BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B69 06095

SUBJECT: Ideas for Improvement of LM Descent Trajectory - Case 310

DATE: June 30, 1969

FROM: G. L. Bush
T. B. Hoekstra
F. LaPiana

ABSTRACT

[redacted]

A LM descent trajectory has been developed which offers several advantages when compared with the current LM descent operational trajectory (O.T.). The proposed trajectory was designed to save ΔV during automatic descents in an effort to give the crew added maneuver time in the event that they assume manual control of the LM. The proposed trajectory provides a ΔV saving of about 204 fps and also reduces the tendency toward non-constant or "drooping" glide slopes. Other trajectory parameters such as visibility time, landing site redesignation capability, dispersions, vertical rates, and pitch and thrust profiles are examined and found to be satisfactory.

The proposed changes provide advantages for both G-type and subsequent missions. On H-type missions, where pinpoint landings will become necessary, the additional ΔV would be especially useful for landing site redesignations and manual maneuvering.

The appendix contains reproductions of Vu-Graphs and comments that served as the basis of a presentation of these proposals to MSC personnel responsible for LM descent trajectory design.

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MEMORANDUM FOR FILE

INTRODUCTION

Two proposals are suggested to save automatic descent ΔV cost. The philosophical guideline is to provide a fuel efficient automatic trajectory, thereby providing additional fuel for pilot use of the landing point designator (LPD) and rate-of-descent (R-O-D) or completely manual descents near touchdown.

The appendix contains reproductions of Vu-Graphs and comments that served as the basis of a presentation of these proposals to MSC personnel in the Guidance and Control Division and the Mission Planning and Analysis Division responsible for LM descent trajectory design. Detailed analysis and design rationale are included.

PROPOSALS

The first suggestion is to reduce flying time in the visibility phase. The second is to lower the visibility phase terminal altitude. The suggested changes are separable; either change alone saves ΔV, while implementing both provides a large ΔV saving.

Reducing the visibility phase time by 20 seconds from that obtained using operational trajectory targets (MSC Internal Note 69-FM-98) saves about 116 feet per second of ΔV. Lowering the terminal altitude for the visibility phase from 150 feet to 100 feet saves about 88 feet per second.

These proposals are simple in concept, and they do not require changing the braking phase in any way: high-gate position and velocity are not altered. In the following paragraphs, the results of changing the visibility phase targets will be analyzed, and comparisons will be made of the proposed trajectory and the current operational trajectory (O.T.).

ANALYSIS AND COMPARISON

Changing the visibility phase target j_{dz} from .0018 ft/sec^3 to .0275 ft/sec^3 changes the visibility phase flying time from 161 to 140 seconds. Table I compares the visibility phases of the O.T. and the proposed trajectory when only the terminal jerk target is changed.

TABLE I

Parameter	Current O.T. Targets	Proposed Trajectory: j_{dz} = .0275	Δ
T_{go}* at Visibility phase start	170.9	150 sec	- 20.9
T_{go} at h = 500 ft	73	53 sec	- 20.
ΔV at h = 500 ft	6198** fps	6145** fps	- 53
ΔV at h = 150 ft	6524** fps	6408** fps	-116
Vertical velocity at h = 500 ft	16 fps	18 fps	+ 2
Forward velocity at range = 2000 ft	70 fps	84 fps	+ 14
Time lookangle > 35° (10° above bottom of window)	117 sec	95 sec	- 22
Cross range redesignation capability after 25 sec into visibility phase (with 60 fps ΔV)	3300 feet	3950 feet	+650

*T_{go} is time-to-go in the visibility phase. When T_{go} = 10, lo-gate is achieved, and landing phase guidance (velocity nulling) is started.

**Recent slight changes to the Descent Propulsion System thrust and I_{SP} values cause slight differences in the ΔV's shown here and those appearing in the O.T. (69-FM-98). Both the targets for the O.T. and the proposed trajectory were run using the same thrust and I_{SP} values, so comparisons on the above chart are valid.

Table I indicates that the proposed trajectory flies a faster, more efficient trajectory. The 2 fps increase in vertical rate at 500 ft should cause little astronaut concern because of recent improvements in R-O-D operation. Savings in ΔV are available for astronaut control anywhere along the trajectory. These savings increase the longer the astronaut allows the automatic descent to continue.

Analysis shows that the proposed trajectory has a more constant glide path (16°) than does the current O.T. When flown over large craters or upward slopes, less "droop" in the glide path is shown by the proposed trajectory. When analyzed from a landing-radar dropout point of view, the proposed trajectory maintains lock throughout the visibility phase, while the O.T. loses lock at an altitude of about 240 ft. Thrust and pitch profiles are only slightly altered from the O.T.

Changing the visibility phase terminal altitude from the O.T. value of 150 feet to a proposed value of 100 feet leaves the above analysis and comparisons approximately the same. A trajectory flown with $j_{dz} = .0275$ ft/sec^3, and the lower target altitude results in a slightly increased vertical rate. At an altitude of 500 feet, that vertical rate is 19.7 ft/sec. The lower hover altitude eliminates 16.6 seconds of vertical descent time, resulting in a ΔV saving of 88 ft/sec. The lower hover altitude (100 ft) appears to be adequate when 3σ altitude dispersions, distance of landing radar to landing probes, and a sufficient safety margin are added.

CONCLUSIONS

The improvements in the LM descent trajectory suggested in this analysis are obtained by slight changes in the visibility phase. These changes result in a more fuel efficient automatic descent, providing increased fuel margins for possible manual maneuvers.

The proposed trajectory has slightly less visibility time, but better redesignation capability. It has a higher vertical rate at 500 feet, but less "droop" approaching hover altitude. It has slightly higher forward velocity on final approach, but slightly improved avoidance of loss of landing radar lock.

A ΔV saving of 204 ft/sec (116 fps from j_{dz} change, 88 fps from hover altitude change) is attractive both for G-type and subsequent missions. On H-type missions, such changes are particularly advantageous since pinpoint landings will require additional propellant margins for landing site redesignation and manual maneuvering.

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Attachment

Vu-Graph 1

A PROPOSED LM POWERED DESCENT TRAJECTORY

OBJECT

- REDUCE ΔV FOR AUTOMATIC DESCENT AND IMPROVE TRAJECTORY SHAPING WITHOUT SIGNIFICANTLY DEGRADING OTHER PERFORMANCE PARAMETERS

ASSUMPTIONS

- G MISSION HARDWARE AND SOFTWARE
- 16° GLIDE SLOPE IN VISIBILITY PHASE
- COMPARISONS MADE WITH TRAJECTORY DEFINED BY 69FM22-79 (MODIFIED TWO-PHASE, 150 FT. "HOVER" ALTITUDE) - 69FM22-79 TRAJECTORY WILL BE TERMED <u>CURRENT</u> TRAJECTORY

Vu-Graph 1 Comments

A trajectory has been designed which reduces the ΔV required to make automatic LM descents. This was done to give the crew additional time margins in the event manual takeover occurs. In addition, the trajectory was designed to minimize the tendency for the trajectory to droop near low-gate when the LM flies over craters or sloped terrain or when landing site redesignations are carried out.

The proposed trajectory only requires changes in the erasable LM Guidance Computer software constants and the 16° glide slope has been maintained. All comparisons are made with the current modified two-phase LM descent trajectory having a 150 hover altitude.

Vu-Graph 2 Comments

In designing the trajectory, the indicated parameters have been analyzed and compared. The ΔV saving and trajectory shaping improvements were the major goals. However, all of the other parameters were examined for suitability.

Vu-Graph 2

PARAMETERS CONSIDERED

- ΔV
- TRAJECTORY SHAPING
- VISIBILITY TIME
- LPD OPERATION
- VERTICAL RATE NEAR LOW-GATE
- PITCH AND THRUST PROFILES
- DISPERSIONS
- EFFECT OF SLOPES
- EFFECT OF CRATERS
- LANDING RADAR OPERATION

Vu-Graph 3 Comments

A. Glide Slope of Visibility Phase.

The current glideslope is 16°. This value is a good compromise between a 12° max. sun angle constraint and high vertical rates on final approach to high-gate. Conclusion: glide slope remains the same.

B. High-Gate State Vector

1. Historical Perspective

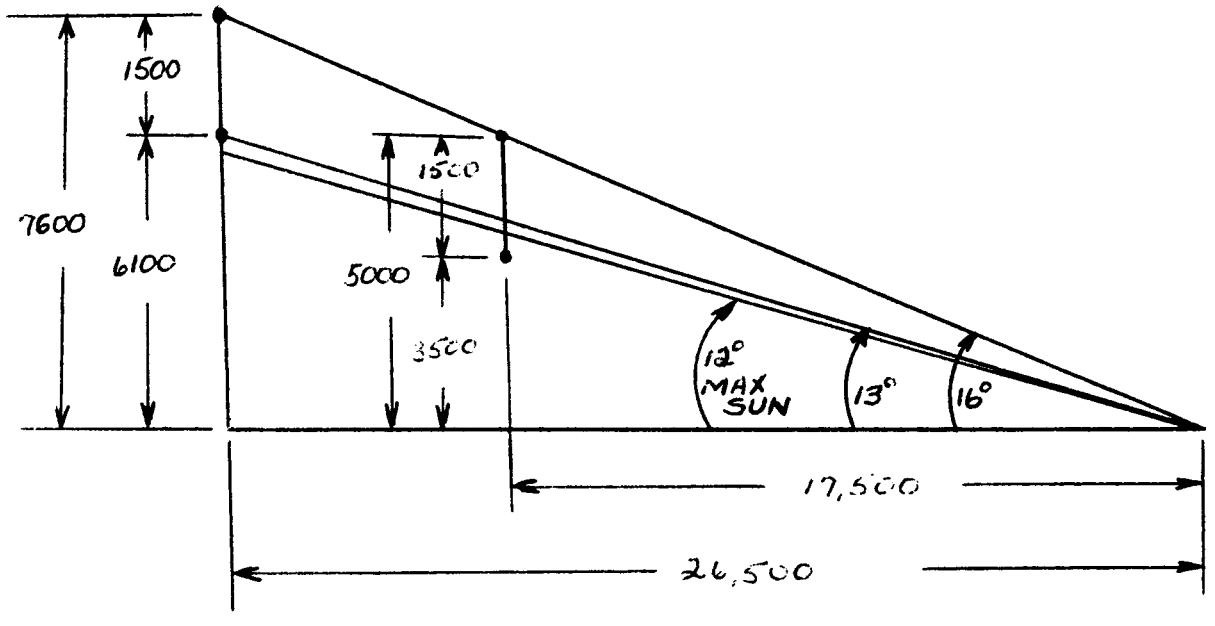
The current high-gate altitude is 7600 feet. High-gate altitude at one time was chosen on the basis of navigational uncertainties in altitude assuming the landing radar had failed. This is no longer a good criterion since MSC initial condition uncertainty estimates of altitude are now larger than was originally believed.

Procedures now require that landing radar altitude updates be available at an altitude of 20,000 feet. There should be little navigational uncertainty in altitude at high-gate.

2. Should high-gate altitude be lowered?

Modified two-phase guidance scheme (with 60-sec. switchover time) produces 500 foot (1σ) dispersions about nominal high-gate altitude. Down-range dispersions are small.

The sketch below is presented to demonstrate that significantly lowering high-gate altitude would violate the sun angle constraint for 3σ dispersions.



Another consideration is LPD capability and time for visual evaluation of the site. Lowering high-gate would allow less time to evaluate before a range (or altitude) is reached where maximum redesignations (within the ΔV budget) are allowable.
Conclusion: Do not lower high-gate altitude.

3. Should high-gate altitude be raised?

   a. With increased velocity at high-gate?

   Time-to-go would have to be increased in order to maintain commanded thrust in throttle-range. Since the braking phase is the most efficient phase to reduce forward velocity, this change does not seem advantageous.
   Conclusion: No.

   b. With decreased velocity at high-gate?

   There is no advantage in this approach since the change would result in more time in the visibility phase and increase ΔV.
   Conclusion: No.

   c. With velocity unchanged at high-gate?

   This change offers no advantage since it would result in more time in the visibility phase and increase ΔV.
   Conclusion: No.

Result: High-gate altitude should remain the same.

4. With high-gate altitude unchanged, should velocity be changed?

   a. Should high-gate velocity be increased?

   This is not possible (unless T_{go} is increased) without violating throttle-range of engine. Increasing T_{go} in the visibility phase costs ΔV.
   Conclusion: No.

   b. Should high-gate velocity be decreased?

   Decreasing high-gate velocity would allow a T_{go} decrease, but any ΔV saving would be taken away by equivalent increases in braking phase time.
   Conclusion: No.

Result: Leave high-gate velocity unchanged: $\underline{v} = \begin{Bmatrix} -139 \\ 0 \\ 505 \end{Bmatrix}$

C. Low-Gate State Vector

1. Position targets

Only altitude was considered. Desired hover altitude can be considered as a separate item from other trajectory targets.

2. Velocity targets

No change from current targets

3. Acceleration targets

A_{DX} and A_{DZ} are significant to trajectory shaping. Their magnitudes must be relatively small to assure slow velocities near high-gate. Their relative magnitudes are important since final pitch from vertical (θ) is controlled by the relation,

$$\theta = \tan^{-1} \frac{A_{DX} + g_m}{A_{DZ}}$$

The current values of $\underline{A}_D$ are $\begin{Bmatrix} A_{DX} = -.26 \\ A_{DY} = 0 \\ A_{DZ} = -.512 \end{Bmatrix}$. A negative value for A_{DX} is necessary to produce small vertical rates near low-gate. The magnitude of A_{DZ} provides trajectory shape for the Z-direction. Changes in A_{DX} and A_{DZ} were made in conjunction with changes with j_{DZ}, but changes in acceleration targets were not found to be advantageous.

4. Desired down-range jerk: j_{DZ}

Final jerk (j_{DZ}) is an important target parameter since it directly controls the flying time in the phase.

D. Effect of Change in Time-to-go for the Current Visibility Phase

1. Small change to initial visibility phase thrust level.

The derivative of thrust acceleration with respect to T_{go} evaluated on current trajectory is small. The magnitude and angle of thrust acceleration is insignificantly changed by a 20 second reduction in T_{go}.

2. Effect on guidance coefficients

Reducing T_{go} while leaving high-gate position and velocity and low-gate position, velocity, and acceleration the same as for the current trajectory changes the quadratic guidance coefficients as shown in the following table.

$^1T_{gol}$	A_{DZ}	j_{DZ}	S_{DZ}	A_{DX}	j_{DX}	S_{DX}
170.9	-.512	.0018077	-.0004466	-.26	-.011324	+.0000134
150.0	-.512	.02749944	-.00021098	-.26	-.02113056	-.00011505
130.0	-.512	.065616	+.000345	-.26	-.041904	-.000494

F. Targets for Proposed Trajectory

A change to only the jerk target at low-gate was found to result in the best trajectory to meet the objective of this study. A j_{DZ} = .02749944 results in a visibility phase time of 150 seconds.

The targets used in this analysis of the proposed and current trajectories are shown in Figure 1.

CHANGES TO CURRENT TRAJECTORY

- HIGH-GATE: TARGETS NOT CHANGED
  - MOVING HIGH-GATE TOWARD LOW-GATE NOT DESIRABLE
    - (1) GUIDANCE ALTITUDE DISPERSIONS FROM NOMINAL CAN VIOLATE MAX SUN ANGLE CONSTRAINT
    - (2) NEED TIME TO EVALUATE SITE AND CAPABILITY TO MAKE LARGE LPD REDESIGNATIONS
  - MOVING HIGH-GATE AWAY FROM LOW-GATE NOT DESIRABLE SINCE BRAKING PHASE IS MOST EFFICIENT PHASE TO REDUCE VELOCITY

CONTINUED NEXT PAGE

Vu-Graph 3 (Continued)

CHANGES TO CURRENT TRAJECTORY

- LOW-GATE: SIMPLE CHANGES PROPOSED
  - CHANGE jdz FROM CURRENT VALUE (.0018 fps^3) TO PROPOSED (.0275 fps^3)
    - RESULTS IN REDUCTION OF VISIBILITY PHASE TIME FROM CURRENT VALUE (171 SEC.) TO PROPOSED VALUE (150 SEC.)
  - LOWER LOW-GATE ALTITUDE
    - RESULTS IN ΔV SAVING
    - SEPARABLE ITEM FROM JERK CHANGE (DISCUSSED SEPARATELY)

Vu-Graph 4 Comments

The effects of changing jdz will be discussed first, followed by a discussion of the effects of changing the hover altitude.

Vu-Graph 4

EFFECTS OF CHANGE IN jdz

Vu-Graph 5 Comments

Figures 2 & 3 illustrate the altitude vs. range in the visibility phase with Time-to-go indicated in brackets. Both trajectories follow a glide slope near 16° until late in the visibility phase. The nominal proposed trajectory stays above the 16° glide slope all the way to touchdown while the current trajectory droops slightly below 16° at altitudes between 1500 and 500 ft.

The current and proposed trajectories enter the visibility phase with identical velocities, but the proposed trajectory maintains a slightly higher velocity as a function of range until hover is reached. Figure 4 illustrates the horizontal velocity as a function of range with Time-to-go indicated in brackets.

The pitch and acceleration due to thrust are shown in Figure 5 . The proposed trajectory is pitched back slightly more than the current trajectory.

The thrust acceleration on <u>both</u> trajectories starts at about 49% but it is higher on the proposed trajectory as a function of Time-to-go. The important fact is that the proposed trajectory is no closer than the current trajectory to the throttle-up boundary at the beginning of the visibility phase.

Vu-Graph 5

DETAILS OF PROPOSED TRAJECTORY

- FLIES ESSENTIALLY THE SAME GLIDE SLOPE
- MAINTAINS SLIGHTLY HIGHER VELOCITIES NEAR LOW-GATE
- PITCHES BACK SLIGHTLY MORE DURING VISIBILITY PHASE
- HAS SAME COMMANDED THRUST AT BEGINNING OF VISIBILITY PHASE BUT SLIGHTLY HIGHER THRUST SUBSEQUENTLY

Vu-Graph 6 Comments

The proposed trajectory has a potential ΔV saving of 116 fps (equivalent to 22 seconds of hover time). If the crew takes over control of the LM at 500 ft., they will have an additional 10 seconds of maneuver capability compared to the current trajectory. As will be discussed later, any lowering of the hover altitude will bring an additional ΔV saving.

Vu-Graph 6

ΔV FOR PROPOSED TRAJECTORY

- SAVES 53 FPS WHEN FLOWN TO 500 FT. ALTITUDE
- SAVES 116 FPS WHEN FLOWN TO END OF VISIBILITY PHASE

Vu-Graph 7 Comments

The savings in ΔV for the proposed trajectory are realized by decreasing the time in the visibility phase. Consequently, there is a decrease in the time that the landing site is visible above the 65° line or the 55° line on the landing point designator scale. Both trajectories comfortably exceed 75 seconds of site visibility above 55° in the window (95 seconds for the proposed trajectory, 117 seconds for the current trajectory).

The visibility phase is designed to give the crew time to assess the landing site and, if they are not satisfied with the current site, to allow redesignations to a new site. Thus, visibility time cannot be considered without considering redesignation capability. Early in the visibility phase time is the relevant criterion for comparing redesignation capability. For example, the crew requires a certain amount of time after the beginning of visibility to assess the landing site and then make any desired redesignations. Figures 7 and 8 show that 25 seconds into the visibility phase the proposed trajectory has about 25% greater redesignation capability, for a given extra ΔV cost, than does the current trajectory.

Later in the trajectory, slant range is the critical parameter for comparing redesignation capability since smaller objects become visible as a function of distance from the object. Since slant range is proportional to altitude, Figures 7 and 8 can be used to compare redesignation capability during the visibility phase. The proposed trajectory provides 30 per cent greater downrange and a 20 per cent greater crossrange redesignation capability with the 60 fps ΔV budgeted for the LPD. Equal redesignations obviously can be made for correspondingly less ΔV. These ratios hold approximately constant during the time the site is visible.

Figure 9 shows that the proposed trajectory tends to stay farther from the expected sun elevation line in the event of site redesignations.

Vu-Graph 7

VISIBILITY TIME AND REDESIGNATION CAPABILITY

PROPOSED TRAJECTORY GIVES ABOUT 22 SEC. LESS VISIBILITY TIME, BUT

- HAS GREATER REDESIGNATION CAPABILITY
  - 25 SECONDS INTO VISIBILITY PHASE
  - AS A FUNCTION OF ALTITUDE (THEREFORE AS FUNCTION OF SLANT RANGE)
- STAYS FARTHER FROM SUN LINE WHEN REDESIGNATED

Vu-Graph 8 Comments

Vertical rate vs. altitude has significance in terms of the APS 4 second abort boundary and in terms of crew takeover from an automatic descent. Vertical velocity on the proposed trajectory is 18 fps at 500 ft. vs. 16 fps on the current trajectory.

Recent modifications to the Rate-of-Descent (R-O-D) mode in the LM Guidance Computer have improved its response time and assured that all R-O-D pulses are accepted. If the crew puts in R-O-D pulses at a uniform rate once the R-O-D pulses are accepted. the pulses can be entered at a surprisingly low rate. Figure 11 shows the average number of R-O-D pulse/second required to null the vertical velocity at touchdown. If the crew takes over at 500 ft. altitude, one R-O-D pulse about every 3 seconds will null the vertical velocity. If the crew waits until the LM reaches about 300 ft. altitude on the automatic trajectory, only about one pulse every 8 to 10 seconds is required.

On either trajectory, with the improved R-O-D mode, the vertical rates are low enough that nulling the vertical velocity should not be difficult and the longer the crew waits to assume control, the lower the rate at which they will have to put in R-O-D pulses.

Vu-Graph 8

VERTICAL RATES

- VERTICAL RATE 18 FPS AT 500 FT. ALTITUDE (VS. 16 FPS CURRENTLY)
- AT 18 FPS VERTICAL RATE ONLY NEED ABOUT 1 R-O-D PULSE EVERY 3 SECONDS TO LAND WITH ZERO VERTICAL VELOCITY
- RECENT R-O-D MODE MODIFICATIONS IMPROVE OPERATION
    - NO MISSED PULSES
    - 1.5 SECOND TIME CONSTANT

Vu-Graph 9 Comments

A Monte Carlo analysis using currently estimated dispersions shows similar results for both trajectories, with perhaps a slight decrease in dispersions on the proposed trajectory. Figures 12 and 13 show the average, 3σ high, 3σ low, and minimum and maximum sampled altitude values vs. range.

The drooping effect caused by upward sloping terrain is less pronounced on the proposed trajectory. Figure 14 compares the two trajectories for 0°, -1°, and -2° slopes (upward toward site).

A series of trajectories was flown over various craters located at varying distances from the landing site. Only very large craters significantly altered the trajectory, even when the craters were placed very near the landing site. As an example, a 300 ft. deep, 1800 ft., diameter crater (about the largest found in an Apollo site) was located with its center 1900 ft. from the site. As shown in Figures 15 and 16 current trajectory drooped to within 70 ft. of the surface while the proposed trajectory drooped to 80 ft. minimum altitude. This is an extreme worst case situation and is only used to show the relative effects of flying over craters with the landing radar (LR) turned on.

The operation of the LR on a nominal descent is improved on the proposed trajectory since the slightly higher vertical velocities keep the beams further from the zero doppler boundaries. On a current nominal trajectory, the LR drops out at an altitude of about 240 ft. while the proposed trajectory maintains lock at least until the switch to the landing phase. Figures 17 and 18 show the LR dropout boundaries.

Vu-Graph 9

OTHER EFFECTS FOR PROPOSED TRAJECTORY

- DISPERSIONS ARE SLIGHTLY SMALLER THAN ON CURRENT TRAJECTORY
- UPWARD SLOPING TERRAIN PRODUCES LESS TRAJECTORY DROOP
  - WITH 2° SLOPE, MINIMUM ALTITUDE IS 100 FT. (VS 70 FT. ON CURRENT TRAJECTORY)
- CRATERS CAUSE LESS TRAJECTORY DROOP
- LANDING RADAR DROPOUT OCCURS LATER IN DESCENT

Vu-Graph 10 Comments

The effects of changing the hover altitude are discussed in the following section.

Vu-Graph 10

CHANGES IN HOVER ALTITUDE

Vu-Graph 11 Comments

In analyzing the descent trajectories, it was decided to separate the target value of the hover altitude from the other hover targets since nearly all the effects of changing hover altitude are separable from the effects of changing the other targets.

The 3σ altitude dispersion at hover is about 60 ft. and the landing radar is mounted about 10 ft. above the ends of the landing probes. Thus, if the hover altitude were 70 ft., with a 3σ low trajectory the probes would contact the surface at the time of entering the landing phase on an automatic descent. Since the nominal trajectory has a 5.5/fps horizontal velocity at this point, a hover altitude greater than 70 ft. is necessary. An additional 30 ft. is suggested in order to allow most of the horizontal velocity to be nulled. In addition, the time constant (currently 10 seconds) for velocity nulling could be reduced to 7 seconds for example, to minimize the horizontal velocity at touchdown. (If the time constant is reduced to 7 seconds, a 5.5 fps hozintal velocity would be reduced to about 1 fps at touchdown in 30 ft. if the horizontal velocity is 3 fps).

Vu-Graph 11

"HOVER" ALTITUDE

- 3σ ALTITUDE DISPERSION IS ABOUT ± 60 FT.
- ABOUT 10 FT. FROM LANDING RADAR TO LANDING PROBES
- NEED ADDITIONAL ALTITUDE TO REDUCE HORIZONTAL VELOCITY (WITH $\tau = 7$ SEC. FOR VELOCITY NULLING, 5.5 FPS HORIZONTAL VELOCITY REDUCED TO ABOUT 1 FPS IN 30 FT. OF ALTITUDE)
- SUGGESTS 100 FT. HOVER ALTITUDE

Vu-Graph 12 Comments

With 100 ft. hover altitude, about 88 fps of ΔV is saved since less time is spent in the landing phase. The vertical rate vs. altitude curve shown in Figure 10 is merely moved to the right 50 ft. resulting in a vertical velocity of 19.7 fps at 500 ft. altitude. The effect on the number of pulses/second required to null this vertical velocity in the R-O-D mode (as illustrated in Figure 11) would be an increase of about 0.1 pulses/second above the values for the current trajectory. The dispersion Figures (12 and 13) and the Figures (14, 15, and 16) illustrating the effects of slopes and craters would be displaced downward by 50 ft. The landing radar operation would be slightly improved, though not significantly, due to the slightly higher vertical velocity.

Vu-Graph 12

100 FT. HOVER ALTITUDE

- SAVES 88 FPS OF ΔV
- VERTICAL RATE AT 500 FT. RAISED TO 19.7 FPS (VS. 16 FPS WITH CURRENT TRAJECTORY AND 18 FPS WITH 150 FT. HOVER ALTITUDE ON PROPOSED TRAJECTORY)

Vu-Graph 13 Comments

The proposed trajectory saves 116 fps of ΔV if the hover altitude is maintained at 150 ft. The reduced visibility time is compensated for by an improved capability to redesignate the landing site. The trajectory has a slightly higher, but still comfortable, vertical rate profile. Disturbances such as redesignations, craters, and, slopes are handled better by the proposed trajectory.

If the hover altitude is reduced to 100 ft. an additional 88 fps of ΔV can be saved without significantly increasing the likelihood of violating the touchdown velocity limits and with only a slight increase in the vertical velocity.

Vu-Graph 13

SUMMARY

- FOR EQUAL HOVER ALTITUDES, THE PROPOSED TRAJECTORY
  - SAVES 116 FPS OF ΔV
  - HAS 22 SECONDS LESS VISIBILITY TIME BUT SUPERIOR REDESIGNATION CAPABILITY
  - HAS SLIGHTLY HIGHER VERTICAL VELOCITY BUT IT IS NOT OBJECTIONABLE
  - HAS LESS TENDENCY TO DROOP WHEN LANDING POINT DESIGNATOR IS USED AND WHEN FLYING OVER SLOPES AND CRATERS
  - MAINTAINS LANDING RADAR LOCK CLOSER TO SITE
- FOR HOVER ALTITUDE OF 100 FT., THE PROPOSED TRAJECTORY
  - SAVES AN ADDITIONAL 88 FPS OF ΔV
  - INCREASES VERTICAL RATE AT 500 FT. TO 19.7 FPS BUT THIS SHOULD PRESENT NO PROBLEMS
  - MAINTAINS SUFFICIENT ALTITUDE IN DISPERSED CASES TO HAVE VERY LOW PROBABILITY OF VIOLATING TOUCHDOWN CRITERIA

Vu-Graph 14 Comments

The basic conclusion is that the increased jdz and decreased lower altitude give an automatic trajectory which has slightly higher velocities near low-gate. This saves ΔV in the automatic mode and permits the crew to fly a much more conservative descent in the event that they assume control of the LM.

The proposed trajectory is obtained by changing jdz from .0018 to .0275, the hover altitude from 150 ft. to 100 ft., and by changing the time constant for velocity nulling in the landing phase from 10 seconds to 7 seconds. All of these changes are in erasable constants in the LM Guidance Computer. The proposed changes save a significant amount of ΔV without significantly altering the shape or "feel" of the trajectory. In fact, the proposed changes make the portion of the trajectory near low-gate very similar to the 77 ft. hover trajectory used until late in 1968.

Thus, significant trajectory improvements are obtained by simple software changes which do not invalidate much of the previous crew training.

Vu-Graph 14

CONCLUSIONS

- TWO VERY SIMPLE CHANGES IN ERASABLE SOFTWARE CONSTANTS CAN SAVE A SIGNIFICANT AMOUNT OF ΔV
  - A TOTAL OF 204 FPS CAN BE SAVED ON AUTOMATIC DESCENTS BY INCREASING jdz TO .0275 FT/SEC^3 AND LOWERING THE HOVER ALTITUDE TO 100 FT.
  - UP TO 40 SECONDS OF ADDITIONAL HOVER CAPABILITY
- WITH THE PROPOSED AUTOMATIC TRAJECTORY, THE GUIDANCE SYSTEM FLYS A SLIGHTLY FASTER TRAJECTORY SO THAT THE CREW CAN FLY A SIGNIFICANTLY MORE CONSERVATIVE TRAJECTORY IF THEY TAKE OVER CONTROL

Figure 1

CURRENT TRAJECTORY TARGETS

WEIGHT (AT POWERED DESCENT IGNITION)	lb_m	33,215
IGNITION STATE VECTOR IN PLATFORM COORDINATES	ft	$\underline{P}_{in}$ = 5536842.,0.0, - 1560180.
(START OF TRIM MANEUVER)	ft/sec	$\underline{V}_{in}$ = 1502.77,0.0,5350.147
IGNITION TEST VALUES AT FIXED THROTTLE POINT		
(NOMINAL POSITION COMPONENTS IN GUIDANCE COORDINATES)	ft	R_{igxG} = 130,520.
	ft	R_{igzG} = 1,430,097.
	ft	R_{igyG} = 0
(NOMINAL TOTAL VELOCITY IN GUIDANCE COORDINATES)	ft/sec	V_{igG} = 5545.56
(GAINS USED IN IGNITION ALGORITHM)		K_x = .617631
		K_y = $.755 \times 10^{-6}$
		K_v = 410
BRAKING PHASE TARGETS	ft	$\underline{P}xG$ = 171.835,0.0, - 10678.6
	ft/sec	$\underline{V}xG$ = 105.876,0.0, - 1.0403
	ft/sec^2	$\underline{a}xG$ = .624126,0.0, - 9.10439
	ft/sec^3	jdz = - .0188267

Continued on Next Page

Figure 1 (Continued)

T SWITCH (BRAKING)	sec	$T_{sb} = 62$
F_{LO}	lb_f	$57\% * F_{max.}$
F_{HI}	lb_f	$63\% * F_{max.}$
VISIBILITY PHASE TARGETS	ft	$\underline{P}xG = 111.0852, 0.0, -26.793$
	ft/sec	$\underline{V}xG = -4.993, 0.0, .24785$
	ft/sec^2	$\underline{a}xG = -.2623717, 0.0, -.512009$
	ft/sec^3	$jdz = +.001807716$
T SWITCH (VISIBILITY)	sec	$T_{sa} = 12$
LANDING PHASE TARGETS	ft/sec	$V_{HDG} = -3.0$
LANDING TIME CONSTANT	sec	$T_{AUG} = 10$

PROPOSED TRAJECTORY TARGETS

SAME TARGETS AS CURRENT TRAJECTORY EXCEPT:

VISIBILITY PHASE JERK FT/SEC^3 $jdz = +.02749944$

FIGURE 2
ALTITUDE VS. RANGE

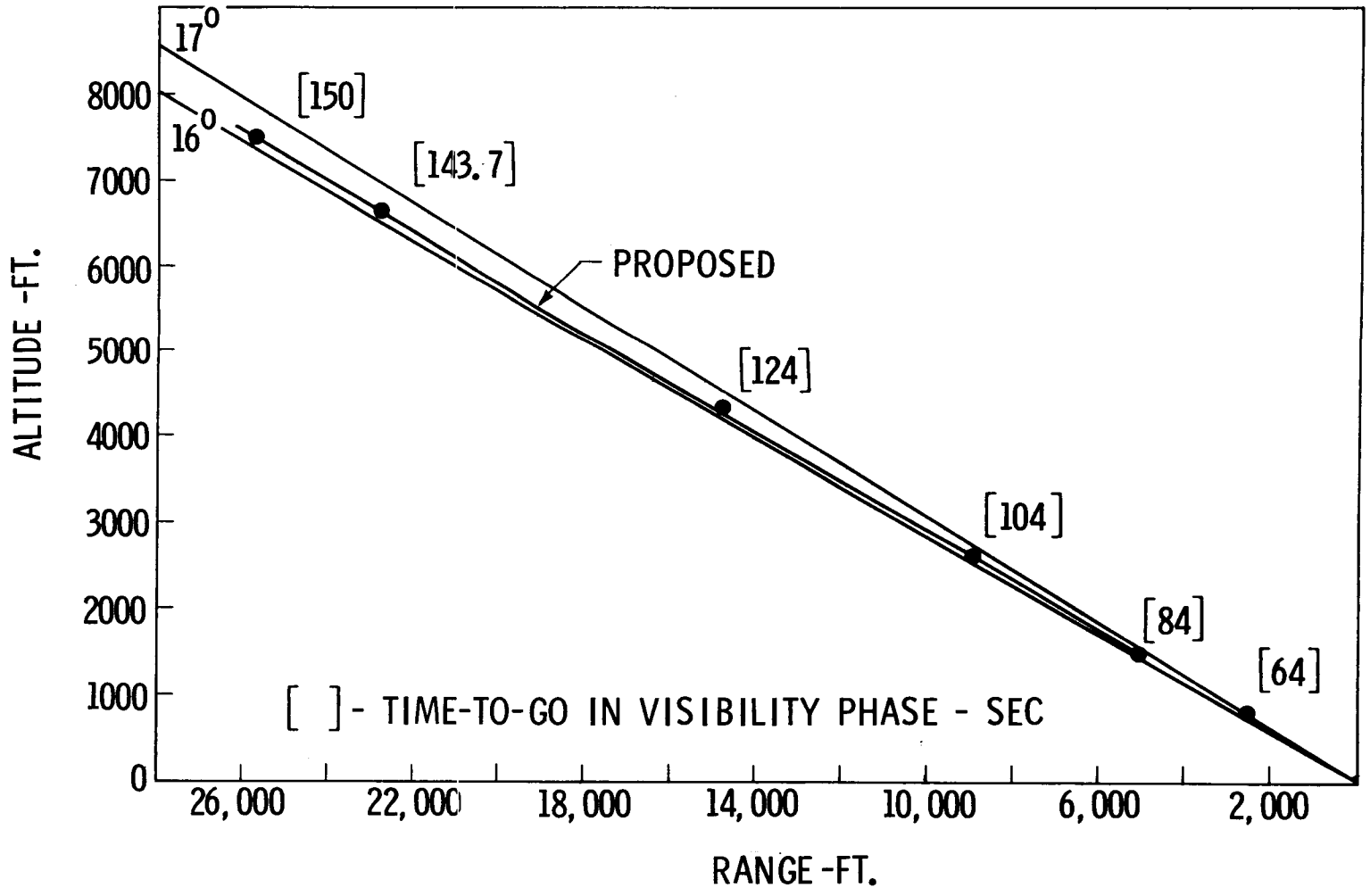


FIGURE 3
ALTITUDE VS. RANGE

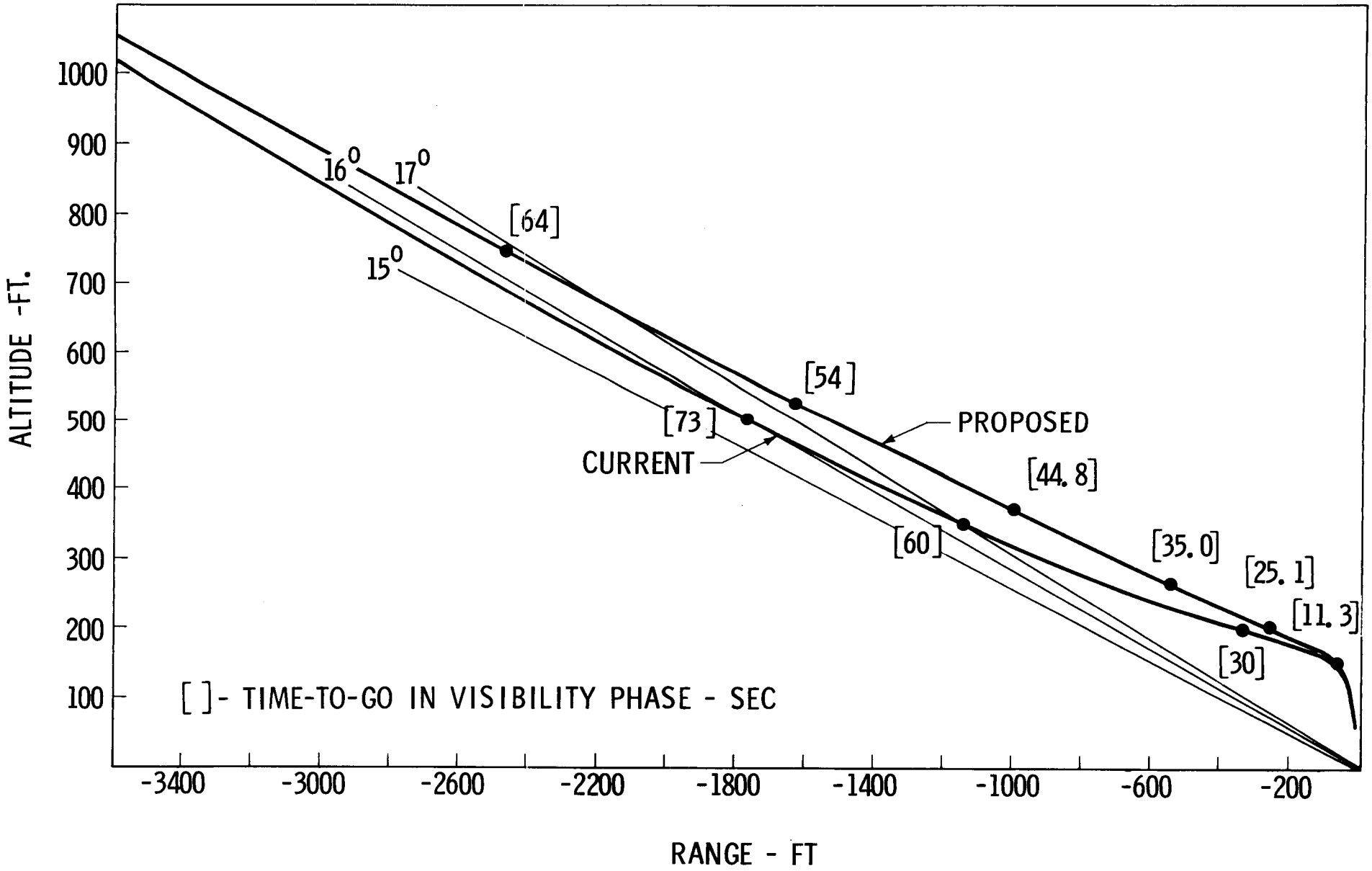


FIGURE 4
V_Z VS. RANGE-TO-GO

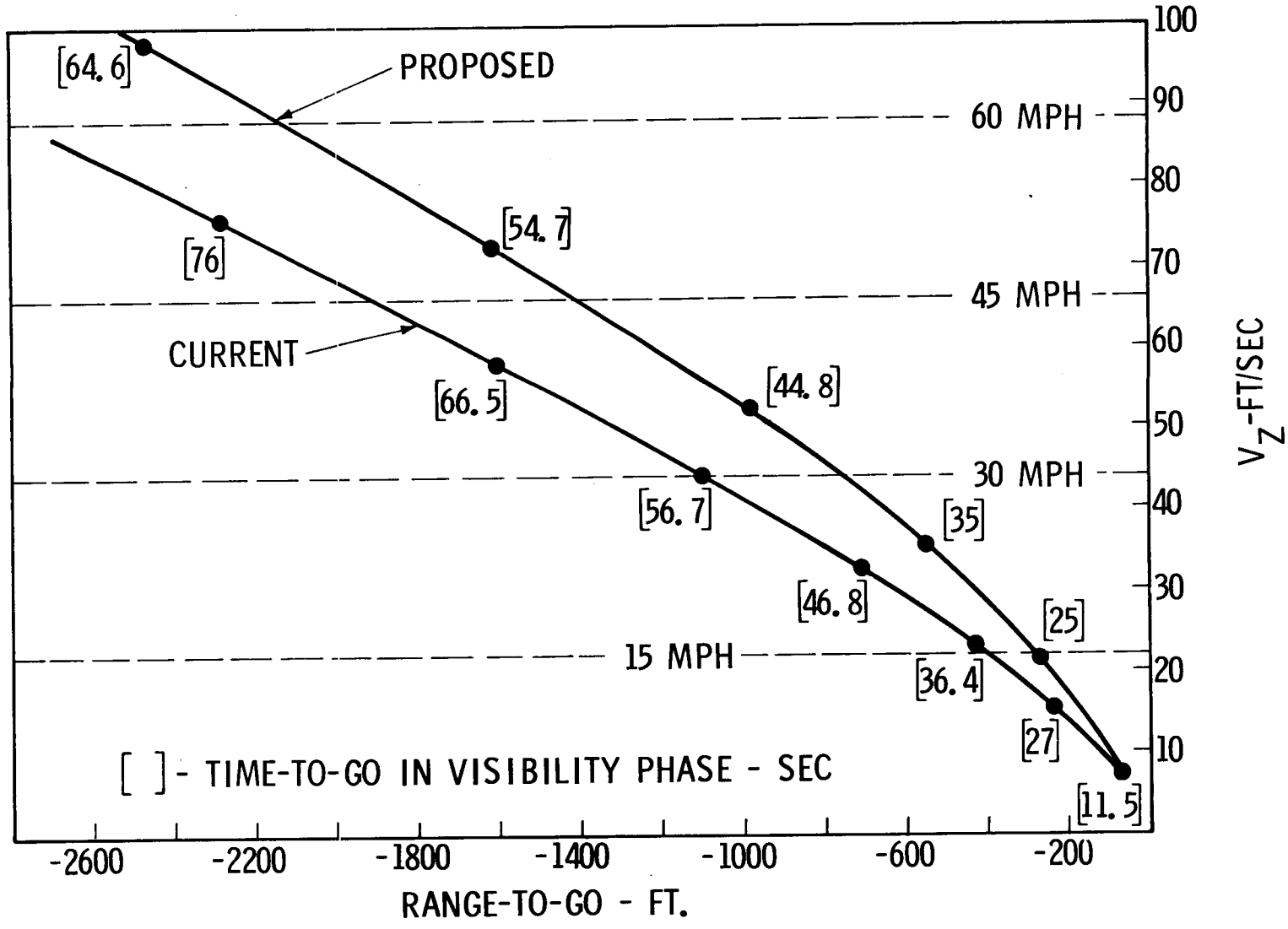


FIGURE 5
PITCH & $|a_T|$ VS. TIME-TO-GO

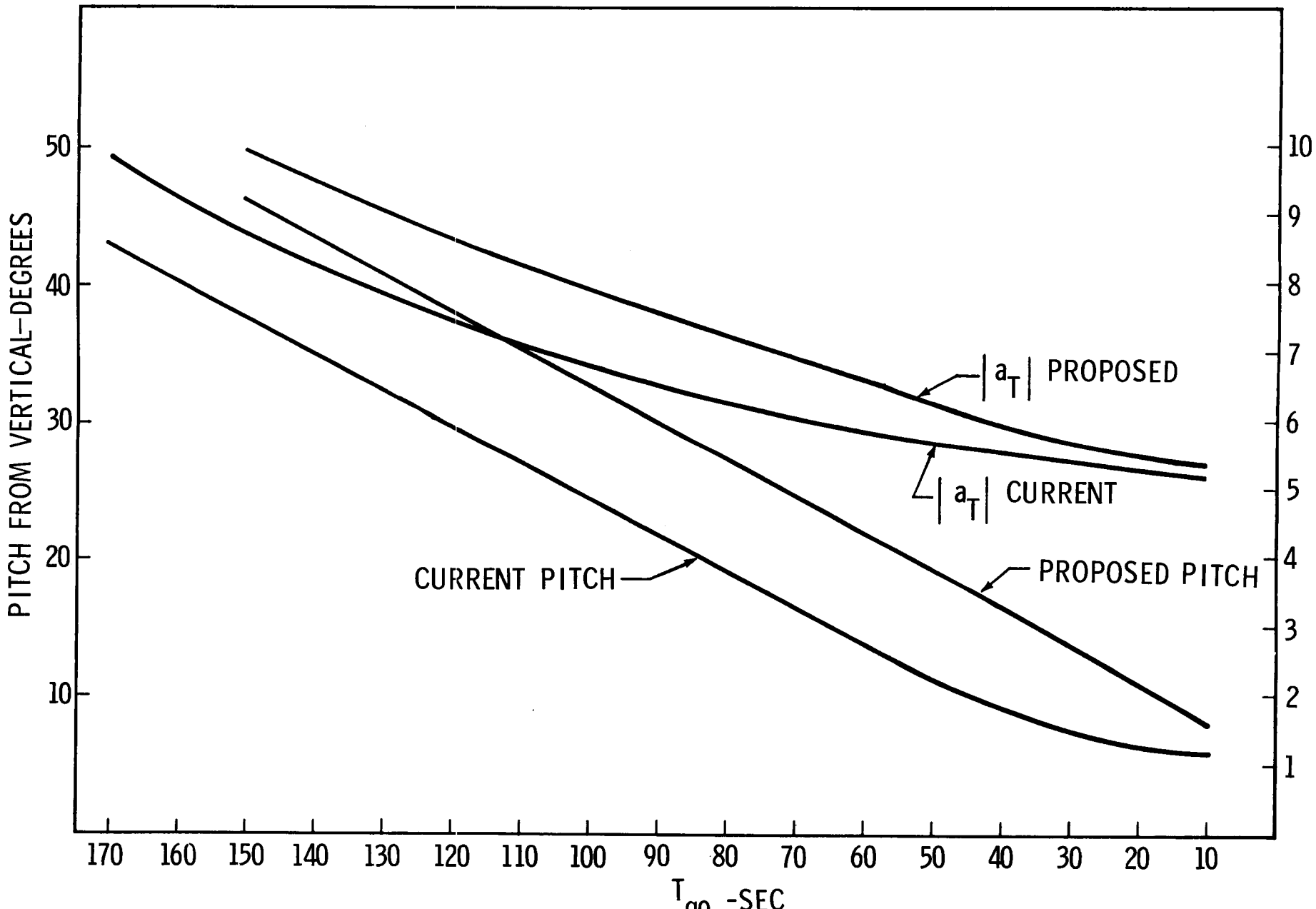


FIGURE 6
LOOK ANGLE VS. TIME-TO-GO

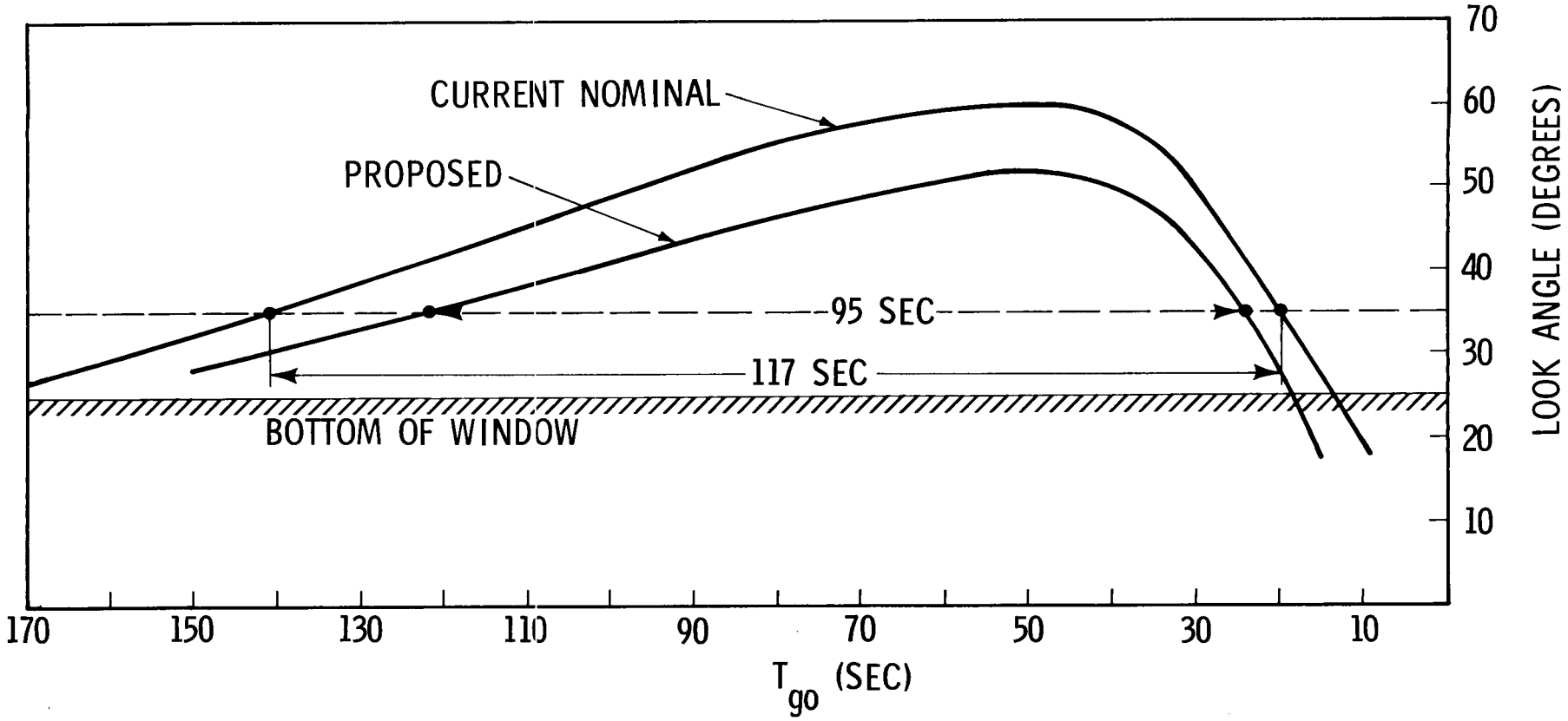


FIGURE 7
DOWNRANGE REDESIGNATION

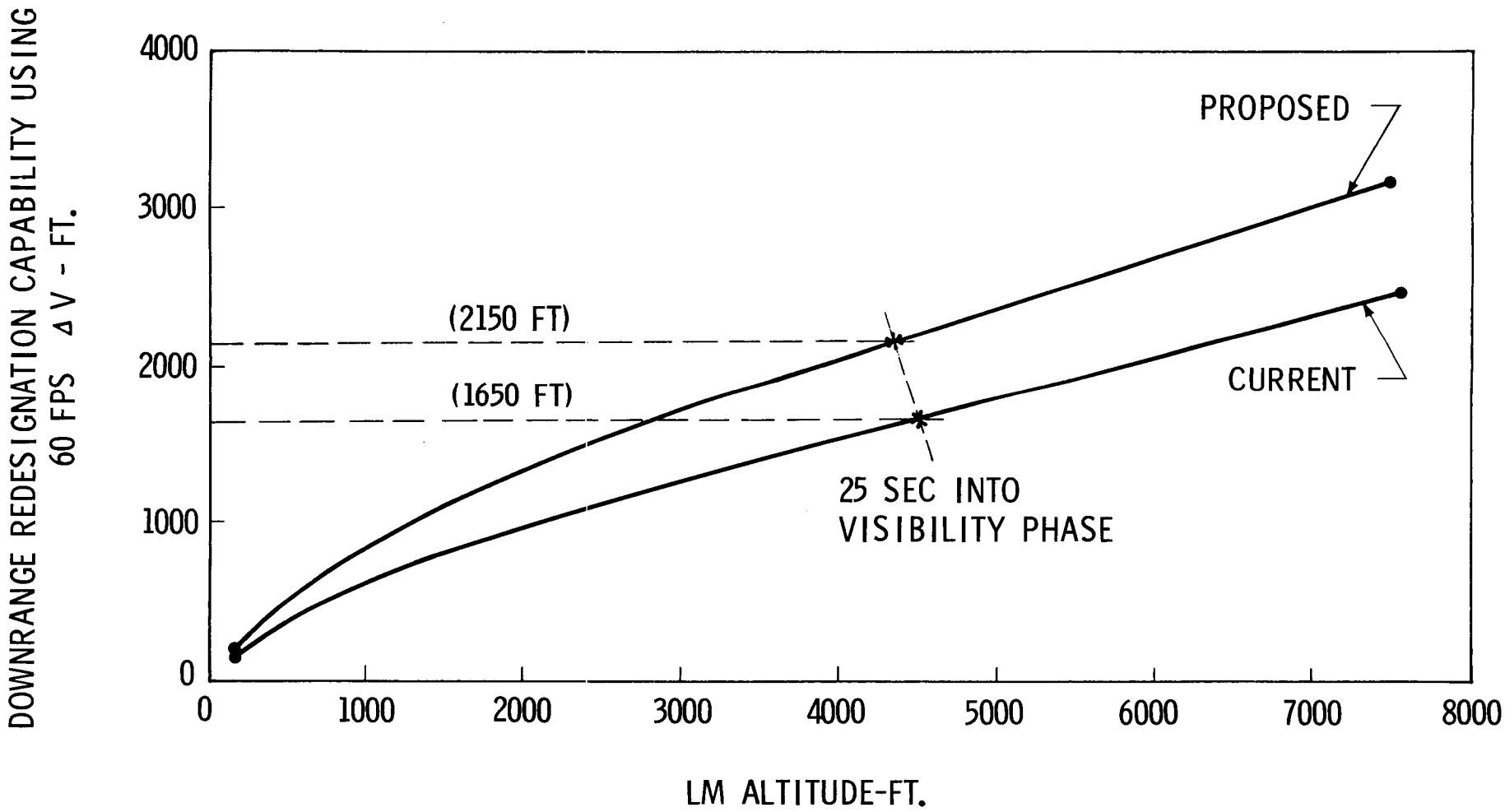


FIGURE 8
CROSSRANGE REDESIGNATION

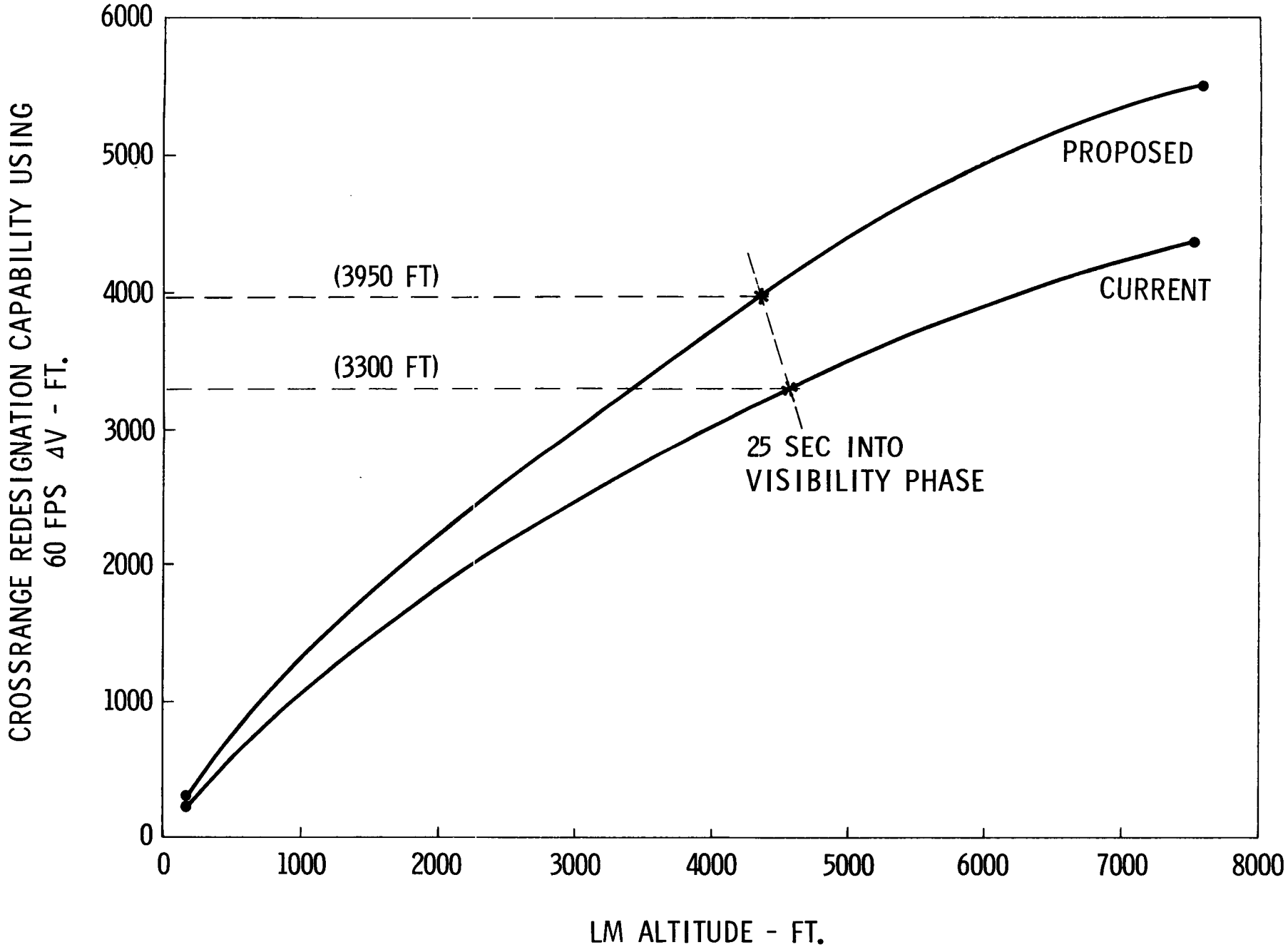


FIGURE 9
EFFECT OF REDESIGNATION

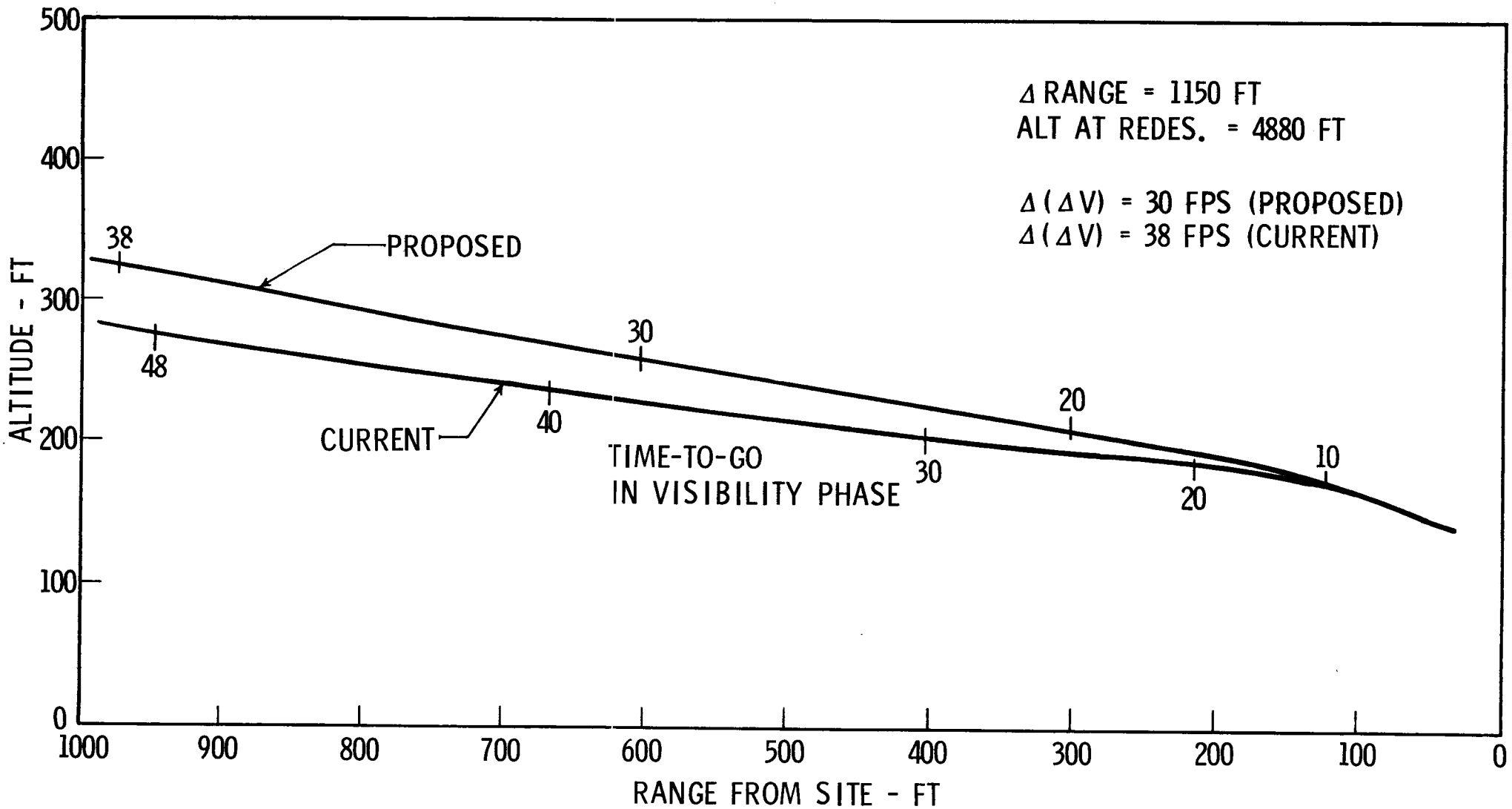


FIGURE 10
VERTICAL RATE VS ALTITUDE

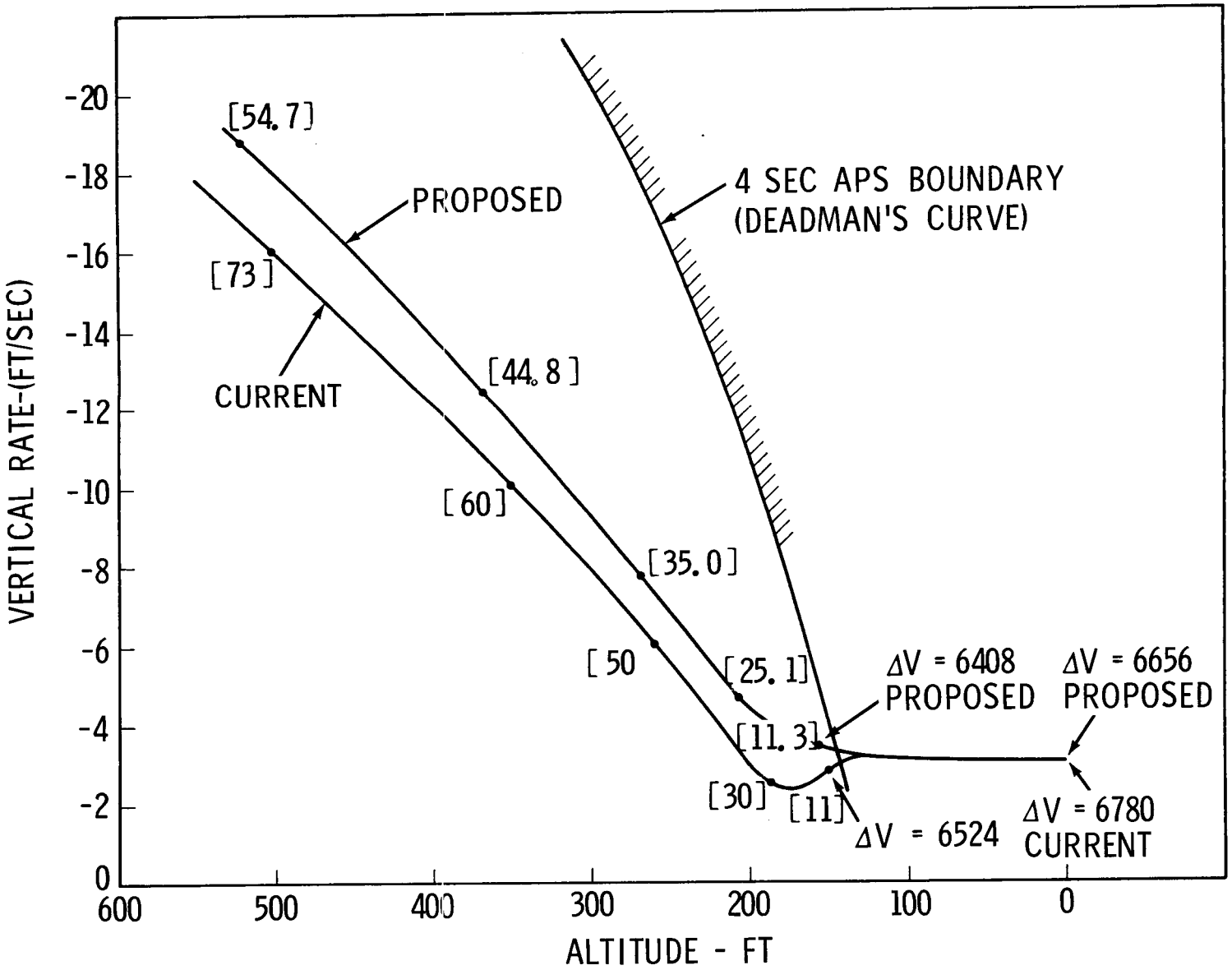


FIGURE 11
AVERAGE R-O-D PULSES/SECOND TO NULL VERTICAL VELOCITY
AT TOUCHDOWN

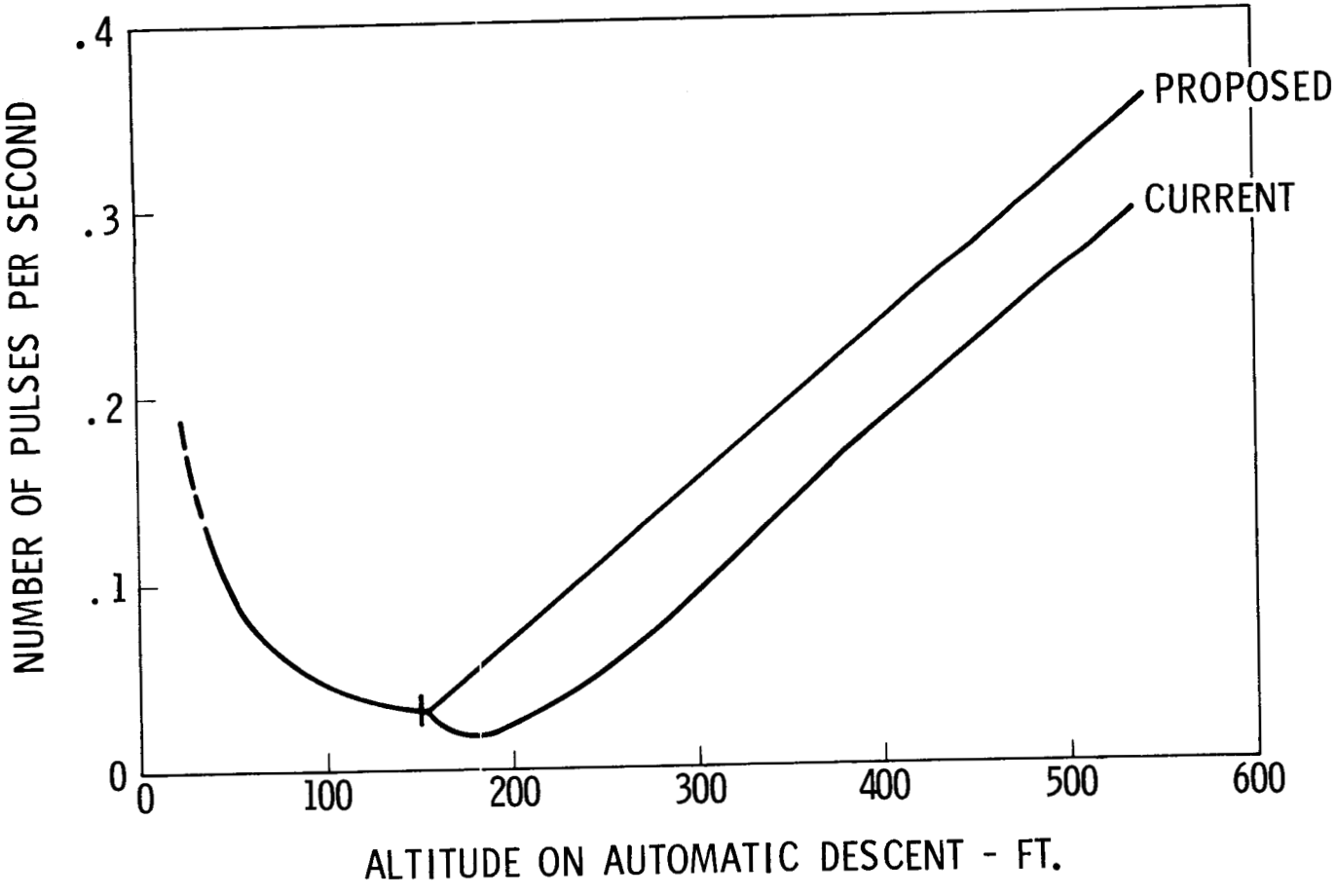


FIGURE 12
MONTE-CARLO ANALYSIS
100 TRAJ.
CURRENT TRAJECTORY

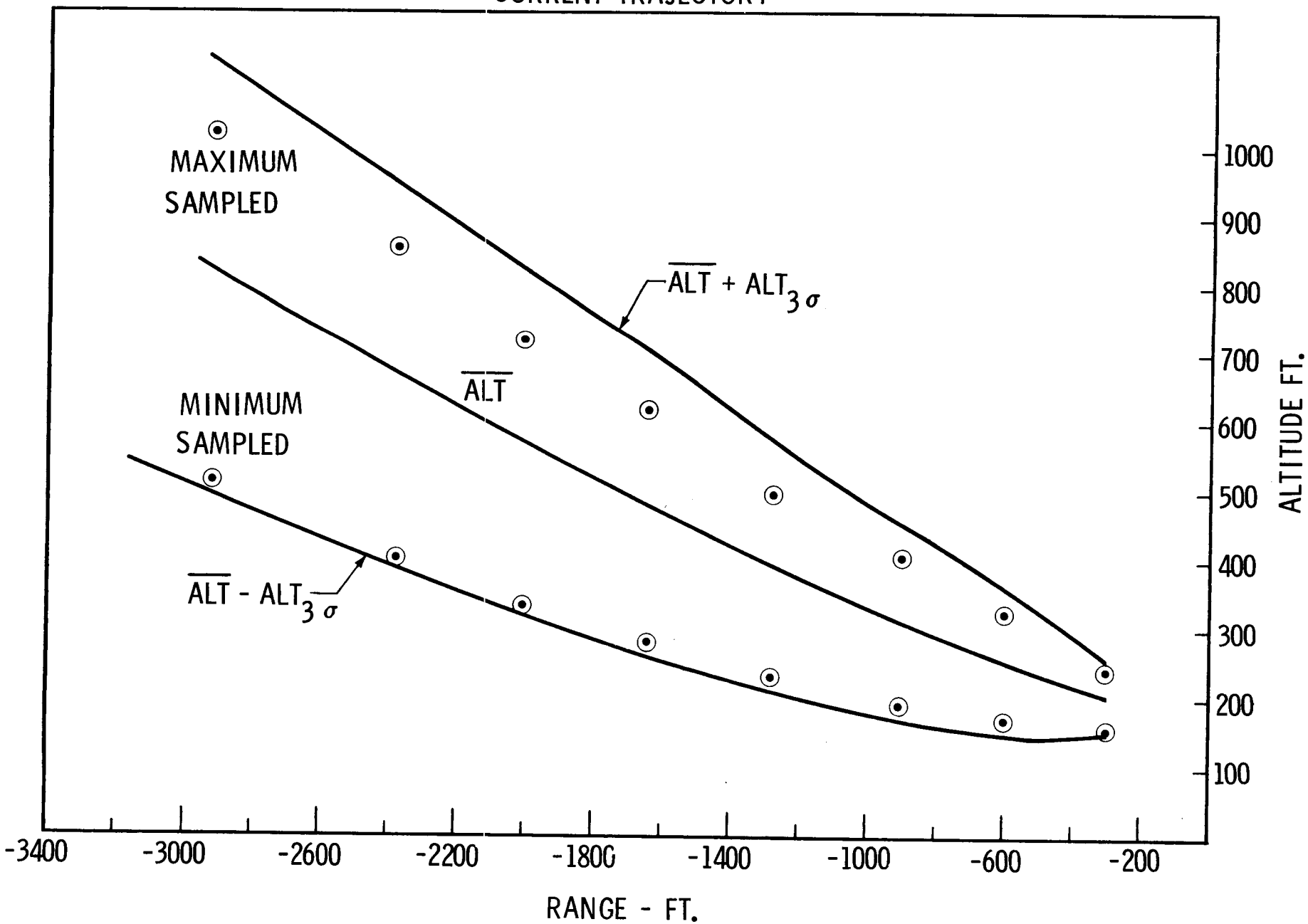


FIGURE 13
MONTE-CARLO ANALYSIS
100 TRAJ.
PROPOSED TRAJECTORY

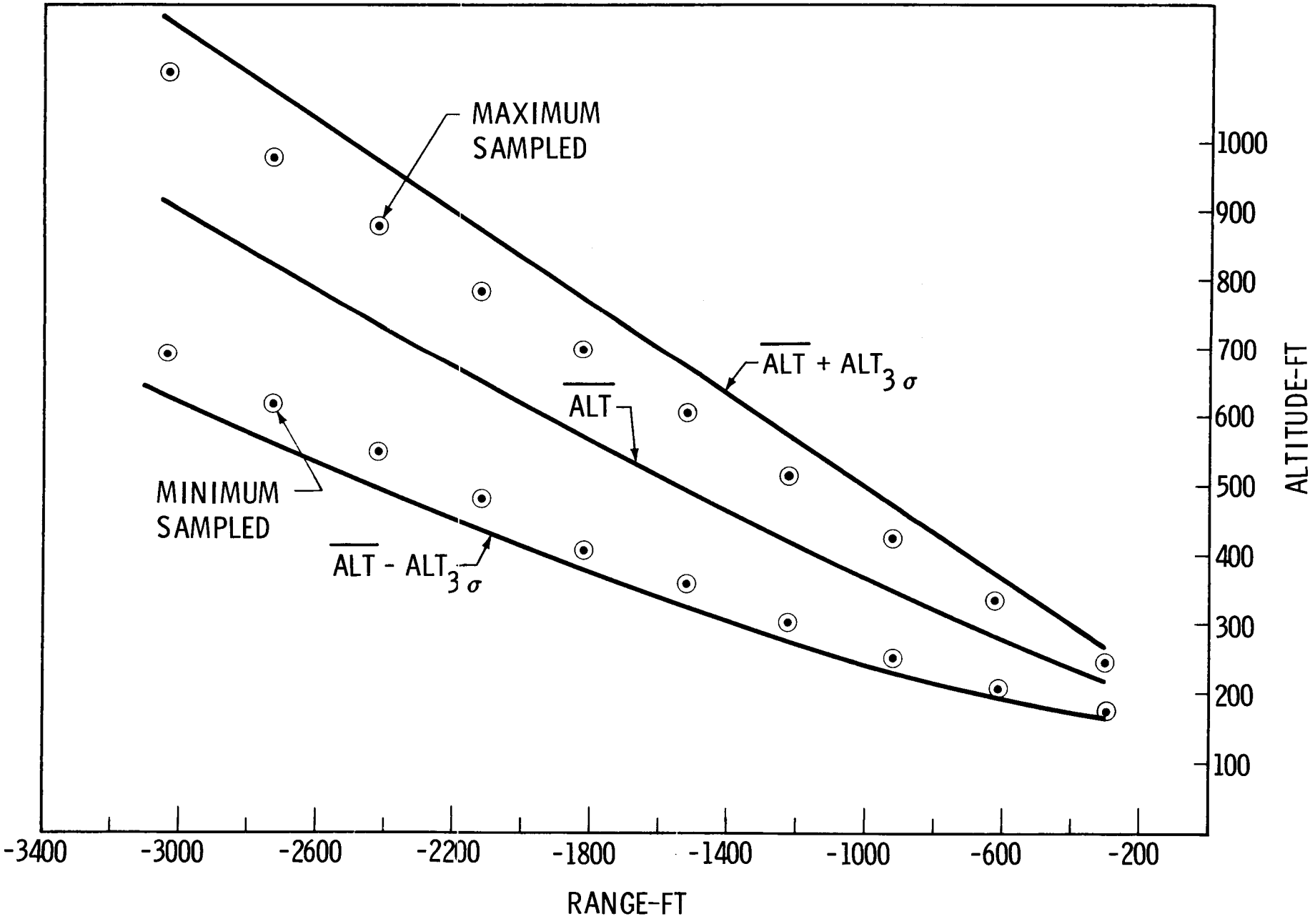


FIGURE 14
EFFECT OF SLOPES ON FINAL TRAJECTORY
(SLOPE BEGINS 120,000 FT FROM SITE)

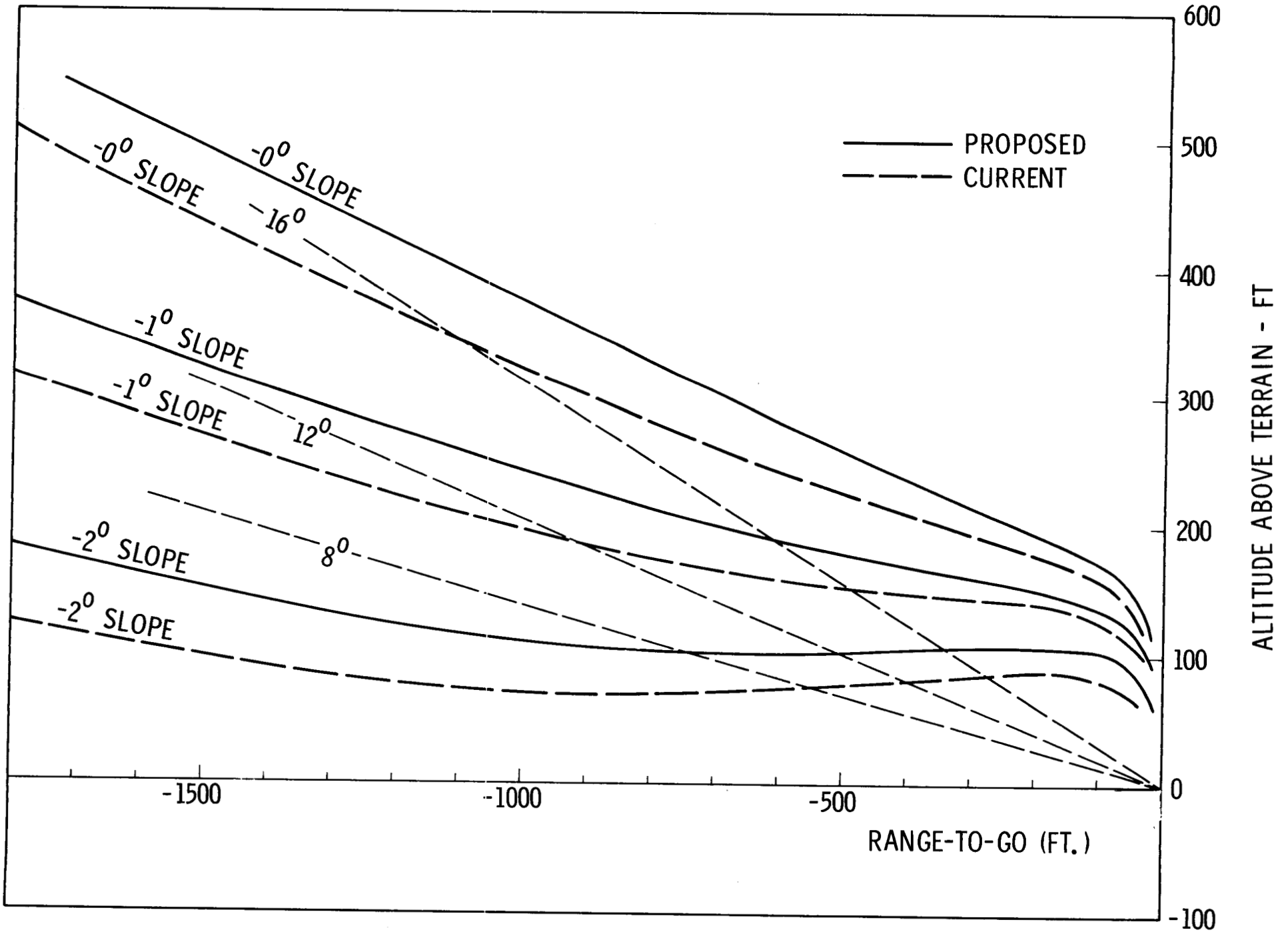


FIGURE 15
EFFECT OF CRATER ON ALTITUDE VS. RANGE
(PRESENT TRAJECTORY)

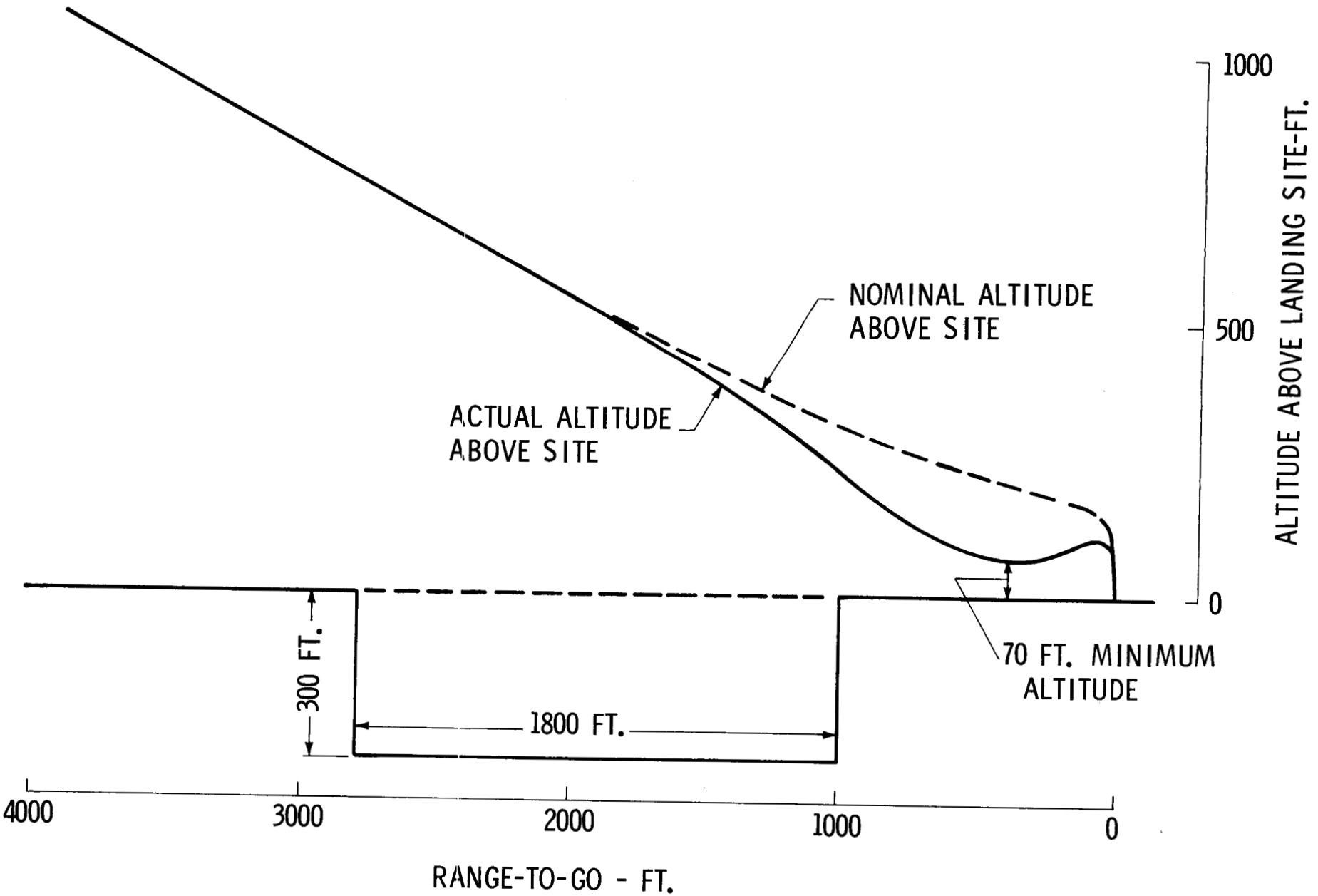


FIGURE 16
EFFECT OF CRATER ON ALTITUDE VS. RANGE
(PROPOSED TRAJECTORY)

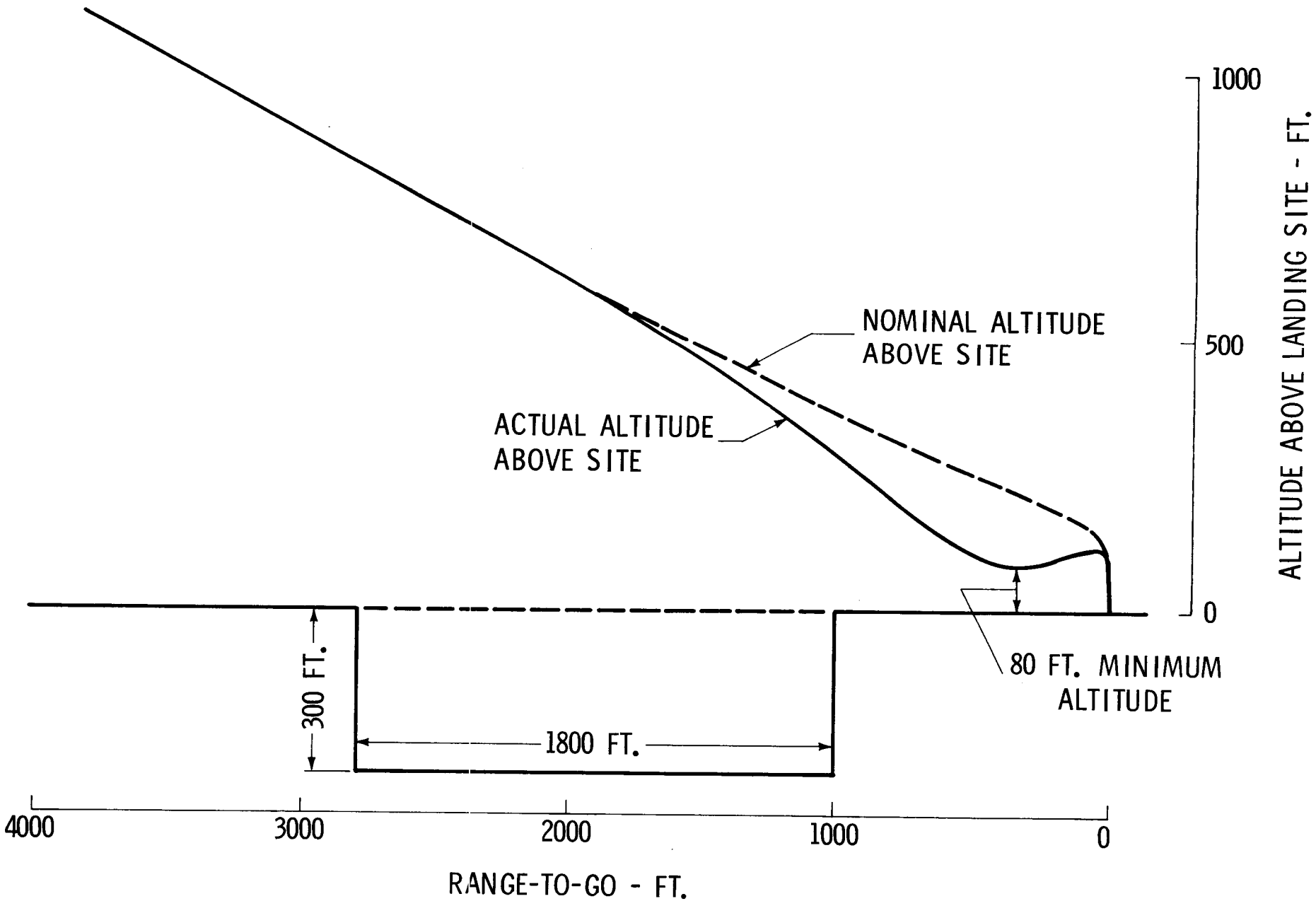


FIGURE 17
LANDING RADAR DROPOUT BOUNDARIES
CURRENT

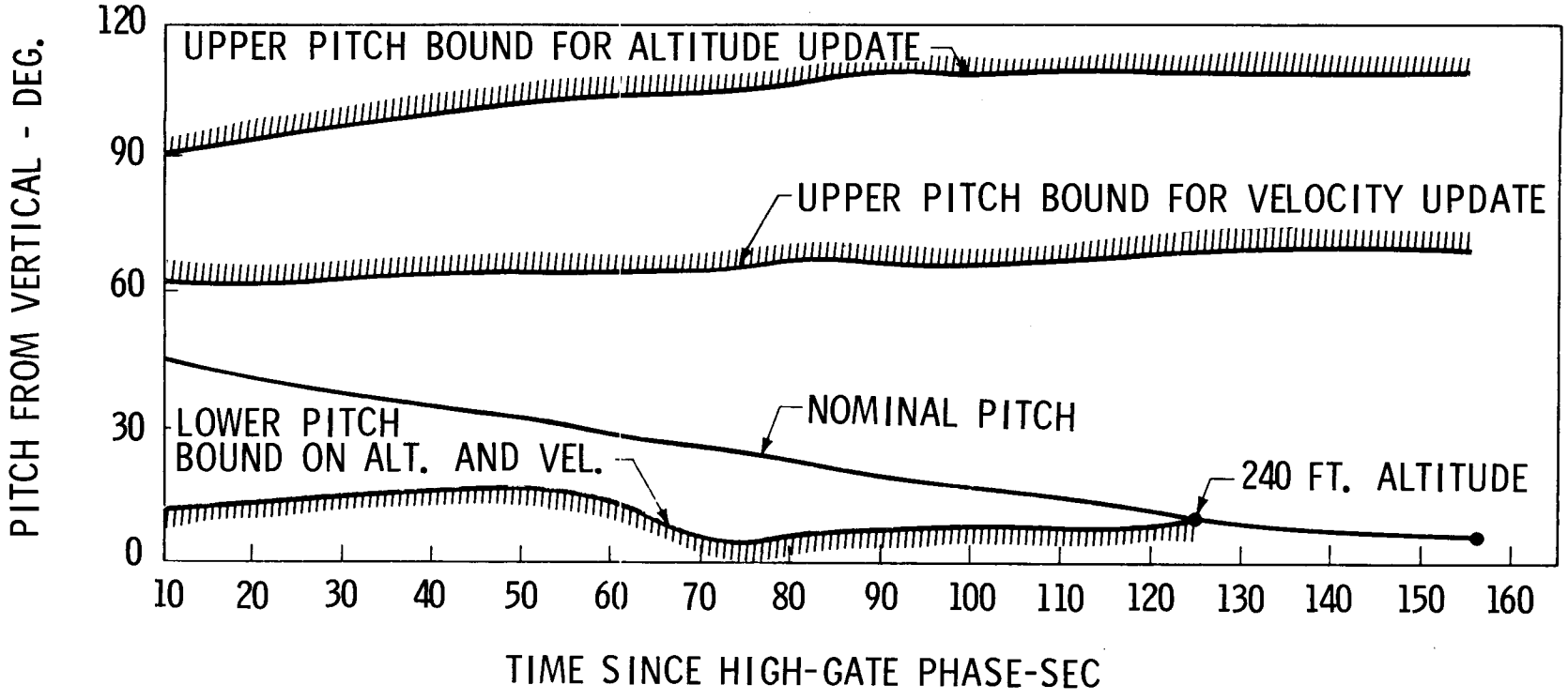
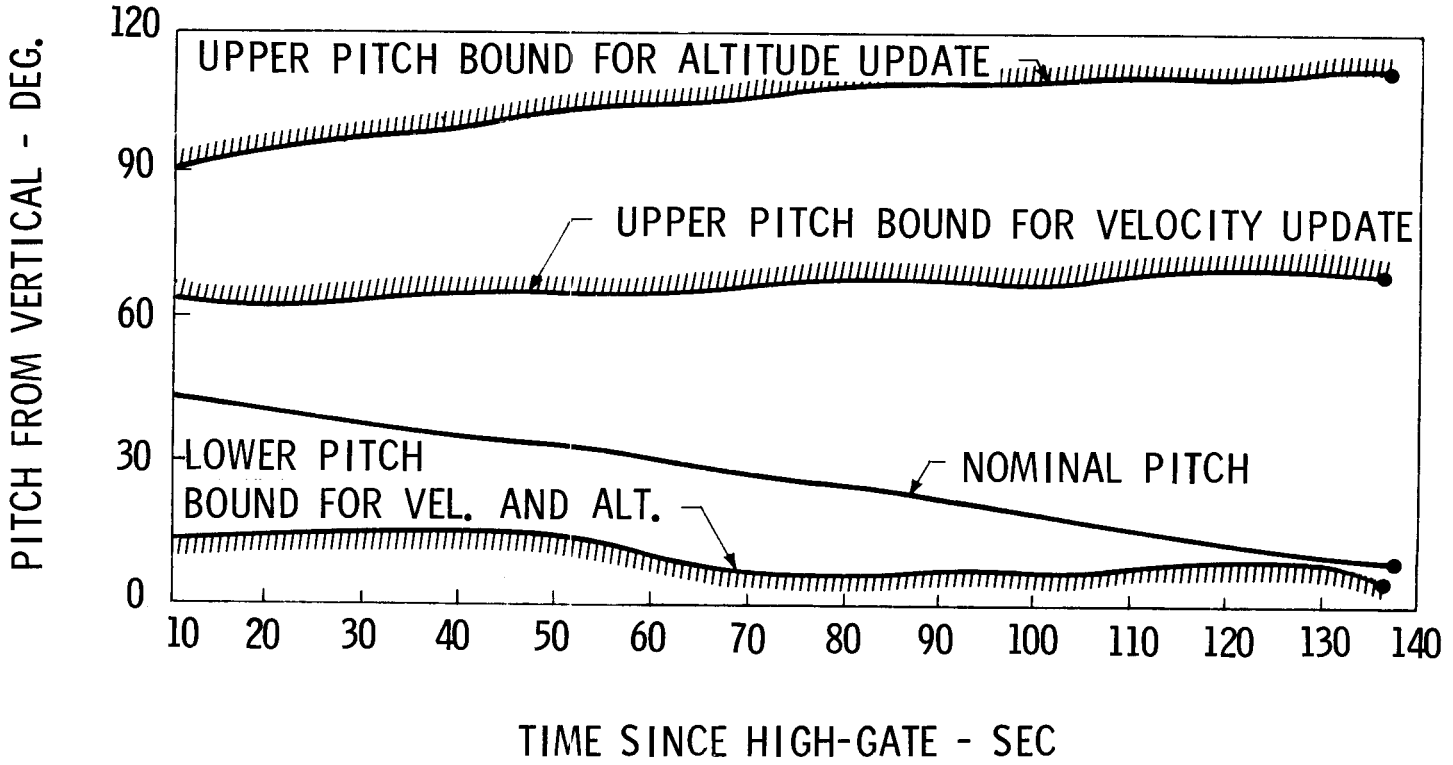


FIGURE 18
LANDING RADAR DROPOUT BOUNDARIES
PROPOSED



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Subject: Ideas for Improvement of LM Descent Trajectory

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T. B. Hoekstra
F. LaPiana

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