NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 68-FM-288

DECEMBER 3, 1968

ONBOARD MIDCOURSE CORRECTION TARGETING DURING THE TRANSEARTH COAST PHASE OF A LUNAR MISSION

FLIGHT ANALYSIS BRANCH
MISSION PLANNING AND ANALYSIS DIVISION

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By Charles E. Foggatt and George L. Carlisle
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ONBOARD MIDCOURSE CORRECTION TARGETING DURING THE TRANSEARTH COAST PHASE OF A LUNAR MISSION

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SUMMARY

An onboard technique to provide midcourse correction (MCC) targeting during the transearth coast (TEC) phase of a lunar mission is presented. Specifically, the use of the earth's terminator to determine the correct thrust direction is discussed for CSM systems problems that include loss of ground communications and the inertial measurement unit (IMU). The procedures are presented along with the required accuracy of the onboard maneuvers.

INTRODUCTION

During the TEC phase of the lunar mission, MCC's will be performed to insure that acceptable entry conditions are achieved. If communications exist, necessary targeting information is obtained through ground tracking. However, if a CSM communications failure occurs, capability for onboard navigation and MCC targeting is required. This document discusses the procedure that may be followed when ground communications are not available and, in addition, an IMU failure has occurred.

ONBOARD TECHNIQUE

If an IMU failure occurs during the transearth injection (TEI) burn, the onboard procedure is to take over the burn using the stabilization and control subsystem (SCS). Although the TEI burn can then be completed and a near-nominal TEC achieved, MCC's will be necessary to insure that the correct entry conditions result. Failure of the IMU, however, results in a loss of the correct CSM state vector at the end of the burn. Subsequent MCC targeting will require knowledge of the present CSM state vector, and hence a state vector update is necessary.

When the IMU failure is accompanied by a communications loss, ground state vector update is precluded, and onboard navigation is required. This requirement is satisfied using the cislunar midcourse navigation program (P23) in the command module computer (CMC). A complete description of CMC P23 is presented in reference 1. Briefly, the purpose of P23 is to do midcourse navigation by incorporating star/earth and star/moon optical measurements. This program does not require that the IMU be on.

Following state vector update with CMC P23, the return-to-earth program (P37) in the CMC is used to compute the required MCC. This program will compute a return-to-earth trajectory providing the CSM is outside the moon's sphere of influence (MSI) at time of ignition. The program will display the three components of ΔV (ΔV_x, ΔV_y, and ΔV_z) at the given time of ignition along local vertical axes. Before the MCC can be initiated, however, the correct thrust direction must be determined. P37 constrains the maneuver to be in the plane of the pre-MCC trajectory. Therefore, a calculation of the thrust vector direction relative to the local horizontal will completely define the correct thrust attitude. This angle, called $\gamma_{\Delta V}$, is defined by the following equation:

$$\gamma_{\Delta V} = -(\tan^{-1} \Delta V_z/\Delta V_x)$$

The thrust vector orientation is shown in figure 1.

It should be noted that $\gamma_{\Delta V}$ will generally be a very small angle which results in a nearly horizontal burn. This is illustrated by the resultant velocity hyperbola in figure 2. At a given radius, the velocity vectors of all conic trajectories having a specified perigee radius terminate on a three-dimensional surface which is a hyperboloid (ref. 2). The dimensions of the hyperboloid are a function of the radial distance at MCC initiation and the desired perigee radius. The velocity vectors terminating outside the region bounded by the two branches of the hyperbola [fig. 2(a)] will all yield trajectories having perigee greater than the desired perigee. Those terminating within this region [fig. 2(b)] will yield trajectories having perigee radii less than that desired. From figure 2 it can be seen that the minimum ΔV necessary to correct an off-nominal transearth velocity vector will be directed in a very nearly horizontal direction. Any vertical component will only result in changes in transearth flight time and will be very small for minimum impulse maneuvers.

Since it was assumed that an IMU failure has occurred, some inertial reference must be used to maneuver the CSM to the correct thrust attitude. Figure 3 shows the earth viewed through the crewman optical alignment sight (COAS) reticle at several points on a typical TEC.

The vertical direction in the figure corresponds to the orbital plane. That is, the thrust vector should be oriented directly above or below the earth's center for an in-plane maneuver. Of primary interest in this figure is the fact that the angle between the CSM X-Y plane (the horizontal direction in fig. 3) and a line drawn connecting the end points of the terminator is relatively constant. For this typical TEC, figure 4 shows the measurement of this angle. From figure 3, therefore, it is seen that a CSM orientation at this angle will be very nearly in-plane for most of the TEC.

The procedure to maneuver to the correct thrust attitude will involve three steps:

1. Maneuver until the earth is centered in the COAS reticle and the terminator is parallel to the X-Y plane. The sunlit region of the earth will be oriented toward the CSM Z-axis.

2. Rotate the CSM about the X-axis until the proper terminator orientation is achieved. For the typical TEC represented in figure 4, this angle is -12°. (This roll angle is -6° for the nominal Apollo 8 mission launched December 21 on a 72° launch azimuth with translunar injection at the first opportunity.)

3. Pitch the CSM about the Y-axis to the desired value of $\gamma_{\Delta V}$ calculated from P37. Although the thrust vector will be nearly horizontal, it will be in either the direction of motion (posigrade) or the opposite (retrograde) direction.

The MCC will now be initiated, and the ΔV from CMC P37 will be applied. Finally, the entire procedure will be repeated until satisfactory entry conditions result.

ANALYSIS

In an effort to determine the required accuracy in the execution of TEC MCC's, errors in the CSM pitch and yaw orientation were evaluated. The error in pitch is equivalent to an error in $\gamma_{\Delta V}$ calculated from the results of CMC P37 or the subsequent pitch maneuver to that attitude. A yaw error (denoted by $\Psi_{\Delta V}$) would result from improper orientation of the earth's terminator in the COAS reticle prior to the pitch maneuver.

In the following analysis, it was assumed that a two-body conic trajectory is sufficiently accurate to simulate all the trajectories prior to and following the MCC. Although conic approximations may result in appreciable differences in ΔV calculations when compared to integrated trajectories in particular cases (near the MSI, for example), if the pre-MCC state vector is also from a conic trajectory, conic midcourse calculations are very accurate.

Also, it was assumed that the acceptable entry corridor is bounded by the zero-lift overshoot boundary and the 12g undershoot boundary. The entry velocity will not change significantly following the minimum ΔV MCC's considered here. From reference 3 the range of acceptable flight-path angles is from $\gamma_{entry} = -5.75°$ (zero-lift overshoot) to $\gamma_{entry} = -7.3°$ (12g undershoot) for an entry velocity of 36 150 fps, which is representative of the lunar return velocities encountered. The allowable errors in $\gamma_{\Delta V}$ and $\Psi_{\Delta V}$ were determined by these boundaries. Finally, following the reasoning of the previous section, it was assumed that in all cases the nominal thrust vector direction was horizontal ($\gamma_{\Delta V} = 0°$).

Figure 5 shows the variation of γ_{entry} as a function of the out-of-plane thrust angle, $\Psi_{\Delta V}$, for various MCC ΔV magnitudes at an altitude of 175 000 n. mi. (approximately MSI exit). Data is included for both posigrade and retrograde maneuvers since slight differences exist. In this figure the return-to-earth maneuver was targeted to a γ_{entry} of $-5.75°$ for the posigrade maneuvers and γ_{entry} of $-7.3°$ for the retrograde. In this manner the absolute maximum of allowable $\Psi_{\Delta V}$ errors are found for entries within the corridor. It should be noted that the smaller MCC ΔV will result in a larger acceptable error in $\Psi_{\Delta V}$.

Although targeting to the upper and lower boundary of the corridor will increase the allowable error in $\Psi_{\Delta V}$, most probably the crew would use the V-γ target line built in CMC P37 (the contingency target line). Figure 6 shows the variation of γ_{entry} as a function of $\Psi_{\Delta V}$ for a MCC ΔV = 100 fps at 175 000-n. mi. altitude. In this figure the curves of figure 5 are compared to posigrade and retrograde burns targeted to the contingency target line ($\gamma_{entry} = -6.5°$ in this case). As might be expected, the allowable $\Psi_{\Delta V}$ is smaller for the contingency target line returns. From figure 6 the maximum out-of-plane angle acceptable is 7.5° for a retrograde MCC and 9.5° for a posigrade MCC at an altitude of 175 000 n. mi. (near the MSI exit point).

Figure 7 is a summary of the allowable out-of-plane thrust angle (i.e., that allows the vehicle to remain in the entry corridor) as a function of the altitude at point of midcourse. As in figure 6, curves are shown for posigrade and retrograde MCC's targeted to the contingency target line ($\gamma_{entry} = -6.5°$) as well as to the corridor extremes. The acceptable $\Psi_{\Delta V}$ increases as the CSM continues along the TEC until at 50 000-n. mi. altitude $\Psi_{\Delta V}$ (posigrade) = 17.5° and $\Psi_{\Delta V}$ (retrograde) = 15.5° to keep the vehicle in the corridor.

The previous paragraphs have described the required accuracy in maneuvering to the correct earth terminator orientation in the COAS reticle. The effects of an error in the subsequent pitch maneuver was also investigated. Figure 8 is a summary of the allowable $\gamma_{\Delta V}$ error to remain in the entry corridor as a function of altitude at point of MCC. In this figure only posigrade and retrograde maneuvers to the contingency target line are included. Again, the allowable error increases as the CSM nears the earth on the TEC.

The investigation of the above maneuver errors show that larger errors are acceptable as the CSM progresses along the TEC. However, a penalty should be expected when the actual initiation of the MCC is delayed. Figure 9 shows the MCC ΔV required as a function of altitude for various off-nominal TEC. These various TEC are characterized by the MCC ΔV required at 175 000 n. mi., or approximately MSI exit. The actual ΔV increases rapidly as the maneuver is delayed. Therefore, midcourses initiated as soon as possible result in the lowest ΔV requirements although from previous paragraphs the execution errors are more restrictive.

CONCLUDING REMARKS

The onboard technique of executing a MCC during the TEC phase of a lunar mission was discussed. System failures which were assumed to have occurred prior to the midcourse were a communications failure and loss of the IMU. The onboard calculations were made using existing CMC programs and the thrust vector direction was obtained using the earth's terminator as a reference. To summarize the sequence of events, they are as follows:

1. Perform state vector update using the cislunar midcourse navigation program (P23) in the CMC.

2. Calculate the midcourse required using the return-to-earth program (P23) in the CMC.

3. Determine the thrust vector direction from the local horizontal ($\gamma_{\Delta V}$) from the results of P37.

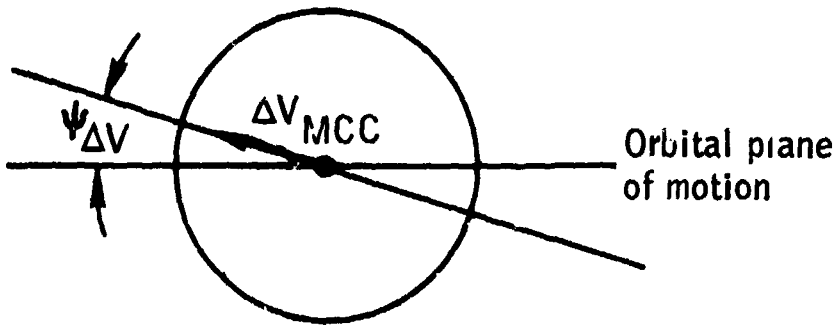
4. Maneuver the CSM until the earth is centered in the COAS reticle and the terminator is horizontal with the lit portion toward the CSM Z-axis.

5. Roll the CSM about the X-axis until the correct terminator orientation is obtained (fig. 4).

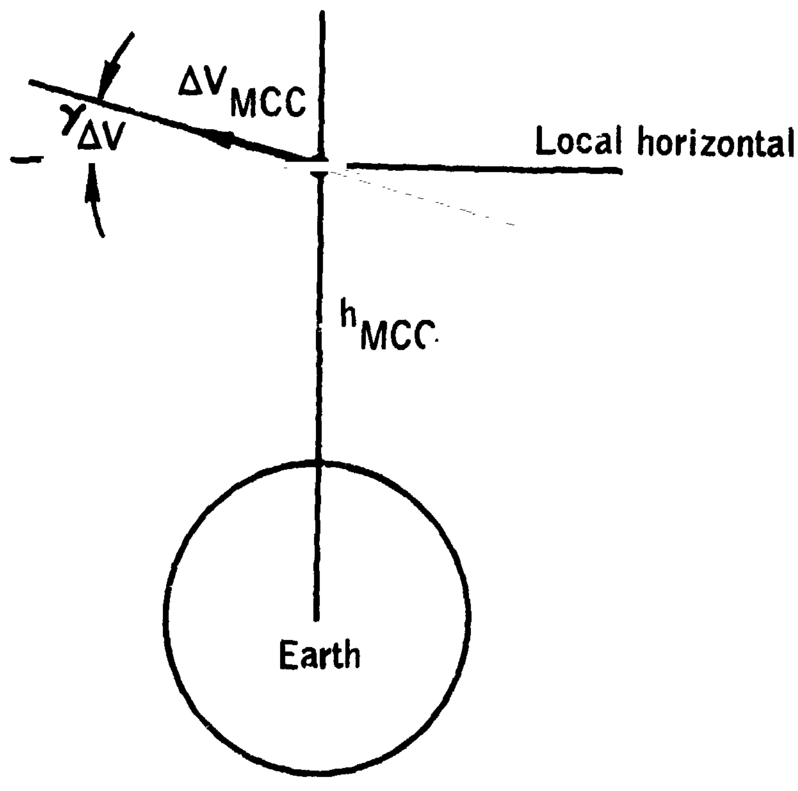
6. Pitch the CSM to the desired $\gamma_{\Delta V}$ orientation.

7. Burn the ΔV calculated in P37.

In summary, a relatively simple method to target a midcourse correction using the earth's terminator as an attitude reference is presented. The technique uses existing onboard computer programs and assumes a communications and IMU failure have occurred. The allowable errors in the orientation of the terminator in the COAS reticle and the allowable pitch errors varied from 8° at MSI exit to 15° at 50 000-n. mi. altitude.



(a) View down radius vector.



(b) View perpendicular to orbital plane of motion.

Figure 1.- Definition of parameters used in analysis of onboard midcourse correction maneuver errors.

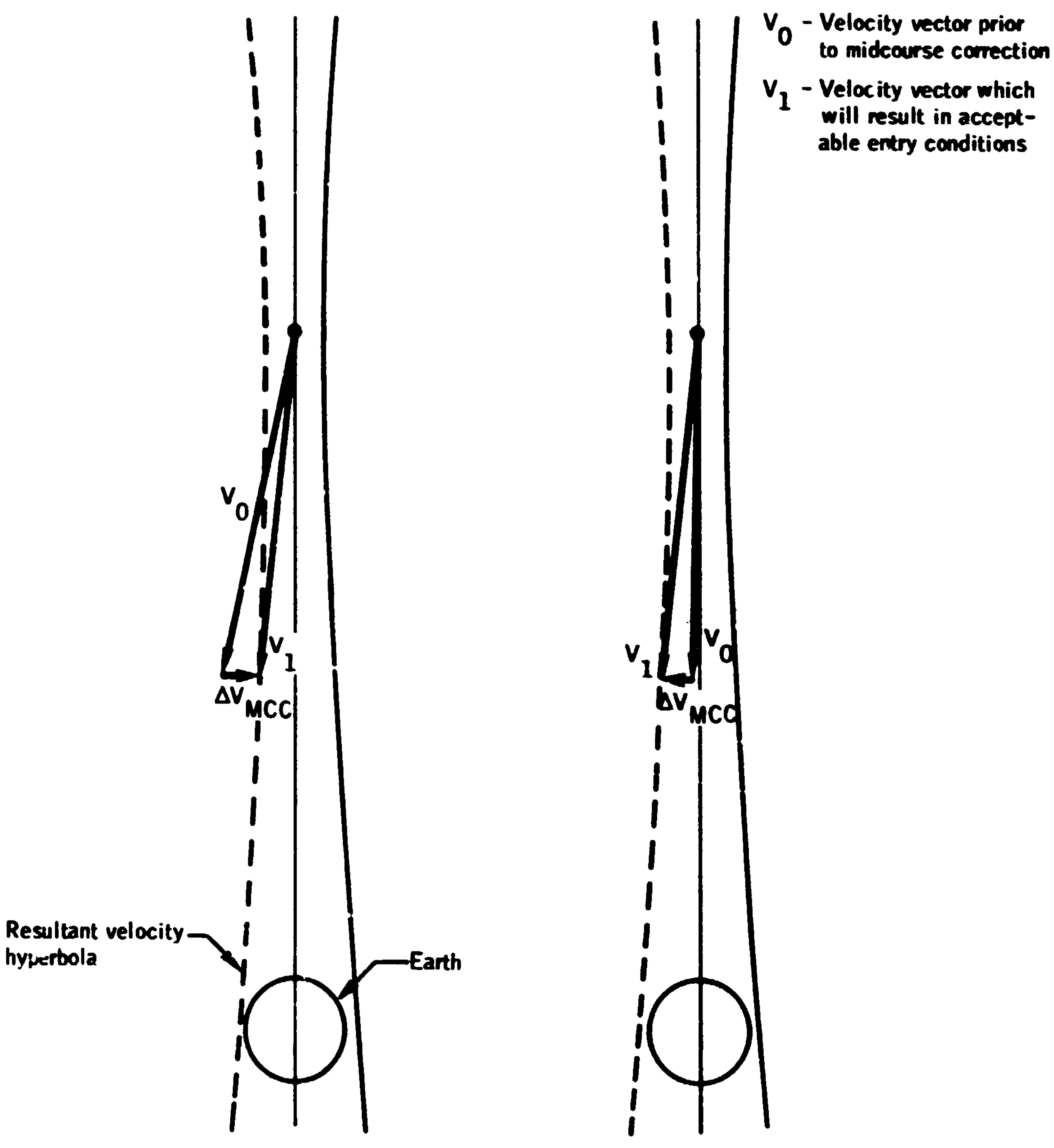
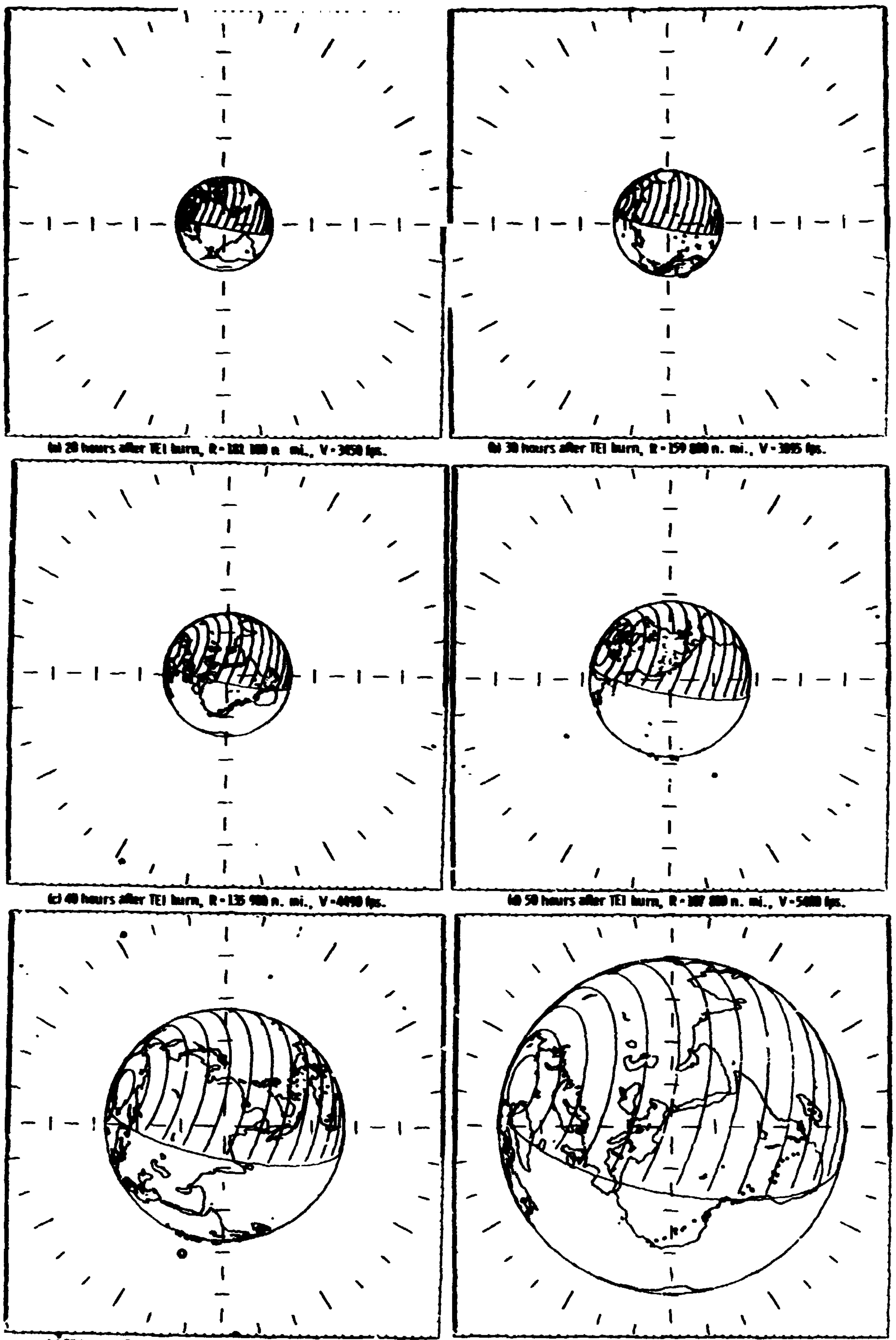


Figure 2.- Graphical representation of minimum impulse midcourse corrections during the transearth coast phase of a lunar mission.



(a) 20 hours after TEI burn, R = 182 100 n. mi., V = 3050 fps.

(b) 30 hours after TEI burn, R = 159 800 n. mi., V = 3095 fps.

(c) 40 hours after TEI burn, R = 135 900 n. mi., V = 4090 fps.

(d) 50 hours after TEI burn, R = 107 800 n. mi., V = 5000 fps.

(e) 55 hours after TEI burn, R = 70 280 n. mi., V = 7145 fps.

(f) 60 hours after TEI burn, R = 50 580 n. mi., V = 8950 fps.

Figure 5.- Earth viewed through COAS reticle during transearth coast.

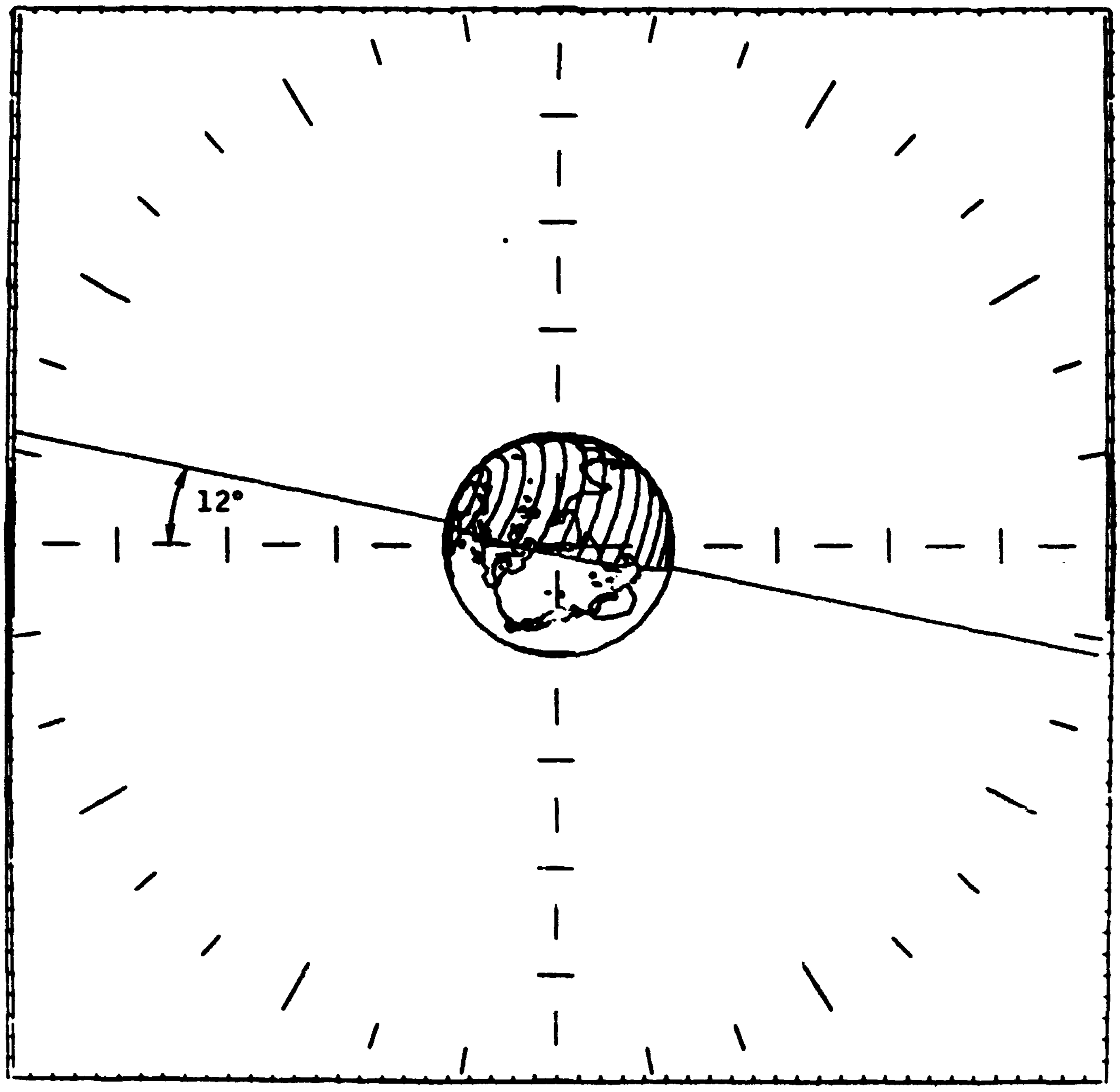


Figure 4.- Inplane orientation of the earth's terminator for midcourse corrections during the transearth coast.

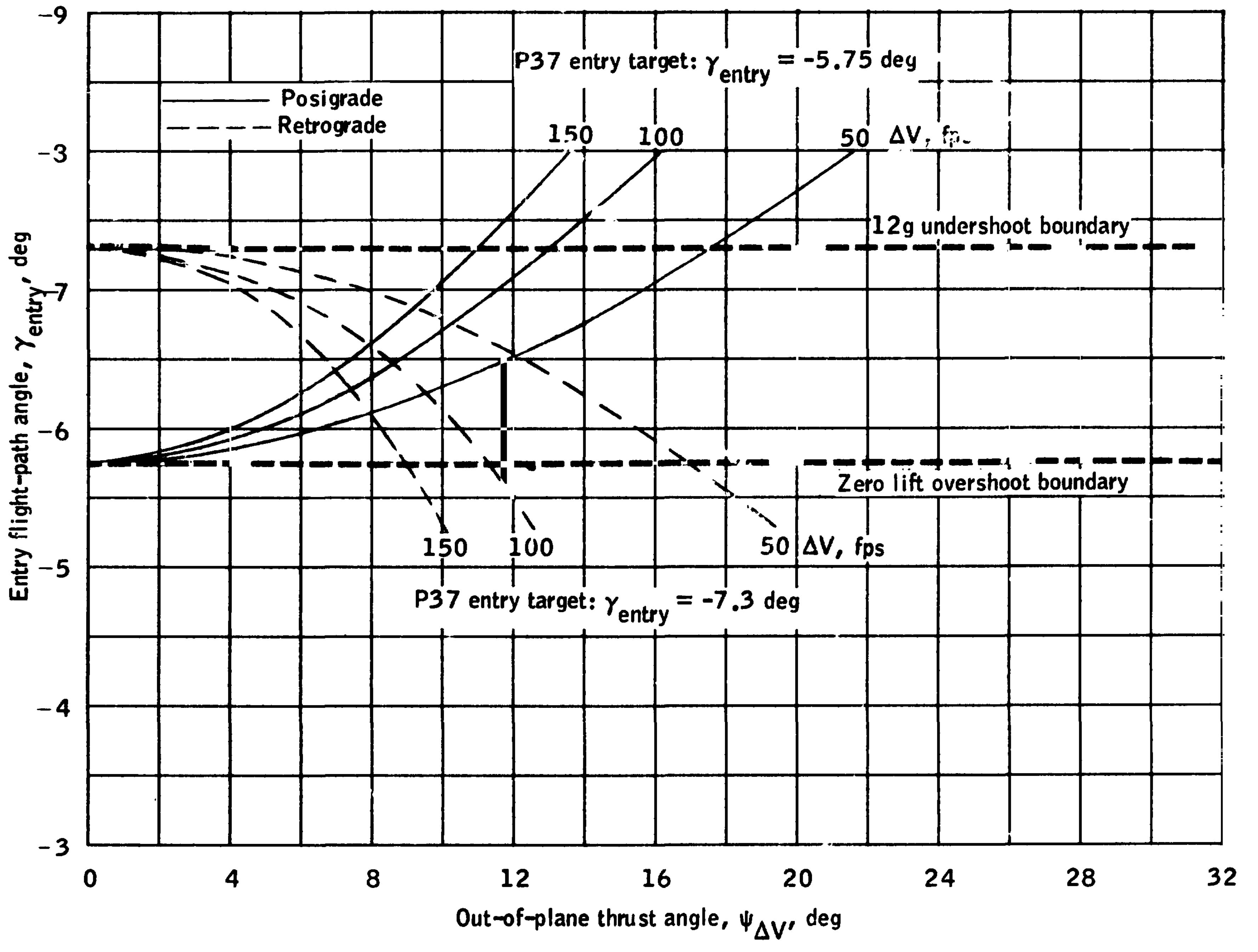


Figure 5.- Variation of entry flight-path angle due to out-of-plane thrust angle for various midcourse ΔV magnitudes (h_{MCC} = 175 000 nautical miles).

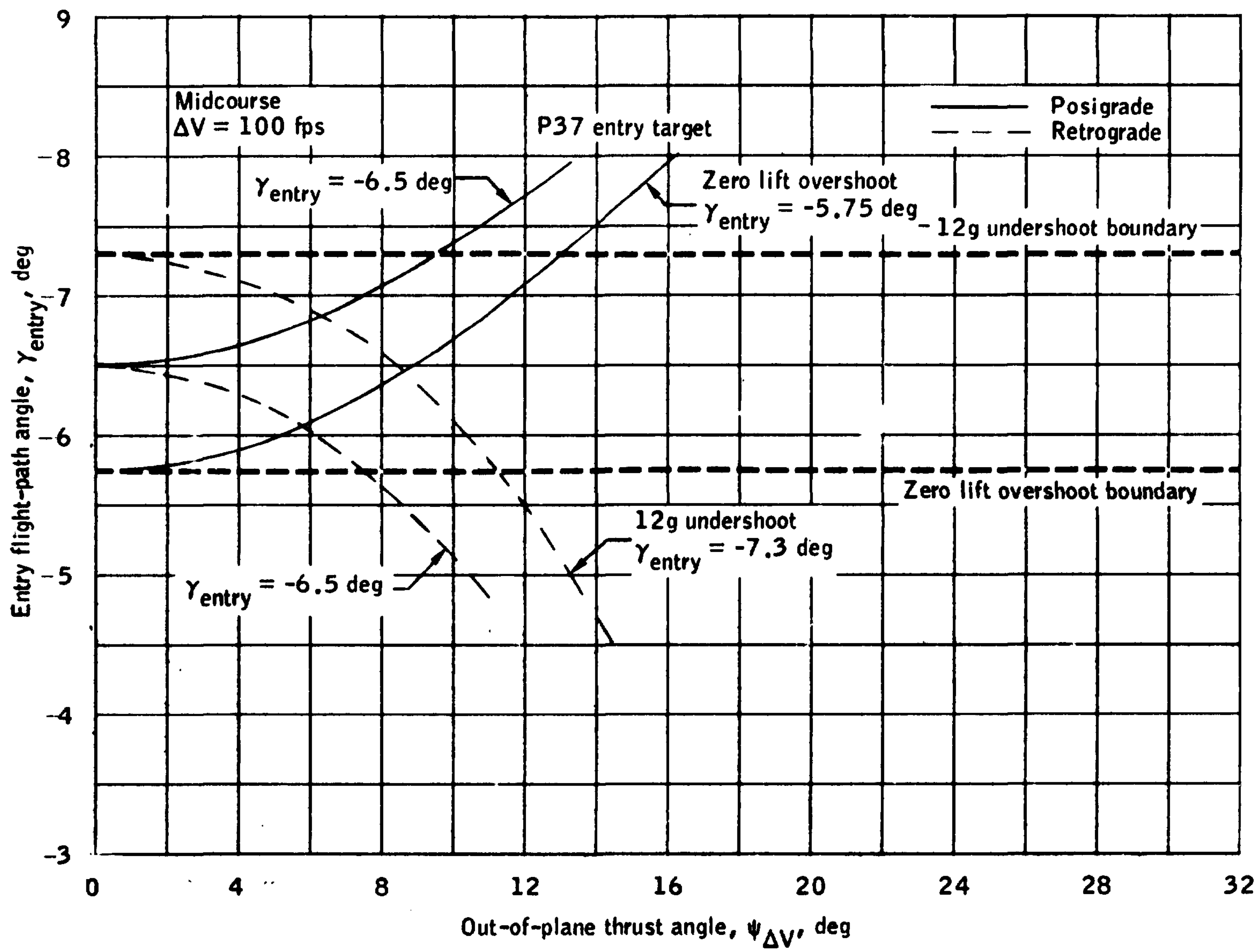


Figure 6.- Comparison of entry flight-path angle variation due to out-of-plane thrust angles for various entry targets (h_{MCC} = 175 000 nautical miles).

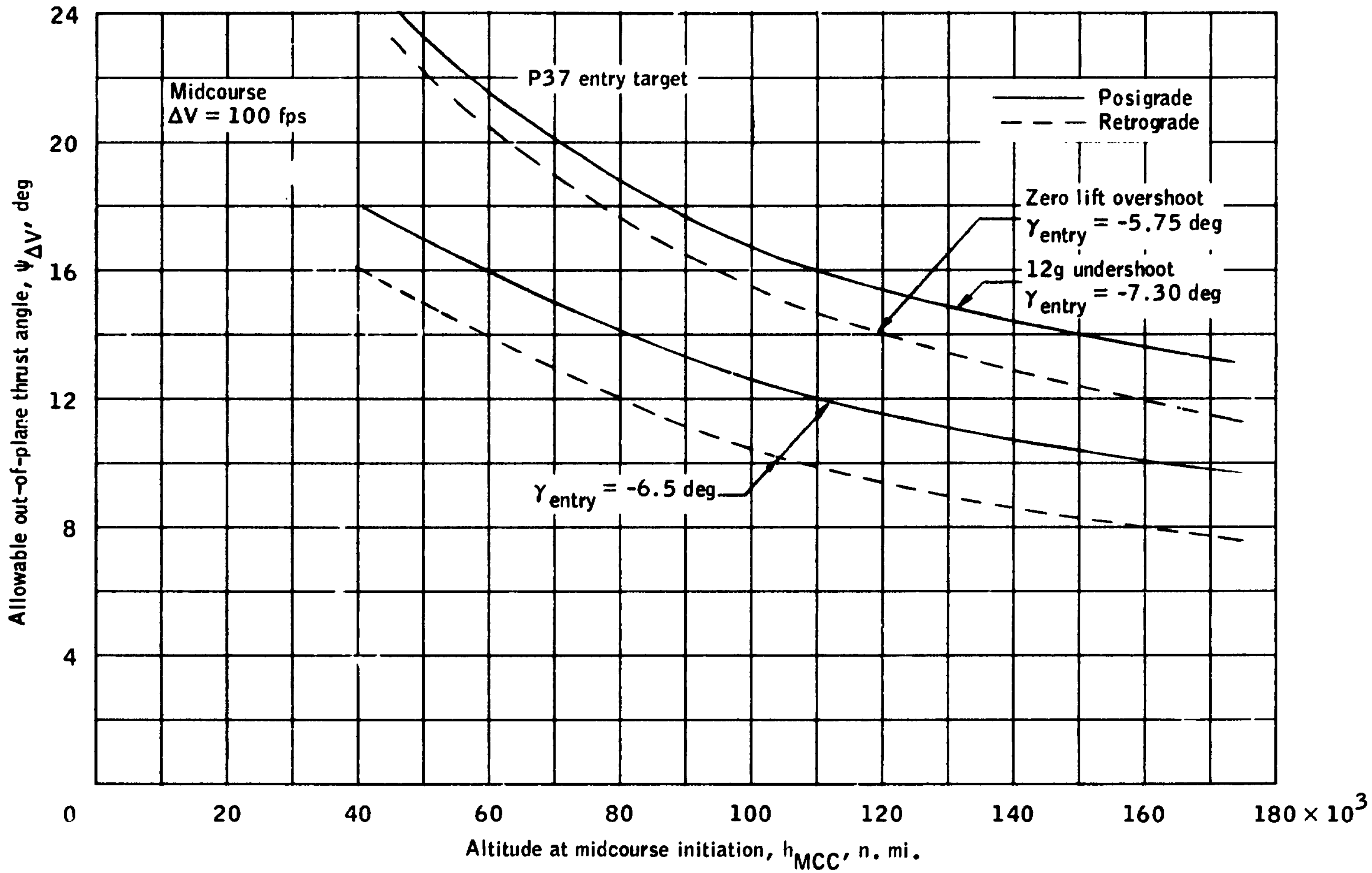


Figure 7.- Allowable out-of-plane thrust angle to remain in entry corridor as a function of altitude at point of midcourse.

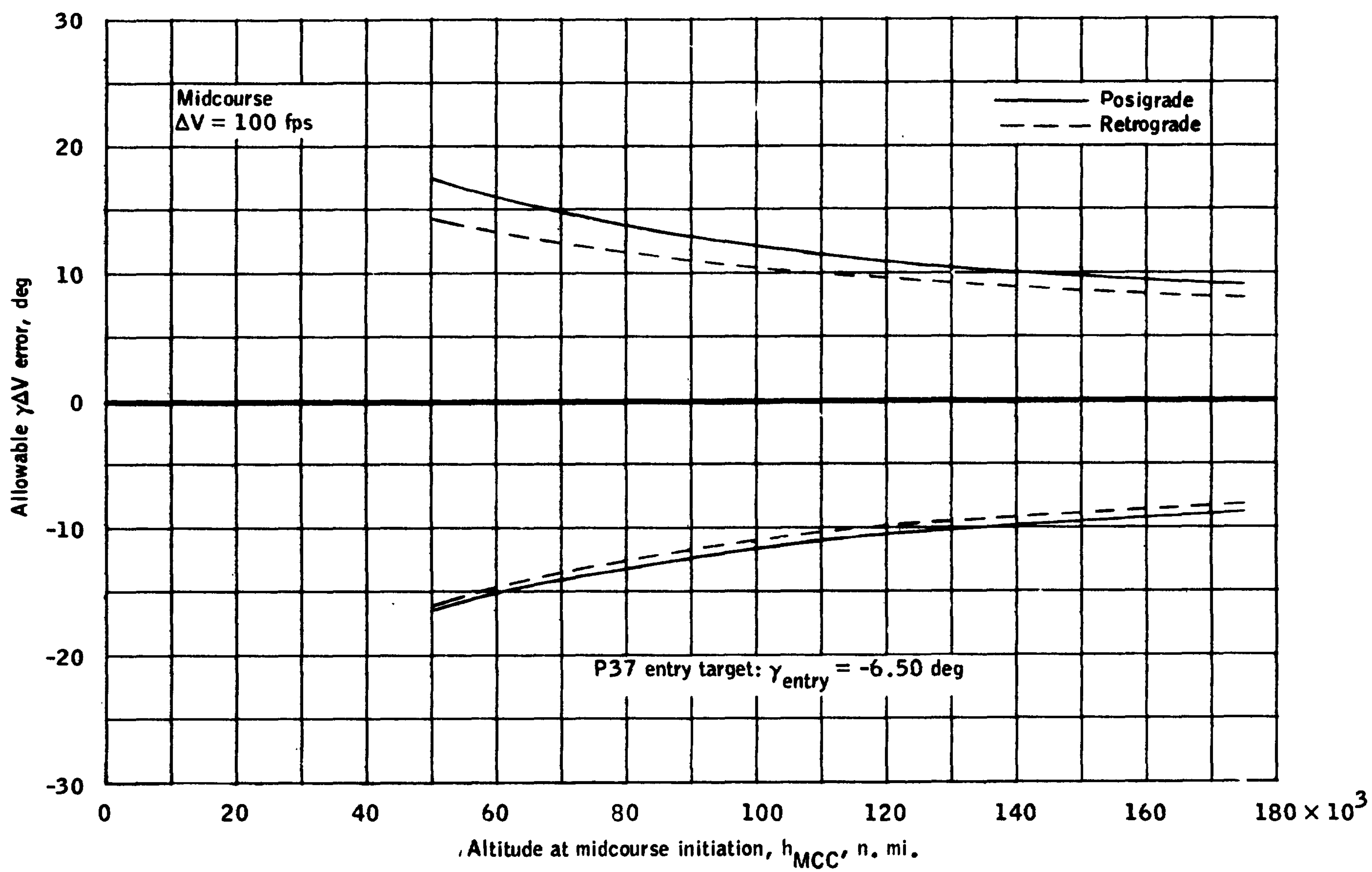


Figure 8.- Allowable $\dot{\gamma}_{\Delta V}$ error to remain in entry corridor as a function of altitude at point of midcourse.

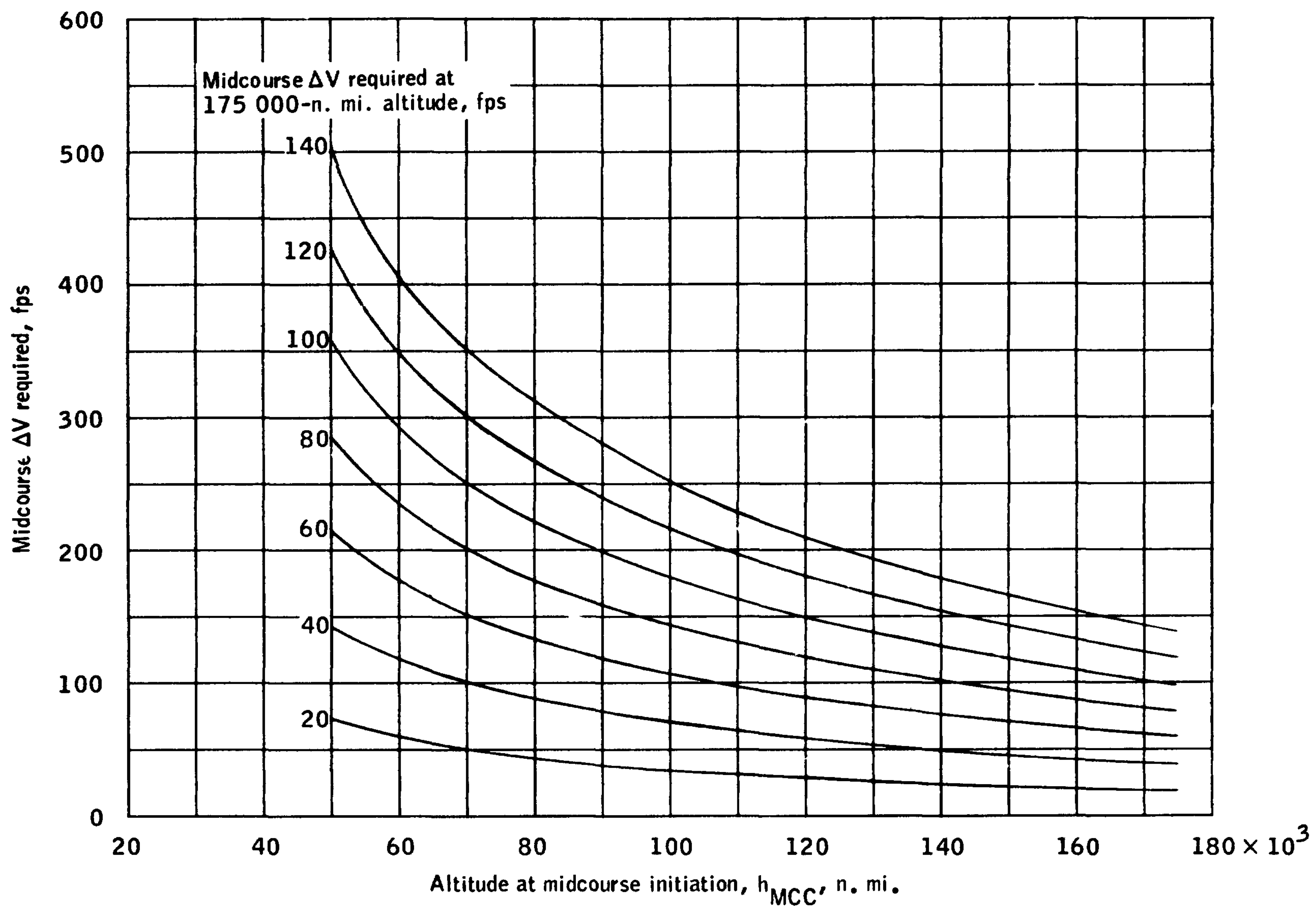


Figure 9.- Midcourse ΔV required as a function of altitude for various non-nominal transearth coasts.

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2. Mission Analysis Branch: A Mechanism to Aid Earth Reference Abort Analysis - The Resultant Velocity Hyperbola. U. S. Government memorandum 66-FM54-103, April 11, 1966.

3. Lunar Mission Analysis Branch: Preliminary V-γ Target Lines for the E and F Missions. U. S. Government memorandum 68-FM53-180, May 13, 1968.