed state.

Delta guidance produces three major changes to the existing equations. These are a) a new time-to-go algorithm, b) added logic which produces a modulated thrust profile during the braking phase, and c) a new acceleration command equation. These changes are analytically evaluated in this memorandum. Then, a comparison is made between delta guidance and the existing equations (explicit quadratic guidance) for nominal and perturbed trajectories. Effects of variations of the maximum thrust levels, high and low initial altitudes, lunar surface features, and landing site redesignations are investigated. Effects of modifying the modulated thrust profile are also examined. The advantages and disadvantages of delta guidance from a trajectory improvement standpoint are listed in the summary of this study.

It is concluded that delta guidance offers a definite means of increasing the LM payload and steering a perturbed descent trajectory back to a nominal approach. Delta guidance should be considered if a future need for these improvements can be foreseen.

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DATE: June 11, 1970

FROM: J. A. Sorensen

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TECHNICAL MEMORANDUM

1.0 OBJECTIVES

This memo studies the effects of several suggested changes to the LM guidance equations. The changes have two objectives, which are:

1. To drive a perturbed LM descent trajectory closer to the nominal approach trajectory than is done by the present explicit (quadratic) guidance; and

2. To lower the amount of propellant required to reach the landing site - both for nominal and perturbed trajectories.

The changes, first suggested by Moore, et al,[1] about a year ago and later modified,[2] are generally known as "delta guidance".

Delta (Δ) guidance really represents two new techniques and their associated guidance equation changes. The first set of changes involves implementing a new steering concept which has primary effect during the visibility (approach) phase of the trajectory. This steering law drives a perturbed trajectory (such as caused by redesignating the landing site) back to the nominal flight path.

The other technique affects the thrust profile during the braking phase. Currently, for a nominal thrust engine, the target constants are selected so that the engine operates at the fixed-throttle position (FTP - with thrust about 94% of maximum) for most of the phase. This period is followed by one (called the throttle margin) in which engine thrust is in the throttlable region. Throttling down to the throttlable region from FTP occurs whenever the commanded thrust falls below a certain value FLO (about 60% of maximum thrust). The nominal throttle margin is selected so that the thrust for a 3σ low-thrust engine coupled with an engine ball-valve failure still causes throttle-down to occur soon enough to allow constraints of the visibility phase to be met.

The required presence of a throttle margin adds propellant cost to LM descent. Simulations have shown that an engine with low thrust during the FTP portion of flight has a lower characteristic velocity (ΔV cost) to land than one with nominal thrust. Delayed throttle recovery causes decreased braking phase flight time and greater effective engine Isp from operating at FTP longer. Thus, the new concept is to cause all engines to perform like an engine with the lowest possible FTP thrust during the braking phase in order to pick up the ΔV savings. This is accomplished by throttling down a number of times to a level which is about 60% of the FTP value to obtain an average thrust equal to that of the low thrust engine. A 3σ low thrust engine with a ball valve malfunction would have no throttle pulses.

There are other ways in which the ΔV savings obtained by implementing a modulated braking phase thrust can be gained. A small throttlable region around FTP would, in principle, produce the same effect as the modulated thrust profile. This idea has been discarded in the past because of the poor performance characteristics of the engine for throttling in the high thrust region.

Another way of lowering the ΔV is to assume that 3σ low thrust and a ball-valve failure will not occur together for the same engine. This essentially allows cutting the throttle margin and its cost (about 100 ft/sec ΔV) in half. There is some risk in this assumption, because if both 3σ low thrust and the ball-valve failure do simultaneously occur, the resulting dispersions at high gate will prevent the trajectory from satisfying approach phase constraints.

A third way of lowering the ΔV cost is to provide a single throttle-down pulse, either manually or automatically, in the middle of the braking phase in place of several pulses of short duration throughout the phase. The potential ΔV saving associated with this method is also examined in the memorandum.

2.0 THEORY OF DELTA GUIDANCE

In this section, the pertinent guidance equations used by the current explicit steering as well as those equations suggested for delta guidance are presented. The trajectories resulting from each concept are compared.

2.1 Visibility Phase Guidance

The explicit steering concept presently used for LM descent assumes that the desired acceleration command $\vec{a}_c$ is a quadratic function of time t. This command can be expressed as a function of time-to-go (t_{go}) to an expected final time T_f, i.e., $t_{go} = T_f - t$. In terms of the required final values of position, velocity, acceleration, jerk, and snap (constant vectors $\vec{P}_T$, $\vec{V}_T$, $\vec{A}_T$, $\vec{J}_T$, and $\vec{S}_T$), the assumed nominal values of position, velocity, and acceleration at t_{go} not equal to zero are

$$\begin{bmatrix} \vec{a}_c \\ \vec{v}_c \\ \vec{p}_c \end{bmatrix} = \begin{bmatrix} t_{go}^2/2 & -t_{go} & 1 & 0 & 0 \\ -t_{go}^3/6 & t_{go}^2/2 & -t_{go} & 1 & 0 \\ t_{go}^4/24 & -t_{go}^3/6 & t_{go}^2/2 & -t_{go} & 1 \end{bmatrix} \begin{bmatrix} \vec{S}_T \\ \vec{J}_T \\ \vec{A}_T \\ \vec{V}_T \\ \vec{P}_T \end{bmatrix} \quad (1)$$

This assumes that the nominal position is a fourth order polynomial function of t_{go}. If these equations are reformulated so that the commanded acceleration and the necessary values of jerk and snap are the unknowns, one gets

$$\begin{bmatrix} \vec{a}_c \\ \vec{J}_T \\ \vec{S}_T \end{bmatrix} = \begin{bmatrix} 1 & -6/t_{go} & 12/t_{go}^2 & -6/t_{go} & -12/t_{go}^2 \\ 6/t_{go} & -18/t_{go}^2 & 24/t_{go}^3 & -6/t_{go}^2 & -24/t_{go}^3 \\ 12/t_{go}^2 & -48/t_{go}^3 & 72/t_{go}^4 & -24/t_{go}^3 & -72/t_{go}^4 \end{bmatrix} \begin{bmatrix} \vec{A}_T \\ \vec{V}_T \\ \vec{P}_T \\ \vec{v}_c \\ \vec{p}_c \end{bmatrix} \quad (2)$$

Now, if it is assumed that the actual position and velocity ($\vec{p}$ and $\dot{\vec{p}}$) are the nominal values, then $\vec{p}$ and $\dot{\vec{p}}$ can replace p_c and v_c.

The negative value of the computed gravity vector $\vec{g}_c$ is added to the modified acceleration command $\vec{a}_c$ to produce $\vec{a}$, the acceleration to be required of the engine:

$$\vec{a} = \vec{A}_T - \frac{6}{t_{go}} (\vec{V}_T + \dot{\vec{p}}) + \frac{12}{t_{go}^2} (\vec{P}_T - \vec{p}) - \vec{g}_c. \qquad (3)$$

If it is assumed that the system is continuous with actual acceleration $\ddot{\vec{p}} = \vec{a} + \vec{g}$, the ideal trajectory has the solution

$$\vec{p} = \vec{P}_T - \vec{V}_T t_{go} + \vec{A}_T \frac{t_{go}^2}{2} - \vec{C}_1 \frac{t_{go}^3}{6} + \vec{C}_2 \frac{t_{go}^4}{24}, \qquad (4)$$

where $\vec{C}_1$ and $\vec{C}_2$ satisfy the initial conditions. $\vec{C}_1$ and $\vec{C}_2$ also are the solutions for $\vec{J}_T$ and $\vec{S}_T$ which come from (2). As seen from (4), the resulting trajectory goes directly to the end conditions without achieving a predetermined nominal fourth order polynomial function of t_{go}. This is the primary characteristic of explicit guidance: it is called "adaptive" in that the trajectory "adapts" to disturbances rather than attempting to restore a predetermined nominal condition.

Time-to-go (t_{go}) is currently determined by adding one more constraint to the terminal conditions - that is, by specifying horizontal jerk J_{Tz}. Then from (2),

$$J_{Tz} - \left(\frac{6}{t_{go}} A_{Tz} - \frac{6}{t_{go}^2} (3V_{Tz} + \dot{z}) + \frac{24}{t_{go}^3} (P_{Tz} - z) \right) = 0, \qquad (5)$$

where $\dot{z}$ and z are the horizontal forward components of $\dot{\vec{p}}$ and $\vec{p}$. The Newton-Raphson method is applied to find the root of this equation which is the new value of t_{go}. First, t_{go} is updated by -2 seconds (the computation cycle period), and then the solution is iteratively found as $t_{go} = t_{go} + \Delta t$, where

$$\Delta t = \frac{J_{Tz}\, t_{go}^{3} - 6A_{Tz}\, t_{go}^{2} + (18V_{Tz} + 6\dot{z}) - 24(P_{Tz} - z)}{3J_{Tz}\, t_{go}^{2} - 12A_{Tz}\, t_{go} + 18V_{Tz} + 6\dot{z}}, \quad (6)$$

which comes from (5).

For delta guidance, suppose it is required to fly from a perturbed state to a nominal trajectory $\vec{p}_c(t_{go})$ before t_{go} reaches zero. Then a reasonable choice for the commanded acceleration might be

$$\vec{a} = \vec{a}_c + K_1(\vec{v}_c - \dot{\vec{p}}) + K_2(\vec{p}_c - \vec{p}) - \vec{g}_c, \quad (7)$$

where $\vec{a}_c$, $\vec{v}_c$, and $\vec{p}_c$ are defined in (1). For an ideal continuous system, Eq. (7) results in the trajectory

$$\vec{p} = \vec{P}_T - \vec{V}_T\, t_{go} + \vec{A}_T \frac{t_{go}^{2}}{2} - \vec{J}_T \frac{t_{go}^{3}}{6} + \vec{S}_T \frac{t_{go}^{4}}{24} + \vec{C}_1\, e^{-b_1 t}$$
$$+ \vec{C}_2\, e^{-b_2 t} \quad (8)$$
$$= \vec{p}_c + \vec{C}_1\, e^{-b_1 t} + \vec{C}_2\, e^{-b_2 t}$$

Here, $b_1, b_2 = \frac{-K_1}{2} \pm \sqrt{\left(\frac{K_1}{2}\right)^2 - K_2}$ and, again, $\vec{C}_1$ and $\vec{C}_2$ satisfy the initial conditions. Time t is initially zero. Equation (7) commands the acceleration required to fly along the desired nominal trajectory $\vec{p}_c$ plus two terms proportional to the differences between the desired and actual components of position and velocity - hence, "delta" guidance.

For a large initial t_{go}, the perturbed trajectory (8) tends to fly asymptotically to the nominal $\vec{p}_c$ if the gains in (7) have the constraints $K_1 > 0$ and $K_2 > 0$.

Equation (7) can be modified so that the nominal is also reached for small initial t_{go}. This is done by replacing constant gains K_1 and K_2 by time variable gains K_1/t_{go} and K_2/t_{go}^2. This also provides the option to revert back to explicit steering. The new commanded acceleration becomes

$$\vec{a} = \vec{a}_c + \frac{K_1}{t_{go}} (\vec{v}_c - \dot{\vec{p}}) + \frac{K_2}{t_{go}^2} (\vec{p}_c - \vec{p}) - \vec{g}_c. \qquad (9)$$

With $\ddot{\vec{p}} = \vec{a} + \vec{g}$, the most general resulting trajectory is

$$\vec{p} = \vec{p}_c(t_{go}) + \vec{C}_1\, t_{go}^{\,b_1} + \vec{C}_2\, t_{go}^{\,b_2}, \qquad (10a)$$

where $b_{1,2} = \dfrac{(K_1+1)}{2} \pm \sqrt{\left(\dfrac{K_1+1}{2}\right)^2 - K_2}$

if $\left(\dfrac{K_1+1}{2}\right)^2 > K_2$.

For $\left(\dfrac{K_1+1}{2}\right)^2 < K_2$, the solution is

$$\vec{p} = \vec{p}_c + t_{go}^{\,r_1} (\vec{C}_1 \cos(r_2 \ln t_{go}) + \vec{C}_2 \sin(r_2 \ln t_{go})) \qquad (10b)$$

where

$$r_1 = \frac{K_1+1}{2}$$

and

$$r_2 = \sqrt{K_2 - \left(\frac{K_1+1}{2}\right)^2} .$$

Again, $\vec{C}_1$ and $\vec{C}_2$ satisfy initial conditions. In both (10a) and (10b) the trajectory approaches the nominal as t_{go} becomes small for

$$K_1 > -1,$$

$$K_2 > 0.$$

The choice of gains $K_1 = 6$, $K_2 = 12$ is a special case because it causes the jerk and snap constants ($\vec{J}_T$ and $\vec{S}_T$) to drop out of (9). The resulting equation is equivalent to (3). In other words, explicit (E) guidance is a special case of delta (Δ) guidance.

The expressions (10a) and (10b) are continuous approximations to the trajectory followed in the plane containing the LM and landing site (x-z plane). The crossrange trajectory is different because the guidance reference frame is continuously being updated so that no crossrange position error y exists. Thus, Eq. (9) produces

$$\ddot{y} = -\frac{K_1}{t_{go}} \dot{y} \qquad (11)$$

for the lateral acceleration, and the lateral component of velocity is driven to zero more quickly as K_1 is increased.

2.2 Braking Phase Guidance

During the braking phase with the present guidance, the basic acceleration command equation is the same as that used during the visibility phase. However, the phase target constants are selected so that the desired acceleration early in the phase is greater than the maximum attainable vehicle acceleration. Therefore, full thrust is produced until the acceleration command magnitude falls below the value FLO, when the engine becomes throttlable.

The actual commanded acceleration is modified when at FTP so that the vertical component is achieved when the available acceleration is less than that commanded (vertical control). This is intended to keep state dispersions small at high gate.

As mentioned previously, target constants for the braking phase are picked so that throttle recovery is achieved 2 minutes before high gate for an engine with normal thrust characteristics. This 2 minute period is provided to insure that in the event of low thrust during the FTP plus a ball-valve failure in the fuel supply, the engine can still attain the throttlable condition soon enough after reaching high gate that approach phase constraints are not violated. A low thrust engine (which causes throttle recovery to occur later in the braking phase) has a lower ΔV cost to reach the target.

It is the intention of Δ guidance during the braking phase to pick up the ΔV savings associated with low thrust. This is achieved by assuming that "nominal" thrust is that of a low thrust engine, and that the throttle is at FTP throughout the phase. Target constants are selected so that throttle recovery does not occur until high gate is reached. To insure that the desired trajectory is followed, the thrust profile of a normal engine is modified occasionally from FTP. This is accomplished by monitoring the horizontal component of velocity $\dot{z}$ which indirectly indicates the thrust level of the engine. If $\dot{z}$ indicates that a higher thrust is occurring, the engine is throttled down to about 60% of full thrust until $\dot{z}$ returns to that value associated with the low thrust engine. Then, the throttle is returned to FTP.

More specifically, the velocity $\dot{z}$ is compared with the nominal value $v_z(t_{go})$. To provide v_z, the time-to-go equation is changed so that t_{go} is solved to match the current value of horizontal position z. That is, if nominal z is p_z, then t_{go} can be incremented iteratively as

$$\Delta t = \frac{p_z - z}{v_z} \tag{12}$$

Equation (12) replaces (6).

Then, with v_z available, the magnitude of the quantity $(v_z - \dot{z})$ determines if the thrust is greater than that of a low thrust engine. When $(v_z - \dot{z})$ drops below DNCRIT, the engine is throttled down to FCDOWN. The throttle remains at FCDOWN until $(v_z - \dot{z})$ becomes greater than UPCRIT, and then it is returned to FTP. This modulated thrust command can cause several pulses to the thrust profile during the braking phase. The pulse frequency is dependent upon the actual FTP thrust, and the values of DNCRIT, UPCRIT, and FCDOWN.

The Δ guidance acceleration command equations (like (7)) for the visibility phase are also used for the braking phase. The vertical control feature of E guidance does not need to be retained when the capability of steering back to the nominal trajectory is present.

2.3 Changes

The basic changes that Δ guidance produce on the LM guidance computer (LGC) equations are:

1. The acceleration command changes from (3) to (7).

2. The time-to-go update changes from (6) to (12).

3. Thrust modulation logic is added to the braking phase.

Other smaller changes suggested are:

1. The guidance frame orientation equations no longer depend on time-to-go. They are moved in front of the equations which compute the guidance coordinate components of $\vec{p}$ and $\dot{\vec{p}}$.

2. The vertical control equations of the braking phase are eliminated.

3. The lead time compensation is eliminated from the acceleration command equations. This lead time is currently used to prevent an LGC-digital autopilot (DAP)

closed loop instability from occurring when t_{go} reaches 18 seconds in the visibility phase. Its need is supposed to be eliminated by choosing gains which limit the natural frequency of the system and by choosing target constants so the end of the visibility phase (low gate) is reached as t_{go} crosses 20 seconds. This point is discussed in more detail later.

4. Braking phase target constants are chosen so that high gate is reached when t_{go} reaches 160 seconds rather than 60 seconds. This eliminates a constant to initialize t_{go} in the visiblity phase. Continually steering back to the nominal trajectory minimizes the resulting dispersions at high gate.

A comparison of the guidance equation arrangement in the LGC is shown in Fig. 1.

3.0 RESULTS OF COMPUTER SIMULATION STUDY OF DELTA GUIDANCE

The delta guidance equations were incorporated in the LM descent simulator program so that various comparisons could be made with the present explicit guidance performance. Guidance constants for the Apollo 12 trajectory[3] were used as the standard for comparison. The delta guidance constants were preliminary values received from MIT/CSDL.[4]

Comparisons between the two schemes are made in four areas:

1. The ΔV costs of unperturbed trajectories are compared. Results with high and low thrust engines are presented.

2. The effects of lurain features and trajectory perturbations other than LPD redesignations on the performance are compared. Trajectory perturbations include altitude variations at ignition (PDI) and landing site (ΔRLS) updates during the braking phase. Lurain features studied include the effects of cliffs and a model of the Copernicus landing site.

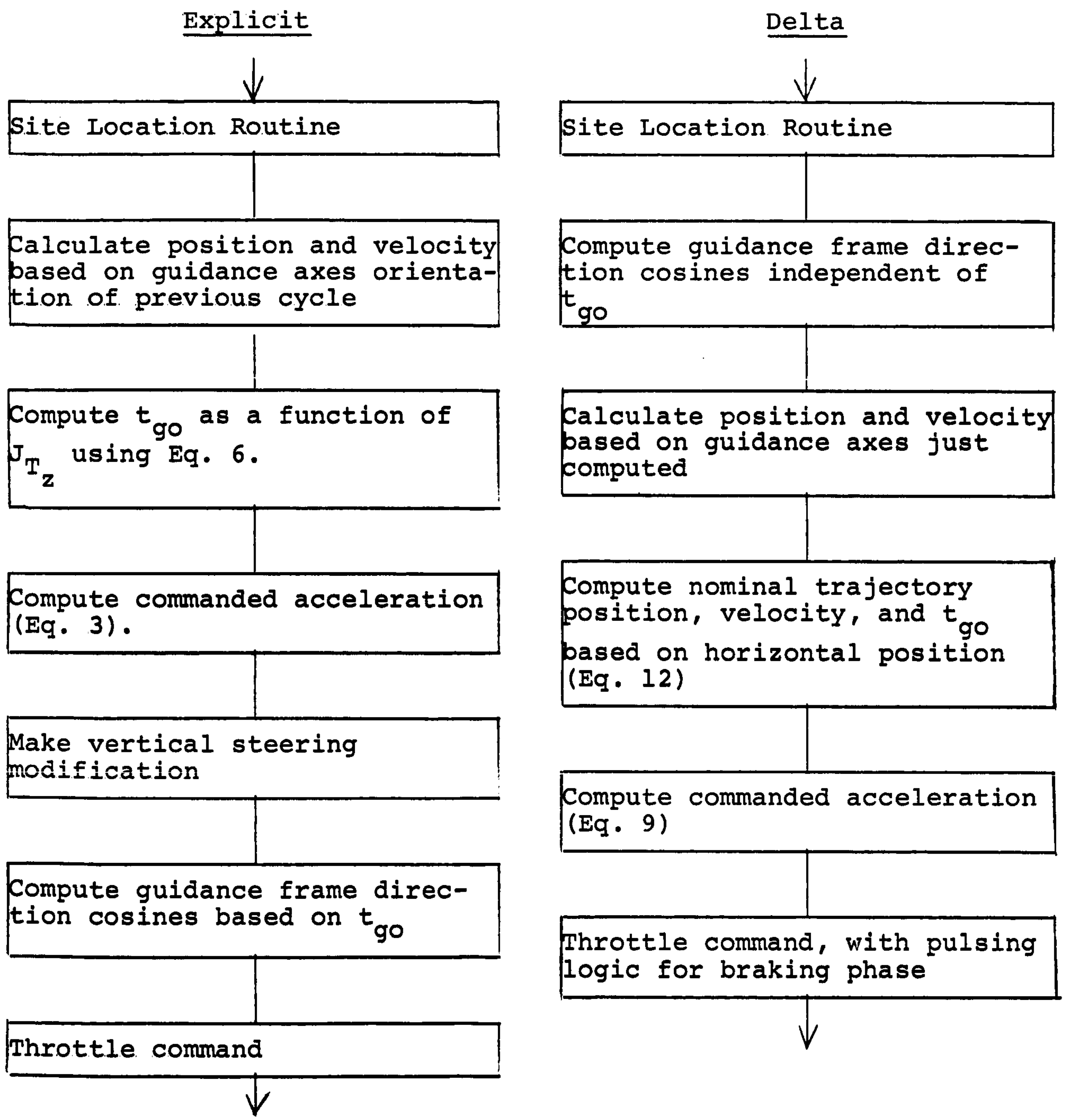

Figure 1. Comparison of guidance equation logic for explicit and delta guidance, as taken from Reference 2.

3. The effects of throttle modulation variations on the ΔV cost are presented. These variations are due to UPCRIT/DNCRIT changes and implementing a single pulse in the explicit equations.

4. The landing point designator (LPD) redesignation performances are compared. The effect of acceleration command gain changes is included.

3.1 Unperturbed Trajectory Comparisons

The first set of computer studies was made to determine the basic increase in vehicle performance obtained by using Δ guidance for unperturbed trajectories. "Unperturbed trajectories" are defined here to mean those with no perturbations to the nominal initial conditions, no RLS changes, and no LPD redesignations. The thrust T during the FTP period is modeled as linearly changing with time, i.e., $T=a(10500)+bt$ lb. The parameters a and b are varied for several of the runs. The nominal gains and target constants are shown in Fig. 2.

Computer run results of these "nominal" trajectories are presented in Fig. 3. The four sets of data represent comparisons of trajectories having the thrust model constants a and b which correspond to those of the nominal Apollo 12 engine and of the low, medium and high thrust engines as defined in Ref. 5. In Fig. 3, the thrust coefficients a and b, the ΔV cost of landing the LM, and the time (throttle margin in seconds) that throttle-down occurs before high gate are given.

Run 1a represents the current performance achieved with E guidance and the Apollo 12 trajectory. Run 1b represents Δ guidance results with target constants as given in Ref. 4. As can be seen, this trajectory results in a ΔV savings of 116 ft/sec. However, throttle-down does not occur until 2 seconds after switchover to the visibility phase. To cause throttle down to occur exactly at switchover, the steering constant S_{Tx} for the braking phase was raised 0.5×10^{-6} ft/sec^4. The resulting trajectory has a ΔV savings of 111 ft/sec. This value of S_{Tx} is used for the rest of the trajectories discussed in this section.

Figure 2. List of target constants used to compare explicit and delta guidance.

Braking Phase

Quantity	Explicit	Delta
P_{Tx}, ft	-3.56205E3	1.2459388E3
P_{Tz}, ft	-1.370571E4	-1.4831755E5
V_{Tx}, ft/sec	-1.8690305E2	1.7943748E2
V_{Tz}, ft/sec	-9.873819E1	-2.0588904E3
A_{Tx}, ft/sec^2	-4.502495E-1	3.7614615
A_{Tz}, ft/sec^2	-9.5150975	-1.6825803E1
J_{Tx}, ft/sec^3	-	2.0291657E-2
J_{Tz}, ft/sec^3	-1.47427E-2	-1.4297583E-2
S_{Tx}, ft/sec^4	-	6.2177952E-6
S_{Tz}, ft/sec^4	-	3.4012486E-6
T_{go}end, sec	60	160
DNCRIT, ft/sec	-	- 10
UPCRIT, ft/sec	-	0
FCDOWN, %	-	60%
FLO, %	57%	61%
FHI, %	65%	63%

Visibility Phase

	Explicit	Delta
P_{Tx}, ft	8.29275E1	9.61428815E1
P_{Tz}, ft	-2.01605E1	-3.0809768E1
V_{Tx}, ft/sec	-3.19E-1	3.1188582
V_{Tz}, ft/sec	3.1233E-1	-1.8084884
A_{Tx}, ft/sec^2	2.9982E-1	3.9388102E-1
A_{Tz}, ft/sec^2	-4.0165E-1	-2.1428741E-2
J_{Tx}, ft/sec^3	-	1.12443301E-2
J_{Tz}, ft/sec^3	3.76954E-2	3.8348318E-2
S_{Tx}, ft/sec^4	-	3.67577883E-4
S_{Tz}, ft/sec^4	-	6.5290219E-5
T_{go}end, sec	10	20

Figure 3. ΔV cost comparison of nominal trajectories using explicit and delta guidance. Thrust is modeled as T = 10,500 a+bt lb. Values of a and b are for the Apollo 12 engine and low, medium, and high thrust engines.

Guidance and Run No.	Thrust constants a and b, - , lb/sec.	Throttle margin, sec	ΔV,* ft/sec	Comments
E, 1a	.9381, .3	114.	6611	Apollo 12 engine
Δ, 1b	"	-2.	6495	$S_{Tx}=6.2177952 \times 10^{-6}$
Δ, 1c	"	0	6500	$S_{Tx}=6.7177952 \times 10^{-6}$
Δ, 1d	"	120.	6602	"Simulated" E guid.
E, 2a	.899, .478	-28.	6376	low thrust
Δ, 2b	"	-8.	6478	"
E, 3a	.925, .554	92.	6600	medium thrust
Δ, 3b	"	0	6512	"
E, 4a	.934, .725	118.	6609	high thrust
Δ, 4b	"	0	6497	"

*Cost to automatic touchdown.

The Δ guidance equations have the property that by choosing steering constants correctly, the resulting trajectory matches that of E guidance. This was tested with the results presented in Run 1d. The steering constants $\vec{P}_T$, $\vec{V}_T$, and $\vec{A}_T$ were the same as those of Run 1a. The constants J_{Tz} and S_{Tz} were chosen so that the new time-to-go equation (11) would produce the same value of t_{go} as the currently used equation (6) at the initial and final points of both phases. The resulting values which were used are:

	Braking Phase	Visibility Phase
J_{Tz}(ft/sec^3)	$-.1413279 \times 10^{-1}$	$.3320087 \times 10^{-1}$
S_{Tz}(ft/sec^4)	$-.5662602 \times 10^{-4}$	$-.3207958 \times 10^{-3}$

There was close agreement between Runs 1a and 1d in throttle margin, ΔV cost, and the trajectory profile followed.

Runs 2a and 2b are results of trajectories using the Data Book low thrust engine. The Data Book thrust values represent dispersions to a class of engines, so it is recognized that this low thrust represents a severe example, i.e., one for which the trajectory is not targeted. However, the example points out that Δ guidance lowers the time past high gate where throttle-down occurs (from 28 sec to 8 sec for this example) for the severe low thrust situation.

Comparison of the medium and high thrust conditions in Runs 3 and 4 shows that Δ guidance saves 88 ft/sec and 112 ft/sec ΔV.

It is seen that Δ guidance can save 88 ft/sec or more ΔV depending upon the engine thrust. The rocket equation states that, $\Delta V = g_o Isp \ln (W_o/W_f)$, where Isp, W_o, and W_f are the effective specific impulse, initial weight, and landing weight respectively. For LM descent, this equation says that a 1 ft/sec ΔV saving corresponds to about 3.3 lb increased payload capability. Hence, Δ guidance provides the capability of adding 300 lb more payload for a nominal trajectory.

The nominal gains K_1 and K_2 used for the Δ guidance trajectories above are based on

$$K_2 = \omega_n^{\ 2} = (2\pi)^2,$$

and

$$K_1 = 2\zeta\omega_n = 2(.707)\ (2\pi).$$

Changing the damping coefficient ζ to 0.5 and 1.0 had negligible effects on the performance of the unperturbed trajectories.

Figure 4 compares the thrust profiles of Runs 3a and 3b. It can be seen that Δ guidance keeps the throttle at FTP about 70 sec longer than E guidance, but the total burn time is about 30 sec shorter.

Figure 5 compares the altitude profile as a function of time for the two guidance concepts. Note that E guidance has a different profile for each thrust condition. Also, the Δ guidance trajectory lingers longer at a higher altitude and then tends to follow the low thrust E guidance trajectory. This characteristic also appears in Fig. 6 which compares the altitude vs. range profiles of a medium thrust engine. The Δ guidance trajectory remains higher longer partially because of different target constants. This may have some effect on the difference in ΔV between the two schemes. Figures 7 and 8 compare the trajectories of Runs 3a and 3b, in pitch angle and vertical rate vs. time. The pitch angle rate of Δ guidance is smoother, and the vertical rate seems to progress in a more monotonic fashion to the minimum point. Both of these features probably aid in lowering ΔV of the Δ guidance trajectory.

3.2 Effect of Perturbations Other Than LPD Redesignations

This portion of the study considers the effect of lunar surface features (lurain), altitude perturbation of the initial conditions, and braking phase changes to the landing site vector stored in the LM guidance computer.

3.2.1 Lurain Features

The sensitivities of E and Δ guidance to lunar surface features were studied by simulating flight passing

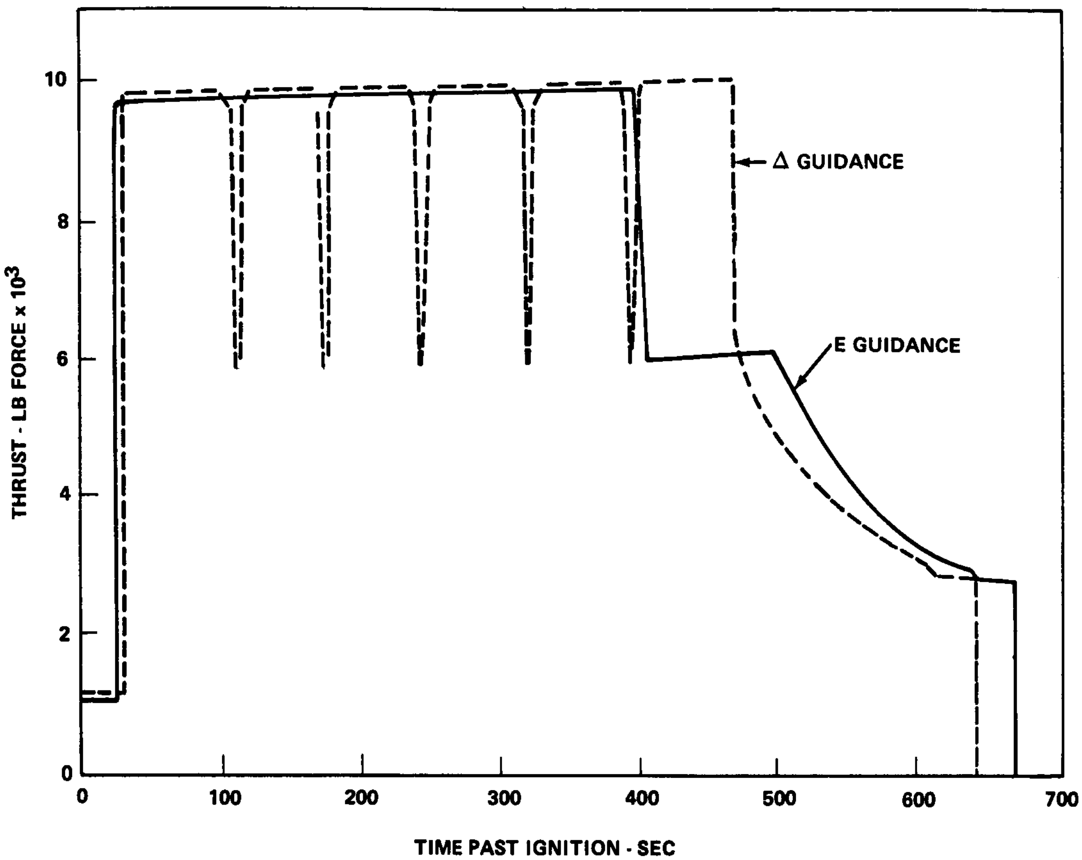

FIGURE 4 - COMPARISON OF THRUST PROFILES WITH E AND Δ GUIDANCE FOR A LM ENGINE WITH MEDIUM THRUST

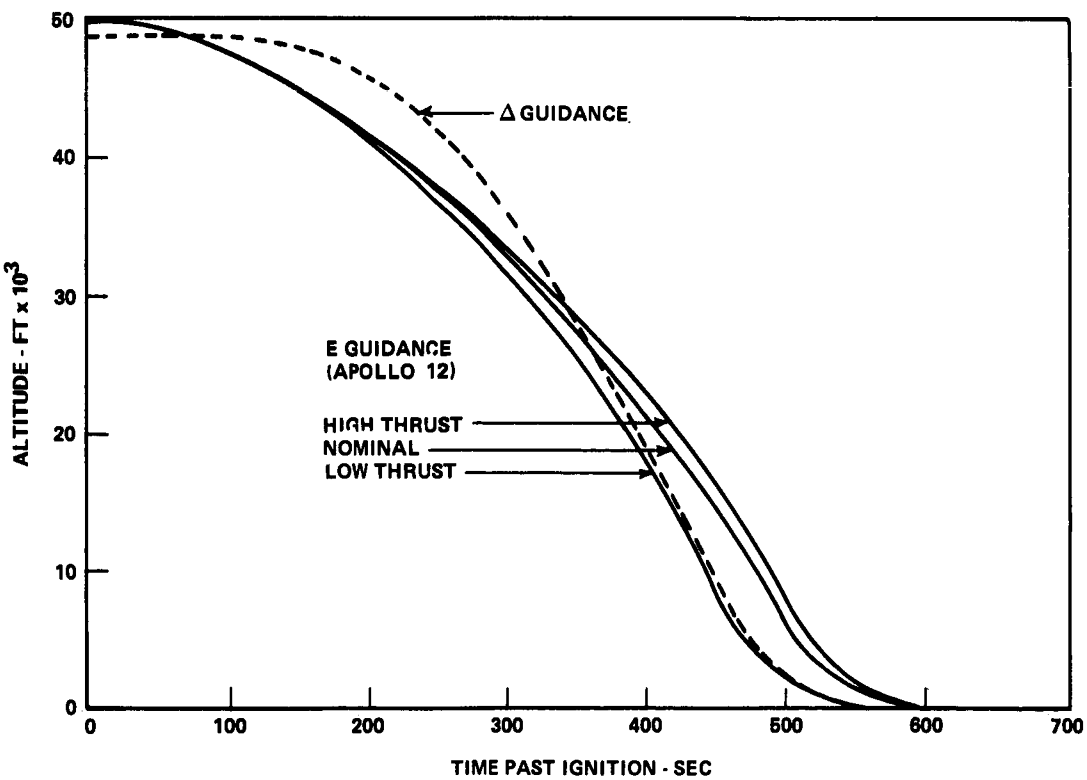

FIGURE 5 - ALTITUDE AS A FUNCTION OF TIME FOR E AND Δ GUIDANCE. THE ENGINE THRUST HAS NO EFFECT ON THE Δ GUIDANCE PROFILE

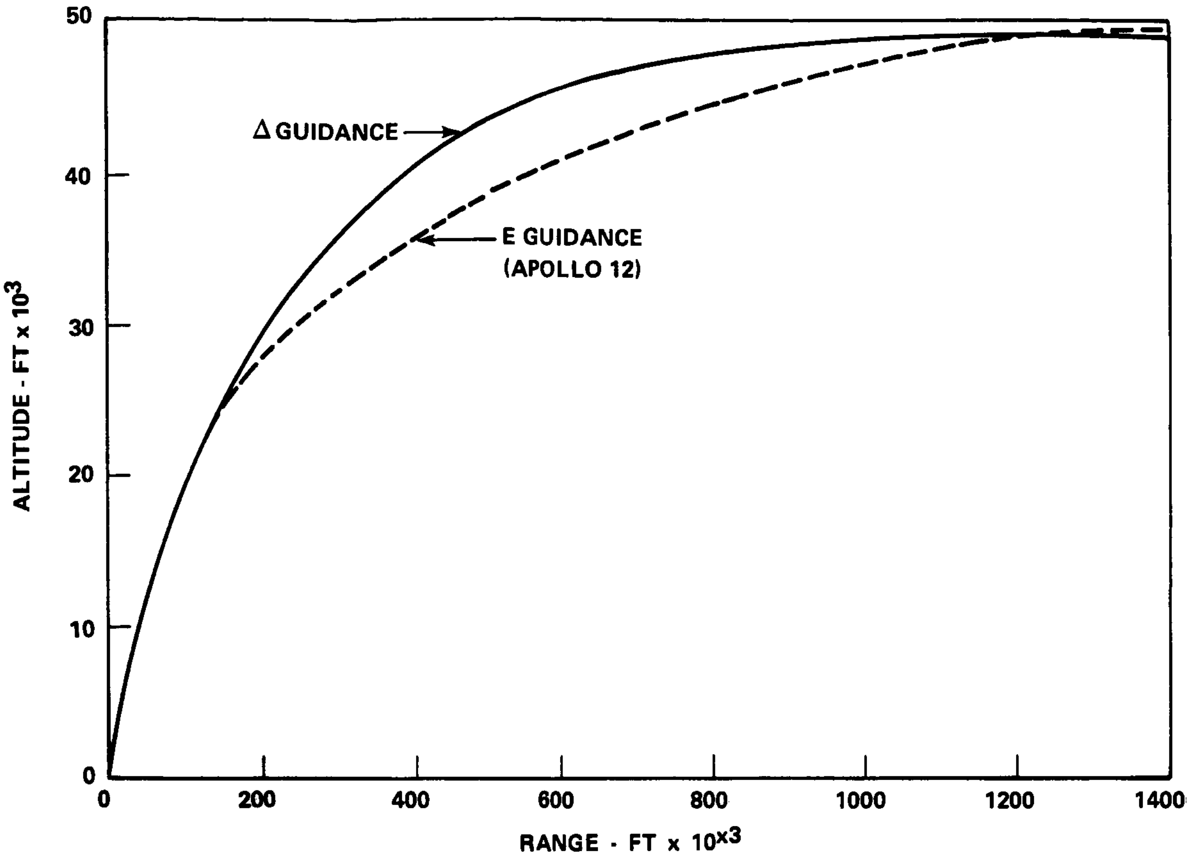

FIGURE 6 - ALTITUDE AS A FUNCTION OF RANGE FOR A MEDIUM THRUST ENGINE AND THE NOMINAL E AND Δ TARGET CONSTANTS

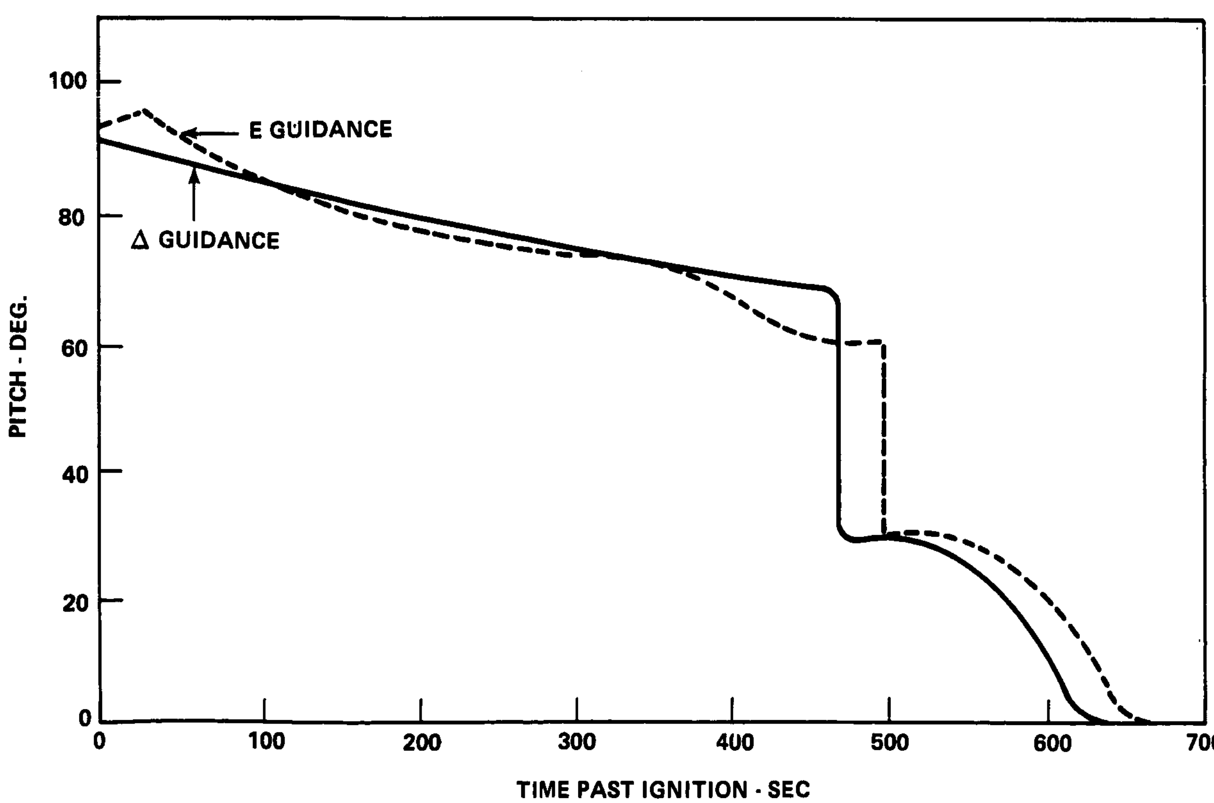

FIGURE 7 - COMPARISON OF THE TWO GUIDANCE METHOD'S PITCH ANGLES FOR A MEDIUM THRUST ENGINE

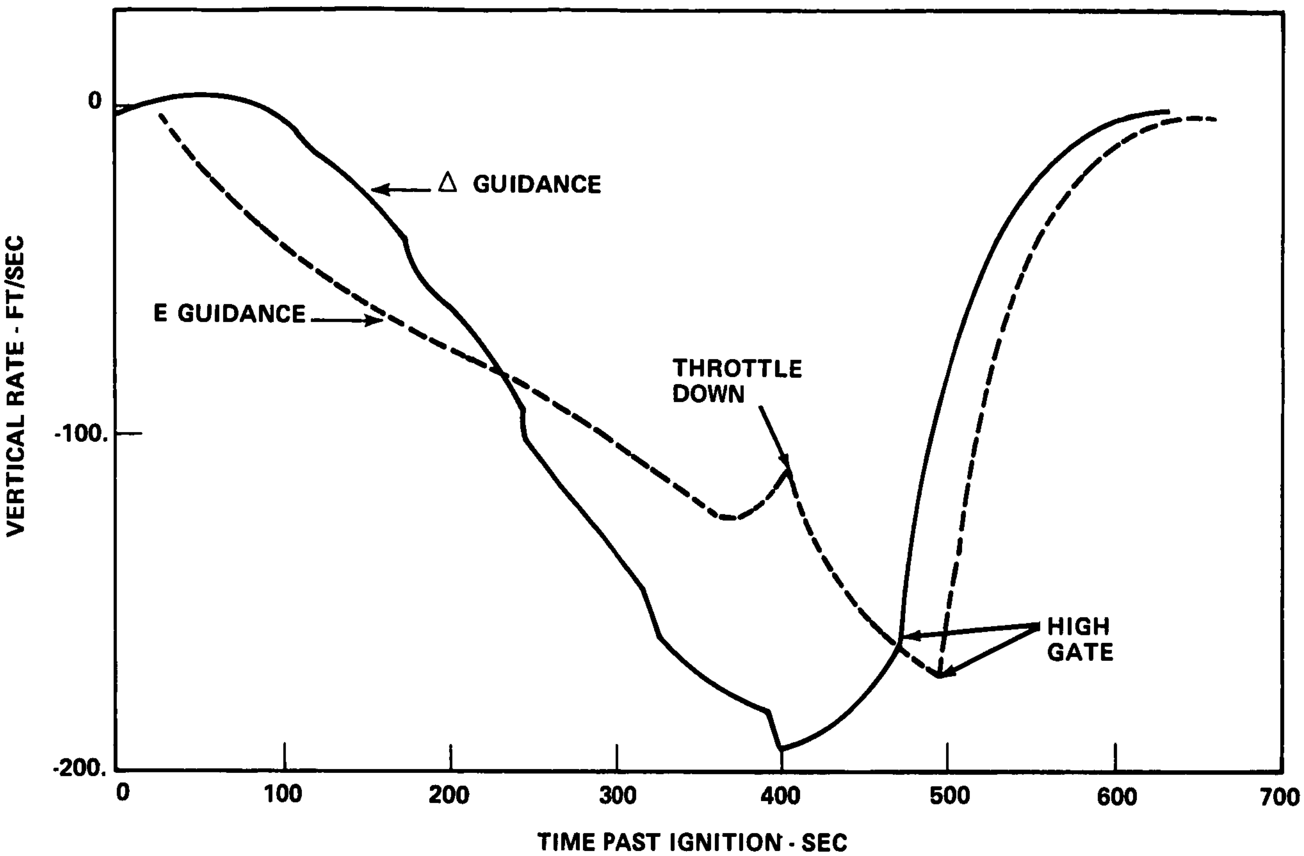

FIGURE 8 - COMPARISON OF THE VERTICAL RATE PRODUCED BY THE TWO GUIDANCE METHODS AS A FUNCTION OF TIME PAST IGNITION. THE BREAKS IN THE Δ GUIDANCE CURVE OCCUR AT POINTS OF ENGINE PULSING

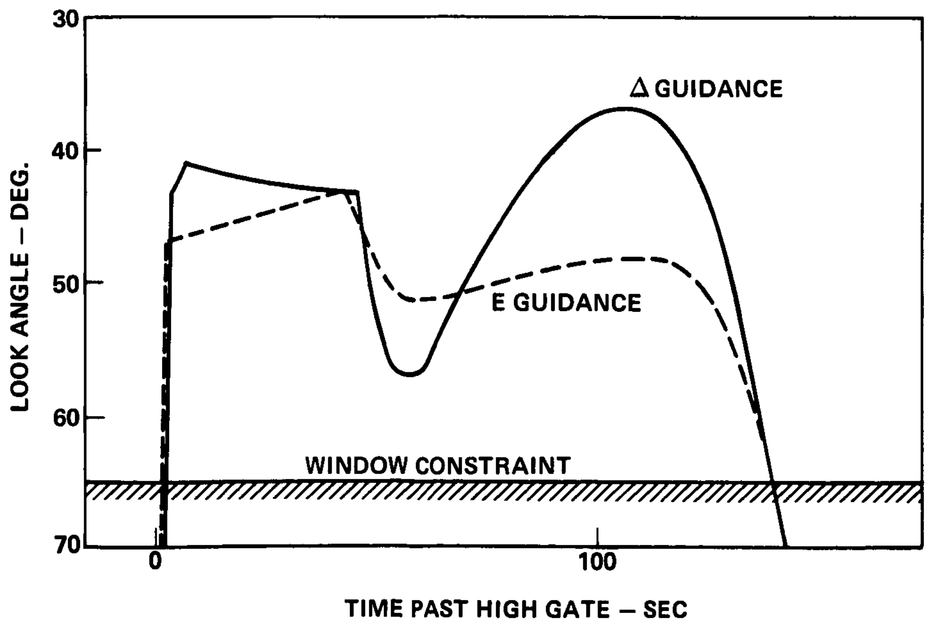

FIGURE 9 - LPD LOOK ANGLE FOR BOTH TYPES OF GUIDANCE WHEN THE LM PASSES OVER A 1000 FT CLIFF 10,000 FT FROM THE LANDING SITE

over a single cliff along the ground track. Cliffs of 1,000 ft and 2,000 ft height dropping downward toward the site were simulated at 5,000 to 200,000 ft from the site. The presence of the cliff caused the ΔV cost to change slightly for both types of guidance, with the Δ guidance cost increases being greater.

Figure 9 compares the landing point designator (LPD) look angles for both types of guidance when the vehicle crosses a 1,000 ft cliff, 10,000 ft from the landing site. It can be seen that using Δ guidance with the chosen nominal gains K_1 and K_2 causes a greater look angle transient, mainly as a result of the greater attitude transient associated with Δ guidance.

Figures 10a and 10b compare the LM vertical rates as a function of altitude for both types of guidance with 1,000 ft cliffs at distances of 5,000 ft to 25,000 ft from the landing site. Also shown is the boundary which allows an abort using the ascent engine (APS). It can be seen that Δ guidance delays the point where the boundary is crossed even when the cliff is only 5,000 ft from the site so that a safer trajectory is produced. Figures 9 and 10 point out part of the tradeoff which exists between the two methods of guidance in the visibility phase. This comparison is discussed in more detail later.

Trajectories were run using a model of the Copernicus landing site to get a typical measure of the effect of lurain on performance. The ΔV costs for trajectories over a smooth surface and Copernicus are as follows:

	Delta Guidance	Explicit Guidance	ΔV Savings
Smooth Surface	6495. fps	6611 fps	116 fps
Copernicus	6545. fps	6632 fps	87 fps
Change	+50. fps	+21 fps	

It can be seen that the tendency of Δ guidance to steer the trajectory to a given altitude above the lurain as a function of t_{go} decreases the gained performance over E guidance by 25%. This number is, of course, dependent upon the steering gains used and the specific lurain profile.

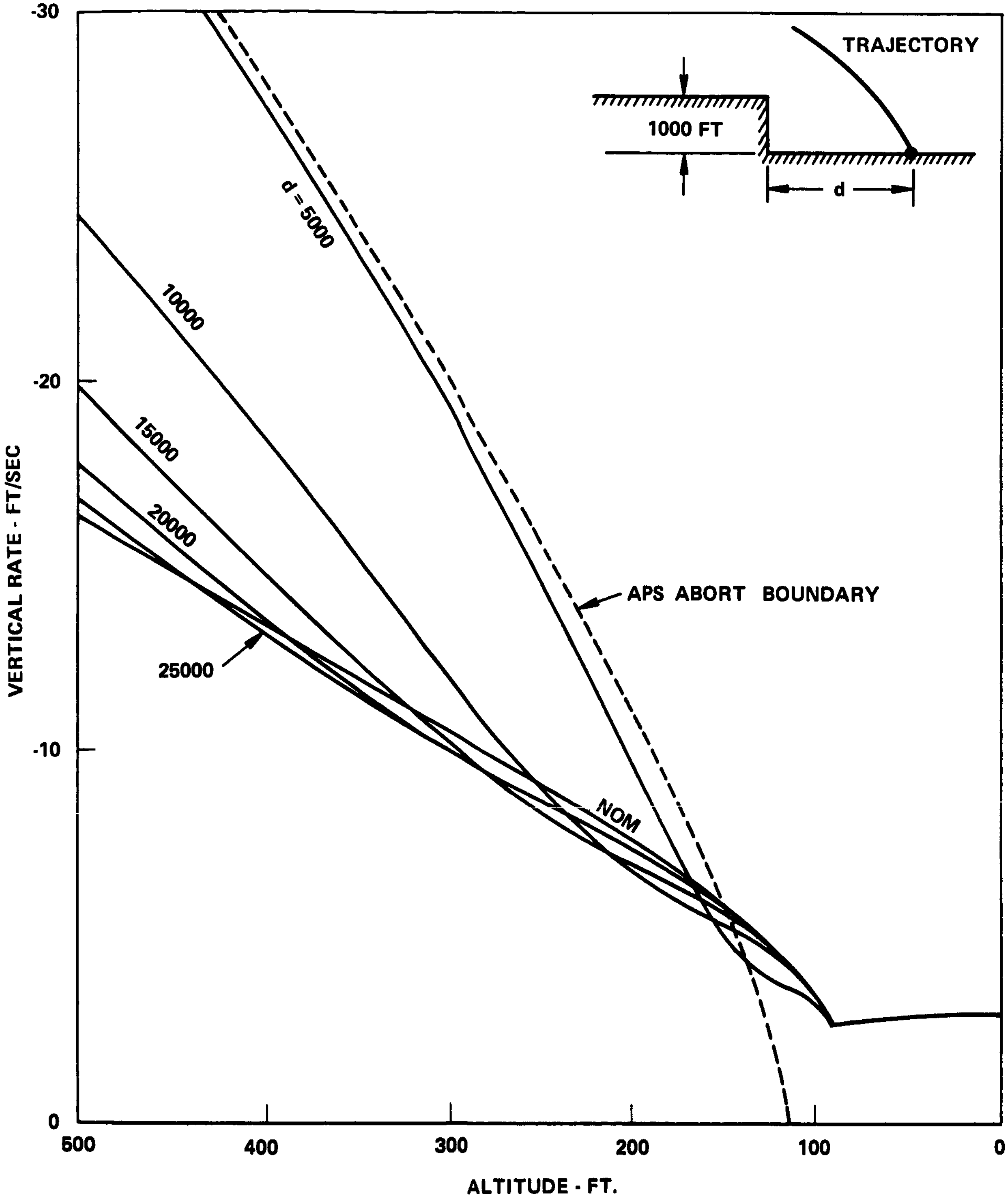

FIGURE 10a - DELTA GUIDANCE TRAJECTORY VERTICAL RATE AS A FUNCTION OF ALTITUDE FOR THE APPROACH PATH HAVING A CLIFF THE INDICATED DISTANCE FROM THE LANDING SITE

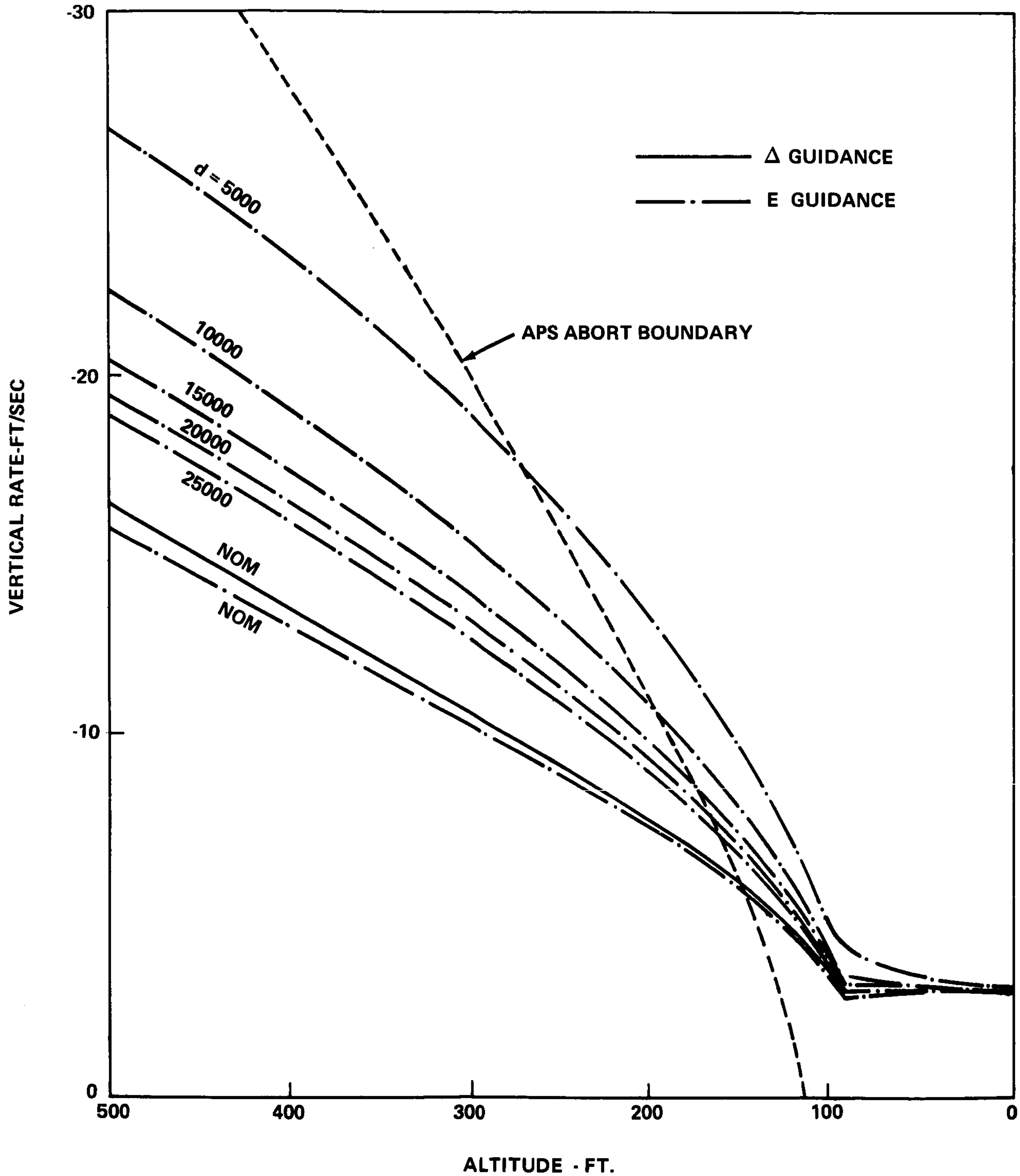

FIGURE 10b - EXPLICIT GUIDANCE TRAJECTORY VERTICAL RATE AS A FUNCTION OF ALTITUDE FOR THE APPROACH PATH HAVING THE SAME CLIFF SITUATION AS SHOWN IN FIGURE 10a

The flight profile of the LM trajectories with E and Δ guidance over Copernicus is shown in Fig. 11. Also shown is a nominal Δ guidance trajectory over a smooth lurain (or over Copernicus with a perfect IMU and radar off). The actual lurain has the effect of causing the Δ guidance trajectory to essentially follow the E guidance trajectory after passing over the Copernicus peak.*

3.2.2 Initial Altitude Perturbations

Lunar orbit insertion errors and navigational perturbations on the orbit can cause a perturbation to the LM altitude at the beginning of the descent burn. The guidance system must be able to steer the LM to the landing site for dispersions as large as ±20,000 ft in the initial altitude. Comparisons were made of trajectories having these initial perturbations with the assumption that total energy of the vehicle for each case was constant at ignition. Thus, the addition of 20,000 ft to the nominal initial altitude caused the speed to drop 14.4 ft/sec.

Results of simulations made using E and Δ guidance with initial high and low altitudes are presented in Fig. 12. The effects of thrust dispersions and gain variations were also simulated. The low thrust model (which is worse than what would actually be encountered) caused throttle-down to occur late for both the high and low altitude trajectories. Except for the low thrust, low altitude case (which is unrealistic), Δ guidance always saved substantial ΔV.

The Δ guidance gain K_1 was varied in value corresponding to the damping coefficient ζ having values of 0.5, 0.707, and 1.0. Also, gains K_1 and K_2 were set equal to 6.0 and 12.0 which caused the acceleration command equations to be equivalent to that of E guidance. Plots of trajectory altitudes as functions of range from the landing site for E guidance and Δ guidance with $\zeta = 0.707$ are presented in Fig. 13. Also depicted is the low altitude trajectory with gains K_1 and K_2 set to 6 and 12. It can be seen that Δ guidance causes low altitude trajectories to loft because the steering tends to drive these trajectories back to the nominal. The vertical control keeps the low altitude E guidance trajectory from rising, although lofting is somewhat a function of the target constants for high gate. The effect of the damping coefficient ζ on the perturbed initial altitude trajectories is illustrated in Fig. 14 where altitude is presented as a

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*With a lurain profile used in the LGC, this dispersion will be decreased.

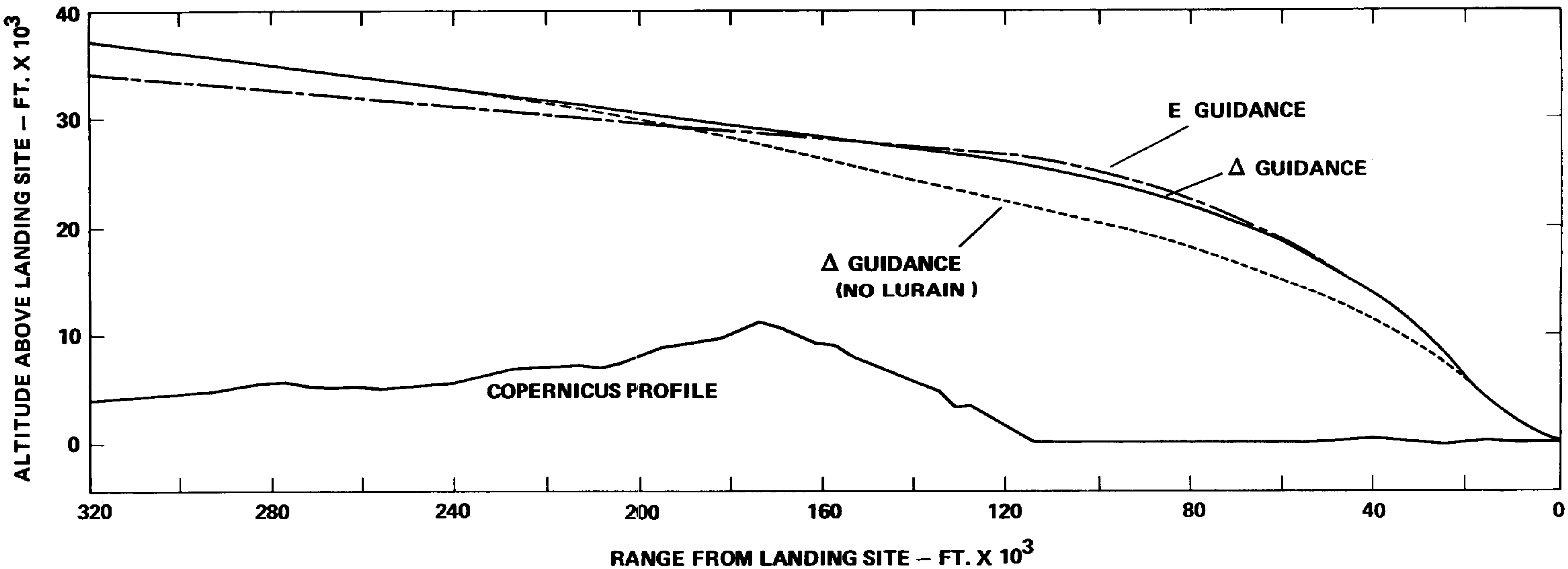

FIGURE 11 - A COMPARISON OF THE E AND Δ GUIDANCE TRAJECTORY PROFILES WHEN FLYING OVER COPERNICUS. ALSO SHOWN IS A NOMINAL Δ GUIDANCE TRAJECTORY WITH A SMOOTH LUNAR SURFACE

Figure 12. Comparison of ΔV costs of explicit and delta guidance with initial altitude perturbations. The thrust models studied were:

Low thrust, $T = 9437 + 0.473t$ lb
Medium, $T = 9705 + 0.554t$
High, $T = 9800 + 0.725t$.

Delta guidance gains were also varied.

Initial Altitude, ft	Thrust Level	Δ Guidance Gains, K_1	K_2	E Guid. ΔV, ft/sec	Δ Guid ΔV, ft/sec	$\Delta(\Delta V)$, ft/sec
29,100.	Low	8.88	39.48	6123[a]	6398[b]	+275
"	High	"	"	6582	6506	-76
"	Medium	"	"	6566	6521	-45
"	"	12.57	"	"	6508	-58
"	"	6.285	"	"	6521	-45
"	"	6.0	12.0	"	6510	-56
69,100	Low	8.88	39.48	6488[c]	6465[d]	-23
"	High	"	"	6654	6540	-114
"	Medium	"	"	6630	6555	=75
"	"	12.57	"	"	6553	-77
"	"	6.285	"	"	6564	-66
"	"	6.0	12.0	"	6536	-94

a. Throttle down 58 sec after high gate

b. " " 24 " " " "

c. " " 14 " " " "

d. " " 18 " " " "

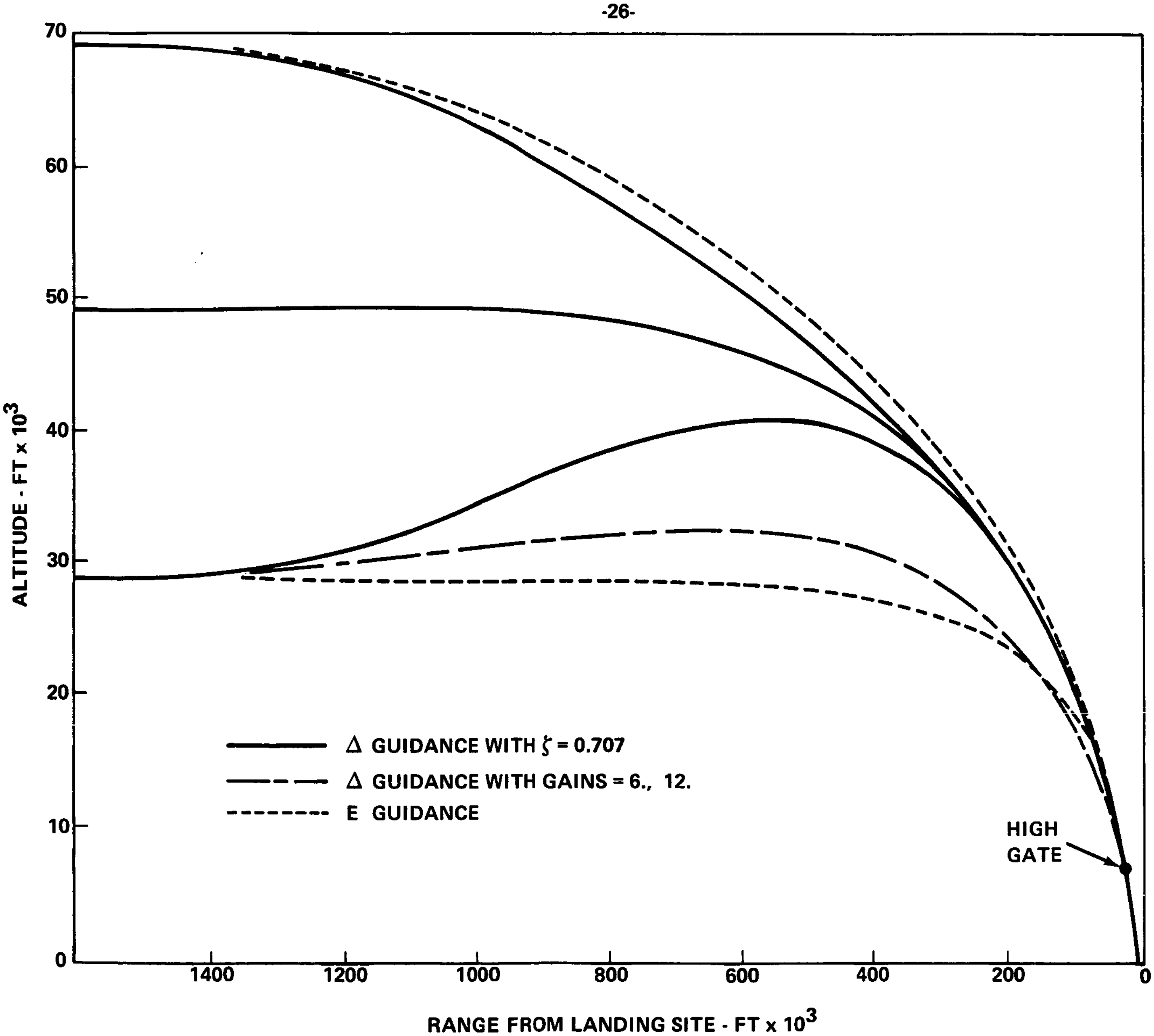

FIGURE 13 - INITIAL ALTITUDE PERTURBATION EFFECT ON TRAJECTORY PROFILES WITH E AND Δ GUIDANCE

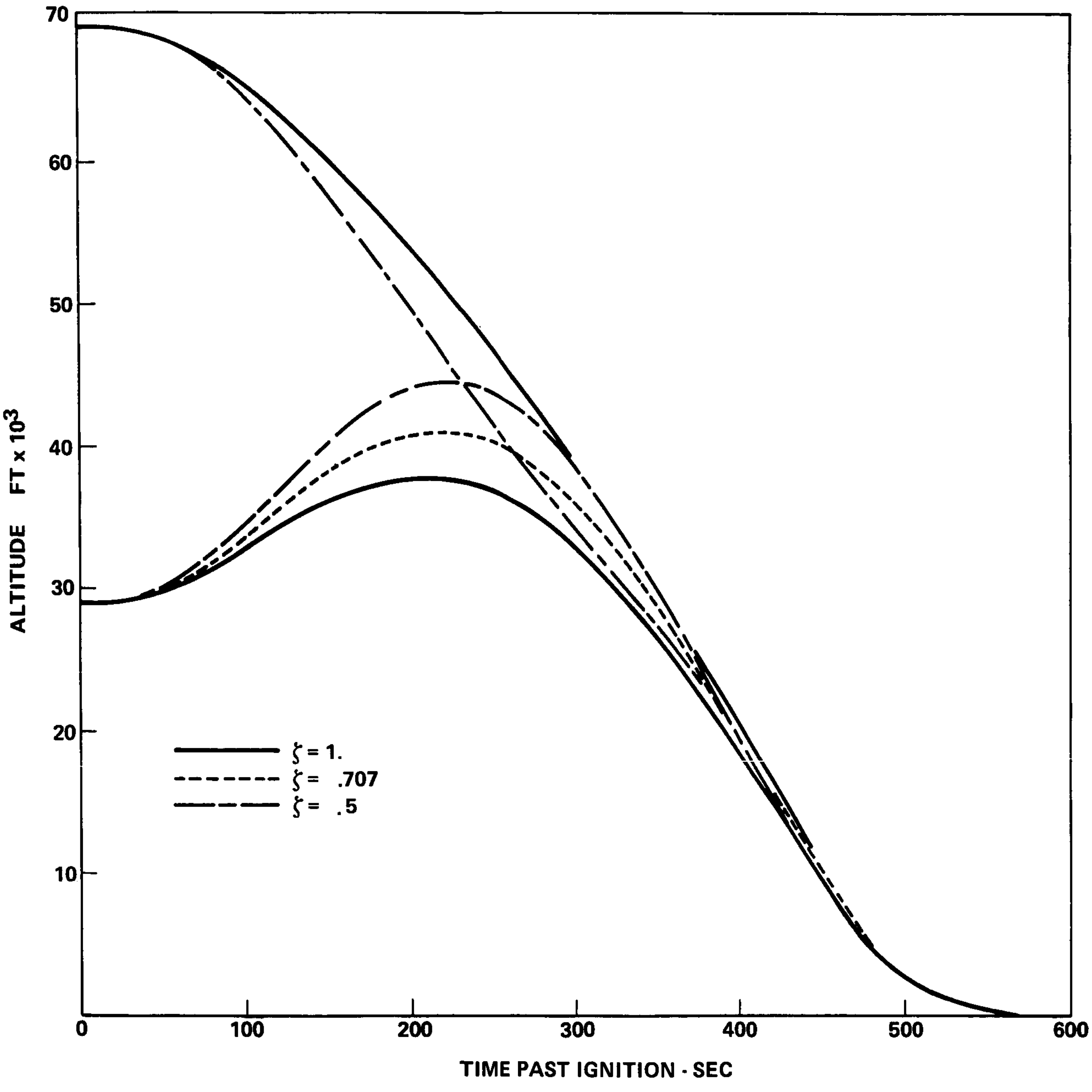

FIGURE 14 - EFFECT OF DAMPING VARIATION ON PERTURBED-INITIAL-ALTITUDE TRAJECTORIES WITH DELTA GUIDANCE

function of time. Variation of ζ has little effect on ΔV for the high altitude case, but can be significant for the low altitude condition. Increased damping decreases the lofting and thereby lowers ΔV.

3.2.3 RLS Variations

The landing site location (RLS) used in the LM guidance computer can be updated by astronaut input to account for measured navigation errors. The ΔV costs of possible RLS state changes were evaluated using both types of guidance. The RLS changes were simulated to occur at 2 minutes after ignition. The change in ΔV for extreme redesignations with both types of guidance are:

		Delta Guidance	Explicit Guidance
		$\Delta(\Delta V)$, ft/sec	$\Delta(\Delta V)$, ft/sec
Downrange	35,000 ft	+ 5	+39
Uprange	35,000 ft	-10	-54
Crossrange	18,000 ft	- 8	+ 3

These numbers were obtained using the nominal guidance constants and the Apollo 12 thrust model. A more detailed study of these costs and the influence of the time past ignition when the ΔRLS input is made can be found in Ref. 6.

3.3 Throttle Modulation Variations

For delta guidance, the thrust level and the LGC constants DNCRIT, UPCRIT, and FCDOWN determine the frequency of pulsing during the braking phase. The difference (UPCRIT-DNCRIT) also affects the dispersions of the state at high gate (which influences the ΔV cost). It is possible that some engine performance is lost because of the modulated thrust profile.[7] It may be desirable to minimize the number of throttle pulses to lower engine nozzle erosion and provide higher Isp. The influence of changing the modulated profile was first studied by changing the constants DNCRIT and UPCRIT. The results for a nominal thrust engine are presented in Fig. 15. Increasing

Figure 15. The effect on pulse length and frequency, state dispersions at high gate, and ΔV cost of the LM descent burn due to changes of the constants UPCRIT and DNCRIT used by delta guidance. Results are for an Apollo 12 nominal thrust engine.

UPCRIT, ft/sec	DNCRIT, ft/sec	Number of Pulses	Pulse Length, sec	ΔV, ft/sec	Changes in State at High Gate			
					Δx, ft	Δz, ft	$\Delta\dot{x}$, ft/sec	$\Delta\dot{z}$ ft/sec
		Nominal				Nominal		
0	-10	7	6	6495.	7210.	-25,201.	-172.	512.
0	-20	6	8	6526.	- 173.	+ 660.	- 3.	- 53.
0	-30	4	10,12	6541.	+ 1.	+ 309.	+ 9.	- 77.
10	-10	5	8	6477.	- 185.	+ 379.	- 3.	+ 15.

the magnitude of DNCRIT causes fewer pulses of greater length. It also causes greater dispersions at high gate, especially in the horizontal component of velocity $\dot{z}$. A 1 ft/sec decrease in the value of $\dot{z}$ at high gate roughly corresponds to an increase in ΔV of about 0.6 ft/sec. When UPCRIT was changed from 0 to +10 ft/sec, the ΔV cost was lowered 18 ft/sec, but throttle-down occurred 4 sec late. The dispersion of $\dot{z}$ at high gate for these cases is highly dependent upon the closeness of the final pulse to high gate. This time period is chiefly a function of the thrust model which is used.

The decrease in ΔV cost due to Δ guidance could theoretically be improved upon by replacing the several small-length pulses by one long pulse occurring early in the braking phase. The problem with implementing a single pulse is to accurately command the length of this pulse early enough so that the full savings can be realized. If a large single pulse is made based upon an inaccurate estimation of how the engine will perform following the pulse, unacceptably large state dispersions could occur at high gate. Thus, if the thrust is to be modulated by a single pulse, the target constants should be selected to allow a small throttlable region near the end of the braking phase.

A single long pulse could be implemented automatically or manually. The sensitivity of the ΔV cost and the throttlable period before high gate (throttle-down margin) are delineated in Figs. 16 and 17 for the Apollo 12 nominal thrust engine and target constants. In these plots, the effect of pulses with lengths of 10, 20, and 30 sec are illustrated. The engine is throttled to 60% full thrust. It can be seen that for any pulse length, the ΔV saving decreases and the throttle-down margin increases as the time past ignition where the pulse begins is increased. It can also be seen that the sensitivity of ΔV and throttle-down margin increase with increased pulse width. To obtain the same savings as the modulated profile requires a single pulse of greater than 20 sec in length. But a 30 sec pulse usually causes throttle-down to occur after high gate, so the pulse length is quite sensitive. Also, a long single pulse is made on the assumption that thrust will return to the original level after returning to FTP. Thus, there is more risk in the single pulse implementation.

Some points which might be used to improve the existing Δ guidance thrust profile during the braking phase are:

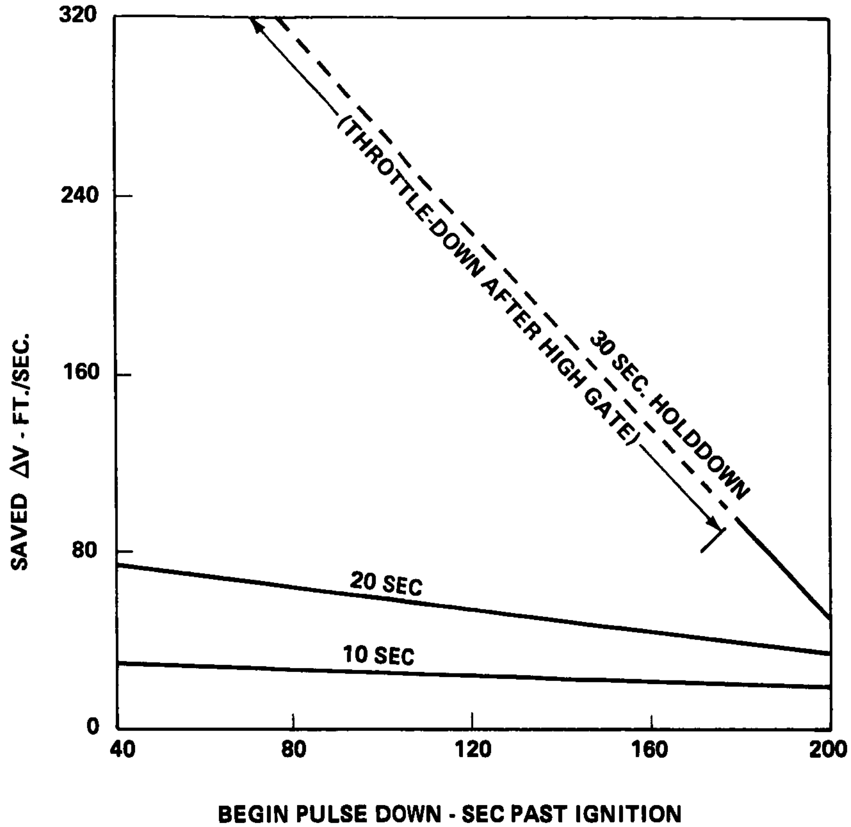

FIGURE 16 - SAVED ΔV COST DUE TO A SINGLE THROTTLE PULSE IN THE BRAKING PHASE FOR A NOMINAL THRUST ENGINE. LENGTH OF THE PULSE IS SHOWN AS A PARAMETER

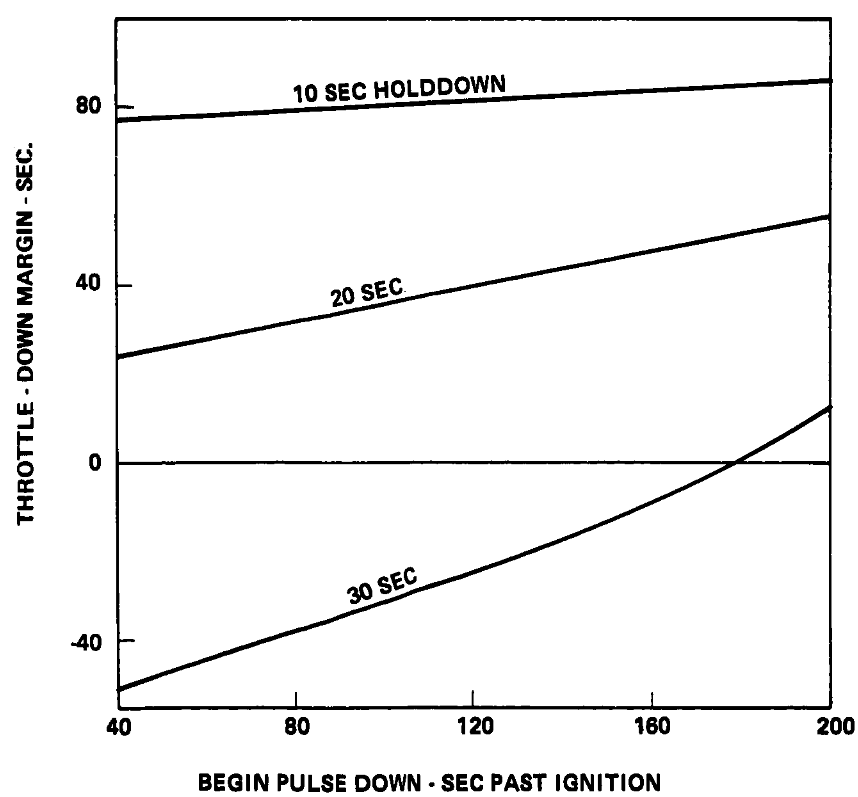

FIGURE 17 - THE AVAILABLE THROTTLE-DOWN PERIOD FOR A NOMINAL THRUST ENGINE WITH A SINGLE THROTTLE PULSE IN THE BRAKING PHASE

1. Delay pulsing until after any RLS changes have been made. Redesignating short (uprange) causes a need for greater deceleration thrust to meet the high gate conditions. There is no point to decreasing thrust by pulsing, if later an increased thrust capability is required.

2. Decrease the number of pulses to the thrust profile. If longer pulses occur early, some ΔV savings might be gained. The engine Isp might have less transient losses if the pulses are longer and fewer. Also, engine reliability might be enhanced by having fewer thrust pulses and nozzle throat erosion might be decreased.

3. Decrease the length of the pulses near high gate. This would lower the dispersions there.

One way that these points can be partially realized is by making the parameter DNCRIT a linear function of t_{go}, i.e.,

$$\text{DNCRIT} = K_{dc1} + K_{dc2} t_{go}.$$

This causes the bandwidth on the horizontal velocity component (which triggers pulsing) to decrease as t_{go} becomes smaller. The constants K_{dc1} and K_{dc2} can be chosen so that pulsing will not occur until after the nominal ΔRLS input time has passed. The resulting pulses are fewer and longer at the beginning of the phase. The pulses can be set smaller near high gate to meet the dispersion requirements. Also, the choice of $K_{dc2} = 0$ allows reversion to the present method.

As an example of improvement due to this modification, a trajectory was simulated using the Apollo 13 thrust model. Nominal thrust after reaching FTP is 9850 + 0.23t lb. For the nominal thrust and with K_{dc1} = -10 ft/sec, K_{dc2} = 0, nine pulses resulted. Changing the DNCRIT constants to K_{dc1} = 17.4 ft/sec, K_{dc2} = -0.14 ft/sec^2 lowered the number of pulses to six. The change in ΔV was insignificant. The same sets of constants were used with a 3σ low thrust of 9730 + 0.23t lb and the landing site was redesignated short 35,000 ft at 2 minutes past ignition. This thrust caused one pulse before redesignation for the constant DNCRIT case and none thereafter. Throttle-down occurred 34 sec after high gate. (15 sec late is all that is acceptable.) For the linearly varying DNCRIT case, no throttle pulses occurred and throttle recovery took place at high gate. It is recommended that the linearly varying DNCRIT be incorporated into the Δ guidance equations, or that thrust modulation is inhibited until after ΔRLS inputs are made, if a constant DNCRIT is used.

3.4 LPD Redesignations

Another comparison of E and Δ guidance was made by simulating LPD redesignations in the visibility phase of LM descent. The original motivation for Δ guidance in this phase was to drive the trajectory to the nominal glide slope after redesignations. Several single downrange (long), uprange (short), and crossrange redesignations were simulated to determine other effects of Δ guidance.

A comparison of E and Δ guidance trajectory shapes for about a 4,500 ft long redesignation is shown in Fig. 18. In this figure, a line representing a 10° sun angle is also shown. The redesignation is made at the time the LM crosses 4,000 ft altitude. The delta guidance perturbed trajectory essentially meets the nominal at 6,000 ft range. At the same range, the E guidance trajectory is about 500 ft low. Figure 18 illustrates the following points which favor delta guidance:

1. For long LPD redesignations, Δ guidance drives the trajectory back to the nominal approach path sooner. This is a possible advantage, helping the crew to view the new landing site and approach it in a standard manner.

2. Redesignating long can cause the new target to drop below the sun angle line. Δ guidance causes the perturbed trajectory to remain under this line for

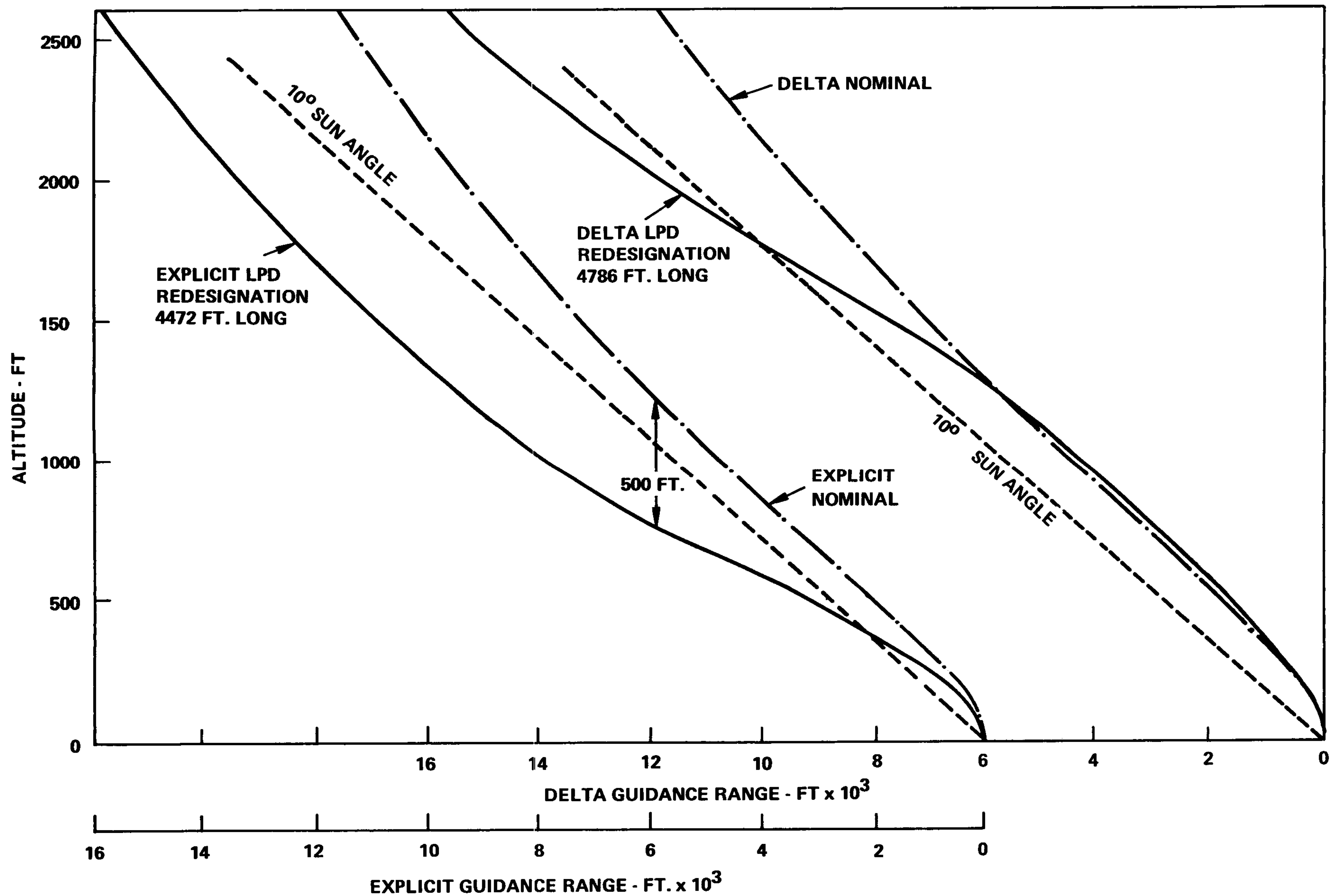

FIGURE 18 - COMPARISON OF APPROACH FLIGHT PATHS FOR LONG REDESIGNATION OF THE LANDING SITE FROM 4000 FT ALTITUDE USING E AND Δ GUIDANCE

a shorter period of time and to cross it at a much higher altitude. This gives the crew a much longer uninterrupted viewing time of the new landing site, and a longer view from a position with greater visual contrast.

3. Redesignating long with E guidance causes the trajectory to droop near the lunar surface. There could exist some danger of impacting a surface with rough features for such a trajectory.

Figure 19 compares E and Δ guidance trajectory shapes for redesignating long and short when the gains of Δ guidance are varied (ζ = 1.0, 0.707, and 0.5). It can be seen that this gain variation has a significant effect, especially on long redesignations. Increased damping causes the trajectory to go more directly to the new landing site.

Figures 20a and b illustrate how the LPD look angle changes as a function of time when the landing site is redesignated about 5,000 ft short from 4,000 ft altitude. Here, it can be seen that Δ guidance with nominal gains causes greater attitude transients to the LM while driving it to the desired trajectory. For the situation of Fig. 20a, Δ guidance actually causes the new landing site to disappear from view for about 10 sec. When the site reappears, it changes position at about 1°/sec. This is approximately 3 times as fast as the E guidance look angle moves after the initial transient, as seen in Fig. 20b.

Δ guidance for short redesignations does offer some possible advantages. In Fig. 20a, it can be seen that after the transient phase has passed, the resulting look angle tends to have the same time history as that of the nominal. Also, E guidance tends to move the entire look angle profile toward the bottom of the window (65°). E guidance causes the new site to permanently disappear from view for smaller short redesignations than does Δ guidance. One cannot argue strongly for Δ guidance when looking at short redesignations; the choice depends on crew preference.

Figures 21 and 22 depict the ground track and bank angle (angle between the LM lateral (pitch) axis and its projection on the local horizontal plane) for a redesignation of 3,400 ft to the left from 4,000 ft altitude. Figure 21 shows that increasing the damping coefficient causes the LM to fly more directly to the new approach path as predicted by Eq. (11). This lowers the time required to attain normal attitude.

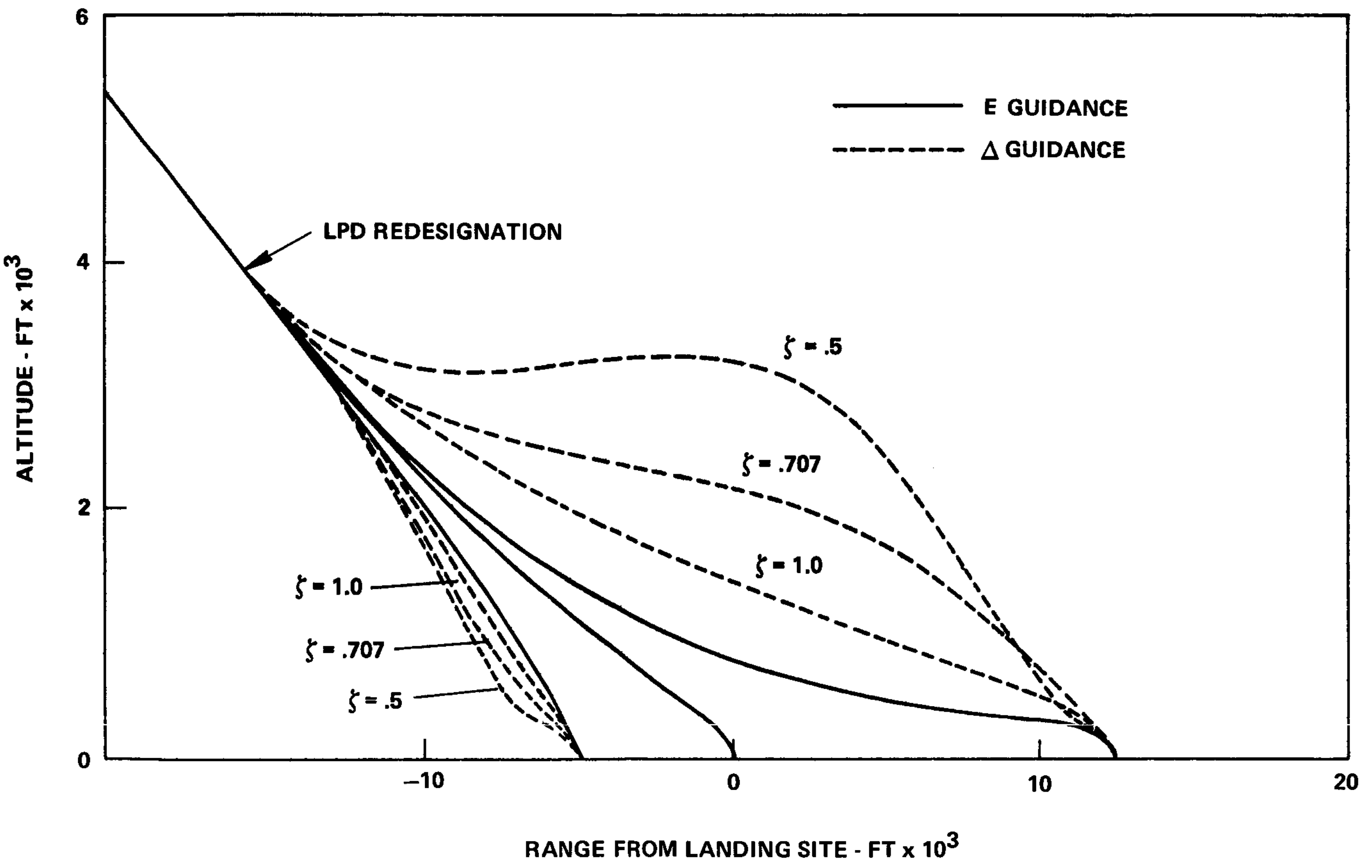

FIGURE 19 - COMPARISON OF E AND Δ GUIDANCE TRAJECTORY SHAPES FOR REDESIGNATING THE LANDING SITE LONG AND SHORT, Δ GUIDANCE DAMPING COEFFICIENT IS THE INDICATED PARAMETER. Δ V COSTS OF THESE TRAJECTORIES ARE PRESENTED IN FIGURE 23.

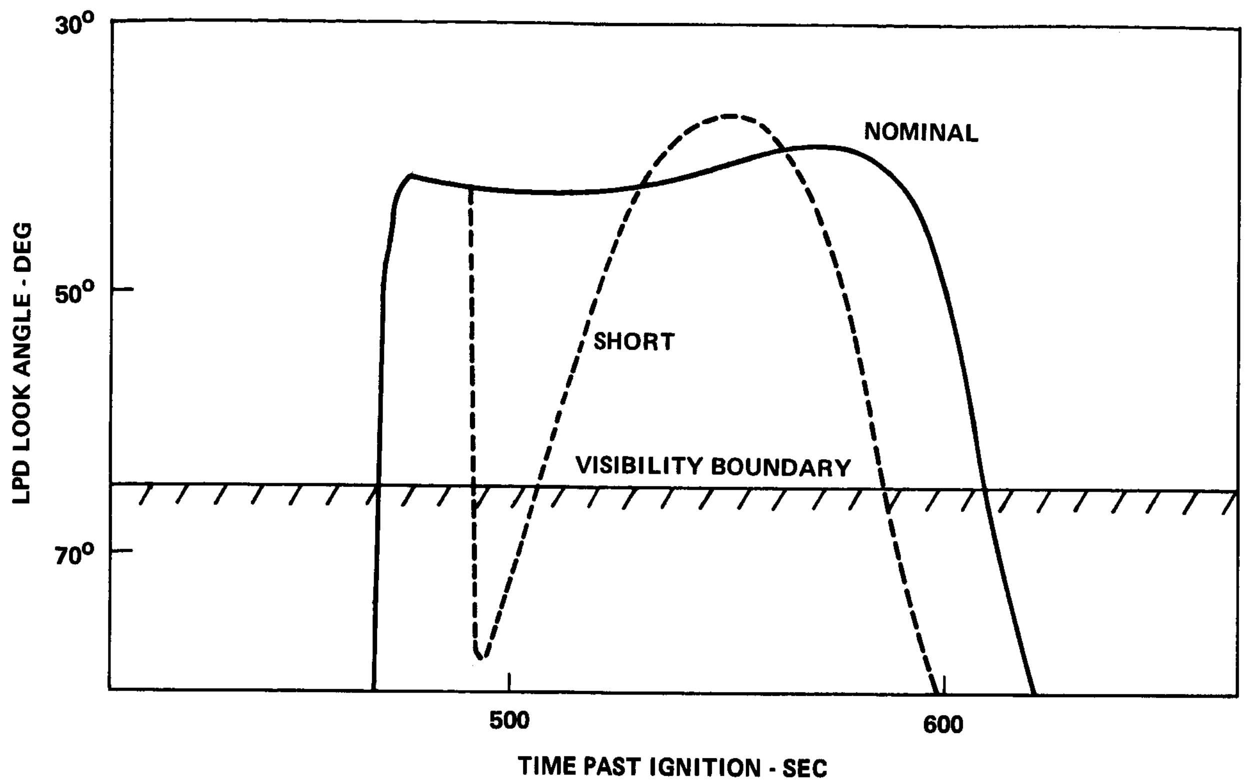

FIGURE 20a - THE LPD LOOK ANGLE FOR A 5000 FT. SHORT REDESIGNATION OF THE LANDING SITE FROM 4000 FT ALTITUDE USING Δ GUIDANCE WITH NOMINAL GAINS

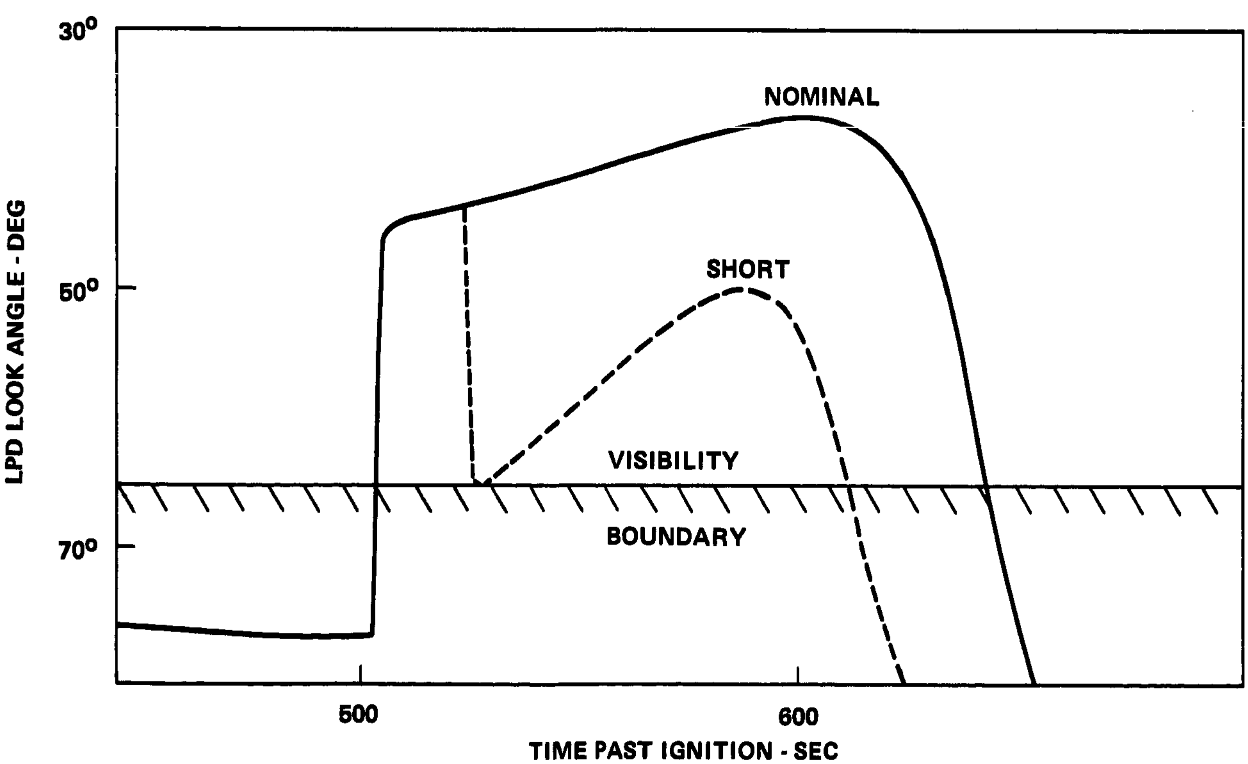

FIGURE 20b - THE LPD LOOK ANGLE FOR THE SAME REDESIGNATION AS IN FIGURE 20a EXCEPT THAT E GUIDANCE IS USED

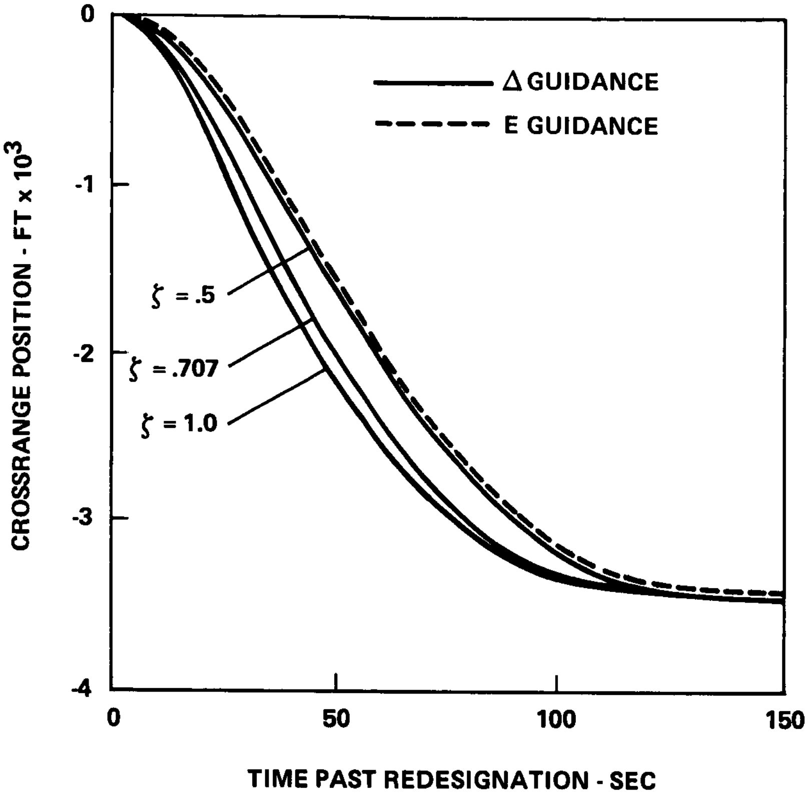

FIGURE 21 - CROSS RANGE POSITION FOR A REDESIGNATION AT 4000 FT ALTITUDE. DAMPING COEFFICIENT IS SHOWN AS A PARAMETER FOR Δ GUIDANCE

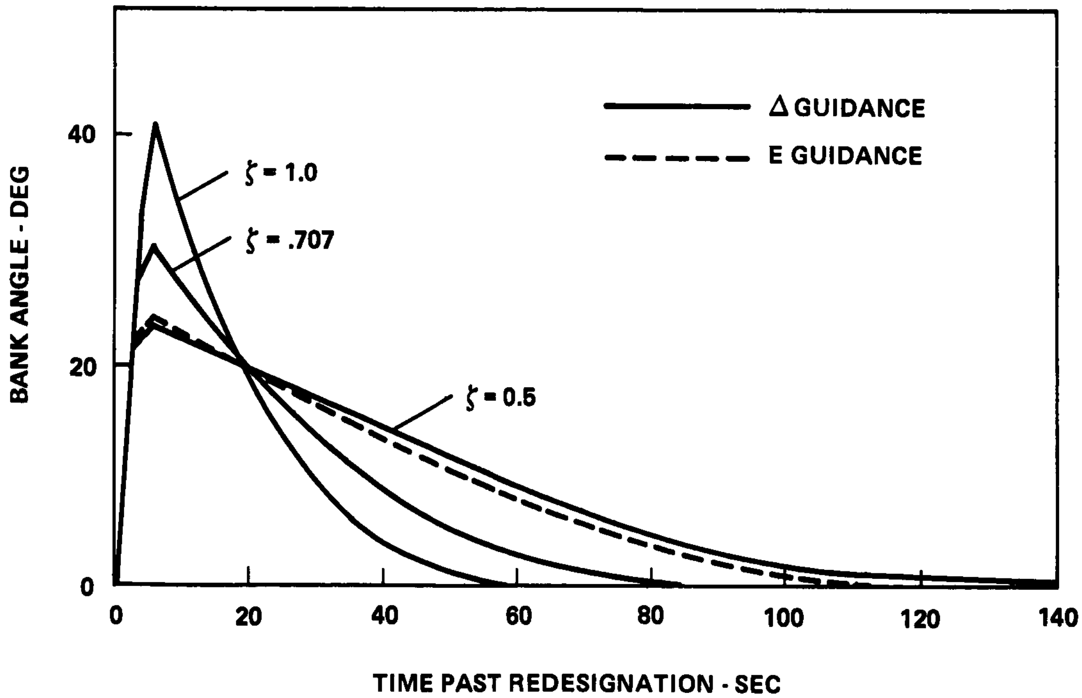

FIGURE 22 - BANK ANGLE FOR CROSS RANGE REDESIGNATIONS SHOWN IN FIGURE 21

From Fig. 22 one sees another aspect of the greater attitude transients which result from Δ guidance. For the same crossrange redesignation, the nominal Δ guidance trajectory has a larger maximum bank angle and a faster bank-angle rate. One can imagine that a smaller bank angle would be more comfortable to the flight crew. Increased damping corresponds to increased bank angle.

There is a significant difference in the ΔV costs of LPD redesignations with the two types of guidance. Figure 23 compares the changes in total ΔV cost for large redesignations of approximately 3,400 ft crossrange, 12,000 ft downrange, and 5,000 ft uprange from 4,000 ft altitude (16,500 ft range-to-go). Also listed are the costs for Δ guidance with gains other than the nominal value. The maximum bank angle required to make the crossrange redesignation is also shown.

The 3,400 ft crossrange redesignation cost is reduced 17 ft/sec using Δ guidance with nominal gains. This causes a 6° increase in maximum bank angles. With the same gains, Δ guidance saves 59 ft/sec for a 12,000 ft downrange redesignation. However, it saves 43 ft/sec less ΔV for a 5,000 ft short redesignation. Crossrange and downrange ΔV costs do not appear to be improved by changing the damping coefficient of the nominal Δ guidance steering gains, although lowering the damping causes the maximum bank angle to decrease.

The choice of the gains K_1, K_2 equal to 6, 12 for Δ guidance produces the same acceleration command as E guidance. However, the resulting crossrange and downrange redesignation trajectories also have ΔV savings. In fact, about one-half of the ΔV savings for crossrange and downrange redesignations results from the change in the target constants and the new time-to-go equation. This says that even without the change in the acceleration command equation, the ΔV cost will be improved by changing the time-to-go equation. For short redesignations, this change also improves the ΔV savings.

It is useful to map the costs of both types of steering (with nominal gains) as a function of the change in landing site. Figure 24 illustrates the change in ΔV for LPD redesignations from 4,000 ft altitude. Also indicated on the plot are the loci of given maximum bank angles for both steering methods. The origin is the nominal landing point. At the bottom of the plots are lines which indicate the boundary beyond which the landing site would disappear momentarily from view (due to window bottom) because of the redesignation.

Figure 23. Comparison of delta and explicit guidance costs for making LPD redesignations of the landing site at 4,000 ft altitude. Crossrange cost is for a 12° azimuth change. The maximum bank angle for this change is also shown. Uprange (short) and downrange (long) costs are for ±6° elevation changes.

Type of Guidance	Steering Gains		Nominal ΔV ft/sec	Crossrange			Downrange		Uprange	
	K_1,	K_2,		Distance, ft	$\Delta(\Delta V)$,* ft/sec	Max. Bank, deg.	Distance, ft	$\Delta(\Delta V)$,* ft/sec	Distance, ft	$\Delta(\Delta V)$,* ft/sec
Nominal Δ	8.88	39.48	6519	3401	19	30	12,349	212	-4986	- 91
Δ	12.57	39.48	6519	3397	22	41	12,403	213	-4991	- 82
Δ	6.285	39.48	6518	3407	27	23	12,356	248	-4993	-106
Δ	6.0	12.0	6519	3536	27	23	13,705	246	-4913	-186
E			6613	3390	36	24	12,224	271	-4957	-134

*$\Delta(\Delta V)$ is the change in the characteristic velocity ΔV required to automatically land the LM following an LPD redesignation.

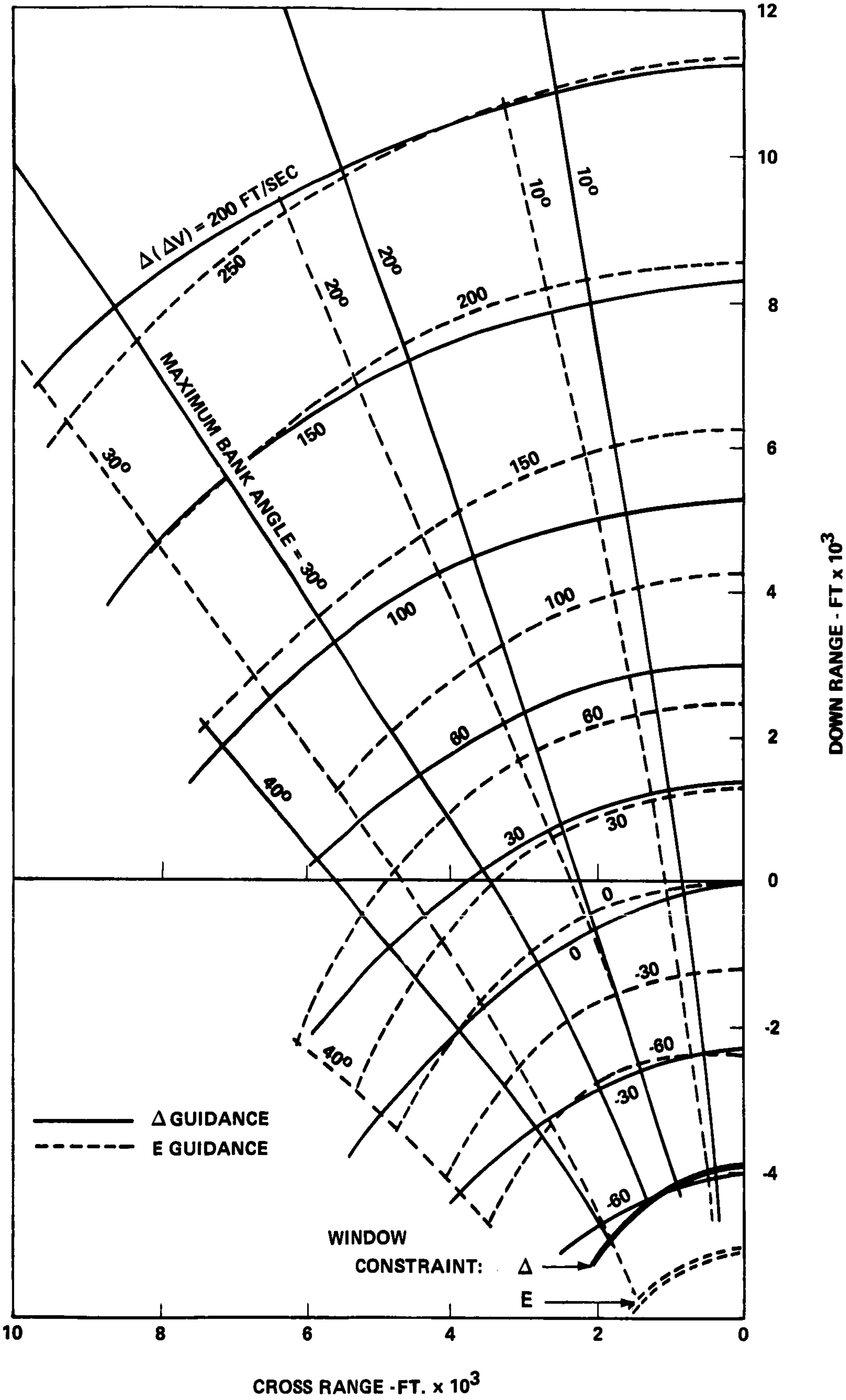

FIGURE 24 - CHANGE IN ΔV COST FOR LPD REDESIGNATIONS OF THE LANDING SITE FROM 4000 FT. ALTITUDE. THE LOOK ANGLE CONSTRAINT IS THE BOUNDARY WHERE THE REDESIGNATION CAUSES THE NEW SITE TO TEMPORARILY DISAPPEAR FROM VIEW

If one assumes that the accessible landing area is bounded by 60 ft/sec cost on the top of the plot, 30° bank angle on the side, and the visibility constraint on the bottom, then E guidance (or different Δ guidance gains) provides a larger accessible landing region. However, it is doubtful that the bank-angle constraint is a valid one.

4.0 STABILITY NEAR THE END OF THE VISIBILITY PHASE

Toward the end of the visibility phase with the present E guidance equations, the position control gain ($12/t_{go}^2$) of the commanded acceleration (3) becomes small. Because of autopilot time delay, computation delay, etc., this steering equation can produce system instability when t_{go} is in the neighborhood of 18 sec. To keep dispersions acceptably small in the vicinity of low gate, it is required to use target constants with low gate occurring at t_{go} equal to 10 sec. To remove the instability, a lead time t_ℓ was factored into the acceleration command. With the definition

$$t_p = t_{go} - t_\ell,$$

the actual LGC acceleration command is now

$$\vec{a} = \left(\frac{-24\, t_p}{t_{go}^3} + \frac{36\, t_p^2}{t_{go}^4}\right)(\vec{P}_T - \vec{p})$$

$$+ \left(\frac{18\, t_p}{t_{go}^2} - \frac{24\, t_p^2}{t_{go}^3}\right)\vec{V}_T + \left(\frac{6\, t_p}{t_{go}^2} - \frac{12\, t_p^2}{t_{go}^3}\right)\dot{\vec{p}}$$

$$+ \left(\frac{6\, t_p^2}{t_{go}^2} - \frac{6\, t_p}{t_{go}} + 1\right)\vec{A}_T - \vec{g}_c,$$

rather than Eq. (3). A similar modification of the Δ guidance Eq. (7) is more complicated.

Delta guidance makes it possible to limit the natural frequency ($\sqrt{K_2}/t_{go}$) of the commanded acceleration equation. Also, the t_{go} cutoff for low gate can be increased from 10 sec because dispersions are lowered with the ability to steer the trajectory back to the nominal. These arguments do not hold, of course, if the gains K_1 and K_2 are selected to be 6 and 12 and the low gate t_{go} is moved back to 10 sec. For the ability to revert back to E guidance with the Δ guidance equations, provision must be made to keep the natural frequency above the stability limit.

The use of the Δ guidance acceleration command equation must be thought of as providing questionable stability at the end of the visibility phase until proven otherwise. Incorporation of the new acceleration command demands that the full qualification tests used to validate the stability of the present equation be remade.

5.0 SUMMARY

Delta guidance proposes three major changes to the present guidance equations. These are:

1. The time-to-go computation is based upon matching the forward horizontal position of the LM to a polynomial function of t_{go} rather than maintaining a constant final horizontal jerk component.

2. The engine thrust is pulsed down from the fixed-throttle position several times during the braking phase by the addition of suitable logic. This keeps the horizontal component of velocity close to a nominal polynomial function t_{go}.

3. The acceleration command equation is changed so that it can drive the trajectory back to a nominal from a perturbed state. This new equation does not have a lead time factored into it.

The effects of these changes are now summarized as apparent advantages and disadvantages. Other points which have been studied are then listed.

5.1 Advantages

1. Pulsing the nominal thrust engine during the braking phase can save 90 or more ft/sec ΔV cost to land the LM. This savings can be converted into 300 lb additional payload or 17 sec additional hover time.

2. Delta guidance also lowers the ΔV costs for trajectories subjected to initial perturbations in altitude, and downrange and crossrange RLS changes. The actual savings are thrust-level dependent. The cost of redesignating the landing site 35,000 ft downrange at 2 minutes past ignition is cut from 39 ft/sec to 5 ft/sec.

3. The new acceleration command decreases the t_{go} point where the APS abort boundary is crossed due to a perturbation caused by rough surface features.

4. The new acceleration command improves the trajectory shape in three ways for long LPD redesignations. These are:

   a. If the trajectory drops below the sun-angle line, it remains there for a shorter period of time and crosses back above at a higher altitude.

   b. The trajectory is driven back to a nominal approach path which should be more familiar to the crew while landing.

   c. The new steering eliminates the drooping nature of the trajectory which is a possible source of impact danger.

5. For short LPD redesignations, the look angle is eventually driven back to a close vicinity of the nominal value. This feature is possibly favorable to the crew, and it is less likely that the new landing site will disappear permanently from view than with E guidance.

6. LPD redesignations using nominal gains cause a small saving in downrange and crossrange ΔV costs. About one-half the saving comes from the new time-to-go equation and steering constants.

7. The delta guidance acceleration command equation has a great deal of flexibility because gains can be chosen to vary the attitude and translational response characteristics of the LM. Different gains can be chosen for each phase. The ability to revert back to the E guidance command is available with some stability qualifications.

5.2 Disadvantages

1. The delta guidance acceleration command with nominal gains causes increased look angle transients and translational motion transients as a result of trajectory perturbations. The latter effect tends to decrease fuel savings due to motion caused by lunar surface features. This loss was 25% when flying with normal radar to the Copernicus landing site.

2. Removing the throttlable portion at the end of the braking phase can cause higher dispersions at high gate.

3. The engine pulsing effect on thrust performance and reliability is not precisely known.

4. Short LPD redesignations are more likely to cause the landing site to momentarily disappear from the astronaut's field of view.

5. Crossrange redesignations have higher maximum bank angles.

6. The control system stability near the end of the visibility phase is unproven.

5.3 Other Points of Interest

1. The delta guidance equations can be reverted back to E guidance by the proper choice of gains K_1 and K_2. To produce the same trajectory profile as with E guidance, the E guidance target constants are also used. Suitable values of horizontal jerk and snap for reversion back are those that cause the new time-to-go equation to produce the same values with respect to the horizontal position at the beginning and end of a phase as the present equation.

2. Much of the gain produced by the thrust pulsing logic can be obtained from a single thrust pulse during the middle of the braking phase. However, performance is very sensitive to the timing of this pulse and to the thrust level at FTP following the pulse. From a guidance standpoint, a single pulse is not preferable to the automatic, multiple pulsing logic of the suggested Δ guidance equations.

3. The current throttle margin could be reduced by assuming that 3σ low thrust and a ball valve failure will not occur together on the same engine. This would also allow picking up some of the ΔV gain achieved by pulsing. This is a risky assumption because in the event that both low thrust and the valve failure did occur, throttle-down would occur too late in the approach phase to enable the current visibility constraints to be met.

4. Changing the lower boundary DNCRIT from a constant to a linear function of t_{go} produces three improvements to the resulting Δ guidance trajectories. They are:

   a. Pulsing can be delayed until the RLS update has been made.

   b. The number of pulses can be decreased.

   c. The dispersions at high gate can possibly be lowered.

5. Delta guidance tends to loft trajectories with initial altitudes lower than the nominal value. This characteristic is partially due to the removal of the vertical control equations, and is partially due to changes in the target constants.

6.0 CONCLUSIONS

It has been shown that delta guidance can save more than 90 ft/sec in characteristic velocity to land the LM. The guidance changes also drive a perturbed descent trajectory closer to the nominal approach trajectory than with the present equations. If there exists a future need for these improvements, then delta guidance should be considered.

The following qualifications to the delta guidance changes are made:

1. The automatic throttle modulation should have DNCRIT as a linear function of t_{go} or have pulsing inhibited until after ΔRLS changes are made. Automatic pulsing is contingent upon the engine being so qualified.

2. The new acceleration command equation should have the following qualifications:

a. If the provision to revert back to the E guidance acceleration command is retained, an upper limit is placed on the gain (K_2/t_{go}^2).

b. Exhaustive qualification tests are run to insure that the resulting LGC-DAP system is stable near the end of the visibility phase.

c. The flight crews' opinions are used in selecting gains for the equation.

It is not necessary to implement both the throttle modulation feature and the new acceleration command equation. From a trajectory improvement standpoint, throttle modulation is preferable to implementing a single pulse or lowering the throttle margin. The motion sensitivities of delta guidance can be improved by use of a simple lurain model (now under study) and a different choice of gains K_1 and K_2.

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