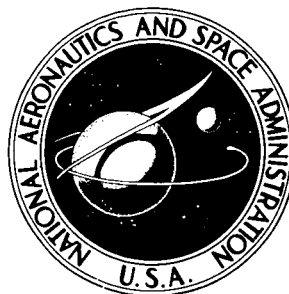


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NASA TN D-7388

NASA TN D-7388

**APOLLO EXPERIENCE REPORT -
EVOLUTION OF THE RENDEZVOUS-MANEUVER
PLAN FOR LUNAR-LANDING MISSIONS**

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1973

1. Report No. NASA TN D-7388		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle APOLLO EXPERIENCE REPORT EVOLUTION OF THE RENDEZVOUS-MANEUVER PLAN FOR THE LUNAR-LANDING MISSIONS				5. Report Date August 1973	
				6. Performing Organization Code	
7. Author(s) James D. Alexander and Robert W. Becker, JSC				8. Performing Organization Report No. JSC S-334	
9. Performing Organization Name and Address Lyndon B. Johnson Space Center Houston, Texas 77058				10. Work Unit No. 924-22-20-00-72	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546				13. Type of Report and Period Covered Technical Note	
				14. Sponsoring Agency Code	
15. Supplementary Notes The JSC Director waived the use of the International System of Units (SI) for this Apollo Experience Report because, in his judgment, the use of SI units would impair the usefulness of the report or result in excessive cost.					
16. Abstract The evolution of the nominal rendezvous-maneuver plan for the lunar landing missions is presented along with a summary of the significant developments for the lunar module abort and rescue plan. A general discussion of the rendezvous dispersion analysis that was conducted in support of both the nominal and contingency rendezvous planning is included. Emphasis is placed on the technical developments from the early 1960's through the Apollo 15 mission (July to August 1971), but pertinent organizational factors also are discussed briefly. Recommendations for rendezvous planning for future programs relative to Apollo experience also are included.					
17. Key Words (Suggested by Author(s)) * Lunar Orbital Rendezvous * Space Rendezvous * Rendezvous Trajectories * Interception * Ascent Trajectories * Abort Trajectories * Trajectory Analysis				18. Distribution Statement	
19. Security Classif. (of this report) None		20. Security Classif. (of this page) None		21. No. of Pages 28	22. Price \$3.00

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SUMMARY

In the nominal rendezvous planning for lunar landing missions, the general progression was from the direct-ascent technique, through the multiple-impulse phasing-orbit technique (coelliptic sequence), to the short rendezvous technique.

The major objective throughout the rendezvous-plan evolution was a standard terminal approach that was executable by use of the reaction control system, that was controllable manually, and that was relatively insensitive to powered-ascent dispersion. Such a terminal approach was characteristic of both the coelliptic sequence and the short rendezvous techniques.

The most significant factor in the simplification and standardization of the originally complex lunar module abort and rescue plan was the incorporation of variable insertion targeting for aborts from powered descent. Other significant developments that improved onboard capability and increased confidence and safety were the implementation of the coelliptic-sequence logic and the very-high-frequency ranging in the command module.

The development of the dispersion and trajectory analysis capability significantly influenced the development of both the nominal and contingency rendezvous planning. Planning disciplines significantly influenced were propellant budgets, mission rules, crew procedures, trajectory constraints, maneuver sequence, and ground and onboard program verification. A significant organizational factor was the eventual assignment to the rendezvous specialists of the responsibilities for the rendezvous dispersion program development and for the rendezvous dispersion analysis.

INTRODUCTION

The purpose of this report is to record significant developments in the evolution of the rendezvous-maneuver plan for the Apollo lunar landing missions and to offer some general recommendations for rendezvous planning for future programs. The development

of the rendezvous plan involved direction, coordination, analyses, and inputs from disciplines and flight experience over several years. Moreover, it involved not only the nominal rendezvous situation but also the contingency rendezvous situations. The disciplines included the crew and onboard systems, navigation planning, ground support, dispersion analysis, consumable analysis, and mission rules. Important flight experiences contributing to Apollo lunar-rendezvous operation planning included the Gemini rendezvous missions and the developmental Apollo rendezvous missions.

In this report, emphasis is placed on the significant technical developments that evolved in the rendezvous-maneuver plan. Other significant developments, including organizational factors, also are identified.

NOMINAL RENDEZVOUS-MANEUVER-PLAN EVOLUTION

The nominal rendezvous-maneuver plan for the lunar-landing missions progressed through the following basic techniques.

1. Direct ascent
2. Phasing (or parking) orbit, which ultimately evolved into the four-impulse coelliptic sequence
3. Short rendezvous

These techniques will be discussed fully later, but an early understanding of their differences and similarities will clarify the evolution of the nominal rendezvous plan.

Originally considered in the early 1960's, the direct ascent theoretically placed the lunar module (LM), at powered-ascent cut-off (insertion), on a trajectory that would intercept the command and service module (CSM). This technique had the following major disadvantages.

1. The incremental velocity (ΔV) requirements during the final approach were beyond the capability of reaction control systems.
2. The final approach (direction and relative velocity) varied as a function of the lift-off time within the normal launch window. Furthermore, powered-ascent dispersions significantly increased the complexity of crew procedures and techniques during final approach.
3. Because an intercept trajectory was targeted at insertion, the insertion targets varied with lift-off time. Therefore, the launch window was undesirably sensitive to unsafe perigee occurrences.

The first two major disadvantages of the direct-ascent technique were overcome by the incorporation of two nominal intermediate maneuvers before the final intercept transfers (the terminal phase). The intermediate maneuver not only regulated the ascent so that the final approach involved relatively low, manually controllable rates within the reaction control system (RCS) capability, but also provided a capability to

economically absorb (before terminal phase) powered-ascent dispersion and, therefore, afforded a high probability of maintaining the standard approach. The new technique was the four-impulse coelliptic sequence for which planning began in late 1964. The coelliptic sequence also eventually involved standard insertion targeting; therefore, the unsafe perigee sensitivity, related to insertion targeting, was eliminated.

The short rendezvous technique was developed beginning in late 1969, following the first lunar-landing mission in which the four-impulse coelliptic sequence was flown. This new technique was a compromise between the first two techniques. The short rendezvous technique involved neither a direct-ascent nor a phasing-orbit coelliptic sequence but incorporated important characteristics of both. It afforded the fast rendezvous time that was characteristic of the direct ascent yet retained the high probability of achieving the standard terminal approach that was characteristic of the phasing-orbit coelliptic sequence. Although the insertion orbit was not an intercept trajectory, an intercept trajectory was established by use of the first in-orbit nominal maneuver (about one-third revolution) after insertion. A nominally zero tweak maneuver scheduled a few minutes after insertion and used in combination with the intercept-transfer maneuver served as a two-impulse (Lambert) dispersion-absorption capability. Therefore, compared with the coelliptic sequence (which essentially involved Hohmann transfers as the means of dispersion absorption) only relatively small powered-ascent dispersions could be absorbed conveniently and economically for the short rendezvous. For larger dispersions or for certain system failures, a "bailout" (abort) to the coelliptic sequence was available to allow the standard final intercept conditions. Because of this resource and because of the confidence derived from the Apollo 11 and 12 missions, the short rendezvous was incorporated as the primary rendezvous technique beginning with the Apollo 14 mission.

The third basic technique has been referred to by three different names: early, short, and direct. Although the term "direct" became the most official name, in this report, the technique is referred to as the short rendezvous to avoid confusion between the terms "direct-ascent rendezvous" and "direct rendezvous." Furthermore, the term designating the number of impulses for a particular rendezvous sequence (for example, four-impulse coelliptic sequence) includes the nominal maneuvers after LM insertion. The terminal phase (intercept transfer initiation and braking) for this impulse-numbering method is assumed to have only two impulses.

The term "concentric sequence" was used in the early nominal planning because the target orbit was always essentially circular. However, when the abort and rescue planning introduced relatively elliptical target orbits, the term "coelliptic sequence" was adopted to emphasize that the constant differential height condition could also be essentially established for elliptical orbits.

Rendezvous planning for certain earth-orbit programs, such as Gemini and Skylab, had used a maneuver-line logic for which the number of maneuvers (or impulses) and the number of revolutions were of prime consideration. By use of this logic, the maneuvers and the revolutions could be treated as variables. However, as the nominal rendezvous plan for the lunar-landing missions evolved, these parameters were not treated as variables, mainly because of limits on time and the concern for safe perilune. The maneuver-line logic could involve nonhorizontal maneuvers, which, in some cases, would lower perigee significantly. Although planning for lunar rendezvous definitely was affected by previous earth-orbit rendezvous planning, a new type of

rendezvous planning was required. However, it might be of interest to note how the number of impulses n and the number of revolutions m varied during the evolution of the nominal rendezvous. To indicate precisely its variation, the variable m , normally expressed as an integer, is expressed in fractions. Hence, for the direct ascent, n equaled 1, and m varied between $1/3$ and $2/3$. During the evolution of the phasing-orbit coelliptic sequence, n increased from 2 to 3 and, finally, to 4, and m increased from approximately $1-1/3$ to $1-2/3$. Then, for the short rendezvous technique, n equaled 2 and m equaled approximately $2/3$. Other prime planning factors for lunar rendezvous included certain characteristics of the terminal phase and the placing of maneuvers relative to the line of apsides.

Generally, the major areas of nominal rendezvous development were launch window, base orbits, maneuver sequence, and terminal phase. Each of these areas is discussed separately. In lunar-mission planning, the maneuver sequence and the terminal phase were the dominant considerations; in fact, developments in these two areas essentially controlled the decisions for the launch window and base orbits. For this reason, the maneuver sequence and the terminal phase are treated in greater detail in the following sections.

Launch Window

The initial philosophy was that a nominal launch window of 4 to 5 minutes should exist. In other words, the nominal rendezvous sequence and time line should be applicable within this window. All direct-ascent technique planning and planning for the first part of the phasing-orbit technique were influenced by this requirement. However, certain proposed changes in the base orbits and in the maneuver sequence (described in the two following sections) would have reduced such a nominal launch window to less than 1 minute. It was then decided that no realistic situations would require a nominal launch window of more than a few seconds. If the LM could not lift off so that the nominal sequence time line could be applied, either a CSM one-revolution delay or a contingency time line could be applied. In effect, the revised philosophy that was used during the remaining rendezvous-technique development meant that no specific nominal launch window existed.

A significant factor in launch-window analysis was the development of the "recommended lift-off time" computer program. The program eventually could determine the optimum lift-off time as a function of desired parameters for either the four-impulse coelliptic sequence or the two-impulse short rendezvous.

Base Orbits

The CSM lunar parking orbit. - The choice of altitude for the CSM lunar parking orbit involved both nominal capabilities (initially including launch-window considerations) and powered-descent-abort phasing and ranging considerations. A nearly circular orbit was chosen because of its rendezvous advantages, mainly monitoring-and-backup-technique simplification. The initial rendezvous planning was based on the assumption of a CSM parking-orbit altitude of 80 nautical miles circular. Directly because of limited LM RCS propellant and indirectly because of limited ascent propulsion system (APS) propellant, the CSM parking-orbit altitude was decreased to

60 nautical miles circular. Lowering this altitude decreased the nominal launch-window capability and was a factor in the elimination of the 4- to 5-minute nominal launch window. The 60-nautical-mile orbit was incorporated into the planning after the basic four-impulse coelliptic sequence was developed, and it was thereafter maintained as the nominal altitude.

The LM insertion orbit. - Throughout the development of the nominal rendezvous plan, the LM insertion-orbit requirement alternated several times between a variable orbit and a constant orbit. A variable-insertion orbit is defined as one for which the insertion targets are directly dependent on the CSM conditions (position, velocity, and so forth). A constant-insertion orbit is defined as one for which the insertion targets remain essentially constant within certain limits regardless of the CSM condition. For the direct-ascent technique, the insertion orbit varied within the nominal launch window and had whatever dimensions were required to establish, at insertion, an intercept trajectory with the CSM in the 80-nautical-mile orbit. The APS was thought capable of obtaining any such required orbit; the only constraint was maintaining a safe perilune.

For the original phasing-orbit technique, a low constant-insertion orbit of approximately 10 nautical miles circular was considered. For the original coelliptic plan, the insertion apolune varied as a function of lift-off time within the nominal launch window. The objective of this variation was to control final transfer initiation time. During this period of development, dispersion analyses showed that the targeted apolune of the insertion orbit (about one-half revolution after insertion) should be no lower than 30 nautical miles to ensure a safe orbit. The insertion altitude at perilune of 60 000 feet (approximately 9.8 nautical miles) was influenced by APS ΔV considerations. The decision was made to incorporate a constant-insertion orbit when the basic four-impulse coelliptic sequence was developed. The approximately 10- by 30-nautical-mile orbit was incorporated at this point and remained nominal throughout most of the development of the coelliptic-sequence plan. Near the end of the development of the coelliptic-sequence plan, the apolune altitude was increased to approximately 45 nautical miles, mainly to decrease the relative range at insertion. The final change to the coelliptic-sequence plan involved inserting the LM with a constant radial-velocity component to shift apolune approximately 5 minutes nearer the insertion point. The apolune altitude remained at approximately 45 nautical miles, but the perilune altitude decreased to approximately 9.2 nautical miles.

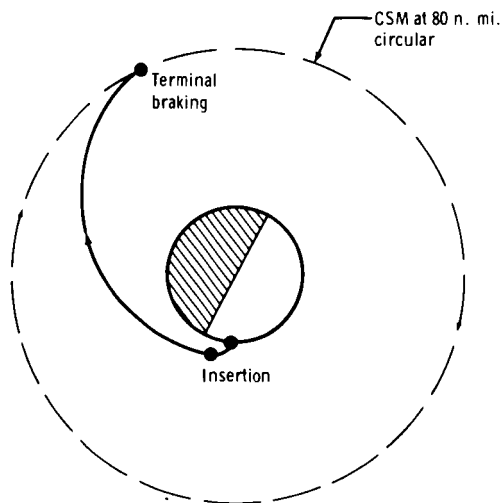
The insertion orbit for the short rendezvous technique was basically the same as for the final coelliptic sequence, but the apolune altitude varied from approximately 45 to 50 nautical miles as a function of the mission plan. The constant radial component at insertion was maintained, and the orbit was targeted to obtain a desired differential height (Δh) at a specified time after insertion. Therefore, the final type of LM insertion orbit could be considered a nearly constant orbit.

Maneuver Sequence

The development of maneuver sequence has been introduced previously but is discussed in detail here.

Direct-ascent technique. - The original concept for the ascent-to-rendezvous technique was the direct-ascent concept. The analysis for the direct-ascent technique

began in the early 1960's, before hardware characteristics and realistic dispersion magnitudes were well defined. An inertial sketch and maneuver-sequence data that are representative of the direct-ascent technique are shown in figure 1. The basic characteristics of this technique were as follows.



1. A variable powered ascent (that is, variable insertion targets) as a function of the lift-off time within the nominal launch window, so that the LM would be inserted on a trajectory intercepting the CSM

2. A variable transfer angle (insertion-to-intercept) that varied from approximately 120° to 300° as a function of lift-off time, with ΔV optimization being the main objective

3. Variable-time and variable-relative-position midcourse corrections that were to include any plane change

The obvious advantage of the direct-ascent technique was the relatively short duration from lift-off to rendezvous completion. However, as a result of experience in the Gemini Program, two major problems were identified in the early development of the Apollo rendezvous technique (early 1964) by the flight crew and flight-control personnel. Because of both the variable transfer angle and the effect of predicted dispersions, the final approach varied considerably. This variable final approach involved complex crew-monitoring, backup, and braking techniques. Furthermore, because most of the rendezvous activities occurred on the far side of the

Nominal rendezvous maneuver	Time from previous maneuver, min	ΔV , fps	Main propulsion system	Resulting orbit, apogee/perigee, n. mi.
Insertion	^a 7	—	APS	83/9
Terminal braking	45	^b 150	RCS	80/80

^aIntercept trajectory targeted at insertion.

^bApproximate operational braking total

Figure 1. - Representative direct-ascent technique.

moon, almost no ground support was available. However, during the later phases of development, the requirement for ground support of the terminal phase was eliminated, primarily because of the development of excellent onboard guidance and navigation systems. Also involved was an undesirable sensitivity to unsafe perilune and complex ascent monitoring techniques because of the variable (lift-off-time dependent) insertion targets. A technique was needed that would afford a standard final approach, ground support of the primary maneuvers (based on assumptions at that time), and constant insertion orbit condition. The direct-ascent technique lacked these characteristics, so planning turned to some type of phasing- or parking-orbit technique.

Multiple-impulse phasing-orbit technique. - The multiple-impulse phasing-orbit technique progressed through several developmental phases. Each phase increased the acceptability of the technique for the required applications.

Original phasing-orbit technique: For the original phasing-orbit technique, the LM was to be inserted into a standard insertion orbit at an 8- to 10-nautical-mile altitude with an apolune altitude of 10 to 20 nautical miles, regardless of the lift-off time within the nominal launch window. The standard insertion would both alleviate the unsafe perilune problem and simplify the crew monitoring techniques, as compared with the variable powered ascent of the direct-ascent technique. Then, at a selected phase angle (or LM-to-CSM elevation angle), a direct intercept was to be initiated with a standard transfer angle of approximately 160° . This maneuver was referred to as terminal phase insertion (TPI). The time of TPI would vary as a function of the lift-off time, but the nominal launch window would be bounded so that the conditions for TPI would occur on the near side of the moon. The new advantages of the phasing-orbit technique were a standard final approach from a relative standpoint (not lighting), increased ground-support capability for the terminal phase, and the opportunity to make a plane change at a common node before the terminal phase.

At this stage of development (early 1965), the following facts became evident.

1. Standard lighting for the terminal phase was important. Because the TPI time could vary considerably as a function of lift-off time within the nominal launch window for this technique, the lighting for the terminal phase could likewise vary.
2. Standard, relatively slow rates before TPI would be advantageous to tracking and monitoring activities. This condition could be effected by a constant differential-height maneuver preceding TPI.
3. To avoid visual loss of the target vehicle, the final braking would have to be performed by the RCS instead of by a major engine. The relative velocity and burn durations for what was then an approximately 70-nautical-mile Δh at TPI were larger than the RCS could accommodate operationally.

Therefore, it was agreed that a technique should be developed that could afford standard lighting for the terminal phase, that would involve a coelliptic-orbit condition before TPI, and that would provide acceptable braking rates for either the LM RCS or the service module (SM) RCS.

Original (three-impulse) coelliptic sequence: For the original three-impulse coelliptic-sequence technique, the apolune of the insertion orbit varied as a function of lift-off time within the nominal launch window. One-half revolution after insertion, a coelliptic maneuver was performed that essentially established a coelliptic or constant Δh . The variation in the insertion orbit and, therefore, the variation in the Δh at the coelliptic maneuver theoretically would cause the desired conditions for TPI to occur at a fixed time regardless of lift-off time within the nominal launch window. The launch window was limited so that it began when the resulting coelliptic Δh was 15 nautical miles and ended when the coelliptic Δh increased to 50 nautical miles. The 50-nautical-mile Δh coincided with an insertion apolune of 30 nautical miles (the CSM being at 80 nautical miles), which had been designated as the lowest safe insertion orbit for which to target. The braking associated with a 50-nautical-mile Δh was then considered acceptable for the RCS systems.

However, detailed dispersion analyses (late 1965 to mid-1966) showed that insertion dispersions could result in large slips in the TPI time for the three-impulse coelliptic technique. No means existed for absorbing insertion dispersions before the terminal phase. Also, the variable insertion orbit was thought to involve complex monitoring techniques. Therefore, a technique was needed for which predictable insertion dispersions could be absorbed before the terminal phase and for which a standard or very nearly standard insertion orbit was applicable. An additional maneuver was needed that could be performed from a standard insertion orbit and that, in combination with the coelliptic maneuver, could adjust for dispersions. In an attempt to provide the additional necessary techniques and maneuvers, the coelliptic-sequence initiation (CSI)/constant-differential-height (CDH) coelliptic sequence was developed.

Original (four-impulse) CSI/CDH coelliptic sequence: The original CSI/CDH coelliptic sequence included the following characteristics.

1. A standard insertion orbit of 30 by 10 nautical miles (insertion at perigee)
2. The CSI maneuver at 30 minutes after insertion
3. The CDH (coelliptic) maneuver at the resulting apolune after CSI
4. The TPI approximately over the landing site
5. The terminal-phase CSM travel angle of 140°

The CSI ΔV direction was constrained to the horizontal to ensure no lowering of the perilune for a posigrade maneuver. The Δh at CDH varied from approximately 15 to 50 nautical miles and the difference in time (Δt), between CSI and CDH, varied from approximately 51 to 28 minutes for the variation in lift-off time within the nominal launch window. By adjusting the catchup rate (that is, by varying the upcoming coelliptic Δh), the CSI allowed not only for the nominal launch window but also for the absorption of insertion dispersions. Performing the CDH at the apolune afforded optimum ΔV usage. Because the CSM orbit was nearly circular, the CDH was always a near-horizontal maneuver.

The new advantages of the CSI/CDH coelliptic sequence were the following.

1. Better control of the TPI time slippage (as the CSI maneuver made this situation less sensitive to insertion dispersion)
2. Use of backup charts to derive solutions because of the generally more standard ranges and rates
3. Decrease in complexity because of the standard conditions around insertion

At this stage of development (early 1967), the rendezvous profile became essentially standard in relation to the landing site (or lighting). For the original three-impulse coelliptic sequence, the TPI had been scheduled at a fixed longitude (for example, 30° E) regardless of the landing-site longitude. The emphasis on ground tracking assistance was changed from post-TPI to pre-TPI as it was realized that the pre-TPI assistance would be of the most value. Detailed analysis concerning the

terminal phase showed that the most favorable TPI lighting (TPI at 20 minutes before darkness) and the most favorable terminal-phase CSM travel angle (130°) were not being used; therefore these optimum values were incorporated. An explanation of the changes is included later in the report.

As the hardware characteristics became more clearly defined and as the planning became more operationally oriented (early 1968), the RCS (that of the LM and, for the rescue sequence, that of the SM) was found to contain insufficient acceleration capability to perform rendezvous for the larger differential heights associated with the nominal launch window. Furthermore, a significantly higher apolune insertion orbit was not advisable because of a diminishing APS propellant margin. Also, for certain dispersions, the rendezvous-radar range limit (400 nautical miles) would be exceeded during the early part of the rendezvous. The solution for these problems was a lower CSM parking orbit; therefore, the planned parking orbit was decreased from 80 to 60 nautical miles. The lowering of the CSM orbit yielded smaller relative ranges and decreased the nominal LM RCS requirement. In addition, it decreased the requirements for the descent propulsion system for the landing phase and for the APS from an LM abort standpoint. The associated elimination of the requirement for the nominal (4- to 5-minute) launch window essentially bounded the acceptable coelliptic Δh to less than approximately 25 nautical miles (allowing predictable dispersions) and, therefore, alleviated the RCS problems of both the LM and SM. Because the Δh variation was small, the CSI-to-TPI time line became more standardized. Otherwise, the time line and maneuver logic remained essentially unchanged.

However, as the NASA Lyndon B. Johnson Space Center (JSC), formerly the Manned Spacecraft Center (MSC), began to develop the detailed procedures for the rendezvous time line (mid-1968), the insertion-to-CSI and CSI-to-CDH time differences were found to be too short. A plane-change capability somewhere between insertion and TPI was also necessary to avoid possible large out-of-plane maneuvers during the terminal phase.

Extended CSI/CDH coelliptic sequence: The extended four-impulse CSI/CDH coelliptic sequence mainly involved increases in the Δt between maneuvers and a forced new nominal lighting requirement for TPI. This extended sequence resulted in the following changes.

1. The insertion-to-CSI Δt was increased to 50 minutes.
2. The Δt between CSI and CDH nominally resulted in an increase to approximately 50 minutes.
3. The initiation of a nominally zero plane change was scheduled for a separate plane-change maneuver (PC) at 90° (approximately 29 minutes) before CDH, and the plane change was to be completed in conjunction with CDH.
4. The TPI lighting was necessarily delayed (to the midpoint of darkness) because CDH now was scheduled only a few minutes before the previous TPI time. Although this new TPI lighting was not totally optimum, it was considered to be a reasonable trade-off for the extended time line.

The longer insertion-to-CSI Δt afforded a more accurate CSI because platform alinement and additional tracking then could be performed before CSI. The platform alinement was originally scheduled after CSI. The pre-terminal-phase plane-change capability could result in a nearly coplanar terminal phase even when out-of-plane dispersions existed at insertion.

Further dispersion analyses in late 1968 disclosed that the Δt between CSI and CDH could decrease sharply for certain dispersions when CDH was performed at the first apsis after CSI, which had been the maneuver logic to this time. Furthermore, a plane-change completion at CDH could result in a ΔV vector that was primarily out of plane, and such a maneuver would be especially costly as compared with combining either the initiation or completion of the plane change with a sizable in-plane maneuver.

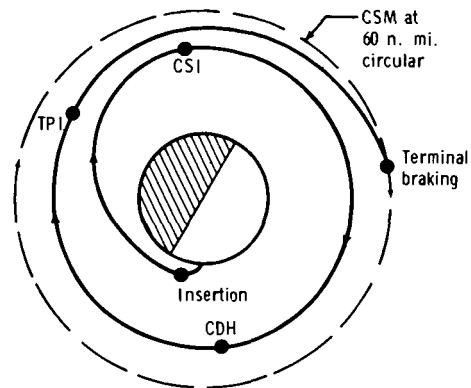
To standardize the time line between CSI and CDH regardless of dispersions, the option to perform CDH one-half period after CSI (instead of at the first apsis after CSI) was incorporated into the planning. Then, to avoid a relatively large radial ΔV at CDH, CSI was scheduled at the apolune of the 30- by 10-nautical-mile insertion orbit (55 minutes after insertion). The plane change was initiated in conjunction with CSI and completed at PC, because this procedure was more economical than the PC/CDH plane change. When a sizable plane change was required, the CSI ΔV normally was significantly larger than that for CDH.

As the crew began rendezvous simulations, the relative range at the beginning of the desired very-high-frequency (VHF)-ranging tracking period before CSI was found to be outside the VHF-ranging limit. In addition, the nominal 33-minute Δt between CDH and TPI was approximately 5 minutes shorter than desirable, considering possible early slippage caused by predictable navigation and maneuver dispersions. Terminal-phase initiation was performed when the nominal elevation angle occurred, instead of precisely at the pre-lift-off nominal time, and the time of occurrence of the nominal elevation angle could vary from the nominal TPI time because of dispersions.

Final CSI/CDH coelliptic sequence: After two additional significant changes, the development of the four-impulse CSI/CDH coelliptic sequence, as flown for Apollo 11 and 12, the first two lunar-landing missions, and as planned for Apollo 13, was complete. Insertion into the 45-nautical-mile apolune orbit corrected the VHF-tracking-range problem by decreasing the relative range at lift-off and did not increase the predictable dispersion situation. Nominally, then, CSI was performed at the desired coelliptic Δh of 15 nautical miles, and CDH was a very small maneuver (theoretically zero if the CSM orbit were perfectly circular and no previous dispersions existed).

To increase the Δt between CDH and TPI by approximately 5 minutes without nominally delaying TPI, an upward radial component of approximately 30 fps was targeted for insertion. The Δt between insertion and apolune (and therefore CSI) was thereby decreased by approximately 5 minutes, as CSI was retained at apolune. Because the CSI-to-CDH Δt was essentially fixed, the 5 minutes were added to the CDH-to-TPI Δt .

The CDH-to-TPI Δt was not adjusted simply by delaying TPI because at that time it was thought that a 5- to 6-minute delay in the nominal TPI lighting combined with a delay caused by predictable dispersions would result in unacceptable final-approach lighting. An inertial sketch and maneuver-sequence data representing the final CSI/CDH coelliptic-sequence technique are shown in figure 2. The final nominal CSI/CDH coelliptic sequence afforded a high probability of achieving a standard terminal phase, from the standpoints of relative motion and lighting considerations, regardless of the occurrence of predictable dispersions. However, the most undesirable factor of the CSI/CDH coelliptical sequence was the relatively long duration from insertion to intercept. The nearly perfect powered ascents and rendezvous of Apollo 11 and 12 significantly increased the confidence in the hardware and systems performance. Therefore, serious consideration was given to designing a technique that would significantly shorten the rendezvous while maintaining the standard (relatively low-rate) terminal phase.



Nominal rendezvous maneuver	Time from previous maneuver, min	ΔV , fps	Main propulsion system	Resulting orbit, apogee/perigee, n. mi.
Insertion	^a 7	—	APS	45/9
CSI	50	50	RCS	45/45
CDH	59	5	RCS	45/45
TPI	40	25	RCS	61/45
Terminal braking	43	^b 45	RCS	60/60

^aFrom LM lift-off.

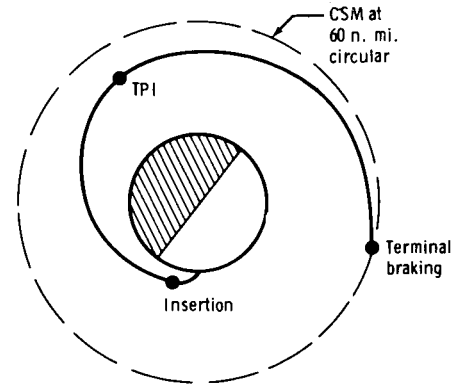
^bApproximate operational braking total.

Figure 2. - Representative phasing-orbit CSI/CDH coelliptic sequence technique.

Short rendezvous technique. - The two-impulse short rendezvous technique was initially proposed and basically designed by the Apollo 15 crewmen, who began experimenting with it during simulations before Apollo 14. The technique was adopted for Apollo 14 mainly because it removed one revolution of approximately 2 hours duration from the rendezvous and, therefore, from the rendezvous day, which had lengthened (using the coelliptic sequence) to 23-1/2 hours. Although the Apollo 15 rendezvous day was not quite as long and the final activities were not quite as demanding, the short rendezvous was incorporated because of its successful application on Apollo 14.

The short rendezvous technique involved a precisely timed insertion into the orbit for which the nominal TPI offset conditions would result at the desired lighting position. The insertion-orbit apolune altitude was between 45 and 50 nautical miles, and the Δt between insertion and TPI was between 38 and 45 minutes. These parameters were a function of the lunar stay time and the exact CSM orbit for the particular mission. As discussed previously, the nominal TPI lighting was delayed several minutes to allow sufficient time between insertion and TPI. Furthermore, because the LM orbit before TPI was not coelliptic with the CSM orbit, the TPI maneuver was not a line-of-sight

maneuver and was large enough to be performed accurately by the APS. Because TPI was no longer a line-of-sight maneuver, it was performed at the pre-lift-off nominal (fixed) time regardless of predictable dispersions. The major portion of the predictable insertion dispersions could be absorbed by an RCS tweak maneuver, used in combination with TPI, performed 2 to 3 minutes after insertion. Should unexpectedly large dispersions or systems failures during the powered ascent render the short rendezvous unsafe, a bailout to a coelliptic sequence rendezvous would be initiated at approximately 5 minutes after insertion. In fact, a major factor in the adoption of the short rendezvous was the convenient bailout capability to the flight-tested coelliptic sequence. Should certain nonnominal situations occur before LM lift-off, the coelliptic-sequence rendezvous then would be flown from lift-off. An inertial sketch and maneuver-sequence data representing the short rendezvous technique are shown in figure 3.



Nominal rendezvous maneuver	Time from previous maneuver, min	ΔV , fps	Main propulsion system	Resulting orbit, apogee/perigee, n. mi.
Insertion	^a 7	—	APS	46/9
TPI	45	73	APS	61/45
Terminal braking	43	^b 45	RCS	60/60

^aFrom LM lift-off.

^bApproximate operational braking total.

Figure 3. - Representative short rendezvous technique.

Terminal Phase

Early in rendezvous development, the major objective became a standard final approach that, regardless of predictable dispersions, would be within the capability of the RCS and could be controlled manually with reasonably standard techniques and procedures. Some of the terminal-phase considerations and requirements changed as the basic rendezvous technique changed, but the ultimate objective, the standard final approach, remained throughout.

Standard approach. - The angular geometry and inertial line-of-sight rates for standard approach were designed to be constant or standard regardless of dispersions. The Δh requirements at TPI or the ΔV requirements could change but were expected not to vary more than 20 to 30 percent from the nominal values. The maintenance of standard angular geometry and nearly zero inertial line-of-sight rates allowed the final velocity match to be achieved by manually controlled braking maneuvers directed along the line of sight to the target vehicle. The braking maneuvers were based on range/range-rate gates and gradually decreased the relative velocity to zero. For the nominal final approach, the LM crossed approximately 4 nautical miles below the CSM and then advanced approximately 1/2 nautical mile in front of the CSM as it matched the altitude of the CSM.

Central travel angle. - The target vehicle central travel angle ϕ was selected as a trade-off between the in-plane ΔV situation and the possible out-of-plane ΔV situation. The ΔV -optimum ϕ for a totally in-plane situation would be nearly 180° . However, when an out-of-plane angle existed, a nearly 180° ϕ became very expensive. Therefore, to ensure avoidance of a significant out-of-plane penalty, the ϕ had to be at least 30° to 40° less than 180° . However, if the ϕ was shortened to less than approximately 120° , the in-plane ΔV penalty again became large, and the terminal-phase time line was impacted seriously. The initial compromise for ϕ was 140° . However, when the inertial line-of-sight rate during the final approach was found to be nearer zero and, therefore, easier to control for a ϕ of 130° , the 130° ϕ was incorporated. This ϕ has been flown for all Apollo rendezvous to date, including the coelliptic sequence and short rendezvous.

Differential height at TPI. - To avoid visual loss of the target vehicle, the RCS system would be required to perform the braking. Therefore, the nominal Δh at TPI was selected so that, for predictable dispersion, braking would remain within the RCS capability and would not become extremely difficult as a manual operation. This nominal Δh value was set at 15 nautical miles, and the dispersion range on the Δh was approximately ± 7 nautical miles. If the Δh became greater than approximately 22 to 25 nautical miles, the braking would be hard to control with the RCS, especially that of the SM. If the Δh became less than 7 or 8 nautical miles, the sensitivity to dispersions involving low closing rates increased rapidly.

The TPI maneuver direction and timing. - Early in rendezvous development, it was decided to incorporate the Gemini-initiated line-of-sight thrusting TPI (that is, the direction of the ΔV vector was approximately along the line of sight to the target vehicle). This type of TPI, when applied from the coelliptic-orbit situation, was not only nearly optimum from a ΔV standpoint and afforded the desired angular geometry discussed previously, but it also afforded a manual backup technique. If no computer solution was available, a ΔV proportional to the estimated Δh applied in the direction of the target vehicle would effect a near-intercept trajectory. When the short rendezvous technique was incorporated for Apollo 14, the line-of-sight TPI was one of the trade-offs for the quicker rendezvous. Because TPI now was performed with the LM in the elliptical insertion orbit, the TPI ΔV vector was not along the line of sight, but, because of a relatively large radially down ΔV component, the ΔV vector direction was below the forward horizontal. Moreover, because of the increased magnitude of the TPI burn (70 to 90 fps), the decision was made to use the APS for execution of the burn. Previously, for the coelliptic-sequence plan, no nominal plan existed for relighting the APS because the largest maneuver, which was CSI, was only 40 to 50 fps.

For the coelliptic sequence, TPI was actually executed when the nominal angular geometry (elevation angle to the target vehicle) occurred and not necessarily at the precise pre-lift-off nominal TPI time. Because of small errors in navigation or small dispersions in the intermediate phasing maneuvers, the occurrence of the nominal elevation angle could slip several minutes either early or late from the nominal TPI time. By executing TPI at the nominal elevation angle (nearly line-of-sight burn), the nominal angular geometry resulted throughout the terminal phase. However, when the switch to the short rendezvous technique was made and the line-of-sight TPI was discontinued

anyway, TPI always was performed at the pre-lift-off nominal TPI time. This fixed-time TPI increased the sensitivity to dispersions of the final approach, but the approach limits for an acceptable final approach were broadened significantly.

Lighting. - Initially, the lighting requirements for the terminal phase mainly involved TPI because the final braking occurred in darkness. The TPI was scheduled at approximately 20 minutes before darkness, a position which optimized pre- and post-TPI tracking. Braking in darkness was no problem because of the LM tracking light and two ranging devices, the rendezvous radar on the LM and the VHF ranging on the CSM. Therefore, a triple failure would have had to occur before the braking in darkness would not be feasible.

However, when the extended coelliptic sequence was incorporated, the nominal TPI lighting was necessarily delayed. The second choice for TPI lighting was at or near the midpoint of darkness, again because of tracking considerations. In addition, the lighting for braking (now in sunlight) became a factor because, if the TPI slipped later than approximately 12 minutes, the LM crewmen would be forced to look directly into the sun during part of the final braking. The TPI or terminal-phase lighting became a compromise between acceptable tracking around TPI and avoidance of sun interference during braking.

When the short rendezvous was incorporated, the TPI lighting was delayed approximately 7 minutes to allow a more acceptable Δt between insertion and TPI. This delay was not critical to the braking lighting because of the associated fixed-time TPI.

Midcourse corrections. - Terminal-phase nominally zero midcourse corrections were scheduled at approximately one-third and two-thirds of the way from TPI to braking. If a maneuver was required to correct the trajectory, the initial intercept position and time were targeted normally. If a major dispersion had caused the predicted braking maneuvers to become unacceptably large, one of the midcourse maneuvers would be used to delay the intercept and thus decrease the braking ΔV . This delaying technique was referred to as TPI₂.

DEVELOPMENT OF LM ABORT AND RESCUE PLAN

From the beginning of the development of the abort and rescue plan, the primary emphasis was on the powered descent and the period immediately after landing. These were considered the most probable phases in which an abort could occur. Considerable planning also was devoted to failures associated with the LM-active Hohmann descent, to cases of no-powered-descent initiation, and to correct-phasing LM ascents before or after the nominal lift-off revolution. Early program contingency planning also included LM lift-offs for any time (without correct phasing) and in time-critical situations; however, because realistic single-failure cases were not identified for these situations, operational planning was limited.

The original abort and rescue maneuver sequences, beginning in 1964, were extremely complex because of the limited onboard capabilities. For example, for an abort occurring any time during powered descent, the LM was targeted for a constant insertion orbit. Therefore, several abort regions existed, and the rendezvous technique

varied for each. For early aborts, the LM final approach to the CSM was from above; for a later region, one-and-a-half revolutions were required between CSI and CDH instead of the normal one-half revolution; and, for late aborts, the LM approached from below the CSM. Because of the complexity in the abort plan, the rescue plan was also complex. The CSM did not have the CSI/CDH logic on board, and the command module pilot had to depend either on the ground or on the mirror-image technique (that is, the method by which the CSM applies the LM-computed maneuver essentially in the opposite direction). The primary rescue technique for bad-phasing situations was the six-impulse technique, whereby the CSM transferred to a 20-nautical-mile circular orbit by means of the first two maneuvers, and then adjusted the phasing, became coelliptic, and executed the terminal phase (theoretically, with two impulses) by means of the last four maneuvers.

In early 1968, analyses for the incorporation of several powered-descent-abort insertion orbits (to vary as a function of abort time regions) were begun. This work evolved by late 1968 into the variable-targeting concept. According to this technique, the correct insertion orbit, that would result in an LM approach from a coelliptic Δh of 15 nautical miles below the CSM, could be targeted for all abort times during the first 10 minutes of powered descent. For an abort after 10 minutes, a constant 30-nautical-mile apolune insertion orbit was targeted; however, an in-orbit phasing maneuver (derived by the use of onboard programs in conjunction with onboard charts) permitted the standard LM approach from below (although one additional revolution was required). For Apollo 12, a second variable-targeting region (by means of a two-revolution rendezvous) replaced this phasing region for aborts occurring after 10 minutes. The variable-targeting concept originally was thought not to be feasible because of the software requirements involved; however, after a detailed analysis of the precise requirements, the technique was deemed feasible, and implementation began in early 1969.

The variable targeting led to simplification and standardization of the abort and rescue plan. The same basic technique now applied to almost all LM-active cases. Therefore, the rescue techniques were standardized; for example, for a CSM-active terminal phase, the CSM would always approach the LM from above.

By this time, the CSI/CDH logic had been placed on board the CSM, and an independent onboard rendezvous solution for the coelliptic sequence could be determined in the CSM. This technique greatly improved the CSM support of any rendezvous sequence using CSI/CDH logic. Spacecraft independence was emphasized because of the uncertainty in the lunar potential; therefore, nearly all rescue plans involved no more than one external (ground) maneuver. When correct phasing existed initially, no external maneuver was required. The addition of VHF-ranging capability to the CSM ensured further independence and confidence. As indicated previously, the VHF-ranging addition also affected the nominal development.

The original rescue ΔV budgeting philosophy, which remained unchanged through Apollo 13, was to allow rescue within the normal LM (ascent stage) lifetime for all feasible rescue situations. However, to allocate a greater ΔV budget for nominal objectives, the rescue ΔV budget for Apollo 14 and subsequent missions had to be lowered, so that rescue for certain possible situations required powering down the LM to a minimum life-support condition. However, the rescue situations that would require such minimum power conditions were extremely improbable.

Beginning with Apollo 13, the abort and rescue plan changed somewhat because of the change to the nominal plan (landing one revolution later relative to the main LM/CSM separation). However, the order of the occurrence of the regions (one-revolution or two-revolution rendezvous) was the only significant change. The basic techniques were the same. The final plan was not simple; but, compared with the plan approximately a year before Apollo 11, the final plan was considerably simpler and also more standard.

EVOLUTION OF APOLLO RENDEZVOUS DISPERSION PROGRAM REQUIREMENTS, DEVELOPMENT, AND ANALYSIS

Rendezvous-Dispersion-Analysis Program Requirements

From the beginning of the Apollo Program, dispersion analyses were essential for all phases of each Apollo mission, particularly for the rendezvous phase. The dispersion analysis was required to aid in defining the nominal propellant budget, in establishing mission rules and crew procedures, in defining constraints, in selecting the maneuver sequence that would give the highest overall probability of success, and in verifying general ground and onboard programs.

To develop a dispersion-analysis program, careful consideration must be given to establishing the detailed program requirements for the overall dispersion-analysis effort for any mission phase. These requirements come from many areas and require a reasonable amount of coordination. For the Apollo Program, most of these requirements came from the support of mission-rules development, crew-procedures development, onboard-chart development, simulations, and propellant budgeting.

The rendezvous-dispersion-analysis program requirements for the Apollo Program were not outlined in the detail required for an efficient program development effort. This was partially because of a lack of knowledge of program objectives and partially because of the manner in which the responsibility for this effort was assigned. These two problems resulted in significant time and manpower losses.

Rendezvous-Dispersion-Analysis Program Development

In developing the rendezvous-dispersion-analysis program and in performing the analysis itself, numerous problems had to be resolved. One of the first important tasks in developing a program of this type is to establish, in the early development stages, the responsible organization for the detailed dispersion analysis. The organization that is selected should be responsible for the detailed mission planning and the trajectory analysis for the particular mission phase because the dispersion analysis coincides with the mission planning and the trajectory analysis work and requires similar skills.

In the Apollo Program, the responsibility was not initially assigned to the organization responsible for the detailed mission planning but instead was assigned to the organization responsible for developing the onboard guidance. The latter organization possessed little understanding of the detailed rendezvous techniques and associated dispersion problems. A significant amount of manpower and time was lost in the

attempt to complete the required program development in an operationally timely manner. When the responsibility was reassigned to the organization doing the detailed mission planning and trajectory analysis, the situation improved, manpower expenditures decreased, and, most important, the analysis was completed in a timely manner. The main reason for this improvement was that, to perform a detailed dispersion analysis on a mission phase, a knowledge of the detailed mission-planning aspects and the trajectory analysis of the phase was more essential than a detailed knowledge of the guidance and control mathematics and systems.

Official data transfer between organizations should be restricted mainly to the type of data that does not change with every minor mission change or procedures change. This type of data should be generated internally in the program, if possible, and detailed verification checks should be made on these data, as required, with the organization or organizations responsible for the data. In this way, mission and procedure changes receive a timely response. Otherwise, interfaces tend to delay the completion of the analysis.

Careful consideration should be given to the construction of models in the program. Complicated modeling should be used only when necessary, especially when simple models, which usually are acceptable from an operational standpoint, will suffice. This modeling problem usually can be resolved by consulting the groups or organizations that have the technical skill in these areas. Consideration also should be given to the operational accuracy requirements of the data; for example, eight-digit accuracy is needless when two- or four-digit accuracy is acceptable.

Program inputs must be kept simple and logical, so that the engineer running the program can make expedient changes to the program input without the assistance of a programmer. Apollo experience also was indicative that covariance matrices are highly effective for those areas in which minor mission or procedure changes do not change the basic dispersion. Covariance matrices are especially useful in the transfer from one mission phase to another.

The actual program should be developed by personnel who are knowledgeable in the particular mission phase that is to be considered. The basic program should be flexible, and the use of engineering simulations of both the onboard targeting and the navigation and ground targeting programs should be detailed. This process saves considerable program-development and verification time because the accuracy with which the onboard and ground programs have been simulated is always a concern. If shortcuts are taken, some important area can be missed, and the correction of the oversight can be time consuming. Apollo experience also proved that solving problems by known "brute force" methods, even if they involve significant additional machine time, is better than attempting to use untried sophisticated methods. When a tight schedule is involved, untried techniques are especially inappropriate because development of these techniques generally involves the expenditure of much money and engineering time, and the techniques still have to be verified by a detailed simulation. Detailed documentation on the program should be kept current. The program also should be programmed in a programming language that can be easily understood and changed by either programmers or engineers.

To perform the Apollo dispersion analysis, programs were developed that included engineering simulations of specific spacecraft, Real Time Computer Complex (RTCC) rendezvous targeting and navigation programs, and various systems models. These models included the engine guidance systems, spacecraft accelerometers, spacecraft platform, rendezvous radar, sextant, and VHF tracking. All major error sources associated with each model in terms of drift, bias, and noise were included. From the start of Apollo 7 to Apollo 11, four different program development efforts were undertaken for various reasons, which resulted in the existence of two operational rendezvous-dispersion-analysis programs by Apollo 9. One program, the lunar ascent and rendezvous program, which was being developed by a support contractor, was dropped before Apollo 7, and the in-house program developed to replace it became the prime operational program. The other operational program, a general Apollo dispersion-analysis program, was developed on the same support contract and actually underwent two different development stages, each of which was considered as a different program development. Parts of the general Apollo dispersion-analysis program were dropped after Apollo 7, but some parts of that program-development effort were used to develop the remaining contractor operational program. The two operational programs were necessary to cross-check the data obtained from each program. This process proved highly beneficial in verifying the operational data and improved the overall probability of mission success.

By the Apollo 11 mission, the nominal rendezvous dispersion analysis was performed similarly in both the in-house and contractor programs. However, the prime in-house program was more versatile and could perform dispersion analysis on any rendezvous profile that the onboard or RTCC systems could fly. The contractor program basically was designed around the nominal mission profile and was developed by an independent source. Therefore, the error model in the contractor's program was not identical to the error model in the in-house program.

The dispersion-analysis program development evolved from the mission planning for each rendezvous mission, with the contractor program following the nominal development, and the in-house program following both the nominal mission planning and the LM abort and rescue planning. The in-house dispersion-analysis program ultimately acquired capabilities that were necessary to keep pace with and support the mission-planning effort. Therefore, the in-house program became the prime tool for dispersion analysis.

Performance of Rendezvous Dispersion Analysis

In performing the dispersion analysis on each development mission preceding the lunar landing mission, different error sources and inputs had to be considered for each mission. Obviously, Apollo 11 had the most complex set of error sources and inputs. On Apollo 7, only one maneuver source (RTCC maneuver solution) up to TPI and two maneuver sources (RTCC maneuver solution and command module computer maneuver

solution) for TPI were used. As many as four computer-maneuver sources (RTCC, command module computer, LM guidance computer, and LM auxiliary guidance system) for specific maneuvers were used on Apollo 11.

Initially, the RTCC, with the aid of ground tracking from the NASA Manned Space Flight Network (MSFN), was considered to have the most reliable maneuver solution, especially for the earth-orbit missions. Therefore, it was used as the standard with which to compare the other solutions and was executed if the other solution or solutions did not compare within a given tolerance. However, for the lunar-orbit missions, the MSFN could not track the spacecraft and determine their orbits for the rendezvous computation as well as it had been able to track them in earth orbit. Thus, the spacecraft onboard navigation and maneuver computation became the prime source for the rendezvous-maneuver solutions. With the change in the RTCC accuracy of the maneuver-solution sources was a high degree of confidence in the onboard systems that had been obtained during the earth-orbital development flights. Therefore, the rendezvous-maneuver solutions went from basically RTCC control on Apollo 7 to spacecraft onboard control on Apollo 11 and subsequent flights. During the rendezvous development phase, the dispersion analysis also was used to assist in establishing the onboard navigation schedules and to establish and verify onboard procedures, crew time lines, and mission rules.

Apollo Program experience has emphasized the need throughout mission planning for dispersion-analysis information. Therefore, an effort to provide dispersion-analysis information and support from the conception stage of the mission to the actual flight must be made. The level of detail will vary throughout mission planning, with the most detailed and complex work being done on the operational trajectory. This work must be started early in the mission-planning stage so that timely inputs to the planning effort are possible and trajectory and procedure changes are minimized.

SIGNIFICANT DEVELOPMENTAL CONTRIBUTIONS

Organizational Contributions

The development of acceptable rendezvous techniques was the result of direction, coordination, analyses, and inputs from several areas. Most of the trajectory design and analysis was performed by mission-planning specialists at the Manned Spacecraft Center. During the planning of the Gemini rendezvous missions, several of the astronauts became actively involved in the rendezvous planning, and their ideas contributed significantly to the initial development of the coelliptic sequence. As the Gemini Program neared completion, several specialists familiar with Gemini procedures became involved in Apollo design work and made valuable contributions.

The original official centerwide interface involving the rendezvous development was accomplished by the Flight Operations Panel. This panel was responsible for the coordination of the constraints and requirements involved in the Apollo mission planning. Later, the development of the detailed techniques was coordinated through the data-priority meetings.

Some of the most important inputs during the year before Apollo 11 came from areas directly involved with the crew procedures, training, and simulations. Many individuals from the flight-crew, flight-control, and guidance and control areas contributed significantly to the design of the Apollo rendezvous techniques.

As the first lunar-landing mission approached, an increasing number of people began working on the planning effort, and the hardware and software constraints and capabilities were defined concretely. As a result, the rendezvous planning became more detailed and precise. Although several minor changes were made to the techniques, no major changes to the nominal or contingency rendezvous plans occurred during the last 6 months before Apollo 11. Furthermore, the only subsequent major change to the basic techniques was the change to the quicker short rendezvous technique for the Apollo 14 and 15 nominal plans.

Organizational factors and developments for the dispersion-analysis development have been discussed previously. The most significant organizational development in this area was the decision to give the responsibility and control of the rendezvous dispersion analysis to the rendezvous specialists.

Contributions From Flight Experience

As the Gemini rendezvous flights were flown, considerable information was introduced into the Apollo rendezvous planning, especially in relation to the terminal phase. The actual flight rehearsals of the coelliptic sequence during Apollo 9 and 10 contributed valuable data. Although a coelliptic rendezvous had been flown in the Gemini Program, the LM hardware and software were tested in actual flight for the first time on Apollo 9. The LM was positioned away from (above and behind) the CSM so that, beginning at CDH, the relative motion and various relative rates were essentially those planned for the lunar-landing-mission rendezvous.

The Apollo 10 rendezvous, a portion of the first LM performance in lunar orbit, actually included a relative-motion profile that was an almost exact model of the lunar-landing-mission rendezvous beginning at insertion. Although the LM was considerably heavier during the Apollo 10 rendezvous than during the lunar-landing mission and therefore the burn durations and handling qualities were different, the information and confidence gained were extremely valuable. The experience gained on Apollo 10 regarding flight-control interface and the development of the LM abort and rescue plan considerably simplified the corresponding Apollo 11 situations. Other valuable information came from the operation of the LM and CSM navigational systems in the uncertain lunar potential.

CONCLUDING REMARKS AND GENERAL RECOMMENDATIONS FOR RENDEZVOUS PLANNING FOR FUTURE PROGRAMS

For the Apollo lunar-landing missions, the change of the nominal rendezvous plan from the direct-ascent rendezvous technique to a four-impulse phasing-orbit (coelliptic sequence) technique was necessary to ensure a standard, manually executable terminal approach. After the first two lunar landing missions, the change to the two-impulse short rendezvous technique occurred because of the significantly increased

confidence in the systems and procedures resulting from actual lunar flight experience and because of the availability for a fallback to the familiar coelliptic sequence for contingency situations.

Some of the most important factors affecting the total rendezvous-plan evolution were the implementation of the variable targeting for powered-descent aborts in the lunar module descent program, the implementation of the coelliptic-rendezvous maneuver sequence in both the lunar module backup guidance system and the command and service module primary guidance system, and the implementation of the very-high-frequency ranging on board the command module.

Several problems had to be corrected to assure a successful rendezvous dispersion and trajectory analysis. These problems included the lack of precisely defined requirements for the overall analysis, the lack of proper interfaces with other responsible organizations, the lack of computer-program flexibility and documentation, and the initial assignment of the dispersion-analysis responsibility to an organization not possessing rendezvous skill.

The following recommendations are divided into the main areas of consideration discussed in the body of the report. Most of the recommendations should apply to rendezvous in almost any situation, whereas a few of the recommendations would apply only for rendezvous conditions similar to those in lunar orbit.

Nominal Launch Window

The recommendations that apply to a nominal launch window relative to a surface vehicle and an orbiting target vehicle are as follows.

1. If the target vehicle has the capability of performing a plane change and a phase change to make its orbit nearly coplanar with the surface vehicle when the optimum lift-off phasing exists, a launch window of only a few seconds is adequate for nominal considerations. Changes in lift-off revolution can also be handled by the plane/phase change capability.
2. A planar situation should be planned that will allow a revolution-late lift-off without an additional target-vehicle plane change and with a minimal plane change for the ascending surface vehicle.

Base Orbits

The recommendations that apply to the design of base orbits are as follows.

1. The target-vehicle parking orbit should be based on both nominal and abort situations, considering ranging and incremental-velocity capabilities of both the target vehicle and the surface vehicle.
2. If not prohibited by other considerations, a circular target orbit should be applied because of the simplification in rendezvous software and procedures.

Maneuver Sequence

Maneuver sequence in general. - The recommendations that apply to the maneuver sequence in general (that is, nominal or abort and rescue) are as follows.

1. Dispersion-absorption and phasing capabilities should exist that will allow a standard terminal phase, especially if the final approach is to be manually controlled. These capabilities may be as simple as a two-impulse tweak sequence if the initial situation is nearly nominal; however, if large dispersions or nonnominal phasing initially exists, the capabilities should involve several maneuvers at approximately half-revolution increments to avoid excessive propellant usage. The coelliptic-sequence rendezvous should be a prime candidate for this latter situation.
2. There should be adequate time between maneuvers to allow for required tracking, alinements, and maneuver preparation.
3. The difference in time between a given pair of maneuvers should be as constant as practical to allow standardization of procedures.
4. When elliptical orbits are involved, maneuvers should be near the line of apsides to optimize incremental-velocity usage.
5. The initial in-orbit maneuvers for the ascending surface vehicle should be designed not to lower the insertion-orbit perigee.
6. The sequence should be designed so that as much of the maneuver sequence as possible is within vehicle-to-vehicle tracking capability.

Nominal ascent-rendezvous-maneuver sequence. - The recommendations that apply specifically to the nominal ascent-rendezvous-maneuver sequence are as follows.

1. A sequence that is as short as practical but allows a reasonable dispersion-absorption capability and a nearly standard terminal phase should be applied, especially if the incremental-velocity situation is tight and the final approach is to be manually controlled.
2. The nominal sequence should allow for a convenient switch to a contingency sequence if large dispersions or certain failures occur.
3. The nominal sequence should be designed to allow backup ground support when practical.

Abort and rescue maneuver sequences. - The recommendations that apply specifically to the abort and rescue planning are as follows.

1. The plan should involve as much standardization as possible, and the sequences should be as similar as possible to the nominal.
2. From a relative standpoint, the terminal phase should be nearly identical to the nominal (for example, the ascending vehicle always approaching from below).

3. Onboard independence should be stressed by designing the sequences to make full use of onboard software (with minimum use of ground-derived maneuvers).

4. The sequences also should be designed to afford use of relatively uncomplicated backup charts.

5. Software that involves insertion into the correct phasing orbit for an abort back to orbit anywhere during the powered descent should be implemented because it affords simplification and standardization.

Terminal Phase

The recommendations that apply specifically to a terminal phase that is manually controlled and executed with a small reaction control system type of propulsion are as follows.

1. The approach should be standard from an angular-geometry standpoint, and the various rates should not vary significantly from those of the nominal case. These rates should be large enough to allow crew determination of and reaction to the closing situation but not so large as to make the braking maneuvers extremely difficult using the relatively small propulsion system.

2. The thruster orientation should allow continuous visual contact between vehicles during the final approach.

3. Although precise lighting is not critical, the final approach should be designed so that the crewmen of the vehicle approaching from below are not required to look within approximately 30° of the sun while maintaining visual contact with the other vehicle.

4. The terminal phase should be nearly coplanar to allow the simplest final braking procedures. This situation should be afforded by designing an in-orbit plane-change capability before the terminal phase.

5. The terminal-phase-initiation maneuver with the incremental-velocity direction along the line of sight to the target vehicle should receive prime consideration if a coelliptic phase is applied, because it allows standard angular geometry throughout the terminal phase and affords a convenient manual backup technique for the initiation maneuver.

6. The type of braking, in which the main maneuvering is along the line of sight to the target vehicle while the inertial line-of-sight rate is maintained near zero should receive prime consideration for a manually controlled final approach.

Dispersion Analysis

The recommendations relative to the development of the dispersion analysis and the associated computer program are as follows.

1. Dispersion analysis should be involved in the planning as early as possible.
2. Detailed requirements for the dispersion-analysis program and overall analysis should be determined early.
3. Proper interfaces with other responsible organizations should exist.
4. Computer-program flexibility and adequate documentation should exist.
5. Responsibility for and control of the rendezvous dispersion analysis should be assigned to the mission planning rendezvous experts.

General Development and Organizational Considerations

Some recommendations generally relating to the development of the maneuver plan and organizational considerations are as follows.

1. Required interfaces with all disciplines and cooperating organizations should occur as early and as often as practical. Such interfaces definitely should involve, in addition to the interfaces with the other mission planning areas, such areas as flight control, flight software, flight crew, flight-crew support, guidance and control, and other areas representing the hardware and science disciplines. The project offices and various panels should organize and centralize these interfaces, but informal working-level interfaces should be permitted.
2. Onboard independence should be stressed in software and hardware design.
3. Ground-based backup for all maneuvers and procedures is desirable but should not necessarily be a dominant factor if adequate onboard autonomy exists.
4. Mission simulations in the control center involving the crew, flight controllers, and support personnel should simulate the various mission phases and involve as many of the potential contingency situations as possible within reasonable manpower requirements.
5. Actual flight rehearsals testing the hardware and software should be performed if practical.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, April 25, 1973
924-22-20-00-72