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PROJECT APOLLO

ANALYSIS OF LANDING POINT DESIGNATOR OPERATION

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INTRODUCTION

The Landing Point Designator (LPD) configuration and its operational application have been the subject of much discussion during the past three years. The trend of design growth has carried the LPD fr m the original telescope-reticle control device as proposed by MIT, to the present window-scribed grid design. Although the general function of the LPD is obvious, insufficient work has been done to describe the details of operational application or to determine the requirements of installation or performance. The work of Allan Klumpp at MIT, reference 1, has led to a concept of incremental inputs to the LEM computer to effect a redesignation of the landing site. This concept appears quite promising but requires supporting analysis that determines the trade-off between required accuracy, number of redesignation corrections (crew task loading) and fuel penalty. It is the purpose of this paper to discuss the relationship of these factors and to develop to a greater extent the logic of the LPD use.

LANDING POINT DESIGNATION OPERATION

General - The general function of the LPD is illustrated in figure 1. The LEM onboard guidance system is initially instructed as to the desired landing site. As the LEM guidance system steers to the desired site, it computes the line-of-sight LOS to the site and displays the value of LOS to the pilot. The crew in turn uses an optical device to look along the computed line-of-sight to the intended landing position. Because of accumulated navigation errors in the guidance system due to lunar orbit navigation errors and inertial system drift, the guidance system LOS will be directed to other than the desired site. The pilot notes the discrepancy between the LOS to the desired landing site and the landing site that will be obtained without correction to the guidance. The magnitude of this discrepancy is input to the guidance system and, assuming no error in the input and neglecting subsequent navigation errors, the guidance system will then take the LEM to the desired landing point.

Optical (LPD) System Description - The optical device referred to in the previous section has evolved to be a pattern of scribed lines on the outer and inner surface of the LEM window. The general configuration as conceived by GAEC of the scribed lines and their relationship to the window are shown in figures 2(a), (b), and (c). The lines when viewed by the pilot in effect, form a lubber line parallel to the LEM X-axis with graduations marks depicting elevation angles measured sequentially down from a reference line that is parallel to the LEM axis.

Error Sources - There are four major error sources known to be associated with the LPD operation; a) IMU alinement errors, b) boresight errors, c) optical application errors and d) absolute altitude errors. Discussion of these errors follows:

a. IMU alinement errors - The guidance system will be referenced to the IMU to determine LOS angles to the landing sight and therefore misalinement of the IMU will contribute angular errors to the LPD operation. Assuming an alinement of the IMU 15 minutes prior to initiating powered descent, an average 3σ IMU misalinement during the terminal portion of the descent trajection (when the LPD is likely to be used) will be about 0.15°. The direction of the misalinement should be assumed nonpredictable prior to the descent but will be approximately (some variation with time) constant during the descent.

b. The boresight error is the incremental relative angular alinement between the navigation base and the LPD grid marking on the window. This error results from manufacturing and installation tolerances and possibly from bending of the structure including the window due to pressurization and/or acceleration forces. This error should be amenable to calibration on the ground prior to flight and possibly to calibration in flight. Considering that compensation of calibrated boresight errors will be made, an estimate of $\frac{1}{4}^{\circ}$ boresight error (3σ) is considered reasonable. The uncompensatable portion of this error is nonpredictable prior to the descent but will be approximately (some variation with descent engine thrust-to-weight ratio) constant during the descent.

c. The optical application error is believed to be the predominant LPD error source. It is due primarily to the error of the pilot in interpreting the target area relationship to the grid markings. The close proximity of the grid markings on the inner and outer window surface in itself will make it very difficult to exactly aline the markings. In addition, when the pilot focuses his eyes on the target landing area, the grid markings, being close to the pilot's eyes will be out of focus and perhaps difficult to keep alined. GAEC has run an initial evaluation using untrained subjects and a 2-degree LPD graduation. This evaluation reported in LMO-480-315 indicated a 3σ error of 1.05 deg. It is expected that this error could be considerably reduced by having one degree graduation and using subjects properly trained (as the astronauts would be) for the task. The present status of tests being conducted by the Guidance and Control Division indicates that a 3σ error of 0.5 degree can be expected and formal reporting is in progress. The vibration of the LEM during powered flight may further contribute to the difficulties of the pilot in obtaining accurate LPD application. The assessment of this problem must await a definition of the LEM vibration environment and an adequate test facility. There are no known plans for such tests.

d. The LPD error associated with absolute altitude errors due to terrain height difference between the landing site and current position is illustrated in figure 3. Because of the relatively low flight path angle during the approach, the altitude error leads to a landing point designation error approximately four times the absolute altitude uncertainty. The figure shows the effect of terrain variation relative to the landing site but the error could also originate from landing radar inaccuracy or from the inertial system when the landing radar weighting function does not predominate.

ANALYSIS AND DISCUSSION

Assumptions - An analysis of the utilization of the LPD involves consideration of the system errors, system constraints such as the minimum increment of LPD change and the logic or ground rules applied by the pilot. Because the latter two factors have not been firmly established, it was necessary to make certain assumptions to facilitate the analysis. These assumptions are as follows:

a. Due to the approach geometry the LPD azimuth errors are less critical than LPD elevation errors, therefore the analysis is limited to errors in elevation only.

b. Changes in the LPD reading will be made in increments of $\frac{1}{2}$ degree only.

c. An LPD change will be made by the pilot only when the apparent error is $\frac{1}{2}$ degree or greater.

d. All LPD errors are bias errors as opposed to random errors.

LPD Application Geometry - With the preceeding assumptions the LPD error at one point on the trajectory results in a fixed-range error on the surface that is purely a geometrical function of the angle of the approach path and the angular magnitude of the LPD error. As the LEM proceeds down its flight path, this range error subtends an LPD angle that grows almost linearly and inversely with altitude. Assuming a nominal flight path of -14 degrees, this geometric growth of LPD error is pictured on figure 4. An example shown on the figure considers the case of 0.5 degree error at 8,000 feet altitude. The initial range error is 1140 ft and by the time the altitude reaches 4,000 ft., this range error subtends an angle of 1 degree. This 1 degree error appears as only $\frac{1}{2}$ degree error to the pilot because of his $\frac{1}{2}$ degree total system error and he would redesignate by $\frac{1}{2}$ degree. The process then repeats at 2,000 ft altitude and so on down as shown on figure 4 until below 1,000 ft altitude the range error represented by $\frac{1}{2}$ degree approached 100 ft. Note that a total of 4 redesignation are made before the error is less than 100 feet.

If the bias error is 1.0 degree, the stair-stepping sequence repeats more often as shown in figure 4 and a total of 6 redesignations are made - the last being at about 500 ft altitude and the error has not yet been lowered to 100 ft. It is apparent that the number of redesignations is directly dependent upon the magnitude of the bias error, the minimum increment of correction and the logic of how the correction is applied. These examples are obviously over simplified because operational logic would indicate that if the corrections are being made in the same direction, a bias is present that would at least deserve an extra unit of correction. Such logic would reduce the number of redesignations and would tend to minimize the unknown bias.

Fuel penalty as a function of landing point redesignation - In order to assess the relative cost of descent engine fuel with LPD errors, the work of reference 2 was extended to determine variations of the parameter characteristic velocity per degree (and per foot) of landing point redesignation with both altitude and downrange distance. These variations are shown in figures 5 and 6 for single and double redesignations, respectively.

From figure 5(a), it is evident that a fuel (delta V) penalty is incurred for redesignating downrange and a fuel saving may be incurred if the range is shortened. Relatively speaking, the penalty is slightly more to go further downrange than is saved by shortening the range a like amount. As the altitude is decreased, the results indicate that the fuel penalty, delta V per degree of redesignation is decreasing, but from figure 5(b), it is evident that the actual penalty per foot of redesignation is increasing.

The results shown in figure 6(a) and (b) show that if a major redesignation is made at an altitude of 8,000 ft, the magnitude and variation of the characteristic velocity parameter will be markedly changed for a subsequent redesignation at lower altitudes. Thus, if a figure such as figure 6 were to be used for assessing fuel costs, it would have application only to a specific case. Figures 5 and 6 provide information that affords appreciation of the LPD problem but does not provide a good means of assessing the general picture of LPD error costs.

Fuel penalty variation with LPD error - To determine relative costs of redesignations with LPD errors, a series of runs were made for LPD error magnitude of 0, $\pm\frac{1}{2}$ degree and ± 1 degree. The series of runs were conducted first where no gross redesignation was made and the corrections started at 8,000 ft, the second series had a gross redesignation of 8,000 ft downrange at 8,000 ft altitude, and the third series had a gross redesignation of 16,000 ft downrange at 8,000 ft altitude. In each case the error was applied at the initial redesignation and was considered as a bias for each subsequent redesignation. The error was then allowed to grow to $\frac{1}{2}$ degree greater than the bias error before a subsequent redesignation correction was made. The first correction made below 1,000 ft of altitude was made with zero error.

The results of the analysis are shown in table 1. These results show rather clearly that negative LPD errors are more costly than positive LPD errors and in fact, positive LPD errors actually lead to a relative fuel saving when large downrange redesignations are made. This is true because the negative errors tend to cause the designation to be short of the intended target and the LEM is slowed at a greater initial acceleration. The result is that it takes a longer time period to reach the desired site and thus the fuel cost is increased. For positive errors, the redesignation is initially further downrange than the desired site and as a result, the guidance calls for less deceleration with the result that with subsequent corrections the desired site is reached in less time than with zero LPD error. It is significant to note that the guidance in this phase does not result in fuel optimum approaches and the savings in fuel with the positive LPD errors is associated with slightly less favorable (but still satisfactory) visibility of the target area during the approach.

The results indicate that whenever there is the possibility of a bias LPD error that the operational logic should call for the pilot to redesignate slightly beyond the target area. Because of the minimum increment size of LPD corrections, this would simply mean that if the correction cannot be made exactly with $\frac{1}{2}$ degree increments, then it is advantageous to redesignate beyond the target by an amount up to $\frac{1}{2}$ degree.

LPD Increment Size - The LPD increment size of $\frac{1}{2}$ degree in elevation and 2 degrees in azimuth as proposed by Klumpp in reference 1, is believed to be a reasonable compromise between having adequate control of landing site redesignation and keeping the required number of correction increments (with Klumpp's method a discrete input must be made for each increment of change) small. Smaller sizes, such as $\frac{1}{4}$ degree, would cause the number of discretes for a given change to be doubled. Although this size could be conveniently used for refining the designation, an initial redesignation of several degrees would probably call for so many discretes that the pilot would have trouble keeping count. A 1.0 degree increment would be easy to keep count on but would be too coarse to accurately designate the target area.

Accuracy of touchdown - The accuracy of an automatically controlled touchdown will primarily be a function of the accuracy of the last redesignation and the navigation errors during the subsequent time interval until touchdown is accomplished. The Apollo Mission Specification lists as a design objective, the ability to land within a 100 CEP of a landing aid.

During the final phase of the lunar landing approach, the landing radar performance will reportably be of the order of accuracy of ± 2 ft/sec (3σ). Assumed that the time of actual landing is 2 minutes after the last LPD update, the navigation system drift will be approximately $\pm$ 240 ft (3σ) because the predominant navigational error is the integrated velocity error. If it is assumed that the last LPD update is made at a range to the landing site of 3,000 ft (nominally this would correspond to about 700 ft of altitude) then a $\frac{1}{2}$ degree LPD 3σ error would give a downrange landing point error of approximately 100 ft and a crossrange error of about 25 ft. Assuming further that the components of the landing point error can be combined by RSS, the 3σ error would be slightly elliptical with the semi-major axis, about ± 265 ft downrange and/or only slightly more than the 3σ value due to navigation errors and the semi-minor axis just slightly greater than the crossrange navigation error or

±240[+] ft. Assuming this 3σ ellipse is adequately approximated by a circle of radius equal to 250 ft, the corresponding CEP is 98 ft or roughly equal to the design objective. For a LPD error of ±1.0 degree, the corresponding CEP would be about 120 ft. In either event, pilot manual control upon approaching the desired position could eliminate practically all errors and a landing within 25 ft of a desired position should be feasible.

CONCLUDING REMARKS

The analysis indicates that the fuel penalties associated with LPD errors of the order of ½ degree are reasonable provided that the logic for the initial LPD application is biased to the positive (downrange) side of the desired target area. The number of redesignations associated with a ½ degree LPD is about four depending upon the altitude of first redesignation, but it is probable that additional logic can be devised that would bracket the target area during the redesignation refinements and could reduce the total number required to the first redesignation and two subsequent refinements. The ½ degree increment associated with LPD updates is believed to be an acceptable compromise between resolution of target designation, number of refinements and final touchdown point accuracy.

REFERENCES

1. Klumpp, Allan R., Computer Aided Manual Landing - An Efficient Technique for Guiding the LEM Spacecraft to a Visible Landing Site, MIT/IL Space Guidance Analysis Memo 17-65, August 26, 1965

2. Steele, David E., Further Investigation of Landing Site Redesignation During the LEM Powered Descent, MSC Internal Note No. 65-EG-32, July 22, 1965

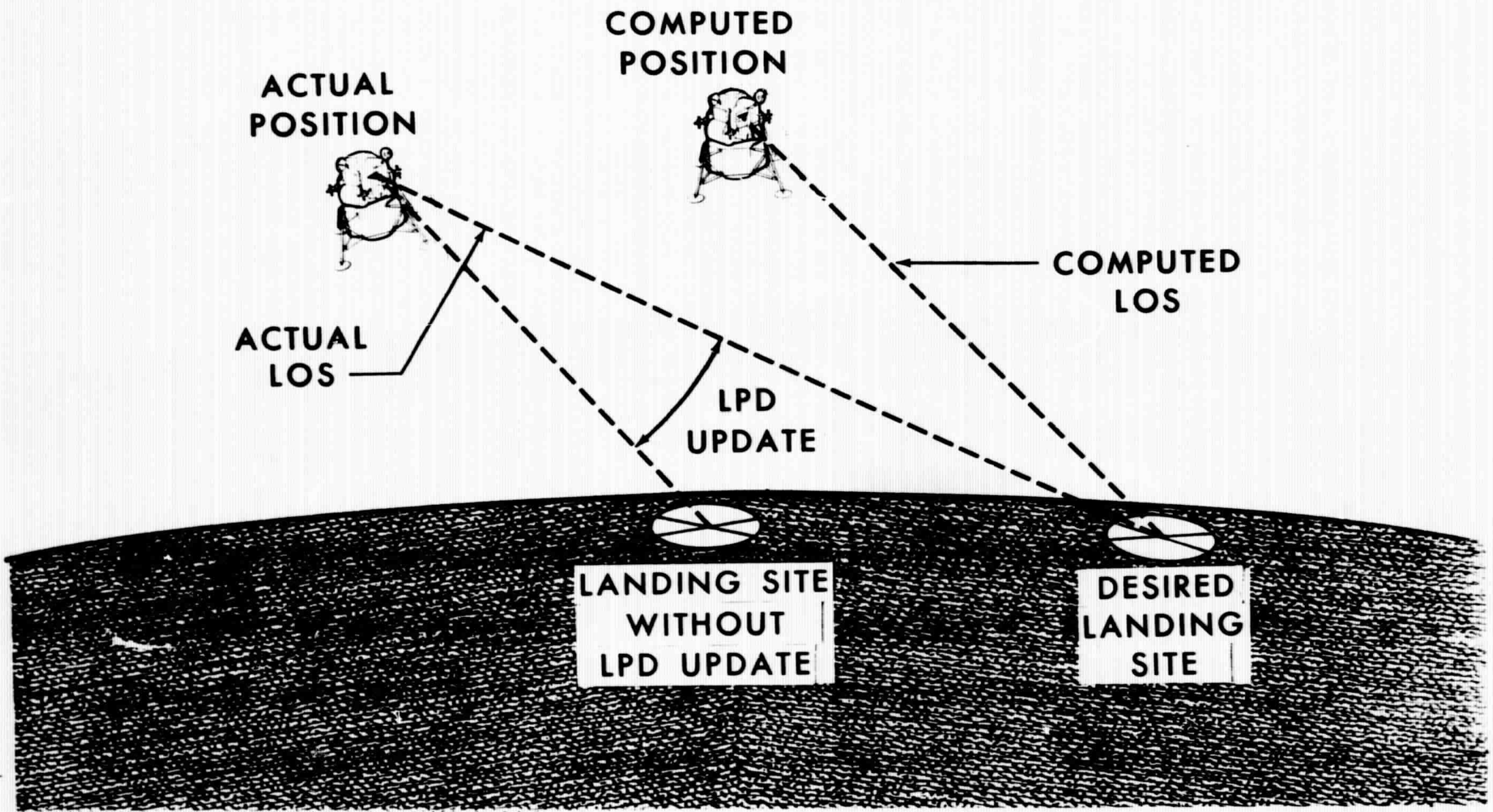

Figure 1.- Landing Site Redesignation with LPD Update

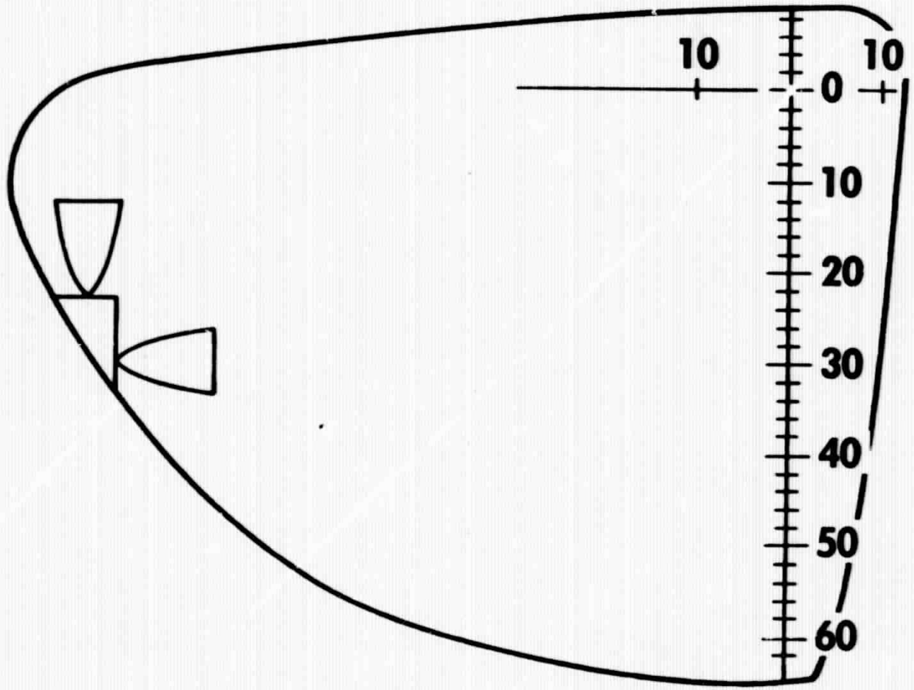

Figure 2.- Landing Point Designator
(a) From Eye Position

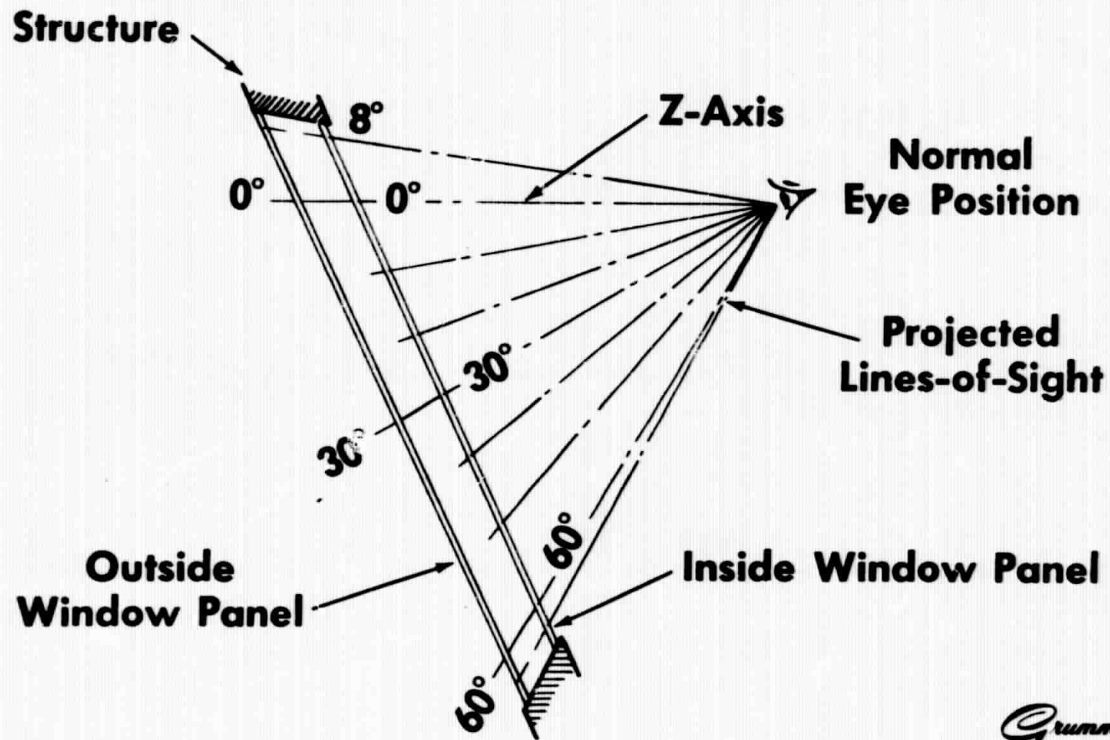

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Figure 2.- (continued)
(b) Side View

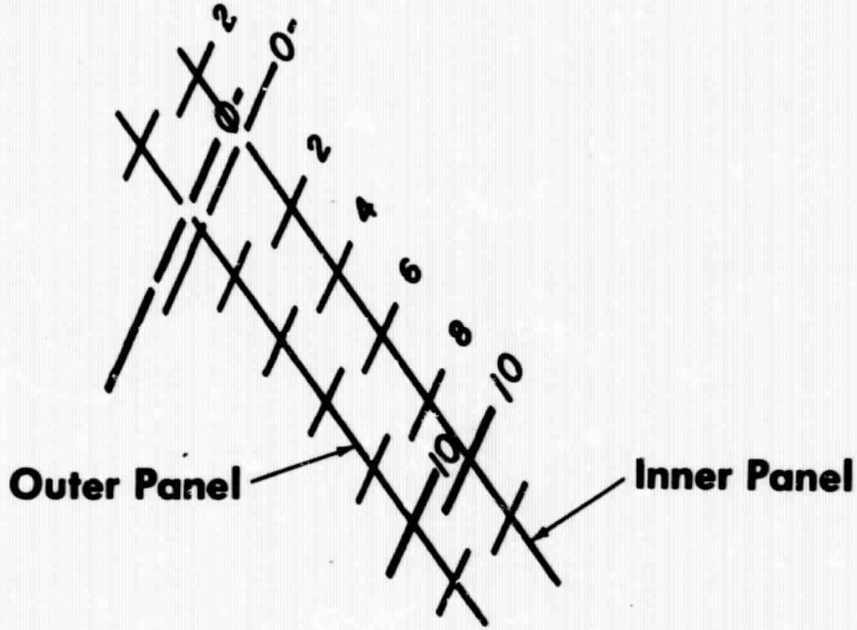

Figure 2.- (concluded)

(c) Inner and Outer Reticles

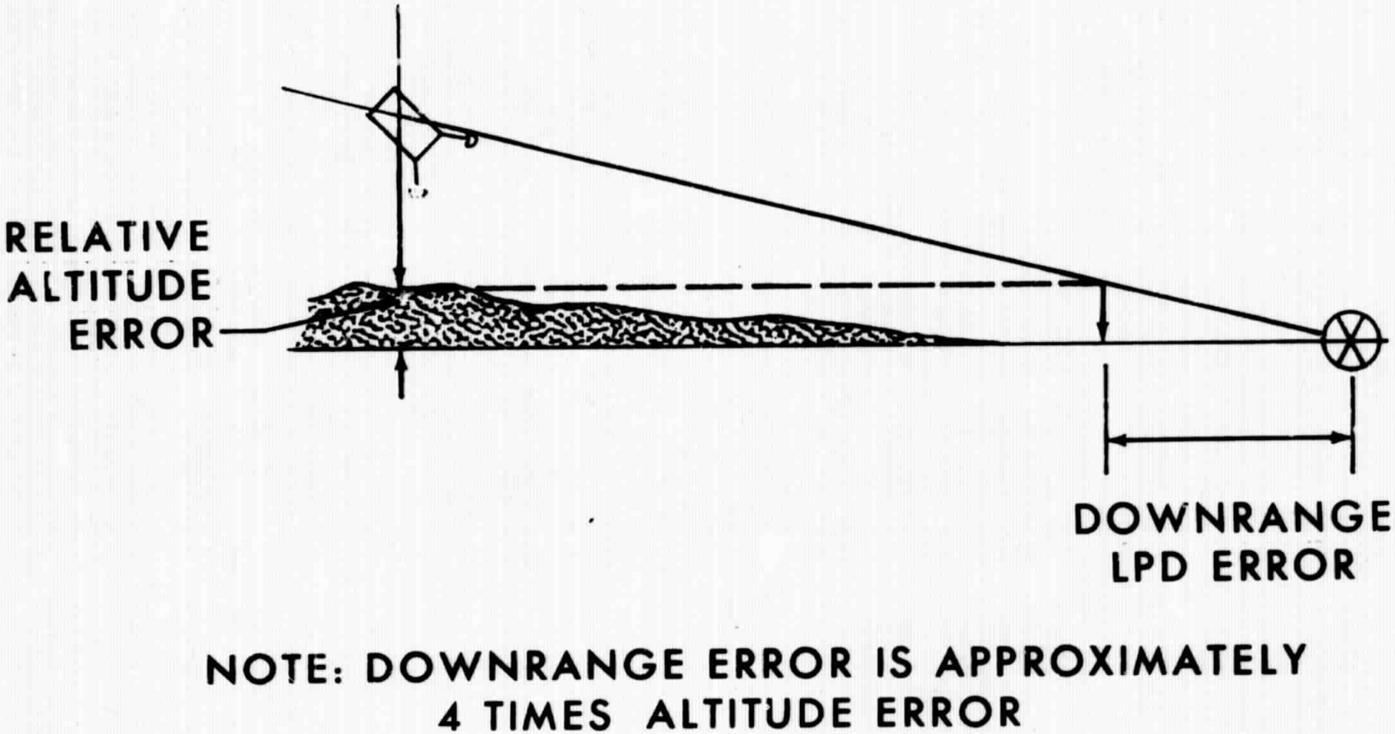

Figure 3.- Altitude Error Effect Upon LPD Downrange Accuracy

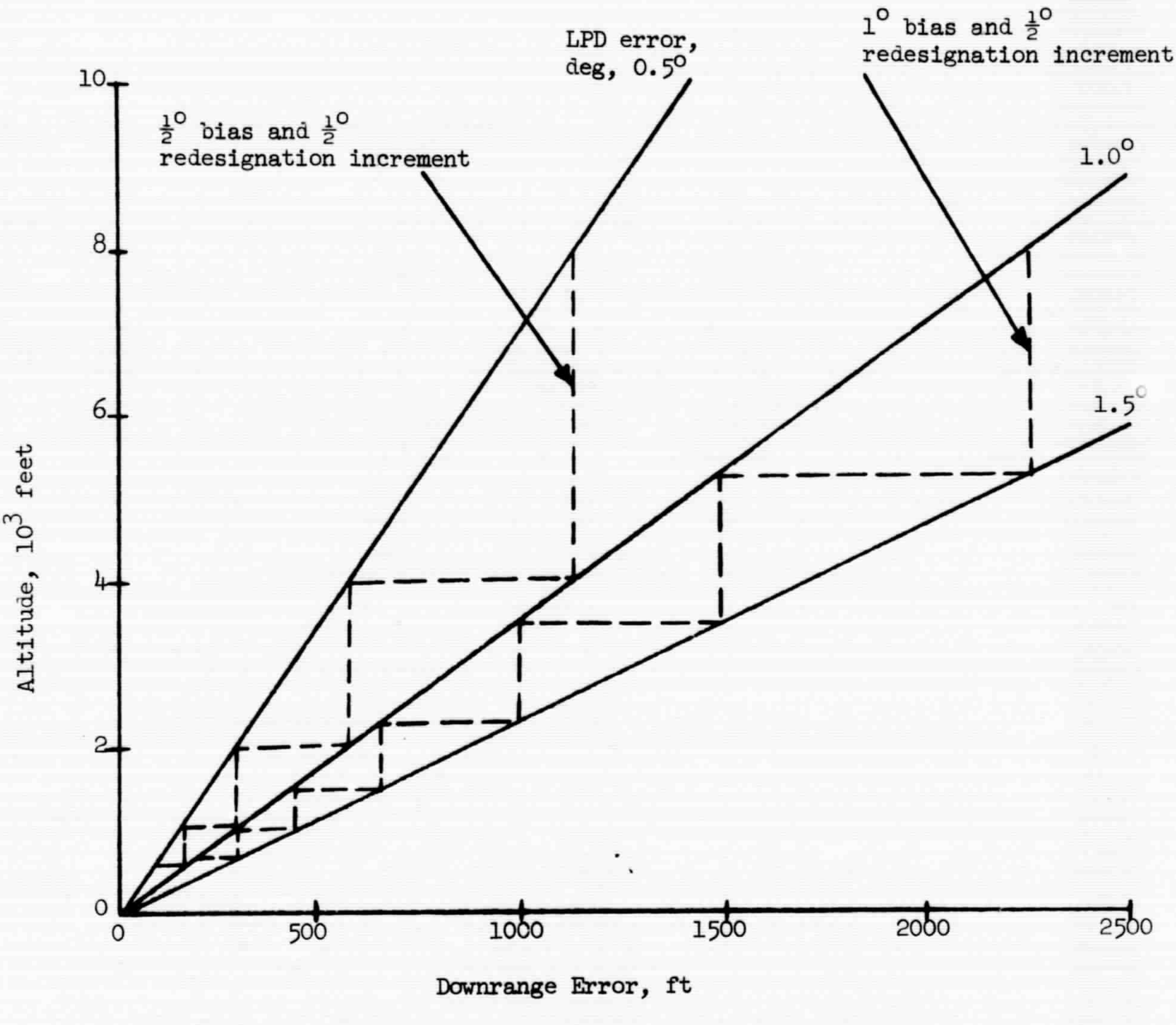

Figure 4.- Geometric Growth of Range Error Resulting From an LPD Bias Error

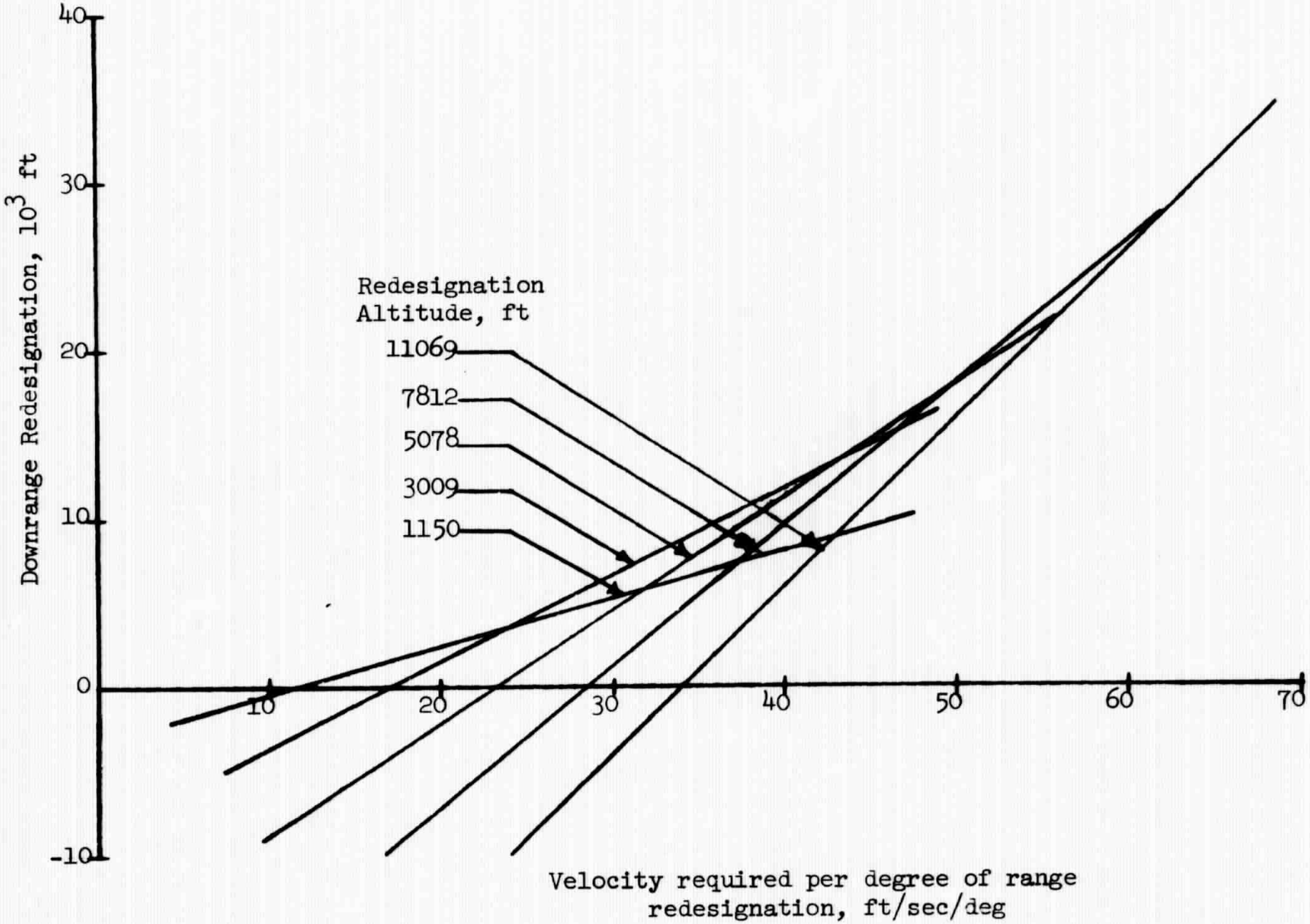

Figure 5.- Variation of Characteristic Velocity Required for Single Redesignations for Various Redesignation Altitudes

(a) Velocity Required per Degree of Downrange Redesignation

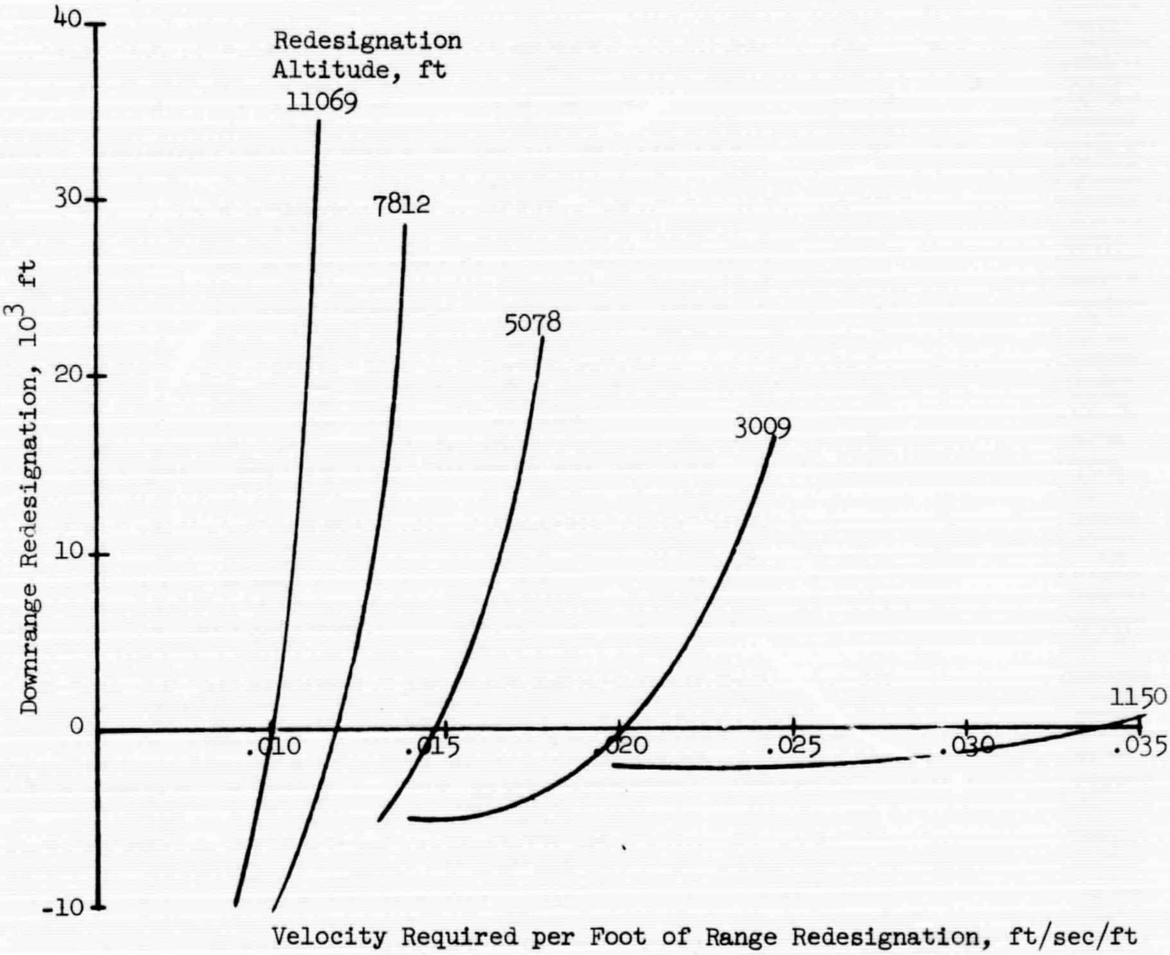

Figure 5.- (concluded)
(b) Velocity Required per Foot of Downrange Redesignation

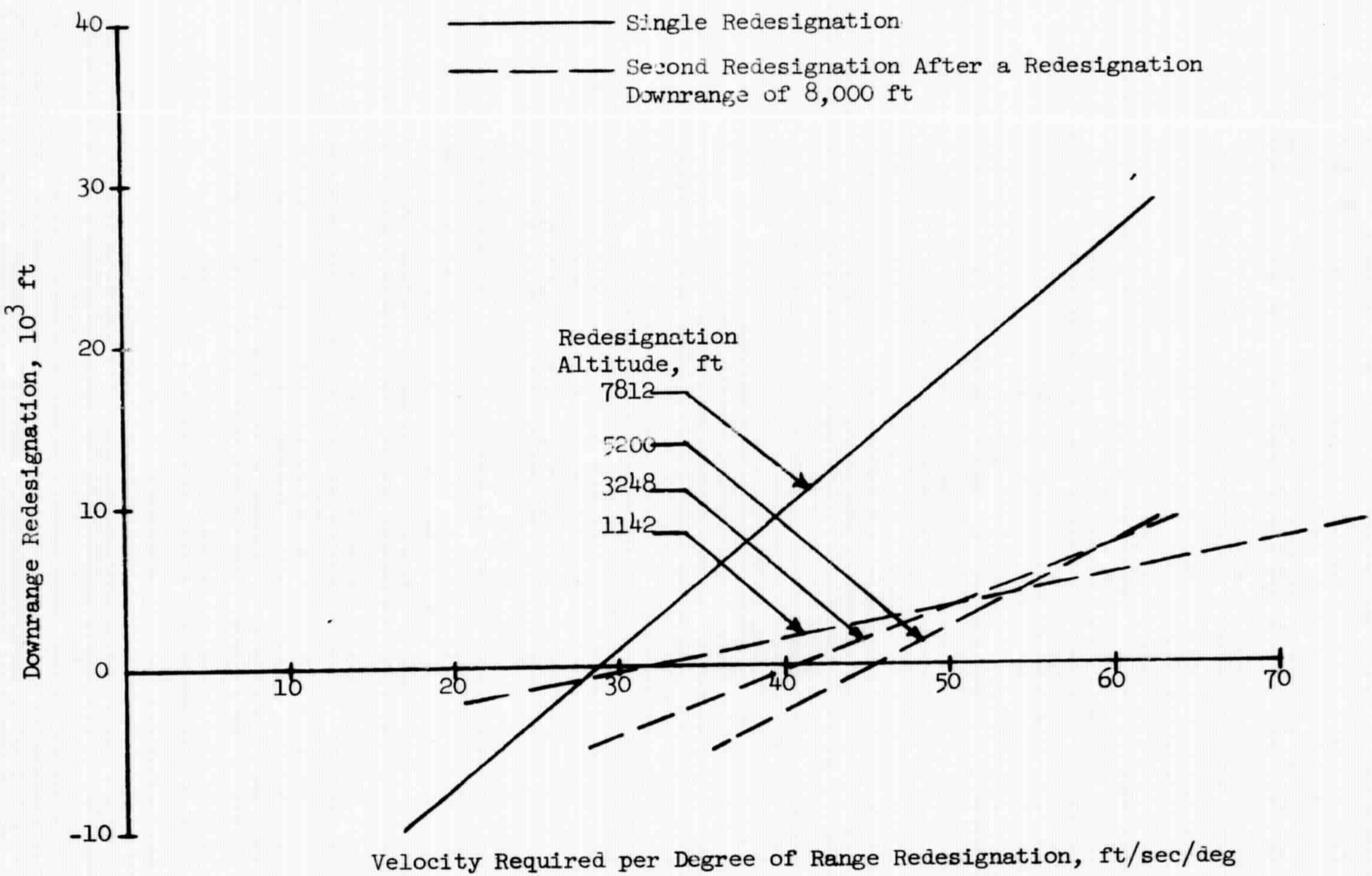

Figure 6.- Variation of Characteristic Velocity Required For Double Redesignations for Various Redesignation Altitudes
(a) Velocity Required per Degree of Downrange Redesignations

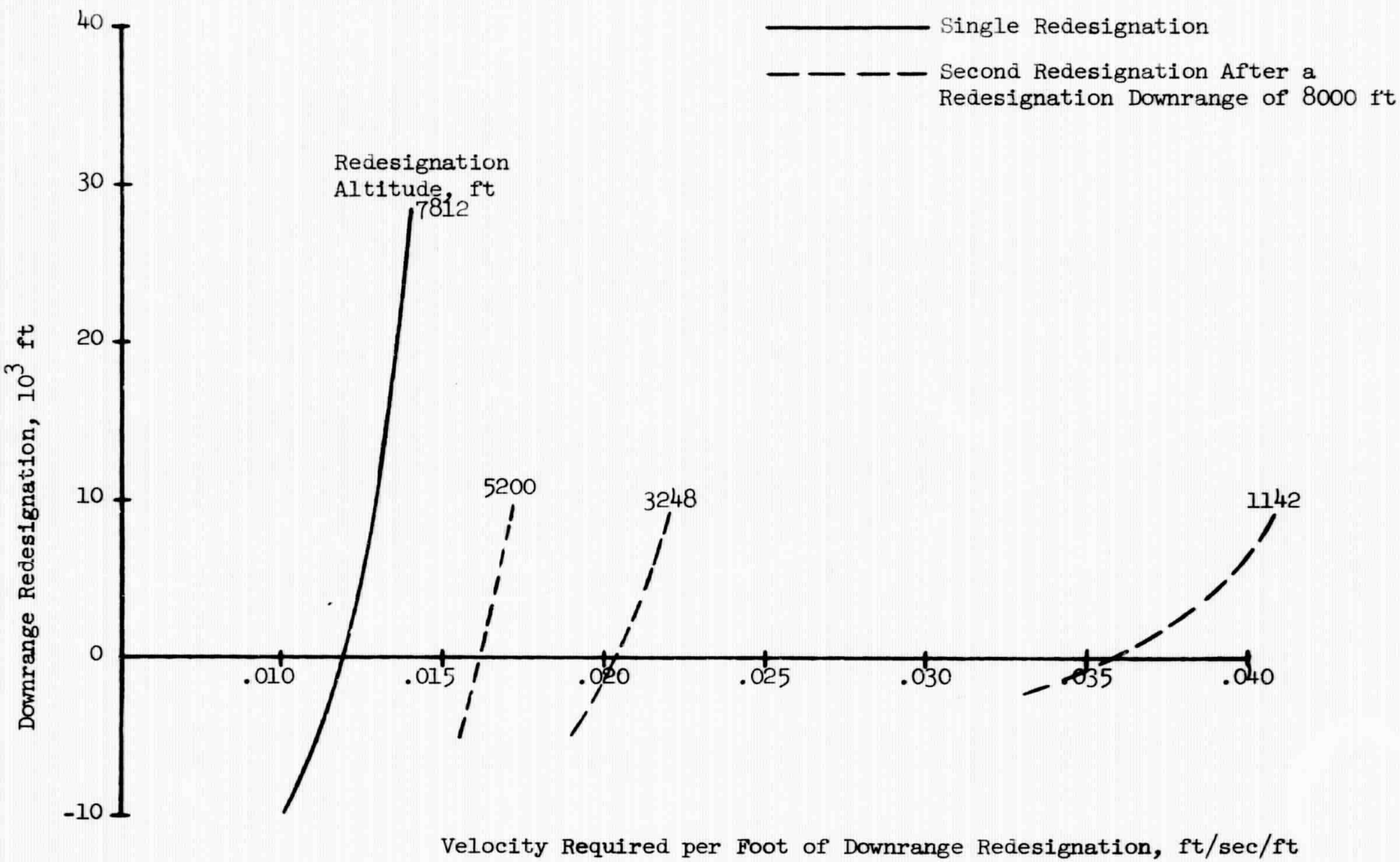

Figure 6.- (concluded)
(b) Velocity Required per foot of Downrange Redesignations

Total Time of Descent (sec)	Downrange (ft)	LPD Error (Deg)	Total V_c (fps)	V_c Relative to Nominal (fps)	V_c Relative to 0^o LPD Error (fps)	Number of Redesignations
100.4	0	0	912.5	0	0	0
101.4	0	1	919.5	7.0	7.0	4
103.2	0	.5	926.4	13.9	13.9	4
110.3	0	-.5	956.7	44.2	44.2	3
112.9	0	-1.	968.8	56.3	56.3	4
125.5	8000	0	1014.6	102.1	0	0
122.2	8000	1.	1003.6	91.1	-11.0	4
125.6	8000	.5	1016.9	104.4	2.3	3
138.0	8000	-.5	1071.1	158.6	56.5	3
142.1	8000	-1.	1090.6	178.1	76.0	3
150.9	16000	0	1125.6	213.1	0	0
142.1	16000	1.	1090.8	178.3	-34.8	2
146.9	16000	.5	1109.8	197.3	-15.8	2
165.7	16000	-.5	1194.1	281.6	68.5	2
172.1	16000	-1.	1225.1	312.6	99.5	2

Table I. Characteristic Velocity Penalties Resulting From Redesignations with LPD Errors From 8000 ft Altitude.