Apollo Lunar Rendezvous

Kenneth A. Young* and James D. Alexander†
NASA Manned Spacecraft Center, Houston, Texas

The coelliptic rendezvous sequence establishes standard lighting conditions and relative position and velocity conditions for the final approach of the lunar module to the command and service module, thereby affording the greatest probability of success in the event of dispersions or system failures. A gradual ascent with intermediate maneuvers to place the lunar module in an orbit coelliptic with the command and service module orbit assures standard intercept initiation and closing conditions that cannot be guaranteed with the faster but more variable direct-ascent technique. Operationally, sufficient time is allowed between maneuvers for onboard alinement, navigation, and maneuver computations. Rendezvous schemes for contingencies such as aborts or rescues use the same basic coelliptic technique, although, in some cases, additional revolutions may be required for the lunar module to catch up with the command and service module. The results of the actual rendezvous on the Apollo 11 mission compared favorably with the permission values.

Introduction

THE rendezvous plan chosen for the Apollo 11 lunar-landing mission was the result of approximately 6 years of analysis and was essentially an adaptation of the coelliptic technique successfully demonstrated on the Gemini rendezvous missions.[1] In this paper, the basic rendezvous design considerations that led to the choice of the coelliptic technique instead of the faster direct-ascent technique are discussed. The operational rendezvous sequence from lunar module (LM) liftoff to interception with the command and service module (CSM) is outlined. The application of the basic technique to the problem of rendezvous in contingency situations (such as aborts from powered descent) is described. Finally, the actual Apollo 11 rendezvous parameters are compared with the premission values.

Rendezvous Design Considerations

Because the terminal phase was to be controlled manually, the prime rendezvous design consideration was to achieve a terminal closing phase that would be essentially standard regardless of the expected dispersions. A standard terminal phase was defined as one for which the final approach direction, the spacecraft-to-spacecraft line-of-sight rates, and the background (lighting) conditions would vary only slightly because of the expected dispersions. In addition, the magnitudes of the braking maneuvers would not differ more than 30 to 40% from those in the dispersion-free case and would not exceed the capability of the small propulsion (reaction control) systems of the spacecraft. If the braking maneuvers should exceed the capability of the reaction control system (RCS), the major propulsion system would have to be used. Because the spacecraft windows are opposite the main engine, loss of visual contact (and, in all probability, loss of radar and vhf contact) would result. The standard background conditions would be achieved by obtaining the standard final approach at a fixed position or time relative to the darkness terminator. The standard final approach desired for the LM was derived from the Gemini rendezvous experience. In this approach, the LM crosses the vertical approximately 3.5 naut miles below the CSM and advances approximately 0.6 naut miles ahead while matching the CSM altitude such that the LM views the CSM against a sky background with the sun behind and above the LM.

If the relative geometry at intercept-trajectory initiation is kept essentially constant for all cases no matter what the initial difference in altitudes might be, then the final-approach direction over a specified terminal-phase travel angle also remains essentially constant. The approach rates (relative velocity) vary as the differential altitude (ΔH) between the LM and the CSM varies. To handle the expected dispersions that result from the initial LM insertion, a technique can be applied that permits control of the angular geometry at a desired intercept-trajectory initiation time by allowing the ΔH (and thus the closing rates) to vary within acceptable limits. A special maneuver performed before the intercept-trajectory initiation maneuver can establish a ΔH condition that will remain essentially constant around the orbit. This condition is referred to as the coelliptic orbital phase. The term "coelliptic" is preferred to "concentric" to emphasize that the constant ΔH condition can be established both for elliptical and for circular orbits.

The constant ΔH allows constant catchup and angular geometry rates and, therefore, simplifies the monitoring of various parameters. Because of these constant rates, an accurate prediction of when the proper angular geometry for the intercept-trajectory initiation maneuver will occur can be made manually. A manual backup technique for the intercept-trajectory initiation maneuver thus exists. This technique involves thrusting at a selected elevation angle along the line of sight to the target spacecraft. The magnitude of the velocity increment (ΔV) to be applied is proportional to the ΔH.

Before the coelliptic and terminal initiation maneuvers, however, a catchup (phasing) maneuver is needed to absorb the powered-ascent dispersions and thereby maintain the final-approach time. Because the perilune after orbital insertion is less than 10 naut miles in the nominal LM ascent, the phasing maneuver should be designed such that it will not lower the perilune. Therefore, the phasing maneuver is constrained to be a horizontal burn (i.e., the ΔV vector always will be along the local horizontal) because a horizontal posigrade burn never lowers the perilune. Because the phasing maneuver is horizontal (essentially a Hohmann transfer that adjusts the orbital period), it can maintain the terminal-phase timing only by varying the resultant ΔH at the opposite end of the orbit where the coelliptic maneuver is performed. However, the resultant ΔH (and thus the final-approach rates)

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* Head, Mission Design Section, Mission Planning and Analysis Division.

† Aerospace Engineer, Mission Design Section, Mission Planning and Analysis Division. Associate Fellow AIAA.

for the dispersed case does not vary more than approximately 30 to 40% from the resultant ΔH in the dispersion-free case.

A further rendezvous design consideration was to allow time between maneuvers for sufficient onboard navigation to determine the two spacecraft orbits accurately and to compute the rendezvous maneuvers. However, because of the possibility of systems degradation, the total time to rendezvous should not be extended unnecessarily. Furthermore, the nominal rendezvous should be designed to be within the direct ranging capability of both spacecraft (approximately 320 naut miles or less) from beginning to end.

In the early planning stages, it was considered important to design the rendezvous to have maximum ground control (backup) support, especially before the initiation of the terminal phase. However, because of the increased onboard capability, the importance of ground support for the nominal LM ascent decreased during the later developmental stages.

Another consideration for the nominal LM ascent was to optimize ΔV usage. Proper choice of the LM lift-off time and a launch into the CSM orbital plane reduce the optimization to an inplane problem. If the LM maneuvers before initiation of the intercept maneuver are designed to be horizontal posigrade thrusts essentially on the line of apsides (i.e., Hohmann transfers), the ΔV costs are optimized. However, because the intercept initiation maneuver was chosen to produce the desirable approach characteristics previously discussed, the transfer is non-Hohmann and the required ΔV for the terminal phase is thus slightly nonoptimum. Furthermore, a restart of the ascent propulsion system after the insertion maneuver cut-off is questionable because of lack of propellant; therefore, all normal rendezvous maneuvers should be within the LM RCS capability.

Direct-Ascent Rendezvous Problems

The original LM ascent rendezvous concept was the direct ascent in which the LM was to be targeted to insert into orbit on an intercept trajectory. The central travel angle from orbital insertion to intercept was to be between 130° and 150°. Therefore, the entire in-orbit ascent would be equivalent in length to the terminal phase in the coelliptic rendezvous plan.

A major problem even for the dispersion-free direct ascent was that the final-approach braking velocity increments were beyond the RCS capability. These maneuvers would be equivalent to those for a coelliptic ΔH of 50–70 naut miles, because the CSM would be in a circular orbit in the 60–80 naut miles-altitude region.

If dispersions should result, the final approach could vary significantly from the nominal plan because of the potentially large variation in the relative position and velocity of the midcourse corrections when dispersions existed. Furthermore, manual backup solutions for these midcourse corrections would be difficult to obtain.

Apollo 11 Coelliptic Rendezvous Plan

Launch Phase

The LM lift-off time is chosen primarily to satisfy a particular phase angle (or relative range) requirement between the LM and the CSM at LM orbital insertion; that is, at the end of the powered-ascent maneuver. The desired relative range depends on the nominal sequence of maneuvers and on the planned catchup rate. Specifically, the lift-off time is chosen such that, after the 7.5-min powered ascent, the LM enters the initial 60,000-ft × 45-naut miles orbit trailing the CSM by approximately 260 naut miles. This lift-off time (calculated by ground control) occurs approximately 70 sec after the CSM, in a 60-naut miles circular orbit, passes over the landing site.

The LM insertion altitude of 60,000 ft is dictated primarily by the amount of available LM ascent-engine propellant and by the requirement to insert the LM high enough to avoid any mountains. The 45-naut miles apolune was chosen to fit desirable rendezvous characteristics; that is, this altitude is the desired 15 naut miles below the CSM altitude. Therefore, nominally only one catchup maneuver is required to "coellipticize" the LM orbit.

After orbital insertion, the onboard navigation procedures are initiated on both the LM and the CSM to compute and prepare for the first maneuver (phasing) 50 min later. The inertial guidance platform of the LM is realined and then the LM rendezvous radar locks on to the CSM to gather data to determine the LM and CSM orbits and the upcoming phasing maneuver. The CSM tracks the LM both optically (with the sextant) and with vhf ranging to determine a backup solution for the rendezvous sequence in the event the LM should be incapacitated and a rescue be necessary.

Catchup Phase

The phasing maneuver adjusts the catchup rate so that the LM will arrive at a particular trailing displacement (actually represented by a selected look angle to the CSM of 26.6° above the LM local horizontal) as the spacecraft reaches the midpoint of the lunar shadow. The maneuver nominally adds approximately 50 fps to the LM velocity, which raises the 60,000-ft perilune to approximately 45 naut miles. If the lift-off should be slightly early or slightly late or if powered-ascent dispersions should result in an incorrect initial orbit, the phasing maneuver ΔV would vary accordingly. Thus, the resultant LM orbital altitude and, consequently, the coelliptic ΔH (nominally 15 naut miles) could vary. The phasing maneuver logic includes the fact that the coelliptic maneuver will be performed one-half orbit (58 min) later; thus, the phasing maneuver begins the coelliptic sequence and generally is called coelliptic sequence initiation (CSI). The coelliptic maneuver is termed the constant differential height (CDH) maneuver.

A corrective (nominally zero) maneuver point is scheduled approximately 90° (29 min) after CSI. If the CSM sextant track (the most accurate navigation device for planar determination) discloses a sizable out-of-plane situation after LM insertion, a ΔV component is added out of plane to the CSI ΔV to force a common node between the two orbital planes 90° from CSI. At this later point, denoted as the plane change (PC) maneuver, a PC ΔV is applied to shift the LM into the CSM orbital plane. Operationally, such a procedure is used only if the out-of-plane ΔV is too large (more than approximately 5 fps) to be eliminated conveniently in the terminal phase.

Approximately 2 hr after lift-off, the LM nominally will be trailing the CSM by approximately 76 naut miles. At this point, the LM orbit is "coellipticized" by the CDH maneuver, which alines the lines of apsides of the two orbits and establishes a constant ΔH (nominally 15 naut miles). Differential altitudes of more than 20 naut miles result in high closing rates and significant ΔV penalties; whereas problems can occur in the low-ΔH region ($\Delta H < 10$ naut miles) because of increased sensitivity to dispersions and low closing rates. Nominally, the CSI essentially circularizes the LM orbit at the 15 naut miles ΔH, and the CDH thus becomes almost zero. However, if the CSI maneuver is varied to adjust for off-nominal phasing, then the CDH maneuver can become a sizeable maneuver because it circularizes the LM orbit at whatever CDH altitude (not necessarily 45 naut miles) results from the CSI maneuver. The nominal orbital geometry from LM liftoff to CDH is shown in Fig. 1.

Terminal Phase

Following the CDH maneuver, onboard navigation resumes so that the LM and CSM can track each other and compute

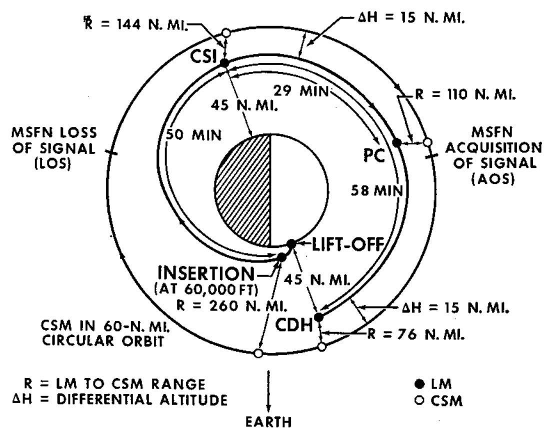

Fig. 1 Orbital geometry from LM liftoff to CDH.

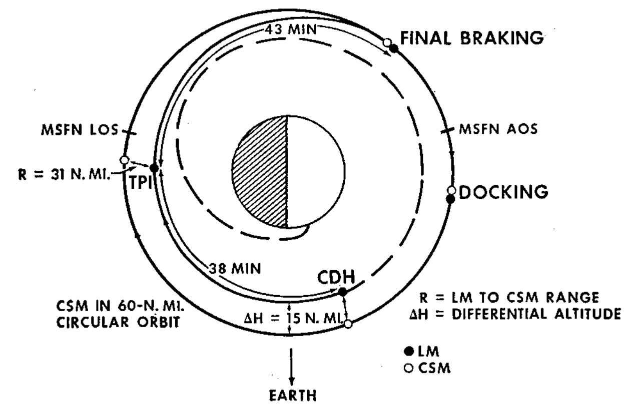

Fig. 2 Orbital geometry from CDH to docking.

the terminal-phase initiation (TPI) burn that will normally occur 38 min later (Fig. 2). The location of TPI at the midpoint of darkness satisfies both the CSM pre-TPI optical tracking requirement and the LM final braking visual requirement. The TPI is performed when the look angle to the CSM, as measured from the LM local horizontal, reaches 26.6°. This angle dictates a TPI solution that, regardless of the ΔH, requires a thrust essentially toward the CSM, thus providing a convenient visual reference in emergency backup situations. The TPI is nominally a 25-fps maneuver that starts the LM on a trajectory that will intercept the CSM approximately 43 min later after approximately 130° of central-angle travel. The 130° travel angle was chosen from Gemini experience as the optimum value to produce desirable line-of-sight rates during the final approach. After TPI has been executed, two small, nominally zero, midcourse corrective maneuvers are scheduled 15 and 30 min later, respectively, to assure a precise intercept trajectory.

As the LM intercepts the CSM from below and slightly ahead (for better visual approach), the LM must slow down. Beginning at a distance of approximately 1 naut mile, when the closing rate is approximately 30 fps, a series of ΔV corrections is applied away from the CSM (in the direction of motion) and perpendicular to the line of sight. These maneuvers raise the LM 45-naut miles perilune and place the LM in the CSM 60-naut miles orbit while matching the LM and CSM velocities. The total propellant normally expended is equivalent to a ΔV of approximately 45 fps. As the distance decreases to a few feet, the relative closing rate is decreased to almost zero, and the LM maneuvers to a docking position. The rendezvous sequence is completed approximately 3.5 hr after lift-off with the physical docking of the two spacecraft.

Rendezvous in Contingency Situations

The LM abort and rescue plans are designed to use the coelliptic rendezvous plan; more specifically, they are designed to re-establish the nominal relative situation at the coelliptic maneuver (i.e., LM below and behind) such that the rendezvous will be essentially nominal from the coelliptic maneuver to intercept. Depending on the relative situation (phase angle) at the beginning of the abort or rescue, the contingency rendezvous can require 3.5 to 11.5 hr, 3.5 hr being the time required for the nominal ascent. An abort or rescue normally is initiated by a maneuver targeted by the ground control center. However, for aborts from powered descent and within a few minutes after landing, the LM has the onboard capability to calculate an orbit with the correct catchup rate and to insert into this orbit. The LM is required to be able to boost its apolune to as high as approximately 200 naut miles for the maximum-apolune abort situation. The required CSM phasing orbit for rescue situations can vary from approximately 20 × 10 naut miles to 350 × 60 naut miles.

A rendezvous profile after an abort approximately halfway into the powered descent is illustrated in Fig. 3 (for Apollo 11). For this case, the rendezvous can be completed in the nominal time following approximately the nominal time line. The required insertion orbit is selected by using onboard equations; the apolune of this orbit is above the CSM orbital altitude because the LM must be slowed down (the orbital period increased) to allow the CSM to get farther ahead. At 50 min after insertion (near the apolune), the horizontal posigrade CSI manuever is performed. Approximately one-half revolution after the CSI maneuver, the CDH (coelliptic) maneuver (in this case, retrograde) is performed. From the CDH maneuver to interception, the rendezvous is nearly identical to the nominal ascent case.

Results of the Apollo 11 Rendezvous

The actual rendezvous performed on the Apollo 11 mission followed closely the planned sequence (Table 1). The difference in some parameters, although well within expected deviations, was primarily caused by two factors: 1) the CSM target orbit was slightly more elliptic than predicted, and 2) the LM crew had difficulty in completing the LM platform alinement after insertion.

The elliptic CSM orbit was a result of unpredicted lunar gravitational effects. Though this situation was handled easily, the CDH maneuver was more costly because a radial ΔV component of 18 fps was required to aline the LM-orbit line of apsides with that of the CSM orbit.

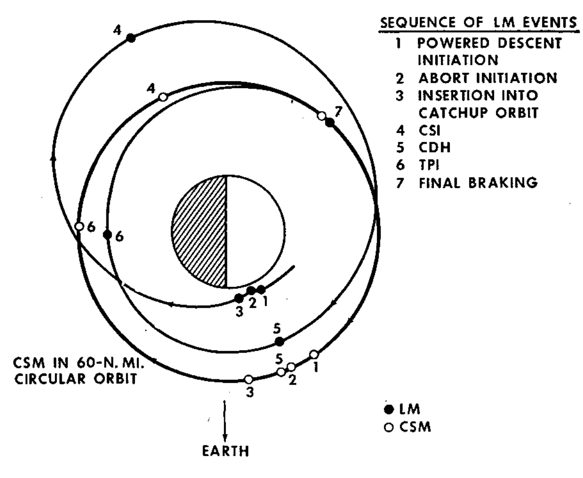

Fig. 3 Typical LM abort rendezvous profile.

Table 1 Comparison of planned and actual Apollo 11 rendezvous parameters

Parameter type	CSM orbital Ha/Hp,[a] naut miles	LM insertion-orbit Ha/Hp, naut miles	LM CSI ΔV, fps	LM CDH ΔV, fps	Time from CDH to TPI, min	CDH ΔH, naut miles	LM TPI ΔV, fps	LM braking ΔV, fps
Preflight planned	59.0/58.3	45/9.7	49.4	4.5	38.5	15.0	24.6	≈45
Actual	62.6/56.4	46.4/9.7	51.6	19.6	45.9	14.0	25.1	≈45

[a] Height at apolune and height at perilune.

Because the platform alinement difficulty delayed the rendezvous-radar navigation schedule by approximately 12 min, the resultant LM onboard estimate of the orbits was not improved significantly over the initial insertion estimate. Consequently, the LM CSI solution was in error by 1.5 fps, which resulted in a ΔH at CDH of 14.0 naut miles, 1.0 naut miles smaller than nominal. This error decreased the catchup rate and thus caused a 6.5-min delay in the TPI time, that is, in the occurrence of the nominal angular geometry for TPI. However, such a delay was well within the expected variation.

No out-of-plane ΔV was applied at CSI or at the optional PC point 29 min later because both spacecraft detected a dispersion of only approximately 2 fps, which was eliminated easily in the terminal phase. The midcourse corrective maneuvers after TPI were small (1.0 and 1.5 fps, respectively). Braking and rendezvous, which occurred out of view of the earth, were routine according to the crew; this fact was verified by the nominal amount of LM propellant remaining after docking.

Conclusion

The coelliptic rendezvous plan will be used on future Apollo missions until confidence in the spacecraft systems increases to the point where expected dispersions decrease significantly. At that point, a shorter and more direct rendezvous technique may be used, with the coelliptic technique reserved as a backup and abort plan.

Reference

[1] *Gemini Midprogram Conference Including Experiment Results*, SP-121, NASA, 1966, pp. 277–278.