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SIMPLIFIED TECHNIQUE FOR ABORTING A LUNAR LANDING MISSION DURING POWERED DESCENT USING MANUAL BACKUP GUIDANCE

by David B. Middleton

Langley Research Center
Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

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SIMPLIFIED TECHNIQUE FOR ABORTING A LUNAR LANDING MISSION

DURING POWERED DESCENT USING MANUAL BACKUP GUIDANCE

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SUMMARY

An analytical study has been made of a simplified technique for aborting the lunar-landing mission from along the powered-descent trajectory. The technique developed is feasible for use with the manual-backup guidance system of the landing spacecraft but could also be implemented with an automatic system. A circular chasing orbit at about a 50 000-foot altitude is used prior to a standardized transfer back to a command spacecraft parked in a circular orbit at 80 nautical miles. The emphasis of the study is on this return-transfer maneuver.

An error analysis was made of a family of transfer orbits having pericynthions 50 000 feet above the mean lunar surface. These orbits ranged from the minimum-energy Hohmann transfer to a synchronous-orbit transfer; rendezvous was normally achieved on the second intercept with the 80-nautical-mile orbit. Associated with the family of orbits is a "transfer window" of about 51 minutes and a maximum incremental-velocity requirement of about 563 fps including midcourse correction. The transfer window was related to a range of elevation angles which the crew of the transferring spacecraft can measure optically or with radar; the transfer was initiated on the basis of this measured elevation angle.

The results of the study indicate that the abort technique is feasible and that reasonable errors in altitude, altitude rate, and thrust angle do not significantly affect the "miss" distance at rendezvous. However, deviations from chasing-orbit circular velocity and errors in thrust cut off can cause significant miss distances but may usually be prevented or corrected. When necessary, midcourse corrections can be made at apocynthion by thrusting along the velocity vector. The special case of abort from hover could also serve as a takeoff and rendezvous scheme.

INTRODUCTION

The Apollo mission plan includes the technique of leaving a command-service module (CSM) in a lunar parking orbit while a lunar excursion module (LEM) makes the descent to the lunar surface. An automatic guidance system will provide basic guidance for the powered LEM descent and also for a return to the CSM from the lunar surface or following an abort from the descent. However, in the event of a failure of the primary system, an alternate and independent guidance mode will be required. In particular, there is a need for further study to develop a simplified abort technique which is applicable to both the primary guidance system and an independent backup system and which is standard for all points along the powered-descent trajectory. This alternate system should make full use of the pilot's capabilities in order to increase the probability of mission success.

The objectives and ground rules of the Apollo mission as described by the NASA Manned Spacecraft Center are firm and have the status of design specifications. However, the technique used in aborting the mission during the LEM descent is not yet a firm element in the mission plan. Direct return to the CSM is apparently the most difficult from the powered-descent phase of the mission because of the LEM's rapidly changing velocity, flight-path angle, thrust-to-weight ratio, and phase angle with the CSM. The merits of a direct return are recognized for certain emergencies, but with less severe time constraints, it may be desirable to use a more flexible maneuver with larger control tolerances and reduced fuel requirements.

Following a decision to abort the landing mission, the LEM must be guided along a trajectory which safely clears lunar-surface obstructions. Several studies have been made on the establishment of a low-altitude chasing orbit and have demonstrated that this orbit can be attained without sophisticated guidance. In a simulation study (ref. 1) the simplicity of manually controlling take-offs from the lunar surface into a near 50 000-foot chasing orbit was demonstrated by using a degraded altimeter display and three-step pitch program. In another more extensive simulation study (performed by the Chance-Vought Corp. under contract to NASA) the chasing orbit was established by degraded radar information and multistep pitch programs for both surface launches and following aborts from the powered descent. One of the conclusions from this latter study is that the LEM crew can efficiently perform the navigation and control tasks and, if required, one man can perform both.

Once in the chasing orbit, the LEM can return to the vicinity of the CSM by means of a simple orbital transfer. A simulation study (ref. 2) has demonstrated that a human pilot can then effect a successful rendezvous from ranges of 10 to 50 statute miles in the presence of relatively severe conditions if given adequate vehicle control and flight-data presentation. Also, the average amount of fuel used by the pilots was only slightly more than the calculated minimum for each case.

The purpose of the present study is to develop and analyze a simplified abort technique suitable for LEM backup-system guidance. Based on the preceding considerations, an abort plan is outlined which will return the LEM to an altitude of 50 000 feet where it is trimmed into circular orbit. Then, the major portion of the study is to determine how and when to make the best orbital transfer back to the CSM. Most of the results of the study are based on a two-impulse transfer maneuver where velocity increments are added in the direction of the velocity vector. However, a three-impulse maneuver is suggested which reduces the overall fuel requirements but increases the transfer time.

The abort and transfer technique discussed herein is not dependent on the present LEM and CSM characteristics but, for convenience, the terms LEM and CSM will be used to identify the landing and the command spacecraft, respectively.

SYMBOLS

The English system of units is used in this study. In case conversion to metric units is desired, the following relationships apply:

1 international foot = 0.3048 meter

1 international statute mile = 5280 feet = 1609.344 meters

g_m gravity at surface of moon, 5.32 fps^2

r radial distance from center of moon, ft

r_m radius of moon, 5.702×10^6 ft

ΔV incremental velocity, fps

α elevation angle to CSM measured upward from forward horizontal, deg

θ central-angle travel in orbit around moon, deg

$\Delta\theta$ phase angle, that is, the central angle between the radius of the LEM and that of the CSM, deg

Subscripts:

a value of the variable at apocynthion

i value of the variable at injection (into transfer orbit)

A dot over a symbol represents a derivative with respect to time.

GENERAL CONSIDERATIONS

Figure 1 shows a typical mission profile in the vicinity of the moon. The following ground-rule assumptions were made for a study of aborts from this mission:

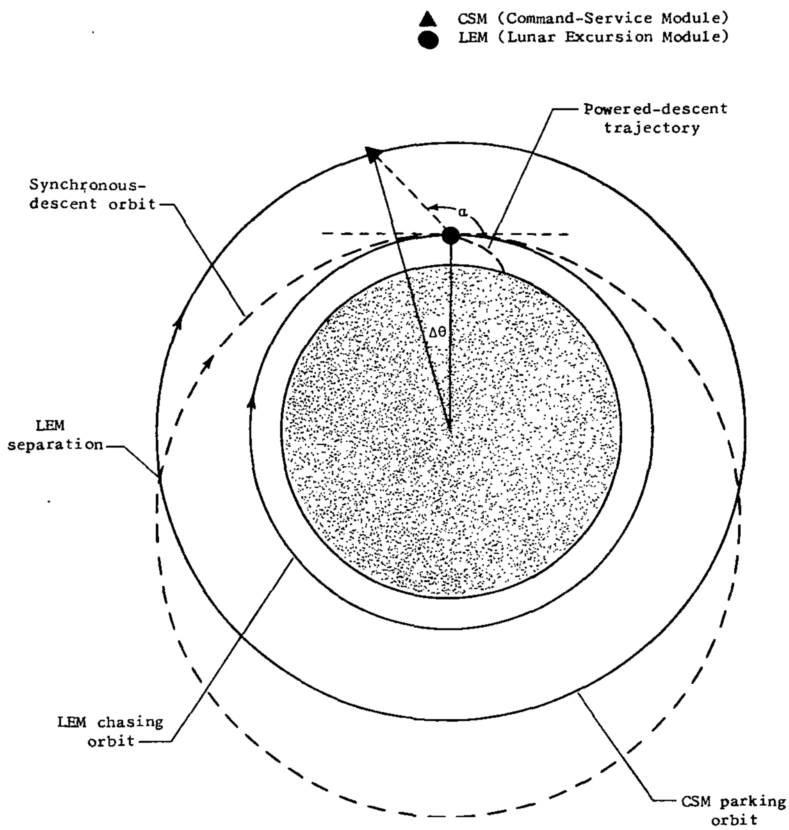


Figure 1.- Typical mission profile in vicinity of moon.

1. The coupled CSM-LEM has been established nominally in an 80-nautical-mile circular parking orbit about the moon.

2. At an appropriate time, the LEM is separated from the CSM and injected into either a Hohmann descent orbit or an equiperiod (synchronous) descent orbit, both having 50 000-foot pericynthions. The Hohmann descent requires minimum fuel while the synchronous-descent orbit is an automatic return trajectory to the CSM should an abort situation be detected prior to reaching pericynthion.

3. At pericynthion, a powered descent to the lunar surface is initiated by applying constant braking thrust and using a programed pitch profile.

4. If an abort is initiated, it must be carried through to its completion.

5. During the abort and subsequent transfer, the LEM has the capability of measuring altitude and tracking the CSM simultaneously. The desired accuracy of any altitude or range measurements should be within 1 percent, but somewhat coarser measurements could probably be tolerated. This information will be displayed to the LEM crew independent of the primary guidance computer.

6. A minimum of 5 minutes to trim up the chasing orbit to circular conditions will be required; additional time is desirable whenever possible.

7. Only transfer orbits having pericynthions of 50 000 feet or higher will be considered; pericynthions below this value would be unsafe in the event the LEM cannot restart its main engine.

8. Midcourse correction of the transfer orbit will be applied only in cases where the LEM will miss the CSM by more than 20 nautical miles at closest approach.

9. The entire abort and transfer maneuver takes place in the plane of the CSM parking orbit.

Nominal Powered Descent

At pericynthion of the synchronous descent orbit, the LEM descent engine is ignited and constant braking thrust is applied in accordance with a predetermined pitch program. After 6 minutes a hovering condition is established at about 2000 feet. Hover is assumed to last 2 minutes, and an additional 4 minutes is allowed for the manually controlled touchdown. Characteristics of this reference trajectory are given in table I. The solid curve in figure 2 is an altitude time history of the trajectory; the abort technique discussed herein is applied at all points along this trajectory. The abort technique is designed primarily for implementation with manual-backup systems; however, it seems equally feasible and, for uniformity, could also be the basis of an abort scheme using automatic guidance.

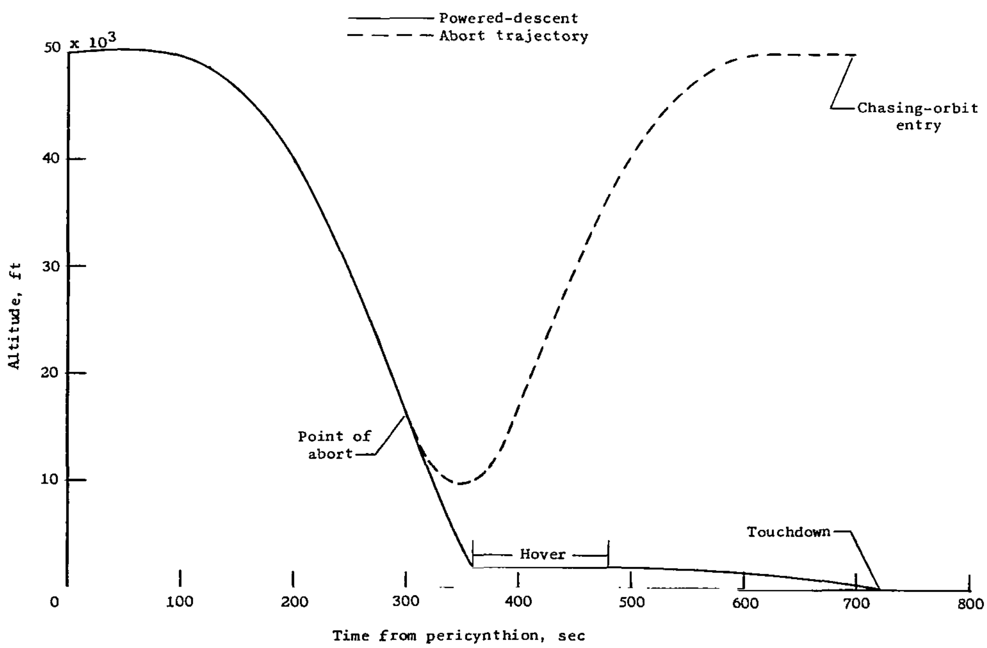


Figure 2.- Altitude time history of the powered-descent trajectory and of a typical abort trajectory.

Mission Abort

For convenience, the abort mission is divided into the following phases:

1. The abort maneuver - that portion of the abort mission between abort decision and injection of the LEM into a low circular orbit at about 50 000 feet

2. The chasing maneuver - a coasting phase in the low circular or "chasing orbit" in which the LEM gains central angle on the CSM while preparing for an orbital transfer

3. The transfer maneuver - that portion of the abort mission between the chasing orbit and rendezvous with the CSM. A midcourse correction (if needed) is also included

Each of these maneuvers places only mild constraints on the succeeding one and thus allows the LEM crew a great deal of volition in executing each phase of the abort mission. For example, a transfer maneuver does not have to be initiated at a precise time; instead, within an appropriate transfer window, it may be initiated as soon as the LEM crew is prepared or it may be delayed while continued or repeated verification of existing conditions is made.

Normal take-offs from the lunar surface can be treated as a special case of abort. Note that they can be approximately represented by aborts from hover but have greater flexibility in the phase angles which can be acquired as the LEM reaches the chasing orbit. Thus the abort technique discussed herein can also serve as a lunar take-off and rendezvous scheme.

EQUATIONS OF MOTION

The trajectory computations for this investigation were made utilizing the following equations of motion:

$$\ddot{r} - r(\dot{\theta})^2 + g_m\left(\frac{r_m}{r}\right)^2 = 0 \tag{1}$$

$$\ddot{\theta} + 2\left(\frac{\dot{r}\dot{\theta}}{r}\right) = 0 \tag{2}$$

These equations were solved on the IBM 7094 electronic data processing system for the conditions of interest in this study; this computer program was used previously in reference 3.

The classical two-body equations of orbital mechanics were used in converting trajectory data to the parameters used herein. These equations are derived in most space dynamics textbooks (e.g., ref. 4).

RESULTS AND DISCUSSION

The results of this study are discussed in the following sections according to mission phase. A section dealing with error considerations is also included.

The Abort Maneuver

The first consideration in an abort situation is to arrest the rate of descent of the LEM as quickly as possible. In the present study the descent engine is immediately staged and the LEM is pitched until the main thrust axis is alined with the local vertical before igniting the ascent engine. Thrusting remains vertical until the descent is stopped and a rate of ascent equal to the rate of descent at abort initiation is acquired. This strategy preserves the horizontal velocity existing at the time of abort and allows the entire thrust to be used to stop the LEM's descent. For a typical initial thrust-to-weight ratio of 0.43 (for the ascent stage), calculations show that the rate of descent can be arrested above the mean lunar surface for aborts from anywhere along the assumed powered-descent trajectory.

At the end of the vertical thrusting period, the LEM is pitched to an angle which is a mirror image (with respect to the local vertical) of the pitch angle at abort. Then during the ascent, a pitch profile is followed which approximates, in reverse fashion, a mirror image of the pitch profile during descent to the point of abort. As a 50 000-foot altitude is approached, the LEM crew attempts to establish a circular orbit as nearly as possible before shutting off the main thruster. A typical abort trajectory is shown by the dashed curve in figure 2.

Table II contains a summary of pertinent information associated with aborts from representative points along the landing trajectory, including hover. An average pitching acceleration of 10 deg/sec^2 was assumed and a generous allowance of 4 seconds was made for abort-recognition time and other system lags; these are combined in the second column. The values in the fourth column are twice the sum of the values in the first three columns (except for the entries after the beginning of hover) and arise from the technique of the mirror-image abort trajectory. The CSM travel angle in the sixth column is just the constant orbital rate of the CSM in orbit times the values in the fourth column. Note that this table does not include any times for monitoring or trimming the chasing orbit.

The Chase Maneuver

Once injection into the chasing orbit has been made, the orbit should be quickly circularized before an orbital transfer can be initiated. It was beyond the scope of this study to determine the ability of the LEM crew to trim up the orbit to certain specifications in a given time; however, an error analysis of the deviations from circular conditions is presented in a later section. Also, a minimum trim-up time of 5 minutes was set because of the phase-angle relationship existing after aborts from early in the powered descent.

The Transfer Maneuver

The orbital transfer maneuver will be considered in terms of the incremental velocity ΔV requirements of the LEM and the range of times that may be selected to initiate a safe transfer based on where along the powered-descent trajectory the abort occurs. (A safe transfer orbit has been defined previously as one which does not have a pericynthion lower than 50 000 feet.)

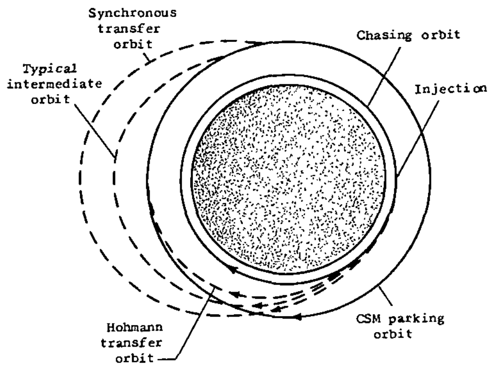


Figure 3.- Family of transfer orbits considered.

Figure 3 shows some typical safe transfer trajectories generated in the following manner: At some point in the chasing orbit about 99 fps ΔV greater than circular velocity is added to the LEM along the velocity vector by some appropriate technique and the result is a Hohmann transfer ellipse up to the CSM orbit. The Hohmann transfer of course is the most efficient method of transfer. But if velocity in excess of this 99 fps is added, the result is a family of orbits having apocynthions greater than 80 nautical miles, and each orbit cuts the CSM orbit in two places. When this excess reaches 91 fps, the result is an orbit which has a period equal to the period of the CSM orbit. Any transfer using this orbit will be referred to as a "synchronous-orbit transfer" and will be used as an upper limit in this study. For distinction, the synchronous orbit used in descending from the CSM down to 50 000 feet prior to the powered descent will be referred to as the "synchronous-descent orbit."

The velocity increment ΔV required to rendezvous with the CSM from the Hohmann transfer orbit is about 97 fps and from the synchronous transfer orbit is about 373 fps. Thus, rendezvous from any of the intermediate orbits is bounded by these two values and the total transfer ΔV used in the family of orbits will range between 196 fps and 563 fps.

For any of these transfer orbits to be appropriate for rendezvous, a particular phase angle $\Delta\theta$ must exist between the two vehicles at the time of injection into the transfer orbit. For example, the CSM must be about $9\frac{1}{2}^{\circ}$ ahead of the LEM for initiation of a Hohmann transfer, about 8° behind for a synchronous-orbit transfer, and somewhere in between to use one of the intermediate orbits. This $17\frac{1}{2}^{\circ}$ range in the phase angle corresponds to a "transfer window" of about 51 minutes. That is, since the LEM in the chasing orbit gains about 0.34° anomaly angle per minute on the CSM in the 80-nautical-mile parking orbit, the appropriate injection time for a synchronous-orbit transfer occurs about 51 minutes after the appropriate time for a Hohmann transfer and, as indicated previously, it is possible to initiate some intermediate transfer orbit at any time during this 51-minute period.

Figure 4 shows the approximate phase angles the pilot can expect to have as the LEM enters the chasing orbit following aborts from anywhere along the powered-descent trajectory. The inside ordinate in this figure shows the expected lead or lag angles which are plotted as a function of the elapsed time between the beginning of the powered descent at pericynthion and the initiation of the abort. The appropriate phase angles for a Hohmann transfer and a synchronous-orbit transfer are also indicated and define the limits of the transfer window.

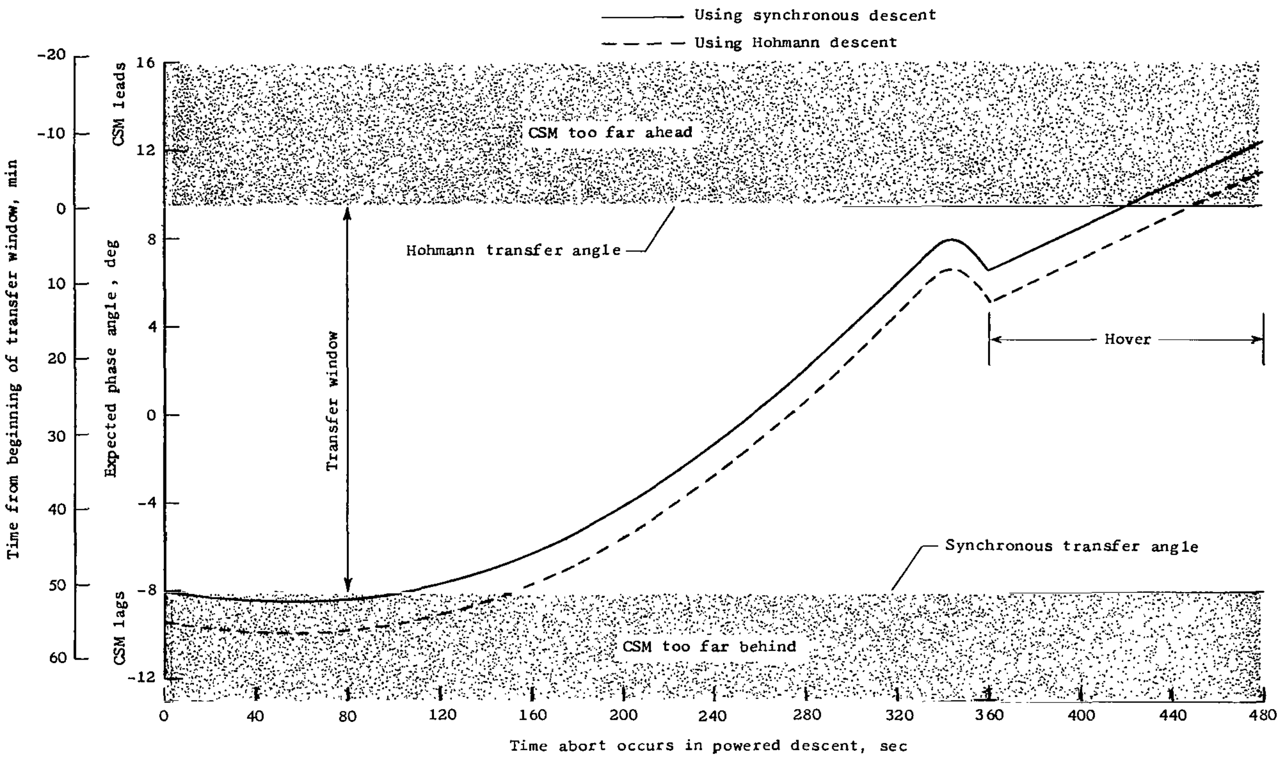


Figure 4.- Transfer window and CSM/LEM relationship as LEM enters chasing orbit after abort from powered descent.

The solid curve applies to abort situations subsequent to using the synchronous-descent orbit to 50 000 feet. This curve does not include the time in the chasing orbit, and each point of the curve must be displaced downward by the amount of time required for trimming up this orbit. The new positions of the displaced points would give the expected phase angles for the earliest transfer-orbit initiations from each point. Note that the entire transfer window is available only for aborts which occur near the end of hover. The peculiar shape of the curve near hover is due to the fact that it takes less time to abort to the chasing orbit from hover than it does a few seconds earlier when a rate of descent must be arrested. (See table II.)

The dashed curve in figure 4 applies to a slightly modified situation in which the LEM uses a Hohmann descent orbit down to 50 000 feet. Note that this curve occupies approximately the position the solid-line one would after a constant 5-minute displacement (corresponding to the assumed minimum trim-up time). The dashed curve must also be displaced downward 5 minutes to give the phase angles for earliest transfer.

The shaded area above the transfer window indicates that it is inappropriate for immediate transfer because the CSM is too far ahead, but after a short wait in the chasing orbit, the entire transfer window will become available. This area only has application to aborts during final letdown or from early take-offs from the lunar surface.

When the phase angle enters the shaded area of the figure below the transfer window, a two-impulse transfer will exceed the ΔV limits of the study. Note that both curves lie in this lower region for early aborts. For these cases, several transfer alternatives exist: (1) delay initiation of the abort a minute or two until the LEM can gain a more favorable phase angle, (2) abort at once and use a higher energy orbit than the synchronous orbit, (3) abort and wait about 17 hours in the chasing orbit and then use a Hohmann transfer, (4) abort and use a three-impulse transfer (discussed later in this report), or (5) use a direct return to the CSM. These alternatives are, obviously, subject to such factors as the continued functioning of the descent engine and time restrictions due to the emergency which caused the abort. The remaining fuel for these cases will probably not be critical since a relatively small amount is required from abort to the chasing orbit. As aborts occur later in the landing mission (see fig. 4), the transfer ΔV approaches the optimum of the Hohmann as the ΔV considerations (fuel onboard) become more critical. Also there is more available preparation time which should increase the probability of initiating a good transfer orbit.

For all the cases within the study range (excluding the five alternatives above), the total time from the point of abort to rendezvous at the second intercept is less than 100 minutes. The corresponding minimum time of about 71 minutes occurs for an abort from the end of hover.

Since the LEM crew has the choice of transferring as soon as possible or remaining for an additional time in the chasing orbit, the penalties should be considered for remaining the additional time. For each minute of delay, an additional 40 seconds will be required for the transfer and an additional 7 fps ΔV will be required. However, the extra waiting time can be used to increase the probability of good injection and thus might preclude the need for correction.

While in the chasing orbit, the LEM's rendezvous radar or pilot observation will continuously sample the elevation angle (α in fig. 1) to the CSM; this angle is related to the phase angle between the vehicles by the solid curve in figure 5. The symmetry of the relationship is indicated by the double scale for α in this figure. The dashed curves give similar information for chasing-orbit altitudes of 40 000 feet and 60 000 feet and show that differences as large as 20 percent in this altitude result in no appreciable error in phase-angle determination. Thus, it seems that the elevation angle then can be used with confidence as the primary parameter in the transfer maneuver.

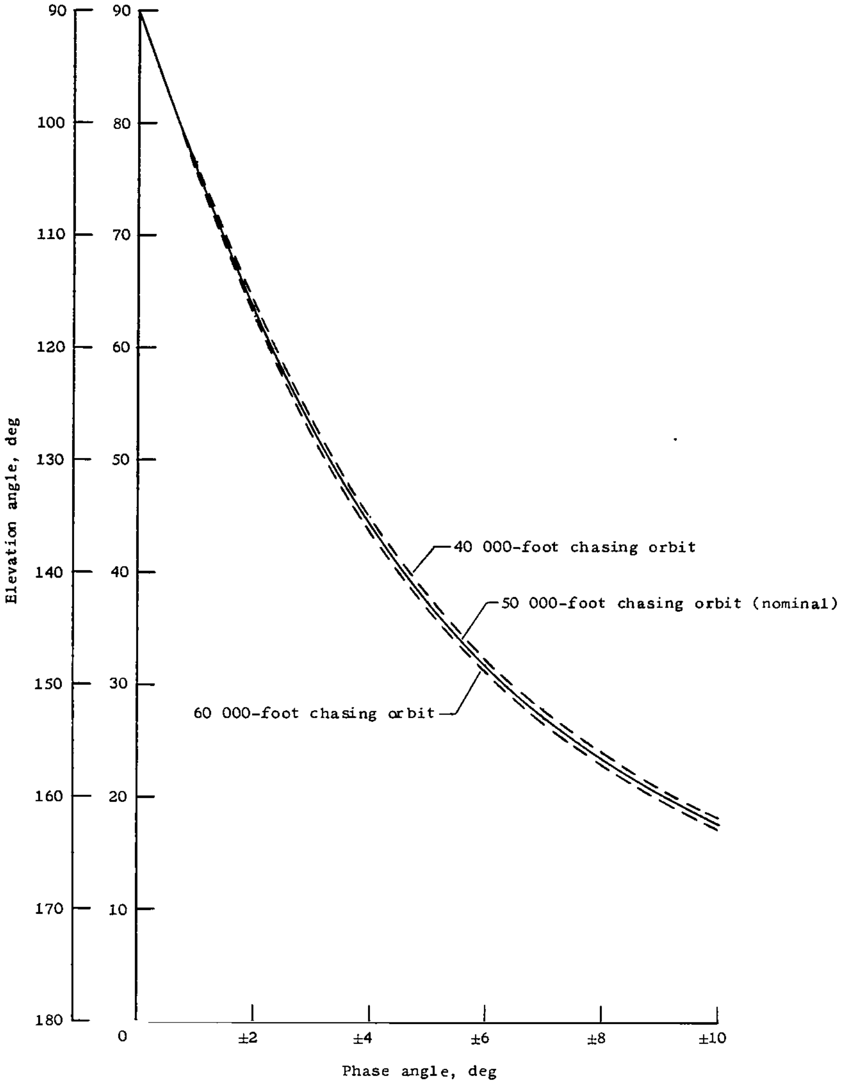


Figure 5.- Relationship of the elevation angle to the phase angle for three chasing-orbit altitudes.

To execute the transfer maneuver properly, the pilot needs to know how much ΔV to add to the LEM for transfer at a given elevation angle. Figure 6 correlates the injection velocity ΔV_i with the appropriate elevation angle α for attempted rendezvous on both the ascent portion of the transfer trajectory (i.e., first intercept of CSM orbit) and the overshoot return portion (second intercept, fig. 3). These relations can be tabulated on cards for use by the LEM crew. Note that for first-intercept rendezvous the elevation angle can be no more than 5° different from the Hohmann elevation angle of 19° or an injection velocity in excess of that required for synchronous-transfer injection (190 fps) will be required. Thus figure 6 shows that a rendezvous plan primarily using the second intercept is more feasible because the range of values of

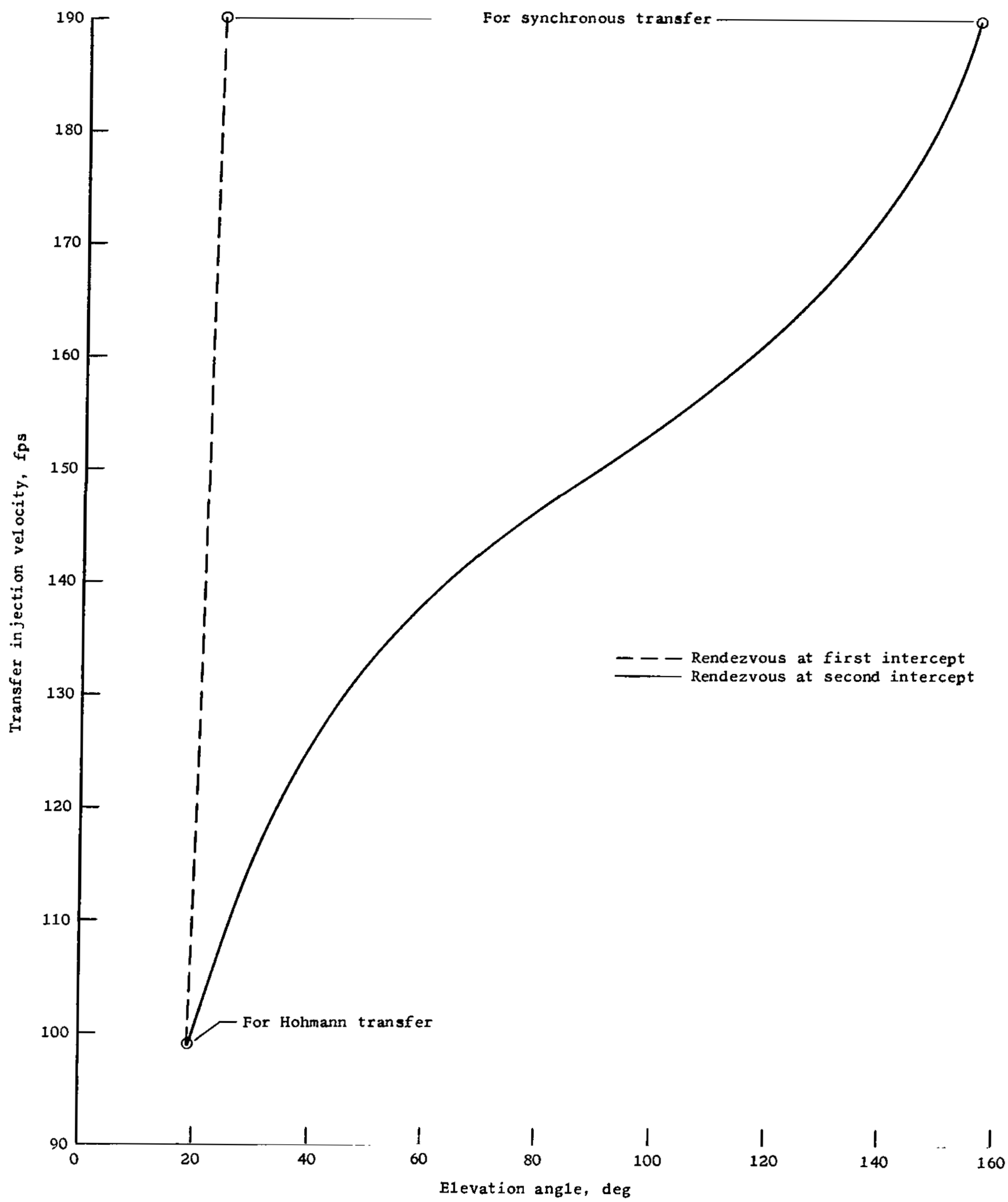


Figure 6.- A correlation of appropriate transfer injection velocity with measured elevation angle.

the elevation angle appropriate for first-intercept rendezvous only occurs for aborts near hover, and then only allows a transfer window of about 5 minutes. (This 5-minute transfer window corresponds to the first 5 minutes of the 51-minute transfer window defined in figure 4 for second-intercept rendezvous.) Incidentally, the first-intercept transfer window could be extended by using other than a zero flight-path angle injection, but the resulting transfer orbit would have a pericynthion lower than 50 000 feet.

During the first-intercept transfer window, there is, however, an interesting tradeoff of total transfer ΔV against time required to make the transfer. For example, consider in figure 6, the limiting ΔV case which occurs when the elevation angle $\alpha = 23.75^{\circ}$. At this angle the time required for first-intercept rendezvous is about 30 minutes compared with slightly over 70 minutes for second-intercept rendezvous. However, calculations show that the associated ΔV requirements are 563 fps and 345 fps, respectively. Figure 7 shows this tradeoff over the range of excess ΔV values which can be appropriately used during the first-intercept transfer window.

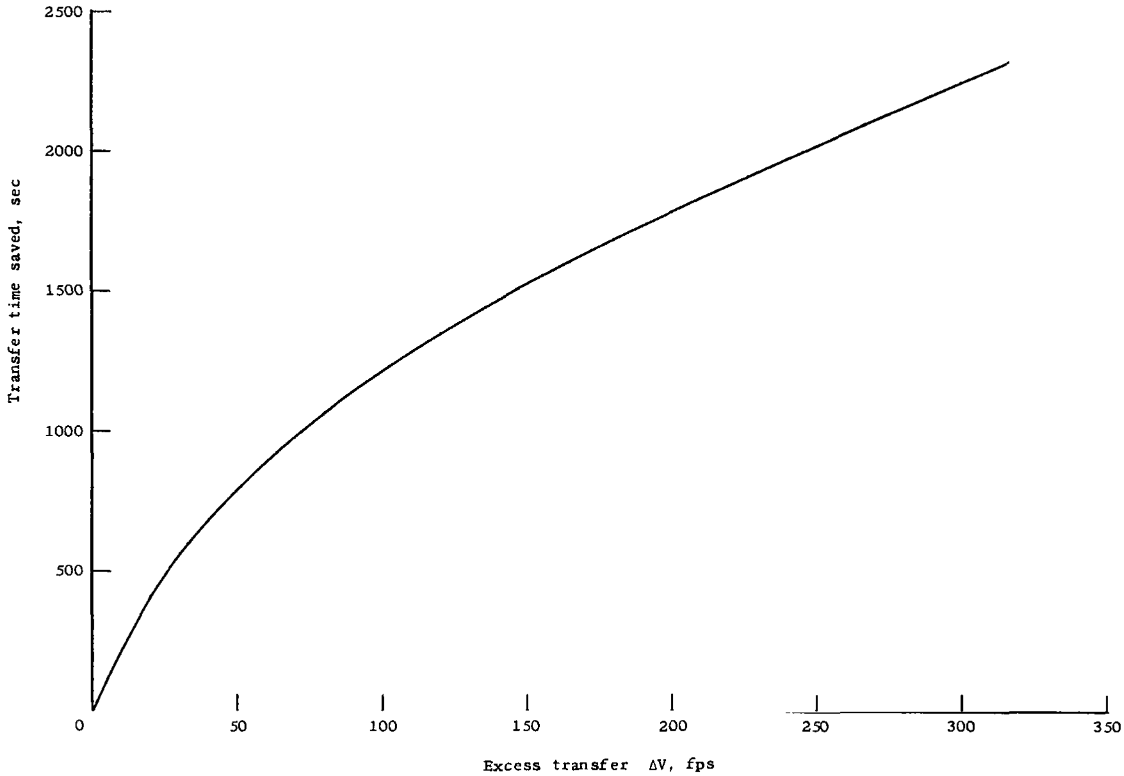


Figure 7.- Transfer-time saving as a function of excess transfer ΔV for rendezvous at first intercept of the Apollo orbit.

Since this time saving is quite substantial, it seems feasible to include first-intercept rendezvous in the abort plan as an option. Note from figure 4 that this option is available only for aborts which occur as the LEM reaches hover. Also, as already noted, the available ΔV is critical for these cases.

Error Considerations

Errors of injection into an intended transfer orbit can arise from: (1) Error in altitude of the chasing orbit, (2) Noncircular chasing orbit at the time of transfer initiation, or (3) Incorrect thrusting. Each of these contributions can be related to a corresponding error in the magnitude of the injection velocity ΔV_i; the error analysis is performed with respect to this quantity.

The errors in ΔV_i will cause the LEM to miss the intended rendezvous position by a certain anomaly angle or distance. However, the real concern is just to reach the CSM rather than to reach a certain point in space coincident with the CSM arrival there. Figure 8 shows the anomaly angle by which the LEM will miss the CSM for various injection-velocity errors over the range of elevation angles appropriate for transfer. In particular, a 5 to 6 fps error will cause a miss distance of approximately 20 nautical miles or about a 1° anomaly angle; a simulation study (ref. 3) has shown that from a range of 20 nautical miles rendezvous can still be accomplished with only a small fuel penalty. Thus, up to 6 fps error in ΔV_i will be considerable tolerable.

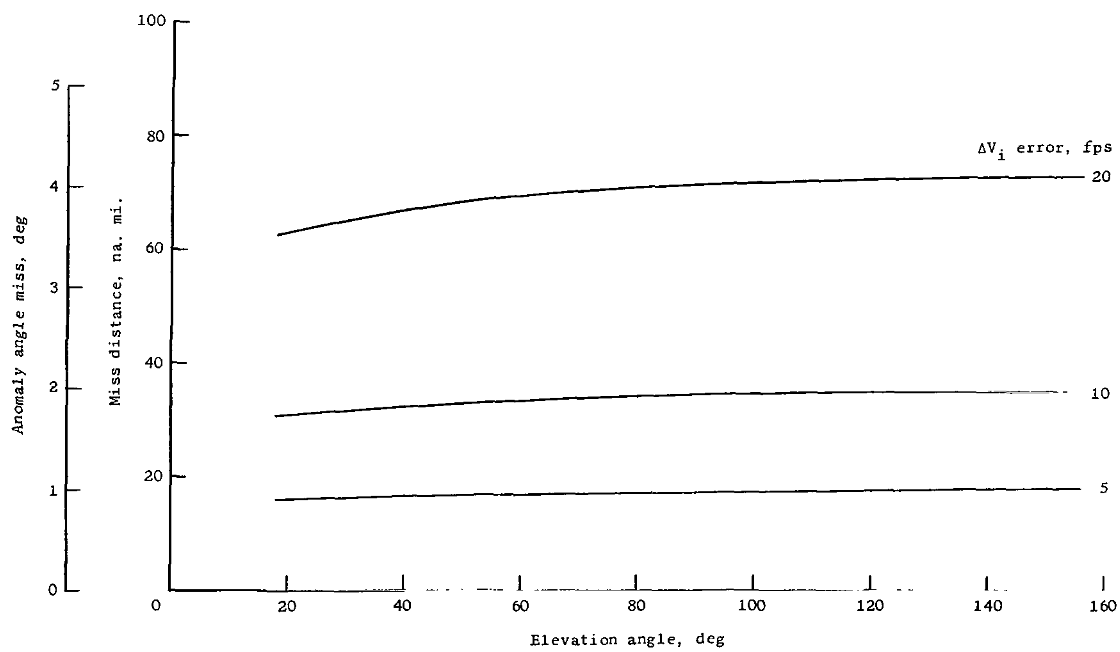


Figure 8.- Rendezvous miss distances at second intercept due to errors in the transfer injection velocity ΔV_i.

Calculations indicate that if the LEM orbit has been circularized at some given altitude near 50 000 feet, each 1000-foot difference of this altitude from 50 000 feet results in about the same miss distance (at rendezvous) as would result from a 0.2 fps error in ΔV_i when transferring from the 50 000-foot orbit. A flight-path-angle error of 0.1° (or approximately 10 fps residual altitude rate) in the chasing orbit results in the equivalent of less than 1 fps error in ΔV_i. Similarly, a thrusting angle error of about 5° also results into an equivalent of about 1 fps error in ΔV_i. Thus each of these sources of error will probably be insignificant.

A velocity deviation above or below circular velocity in the chasing orbit will be transferred directly as an error in ΔV_i; this error could be rather sizable if the pilot has no functioning velocity display (except altitude rate). The importance of carefully trimming the chasing orbit for as long as possible before initiating the transfer is thus emphasized as a primary piloting task.

Errors in thrust-cutoff time can also introduce significant errors in ΔV_i. To prevent large errors of this type, it may be necessary to include an integrating accelerometer on the thrust axis to terminate the thrusting from a velocity cue. The accuracy of the cut-off needs to be about 0.5 second to insure that the ΔV_i error will be 6 fps or less.

An attractive feature of the transfer technique is that the injection-velocity errors may be accurately detected at apocynthion - that is, the change in apocynthion altitude is very sensitive to such errors; for each fps error the altitude change is nearly 5000 feet. This relation is nearly linear over the ΔV_i range under consideration, and if the accuracy of the radar measurement of altitude is within 1 percent, the ΔV_i can be determined to less than 2 fps.

If upon reaching apocynthion, the ΔV_i error is determined to be greater than 6 fps, some type of midcourse correction should be considered which does not reduce the pericynthion altitude of the transfer orbit below 50 000 feet. Consider a range of velocity increments ΔV_a added along the velocity vector at apocynthion. Figure 9 is a plot of possible anomaly-angle change at the second intercept due to these increments for a range of ΔV_i. The ΔV_a increments are limited to less than 100 fps or the new orbit pericynthion will be greater than 80 nautical miles and there will be no second intercept of CSM orbit. For clarity, the ΔV_i = 105 fps and 115 fps curves are considered the near-Hohmann cases and the ΔV_i = 175 fps and 190 fps curves are considered near-synchronous orbit cases. Figure 9 shows that the error-correction capability of the near-Hohmann transfers is very poor; the anomaly-angle change of less than $\pm 0.2^\circ$ corresponds to an error in ΔV_i of less than 1 fps. Since an error up to 6 fps in ΔV_i is assumed tolerable, a ΔV_i error greater than 7 fps cannot be adequately corrected by the apocynthion technique.

If the ΔV_i error is greater than 7 fps, the LEM orbit can be circularized at the apocynthion altitude and, if necessary, the LEM can rely on the CSM to make the rendezvous. Also, by circularizing, the thrusting restrictions on

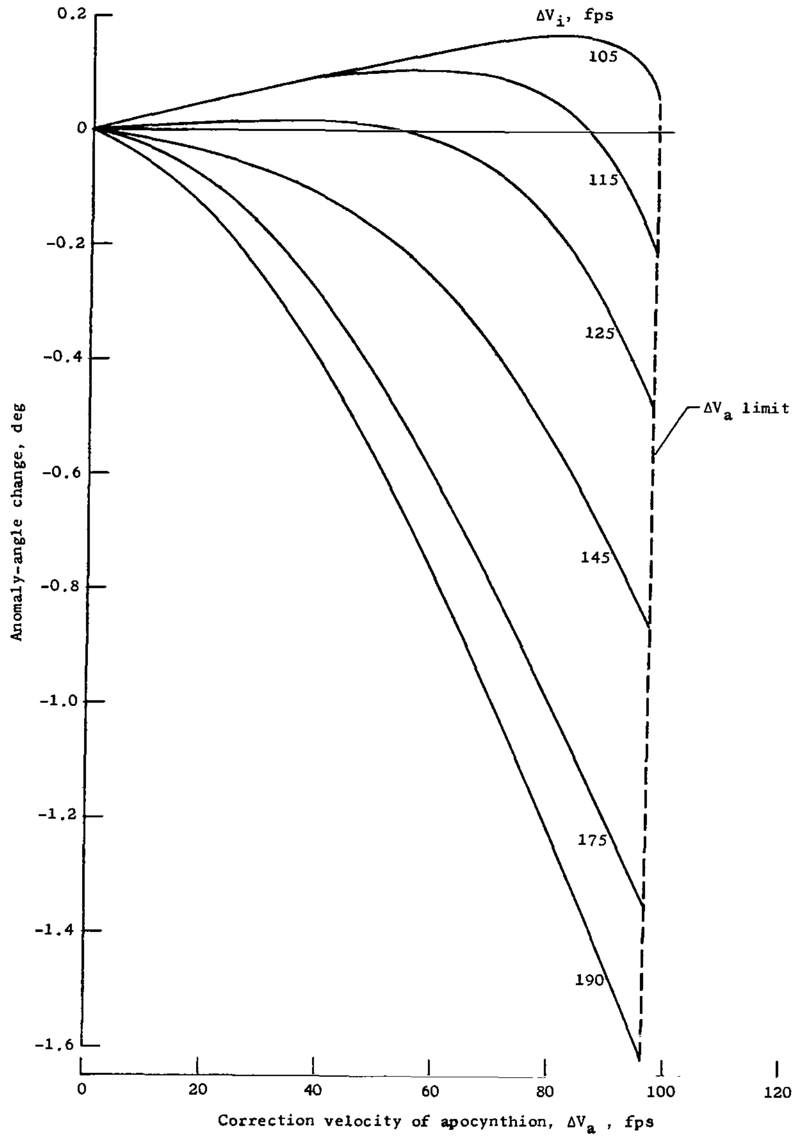
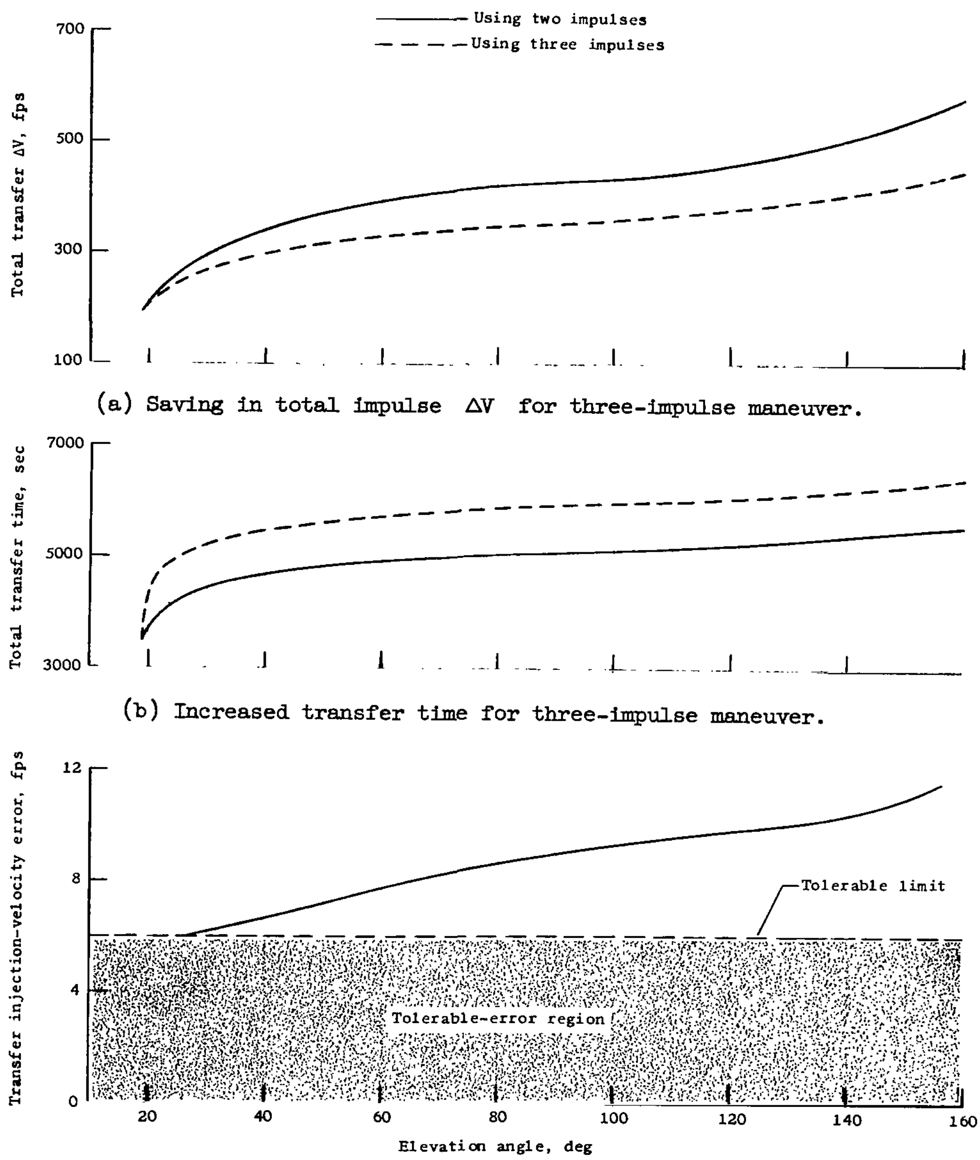


Figure 9.- Anomaly-angle change of second intercept due to velocity added at apocynthion of transfer orbit.

LEM due to the 50 000-foot pericynthion are lifted and a wide variety of maneuvers are now available for the LEM to effect a later rendezvous or to assist the CSM in achieving it.

The near-synchronous orbit transfers can be corrected for ΔV_i errors of 14 fps above the intended ΔV_i; this value corresponds to the 1.6° anomaly-angle gain in figure 9. The ΔV_a (or fuel) required to achieve this correction (nearly 100 fps) may seem like an excessive amount to use for correction purposes, but the subsequent rendezvous fuel requirement is reduced by more than this amount, and thus less total fuel is required than if no error had been made at injection. However, the fuel saving is attained at the expense of longer transfer time.

Figure 10 shows the tradeoff of ΔV saved against increased transfer time for an impulse, $\Delta V_a = 75$ fps, over the range of elevation angles α appropriate for transfer. Also shown is the ΔV_i error that this same impulse will



(c) Injection-velocity error which can be corrected (with $\Delta V_a = 75$ fps) to the equivalent of a 6 fps error.

Figure 10.- Comparison of transfer time and velocities for the two- and the three-impulse transfer maneuvers ($\Delta V_a = 75$ fps for the three-impulse maneuvers).

correct to less than a 20-nautical-mile miss distance at the second intercept (or the equivalent of a 6 fps error in ΔV_i). The $\Delta V_a = 75$ fps was arbitrarily selected here to illustrate the three-impulse features.

Figure 10 suggests that for the near-synchronous orbit transfers (i.e., when the elevation angle is near 160°) it is advantageous to add deliberately several fps too much ΔV_i at injection with the intention of adding a sizable corrective ΔV_a at apocynthion. This procedure insures that the resulting transfer will be capable of correction and that it will require less total transfer fuel than for a comparable two-impulse transfer. The penalty for this variation will be only a 10- or 15-minute increase in transfer time. Note that this option is not available for the near-Hohmann transfer - that is, for values of the elevation angle near 20°.

CONCLUSIONS

An analytical study of a simplified technique for aborting a lunar landing mission during the powered descent portion with application to manual backup guidance yielded the following conclusions:

1. The lunar excursion module (LEM) descent engine may be immediately staged in an abort situation and the ascent engine will safely arrest the rate of descent for aborts at all points along the assumed powered-descent trajectory.

2. By using the two-impulse transfer technique, rendezvous can be achieved within 100 minutes from the time of abort; the minimum time for such a maneuver is about 71 minutes.

3. The transfer maneuver allows a time flexibility in the chasing orbit for the LEM crew to evaluate their situation better before committing the LEM to a rendezvous trajectory (transfer). The time flexibility for initiating a transfer is greatest for aborts from the most critical part of the landing trajectory (near hover). For these cases, nearly all the 51-minute "transfer window" is available when rendezvous is made at the second intercept of the command-service module (CSM) orbit. During the first 5 minutes of the transfer window there is an option of rendezvous at the first intercept of the CSM orbit. However, even though the incremental-velocity requirements are much higher than for second-intercept rendezvous, the time saving can be quite substantial. While in the transfer window, each minute of delay in initiating the transfer maneuver only adds about 40 seconds to the time required for the transfer.

4. It seems feasible to perform the guidance tasks during each phase of the abort mission by using simplified manual control; many of these tasks have already been successfully performed by pilots during separate simulation studies.

5. The incremental-velocity requirements for the two-impulse transfer maneuvers (including corrections) in all the cases considered are less than 563 fps. The transfers which require the most fuel and have the least available preparation time are called for after early aborts when the available incremental velocity is not critical. Then as aborts occur later in the landing mission, the required transfers approach an optimum in fuel as the ΔV considerations become more significant. The incremental-velocity penalty for a transfer-initiation delay is about 7 fps per minute for any of the transfers.

6. The following sources of transfer-injection error will cause less than the equivalent of 1 fps error in injection velocity (6 fps is considered tolerable): a 5000-foot deviation (from 50 000 feet) in the altitude of the chasing orbit; a residual altitude rate of 10 fps in the "circular" chasing orbit; a thrusting-angle error of about 5° while adding the injection velocity.

7. Significant errors in injection velocity (i.e., 6 fps or greater) can be introduced by either a velocity deviation above or below circular velocity in the chasing orbit, or errors in thrust cut-off time. (However, the use of an integrating accelerometer for automatic thrust cut off could keep this error to an insignificant level.)

8. An error in the transfer-orbit injection velocity can be determined to less than 2 fps by using only altitude information (accurate to 1 percent) when the LEM reaches apocynthion.

9. Transfer-correction impulses at apocynthion must be approximately in the direction of the total velocity vector or an unsafe orbit may be introduced. For near-Hohmann transfers, this method of correction is ineffective. For near-synchronous-orbit transfer, errors of 14 fps above the intended injection velocity can be corrected to a tolerable value; the total fuel used in the transfer maneuver is actually reduced when the corrective impulse is used but the transfer time is increased.

10. Based on the preceding conclusion, a three-impulse transfer technique can be used in near-synchronous-orbit cases in order to save fuel when the additional transfer time can be tolerated.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 22, 1964.

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TABLE I.- CHARACTERISTICS OF THE POWERED-DESCENT TRAJECTORY

Time from pericynthion, sec	Range angle, deg	Altitude, ft	Altitude rate, fps	Total velocity, fps	Thrust-to-weight ratio of LEM	LEM thrusting angle, deg
0	0	50,000	0	5673.67	0.400	180
50	2.67	50,239.9	3.67	4994.80	.427	177.80
100	4.98	49,699.4	-31.94	4293.34	.458	176.46
125	6.00	48,587.5	-60.81	3920.7	.475	175.21
150	6.94	46,596.0	-95.40	3533.82	.494	174.21
175	7.76	43,767.75	-133.07	3134.34	.515	173.09
200	8.49	39,937.0	-171.53	2719.74	.536	171.87
225	9.11	36,899.2	-207.99	2290.32	.560	170.56
250	9.63	29,575.9	-240.03	1845.03	.587	169.15
275	9.78	23,255.6	-263.12	1383.38	.614	168.39
300	10.15	16,455.3	-274.70	905.08	.646	166.08
310	10.37	12,997.4	-272.74	677.79	.663	165.15
320	10.44	11,031.2	-271.22	533.74	.674	164.62
330	10.48	8,213.7	-264.64	363.02	.688	163.89
340	10.49	5,809.6	-246.96	252.05	.703	159.74
350	10.50	3,905.0	-155.43	157.01	.721	124.87
360	10.50	2,000.0	0	0	.740	90

TABLE II.- SUMMARY OF INFORMATION ASSOCIATED WITH ABORTS

FROM POINTS ALONG POWERED-DESCENT TRAJECTORY

Time from pericynthion to abort, sec	Time to pitch LEM to vertical, sec	Time for ascent engine to stop descent, sec	Time from pericynthion to chasing-orbit entry, sec	Range angle from pericynthion to chasing-orbit entry, deg	CSM travel angle, deg
50	11	1	124	6.54	6.07
100	11	3	228	11.24	11.16
125	11	7	286	13.48	14.00
150	11	11	344	15.54	16.84
175	11	15	402	17.26	19.68
200	10	20	460	18.64	22.52
225	10	23	516	19.76	25.26
250	10	27	574	20.64	28.10
275	9	29	626	21.06	30.64
300	9	31	680	21.28	33.29
310	9	30	698	21.28	34.17
320	9	30	718	21.24	35.15
330	9	29	736	21.16	36.12
340	8	28	752	21.04	36.91
350	6	19	750	21.02	36.71
*360	4	0	728	21.00	35.54
420	4	0	788	21.00	38.47
480	4	0	848	21.00	41.41

*Beginning of hover.

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