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APOLLO 9 SPACECRAFT

OPERATIONAL DISPERSION ANALYSIS

VOLUME I

DISPERSION ANALYSIS SUMMARY

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PROJECT APOLLO

APOLLO 9 SPACECRAFT OPERATIONAL DISPERSION ANALYSIS
VOLUME I - DISPERSION ANALYSIS SUMMARY

By Anne Accola
Guidance and Performance Branch

February 19, 1969

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
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APOLLO 9 SPACECRAFT OPERATIONAL DISPERSION ANALYSIS

VOLUME I - DISPERSION ANALYSIS SUMMARY

By Anne Accola

SUMMARY

The spacecraft dispersion analysis for the Apollo 9 mission is presented in this document. This dispersion analysis comprises Volume I of the Apollo 9 Spacecraft Operational Dispersion Analysis. Volume II was published as MSC IN 69-FM-35, and Volume IV was published as MSC IN 69-FM-7. To obtain the data presented in this document, the mission was simulated with an analytic Monte Carlo program. The effects of navigation uncertainties, performance and platform errors, and retargeting were included.

In the case of the rendezvous, analysis of the data reveals that several preliminary mission limits have been exceeded. The 3σ TPI time variation of ± 4 minutes 8 seconds violates the constraint that TPI be no earlier than 3 minutes 30 seconds. The problem can be alleviated by use of the time option instead of the elevation angle option in the TPI program for those cases which violate the constraint. Several limits on the difference between PGNCS and MSFN solutions have been violated, and new limits are suggested.

Although orbital dispersions for the APS burn to depletion are large, these dispersions should not provoke unnecessary concern. The external ΔV targets have been biased sufficiently to guarantee propellant depletion.

No unreasonable trajectory dispersions result from the SPS and DPS burns. There is a very slight possibility that SPS-1 will not be a short burn. It could easily be forced to be short with minor impact on the following maneuvers. Reentry deviations are considered small and present no problem. A propellant summary for the major maneuvers indicates that dispersions are within the allowable budgets.

NOMENCLATURE

APS	ascent propulsion system
CDH	constant differential height
CSI	concentric sequence initiation
CSM	command and service modules
DPS	descent propulsion system
g.e.t.	ground elapsed time
LM	lunar module
IMU	inertial measurement unit
MCC	midcourse correction
MCC-H	Mission Control Center - Houston
MSFN	Manned Space Flight Network
OT	operational trajectory
PGNCS	primary guidance, navigation, and control system
RCS	reaction control system
RTCC	Real-Time Computer Complex
S-IVB	fourth stage of the Saturn V launch vehicle
SM	service module
SPS	service propulsion system
TLI	translunar injection
TPF	terminal phase finalization
TPI	terminal phase initiation

INTRODUCTION

This document is the first volume of the series entitled "Apollo 9 Spacecraft Operational Dispersion Analysis." Volume II of the series, "Rendezvous Dispersion Analysis", was published as MSC IN 69-FM-35 (February 1969). The fourth volume, "Navigational Error Analysis", was compiled by David Dvorkin and was published as MSC IN 69-FM-7 (January 1969).

This dispersion analysis was performed in three parts: the rendezvous phase, the APS burn to depletion, and the remainder of burns during the mission. Because the burns prior to rendezvous were designed to insure the proper tracking, lighting, and orbital conditions, no initial state vector dispersions were simulated. Rendezvous radar and MSFN navigation were modeled with navigation covariance matrices, and PGNCS and RTCC targeting techniques were used for the maneuvers. Three hundred Monte Carlo cycles of the rendezvous were run.

The APS burn to depletion was analyzed individually. Two hundred cycles of the burn were simulated with tracking uncertainties and with performance and platform errors. This burn was not retargeted.

The third part includes the remainder of the mission: five SPS burns and one DPS burn prior to the rendezvous and three SPS burns after it. This simulation extends from orbital insertion to 400 000-ft altitude with a coast period through the rendezvous.

A navigation update was performed prior to each burn. Initial state vector uncertainties caused by launch vehicle errors were simulated. The docked DPS burn was not retargeted; the deorbit burn was retargeted to the nominal inertial velocity magnitude and flight-path angle values at the end of the deorbit maneuver. The other burns were retargeted to the nominal apogee altitude, perigee altitude, and right ascension of the ascending node. The retargeting process was performed by iterating on selected parameters (i.e., the solution was obtained by checking to see if successive guesses were within specified tolerances). The solution obtained is not necessarily the optimum one. The tolerances used were 1 n. mi. for apogee altitude, 5 n. mi. for perigee altitude, 0.03° for flight-path angle, 0.5° for right ascension of the ascending node, and 10 fps for inertial velocity magnitude. The retargeting tolerances and parameters are somewhat arbitrary. Changing them would change the statistical results to some extent. The parameters were selected to control the orbit as it would be controlled in real time. The tolerances were selected to keep the orbit as nominal as possible without causing excessive ΔV deviations. The platform was alined for

the rendezvous maneuvers so that at TPI it would be at the preferred orientation. For all other maneuvers, the platform was alined to the preferred orientation.

Mission Profile and Simulation

The mission which was simulated was taken from the D mission operational trajectory (refs. 1, 2, and 3). For each part, a case with no errors was run to serve as the simulation nominal. Those nominal trajectory parameters are given in the maneuver summary tables. In general, they do not differ significantly from the OT. Differences can be attributed to the analytic coast routine and to the analytic burn model used in the simulation.

The spacecraft was initially inserted into a 110-n. mi. circular orbit. The LM extraction from the S-IVB was simulated only as a weight loss at the nominal time of $4^h08^m57^s$ g.e.t. The SPS-1 is a systems test of the SPS engine which exercises the short burn logic in the onboard computer. Nominally, it is a 5-second burn of 37 fps. In the simulation, it was retargeted to return to the nominal apogee altitude and perigee altitude. The SPS-1 is performed close to perigee and raises apogee altitude to 132 n. mi. In real-time operations, it will be necessary for the SPS-1 to be 5 seconds long.

In combination with SPS-3, the SPS-2 reduces the mass of the spacecraft to increase the SM RCS deorbit capability and to provide CSM rescue capability of the LM. The half-amplitude stroking test which occurs during this burn was not simulated because it has no effect on dispersion results. Nominally, the SPS-2 is 112 seconds in duration and has a ΔV of 850 fps; it raises apogee altitude to 193 n. mi.

The SPS-3 maneuver occurs two revolutions after the SPS-2. It raises apogee altitude to 272 n. mi.; it is a 281-second burn of 2549 fps. Crossover from the SPS storage tank to the sump tank occurs 75 seconds into the burn and results in slightly higher thrust and weight flow rate values. The full-amplitude stroking test takes place during this burn but was not simulated. Completion of SPS-2 and SPS-3 provides much of the nodal shift required for proper rendezvous lighting.

The main purpose of the SPS-4 burn is to provide ΔV for phasing changes and nodal shifts needed for late lift-offs. Nominally, it is an out-of-plane burn of 28 seconds and 300 fps. A 20-second, two-jet RCS ullage precedes the burn.

The docked DPS burn provides the first manned systems test of the DPS engine and provides some of the nodal shift required for proper

rendezvous lighting and phasing. Reference 1 contains the thrust profile to be followed. During the last 58 seconds, the engine is to be manually throttled by a crewman. The external ΔV targets have been biased to insure that the crewman and not the PGNCS will shut off the engine. The crewman will cut off the burn at a guidance time-to-go of 4 seconds, which is a V_g of approximately 10 fps. In the Monte Carlo simulation, the burn cutoff is based on the magnitude of the V_g that remains (10 fps) and is not retargeted. The latest available Apollo 9 DPS engine data was used (ref. 4) and it differs slightly from the data used in the OT. Consequently, the nominal burn time in the simulation differs from the burn time in the OT by approximately 12 seconds. The burn is mostly out of plane and is preceded by a 10-second, two-jet RCS ullage. The nominal ΔV gained is 1696 fps.

The SPS-5 circularizes the orbit at 130 n. mi. for the rendezvous (128 by 137 n. mi. in the nominal simulation caused by Keplerian approximations in the targeting). Nominally, it gains 551 fps and lasts 42 seconds. A 20-second, two-jet RCS ullage precedes it. A hardware limitation constrains SPS-5 to be at least 40 seconds long.

The CSM separation from the LM is a radially-down maneuver of 5 fps performed by the CSM RCS. A stationkeeping uncertainty of 0.6 fps (3σ) is imparted to each component of the CSM actual vector. A perfectly executed impulsive maneuver is assumed, and the estimated state is updated.

The phasing maneuver is a prespecified, radially-up maneuver of 85 fps. It consists of a 7-second ullage, 15 seconds at the 10 percent throttle setting on the DPS engine, and the remainder of the burn at a 40 percent thrust. The phasing maneuver places the LM in an equiperiod orbit so that the LM varies in its distance from the CSM from a maximum of 48 n. mi. to a minimum of 3 n. mi. The apogee and perigee of the orbit are approximately 11 n. mi. above and below those of the CSM.

After the phasing maneuver, the rendezvous sequence could be aborted by performance of a TPI_0 maneuver. Many systems test objectives would have been satisfied prior to this time. Nominally, the TPI_0 is not executed.

The next burn is insertion, which nearly circularizes the orbit of the LM 11 n. mi. above the orbit of the CSM. It is a burn of 25-seconds duration which gains 40 fps at 10 percent DPS thrust. The current plan is for insertion to be computed in the RTCC; however, it was calculated in the simulation by the onboard CDH routine with the PGNCS state vectors at a specified time. After insertion, the LM coasts 40 minutes to CSI initiation and stages the descent stage.

The purpose of the CSI is to establish proper phasing conditions at CDH so that the time and elevation angle at TPI will be nominal. As a result of CSI, the LM orbit has a perigee that is 10 n. mi. below the perigee of the CSM. This maneuver gains 38 fps and uses the RCS through the APS interconnect.

The CDH establishes a constant delta height of 10 n. mi. with the LM behind and below the CSM. A 3-second APS burn provides 38 fps and is preceded by a 4-second, four-jet RCS ullage.

In the simulation, no time constraint was applied to the TPI. It was initiated on an elevation angle of 27.5°. Nominally, it is a four-jet RCS maneuver of 18 seconds and 23 fps.

Two nominally zero midcourse corrections at 10 and 22 minutes after TPI initiation are used to correct the intercept trajectory if required. These midcourse corrections are followed by the TPF braking maneuver which nullifies the relative closing rate.

After the rendezvous, the ascent stage is separated from the CSM, and the ascent stage propellant is burned to depletion. The ΔV targets are biased to insure depletion. For the Monte Carlo simulation, the burn was not retargeted, and it was cut off on the nominal end-of-burn weight. The maneuver results in an orbit of 3249 by 126 n. mi. It is 360 seconds in duration, gains 5254 fps, and is preceded by a 3-second, four-jet ullage.

The SPS-6 and the SPS-7 are orbit shaping and adjusting maneuvers in preparation for deorbit. The SPS-6 is a 2.6-second burn of 65 fps which will exercise the short burn logic. The resulting apogee and perigee are 131 n. mi. and 97 n. mi., respectively. The SPS-7 is a 6-second burn which gains 156 fps. It results in a 215-n. mi. by 95-n. mi. orbit. Both maneuvers are preceded by a 20-second, two-jet RCS ullage and are retargeted to the nominal apogee altitude, perigee altitude, and right ascension of the ascending node.

The eighth SPS burn is the deorbit maneuver. It consists of a 20-second, two-jet RCS ullage, and a 12-second SPS burn that gains 314 fps. Desired inertial velocity magnitude and flight-path angle were the retargeting criteria in the Monte Carlo simulation. After the SPS-8, the spacecraft coasts to an altitude of 400 000 ft (entry interface).

Error Sources

The launch vehicle covariance matrix for Apollo 9 was not available at the time of this analysis. The lunar landing mission covariance matrix

before the second translunar injection opportunity (ref. 5) was considered to be representative and was used instead. The MSFN covariance matrices of tracking uncertainties and the PGNCS covariance matrices of rendezvous radar tracking uncertainties are contained in reference 6. Navigation update matrices valid at the time of burn initiation for the other burns were obtained from references 7 and 8.

Performance, platform, and thrust mistrim errors came from references 4 and 9. They were considered random with one exception: platform errors were considered static during the rendezvous. A list of the error values is given in appendix B. Reference 10 provided the platform alinement times. Thrust tailoff was not simulated for the rendezvous maneuvers, but was considered for the others.

ANALYSIS OF RESULTS

This section presents a discussion of the results at each major event in the mission. A table which lists orbital parameters and powered flight characteristics is presented for each maneuver. For the rendezvous, tables are given which present the PGNCS, MSFN, and actual solutions and their errors and expected differences. Differential height information is given for the insertion and CDH maneuvers. For the rendezvous phase, the error in a solution is the difference between that solution and the solution based on the actual state vector. The expected difference is the difference between the PGNCS solution and the MSFN solution. (A further explanation is presented in reference 11.) Definitions of the coordinate systems of the ΔV gained and the V_g residuals are given in appendix A.

SPS-1 Maneuver

Both pre- and postburn orbital statistics and maneuver summary information for the SPS-1 are presented in table I. A mean burn duration of 5.09 seconds and a 3σ deviation of 0.95 second could result in a 6.04-second burn which would not exercise the short burn logic in the onboard computer. A large part of the burn time deviation is caused by retargeting to constrain the estimated apogee to within 1 n. mi. of its nominal value. In real time, a short burn will be assured by limiting the duration to exactly 5 seconds.

The following SPS burns would fine-tune the orbit. A tally of the Monte Carlo cycles shows that the SPS-1 was retargeted in 54 percent of the cycles. This retargeting adds to the actual ΔV dispersions, and the 3σ actual total ΔV deviation is 6.98 fps. The 3σ V_g residual deviation of 1.88 fps is due primarily to the thrust mistrim.

SPS-2 Maneuver

The maneuver summary for the SPS-2 is given in table II. Because the SPS-1 is a horizontal posigrade maneuver executed close to perigee to raise apogee altitude, apogee altitude is sensitive to errors. The retargeting of the SPS-2 is an attempt to achieve the nominal apogee altitude, and, by doing this, a 3σ actual ΔV_x deviation of 4.83 fps results. The actual total ΔV deviation is 2.68 fps (3σ), and the 3σ burn time deviation is 1.18 seconds. The SPS-2 burn is retargeted only

30 percent of the time. The largest ΔV component is ΔV_y, and thus the effect of 4.83 fps ΔV_x 3σ deviation is diminished in the total 3σ deviation of 2.68 fps.

SPS-3 Maneuver

Maneuver summary information for the SPS-3 is presented in table III. The SPS-3 is retargeted 20 percent of the time. The 3σ total ΔV deviation is 5.96 fps with a 3σ burn duration dispersion of 2.97 seconds. Because the burn is executed close to perigee altitude, the largest dispersions are at apogee altitude. After the maneuver, the apogee altitude uncertainty is 4.41 n. mi. (3σ), and the perigee altitude uncertainty is 1.14 n. mi. (3σ).

SPS-4 Maneuver

Both pre- and postburn and maneuver statistics for the SPS-4 are contained in table IV. The 3σ burn duration deviation of 0.31 second and actual ΔV deviation of 1.64 fps are quite small. The primary reason for the small values is that SPS-4 is retargeted less than 1 percent of the time. The first three SPS burns are all retargeted to the nominal apogee altitude, perigee altitude, and right ascension of the ascending node. Thus, by the time of the SPS-4, the orbit is nearly nominal according to the estimated state. To provide for a return to the nominal lighting conditions in real time, the SPS-4 will be targeted to compensate for accumulated period differences that result from previous maneuver dispersions. The 3σ preburn deviations given in table IV result from navigation uncertainties and retargeting tolerances. Performance and IMU errors during the burn increase the deviations slightly.

DPS

Maneuver summary information for the docked DPS burn is presented in table V. In the simulation, the maneuver was cut off on a V_g remaining that corresponded to a guidance time-to-go of 4 seconds. As a result, the V_g residual deviations are quite small, and the burn time deviation is large, 15.05 seconds (3σ). Because the burn is not retargeted, orbital deviations increase during the maneuver. It was not retargeted because the external ΔV targets have been biased to insure that the crewman will shut off the engine manually. The latest available Apollo 9 DPS engine data was used in the simulation (ref. 4). Thrust values and weight flow rates are larger than the values used in the OT. Consequently, the nominal burn duration in the OT is 364 seconds, whereas in the simulation it is

353 seconds. A perturbed thrust during the maneuver should cause no problem because the crewman terminates it on a specified guidance time-to-go.

SPS-5 Maneuver

The SPS-5 maneuver summary is presented in table VI. True anomaly is meaningless upon execution of the circularization maneuver. The SPS-5 was retargeted 75 percent of the time, largely because of dispersions from the DPS burn since it was not retargeted. Because the SPS-5 is the last maneuver which can provide proper rendezvous lighting and phasing, it will be retargeted in real time, if required, to compensate for SPS-4 and DPS dispersions. This compensation is not reflected in these results because it was not necessary to do so in the simulation set-up. The 3σ actual ΔV deviation is 9.44 fps, and the burn duration deviation is 0.83 second.

Separation and Phasing Maneuvers

No solution statistics are presented on the separation and phasing maneuvers because they are prespecified. Their maneuver summaries are presented in tables VII and VIII. The mean closest point-of-approach after the phasing maneuver is close to the nominal value of -20 057 ft, and the standard deviation of 6507 ft makes the probability of recontact extremely small, even in the presence of a 0.6 fps (3σ) stationkeeping uncertainty.

TPI_0 Maneuver

The TPI_0 maneuver is executed only in case of aborts from the nominal rendezvous sequence. Actual, PGNCS, and MSFN solutions, as well as the expected difference and the error in the PGNCS and MSFN solutions, are presented in table IX. Preliminary mission rules state that the expected difference between the PGNCS and MSFN TPI_0 solutions should not be greater than ±2 fps in each component and ±4 minutes in ignition time. As seen in table IX, the 3σ $\dot{Z}$ expected difference is 17.64 fps, and the 3σ $\dot{Y}$ expected difference is 2.34 fps. Both of these components are valid, although they exceed the suggested limits. These large deviations are correlated to the 3σ time slip of 3.5 minutes. Increases in the allowable differences from ±2 fps to ±20 fps for $\dot{Z}$ and from ±2 fps to ±3 fps for $\dot{Y}$ are recommended to avoid the elimination of valid solutions.

Insertion Maneuver

The maneuver summary for the insertion maneuver is presented in table X. The PGNCS, MSFN, and actual solutions, the error in the solutions, and the expected differences for the insertion maneuver are presented in table XI. The errors and the expected differences are quite small. Differential altitude information is given in table XII. The mean values for the maximum and minimum differential altitudes of -11.06 and -11.36 n. mi. match the nominal values of -11.07 and -11.34 n. mi. very well. Three-sigma deviations of 0.36 and 0.30 n. mi. for maximum and minimum ΔH and 0.24 n. mi. for $\Delta\Delta H$ are small and violate no limits.

CSI Maneuver

The maneuver summary for the CSI is presented in table XIII. The PGNCS, MSFN, and actual solutions, the error in the solutions, and the expected difference for CSI are presented in table XIV. Only ΔV_x solutions are obtained because CSI is constrained to be horizontal. The PGNCS errors, MSFN errors, and the expected difference are all small.

CDH Maneuver

The maneuver information for the CDH is presented in table XV. As was the TPI_0, the CDH is a variable time maneuver, and the 3σ time deviation of 32.31 seconds results in a 3σ $\dot{Z}$ expected difference of 3.27 fps, as shown in table XVI. Because the error in PGNCS CDH time is more than twice that of the MSFN CDH time, it can be concluded that the timing error results from insufficient and relatively long-distance rendezvous radar tracking. In light of the 3σ $\dot{Z}$ expected difference of 3.27 fps, the allowable limit should probably be changed to 5 fps. Differential altitude information is presented in table XII. The mean maximum and minimum differential altitudes of 10.23 and 10.03 n. mi. agree very well with the nominal values of 10.22 and 10.04 n. mi. The 3σ deviations of 0.81 and 0.84 n. mi. are small. CDH coellipticizes the orbit as evidenced by a 3σ $\Delta\Delta H$ of 0.15 n. mi.

TPI Maneuver

The maneuver summary for TPI is presented in table XVII. The PGNCS, MSFN and actual solutions, errors in the PGNCS and MSFN solutions, and the expected difference for the TPI maneuver are given in table XVIII.

The TPI targeting is based on a 130° central transfer angle. It is a variable time maneuver, and the 3σ deviation of 4 minutes 7.5 seconds violates the lighting constraint limit of 3 minutes 30 seconds. The problem can be alleviated by use of the time option instead of the elevation angle option in the TPI program for those cases that violate the constraint.

Midcourse Correction Maneuvers

Although the first midcourse correction is nominally zero in the operational trajectory, a nominal ΔV of 1.39 fps is calculated by the PGNCS. The mean is 2.04 fps with a 3σ deviation of 3.15 fps. The second midcourse correction is also nominally zero. It has a mean of 1.76 fps with a 3σ deviation of 3.09 fps. Calculated ΔV's of less than 1 fps are not executed, and the statistics are based on those maneuvers that were executed. Data for both midcourse corrections are given in table XIX. The current plan is to burn out the V_g one component at a time. This plan results in larger ΔV mean and 3σ values than burning along the V_g vector would.

TPF

The mean distance of closest approach after the midcourse corrections is 33 ft with a 3σ deviation of 729 ft. The greatest part of this dispersion probably is due to the failure to execute the second midcourse correction if it is less than 1 fps. The data for the TPF are summarized in table XII.

APS Burn-to-Depletion Maneuver

Maneuver summary information on the APS burn to depletion is contained in table XX. This is a large maneuver of 5251 fps with a 3σ deviation of 261 fps. In the simulation, the burn was cut off on the nominal end-of-burn weight. The postburn weight deviation of 1.3 lb is within the noise of the calculations. It can be seen in table XX that the external ΔV targets have been biased sufficiently to guarantee depletion of the APS propellant. Because it is a long burn and because it is terminated on propellant depletion, the dispersions are large. The maneuver is performed at perigee altitude, which produces the greatest error at apogee altitude. The 3σ apogee altitude deviation is 253 n. mi., and the perigee altitude deviation is 0.3 n. mi. The 3σ inertial velocity magnitude deviation is 199 fps. Although these are large deviations, they present no cause for concern in the resulting orbit (3249 by 126 n. mi.).

SPS-6 Maneuver

The maneuver summary for the SPS-6 is presented in table XXI. The effect of the burn is to reshape the orbit from 135 by 129 n. mi. to 130 by 97 n. mi. By this reshaping, the 3σ apogee altitude deviation is increased from 2.25 n. mi. to 2.87 n. mi. Perigee altitude deviation decreases from 6.26 n. mi. to 2.72 n. mi. Chiefly as the result of retargeting, the actual ΔV deviation is 5.19 fps. The nominal V_{gx} residual is -2.69 fps because the burn is performed by use of the short burn logic.

SPS-7 Maneuver

Both pre- and postburn statistics for the SPS-7 burn are given in table XXII. It is a horizontal, posigrade maneuver which raises apogee altitude to 215 n. mi. and raises perigee altitude to 95 n. mi. The 3σ apogee postburn deviation is 2.93 n. mi. The 3σ perigee postburn deviation is 3.93 n. mi., which is probably caused by the 5-n. mi. retargeting tolerance. The actual ΔV deviation is 5.46 fps (3σ). Tailoff accounts for the V_{gx} residual deviation of 3.10 fps (3σ).

SPS-8 Maneuver

The deorbit burn (SPS-8) statistics are contained in table XXIII. Because the retargeting tolerance is 10 fps for velocity magnitude and 0.03° for flight-path angle, their 3σ deviations of 21.02 fps and 0.24°, respectively, are largely the result of navigation uncertainties. Perigee altitude deviation increases to 15.57 n. mi. (3σ), because it is not constrained by the retargeting and because the maneuver is performed near apogee altitude. The actual ΔV deviation is 27.72 fps (3σ).

Entry Interface

A coast to 400 000-ft altitude occurs after the deorbit burn. A summary of the deviations is given in table XXIV. The 3σ deviation of 336 seconds for coast time results from the uncontrolled altitude during the deorbit burn. Even with such a deviation, the coast time is never less than the required 10 minutes. The uncertainties in the predicted landing site point in table XXIV are translated into a downrange landing error of 4.2 n. mi. (3σ) and a cross-range landing error of 6.8 n. mi. (3σ) in reference 12.

A propellant summary for the maneuvers which were simulated is presented in table XXV. The 3σ deviations are well within the allowable budgets.

CONCLUSIONS

This document has presented results of a Monte Carlo dispersion analysis of the Apollo 9 mission. Conclusions which have been drawn from the analysis of the data are listed below.

1. The rendezvous is accomplished very accurately. Differential height deviations after insertion and CDH are well within tolerable limits. The midcourse corrections required after TPI are small, and the mean and standard deviation of the closest point-of-approach after the second midcourse correction are -33 ft and 243 ft, respectively.

2. Several expected differences in the PGNCS and MSFN solutions for the rendezvous maneuvers exceed the current limits. New limits have suggested for those cases to avoid elimination of valid solutions.

3. The 3σ TPI time slip of ± 4 minutes 7.5 seconds violates the lighting constraint associated with the early solution of 3 minutes 30 seconds. The probability of such a solution is extremely low and should cause no concern. The lighting constraint time slip has been changed to 4 minutes in the Rendezvous Techniques Document (ref. 13).

4. With the retargeting criteria and parameters used in this simulation, there is a very small probability that the SPS-1 will not be a short burn. In real time, it will be forced to be short. The following maneuver could be retargeted to return to the nominal situation.

5. The dispersions following the APS burn to depletion are large, but should not be a problem in the 3248- by 126-n. mi. orbit. The external ΔV targets have been biased sufficiently to insure propellant depletion.

6. The deviations at 400 000-ft altitude (reentry interface) are small. They result in a 3σ down-range landing error of 4.2 n. mi. and a cross-range landing error of 6.8 n. mi. Both are considered acceptable.

7. Propellant deviations for the maneuvers which were simulated are within their budgets.

In summary, there are no unreasonable dispersions associated with the Apollo 9 mission. There are no trajectory dispersions which would compromise the successful completion of the mission, with the exception of the previously mentioned minor changes. Several minor updates in the operational trajectory are documented in a revision (18-second, four-jet RCS ullages for SPS-4 and SPS-5 and revised external ΔV targets for the DPS). These changes will not have a significant effect on these results.

TABLE I.- SPS-1 MANEUVER SUMMARY

[IMU alinement time 05:24:40 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	111.86	111.90	1.87	Burn initiation g.e.t., hr:min:sec	06:01:40	06:01:40	--
	Postburn	132.00	131.85	3.81				
Perigee altitude, n. mi.	Preburn	110.29	110.38	1.35	Burn duration (not including ullage), sec	5.11	5.09	.95
	Postburn	110.66	110.84	1.07				
Semimajor axis, n. mi.	Preburn	3 551.78	3 551.85	1.40	Actual total ΔV gained, fps	36.76	36.59	6.98
	Postburn	3 562.01	3 562.03	2.04				
Altitude, n. mi.	Preburn	110.66	110.85	1.05	Actual ΔV_X gained, fps	36.76	36.59	6.98
	Postburn	110.67	110.86	1.05				
Right ascension of the ascending node, deg	Preburn	251.05	251.06	.04	Actual ΔV_Y gained, fps	.00	.00	.31
	Postburn	251.05	251.05	.04				
Inclination, deg	Preburn	32.56	32.56	.0083	Actual ΔV_Z gained, fps	.13	.10	.58
	Postburn	32.56	32.56	.0084				
Inertial flight-path angle, deg	Preburn	-.0108	-.0097	.0172	V_{gx} residual, fps	.07	.105	.993
	Postburn	-.0079	-.0070	.0176				
Eccentricity	Preburn	.0002	.0002	.0003	V_{gy} residual, fps	.00	.005	.409
	Postburn	.0030	.0029	.0005				
Spacecraft weight, lb	Preburn	91 130.73	91 138.82	275.39	V_{gz} residual, fps	.00	-.013	1.882
	Postburn	90 798.63	90 808.38	284.844				
Inertial velocity, fps	Preburn	25 542.01	25 541.43	5.82	Main engine ΔV expended, fps	36.76	36.59	6.98
	Postburn	25 579.30	25 577.99	8.28				
True anomaly, deg	Preburn	N/A	N/A	N/A	RCS ΔV expended for trim and ullage, fps	.00	.00	.00
	Postburn	357.34	357.57	2.21				

COMMENTS:

The short burn logic in the onboard computer is exercised during the SPS-1. The statistics on burn duration show that, even with retargeting, it will probably be a short burn. In real time, it will be mandatory to exercise the short burn logic. The main effect of this burn is to raise apogee altitude to 132 n. mi. It was retargeted to return apogee altitude and perigee altitude to their nominal values. The retargeting of the SPS-1 takes out most of the errors introduced by the launch vehicle covariance matrix. The V_{gz} residual 3σ deviation of 1.88 fps is due primarily to thrust mistrim. True anomaly is meaningless in the circular insertion orbit.

TABLE II.- SPS-2 MANEUVER SUMMARY

[IMU alinement time 21:38:00 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	132.37	132.24	3.90	Burn initiation g.e.t., hr:min:sec	22:12:00	22:12:00	--
	Postburn	192.86	192.91	2.28				
Perigee altitude, n. mi.	Preburn	109.80	109.98	.99	Burn duration (not including ullage), sec	111.53	111.54	1.18
	Postburn	110.94	111.10	1.05				
Semimajor axis, n. mi.	Preburn	3 562.79	3 562.81	2.24	Actual total ΔV gained, fps	850.00	850.08	2.68
	Postburn	3 593.14	3 593.25	1.49				
Altitude, n. mi.	Preburn	111.19	111.33	1.15	Actual ΔV_X gained, fps	94.55	94.84	4.83
	Postburn	111.00	111.16	1.07				
Right ascension of the ascending node, deg	Preburn	246.04	246.04	.04	Actual ΔV_Y gained, fps	-844.67	-844.72	2.59
	Postburn	248.94	248.94	.12				
Inclination, deg	Preburn	32.57	32.57	.0086	Actual ΔV_Z gained, fps	9.37	9.38	2.57
	Postburn	33.58	33.58	.1044				
Inertial flight-path angle, deg	Preburn	-.0873	-.0852	.0273	V_{gx} residual, fps	-.039	-.038	.918
	Postburn	-.0351	-.0332	.0262				
Eccentricity	Preburn	.0032	.0031	.0005	V_{gy} residual, fps	.00	.00	.001
	Postburn	.0114	.0114	.0003				
Spacecraft weight, lb	Preburn	90 798.63	90 808.38	284.84	V_{gz} residual, fps	.00	.00	.001
	Postburn	83 450.13	83 458.16	263.84				
Inertial velocity, fps	Preburn	25 571.07	25 570.08	6.47	Main engine ΔV expended, fps	850.00	850.08	2.57
	Postburn	25 682.89	25 682.07	6.31				
True anomaly, deg	Preburn	331.16	331.52	6.20	RCS ΔV expended for trim and ullage, fps	.00	.00	.00
	Postburn	356.89	357.05	2.30				

COMMENTS:

The SPS-2 maneuver raises apogee altitude to 193 n. mi., with the remainder of the ΔV going out of plane. A half-amplitude stroking test is performed during this burn but was not simulated because it has no effect on the trajectory. Retargeting was based on returning apogee altitude, perigee altitude, and right ascension of the ascending node to their nominal values. The tolerance on the node was 0.5 degree, which is fairly large. As a result, the retargeting seldom had to correct out-of-plane errors, which accounts for the small 2.59-fps ΔV_y deviation (3σ). The largest ΔV component is ΔV_y; thus, the effect of 4.83-fps ΔV_x 3σ deviation is diminished in the total 3σ ΔV deviation of 2.68 fps.

TABLE III.- SPS-3 MANEUVER SUMMARY

[IMU alinement time 24:35:30 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	192.18	192.23	2.22	Burn initiation g.e.t., hr:min:sec	25:18:30	25:18:30	--
	Postburn	272.11	272.07	4.41				
Perigee altitude, n. mi.	Preburn	111.65	111.81	1.11	Burn duration (not including ullage), sec	280.62	280.58	2.97
	Postburn	113.66	113.85	1.14				
Semimajor axis, n. mi.	Preburn	3 592.40	3 592.54	1.41	Actual total ΔV gained, fps	2549.02	2549.00	5.96
	Postburn	3 633.22	3 633.32	2.31				
Altitude, n. mi.	Preburn	112.94	113.13	1.00	Actual ΔV_X gained, fps	16.59	16.44	7.13
	Postburn	119.57	119.78	1.10				
Right ascension of the ascending node, deg	Preburn	248.00	248.00	.114	Actual ΔV_Y gained, fps	-2548.96	-2548.94	5.96
	Postburn	258.10	258.10	.23				
Inclination, deg	Preburn	33.57	33.57	.10	Actual ΔV_Z gained, fps	3.70	3.84	6.49
	Postburn	33.93	33.93	.48				
Inertial flight-path angle, deg	Preburn	.1610	.1622	.0269	V_{gx} residual, fps	-.036	-.026	1.29
	Postburn	.4735	.4737	.0285				
Eccentricity	Preburn	.0112	.0112	.0003	V_{gy} residual, fps	.00	.000	.001
	Postburn	.0218	.0218	.0006				
Spacecraft weight, lb	Preburn	83 450.13	83 458.16	263.84	V_{gz} residual, fps	.00	.000	.001
	Postburn	64 793.94	64 800.04	234.13				
Inertial velocity, fps	Preburn	25 671.70	25 670.72	6.58	Main engine ΔV expended, fps	2549.02	2549.00	5.96
	Postburn	25 772.07	25 765.19	9.45				
True anomaly, deg	Preburn	14.68	14.82	2.59	RCS ΔV expended for trim and ullage, fps	.00	.00	.00
	Postburn	22.76	22.79	1.41				

COMMENTS:

The full-amplitude stroking test takes place during the SPS-3 burn. It was not simulated because it has no effect on the trajectory. In addition, crossover from the SPS storage tank to the sump tank occurs 75 seconds into this burn. Crossover raises the thrust and weight flow rate slightly. The SPS-3 raises apogee altitude, and the retargeting criteria were the nominal values of apogee, perigee, and right ascension of the ascending node. The relatively large increase in the inclination deviation is not surprising because inclination is uncontrolled in the retargeting.

TABLE IV.- SPS-4 MANEUVER SUMMARY

[IMU alinement time 27:42:40 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	272.15	272.11	4.39	Burn initiation g.e.t., hr:min:sec	28:27:40	28:27:40	--
	Postburn	272.35	272.30	4.19				
Perigee altitude, n. mi.	Preburn	113.59	113.78	1.16	Burn duration (not including ullage), sec	28.32	28.31	.31
	Postburn	113.39	113.58	1.17				
Semimajor axis, n. mi.	Preburn	3 633.27	3 633.37	2.29	Actual total ΔV gained, fps	300.04	300.04	1.64
	Postburn	3 633.36	3 633.45	2.18				
Altitude, n. mi.	Preburn	122.00	122.19	1.08	Actual ΔV_X gained, fps	-1.70	-1.72	1.55
	Postburn	124.58	124.77	1.12				
Right ascension of the ascending node, deg	Preburn	257.21	257.21	.22	Actual ΔV_Y gained, fps	-300.02	-300.03	1.63
	Postburn	258.38	258.38	.23				
Inclination, deg	Preburn	33.93	33.93	.49	Actual ΔV_Z gained, fps	-2.06	-2.05	1.13
	Postburn	33.81	33.82	.54				
Inertial flight-path angle, deg	Preburn	.5606	.5601	.0299	V_{gx} residual, fps	-.026	-.026	1.28
	Postburn	.6413	.6407	.0285				
Eccentricity	Preburn	.0218	.0218	.0006	V_{gy} residual, fps	.00	.000	.022
	Postburn	.0219	.0218	.0006				
Spacecraft weight, lb	Preburn	64 793.94	64 800.04	234.14	V_{gz} residual, fps	.00	.000	.019
	Postburn	62 891.04	62 897.25	229.49				
Inertial velocity, fps	Preburn	25 748.84	25 747.76	11.68	Main engine ΔV expended, fps	298.09	298.09	1.63
	Postburn	25 730.22	25 729.18	11.75				
True anomaly, deg	Preburn	27.20	27.22	1.78	RCS ΔV expended for trim and ullage, fps	1.95	1.95	.01
	Postburn	31.43	31.44	1.74				

COMMENTS:

The SPS-4 is an out-of-plane burn preceded by a 20-second RCS ullage. Its chief purpose is to provide ΔV capability for phasing changes and nodal shifts required for late lift-offs. For purposes of this simulation, the burn was retargeted to nominal apogee altitude, perigee altitude, and right ascension of the ascending node. This maneuver was retargeted less than 1 percent of the time. The first three SPS burns are retargeted on the same parameters. Thus, by the time of the SPS-4, the orbit is nearly nominal according to the estimated state. The infrequent retargeting explains the small ΔV deviations.

TABLE V.- DPS MANEUVER SUMMARY

[IMU alinement time 49:17:50 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	272.35	272.32	4.38	Burn initiation g.e.t., hr:min:sec	49:42:50	49:42:50	--
	Postburn	271.43	271.25	5.95				
Perigee altitude, n. mi.	Preburn	113.20	113.38	1.04	Burn duration (not including ullage), sec	352.59	352.79	15.05
	Postburn	113.48	113.67	1.22				
Semimajor axis, n. mi.	Preburn	3 633.23	3 633.33	2.39	Actual total ΔV gained, fps	1696.72	1696.44	7.18
	Postburn	3 632.92	3 632.95	2.92				
Altitude, n. mi.	Preburn	113.24	113.46	1.00	Actual ΔV_X gained, fps	-56.35	-56.59	7.55
	Postburn	121.45	121.58	3.03				
Right ascension of the ascending node, deg	Preburn	252.32	252.32	.18	Actual ΔV_Y gained, fps	-1695.77	-1695.49	7.13
	Postburn	259.00	258.99	.32				
Inclination, deg	Preburn	33.81	33.82	.54	Actual ΔV_Z gained, fps	-4.12	-4.01	7.87
	Postburn	33.80	33.83	1.00				
Inertial flight-path angle, deg	Preburn	.0376	.0345	.1334	V_{gx} residual, fps	10.41	10.41	.02
	Postburn	.5455	.5410	.1101				
Eccentricity	Preburn	.0219	.0219	.0006	V_{gy} residual, fps	.00	.003	.080
	Postburn	.0217	.0217	.0008				
Spacecraft weight, lb	Preburn	62 891.04	62 897.25	229.49	V_{gz} residual, fps	.00	-.002	.086
	Postburn	52 816.89	52 823.75	238.86				
Inertial velocity, fps	Preburn	25 810.57	25 809.22	9.73	Main engine ΔV expended, fps	1695.70	1695.42	7.18
	Postburn	25 752.22	25 750.23	30.63				
True anomaly, deg	Preburn	1.75	.71	2.05	RCS ΔV expended for trim and ullage, fps	1.02	1.02	.00
	Postburn	26.52	26.38	6.24				

COMMENTS:

The DPS burn is a systems test of the DPS engine. The thrust profile is given in reference 1. The ΔV targets have been biased to insure that the crewman will shut off the engine manually. For this reason, the burn was not retargeted in this simulation. Because the burn is cut off on V_g (10.41 fps), the 3σ deviation in burn time is larger than normally expected, and the V_g residuals of 0.02, 0.08, and 0.086 fps are quite small. The ΔV deviations are the result of accelerometer errors.

TABLE VI.- SPS-5 MANEUVER SUMMARY

[IMU alinement time 52:31:56 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	271.64	271.44	5.91	Burn initiation g.e.t., hr:min:sec	54:25:56	54:25:56	--
	Postburn	137.24	137.46	2.87				
Perigee altitude, n. mi.	Preburn	113.19	113.39	1.26	Burn duration (not including ullage), sec	41.96	41.90	.83
	Postburn	129.10	128.70	6.17				
Semimajor axis, n. mi.	Preburn	3 633.25	3 633.27	2.79	Actual total ΔV gained, fps	551.00	550.07	9.44
	Postburn	3 574.24	3 574.16	2.72				
Altitude, n. mi.	Preburn	127.49	127.58	4.63	Actual ΔV_X gained, fps	-215.63	-215.95	16.05
	Postburn	129.43	129.51	5.10				
Right ascension of the ascending node, deg	Preburn	257.66	257.65	.30	Actual ΔV_Y gained, fps	-367.86	-367.90	1.95
	Postburn	259.02	259.00	.28				
Inclination, deg	Preburn	33.81	33.83	1.00	Actual ΔV_Z gained, fps	348.97	347.19	17.16
	Postburn	33.48	33.50	1.11				
Inertial flight-path angle, deg	Preburn	.7160	.7109	.1118	V_{gx} residual, fps	-.020	.040	1.59
	Postburn	-.0257	-.0270	.0948				
Eccentricity	Preburn	.0218	.0218	.0008	V_{gy} residual, fps	.00	.000	.002
	Postburn	.0011	.0012	.0012				
Spacecraft weight, lb	Preburn	52 816.89	52 823.75	238.86	V_{gz} residual, fps	.00	.000	.002
	Postburn	50 004.11	50 015.24	231.89				
Inertial velocity, fps	Preburn	25 708.28	25 706.23	43.25	Main engine ΔV expended, fps	548.60	547.67	9.43
	Postburn	25 487.23	25 484.92	33.04				
True anomaly, deg	Preburn	35.51	35.54	7.18	RCS ΔV expended for trim and ullage, fps	2.40	2.40	.01
	Postburn	N/A	N/A	N/A				

COMMENTS:

The purpose of the SPS-5 maneuver is to circularize the orbit at 130 n. mi. Because of Keplerian approximations for apogee altitude and perigee altitude in the targeting, the nominal and mean values of apogee altitude and perigee altitude in the simulation are 137 n. mi. and 129 n. mi., respectively, instead of 130 n. mi. for both altitudes. The ΔV in this maneuver is used to fine-tune the orbit prior to rendezvous. Upon execution of this maneuver, true anomaly becomes meaningless. The ΔV durations are caused mainly by retargeting.

TABLE VII.- CSM SEPARATION MANEUVER SUMMARY

[IMU alinement time 92:33:49.6 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	126.30	126.30	.00	Burn initiation g.e.t., hr:min:sec	93:05:50	93:05:50	--
	Postburn	126.58	126.58	.12				
Perigee altitude, n. mi.	Preburn	125.90	125.90	.00	Burn duration (not including ullage), sec	10.90	10.85	.43
	Postburn	125.61	125.61	.12				
Semimajor axis, n. mi.	Preburn	3 572.70	3 572.70	.23	Actual total ΔV gained, fps	5.0	5.0	0.19
	Postburn	3 572.70	3 572.70	.23				
Altitude, n. mi.	Preburn	127.83	127.83	.80	Actual ΔV_X gained, fps	0.0	0.0	0.05
	Postburn	127.83	127.83	.80				
Right ascension of the ascending node, deg	Preburn	-112.82	-112.82	.004	Actual ΔV_Y gained, fps	0.0	0.0	0.05
	Postburn	-112.82	-112.82	.004				
Inclination, deg	Preburn	33.36	33.36	.004	Actual ΔV_Z gained, fps	5.0	4.98	.19
	Postburn	33.36	33.36	.004				
Inertial flight-path angle, deg	Preburn	-.004	-.004	.0017	V_{gx} residual, fps	0.0	0.0	0.
	Postburn	.007	.007	.0016				
Eccentricity	Preburn	.0007	.0007	.00006	V_{gy} residual, fps	0.0	0.0	0.
	Postburn	.0007	.0007	.00006				
Spacecraft weight, lb	Preburn	27 558	27 558	.00	V_{gz} residual, fps	0.0	0.0	0.
	Postburn	27 543	27 543	.60				
Inertial velocity, fps	Preburn	25 483	25 483	.76	Main engine ΔV expended, fps	5.0	4.98	.19
	Postburn	25 483	25 483	.76				
True anomaly, deg	Preburn	5.25	5.34	2.29	RCS ΔV expended for trim and ullage, fps	0.0	0.0	0.
	Postburn	-10.18	-10.14	2.40				

COMMENTS:

The SM RCS engines are used to perform the CSM separation maneuver which is 5 fps radially down and which places the CSM in a small equiperiod orbit (mini-football) with the LM. The purposes of this maneuver are to eliminate the requirements for stationkeeping during the checkout of the LM systems and also to establish a physical separation to allow a rendezvous radar system check. No initial actual state vector dispersions were simulated, which accounts for the small 3σ deviations in the table.

TABLE VIII.- LM PHASING MANEUVER SUMMARY

[IMU alinement time 92:33:49.6 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	126.58	126.58	0.12	Burn initiation g.e.t., hr:min:sec	93:49:56.6	93:49:56.6	0.0
	Postburn	138.92	138.90	0.12				
Perigee altitude, n. mi.	Preburn	125.59	125.61	0.12	Burn duration (not including ullage), sec	24.95	24.96	.40
	Postburn	113.56	113.39	0.12				
Semimajor axis, n. mi.	Preburn	3 572.60	3 572.61	.15	Actual total ΔV gained, fps	85.0	85.05	.62
	Postburn	3 572.78	3 572.78	.08				
Altitude, n. mi.	Preburn	127.73	127.73	.26	Actual ΔV_X gained, fps	1.34	2.52	5.08
	Postburn	127.78	127.78	.26				
Right ascension of the ascending node, deg	Preburn	-113.04	-113.04	.004	Actual ΔV_Y gained, fps	0.0	.04	5.09
	Postburn	-113.05	-113.05	.005				
Inclination, deg	Preburn	33.35	33.35	.004	Actual ΔV_Z gained, fps	-84.99	-84.98	.62
	Postburn	33.36	33.36	.004				
Inertial flight-path angle, deg	Preburn	-.013	-.013	.0009	V_{gx} residual, fps trimmed	0.0	-.0124	.003
	Postburn	-.204	-.204	.0016				
Eccentricity	Preburn	.000778	.000778	3.4×10^{-5}	V_{gy} residual, fps trimmed	0.0	.0497	5.07
	Postburn	.00364	.00364	3.0×10^{-5}				
Spacecraft weight, lb	Preburn	22 405	22 405	0.	V_{gz} residual, fps trimmed	0.0	.187	5.04
	Postburn	22 203	22 195	15.6				
Inertial velocity, fps	Preburn	25 484	25 484	1.6	Main engine ΔV expended, fps	82.99	83.02	.61
	Postburn	25 483	25 483	1.8				
True anomaly, deg	Preburn	16.53	16.53	1.40	RCS ΔV expended for trim and ullage, fps	2.01	3.00	2.48
	Postburn	78.28	78.30	1.04				

COMMENTS:

The LM phasing maneuver is a fixed magnitude, variable thrust (10 to 40 percent) DPS maneuver which is 85 fps radially up. After a 7-second, two-jet ullage, the DPS is burned at a 10 percent throttle setting for 15 seconds and is followed by a 40 percent setting for the remainder of the maneuver. The maneuver inserts the LM into an equiperiod elliptic orbit (football) which provides an opportunity for early LM abort while it allows many of the system test objectives to be accomplished. The 3σ V_{gy} and V_{gz} residual deviations of 5.07 fps and 5.04 fps, respectively, are thrust mistrim. The V_{gx} residual deviation is small because thrust tailoff was not simulated.

TABLE IX.- EVALUATION OF SOLUTIONS FOR TPI_0 MANEUVER[a]

	Parameter	Mean	3σ
PGNCS solution at PGNCS time	ΔV_x, fps	-18.07	.51
	ΔV_y, fps	-.19	1.74
	ΔV_z, fps	5.92	17.49
	Total ΔV, fps	19.80	5.85
	Time, hr:min:sec	95:00:26	2:52.8
MSFN solution at MSFN time	ΔV_x, fps	-18.03	.90
	ΔV_y, fps	-.22	2.19
	ΔV_z, fps	6.52	21.75
	Total ΔV, fps	20.31	8.58
	Time, hr:min:sec	95:00:33	4:12.57
Actual solution at PGNCS time	ΔV_x, fps	-18.07	.66
	ΔV_y, fps	-.25	.99
	ΔV_z, fps	6.06	15.54
	Total ΔV, fps	19.67	5.25
	Time, hr:min:sec	95:00:27	2:38.7
Actual solution at MSFN time	ΔV_x, fps	-18.03	1.71
	ΔV_y, fps	-.25	.99
	ΔV_z, fps	6.47	17.31
	Total ΔV, fps	19.87	7.17
	Time	--	--
Actual solution at actual time	ΔV_x, fps	-18.08	.45
	ΔV_y, fps	-.25	.99
	ΔV_z, fps	6.06	15.33
	Total ΔV, fps	19.68	5.07
	Time	--	--
Error in PGNCS solution	ΔV_x, fps	-.008	.36
	ΔV_y, fps	.059	1.44
	ΔV_z, fps	-.13	5.52
	Total ΔV, fps	.13	1.86
	Time, sec	-.79	59.70
Error in MSFN solution	ΔV_x, fps	-.0005	2.19
	ΔV_y, fps	.04	1.92
	ΔV_z, fps	.05	8.19
	Total ΔV, fps	.44	2.64
	Time, sec	5.80	199.50
Expected difference between PGNCS and MSFN solution	ΔV_x, fps	-.04	.84
	ΔV_y, fps	.02	2.34
	ΔV_z, fps	-.60	17.64
	Total ΔV, fps	-.51	7.47
	Time, sec	-6.61	210.00

[a]Nominal conditions:

ΔV_x, fps	-18.13
ΔV_y, fps	-.27
ΔV_z, fps	5.88
Total ΔV, fps	19.06
Time, hr:min:sec	95:00:26

TABLE X.- LM INSERTION MANEUVER SUMMARY

[IMU alinement time 95:03:52 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	138.82	138.90	0.12	Burn initiation g.e.t., hr:min:sec	95:41:41	95:41:41	0.
	Postburn	138.47	138.47	0.12				
Perigee altitude, n. mi.	Preburn	113.29	113.39	0.15	Burn duration (not including ullage), sec	24.80	24.79	1.13
	Postburn	136.18	136.18	0.39				
Semimajor axis, n. mi.	Preburn	3 573.37	3 573.37	.26	Actual total ΔV gained, fps	39.85	39.86	.56
	Postburn	3 584.45	3 584.45	.30				
Altitude, n. mi.	Preburn	139.41	139.40	.27	Actual ΔV_X gained, fps	39.82	39.81	.56
	Postburn	139.49	139.49	.27				
Right ascension of the ascending node, deg	Preburn	-113.54	-113.54	.004	Actual ΔV_Y gained, fps	0.0	0.0	0.0
	Postburn	-113.55	-113.55	.004				
Inclination, deg	Preburn	33.36	33.36	.004	Actual ΔV_Z gained, fps	1.70	1.74	2.98
	Postburn	33.36	33.36	.004				
Inertial flight-path angle, deg	Preburn	0.003	.003	.004	V_{gx} residual, fps trimmed	0.0	0.0	0.0
	Postburn	+.010	.010	.004				
Eccentricity	Preburn	.0025	.0025	2.9×10^{-5}	V_{gy} residual, fps trimmed	0.0	0.019	2.16
	Postburn	.0006	.0006	6.3×10^{-5}				
Spacecraft weight, lb	Preburn	22 203	22 195	15.6	V_{gz} residual, fps trimmed	0.0	.02	2.42
	Postburn	22 108	22 096	17.2				
Inertial velocity, fps	Preburn	25 399	25 399	1.2	Main engine ΔV expended, fps	37.84	37.82	.56
	Postburn	25 438	25 438	1.5				
True anomaly, deg	Preburn	-178.74	-178.7	1.04	RCS ΔV expended for trim and ullage, fps	2.01	2.29	.70
	Postburn	-15.67	-15.61	6.21				

COMMENTS:

The LM insertion maneuver will be computed in the MCC-H; however, for this document, it was computed by the LM PGNCS. The maneuver is nominally 39.9 fps posigrade and is executed by use of the LM DPS at 10 percent throttle setting after a 7-second, two-jet ullage. The maneuver inserts the LM into a near-circular orbit 11.2 n. mi. above the CSM. The maneuver is performed if a GO decision for the planned rendezvous is made. The planned rendezvous provides for rendezvous navigation checks at larger distances and evaluation of the onboard CSI/CDH logic. There is no V_{gx} residual deviation because thrust tailoff was not simulated. The V_{gy} and V_{gz} residual deviations are the result of thrust mistrim.

TABLE XI.- EVALUATION OF SOLUTIONS FOR INSERTION MANEUVER[a]

	Parameter	Mean	3σ
PGNCS solution	ΔV_x, fps	39.83	.54
	ΔV_y, fps	0.00	.00
	ΔV_z, fps	1.63	2.01
	Total ΔV, fps	39.87	.54
MSFN solution	ΔV_x, fps	39.90	.54
	ΔV_y, fps	0.00	.00
	ΔV_z, fps	1.47	1.95
	Total ΔV, fps	39.93	.54
Actual solution	ΔV_x, fps	39.83	.39
	ΔV_y, fps	0.00	.00
	ΔV_z, fps	1.64	1.95
	Total ΔV, fps	39.86	.39
Error in PGNCS solution	ΔV_x, fps	.0007	.33
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-.01	.51
	Total ΔV, fps	.00	.33
Error in MSFN solution	ΔV_x, fps	-.002	.36
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.001	.27
	Total ΔV, fps	-.002	.36
Expected difference in PGNCS and MSFN solutions	ΔV_x, fps	-.077	.51
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.16	.60
	Total ΔV, fps	.07	.51

[a]Nominal conditions: ΔV_x, fps 39.82
ΔV_y, fps 0.00
ΔV_z, fps 1.70
Total ΔV, fps 39.85
Time[b], hr:min:sec 95:41:41

[b]Time of maneuver is fixed.

TABLE XII.- ACTUAL VARIATION IN ΔH, TPI TIME,

AND CLOSEST POINT-OF-APPROACH

Parameter	Nominal	Mean	3σ
Closest point-of-appraoch after phasing maneuver (CPA), ft	-20057	-19963	19521
Maximum ΔH after insertion maneuver, n. mi.	-11.07	-11.06	.36
Minimum ΔH after insertion maneuver, n. mi.	-11.34	-11.36	.30
Variation in ΔH (ΔΔH) after insertion maneuver, n. mi.	.27	.30	.24
Maximum ΔH after CDH maneuver, n. mi.	10.22	10.23	.81
Minimum ΔH after CDH maneuver, n. mi.	10.04	10.02	.84
Variation in ΔH (ΔΔH) after CDH maneuver, n. mi.	.18	.20	.15
TPI time, hr:min:sec (g.e.t.)	97:59:20	97:59:28	247.5
Closest point-of-approach after second midcourse correction (MCC-2), ft	-127	-33	729
Time of closest point-of-approach after MCC-2, hr:min:sec (g.e.t.)	98:31:33	98:31:44	246.9

TABLE XIII.- LM CSI MANEUVER SUMMARY

[IMU alinement time 95:03:52 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	138.41	138.47	0.12	Burn initiation g.e.t., hr:min:sec	96:22:00	96:22:00	0.0
	Postburn	136.50	136.58	0.39				
Perigee altitude, n. mi.	Preburn	136.11	136.18	0.39	Burn duration (not including ullage), sec	30.68	30.67	1.60
	Postburn	117.14	117.02	0.81				
Semimajor axis, n. mi.	Preburn	3 585.42	3 585.42	.30	Actual total ΔV gained, fps	37.90	37.88	1.82
	Postburn	3 574.68	3 574.68	.44				
Altitude, n. mi.	Preburn	136.96	136.95	.45	Actual ΔV_X gained, fps	-37.90	-37.88	1.82
	Postburn	137.00	137.00	.45				
Right ascension of the ascending node, deg	Preburn	-113.76	-113.76	.004	Actual ΔV_Y gained, fps	0.0	0.0	0.0
	Postburn	-113.76	-113.76	.004				
Inclination, deg	Preburn	33.37	33.37	.004	Actual ΔV_Z gained, fps	0.0	0.0	0.0
	Postburn	33.37	33.37	.004				
Inertial flight-path angle, deg	Preburn	+.010	.010	.004	V_{gx} residual, fps trimmed	0.0	0.0	0.0
	Postburn	+.013	.013	.005				
Eccentricity	Preburn	.00137	.00137	6.3×10^{-5}	V_{gy} residual, fps trimmed	0.0	0.0	0.0
	Postburn	.0017	.0017	.00019				
Spacecraft weight, lb	Preburn	10 438.	10 438.	169.2	V_{gz} residual, fps trimmed	0.0	0.0	0.0
	Postburn	10 394.	10 392.	161.6				
Inertial velocity, fps	Preburn	25 454.	25 454.	2.3	Main engine ΔV expended, fps	37.90	37.88	1.82
	Postburn	25 416.	25 416.	3.7				
True anomaly, deg	Preburn	-7.38	-7.42	2.88	RCS ΔV expended for trim and ullage, fps	0.0	0.0	0.0
	Postburn	-172.08	-172.07	2.56				

COMMENTS: The LM CSI maneuver will be computed by the LM PGNCS. The maneuver is nominally 37.8 fps retrograde and is executed by use of four RCS engines with the RCS interconnect. The purpose of this maneuver is to establish the proper phasing conditions at CDH (next maneuver) so that after the CDH maneuver is executed, TPI will be at the desired time (g.e.t.) and elevation angle.

TABLE XIV.- EVALUATION OF SOLUTIONS FOR CSI MANEUVER[a]

	Parameter	Mean	3σ
PGNCS solution	ΔV_x, fps	-37.90	1.65
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	37.90	1.65
MSFN solution	ΔV_x, fps	-37.77	1.62
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	37.77	1.62
Actual solution	ΔV_x, fps	-37.90	1.53
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	37.90	1.53
Error in PGNCS solution	ΔV_x, fps	.004	.60
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	.004	.60
Error in MSFN solution	ΔV_x, fps	.004	.51
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	.004	.51
Expected difference in PGNCS and MSFN solution	ΔV_x, fps	-.13	.81
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.00	.00
	Total ΔV, fps	.13	.81

[a]Nominal conditions: ΔV_x, fps . . . . . -37.90
ΔV_y, fps 00
ΔV_z, fps 00
Total ΔV, fps 37.90
Time[b], hr:min:sec 96:22:00

[b]Time of maneuver is fixed.

TABLE XV.- LM CDH MANEUVER SUMMARY

[IMU alinement time 95:03:52 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	136.50	136.58	0.39	Burn initiation g.e.t., hr:min:sec	97:06:54.3	97:06:52.8	44.0
	Postburn	117.16	117.10	0.63				
Perigee altitude, n. mi.	Preburn	117.14	117.02	0.81	Burn duration (not including ullage), sec	3.09	3.08	.25
	Postburn	115.15	115.26	0.96				
Semimajor axis, n. mi.	Preburn	3 574.69	3 574.70	.41	Actual total ΔV gained, fps	37.96	37.97	2.11
	Postburn	3 564.01	3 564.02	.92				
Altitude, n. mi.	Preburn	117.48	117.48	1.04	Actual ΔV_X gained, fps	-37.96	-37.93	2.12
	Postburn	117.50	117.50	1.04				
Right ascension of the ascending node, deg	Preburn	-113.98	-113.98	.004	Actual ΔV_Y gained, fps	0.0	-.013	2.24
	Postburn	-113.98	-113.98	.004				
Inclination, deg	Preburn	33.37	33.37	.004	Actual ΔV_Z gained, fps	-.31	-.55	5.28
	Postburn	33.37	33.37	.005				
Inertial flight-path angle, deg	Preburn	.002	.002	.005	V_{gx} residual, fps trimmed	0.0	-.046	.092
	Postburn	.001	.001	.005				
Eccentricity	Preburn	.0038	.0038	.00019	V_{gy} residual, fps trimmed	0.0	-.023	2.67
	Postburn	.0008	.0008	5.7×10^{-5}				
Spacecraft weight, lb	Preburn	10 394.	10 392.	169.2	V_{gz} residual, fps trimmed	0.0	.002	2.43
	Postburn	10 354.	10 350.	160.7				
Inertial velocity, fps	Preburn	25 555.	25 555.	6.0	Main engine ΔV expended, fps	32.99	33.02	2.22
	Postburn	25 517.	25 517.	4.7				
True anomaly, deg	Preburn	-.531	-.594	1.35	RCS ΔV expended for trim and ullage, fps	4.97	5.07	.74
	Postburn	-1.023	-.979	5.85				

COMMENTS: The LM CDH maneuver will be computed by the LM PGNCS. The maneuver is nominally 38.0 fps retrograde and is executed by use of the LM APS after a 4-second, four-jet ullage. This maneuver inserts the LM into a near-circular orbit that is nominally 10.1 n. mi. below and coelliptic to the CSM orbit. The V_{gx} residual deviation is small because thrust tailoff was not simulated. The V_{gy} and V_{gz} residual deviations result from thrust mistrim.

TABLE XVI.- EVALUATION OF SOLUTIONS FOR CDH MANEUVER[a]

	Parameter	Mean	3σ
PGNCS solution at PGNCS time	ΔV_x, fps	-37.93	2.19
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-.45	3.60
	Total ΔV, fps	37.95	2.19
	Time, hr:min:sec	97:06:52	43.8
MSFN solution at MSFN time	ΔV_x, fps	-37.73	2.25
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-1.65	2.52
	Total ΔV, fps	37.77	2.31
	Time, hr:min:sec	97:06:47	27.0
Actual solution at PGNCS time	ΔV_x, fps	-37.92	2.16
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-.46	3.45
	Total ΔV, fps	37.94	2.16
	Time, hr:min:sec	97:06:52	43.8
Actual solution at MSFN time	ΔV_x, fps	-37.74	2.16
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-1.64	2.13
	Total ΔV, fps	37.77	2.19
	Time, hr:min:sec	97:06:47	27.0
Error in PGNCS solution	ΔV_x, fps	-.01	.30
	ΔV_y, fps	.00	.00
	ΔV_z, fps	.01	1.02
	Total ΔV, fps	.013	.30
	Time, sec	.036	28.20
Error in MSFN solution	ΔV_x, fps	.008	.96
	ΔV_y, fps	.00	.00
	ΔV_z, fps	-.009	1.29
	Total ΔV, fps	-.005	.99
	Time, sec	-.24	12.03
Expected differences between PGNCS and MSFN solutions	ΔV_x, fps	-.20	.99
	ΔV_y, fps	.00	.00
	ΔV_z, fps	1.21	3.27
	Total ΔV, fps	.18	1.02
	Time, sec	5.31	32.31

[a]Nominal conditions: ΔV_x, fps . . . . . -37.96
ΔV_y, fps 00
ΔV_z, fps . . . . . -.31
Total ΔV, fps 37.96
Time, hr:min:sec 97:06:28

TABLE XVII.- LM TPI MANEUVER SUMMARY

[IMU alinement time 95:03:52 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	117.16	117.10	0.39	Burn initiation g.e.t., hr:min:sec	97:59:20.4	97:59:27.8	4:7.5
	Postburn	128.21	128.21	0.15				
Perigee altitude, n. mi.	Preburn	117.14	117.02	0.81	Burn duration (not including ullage), sec	17.68	17.67	1.47
	Postburn	114.68	114.72	0.15				
Semimajor axis, n. mi.	Preburn	3 562.23	3 562.22	.80	Actual total ΔV gained, fps	22.00	21.99	1.77
	Postburn	3 567.61	3 567.60	.71				
Altitude, n. mi.	Preburn	116.68	116.71	1.44	Actual ΔV_X gained, fps	19.43	19.50	1.67
	Postburn	116.74	116.77	1.46				
Right ascension of the ascending node, deg	Preburn	-114.25	-114.25	.029	Actual ΔV_Y gained, fps	-.24	-.27	2.35
	Postburn	-114.25	-114.25	.031				
Inclination, deg	Preburn	33.35	33.35	.011	Actual ΔV_Z gained, fps	-10.32	-10.12	1.56
	Postburn	33.35	33.35	.012				
Inertial flight-path angle, deg	Preburn	0.06	.005	.0076	V_{gx} residual, fps trimmed	0.0	0.0	0.0
	Postburn	-.019	-.019	.0061				
Eccentricity	Preburn	.000972	.000966	.000232	V_{gy} residual, fps trimmed	0.0	0.0	0.0
	Postburn	.00249	.00249	.000290				
Spacecraft weight, lb	Preburn	10 354.	10 350.	160.7	V_{gz} residual, fps trimmed	0.0	0.0	0.0
	Postburn	10 329.	10 324.	160.1				
Inertial velocity, fps	Preburn	25 527.	25 527.	5.5	Main engine ΔV expended, fps	22.00	21.99	1.77
	Postburn	25 546.	25 546.	7.0				
True anomaly, deg	Preburn	-5.91	-5.49	6.98	RCS ΔV expended for trim and ullage, fps	0.0	0.0	0.0
	Postburn	7.58	7.74	3.30				

COMMENTS: The LM TPI maneuver will be computed by the LM PGNCS. The maneuver is nominally 22.6 fps and is executed using four RCS engines. This maneuver places the LM on an intercept trajectory with the CSM. The point of interception will be approximately 130° (32.5 minutes) from TPI

TABLE XVIII.- EVALUATION OF SOLUTIONS FOR TPI MANEUVER[a]

	Parameter	Mean	3σ
PGNCS solution at PGNCS time	ΔV_x, fps	19.40	1.53
	ΔV_y, fps	-.27	1.92
	ΔV_z, fps	-10.29	1.53
	Total ΔV, fps	21.97	1.92
	Time, hr:min:sec	97:59:28	247.5
MSFN solution at MSFN time	ΔV_x, fps	19.47	1.50
	ΔV_y, fps	-.21	2.88
	ΔV_z, fps	-10.31	1.56
	Total ΔV, fps	21.99	1.86
	Time, hr:min:sec	97:59:32	257.4
Actual solution at PGNCS time	ΔV_x, fps	19.40	1.56
	ΔV_y, fps	-.23	.84
	ΔV_z, fps	-10.31	1.80
	Total ΔV, fps	21.98	1.89
	Time, hr:min:sec	97:59:28	247.5
Actual solution at MSFN time	ΔV_x, fps	19.36	1.77
	ΔV_y, fps	-.23	.84
	ΔV_z, fps	-10.48	3.87
	Total ΔV, fps	22.06	2.10
	Time, hr:min:sec	97:59:32	257.4
Actual solution at actual time	ΔV_x, fps	19.41	1.53
	ΔV_y, fps	-.23	.84
	ΔV_z, fps	-10.29	1.53
	Total ΔV, fps	21.97	1.89
	Time, hr:min:sec	97:59:27	246.3
Error in PGNCS solution	ΔV_x, fps	.001	.18
	ΔV_y, fps	-.04	1.68
	ΔV_z, fps	.03	1.56
	Total ΔV, fps	-.009	.69
	Time, sec	.35	18.99
Error in MSFN solution	ΔV_x, fps	.04	.81
	ΔV_y, fps	.04	2.70
	ΔV_z, fps	.18	3.27
	Total ΔV, fps	-.06	.93
	Time, sec	3.60	67.23
Expected difference between PGNCS and MSFN solutions	ΔV_x, fps	-.005	.21
	ΔV_y, fps	-.004	3.24
	ΔV_z, fps	.02	.81
	Total ΔV, fps	-.02	.48
	Time, sec	-3.25	69.24

[a]Nominal conditions:

ΔV_x, fps	19.43
ΔV_y, fps	-.23
ΔV_z, fps	-10.32
Total ΔV, fps	22.00
Time, hr:min:sec	97:59:20

TABLE XIX.- ESTIMATED MIDCOURSE CORRECTION ΔV EXPENDED[a]

Parameter	Nominal	Mean	3σ
First midcourse correction (MCC-1), fps	1.39	2.04	3.15
Second midcourse correction (MCC-2), fps	.02	1.76	3.09
Total estimated ΔV expended, fps	1.41	3.22	4.50

[a]The midcourse corrections were performed by burning out the V_g one component at a time in accordance with the current plan.

TABLE XX.- APS BURN-TO-DEPLETION MANEUVER SUMMARY

[IMU alinement time 100:25:57 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	132.12	132.12	.20	Burn initiation g.e.t., hr:min:sec	98:27:57	98:27:57	--
	Postburn	3 244.29	3 248.82	252.55				
Perigee altitude, n. mi.	Preburn	129.11	129.11	.12	Burn duration (not including ullage), sec	357.89	358.01	25.13
	Postburn	126.54	126.45	.25				
Semimajor axis, n. mi.	Preburn	3 571.39	3 571.39	.10	Actual total ΔV gained, fps	5250.87	5254.09	260.94
	Postburn	5 127.30	5 129.63	126.31				
Altitude, n. mi.	Preburn	129.24	129.24	.15	Actual ΔV_X gained, fps	3176.59	3178.70	149.69
	Postburn	137.22	142.93	1.49				
Right ascension of the ascending node, deg	Preburn	244.94	244.94	.01	Actual ΔV_Y gained, fps	-4023.89	-4026.06	199.88
	Postburn	258.47	258.47	.55				
Inclination, deg	Preburn	33.34	33.34	.00	Actual ΔV_Z gained, fps	1135.42	1136.65	83.84
	Postburn	29.89	29.89	.23				
Inertial flight-path angle, deg	Preburn	-.0097	.-0097	.001	V_{gx} residual, fps	1222.35	1219.31	261.67
	Postburn	2.65	2.65	.09				
Eccentricity	Preburn	--	--	--	V_{gy} residual, fps	.00	-.04	1.26
	Postburn	--	--	--				
Spacecraft weight, lb	Preburn	9 805.00	9 807.23	249.92	V_{gz} residual, fps	.00	-.02	1.21
	Postburn	5 792.86	5 792.92	1.32				
Inertial velocity, fps	Preburn	25 479.03	25 479.03	1.33	Main engine ΔV expended, fps	5246.94	5250.16	260.84
	Postburn	28 994.01	28 996.71	198.99				
True anomaly, deg	Preburn	--	--	--	RCS ΔV expended for trim and ullage, fps	3.93	3.93	.10
	Postburn	--	--	--				

COMMENTS: The APS burn to depletion was not performed in the sequence with the other burns. Navigation, IMU, and performance errors were simulated. It was not retargeted, and it was cut off based on the nominal end-of-burn weight. The ΔV gained deviations are thus larger, and biased ΔV targets result in a mean ΔV_x residual of 1220 fps. The small preburn dispersions are the consequence of state vector uncertainties. No actual state vector dispersions were run for this burn.

TABLE XXI.- SPS-6 MANEUVER SUMMARY

[IMU alinement time 128:58:40 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	134.78	135.35	2.25	Burn initiation g.e.t., hr:min:sec	121:21:40	121:21:40	--
	Postburn	130.29	130.30	2.87				
Perigee altitude, n. mi.	Preburn	129.54	128.77	6.26	Burn duration (not including ullage), sec	2.61	2.60	.21
	Postburn	97.49	97.45	2.72				
Semimajor axis, n. mi.	Preburn	3 572.76	3 572.70	2.30	Actual total ΔV gained, fps	65.47	65.17	5.19
	Postburn	3 554.55	3 554.58	1.93				
Altitude, n. mi.	Preburn	130.22	130.07	3.52	Actual ΔV_X gained, fps	-65.47	-65.17	4.88
	Postburn	130.22	130.07	3.50				
Right ascension of the ascending node, deg	Preburn	238.43	238.42	.14	Actual ΔV_Y gained, fps	.00	-.002	.609
	Postburn	238.55	238.38	.14				
Inclination, deg	Preburn	33.47	33.50	1.12	Actual ΔV_Z gained, fps	-.02	.344	8.671
	Postburn	33.47	33.57	1.10				
Inertial flight-path angle, deg	Preburn	.0314	.0277	.1095	V_{gx} residual, fps	-2.66	-2.69	3.456
	Postburn	.0255	.0243	.1126				
Eccentricity	Preburn	.0007	.0009	.0011	V_{gy} residual, fps	.00	.010	.719
	Postburn	.0046	.0046	.0005				
Spacecraft weight, lb	Preburn	28 059.75	28 070.88	231.89	V_{gz} residual, fps	.00	.004	.734
	Postburn	27 876.30	27 888.02	230.66				
Inertial velocity, fps	Preburn	25 475.92	25 478.91	17.60	Main engine ΔV expended, fps	60.97	60.67	5.15
	Postburn	25 410.16	25 413.51	18.25				
True anomaly, deg	Preburn	N/A	N/A	N/A	RCS ΔV expended for trim and ullage, fps	4.50	4.50	.04
	Postburn	174.48	174.77	25.07				

COMMENTS: The SPS-6 maneuver reshapes the orbit to 131- by 97 n. mi. It is a short 2.6-second burn which exercises the short burn logic. It is retargeted based on the nominal apogee altitude, on the perigee altitude, and on the right ascension of the ascending node. The ΔV_Z deviation is the combined result of retargeting and thrust mistrim.

TABLE XXII.- SPS-7 MANEUVER SUMMARY

[IMU alinement time 169:01:40 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	128.49	128.51	3.51	Burn initiation g.e.t., hr:min:sec	169:46:40	169:46:40	--
	Postburn	214.70	214.82	2.93				
Perigee altitude, n. mi.	Preburn	93.19	93.11	2.69	Burn duration (not including ullage), sec	6.24	6.25	.24
	Postburn	95.53	95.47	3.93				
Semimajor axis, n. mi.	Preburn	3 551.25	3 551.29	2.52	Actual total ΔV gained, fps	156.13	156.37	5.46
	Postburn	3 595.53	3 595.63	2.21				
Altitude, n. mi.	Preburn	96.71	96.65	4.52	Actual ΔV_X gained, fps	156.13	156.35	5.44
	Postburn	96.34	96.29	4.42				
Right ascension of the ascending node, deg	Preburn	223.57	223.57	.23	Actual ΔV_Y gained, fps	.00	-.14	6.66
	Postburn	223.57	223.56	.22				
Inclination, deg	Preburn	33.47	33.49	1.12	Actual ΔV_Z gained, fps	.88	.89	1.56
	Postburn	33.47	33.49	1.12				
Inertial flight-path angle, deg	Preburn	-.1705	-.1681	.0873	V_{gx} residual, fps	-.02	-.15	3.10
	Postburn	-.1563	-.1540	.0885				
Eccentricity	Preburn	.0050	.0050	.0007	V_{gy} residual, fps	.00	-.023	1.42
	Postburn	.0166	.0166	.0007				
Spacecraft weight, lb	Preburn	27 876.30	27 888.02	230.66	V_{gz} residual, fps	.00	.048	1.48
	Postburn	27 445.94	27 456.84	228.59				
Inertial velocity, fps	Preburn	25 640.67	25 643.32	28.01	Main engine ΔV expended, fps	151.60	151.84	5.42
	Postburn	25 799.55	25 802.29	25.41				
True anomaly, deg	Preburn	321.00	321.63	23.74	RCS ΔV expended for trim and ullage, fps	4.53	4.53	.04
	Postburn	350.37	350.47	21.67				

COMMENTS: The SPS-7 maneuver also reshapes the orbit in preparation for the deorbit burn. This burn was retargeted based on the nominal apogee altitude, on the perigee altitude, and on the right ascension of the ascending node. Tailoff accounts for the V_{gx} residual deviation of 3.10 fps (3σ).

TABLE XXIII.- SPS-8 MANEUVER SUMMARY

[IMU alinement time 236:36:40 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	205.76	205.87	4.39	Burn initiation g.e.t., hr:min:sec	238:09:40	238:09:40	--
	Postburn	213.01	212.55	3.76				
Perigee altitude, n. mi.	Preburn	99.81	99.76	3.98	Burn duration (not including ullage), sec	12.48	12.42	.44
	Postburn	-17.79	-19.15	15.57				
Semimajor axis, n. mi.	Preburn	3 595.12	3 595.17	1.29	Actual total ΔV gained, fps	314.23	313.31	10.06
	Postburn	3 540.14	3 539.23	8.22				
Altitude, n. mi.	Preburn	205.35	205.10	7.23	Actual ΔV_X gained, fps	-204.77	-208.19	27.72
	Postburn	203.72	203.51	8.06				
Right ascension of the ascending node, deg	Preburn	203.10	203.10	.47	Actual ΔV_Y gained, fps	.27	.32	1.19
	Postburn	203.09	203.10	.46				
Inclination, deg	Preburn	33.49	33.52	1.12	Actual ΔV_Z gained, fps	238.36	233.77	29.83
	Postburn	33.49	33.5	1.1				
Inertial flight-path angle, deg	Preburn	-.1044	-.1031	.2978	V_{gx} residual, fps	-.10	-.058	2.851
	Postburn	-.7346	-.7231	.2439				
Eccentricity	Preburn	.0147	.0148	.0007	V_{gy} residual, fps	.00	.008	.535
	Postburn	.0326	.0327	.0024				
Spacecraft weight, lb	Preburn	27 445.94	27 456.84	228.59	V_{gz} residual, fps	.00	.006	.572
	Postburn	26 601.42	26 614.56	221.74				
Inertial velocity, fps	Preburn	25 013.24	25 018.49	35.56	Main engine ΔV expended, fps	309.62	308.71	10.02
	Postburn	24 823.14	24 824.01	21.02				
True anomaly, deg	Preburn	187.00	186.99	20.38	RCS ΔV expended for trim and ullage, fps	4.61	4.60	.04
	Postburn	202.43	201.93	6.47				

COMMENTS: The SPS-8 maneuver is the deorbit burn. It was retargeted to the desired velocity magnitude and flight-path angle at the end of the burn. Because the burn is performed near apogee altitude and because perigee altitude is not controlled during the retargeting, the 3σ perigee altitude deviation increases significantly.

TABLE XXIV.- REENTRY SUMMARY[a]

Parameter	Nominal	Mean	3σ
Time from deorbit to entry interface, sec	1 207.94	1 210.17	151.27
Altitude, ft	400 000	400 000	b
Apogee altitude, n. mi.	217.38	216.85	3.45
Perigee altitude, n. mi.	-22.02	-23.12	15.97
Semimajor axis, n. mi.	3 540.08	3 539.27	10.20
Right ascension of the ascending node, deg	203.06	203.07	.45
Inclination, deg	33.49	33.52	1.10
Inertial flight-path angle, deg	-1.87	-1.88	.15
True anomaly, deg	283.55	283.14	5.13
Eccentricity	.0338	.0339	.0021
Inertial velocity, fps	25 814.52	25 809.96	28.58
Spacecraft weight, lb	26 601.42	26 615.30	222.42

[a]After transformations into uncertainties at the landing site point (ref. 12), the deviations represent 4.2-n. mi. down range error (3σ) and 6.8-n. mi. cross range error (3σ).

[b]The statistics were formed at 400 000-ft altitude, and any altitude deviation would be within the noise of the calculations.

TABLE XXV.- MANEUVER PROPELLANT SUMMARY

Burn	System	Weight of propellant used, lb		
		Nominal	Mean	3σ
SPS-1	SPS	332.10	330.43	62.90
	SM RCS	0	0	0
SPS-2	SPS	7 348.50	7 350.22	50.42
	SM RCS	0	0	0
SPS-3	SPS	18 656.20	18 658.11	105.42
	SM RCS	0	0	0
SPS-4	SPS	1 888.65	1 888.50	14.98
	SM RCS	14.3	14.3	0
DPS	DPS	10 066.82	10 066.16	143.45
	LM RCS	7.33	7.33	0
SPS-5	SPS	2 798.53	2 794.20	49.67
	SM RCS	14.3	14.3	0
Separation	SM RCS	15.0	15.0	0.6
Phasing	DPS	196.95	197.08	9.93
	LM RCS	5.13	13.01	1.32
Insertion	DPS	90.26	90.17	4.86
	LM RCS	5.13	8.73	5.67
CSI	APS	[a]43.82	43.82	2.28
CDH	APS	34.35	34.36	2.40
	LM RCS	5.71	7.56	3.12
TPI	LM RCS	25.26	25.52	2.10
MCC-1	LM RCS	1.60	2.00	4.68
MCC-2	LM RCS	.01	2.91	12.03
APS BTD	APS	4 007.70	4 005.52	249.9
	LM RCS	4.40	4.40	0
SPS-6	SPS	169.20	168.56	14.55
	SM RCS	14.3	14.3	0
SPS-7	SPS	416.11	416.88	15.20
	SM RCS	14.3	14.3	0
SPS-8	SPS	830.27	827.98	27.96
	SM RCS	14.3	14.3	0
Total	SPS	32 439.55	32 434.88	146.72
	SM RCS	86.5	86.5	0.6
	APS	4 085.87	4 083.70	219.92
	DPS	10 354.18	10 353.41	143.88
	LM RCS	54.57	71.46	14.65

[a]APS propellant through the RCS interconnect was used for CSI.

APPENDIX A

COORDINATE SYSTEMS

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COORDINATE SYSTEMS

The actual velocity gained and the ΔV residuals for the burns are presented in tables I through XXIII. The values are given by components in coordinate systems defined as follows:

The actual velocity gained components, ΔV_x, ΔV_y, and ΔV_z, are in the local vertical/local horizontal coordinate system.

$$\bar{x} = (\bar{r} \times \bar{v}) \times \bar{r}$$

$$\bar{y} = \bar{z} \times \bar{x}$$

$$\bar{z} = -\bar{r}$$

where $\bar{r}$ = position vector in inertial coordinates at time of ignition

$\bar{v}$ = velocity vector in inertial coordinates at time of ignition

The ΔV residuals, V_{gx}, V_{gy}, and V_{gz}, are in the spacecraft control axis coordinates. The x, y, and z refer to the spacecraft axes rotated 7°15' to the RCS thrust axes in the spacecraft y-z plane.

APPENDIX B

ERROR SOURCE MAGNITUDES

APPENDIX B

ERROR SOURCE MAGNITUDES

TABLE B-I.- ERROR SOURCE MAGNITUDES USED IN SIMULATION[a]

[3σ deviations]

Source	CSM	LM
Platform misalinement angle, deg	0.033	0.057
Static gyro drift rates, deg/sec	.251E-6	.251E-6
Input axis g-sensitive gyro drift, deg/sec/ft/sec^2	.312E-5	.312E-5
Spin reference axis g-sensitive gyro drift, deg/sec/ft/sec^2	.195E-7	.195E-7
Accelerometer misalinement angles, deg	.018	.018
Accelerometer biases, ft/sec^2	.021	.021
Accelerometer scale factors, ppm	348.	300.
Accelerometer nonlinearity coefficient, sec^2/ft	.939E-6	.939E-6
Attitude misalinement angles, deg	2.	2.
Thrust cutoff uncertainty impulse, lb-sec	2499.	207.
Weight uncertainty, lb	258.	258.
Error in RTCC estimate of weight, lb	642.	642.
Thrust uncertainty, lb	SPS[b] 195. 198.6	10% DPS [c]33.0 APS 87.6 RCS 3.39
I_{sp} uncertainty, sec	SPS 1.587	10% DPS [c]7.23 APS 2.514 RCS 8.79
Coefficient of drag uncertainty	.6	.6

[a]For the rendezvous, a thrust mistrim error of 6 percent of the total ΔV was used as the 3σ value. For the SPS burns, thrust mistrim data was obtained from reference 2. MSFN update matrices for the rendezvous and PGNCS rendezvous radar covariance matrices came from references 4 and 5; references 6 and 7 supplied the navigation covariance matrices for the other maneuvers.

[b]SPS thrust uncertainty before crossover from the storage tank to the sump tank is 195 lb. After crossover, it is 198.6 lb. Crossover occurs 75 seconds into the third SPS burn.

[c]The 3σ thrust error randomly applied at each thrust level of the docked DPS burn was 2.1 percent of the nominal thrust at that level. For I_{sp}, 1.5 percent of the nominal I_{sp} was used as the 3σ value.

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