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APOLLO EXPERIENCE REPORT - SPACECRAFT RELATIVE MOTION AND RECONTACT ANALYSES

Robert E. McAdams, Charles J. Gott, and Marland L. Williamson

Lyndon B. Johnson Space Center
Houston, Texas 77058

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16. Abstract

Potential collision or accidental recontact problems between the spacecraft and other space vehicles (or components) existed during most of the Apollo missions. These problems were identified before each Apollo flight, and appropriate solutions for eliminating or minimizing the chance of collision were determined through relative motion analyses. This report presents a summary of the identification, solution, and analysis process for some of the more significant of these separation problems. In addition, the scope of responsibility, the development of the study effort, and the computer simulation development, which supported the analysis process, are described.

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APOLLO EXPERIENCE REPORT

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SPACECRAFT RELATIVE MOTION AND RECONTACT ANALYSES

By Robert E. McAdams, Charles J. Gott, and Marland L. Williamson
Lyndon B. Johnson Space Center

SUMMARY

The use of a separable space vehicle during the Apollo Program required that premission planning include the definition of separation procedures that would avoid accidental recontact and ensure maximum crew safety. Potential collision or accidental recontact problems between the spacecraft and other space vehicles (or components) existed during most of the Apollo missions. These problems were identified before each Apollo flight, and appropriate solutions for eliminating or minimizing the chance of collision were determined through relative motion analyses. More than 50 individual separation procedures were designed, analyzed, and documented for each of the final Apollo flights. The more significant of these separation studies and the accidental recontact problems associated with them are presented in this report; information is given for each of the Apollo missions.

After initial planning for the Apollo Program was underway, it became obvious that a large, well-organized, and well-managed separation study would be required to supplement the total mission planning effort. The development of this effort and the scope of the responsibilities involved in meeting the requirement are discussed in this report. In addition, the computer simulation development that made possible the solutions to the many separation problems encountered is summarized.

INTRODUCTION

The primary reason for a spacecraft-separation study was to identify potential collision or accidental recontact problems between the spacecraft and other space vehicles (or components) and to determine, by performing relative motion analyses, appropriate solutions to eliminate or minimize the chance of collision. The identification of problem areas was accomplished by analyzing and verifying that the premission nominal and contingency operational spacecraft separation sequences and procedures were free of accidental recontact problems or, if no separation procedure existed, by defining procedures that were free of accidental recontact problems. In addition, the separation study effort included the verification that integrated separation system hardware did not have inherent recontact problems, particularly with respect to motion occurring immediately after the separation event; for example, the mechanical ejection of the lunar module (LM) from the spacecraft lunar module adapter (SLA). The following objectives were included in the separation study effort: identification of safe spacecraft operational limits (e.g., the maximum permissible spacecraft attitude rates during LM extraction from the SLA); confirmation of previously defined operational separation sequences and procedures for subsequent missions; validation of recommendations for mission rules; investigation of the sensitivities of separation dynamics for various spacecraft and space vehicle configurations; and graphic presentation and illustration of the relative motions of various space vehicles (or components) in a separation procedures handbook for each Apollo mission. The results of the separation study efforts were required and used in flight planning, hardware design, crew procedures and checklists, separation techniques, real-time mission support, and postflight mission evaluations. All results were officially documented and published as formal separation procedures (internal notes) at the NASA Lyndon B. Johnson Space Center (JSC) (formerly the Manned Spacecraft Center (MSC)). A significant study effort was necessary to provide the required analyses for the spacecraft elements and systems modes of operation in the Apollo Program.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

DEVELOPMENT OF THE SEPARATION STUDY EFFORT

During early phases of the manned spacecraft programs, only a small separation study effort was established. Project Mercury and the Gemini Program consisted of flights that involved relatively simple separation procedures for a small number of modules or components. However, the Apollo Program consisted of flights that involved separation procedures of greater complexity than those of earlier programs, because of an increase in the number of modules and components requiring separation. The possible abort or alternate missions further complicated the magnitude of the analysis required. Therefore, the separation study effort was greatly expanded for the Apollo missions to ensure that all accidental recontact problems would be identified and resolved or reduced to an acceptable level of probability before each flight.

The study of potential recontact problems began during 1964 as part of the Apollo trajectory definition effort being performed at MSC. Various MSC organizations, with the assistance of the prime and support contractors for the Apollo Program, were originally involved in the identification of the potential collision problems and the definition of corrective action to avoid these problems. In addition, generalized separation studies were performed by a support contractor. In November 1966, the scope of this support was altered from studies of a general nature to studies directly applicable to specific Apollo missions. During this time, no single MSC organization had overall responsibility for the analyses. Consequently, crew procedures, separation techniques, control modes, and operational requirements were obtained from a variety of sources. Because of this fact, it was recognized that efficiency and mission operations could be improved by assigning the functional responsibility of performing the Apollo separation and recontact analysis to a single organization. Because the problem was basically operational in nature, the Flight Operations Directorate (FOD) at the MSC was selected for this task in June 1967.

The scope of the separation analyses was defined officially to include the following objectives.

1. Evaluate operationally the separation modes defined for each Apollo mission.

2. Verify separation techniques, identify accidental recontact problem areas, establish a sequence of events, and recommend procedural or technical changes whenever necessary.

3. Develop the necessary analytical procedures and techniques required to perform a detailed analysis.

The Apollo Joint Separation and Recontact Working Group, composed of representatives from the prime and support contractors and of appropriate MSC personnel, was established in May 1968. At these working group meetings, which were chaired by MSC personnel, the knowledge and capabilities of the prime and support contractors were used by seeking their technical expertise to aid in decisionmaking and by using their capability to supply most of the input data required for separation analyses. In addition, the working group assisted each organization in recognizing and understanding the problems faced by the other organizations; achieved the goal of coordinating the activities of the different participating organizations in the separation study effort; and minimized duplications, errors, and confusion.

The separation and recontact effort for the Apollo Program remained with the FOD through the final Apollo mission. A broad base of experience was developed by placing the responsibility for the separation and recontact effort with one organization. This experience proved advantageous in solving the Apollo separation problems.

COMPUTER SIMULATION DEVELOPMENT

The use of separable spacecraft modules or components for the Apollo Program required the development of procedures and maneuvers to ensure a safe and proper separation. The analysis included nonnominal situations to reduce the possibility of accidental recontact or collision should a contingency occur. The recontact could have occurred during the actual separation or ejection process or subsequently during the resulting relative motion of the separated components. The analysis required the use of three- and six-degree-of-freedom computer programs so that all Apollo separation sequencing could be fully and accurately simulated. To better understand the complexity of the problem and the system modeling required to perform the analysis, the following separation events are given in the order of occurrence during a typical lunar landing mission:

1. The launch escape tower (LET) from the command and service module (CSM)

2. The CSM from the SLA panels and the Saturn IVB (S-IVB)

3. The SLA panels from the S-IVB

4. The LM from the S-IVB

5. The service module (SM) scientific instrument module (SIM) bay door from the CSM

6. The CSM from the LM

7. The LM ascent stage from the LM descent stage

8. The LM from the CSM

9. The subsatellite from the CSM

10. The experiment instrument booms from the CSM

11. The docking ring and probe adapter from the CSM

12. The CM from the SM

One of the primary problems that had to be solved was the inadequacy of the available three- and six-degree-of-freedom computer programs to provide the simulation capability required to analyze the many Apollo separation events. Therefore, the evolution of the required simulation capabilities was important to the overall experience gained from the Apollo Program in the separation study effort.

Originally, the computer simulation capability was a multivehicle, three-degree-of-freedom program that had been modified to perform simple separation studies. To increase the efficiency in running general parametric studies, separation computer programs to be run on an analog computer system were developed in mid-1966. Late in 1966, the analog capability evolved into a hybrid computer concept in which the advantages of a digital and analog system were combined into one computer. In mid-1967, a detailed review of the Apollo separation and recontact simulation capability resulted in a decision to continue the support contractor's hybrid programing effort then in progress and to transfer this capability to the MSC hybrid system when the effort was completed. During the same period, MSC personnel had expanded and modified the original two-vehicle, three-degree-of-freedom digital program to accommodate simultaneously as many as eight vehicles; this expansion, combined with the aforementioned planned transfer of the support contractor's hybrid program effort to MSC, was expected to provide all the simulation capability necessary to analyze the separation sequences for future Apollo missions.

Because of rigid schedules and the large volume of productivity that was required, the original decision to move all the hybrid capability to MSC was altered to retain a portion of the capability at the support contractor facility and to divide the desired capabilities between the two hybrid systems. The altered plan also provided for the retention of the entire set of hybrid capabilities in a digital program that was developed for verification. Initially, the purpose of this digital program was to provide a verification base for the two hybrid programs and to provide an analysis capability for time-critical problems. However, as the Apollo Program entered the operational phase, the hybrid capabilities could not provide the required output because of the increase in time-critical problems and the constraints of the associated schedules. Thus, the use of these programs diminished to such a point that all maintenance and updating efforts were terminated, and all further analysis was performed by using an all-digital simulation. Termination of the hybrid capability allowed the concentration of all resources on the all-digital program, named Dynamic Analyzer for Separation and Recontact, which proved advantageous for solving the separation analysis problem.

SUMMARY OF SIGNIFICANT SEPARATION STUDIES FOR EACH APOLLO MISSION

Many separation studies were performed during the Apollo Program. The more significant of these analyses, the accidental recontact problems identified, and the solutions to these problems for each of the Apollo missions are described in this report to emphasize the importance of comprehensive detailed project planning. Without this detailed planning, some of the problem areas presented and discussed here would have remained unidentified and unsolved; they could have become critical real-time problems, jeopardizing crew safety and mission success. The following discussion of the more significant separation problem areas emphasizes the impact of these problem areas on crew safety and mission success. The discussion demonstrates that, through detailed comprehensive planning, these problem situations can be identified and resolved before the mission rather than during real time or after the flight.

Apollo 1

The first Apollo mission was an unmanned ballistic mission performed to assess the maximum total heat rate on the command module (CM) at supercircular entry velocities and to evaluate the Saturn IB (S-IB) launch vehicle.

Possible recontact situations between the CSM and S-IVB, between the CM and SM, and between the CM and S-IVB were investigated before the mission. Results indicated that the CSM separation from the S-IVB could be performed with SM reaction control system (RCS) separation maneuvers as small as 11 seconds in duration and still remain free of recontact problems.

A parametric CSM separation study indicated that separation distances varied only slightly when the CM and the SM were separated at attitudes between 0° and 100°, plus-X axis above the local horizontal plane. Therefore, an attitude of 60° above the local horizontal plane was selected for the first Apollo mission primarily because separation at this attitude required very little CM orientation to achieve the entry attitude.

A determination of when the S-IB should be shut down to allow the launch escape vehicle (LEV) to perform a safe abort separation of the CM from the S-IVB was the objective of another analysis. The results of this analysis indicated that, to ensure no recontact between the aborting LEV and the S-IB, the time for booster engine cutoff enable should be 40 seconds after lift-off. This booster engine cutoff time was accepted by the United States Air Force Eastern Test Range safety personnel.

Apollo 2

No separation studies were performed for the Apollo 2 mission because it was a test of the launch vehicle only. The spacecraft was not flown; therefore, no separation procedures were required.

Apollo 3

The evaluation of the S-IB launch vehicle and a test on the performance of the spacecraft heat shield during a high-heat-load, long-duration entry were the prime objectives of the Apollo 3 mission.

Separation studies of the CSM and S-IVB indicated that a 0.91-m/sec (3 ft/sec) separation maneuver would be sufficient to preclude recontact. The CM/SM study showed that, for abort and nominal entries, SM separation from the CM at 60° above the positive local horizontal would yield maximum separation clearances. In addition, the study showed that, if the CM service propulsion system (SPS) failed to ignite at the time of the first burn, accidental recontact could be avoided by extending the CSM RCS plus-X translation to 75 seconds, by initiating the S-IVB engine cutoff, and by ensuring the S-IVB attitude control during venting.

Apollo 4

The unmanned Apollo 4 mission used the S-IVB to insert the spacecraft into a circular Earth parking orbit and to perform a simulated translunar injection maneuver to place the spacecraft on a highly elliptical Earth-intersecting trajectory.

Only two separations, CSM/S-IVB and CM/SM, were associated with the Apollo 4 mission; however, several accidental recontact problems were identified. During the launch phase, if an abort occurred involving an SPS ignition failure, recontact between the CSM and the S-IVB would be imminent. This problem could be avoided by commanding the S-IVB ullage maneuver off upon S-IVB abort shutdown.

For the nominal CSM/S-IVB separation sequence, an inoperative SPS could result in recontact between the spacecraft and fragments of the destructed S-IVB after the planned bulkhead-reversal test. The solution for avoiding this problem was to establish warning times, for the crew and ground control, that would provide sufficient time to enable a two-jet or four-jet RCS separation to achieve a safe separation clearance and avoid recontact with the debris.

Another potential problem area concerned the possibility of the LEV recontacting the Saturn IV booster if a launch phase abort occurred. If the booster were to cut off at approximately 42 seconds after lift-off, the 243.8-meter (800 foot) constraint on lateral separation distance between the LEV and the booster would be violated. Therefore, the recommendation that the booster enable cutoff setting be 30 seconds or less was implemented to ensure adequate separation clearances.

Apollo 5

The Apollo 5 mission was flown primarily to test the LM in a near-Earth-orbital environment for verification of LM systems. After orbit insertion, the aerodynamic shroud was separated from the S-IVB and then the four SLA panels were opened. After S-IVB/LM separation, LM abort staging using the ascent propulsion system was planned.

The nominal aerodynamic shroud jettison procedure was found to be free of recontact problems, and recommendations were made for shroud jettison procedures to be used in the event of an abort mission. The S-IVB passivation experiment procedures were analyzed, and the results were used to define the safe range of operational attitudes that would avoid potential collisions during the experiment. The LM abort staging sequence was free of recontact problems as planned.

Apollo 6

The Apollo 6 mission was similar to the Apollo 4 mission in that a translunar injection burn was simulated. Following translunar injection, it was planned that the S-IVB attitude propulsion system would perform a reorientation maneuver to the CSM SPS retrograde burn attitude; then the CSM would separate and return to Earth. The separation analysis of this procedure indicated that the S-IVB would probably recontact the CSM if the S-IVB attitude propulsion system failed to properly orient the CSM to the correct burn attitude. A solution to the problem specified that the CSM, and not the S-IVB, should orient to the burn attitude and that the CSM should perform a 10-second, four-jet RCS translation to achieve adequate clearance from the S-IVB. This solution was also recommended to preclude a possible recontact problem for an early translunar injection burn termination.

Another CSM/S-IVB recontact problem was identified for an alternate Earth parking orbit where the S-IVB was to be positioned above and in front of the CSM at the time of the SPS burn ignition. A procedure was designed to eliminate recontact for this case by proper orbital positioning of the CSM/S-IVB separation maneuver at one revolution before the first SPS burn.

Apollo 7

Apollo 7, the first manned Apollo mission, was flown to evaluate the crew/spacecraft operational compatibility, to evaluate a transposition and simulated docking exercise, and to evaluate a CSM-active rendezvous procedure.

All CSM/S-IVB separations investigated were free of recontact problems except for launch phase aborts after the LET jettison in which the SPS thrust-vector-control rate damping was used. This recontact possibility, which was identified to exist at any time during the entire launch phase, could be procedurally avoided by requiring a faster crew reaction in identifying and initiating an abort.

A relative motion analysis of the transposition and docking simulation exercise, and of the CSM-active rendezvous, indicated that all sequences were free of accidental recontact problems.

Beginning with the Apollo 7 mission, the separation attitude for the CM and SM was changed from an in-plane attitude used on previous Apollo missions to an out-of-plane attitude. The new separation attitude was to be attained by inertially holding the deorbit burn attitude and yawing the CSM 45° out of the orbit plane. This procedure would preclude a possible recontact between the CM and SM for any entry, regardless of the aerodynamic lift profile of either vehicle. The recommendation was made and accepted to perform this out-of-plane SM jettison as soon as possible after deorbit burn cutoff to increase the separation distances during entry.

Procedures were designed for a contingency in which nominal CSM separation from the S-IVB could not be accomplished. If this failure occurred, only the CM would be separated from the SM/S-IVB configuration, and the mission would be terminated.

Postflight analysis of the SM relative motion from the CM was made for this mission because of a deviation between the actual SM trajectory, which was determined by radar tracking, and the predicted trajectory. The reconstructed trajectory indicated a total relative separation delta velocity (ΔV) of approximately 9.14 m/sec (30 ft/sec), which was much smaller than the predicted 88.39 m/sec (290 ft/sec). The reduction in relative separation velocity occurred because the SM failed to remain spin stabilized throughout the complete separation maneuver. However, the analysis indicated that, although the separation velocity had been reduced significantly, the reduction did not create a recontact problem between the CM and SM during entry.

Apollo 8

The Apollo 8 mission was the first manned flight in which the three-stage Saturn V rocket booster was used and the first mission in which the crew orbited the Moon. Therefore, new separation procedures and analyses were required for almost every phase of the mission. Abort and alternate mission plans were new and were thoroughly analyzed for identification of possible recontact problems. The same kind of CSM evasive maneuver used during the Apollo 7 mission to evade the S-IVB was not applicable for the Apollo 8 mission because the Earth-orbital effects on relative motion could not be used advantageously. The evasive maneuver for the Apollo 8 mission would be required after the translunar injection burn; therefore, the separation trajectory would not be perturbed significantly by orbital effects. The CSM evasive maneuver was redesigned to consist of a 0.46-m/sec (1.5 ft/sec) RCS translation along the positive radius vector of the Earth (away from the Earth). The maneuver was designed to be initiated with the spacecraft located in a stationkeeping position 15.2 meters (50 feet) ahead of and 12.2 meters (40 feet) above the S-IVB, with the CSM apex pointed toward the Earth.

The CSM minus-X RCS translation should have produced an adequate, safe displacement from the S-IVB and avoided any recontact problems during the launch vehicle lunar targeting maneuvers. However, the actual stationkeeping maneuvers were not executed correctly; at the time for the nominal evasive maneuver, the spacecraft was not located in the correct stationkeeping position. This fact was unknown to the crew or ground control at the time and, thus, the evasive maneuver was executed from the incorrect relative position. The objective of satisfactorily evading the S-IVB was not achieved, and this failure was soon confirmed through visual tracking reported by the crew. A second ground-computed evasive maneuver was defined, relayed to the crew in real time, and executed satisfactorily to alleviate the unfavorable relative position between the two vehicles. Postflight analysis of this problem revealed that the spacecraft did not orient the full 180° in the pitch plane after initially separating from the S-IVB, which was necessary to null the separation velocity completely and therefore establish a stationkeeping position. In addition, the spacecraft plus-X axis could not be alined visually along the negative radius vector as originally planned for the first evasive maneuver. As a result, the spacecraft attitudes were approximately 15° and 45° in error for the first and second maneuvers, respectively.

It was evident that for future missions each stationkeeping and evasive maneuver should be defined to include the following: (1) specific spacecraft inertial measurement unit gimbal attitudes that are computed and simulated before the mission and updated in real time and (2) visual, out-the-window monitoring attitudes of the S-IVB or any other space vehicle in the vicinity of the spacecraft when maneuvers are planned.

The Apollo 8 mission was also the first mission during which the SLA panels were jettisoned from the S-IVB. The primary objective of jettisoning the four panels was to prevent the SM RCS thrust plumes from reflecting off the deployed panels and onto the LM. At spacecraft separation, the SLA was pyrotechnically severed from the SM and into four panels that were hinged to the S-IVB. As the CSM translated forward, the four panels deployed or rotated outward from the S-IVB and LM; and, after opening through an angle of approximately 90°, they were spring ejected from the S-IVB with a velocity of 2.44 m/sec (8 ft/sec) or greater.

An analysis was performed to determine if the panel jettisons would create any potential recontact problems with the spacecraft for the nominal mission, for launch-phase or Earth-orbital aborts, or for alternate missions. The results indicated adequate separation clearances for all phases of flight, with the single exception of retrograde mode III SPS aborts. For this particular abort, the essential retrograde mode III burn would cause the spacecraft to fly in and through the area in which the four panels had been jettisoned. However, the low probability of a mode III retrograde abort combined with the low probability of recontact was considered acceptable.

Apollo 9

The Apollo 9 mission was a 10-day, Earth-orbital mission that was flown to demonstrate the combined operational capability of the CSM and LM to perform selected functions of the lunar landing mission.

The following nominal separations were analyzed for the immediate, close-in, and eventual recontact regions: CSM separation from the S-IVB, jettison of the four SLA panels, LM ejection from the S-IVB, LM undocking from the CM, LM staging, LM ascent stage jettison from the CSM, and CM/SM separation.

Following transposition and docking, the CSM/LM configuration was spring ejected from the S-IVB. This was the first Apollo mission in which the docked configuration used four compressed springs to expel itself from the S-IVB. Originally, it had been planned to use the CSM RCS thrusters to withdraw the LM; however, primarily because of jet plume impingement onto the LM, the withdrawal technique was replaced by the spring-ejection method. This was the same kind of problem that resulted in the decision to jettison the four SLA panels on the Apollo 8 mission. The LM ejection procedure was evaluated and proved to be a successful separation technique for Apollo 9 and subsequent missions.

The performance of a planned postejection CSM/LM Earth-orbital maneuver to evade the S-IVB was based on premission separation and recontact analysis. A minus-X RCS translation burn was to be performed in a pitched-down attitude, taking advantage of the continuous propulsive venting of liquid hydrogen from the S-IVB and advantage of the orbital motion effects to produce the desired separation clearances.

For LM jettison and subsequent ascent propulsion system testing, the spacecraft was to be placed in a safe relative position with respect to the LM by orienting the CSM/LM configuration to the ascent propulsion system burn attitude and then holding the configuration inertially stable. Before executing the burn, the CSM was to jettison the LM, maneuver to a stationkeeping position, execute a pitchdown and yaw out-of-plane orientation maneuver, and then perform a four-jet minus-X RCS evasive maneuver to obtain the desired displacement between the CSM and the LM ascent stage. This procedure would permit as much as a 0.61-m/sec (2 ft/sec) error in stationkeeping relative velocities and would still ensure a safe separation distance at the time of ascent propulsion system ignition. It was designed to avoid the repetition of problems experienced during the Apollo 8 mission because of stationkeeping maneuver errors.

A new SLA panel separation and recontact evaluation was based on new attitudes and resultant velocities that encompassed the higher panel-deployment rates of 60 to 74 deg/sec observed in the Apollo 7 postflight analysis. The higher opening rate of 74 deg/sec could result in panel jettisons at a maximum attitude of 130° and at a maximum velocity of 4.27 m/sec (14 ft/sec). Minimum values previously analyzed were 90° and 2.44 m/sec (8 ft/sec). The new separation attitudes and jettison velocities were free of recontact problems for all mission phases except for the retrograde mode III abort region, which was previously identified.

Apollo 10

The Apollo 10 mission was flown to evaluate the LM operationally in lunar orbit while separated from the CSM. No landing was attempted, but the LM did maneuver into a low perigee orbit similar to the one from which a landing would be attempted on the next Apollo mission.

The Apollo 10 mission was the first mission for which a separation procedures handbook was published in addition to the separation analysis summary document. The procedures handbook was originated primarily to furnish the flight controllers a convenient separation reference during premission simulations and during the actual mission. It proved to be a valuable aid and was published for each of the remaining Apollo missions.

Beginning with the Apollo 10 mission, a more conservative transposition and docking procedure was defined, with only minor changes from the one used on the Apollo 7 and 9 missions. The initial separation velocity and the first nulling maneuver were reduced in magnitude to save RCS propellant and to decrease the separation distance from the S-IVB. The new transposition and docking procedure was found safe and was used without change for the remaining Apollo missions.

Primarily to conserve RCS fuel and to eliminate the effects of errors for small RCS maneuvers, a decision was made to use the CSM SPS for the post-transposition-docking-and-extraction evasive maneuver from the S-IVB. This was a new separation procedure for the Apollo 10 mission; and subsequent analysis revealed that, if the S-IVB liquid hydrogen propulsive vent did not close before LM ejection, a potential recontact problem would exist between the S-IVB and LM after ejection. Therefore, a decision was made to orient the CSM to the evasive maneuver attitude immediately after ejection and to perform a 5-second plus-X RCS translation, if necessary.

During the nominal lunar rendezvous, the LM descent stage was planned to be jettisoned in a posigrade direction 10 minutes before the ascent-stage insertion maneuver, which was performed in a retrograde direction 27° above the local horizontal. If LM staging were performed as planned at 10 minutes before the insertion maneuver, then the LM descent stage would be ahead and above the ascent stage at the time of the insertion maneuver, and there would be no possibility of recontact. However, if staging were executed early, then the trajectories of the two vehicles would intersect. The descent stage would have required 65 minutes to reach this intersection point, and the LM ascent stage would have required 2 minutes to reach the same point. Consequently, if staging had been performed at 63 minutes before the insertion maneuver, the ascent stage would have recontacted the descent stage 2 minutes after the insertion maneuver. For this reason, early staging was to have been avoided. To ensure that the descent stage was in a safe relative position for the ascent stage insertion burn, and thus avoid any accidental recontact problems, it was recommended that staging not be performed between 53 and 73 minutes before the insertion maneuver.

After staging, the descent-stage motion relative to the CSM was retrograde; and, because of the longer orbital period, the descent stage would approach the CSM from a posigrade direction approximately 15 revolutions later. Real-time monitoring of this relative motion problem was performed to determine if a CSM out-of-plane evasive maneuver was required. The crewmen saw the descent stage approaching, but it was determined through real-time computations that the descent stage would pass to the rear of the spacecraft with adequate separation clearance. No CSM evasive maneuvers were required.

Originally, the procedure for LM ascent-stage jettison was planned to be the same as that used during the Apollo 9 mission, in which the ascent propulsion system was allowed to burn to fuel depletion. At the crew's preference, the procedure was changed to the extent that, after ascent-stage jettison, the CSM would maneuver from a position below the LM to one above it and then perform a radially upward evasive maneuver of 0.61 m/sec (2 ft/sec). This would cause the spacecraft to translate above and behind the LM and place the crew in a favorable relative position for observing the ascent propulsion burn. Upon ascent-stage jettison, however, a separation velocity, which was larger than predicted, was imparted to the CM and LM from the severance of the docking tunnel. This caused the spacecraft to translate rapidly below and ahead of the LM, which resulted in sunlight interference in the CM windows when visual acquisition of the LM was attempted. Therefore, the crew-preferred relative position was not attained because the necessary CSM maneuvers to achieve that position were not attempted. The CSM drifted below and ahead of the LM instead of above and behind. However, no recontact problems were detected. A separation velocity that was higher than expected was probably produced by higher-than-expected gas pressure in the docking tunnel.

Apollo 11

The Apollo 11 mission was flown to attempt the first manned lunar landing, to conduct exploration and scientific experiments, and to retrieve lunar soil and rock samples.

For the Apollo 11 mission, the LM ascent stage did not contain enough propellant to achieve solar orbit with a fuel depletion burn as had been done on the Apollo 10 mission. Instead, the separation procedure for the ascent stage was altered to leave it in lunar orbit and place the CSM in a safe position to continue the nominal time line. The jettison sequence for the LM was planned and executed with a local spacecraft pitch attitude of 45° and a four-jet minus-X RCS translation for a ΔV of 0.30 m/sec (1 ft/sec), to avoid any possible recontact.

Possible ascent-stage recontact with the descent-stage plume deflectors during lift-off from the lunar surface was investigated for this first lunar landing mission. Lunar slopes as steep as 45°, which was the static stability limit of the LM, were considered. Results of the analysis indicated that even for a worst-case (45°) slope, a minimum clearance of over 18 centimeters (7 inches) was maintained between the ascent stage and the plume deflectors of the descent stage.

Immediate recontact problems associated with the LM RCS staging under nonnominal and alternate mission conditions were also investigated. Nominal LM staging under abort-guidance-section control could best be performed with narrow dead-band limits for rates less than 6 deg/sec; and, for rates of 6 deg/sec or greater, staging could best be accomplished with a 1-second plus-X RCS direct ullage maneuver without LM digital autopilot or abort-guidance-section control. No control mode was available that would completely eliminate interstage recontact for an inadvertent staging. Recontact would most likely occur between the ascent-stage fuel tank brace and the jet plume deflector supports approximately 10 seconds after inadvertent staging when narrow dead band was used and the ascent propulsion system ignition signal delay was 0 seconds. For nominal, powered-descent, abort-staging procedures, a recontact situation existed at the environmental control system lines when the descent propulsion system tail-off thrust was nominal or greater than nominal. To avoid this problem, a decision was made to use plus-X RCS translation at LM staging.

For CM/SM separation, a minus-X RCS separation burn to fuel depletion was planned to increase the SM entry velocity and decrease the flightpath angle so the SM would graze the Earth atmosphere and "skip out" into an orbit with an apogee greater than 926 000 kilometers (500 000 nautical miles). However, based on crew sightings of the SM and based on the atmospheric breakup, it was concluded that the SM separation sequence was not occurring as predicted. Although there was no apparent recontact problem, the fact that the Apollo 11 crew saw the SM when they should not have and the fact that radar tracking of the Apollo 10 SM also indicated this anomaly prompted a detailed study of the SM stability and trajectory deviation after separation. The purpose of the study was to determine if an unstable SM could result in the deviated trajectory and, if so, to determine the cause of the SM instability following separation. If possible, a new procedure that would ensure a stable SM separation burn would be defined and verified. Particular emphasis was given to the effect of propellant slosh, which was shown to be capable of producing the erratic SM behavior that was actually observed. Two dynamic models of propellant slosh were developed and were used to analyze the SM jettison procedure. The results led to the use of a new jettison procedure that would ensure stable SM attitudes during the separation burn. The new procedure involved reducing the RCS roll thrust duration from 5.5 to 2.0 seconds and setting the minus-X RCS burn to a duration of 25 seconds instead of a burn to propellant depletion. These changes were used for the Apollo 13 mission and subsequent missions. Sufficient time was not available to make the necessary SM hardware changes for the Apollo 12 mission; therefore, SM separation was performed using the burn-to-fuel-depletion sequence of the Apollo 11 mission.

Apollo 12

The Apollo 12 mission was flown to continue lunar surface exploration and scientific experiments and to retrieve lunar soil and rock samples from a different surface area than the Apollo 11 mission.

For the Apollo 12 mission, the attitude propulsion system burn, which was used on the Apollo 11 mission to target the S-IVB for a preselected lunar impact point, was also used as an evasive maneuver. This action deleted the requirement for a spacecraft SPS evasive burn following transposition, docking, and extraction. The new evasive procedure was analyzed for the Apollo 12 mission and verified as being free of recontact problems. After CSM/LM ejection from the S-IVB, the spacecraft was oriented to a viewing attitude that would enable the crew to visually monitor the S-IVB evasive maneuver sequence. The spacecraft viewing attitude also doubled as a backup CSM evasive maneuver attitude.

Apollo 13

The Apollo 13 mission was flown to continue lunar surface exploration and experiments and to collect additional soil and rock samples. Analysis of the Apollo 13 launch vehicle operational trajectory indicated that the procedure for mode II aborts of orienting the CM to the entry attitude prior to SM jettison was not the best procedure to produce maximum separation distances during entry. The analysis indicated that orientation to the CM entry attitude before the SM separation was satisfactory for an abort from a nominal booster trajectory. However, certain other aborts (e.g., an abort resulting from a time-of-free-fall limit-line violation) would result in SM jettison near the time-of-entry interface that, if performed with the CM oriented to the entry attitude, would reduce significantly the separation clearances. Therefore, a decision was made to jettison the SM immediately following the RCS abort maneuver before the orientation of the CM to the entry attitude.

The lunar descent phase abort procedures were entirely different from those previously planned for the Apollo 11 and 13 missions because the CSM was to perform the descent orbit insertion maneuver for the Apollo 13 mission. The new procedures were evaluated and potential recontact problems were identified. The most probable opportunity for a recontact problem to develop would be for a powered descent abort that was initiated at approximately 10 minutes and 10 seconds after the first powered descent initiation maneuver. If an abort occurred at this time, a recontact problem between the CSM and the LM ascent stage would exist. This problem was resolved by specifying that the LM execute an out-of-plane velocity component in its insertion maneuver, or that the CSM perform an out-of-plane maneuver at the time of LM insertion. Subsequent maneuvers during rendezvous would null the effects of the out-of-plane avoidance maneuvers, but only after the dangers of an accidental collision had passed.

When the Apollo 13 SM oxygen tanks ruptured during translunar coast, no emergency procedure had been defined for the exact situation in which the SM was inoperative and unusable for return to Earth. However, a premission separation procedure had been defined for returning to Earth with the LM, jettisoning it 1 hour before entry, and then jettisoning the SM before entry interface. This procedure specified that the SM was to produce the separation velocity required for LM jettison by using its RCS. Because this system was now inoperative, a technique was developed for using the LM RCS to produce the SM jettison velocity and using the LM docking tunnel pressure to produce the LM separation velocity. The separation attitudes for the SM and LM were the same as those defined in the premission analysis for LM jettison 1 hour before entry interface.

The SM jettison procedure was defined by the following: aline the LM plus-X axis along the positive radius vector, away from Earth; yaw out-of-plane to the south of the CM groundtrack; perform an LM RCS four-jet plus-X translation burn for a velocity of 0.15 m/sec (0.5 ft/sec); jettison the SM; and perform an LM minus-X translation burn for a velocity of 0.15 m/sec (0.5 ft/sec) to null the original maneuver. This separation maneuver, performed with the push-pull technique, was to occur 2 hours before entry interface and leave the CM docked with the LM.

The LM/CM separation procedure that was planned to occur 1 hour before entry interface was analyzed for separation velocity values of 0.30, 0.61, and 0.91 m/sec (1.0, 2.0, and 3.0 ft/sec). The results provided a parametric evaluation of the relative separation distances for various LM separation velocity values. The evaluation was necessary because of the uncertainty associated with the prediction of separation velocity resulting from severing the pressurized docking tunnel between the LM and CM. The LM jettison attitude was to be attained by alining the CM plus-X axis with the positive radius and yawing 45° out-of-plane to the south, which was the same as that used for the SM.

As the Apollo 13 mission progressed, other separation times and procedures were evaluated. For SM jettison, separation times of 3.5, 4.5, 5.5, 6.5, and 7.5 hours before entry interface were assessed. It was discovered during these simulations that, because of the earlier jettison times then under consideration, the SM out-of-plane jettison would not result in greater separation clearances. Consequently, the recommendation was made that SM jettison be performed in-plane to achieve the maximum separation displacement from the CM. The latest separation procedures, in which SM jettison was set at 4.5 hours before entry interface and LM jettison at 1.0 hour before entry interface, were furnished to the flight controllers and verified as being free of any recontact problems.

The actual SM and LM separations were not performed exactly as had been planned. The SM jettison occurred 4 hours 40 minutes before entry, rather than the expected 4.5 hours before entry interface. The separation velocity of 0.58 m/sec (1.9 ft/sec) achieved from the push-pull technique was larger than the predicted 0.30 m/sec (1 ft/sec). As a result, the separation distances between the SM and the CM and LM were greater than predictions made before separation. The LM jettison occurred approximately 11 minutes earlier than planned and in an unplanned, but acceptable, attitude. The LM was jettisoned 64° out-of-plane to the north rather than 45° out-of-plane to the south, and the pitch attitude of 64° above the local horizontal should have been 90°. The actual separation velocity was 0.76 m/sec (2.5 ft/sec), 0.15 m/sec (0.5 ft/sec) higher than the highest value considered before jettison. This combination of differences resulted in a decrease in total separation range from that predicted. At entry interface, the LM/CM clearance was 1372 meters (4500 feet), approximately 1067 meters (3500 feet) closer than previously estimated; however, no recontact problems were evident and none were reported.

Apollo 14

The Apollo 14 mission was flown to continue lunar surface exploration, to conduct scientific experiments, and to collect lunar surface samples. During this mission, the CSM encountered difficulty in performing a satisfactory docking with the LM/S-IVB configuration after translunar injection. Because of this problem, plans for using the backup evasive maneuver separation technique were considered. After several attempts, a successful docking was finally accomplished, and the nominal post transposition, docking, and extraction evasive maneuver sequence was used. Using the same procedures that had been developed for previous missions, all other separation phases of the mission were nominal and without incident.

Several new contingency procedures were developed for the Apollo 14 mission but were not required. These procedures included a method for safely returning the crew if the SLA failed to separate from the CSM after the translunar injection maneuver. This method would involve flying the complete launch vehicle/spacecraft configuration through a translunar coast, around the Moon, and to a transearth coast; and then executing a CM separation before Earth entry. Specific separation procedures were also developed and documented to cover an SM contingency of the type that occurred on the Apollo 13 mission after the translunar injection.

Apollo 15

The Apollo 15 mission was flown to continue lunar surface exploration, to conduct scientific experiments, and to collect lunar surface samples. This was the first Apollo mission to use the lunar roving vehicle (LRV) to aid in surface exploration and sample collection and also the first mission to place a subsatellite in lunar orbit.

The addition of another interstage oxygen quick-disconnect line necessitated stage-separation studies of the Apollo 15 LM for the nominal lift-off sequence, for the aborts from main powered descent, for an RCS staging, and for an inadvertent staging. This high-pressure line would exert approximately 4448 newtons (1000 pounds) of additional force between the stages when it was severed at separation, substantially modifying the LM staging dynamics. The Apollo 15 analysis indicated that the RCS and inadvertent staging dynamics were improved by the addition of this interstage oxygen line, and the separation sequence for the nominal lunar lift-off staging precluded a recontact with or without the additional oxygen line. However, the Apollo 15 analysis did indicate the possibility that one of the plus-X RCS thruster skirts could be in the path of, and recontact, one of the four thrust plume deflectors as they collapsed outward during staging. This situation would exist only for aborts initiated after descent engine shutdown during the main powered descent phase, and the recontact problem could only occur for negative pitch rates combined with equal positive roll rates on the LM during staging, which was not expected to occur.

New nominal separation procedures were required for the Apollo 15 mission because of the addition of the SIM to the mission configuration. The SIM, which was installed in one of the SM structural bays, contained scientific experiment instruments for use in lunar orbit. The structural metal surface of the SM, covering the SIM for protection, was designed to be severed pyrotechnically and jettisoned before instrument use. A jettison procedure was defined and used successfully 4.5 hours before lunar orbit insertion. One of the instruments contained in the scientific instrument bay was a subsatellite that was designed to be jettisoned and left in lunar orbit. On the Apollo 15 mission, the subsatellite was jettisoned at the orbital ascending node, normal to the ecliptic plane, toward the north, on revolution 73. This jettison attitude and the 1.22-m/sec (4 ft/sec) jettison velocity ensured adequate separation clearances between the subsatellite and the CSM for the Apollo 15 mission.

New contingency jettison procedures for the two experiment instrument booms were developed for use in the event that one of the booms, which were deployed to a length of 6.10 meters (20 feet), failed to retract satisfactorily into the SIM bay. The booms, which must be retracted before all major SPS maneuvers, were designed to be jettisoned from the SM in the event of an unsatisfactory retraction.

Apollo 16

The Apollo 16 mission was flown to continue lunar orbit and surface experiments and for lunar surface exploration and sample collections. The LRV and subsatellite were also used on Apollo 16.

The Apollo 15 nominal separation procedures were used on the Apollo 16 mission except for the final jettison of the LM ascent stage, which occurred in lunar orbit after rendezvous and docking on revolution 53. The CSM 0.61-m/sec (2 ft/sec) evasive maneuver from the ascent stage was executed at 5 minutes after the LM jettison and was made in a posigrade instead of a retrograde direction as was planned for the previous missions. This change ensured that the CSM would be pointed away from the LM ascent stage for the evasive maneuver, even if it was delayed as much as 45 minutes.

No new contingency procedures were developed for the Apollo 16 mission. The same contingency or alternate mission procedures developed for previous Apollo missions would have been used, if required.

Apollo 17

The final Apollo mission was flown to continue lunar surface sample collections, to continue exploration, and to conduct orbital and surface scientific experiments.

The final lunar landing mission of the Apollo Program used separation procedures identical to the previous mission with the addition of jettison procedures for the two high-frequency antenna booms of the lunar sounder experiment. These two antennas were nominally retracted into the scientific instrument bay of the SM, but would have to be jettisoned if a retraction failure occurred. No failure occurred, however, but jettison procedures were defined and verified before the Apollo 17 mission. No other accidental recontact problem areas were identified or encountered during this mission.

CONCLUSIONS AND RECOMMENDATIONS

For each of the Apollo missions, all separation procedures for the nominal, alternate, and abort mission time lines were documented and published in one document. The separation procedures handbook became a valuable aid in quickly determining the correct separation sequencing to be used in the event a contingency developed during the mission. The handbook concisely described each separation sequence, pictorially depicted the vehicles being separated in their correct separation attitude, and graphically presented the resulting relative motions for each vehicle. For some separations, the spacecraft out-the-window viewing attitudes were provided so the crew could visually track what they were separating from.

The Apollo spacecraft separation and recontact study effort progressed from small parametric separation analyses for the first two missions to major evaluations of all separation sequences for the remaining missions. The results and recommendations of these analyses were obtained from many organizations, both Government and contractor. A close working relationship was maintained among the personnel performing the separation studies, the flight crew support personnel, the flight controllers, and the support contractors.

Use of the spacecraft prime contractors later in the program helped make the total effort a success because of their knowledge of the structures and subsystems of the spacecraft. The establishment of the Apollo Joint Separation and Recontact Working Group, an informal organization with representatives from the prime and support contractors, aided significantly in obtaining full cooperation from the various organizations and individuals involved in the separation activities. From the experience gained to date, it is recommended that, for future programs, the spacecraft prime contractors be included in the major separation and recontact analyses, starting at the beginning of the program.

For large complicated systems like those involved in the Apollo Program, the need for this type of analysis and results should be recognized early in the program, and the overall responsibility should be assigned to a single organization. Preparation should be made to handle all interfaces in all operational modes, including failure situations.

Based on the Apollo experience, it was very difficult and inefficient to develop the large, complicated computer tools at widely dispersed geographical locations, on different computer hardware, and with several groups involved. For future activities requiring large, complex computer programing and analysis efforts, consolidation is mandatory for gaining efficiency in identifying and solving recontact problems.

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