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PROJECT APOLLO

APOLLO 10 SPACECRAFT DISPERSION ANALYSIS VOLUME IV RENDEZVOUS DISPERSION ANALYSIS

MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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VOLUME IV
RENDEZVOUS DISPERSION ANALYSIS

By D. M. Detchmendy
Mission Analysis Section
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NOMENCLATURE

AEG	analytic ephemeris generator
APS	ascent propulsion system
CDH	constant delta height
CMC	command module computer
CSI	coelliptic sequence initiation
CSM	command and service module
DCA	distance of closest approach
DOI	descent orbit initiation
DPS	descent propulsion system
g. e. t.	ground elapsed time
GMT	Greenwich mean time
IMU	inertial measurement unit
LM	lunar module
MCC	midcourse correction
MSFN	Manned Space Flight Network
PC	plane change
PGNCS	primary guidance navigation and control system
RCS	reaction control system
SXT	sextant
TPF	terminal phase final
TPI	terminal phase initiation
VHF	range device
X	horizontal component in Apollo local vertical system (positive downrange)

NOMENCLATURE (Continued)

Y	out-of-plane component in Apollo local vertical system (positive to right)
Z	radially-down component in Apollo local vertical system (positive down)
ΔH	difference in height of CSM and LM
$\Delta(\Delta H)$	difference in maximum and minimum ΔH

APOLLO 10 SPACECRAFT DISPERSION ANALYSIS

VOLUME IV

RENDEZVOUS DISPERSION ANALYSIS

By D. M. Detchmendy
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1. SUMMARY

This document presents the results of the Apollo 10 mission rendezvous dispersion analysis. The analysis was conducted on the data from 100 cycles of a Monte Carlo simulation. The effects included are rendezvous radar navigation uncertainties, sextant and VHF navigation uncertainties, MSFN navigation uncertainties, maneuver execution errors, and effects of onboard targeting procedures. A discussion of MSFN navigation uncertainties and lunar potential uncertainties is contained in Volume I.

This analysis has shown that the coelliptic altitude (delta h) achieved at CDH will have a three sigma variation of approximately two nautical miles about the nominal value of 15 nautical miles. The three sigma variation in the change in delta h (delta delta h) following CDH is approximately 0.5 nautical mile. The mean in delta-delta h following CDH is approximately 0.5 nautical mile. The three sigma variation in the TPI time is approximately 9 minutes.

Based upon the models used in this report, it is concluded that no unreasonable dispersions are associated with the Apollo 10 mission rendezvous sequence and that the mission objectives and ground rules can be satisfied using the present rendezvous techniques.

2. INTRODUCTION

This document represents one of six volumes of the Apollo 10 mission dispersions analyses and is concerned with dispersions during the LM-active rendezvous sequence. The purpose of the analysis is to assist in establishing and validating mission rules, ground procedures, crew procedures, propellant budgets, and to provide a general awareness of the expected dispersions throughout the rendezvous sequence.

The results of the Apollo 10 mission rendezvous dispersion analyses presented in this document have been generated using a Monte Carlo simulation of the rendezvous sequence. This simulation has been developed such that it models the onboard guidance and navigation functions and, furthermore, estimates real-world errors to gain statistical data on state uncertainties. Sextant plus VHF and MSFN navigation are simulated using estimated real-world covariance matrices. A discussion of MSFN navigation uncertainties and lunar potential uncertainties is contained in Volume I. Rendezvous radar navigation is simulated using tracking, normal matrices. The PGNCS and CMC targeting techniques have been reproduced to render the simulation as realistic as possible. The major maneuvers are simulated using an analytic, finite-burn model which is able to account for all the pertinent real-world errors. The actual and estimated states of both the CSM and the LM are carried throughout where the estimate contains both the CMC and rendezvous radar (PGNCS) states.

This dispersion analysis is based on certain critical assumptions which are outlined in the text. It includes latest inputs concerning navigation schedules and mission rules.

3. INPUT DATA

Below are outlined the input quantities necessary to this analysis. Following a cursory outline of the rendezvous mission profile, a discussion of the pertinent error sources is presented.

3.1 Rendezvous Mission Profile

The Operational Trajectory which was employed for this analysis is described in Reference 1. This trajectory has the phasing maneuver 8 minutes earlier than the current Operational Trajectory.* However, this does not affect the rendezvous dispersion analysis.

This section presents a brief discussion of the nominal rendezvous profile and may be supplemented by referring to Figure 1, a CSM-centered relative motion plot which depicts the nominal rendezvous sequence.

Though the launch date will be 18 May 1969, this analyses assumed launch to occur at 16^h:33^m:49.3^s Greenwich mean time (GMT) on 17 May 1969.* The remainder of the mission is referenced to launch time and the time of each event will be measured in ground elapsed time (g.e.t.).

The simulation begins at the separation maneuver taken to be at $98^h 55^m 43.9^s$ g.e.t. (ignition time). The separation maneuver is a radially-down maneuver of 2.5 fps performed by the SM/RCS which results in the CSM leading the LM by 11,400 feet at descent orbit insertion (DOI) one-half revolution later. Also, if DOI is not performed, this maneuver places the CSM in a position for redocking one revolution later.

The DOI maneuver is performed 195° prior to the landing site and is a PGNCS controlled retrograde burn of about 71.6 fps using the descent propulsion system (DPS). This Hohmann descent transfer maneuver serves to reduce perilune to 50,000 feet at 15° prior to the landing site, the position at which powered descent will be initiated for the lunar landing mission. Following DOI, approximately 64.5 minutes of coasting flight will allow close observation of the planned landing site(s). Figure 1 shows the relative position of the LM with respect to the CSM from separation thru the terminal phase of the LM active rendezvous.

Approximately 7.5 minutes (23°) past perigee or approximately 2.5 minutes (8°) past the landing site, a LM phasing maneuver of 174.5 fps is performed using the DPS. This posigrade maneuver is designed to establish the same CSM-LM relative conditions which occur at nominal powered ascent cutoff in the lunar landing mission. The LM apolune altitude resulting from the phasing maneuver is 195 nautical miles which affords the required CSM catch-up time between phasing and the next maneuver (insertion). The CSM lead angle is approximately -9° at phasing

*The relative geometry after insertion is not affected by this change.

and +15.5° at the insertion maneuver time. The resulting altitude at the insertion maneuver point is approximately 60,000 feet which is the nominal altitude at powered ascent cutoff for the lunar landing mission.

Immediately prior to insertion, the LM descent stage is jettisoned and the LM Insertion Maneuver of 195.9 fps is performed. This retrograde maneuver using the Ascent Propulsion System (APS) is designed to establish the equivalent of the LM insertion orbit (43 by 8.9 nautical miles) of the lunar landing mission. At the completion of the Insertion Maneuver, the conditions are equivalent to those at powered ascent cutoff for the lunar landing mission, and the LM active rendezvous is initiated.

Approximately 50 minutes after LM insertion, the CSI maneuver is performed using the LM RCS. This 50.4 fps maneuver results in a LM orbit of approximately 45 by 42.4 nautical miles. The CDH maneuver is executed one-half of the LM orbital period (approximately 58 minutes) after CSI and is designed to circularize the LM orbit at a constant delta height of 15 nautical miles below the CSM orbit. When the elevation angle from the LM to the CSM reaches 26.6 degrees (approximately 37 minutes after CDH), the LM terminal phase initiation (TPI) maneuver is executed. This 24.6 fps maneuver is designed to place the LM on a trajectory that will intercept the CSM orbit after 130° of CSM travel. Terminal phase final (TPF) braking is initiated 42.6 minutes after TPI.

Two, nominally zero, midcourse corrections at 15 and 30 minutes after TPI initiation are considered after which braking is initiated by controlling line-of-sight rate and range rate.

3.2 Error Sources

The error sources being considered in this analysis are of three categories:

- IMU guidance errors and gravitational errors
- Dynamic performance errors
- Navigation errors

Table I summarizes the guidance errors considered in the investigation. All of the error source values are one-sigma and have been taken from Reference 2.

Navigation errors for the rendezvous radar tracking are provided by input tracking normal matrices as described in References 3 and 4. These matrices account for the errors associated with measurement noise and biases, platform misalignments and drifts, uncertainties in the location of the CSM, and uncertainties in the moon's gravitational constant. Other lunar potential uncertainties are included in the MSFN covariance matrix.

Navigation errors for the MSFN updates and the sextant and VHF tracking are provided by input covariance matrices. The SXT + VHF and MSFN covariance matrices, contained in References 5 and 6, are combined with the real-world model errors presented in Table I. Figure 2 presents the rendezvous radar and sextant plus VHF tracking schedule as published in Reference 7.

4. GROUND RULES AND ASSUMPTIONS

The ground rules under which the rendezvous sequence is to be executed are outlined in Reference 8. The intent of this section is to enumerate the assumptions used in the rendezvous dispersion analysis.

General

- The targeting logic for LM/PGNCS and CSM/CMC computations are very close approximations to the true logic.

- Estimated states for the CSM/CMC and MSFN updates of the CSM estimated state for the CMC and PGNCS are generated using precomputed covariance matrices of the navigation uncertainty.

- Estimated states for the LM in the LM/PGNCS are computed using tracking normal matrices as outlined in Reference 9. Real-world effects included in these matrices are measurement noise and biases, platform misalignments and drifts, uncertainties in the moon's gravitational constant, and uncertainties in the location of the CSM.

- Actual and estimated state vectors are propagated using an AEG with two harmonic terms (J_2, J_{22}).

- The CSM actual state prior to separation is assumed to be the reference state.

CSM

- The CSM estimated state is updated in the PGNCS (for the separation burn) by assuming a perfectly executed, impulsive maneuver.

- The CSM/CMC calculation of CSI and CDH is done at the PGNCS times.

- The CSM/CMC calculation of TPI is based upon its own elevation angle.

LM

- A station-keeping uncertainty of 0.2 fps standard deviation is imparted to each component of the LM actual velocity vector prior to the separation maneuver.

- The DOI, phasing, and insertion maneuvers are executed using prespecified or "canned" ΔV's.

- An analytic, variable-thrust DPS model is employed for the DOI and phasing burn.

- An analytic burn model is employed for the insertion, CSI, and TPI maneuvers. The PC, CDH, MCC-1, and MCC-2 maneuvers are performed impulsively.

- Platform realignments are simulated at DOI - 10 minutes and Insertion + 10 minutes by reselecting platform misalignments from the input sigmas. The drift rates will remain constant throughout each Monte Carlo cycle.

- Plane changes less than 2 fps are not applied.

- Midcourse corrections less than 1 fps are not applied.

- The CSM state vector is updated in the PGNCS in the simulation at separation and at insertion.

- The three sigma cross-axis velocities errors were assumed to be 1/2 percent of the magnitude of the maneuver.

- All LM maneuvers are trimmed back to zero.

5. ANALYSIS AND RESULTS

As previously discussed, the rendezvous dispersion analysis data presented herein were generated with a high-speed, Monte Carlo simulation. As many error sources as considered pertinent are included and their values presented in Table I. A step-by-step discussion of the simulation is presented in Appendix A. As a means of verifying that the simulation would provide valid results, a no-error case was executed in an attempt to match the Operational Trajectory. The results of this comparison is presented in Appendix B. Investigation of this comparison reveals that the simulation is adequate.

The remainder of this section will be devoted to a discussion of the results at each major event of the rendezvous sequence. For each event, two sets of data are presented. One table presents the individual solutions (PGNCS, CMC, actual) and their errors and expected deviations, while the other contains certain orbital quantities before and after the burns. For the CDH maneuver differential height information is presented in Table II.

Reference 10 contains a precise definition and discussion of the quantities "error in a solution" and "expected differences" in solutions. For this analysis the error in a solution is taken to be the difference in that solution and the actual solution.* The comparison is usually made using the same targeting program where one calculation uses the estimated state and the other uses the actual state. The expected difference (as noted on the charts) is the difference between the PGNCS solution and the CMC solution. This is the comparison to be made in real time in order to evaluate the onboard solution.

5.1 Separation

No solution statistics are presented for the 2.5 fps, radially-down CSM maneuver, since the maneuver is predesignated. The preburn and postburn characteristics are presented in Table III.

5.2 DOI, Phasing, Insertion

No solution statistics are presented for the LM DOI, phasing, or insertion maneuvers since for the simulation the ΔV's are predesignated. The preburn and postburn characteristics are presented in Tables IV, V, and VI respectively.

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*The actual solution is defined to be the solution generated on the actual state vectors.

5.3 CSI

The CSI maneuver is computed by the PGNCS and performed at a fixed time. It is nominally 50.4 fps posigrade and is a four-jet RCS-interconnect burn. The purpose of this burn is to establish the proper phasing conditions at CDH (next maneuver) so that, after the CDH maneuver is performed, TPI will occur at the desired time and elevation angle. Since CSI is performed at a prespecified time, only the PGNCS, CMC, and actual solutions (at this given time) need be computed. The error in the solutions and the expected differences are also calculated and summarized in Table VII. Table VIII presents the preburn and postburn orbital characteristics.

The three sigma errors in the PGNCS and CMC solutions are 1.62 fps and 2.52 fps respectively. The expected difference between the PGNCS and the CMC shows a mean or bias of -.85 fps (magnitude of CMC solution is greater than the magnitude of the PGNCS solution) and a three sigma value* of 3.09 fps. This suggests an $\dot{X}$ comparison limit of 4 fps. Since TPI time is highly sensitive to errors in the CSI ΔV this analysis suggests that additional sources of comparison for the CSI validation be used.

A PC maneuver is computed by the CMC and is performed by the LM in conjunction with the CSI maneuver. The purpose of this maneuver is to zero the relative out-of-plane velocity. It is nominally a zero maneuver. Table VIII presents the CMC solution, the actual solution, and the error in the solution.

The threshold value of ±2 fps is sound in light of a three-sigma error of 1.62.

5.4 PC

The second PC maneuver is computed by the CMC and is performed by the LM at the PGNCS CDH time minus 30 minutes. The purpose of this maneuver is to zero the relative out-of-plane velocity. It is nominally a zero maneuver. Table IX presents the CMC solution, the actual solution and the error in the solution.

The threshold value of ±2 fps is sound in light of a three-sigma error of 1.62 fps.

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*Throughout this analysis, the phrase "three-sigma" will be taken to mean three times the standard deviation of a particular quantity. A probability of occurrence should not be implied from this number, since knowledge of the distribution function is first required for such interpretation.

5.5 CDH

This is a PGNCS-computed maneuver and is executed using the LM/RCS. The LM is injected into a near-circular orbit which is nominally 15 nautical miles below and coelliptic to the CSM orbit. All the solutions for the CDH maneuver are calculated at the PGNCS time. Table X presents these quantities as well as the expected difference in the PGNCS and CMC solutions. Table XI presents the preburn LM and postburn orbital characteristics.

The three-sigma variation in the PGNCS CDH time is less than 5 seconds. The three-sigma errors in the PGNCS solution are 1.23 fps and 4.20 fps for the $\dot{X}$ and $\dot{Z}$ components respectively. The three-sigma errors in the CMC solution are 1.17 fps and 4.29 fps for the $\dot{X}$ and $\dot{Z}$ components respectively. The three sigma expected deviations between the PGNCS and CMC solutions are 1.56 fps and 5.43 fps for the $\dot{X}$ and $\dot{Z}$ components respectively.

The actual coelliptic altitude (delta h) achieved at CDH has a three-sigma variation of 1.95 nautical miles. The three sigma variation in delta-delta h following CDH is .54 nautical miles. This data is presented in Table II.

The third PC maneuver is computed by the CMC and is performed by the LM in conjunction with the CDH maneuver. The purpose of this maneuver is to zero the relative out-of-plane velocity. It is nominally a zero maneuver. Table X presents the CMC solution, the actual solution, and the error in the solution.

The threshold value of ±2 fps is sound in light of a three-sigma error of 1.80.

5.6 TPI

The TPI maneuver is a PGNCS controlled, two-jet RCS maneuver initiated on a 26.6-degree line-of-sight elevation angle and nominally burned along that line-of-sight. The targeting is based on a 130-degree CSM central travel angle between TPI and TPF. Since this is variable-time maneuver, the actual solution is calculated at both the CMC and PGNCS estimated times and is used in calculating the error in the PGNCS solution and the error in the CMC solution. Table XII presents the individual PGNCS, actual and CMC solutions as well as the error in PGNCS, the error in the CMC and the expected difference. Table XIII presents the preburn and postburn orbital characteristics.

The three-sigma values for the actual, the PGNCS, and the CMC TPI time variations are 8^m18^s, 8^m30^s and 8^m36^s respectively. The three-sigma errors in the PGNCS and CMC are 1^m15^s and 1^m30^s respectively. The three-sigma value for the expected difference between the PGNCS and CMC TPI time is 2^m5^s.

The three-sigma errors in the PGNCS ΔV solution are 1.14 fps, 3.48 fps, and 6.87 fps in the $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ components respectively. The three-sigma errors in the CMC ΔV solution are .66 fps, 2.17 fps, and 7.26 fps in the $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ components respectively. The three-sigma expected difference between the PGNCS and the CMC ΔV solutions are 4.05 fps, 4.08 fps, and 6.06 fps in the $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ components respectively.

5.7 MCC-1

The first midcourse correction is placed at 15 minutes after TPI initiation and is nominally zero. The TPI dispersion and the limited tracking, however, cause this value to increase to a mean of 4.50 fps and three-sigma deviation of 9.15 fps. These data are presented in Table XIV.

5.8 MCC-2

The nominally-zero, second midcourse correction is smaller (2.17 fps mean and a three-sigma deviation of 5.46 fps). The data for MCC-2 are also presented in Table XIV.

5.9 TPF

The mean time of arrival at impulsive braking is calculated to be 106^h:13^m:48.6^s g.e.t. with a one-sigma deviation of 50 seconds. The mean distance of closest approach is 1491 feet and has a standard deviation of 1126 feet.

6. CONCLUSIONS

This document has presented rendezvous dispersion analysis data to support the Apollo 10 mission rendezvous sequence. The data have been generated from 100 samples using a Monte Carlo simulation designed to simulate both the fit-world errors* and the real-world errors. Detailed analysis of the results has been presented and the following significant conclusions can be drawn.

1. The expected difference between the LM PGNCS and the CMC solutions at CSI (4 fps) is too large to determine which solution should be executed at CSI. Therefore other solutions must be considered in the comparison.

2. The largest three-sigma error in the plane change ΔV solutions is 1.80 fps. Thus the ± 2 fps threshold on the PC maneuver is realistic.

3. The three-sigma expected differences between the PGNCS and CMC CDH solutions are 1.56 fps and 5.43 fps in the $\dot{X}$ and $\dot{Z}$ components respectively. This analysis shows that it is feasible to set up comparison limits to determine which solution to execute at CDH.

4. The actual coelliptic altitude (delta h) achieved at CDH has a three sigma variation of 1.95 nautical miles. The three sigma variation in delta-delta h following CDH is .54 nautical miles. Thus a high degree of coellipticity has been achieved.

5. The three-sigma variation in the actual TPI time is $8^m 18^s$. This variation is within the limits specified by the ground rules and handled by the mission techniques.

6. The three-sigma value for the expected difference between the PGNCS and the CMC TPI time is 2^m05^s. This is acceptable.

7. The three-sigma expected differences between the PGNCS and CMC TPI solutions are 4.05 fps, 4.08 fps, and 6.06 fps in the $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ components respectively. This analysis shows that it is feasible to set up comparison limits to determine which solution to execute at TPI.

It is concluded, based upon the models used, that no unreasonable dispersions are associated with the Apollo 10 mission rendezvous sequence provided the navigation schedules outlined in this document are followed. The mission objectives and ground rules can be satisfied using the present rendezvous techniques.

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*The distinction here is that "fit-world" implies an error which is known, such as a modeling error; whereas, "real-world" denotes unknown errors such as noise, biases, etc.

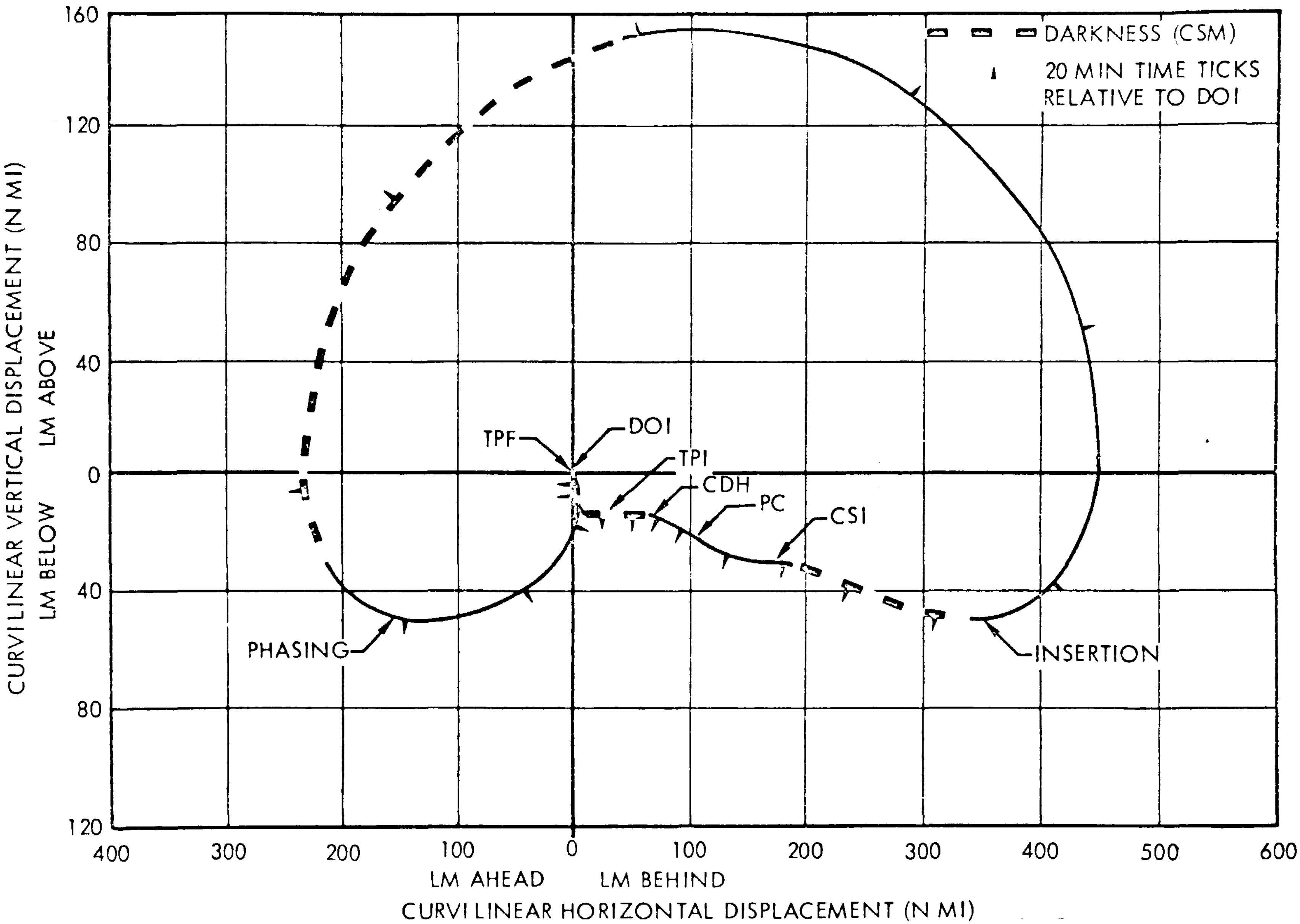

Figure 1. CSM Centered Relative Motion Diagram

Figure 2. Onboard Tracking Schedule for Mission F

LM Events	Time From Insertion	CSM Events	Time From Insertion
Insertion	0	Insertion**	0
V93 before first mark, W = 10000 ft. - 10 fps- 15 MRAD Initiate tracking	 18	V93 before first mark, W = 10000 ft., 10 fps Initiate tracking	 19
Cease tracking	39	Cease tracking	24
CSI	51	V93 before first mark W = 10000 ft, 10 fps,	
Initiate tracking V93 after fourth mark, W = 2000 ft. -2 fps- 5 MRAD	56	Initiate tracking VHF only	26
Cease tracking	74	Cease Tracking	39
Plane change	80	CSI	51
Initiate tracking V93 after fourth mark, W = 2000 ft. -2 fps- 5 MRAD	82	Initiate tracking	58
Cease tracking	97	V93 after third mark, W = 2000 ft., 2 fps	
CDH	109	Cease tracking	79
Initiate tracking V93 after fourth mark, W = 2000 ft. -2 fps- 5 MRAD	111		
Cease tracking	134	Plane change	80
TPI	146	Initiate tracking	85
Initiate tracking V93 before first mark, W = 2000 ft. -2 fps- 5 MRAD	149	V93 after third mark, W = 2000 ft., 2 fps Cease tracking	 97

**Before insertion there is a P27 update of the MSFN CSM state to the CSM and following Insertion there is a P27 update of the LGC LM state to the CMC.

Figure 2. Onboard Tracking Schedule for Mission F (Continued)

LM Events	Time From Insertion	CSM Events	Time From Insertion
Cease tracking	158	CDH	109
MC1	161	Initiate tracking	115
Initiate tracking V93 before first mark, W = 2000 ft. -2 fps- 5 MRAD	163	V93 after third mark, W = 2000 ft., 2 fps Cease tracking	133
Cease tracking	173	TPI	146
MC2	176	V93 before first mark, W = 2000 ft., 2 fps Initiate tracking	151
		Cease tracking	158
		MC1	161
		V93 before first mark, W = 2000 ft., 2 fps Initiate tracking	164
		Cease tracking	173
		MC2	176

Table I. Simulation Model Errors

	Performance Errors		
	DPS	APS	RCS
Thrust uncertainty (lb)	11.0 @ 10% 44.0 @ 40%	40.4	1.13
ISP uncertainty (sec)	2.41 @ 10% 2.50 @ 40%	1.51	2.93

	IMU Errors	
	LM	CSM
Platform misalignment (deg)	.018	.011
Platform drift rate (deg/sec)	8.33×10^{-6}	8.33×10^{-6}
Accelerometer bias (fps^2)	6.56×10^{-3}	6.56×10^{-3}
Accelerometer scale factor error (nd)	1×10^{-4}	1.16×10^{-4}

	Free-flight Model Errors
Gravitational constant (ft^3/sec^2)	$.71 \times 10^{10}$

Table II. Actual Variation in ΔH, TPI Time, and Closest-Point-of-Approach

Parameter	Nominal	Mean	Sigma	Maximum	Minimum
Maximum ΔH following CDH, n mi	14.93	15.02	0.65	16.63	13.34
Minimum ΔH following CDH, n mi	14.84	14.70	0.63	15.94	13.20
Variation in ΔH ($\Delta\Delta H$) following CDH, n mi	0.09	0.32	0.18	0.9	0.02
TPI time, hr:min:sec (g. e. t.)	105:29:15.6	105:28:37	2.50	105:36:15	105:22:07
Closest-point-of-approach following second midcourse correction (MCC2), ft	50.0	1491.0	1126.0	8476.0	97.0
Time of closest-point-of-approach following MCC2, hr:min:sec (g. e. t.)	106:12:24	106:13:48	50.0	106:16:58	106:10:43

Table III. CSM Separation Maneuver Evaluation

IMU Alignment Time 97:59:39 g. e. t.

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	59.91	59.93	0.00
	Postburn	60.35	60.28	0.31
Perilune altitude (h_p), n mi	Preburn	57.58	57.56	0.00
	Postburn	57.15	57.21	0.22
Altitude (R), ft	Preburn	364,418	364,417	0.0
	Postburn	364,418	364,417	0.0
Inertial flight path angle (γ), deg	Preburn	90.03	90.03	0.0
	Postburn	90.05	90.05	1.5×10^{-3}
Semimajor axis (a), ft	Preburn	6,060,048	6,060,462	0.0
	Postburn	6,060,048	6,060,466	702
Longitude ascending node (A), deg	Preburn	170.38	170.38	0.0
	Postburn	170.38	170.38	5.1×10^{-6}
Inclination (i), deg	Preburn	154.05	154.05	0.0
	Postburn	154.05	154.05	4.8×10^{-5}
Eccentricity (e)	Preburn	0.0011	0.0011	0.0
	Postburn	0.0014	0.0014	9.0×10^{-5}
True anomaly (θ) deg	Preburn	-152.21	-152.27	0.0
	Postburn	-135.73	-135.82	3.21
Vehicle weight, lbs	Preburn	37,767	37,767	0.0
	Postburn	37,758	37,758	0.66
Inertial speed (V), fps	Preburn	5,339.38	5,339.38	0.0
	Postburn	5,339.39	5,339.39	4.5×10^{-3}

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g. e. t. (h:m:s)	98:59:39.7	98:55:39.7	-
Burn duration, sec (including ullage)	7.1	7.1	0.0
Actual ΔV total, fps	2.5	2.5	0.19
Actual ΔVX, fps	0.0	0.0	0.0
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	2.5	2.5	0.19
Vgx residual trimmed, fps	0.0	0.0	0.0
Vgy residual trimmed, fps	0.0	0.0	0.0
Vgz residual trimmed, fps	0.0	0.0	0.0
Main engine ΔV extended excluding ullage and trim, fps	-	-	-
RCS ΔV expended, fps (ullage and residual trimmed)	0.0	0.0	0.0

Comments: The SM/RCS engines are used to perform this maneuver which is 2.5 fps radially down. This places the CSM in a small equal period orbit (mini-football) with the LM.

Table IV. LM DOI Maneuver Evaluation

IMU Alignment Time 99:44:12.3 g.e.t.

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	60.27	60.29	0.18
	Postburn	57.35	57.34	0.23
Perilune altitude (h_p), n mi	Preburn	57.21	57.19	0.09
	Postburn	8.37	8.37	0.42
Altitude (R), ft	Preburn	348,473	348,427	1,404
	Postburn	348,535	348,488	1,404
Inertial flight path	Preburn	89.96	89.96	2.7×10^{-4}
	Postburn	90.01	90.01	0.012
Semimajor axis (a), ft	Preburn	6,060,438	6,060,415	702
	Postburn	5,903,199	5,903,167	1,428
Longitude ascending node (A), deg	Preburn	170.39	170.39	3×10^{-6}
	Postburn	170.39	170.39	1.5×10^{-3}
Inclination (i), deg	Preburn	154.05	154.05	4.2×10^{-6}
	Postburn	154.05	154.05	9×10^{-3}
Eccentricity (e)	Preburn	0.0016	0.0016	1.5×10^{-4}
	Postburn	0.025	0.025	2.7×10^{-4}
True anomaly (θ) deg	Preburn	19.48	19.44	1.5
	Postburn	-179.37	-179.36	0.48
Vehicle weight, lbs	Preburn	31,242	31,242	0.0
	Postburn	31,010	31,010	2.01
Inertial speed (V), fps	Preburn	5,353.43	5,353.47	1.23
	Postburn	5,281.86	5,281.86	1.44

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g.e.t. (h:m:s)	99:54:12.3	99:54:12.3	-
Burn duration, sec (including ullage)	34.4	34.4	0.0
Actual ΔV total, fps	71.65	71.65	0.6
Actual ΔVX, fps	71.61	71.61	0.1
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	2.26	2.26	0.0
Vgx residual trimmed, fps	0.0	0.1	0.2
Vgy residual trimmed, fps	0.0	0.2	0.4
Vgz residual trimmed, fps	0.0	0.1	0.4
Main engine ΔV expended excluding ullage and trim, fps	70.00	70.0	0.06
RCS ΔV expended, fps (ullage and residual trimmed)	1.65	1.85	0.6

Comments: This is a varible thrust (10-40 percent) DPS maneuver. After a 5.5 second, 4-jet ullage, the DPS is burned at 10 percent throttle for 15 seconds and followed by a 40 percent setting for the remainder of the maneuver. This Hohmann descent transfer maneuver serves to reduce perilune to 50,000 feet at 15° prior to the landing site (the position at which powered descent will be initiated for the lunar landing mission).

Table V. LM Phasing Maneuver Evaluation

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	57.96	57.95	0.24
	Postburn	195.88	195.86	0.81
Perilune altitude (h_p), n mi	Preburn	7.98	7.98	0.42
	Postburn	9.65	9.65	0.45
Altitude (R), ft	Preburn	61,723	61,731	2,484
	Postburn	64,364	64,374	2,481
Inertial flight path angle (r), deg	Preburn	39.43	89.43	0.014
	Postburn	89.35	89.35	0.036
Semimajor axis (a),	Preburn	5,903,911	5,903,884	1,425
	Postburn	6,327,953	6,327,912	1,320
Longitude ascending node (A), deg	Preburn	170.40	170.40	1.5×10^{-3}
	Postburn	170.40	170.40	1.5×10^{-2}
Inclination (i), deg	Preburn	154.04	154.05	0.009
	Postburn	154.04	154.05	0.026
Eccentricity (e)	Preburn	0.025	0.025	2.7×10^{-4}
	Postburn	0.089	0.089	5.4×10^{-4}
True anomaly (θ) deg	Preburn	23.07	23.09	0.54
	Postburn	7.91	7.92	0.42
Vehicle weight, lbs	Preburn	31,010	31,010	2.01
	Postburn	30,455	30,455	4.74
Inertial speed (V), fps	Preburn	5,545.15	5,545.14	1.74
	Postburn	5,717.20	5,717.19	2.55

IMU Alignment Time 99:44:12.3 g.e.t.

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g.e.t. (h:m:s)	100:58:36.5	100:58:36.5	-
Burn duration, sec (including ullage)	47.2	47.2	0.0
Actual ΔV total, fps	174.90	174.90	1.45
Actual ΔVX, fps	174.46	174.46	0.15
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	3.37	3.37	0.0
Vgx residual trimmed, fps	0.0	0.1	0.4
Vgy residual trimmed, fps	0.0	0.2	0.9
Vgz residual trimmed, fps	0.0	-0.1	0.9
Main engine ΔV expended excluding ullage and trim, fps	172.81	172.81	0.15
RCS ΔV expended, fps (ullage and residual trimmed)	1.65	1.85	1.40

Comments: This is a variable thrust (10-100 percent) DPS maneuver. After a 5.5 second, 4-jet ullage, the DPS is burned at 10 percent throttle for 26 seconds and followed by a 100 percent setting for the remainder of the maneuver. This maneuver affords the required CSM catch-up time between phasing and the next maneuver (insertion).

Table VI. LM Insertion Maneuver Evaluation

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	195.64	195.62	0.78
	Postburn	42.88	43.00	1.08
Perilune altitude (h_p), n mi	Preburn	9.82	9.82	0.42
	Postburn	8.99	8.91	0.63
Altitude (R), ft	Preburn	59,833	59,832	2,589
	Postburn	60,043	60,047	2,577
Inertial flight path angle (γ), deg	Preburn	90.03	90.03	0.03
	Postburn	89.67	89.67	0.03
Semimajor axis (a), ft	Preburn	6,327,783	6,327,737	1,317
	Postburn	5,861,163	5,861,287	2,007
Longitude, ascending node (A), deg	Preburn	170.41	170.41	0.015
	Postburn	170.41	170.41	0.011
Inclination (i), deg	Preburn	154.04	154.04	0.026
	Postburn	154.04	154.04	0.023
Eccentricity (e)	Preburn	0.089	0.089	5.4×10^{-4}
	Postburn	0.017	0.017	7.5×10^{-4}
True anomaly (θ) deg	Preburn	-0.42	-0.41	0.42
	Postburn	18.8	19.03	2.43
Vehicle weight, lbs	Preburn	8,382	8,382	0.0
	Postburn	8,215	8,215	0.27
Inertial speed (V), fps	Preburn	5,721.26	5,721.26	2.67
	Postburn	5,527.42	5,527.48	2.64

IMU Alignment Time 99:44:12.3 g.e.t.

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), (g.e.t. (h:m:s)	103:03:29.9	103:03:29.9	-
Burn duration, sec (including ullage)	16.6	16.6	0.75
Actual ΔV total, fps	195.9	195.9	1.5
Actual ΔVX, fps	193.6	193.6	0.1
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	29.8	29.8	0.0
Vgx residual trimmed, fps	0.0	0.1	0.6
Vgy residual trimmed, fps	0.0	-0.1	1.0
Vgz residual trimmed, fps	0.0	0.2	1.0
Main engine ΔV expended excluding ullage and trim, fps	192.8	192.8	0.1
RCS ΔV expended, fps (ullage and residual trimmed)	3.1	3.6	1.5

Comments: This is a LM APS maneuver. After 3.0 second, 4 jet ullage, the APS is burned for the remainder of the maneuver. This maneuver establishes the equivalent of the LM insertion orbit of the lunar landing mission.

Table VII. Evaluation of Solutions for CSI Maneuver

Parameter		$\dot{X}$, fps	Y,[+] fps	$\dot{Z}$, fps	Total ΔV fps	*Time
Nominal		50.57	0.0	0.0	50.47	103:54:32.6
PGNCS solution (LM active)	Mean	50.59	-	0.0	50.59	103:54:32.6
	Sigma	0.75	-	0.0	50.59	103:54:32.6
	Maximum	52.65	-	0.0	52.65	103:54:32.6
	Minimum	48.93	-	0.0	48.93	103:54:32.6
CMC solution (CSM active)	Mean	-51.40	0.02	0.0	51.40	103:54:32.6
	Sigma	0.94	0.86	0.0	0.94	103:54:32.6
	Maximum	-48.88	2.72	0.0	53.39	103:54:32.6
	Minimum	-53.39	-1.85	0.0	48.88	103:54:32.6
Actual solution	Mean	50.58	0.02	0.0	50.58	103:54:32.6
	Sigma	0.46	0.75	0.0	0.46	103:54:32.6
	Maximum	51.69	2.17	0.0	51.69	103:54:32.6
	Minimum	49.50	-2.12	0.0	49.50	103:54:32.6
Error in PGNCS solution	Mean	0.01	-	0.0	0.01	103:54:32.6
	Sigma	0.54	-	0.0	0.54	103:54:32.6
	Maximum	1.21	-	0.0	1.21	103:54:32.6
	Minimum	-1.24	-	0.0	-1.24	103:54:32.6
Error in CMC solution	Mean	-0.06	0.0	0.0	-0.06	103:54:32.6
	Sigma	0.84	0.54	0.0	0.84	103:54:32.6
	Maximum	2.02	1.37	0.0	2.02	103:54:32.6
	Minimum	-2.10	-1.24	0.0	-2.10	103:54:32.6
Expected difference between PGNCS and CMC solutions	Mean	-0.8	-	0.0	-0.8	103:54:32.6
	Sigma	1.03	-	0.0	1.03	103:54:32.6
	Maximum	2.25	-	0.0	2.25	103:54:32.6
	Minimum	-3.17	-	0.0	-3.17	103:54:32.6

*Time of maneuver is fixed.
+Plane change (LM active)

Table VIII. LM CSI Maneuver Evaluation

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	42.54	42.61	0.96
	Postburn	45.36	45.45	1.08
Perilune altitude (h_p), n mi	Preburn	9.16	9.13	0.51
	Postburn	42.46	42.34	0.93
Altitude (R), ft	Preburn	258,703	259,092	606
	Postburn	258,655	259,031	600
Inertial flight path angle (γ), deg	Preburn	90.00	90.00	0.039
	Postburn	90.01	90.02	0.042
Semimajor axis (a), ft	Preburn	5,860,060	5,860,728	2,001
	Postburn	5,970,328	5,970,255	390
Longitude ascending node (A), deg	Preburn	170.42	170.42	0.011
	Postburn	170.42	170.42	0.012
Inclination (i), deg	Preburn	154.04	154.04	0.023
	Postburn	154.04	154.04	0.016
Eccentricity (e)	Preburn	0.017	0.017	7.5×10^{-4}
	Postburn	0.0015	0.0015	6.6×10^{-4}
True anomaly (θ) deg	Preburn	-179.69	-96.65	353.0
	Postburn	-11.67	-15.83	31.77
Vehicle weight, lbs	Preburn	8,215	8,215	0.27
	Postburn	8,168	8,168	1.65
Inertial speed (V), fps	Preburn	5,342.93	5,342.64	4.80
	Postburn	5,393.54	5,393.18	4.62

IMU Alignment Time 103:13:29 g. e. t.

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g. e. t. (h:m:s)	103:54:32.6	103:54:32.6	-
Burn duration, sec (including ullage)	31.1	31.0	2.37
Actual ΔV total, fps	50.57	50.59	2.34
Actual ΔVX, fps	50.57	50.59	2.34
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	0.0	0.0	0.0
Vgx residual trimmed, fps	0.0	0.0	0.0
Vgy residual trimmed, fps	0.0	0.0	0.0
Vgz residual trimmed, fps	0.0	0.0	0.0
Main engine ΔV expended excluding ullage and trim, fps	50.57	50.59	2.34
RCS ΔV expended, fps (ullage and residual trimmed)	0.0	0.0	0.0

Comments: This maneuver is nominally 50.5 fps posigrade and is executed utilizing 4 RCS engines with the RCS - interconnect. The purpose of this maneuver is to establish the proper phasing conditions at CDH so that after the CDH maneuver is executed, TPI will be at the desired time and elevation angle.

Table IX. Evaluation of Solutions for PC Maneuver (at CDH-30 Min)

Parameter		$\dot{X}$, fps	$\dot{Y}$, fps	$\dot{Z}$, fps	Total ΔV, fps
Nominal		0.0	0.0	0.0	0.0
CMC solution (LM active)	Mean	0.0	-0.08	0.0	-.08
	Sigma	0.0	0.54	0.0	0.54
	Maximum	0.0	1.66	0.0	1.66
	Minimum	0.0	-1.22	0.0	-1.22
Actual solution	Mean	0.0	0.00	0.0	0.00
	Sigma	0.0	0.22	0.0	0.22
	Maximum	0.0	0.56	0.0	0.56
	Minimum	0.0	-0.60	0.0	-0.60
Error in CMC solution	Mean	0.0	-0.08	0.0	-0.08
	Sigma	0.0	0.54	0.0	0.54
	Maximum	0.0	1.62	0.0	1.62
	Minimum	0.0	-1.21	0.0	-1.21

Table X. Evaluation of Solutions for CDH Maneuver

Parameter		$\dot{X}$, fps	$\dot{Y}$,* fps	$\dot{Z}$, fps	ΔV Total, fps	Time
Nominal		-.2	0.0	7.75		104:52:35.5
PGNCS solution at PGNCS time (LM active)	Mean	-.13	-	7.85	7.93	104:52:35.5
	Sigma	1.10	-	1.54	1.53	0.5
	Maximum	2.32	-	10.55	10.57	104:52:36.6
	Minimum	-2.67	-	4.06	4.25	104:52:34.2
CMC solution at PGNCS time (CSM active)	Mean	-.08	-.11	-7.54	7.62	104:52:35.5
	Sigma	1.00	.81	1.59	1.57	0.5
	Maximum	2.20	1.70	-11.27	11.28	104:52:36.6
	Minimum	-2.87	-2.33	-3.72	3.72	104:52:34.2
Actual solution at PGNCS time (LM active)	Mean	-.01	-.03	7.75	7.82	104:52:35.5
	Sigma	.97	.57	.69	0.68	0.5
	Maximum	2.05	1.12	9.33	9.52	104:52:36.6
	Minimum	-2.71	-1.63	6.15	6.19	104:52:34.2
Error in PGNCS solution	Mean	.00	-	.09	-.11	0.0
	Sigma	.41	-	1.40	1.39	0.4
	Maximum	1.02	-	2.90	2.87	1.1
	Minimum	-1.12	-	-2.89	-3.07	-.9
Error in CMC solution	Mean	-.01	-.08	.03	-.03	-
	Sigma	.39	.60	1.43	1.41	-
	Maximum	1.06	1.60	3.49	3.37	-
	Minimum	-.88	-1.63	-3.39	-3.31	-
Expected difference between PGNCS and CMC solutions	Mean	-.22	-	.30	.20	-
	Sigma	.52	-	1.81	1.41	-
	Maximum	1.16	-	4.88	3.41	-
	Minimum	-1.49	-	-4.30	-3.13	-

*Plane change (LM active)

Table XI. LM CDH Maneuver Evaluation

Trajectory Characteristics				
Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	44.81	44.98	1.01
	Postburn	45.26	45.23	1.26
Perilune altitude (h_p), n mi	Preburn	43.00	42.80	0.78
	Postburn	42.40	42.28	1.71
Altitude (R), ft	Preburn	274,871	273,334	624
	Postburn	274,871	273,334	624
Inertial flight path angle (γ), deg	Preburn	89.97	89.97	0.03
	Postburn	90.05	90.05	0.04
Semimajor axis (a), ft	Preburn	5,970,294	5,970,223	390
	Postburn	5,969,853	5,969,386	672
Longitude ascending node (A), deg	Preburn	170.42	170.43	0.021
	Postburn	170.42	170.43	0.021
Inclination (i), deg	Preburn	154.04	154.04	0.015
	Postburn	154.04	154.04	0.015
Eccentricity (e)	Preburn	0.0011	0.0011	8×10^{-4}
	Postburn	0.0014	0.0014	9×10^{-4}
True anomaly (θ) deg	Preburn	156.66	146.61	108.00
	Postburn	-136.83	-136.83	17.19
Vehicle weight, lbs	Preburn	8,168	8,168	1.68
	Postburn	8,161	8,161	5.64
Inertial speed (V), fps	Preburn	5,379.80	5,380.26	4.65
	Postburn	5,379.60	5,379.88	3.27

IMU Alignment Time 103:13:29 g.e.t. Maneuver Characteristics			
Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g.e.t. (h:m:s)	104:52:35.5	104:52:35.5	1.5
Burn duration, sec (including ullage)	9.2	9.2	3.9
Actual ΔV total, fps	7.76	7.93	4.59
Actual ΔVX, fps	0.2	0.13	3.3
Actual ΔVY, fps	0.0	0.0	0.0
Actual ΔVZ, fps	7.75	7.85	4.64
Vgx residual trimmed, fps	0.0	0.0	0.0
Vgy residual trimmed, fps	0.0	0.0	0.0
Vgz residual trimmed, fps	0.0	0.0	0.0
Main engine ΔV expended excluding ullage and trim, fps	-	-	-
RCS ΔV expended, fps (ullage and residual trimmed)	0.0	0.0	0.0

Comments: This maneuver is nominally a 7.8 fps radial maneuver and is executed utilizing 2 RCS engines. This maneuver inserts the LM into a near-circular orbit that is nominally 15 n mi below and coelliptic to the CSM orbit.

Table XII. Evaluation of Solutions for TPI Maneuver

Parameter		$\dot{X}$, fps	$\dot{Y}$, fps	$\dot{Z}$, fps	Total ΔV, fps	Time
Nominal		21.30	-.03	-10.56	23.77	105:28:11.9
PGNCS solution	Mean	21.21	-.13	-11.19	24.10	105:27:24.6
at PGNCS time	Sigma	1.04	1.53	1.86	1.23	2:50
(LM active)	Maximum	25.29	4.08	-6.62	27.39	105:35:49.7
	Minimum	19.29	-4.07	-15.40	21.42	105:21:31.0
CMC solution	Mean	-21.90	.05	12.00	25.01	105:27:41.8
at CMC time	Sigma	.91	.91	1.22	1.25	2:52
(CSM active)	Maximum	-19.88	2.18	16.22	28.52	105:36:14.6
	Minimum	-24.32	-1.92	9.65	22.17	105:21:4.5
Actual solution	Mean	21.23	-.09	-11.29	24.13	105:27:3.7
at PGNCS time	Sigma	.94	.82	1.64	0.84	2:46.6
(LM active)	Maximum	25.21	2.01	-6.91	26.69	105:35:28.2
	Minimum	19.67	-3.26	-16.60	22.59	105:21:50.4
Actual solution	Mean	-21.87	.06	12.26	25.13	105:27:41.8
at CMC time	Sigma	.89	.59	1.66	1.07	2:52
(CSM active)	Maximum	-19.98	1.54	16.38	27.40	105:36:14.6
	Minimum	-24.03	-1.69	7.86	22.28	105:21:4.5
Actual solution	Mean	21.32	-.09	-11.24	24.17	105:27:33.7
at actual time	Sigma	1.01	.81	1.40	0.74	2:46
(LM active)	Maximum	25.71	1.91	-7.46	26.78	105:35:28.2
	Minimum	19.66	-3.41	-15.62	22.42	105:21:50.3

Table XII. Evaluation of Solutions for TPI Maneuver (Continued)

Parameter		$\dot{X}$, fps	$\dot{Y}$, fps	$\dot{Z}$, fps	Total ΔV, fps	Time
Error in PGNCS solution	Mean	-.02	-.04	.09	-.03	.01
	Sigma	.38	1.16	2.29	1.37	25.2
	Maximum	1.34	2.86	5.18	3.37	58.3
	Minimum	-1.05	-2.74	-5.20	-4.07	-52.7
Error in CMC solution	Mean	-.03	-.01	-.26	-.12	3.9
	Sigma	.22	.73	2.42	1.26	30.2
	Maximum	.57	1.53	4.09	2.21	1:15.1
	Minimum	-.59	-1.93	-6.72	-3.55	-56.8
Expected difference between PGNCS and CMC solutions	Mean	-.69	-.08	.80	-.91	-7.3
	Sigma	1.35	1.36	2.02	1.56	41.6
	Maximum	4.56	3.16	5.99	3.90	1:16.2
	Minimum	-4.16	-3.03	-5.75	-5.90	-2:6.3

Table XIII. LM TPI Maneuver Evaluation

Trajectory Characteristics

Parameter		Nominal	Mean	3 Sigma
Apolune altitude (h_a), n mi	Preburn	45.83	45.61	1.23
	Postburn	62.13	63.11	2.77
Perilune altitude (h_p), n mi	Preburn	41.71	41.79	1.68
	Postburn	41.94	41.99	1.53
Altitude (R), ft	Preburn	257,026	256,674	846
	Postburn	257,030	256,663	852
Inertial flight path angle (γ), deg	Preburn	90.05	90.05	0.04
	Postburn	89.96	89.97	0.04
Seminajor axis (a), ft	Preburn	5,969,505	5,969,070	616
	Postburn	6,019,674	6,022,832	1809
Longitude ascending node (A), deg	Preburn	170.43	170.43	0.021
	Postburn	170.44	170.44	0.075
Inclination (i), deg	Preburn	154.04	154.04	0.015
	Postburn	154.03	154.03	0.013
Eccentricity (e)	Preburn	0.0019	0.0019	1×10^{-4}
	Postburn	0.010	0.010	18×10^{-4}
True anomaly (θ) deg	Preburn	-27.98	-28.73	18.75
	Postburn	3.64	2.39	4.11
Vehicle weight, lbs	Preburn	8,168	8,161	5.61
	Postburn	8,145	8,136	6.84
Inertial speed (V), fps	Preburn	5394.64	5394.78	5.67
	Postburn	5417.00	5418.73	4.35

IMU Alignment Time 103:13:29 g.e.t.

Maneuver Characteristics

Parameter	Nominal	Mean	3 Sigma
Burn initiation (Tig), g.e.t. (h:m:s)	105:28:11.9	105:27:24.6	8:30
Burn duration, sec (including ullage)	15.5	15.7	3.01
Actual ΔV total, fps	23.77	24.10	3.69
Actual ΔVX, fps	21.30	21.21	3.12
Actual ΔVY, fps	0.03	0.13	4.59
Actual ΔVZ, fps	10.56	11.19	6.58
Vgx residual trimmed, fps	0.00	0.00	0.00
Vgy residual trimmed, fps	0.00 0.00	0.00 0.00	0.00 0.00
Vgz residual trimmed, fps	0.00	0.02	0.27
Main engine ΔV expended excluding ullage and trim, fps	-	-	-
RCS ΔV expended, fps ullage and residual trimmed)	0.00	0.00	0.00

Comments: This maneuver is nominally a 23.7 fps maneuver and is executed utilizing 2 RCS engines. This maneuver places the LM on an intercept trajectory with the CSM. The point of interception will be approximately 130 degrees from TPI.

Table XIV. Estimated Midcourse Correction ΔV Expended

Parameter	Nominal	Mean	Sigma	Maximum	Minimum
First midcourse correction (MCC1), fps	0.0	4.50	3.05	12.79	0.33
Second Midcourse correction (MCC2), fps	0.0	2.07	1.82	6.58	0.27

APPENDIX A

SIMULATION PHASES

This appendix presents a phase-by-phase description of the Monte Carlo simulation.

1. INITIALIZATION

- LM and CSM actual states set equal at time of separation

- Both vehicles' actual states perturbed using MSFN covariance matrix to obtain the estimated states

- LM actual state perturbed by station-keeping error of 0. 2 fps (one-sigma) in each component of velocity

- μ uncertainty initiated using standard deviation of $.71 \times 10^{10}$

2. SEPARATION BURN

- Performed impulsively using SM/RCS (2. 5 fps radially down) on the estimated state

- The estimated CSM state after the burn contains no execution error, thereby simulating the LM P76 Target ΔV program

- The actual state reflects the execution errors as described in Table I

3. FREE FLIGHT TO DOI MANEUVER

- Actual and estimated states are propagated using the AEG with two harmonic terms (J_2, J_{22})

- μ uncertainty is included in the actual state propagation

4. DOI MANEUVER

- Perform 5. 5 second RCS ullage (four-jet)

- Maneuver performed using specified target vector at prespecified time in External ΔV mode

- Finite burn simulation performed using 10-percent DPS thrust for 15 seconds and 40 percent for the remainder

- Onboard target vector rotation angle calculated using thrust value of 9500 pounds

- State vectors (estimate and actual) propagated through the burn using average g. Only the actual value of μ is used (for both states)

5. FREE FLIGHT TO PHASING

- Propagate to nominal phasing time (prespecified)

6. PHASING MANEUVER

- Perform 5.5 second ullage (four-jet)

- Maneuver performed using external ΔV mode using the same model as described in No. 4

- DPS thrust is 10 percent for 25 seconds and 100 percent for the remainder

7. FREE FLIGHT TO INSERTION MANEUVER

- Propagate to nominal insertion time (prespecified)

8. INSERTION MANEUVER

- LM is staged prior to APS burn

- Perform 3.0 second ullage (four-jet)

- Maneuver performed using external ΔV mode.

- Onboard target vector rotation angle calculated using thrust value of 3500 pounds

- Otherwise, burn is performed as in No. 4

9. UPDATE - PGNCS

- Calculate CSM estimated state vector (PGNCS) by sampling with a prespecified, real-world covariance matrix

10. FREE FLIGHT TO BEGINNING OF RR TRACKING

- Propagate to nominal time (prespecified)

11. UPDATE - PGNCS

- Calculate LM estimated state vector (PGNCS) by using tracking normal matrices

- 22 RR marks are incorporated

- W matrix is reinitialized to 10,000 ft, 10 ft/sec, and 15 mr before 1st mark

12. FREE FLIGHT TO CSI MANEUVER

- Propagate to nominal time (prespecified)

13. UPDATE - CMC

- Calculate CSM and LM estimated state vector (CMC) by sampling with a prespecified, real-world covariance matrix

14. COMPUTE CSI MANEUVER - CMC

- Compute CSI maneuver using CMC estimated and actual states

- The CMC time of CSI is the PGNCS time of CSI

- Time of CDH maneuver for CMC estimated state will be an output quantity

- Compute PC maneuver, LM performs this maneuver in conjunction with CSI if greater than 2 fps

15. COMPUTE CSI MANEUVER - PGNCS

- Compute CSI maneuver with the onboard PGNCS program for both the actual and estimated states

16. CSI

- No ullage

- Perform burn using RCS interconnect (four-jet) external ΔV mode

- Onboard, prethrust target vector rotation based on true thrust level

- Otherwise, burn is performed as in No. 4 (PGNCS solution)

17. FREE FLIGHT TO BEGINNING OF RR TRACKING

- Propagate to nominal time (prespecified)

18. UPDATE - PGNCS

- Calculate LM estimated state vector (PGNCS) by using tracking normal matrices

- 19 RR marks are incorporated

- W matrix is reinitialized to 2000 ft, 2 ft/sec, and 5 mr prior to 5th mark

19. FREE FLIGHT TO PC MANEUVER

- Propagate to PGNCS time of CDH minus 1800 seconds

20. UPDATE - CMC

- Calculate CSM and LM estimated state vectors (CMC) by sampling with a prespecified, real-world covariance matrix

21. COMPUTE PC MANEUVER - CMC

- Compute PC maneuver with the onboard CMC program for both the actual and estimated states

22. PC MANEUVER

- Simulate LM impulsive maneuver using RCS (two-jet) if greater than 2 fps

23. FREE FLIGHT TO BEGINNING OF RR TRACKING

- Propagate to nominal time (prespecified)

24. UPDATE - PGNCS

- Compute LM estimated state vector (PGNCS) as described in No. 18

- 16 RR marks are incorporated

25. FREE FLIGHT TO CDH TIME

- Propagate to the PGNCS time of CDH

26. UPDATE - CMC

- Calculate CSM and LM estimated state vectors (CMC) by sampling with a prespecified, real-world covariance matrix

27. CALCULATE CDH MANEUVER

- Use CSI/CDH onboard program in CDH mode to calculate CDH ΔV on PGNCS estimated and actual states at PGNCS time (LM active)

- Use CSI/CDH onboard program in CDH mode to calculate CDH ΔV on CMC estimate and actual states at PGNCS time (CSM active)

28. CALCULATE PC MANEUVER - CMC

- Compute PC maneuver with the onboard CMC program for both the actual and the CMC estimated states

- The LM performs the PC maneuver in conjunction with CDH if the PC ΔV is greater than 2 fps

29. CDH MANEUVER

- Simulate LM impulsive maneuver using RCS (two-jet)

30. FREE FLIGHT TO BEGINNING OF RR TRACKING

- Propagate to nominal time (prespecified)

31. UPDATE - PGNCS

- Compute LM estimated state vector (PGNCS) as described in No. 18

- 16 marks are incorporated

32. FREE FLIGHT ACTUALS TO NOMINAL TPI TIME

- Propagate LM and CSM actuals to nominal time (prespecified)

33. UPDATE - CMC

- Calculate CSM and LM estimated state vectors (CMC) by sampling with a prespecified, real-world covariance matrix

34. FREE FLIGHT BACK TO PRETPI TIME

- Propagate the actual state and the CMC estimated states back to the prespecified time of the TPI time calculations

35. CALCULATE TPI TIMES

- Calculate TPI times based on a look angle of 26.6 degrees for the actual states and the PGNCS estimated states

- Calculate TPI times based on a look angle of 208.3 for the actual states and the CMC estimated states

36. FREE FLIGHT TO TPI TIME

- Propagate the PGNCS estimated states to the estimated PGNCS time

- Propagate the actual states to the estimated PGNCS time, to the estimated CMC time, and to the actual time

- Propagate the CMC estimated states to the CMC estimated time

37. CALCULATE TPI MANEUVER

- Calculate TPI ΔV based on a 130-degree conic transfer

- Use the actual state at the actual time, the actual state at the PGNCS time, the CMC state at the CMC time, and the PGNCS state at the PGNCS time (the LM is the active vehicle for PGNCS and actual time, the CSM is the active vehicle for the CMC time)

- Estimate TPF time (PGNCS estimate)

38. TPI MANEUVER

- No ullage

- Perform burn using RCS (two-jet) in Lambert mode

- Prethrust target vector rotation based on the true thrust level

- Otherwise, burn is performed as in No. 4 (onboard solution)

39. FREE FLIGHT TO BEGINNING OF RR TRACKING

40. UPDATE - PGNCS

- Compute LM estimated state vector (PGNCS) using tracking normal matrices

- 10 marks are incorporated

- W matrix is reinitialized to 2000 ft, 2 ft/sec, and 5 mr prior to 1st mark

41. FREE FLIGHT TO MCC-1

- Free flight PGNCS estimated and actual states to the first mid-course time which is TPI plus 15 minutes

42. COMPUTE ΔV OF MCC-1

- Calculate ΔV based on a conic transfer time of the estimated CSM state corresponding to the time differential of the present time and the estimated TPF time (no. 37)

43. MCC-1

- Simulate impulsive maneuver using main burn RCS (two-jet) if greater than 1 fps

44. FREE FLIGHT TO BEGINNING OF RR TRACKING

45. UPDATE - PGNCS

- 11 marks are incorporated as in No. 40

46. FREE FLIGHT TO MCC-2

- Free flight estimate and actual states to be second midcourse time which is TPI plus 30 minutes

47. COMPUTE ΔV OF MCC-2

- Calculate ΔV based on a conic transfer time of the estimate CSM state corresponding to the time differential of the present time and the estimated TPF time (No. 37)

48. MCC-2

- Perform impulsive maneuver using main burn RCS (two-jet) if greater than 1 fps

49. CALCULATE DCA

- Calculate the distance of closest approach of the actual LM and CSM

50. FREE FLIGHT TO DCA TIME

51. COMPUTE ΔV OF TPF AND PROPELLANT USED

- Compute TPF ΔV as antiparallel to the relative velocity of the estimated active and passive vehicles

- Compute propellant used and multiply by scale factor (2) to simulate braking

APPENDIX B

REFERENCE PROFILE

As a means of validating the simulation, a single run without navigation or execution errors was made in an attempt to match the reference trajectory. Since for the purposes of the simulation the separation, DOI, phasing, and insertion maneuvers are executed using the prespecified reference values, the results are summarized from CSI to TPF only.

CSI	REFERENCE	SIMULATION	DIFFERENCE
time (g. e. t.)	$103^h54^m32.6^s$	$103^h54^m32.6^s$	0.
ΔV_x	50. 41	50. 57	0. 36
ΔV_y	0.	0.	0.
ΔV_z	0.	0.	0.
$\lvert\Delta V\rvert$	50. 41	50. 57	0. 36
CDH			
time (g. e. t.)	$104^h52^m33.3^s$	$104^h52^m35.5^s$	2.2^s
ΔV_x	-0. 43	-0. 20	0. 27
ΔV_y	0.	0.	0.
ΔV_z	5. 71	7. 75	2. 04*
$\lvert\Delta V\rvert$	5. 72	7. 75	2. 03
TPI			
time (g. e. t.)	$105^h29^m15.6^s$	$105^h28^m32.6^s$	42.8^s
ΔV_x	21. 98	21. 96	-0. 02
ΔV_y	-0. 02	-0. 02	0.
ΔV_z	-11. 26	-11. 11	0. 15
$\lvert\Delta V\rvert$	24. 69	24. 60	0. 09
TPF			
time (g. e. t.)	$106^h12^m1^s$	$106^h11^m41.2^s$	42.8^s
DCA	-	2016 ft	-
ΔV_x	18. 75	19. 72	0. 97
ΔV_y	-0. 02	0.	0. 02
ΔV_z	25. 52	23. 82	-1. 70
$\lvert\Delta V\rvert$	31. 70	30. 92	0. 78

*For this profile the CDH maneuver, which is nominally small, is very sensitive to the DOI phasing and insertion burn. This difference reflects the fact that these burns were not performed identically in the two simulations.

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