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APOLLO 10 SPACECRAFT DISPERSION ANALYSIS VOLUME III LOI, TEI, AND APS BURN-TO-DEPLETION MANEUVERS

Guidance and Performance Branch
MISSION PLANNING AND ANALYSIS DIVISION
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HOUSTON, TEXAS

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APOLLO 10 SPACECRAFT DISPERSION ANALYSIS
VOLUME III - LOI, TEI, AND APS BURN-TO-DEPLETION MANEUVERS

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May 13, 1969

MISSION PLANNING AND ANALYSIS DIVISION
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APOLLO 10 SPACECRAFT DISPERSION ANALYSIS

VOLUME III - LOI, TEI, and APS BURN-TO-DEPLETION MANEUVERS

R. Leroy McHenry

SUMMARY

A spacecraft dispersion analysis is presented for the LOI-1, the LOI-2, the TEI, and the APS burn to depletion maneuvers of Apollo 10 (Mission F). The analysis was performed in two parts. The first part consisted of a trajectory sequence which modeled the targeting and performance of LOI-1, LOI-2, and TEI, and the second part was an individual dispersion analysis of the APS burn to depletion maneuver.

Analysis of the first part showed that the primary effect of translunar midcourse correction errors was to increase the required LOI-1 ΔV. The MSFN inaccuracies prior to LOI-2 were the primary cause of the dispersions for LOI-2. The MSFN dispersions at TEI update time caused large deviations in TEI ignition time. However, there was a negligible increase in the ΔV requirements for the TEI maneuver.

The analysis of the APS burn to depletion maneuver showed that the ΔV targets were sufficiently biased to prevent the occurrence of a guided cutoff prior to APS propellant depletion.

INTRODUCTION

The results of a dispersion analysis for the LOI-1, the LOI-2, the TEI, and the APS burn-to-depletion maneuvers of Apollo 10 (Mission F) are presented in this report. One hundred and thirty random trajectories were generated for this analysis by use of a Monte Carlo sampling technique.

Except for the APS burn to depletion maneuver, an estimated MSFN state vector and target update was simulated prior to each maneuver. Targeting of the maneuvers was modeled as closely as possible to reflect real-time targeting procedures. However, the capability to retarget LOI-1 and LOI-2 to any orbital plane which passes within the allowable range of azimuths over the landing site was not available in the computer program simulation. The program does have the capability to compute targets to obtain a selected set of desired conditions of the nominal trajectory. This capability allows LOI-1 and LOI-2 to be targeted such that the resultant orbits will have a satisfactory shape, even though they are not constrained to pass over the landing site. The nominal plane change was applied to each dispersed trajectory at LOI-1 since neglect of relatively small adjustments to the nominal plane change has little effect on the total ΔV requirement.

The TEI maneuver was targeted for a selected set of nominal conditions at cutoff. Even though this targeting does not insure the proper conditions at earth entry interface, it was felt that targeting in this manner would yield a good representation of the total ΔV requirement for this maneuver.

NOMENCLATURE

AGS	lunar module abort guidance system
APS	lunar module ascent propulsion system
ΔV	incremental change in velocity
LOI-1	lunar orbit insertion maneuver
LOI-2	circularization maneuver
MCC-H	Mission Control Center-Houston
MSFN	Manned Space Flight Network
PGNCS	primary guidance and navigation control system
SPS	service propulsion system
TEI	transearth injection maneuver

METHODS OF ANALYSIS

The dispersion analysis for the LOI-1, the LOI-2, and the TEI maneuvers was performed in a trajectory sequence so that the targeting and performance of LOI-1 on any given trajectory directly affected the performance requirements for LOI-2; similarly, the targeting and performance of LOI-2 affected the performance requirements for TEI. For each of the trajectories simulated, an actual state vector at nominal LOI-1 ignition time was constructed by random sampling of a covariance matrix of the expected errors at LOI-1 which result from translunar midcourse maneuver errors. An MCC-H update was simulated prior to LOI-1 ignition as an estimated state vector which differed from the actual state vector by random errors in the best MSFN estimate.

Targeting of LOI-1 for pericynthion and apocynthion and the nominal out-of-plane ΔV was based on the updated state vector. After the targets were computed, the maneuver was simulated with all of the significant spacecraft errors applied.

The actual state vector at the time of pre-LOI-2 ignition search was computed from the actual state vector at LOI-1 cutoff time by the lunar analytic ephemeris generator (LAEG). The estimated state vector used to compute the targets and to simulate an MCC-H update was determined by application of randomly sampled MSFN state vector errors to the actual state vector.

The LOI-2 maneuver was targeted to circularize the spacecraft orbit at the 60-n. mi. altitude prior to perigee if the initial pericynthion altitude was less than 60 n. mi. For cases in which the initial pericynthion altitude equaled or exceeded 60 n. mi., the maneuver was targeted to occur at pericynthion.

After the LOI-2 maneuver simulation was performed, the actual state vector was advanced with the LAEG to a fixed elapsed time prior to the TEI maneuver. At this point, an estimated state vector was constructed by application of random MSFN state vector errors to the actual state vector, thereby simulating an MCC-H update. From the updated state vector, a TEI ignition time was computed based on the time of passage over the longitude at nominal TEI ignition. Delta V targets for the TEI maneuver were then computed. The targeting criteria for the TEI maneuver were the nominal velocity magnitude, flight-path angle, and azimuth at cutoff.

A 20-second two-jet RCS ullage maneuver was simulated prior to the main engine ignition for the TEI maneuver. After 75 seconds of the SPS burn, crossover from the propellant storage tank to the sump tank was simulated. The effect of crossover is a slightly higher thrust and propellant flow rate.

The LOI-1, LOI-2, and TEI maneuvers were all simulated under control of the PGNCS. For these maneuvers, it was assumed that the PGNCS platform was alined 55 minutes prior to nominal ignition time.

The dispersion analysis for the APS burn to depletion maneuver was performed separately from the dispersion analyis for the trajectory sequence described previously. No retargeting of the maneuver was simulated. The maneuver was simulated with AGS control. The last LM PGNCS alinement time was assumed to be 5.5 hours prior to ignition. Also, it was assumed that the AGS was alined to the drifted PGNCS at 1.5 hours prior to ignition.

The results of this dispersion analysis are presented in tables I, II, III and IV. The coordinate systems used for the parameters presented in the tables are defined in appendix A. The error sources and their respective values that were modeled in this analysis are presented in appendix B.

ANALYSIS OF RESULTS

Lunar Orbit Insertion Maneuver - LOI-1

Errors in the translunar midcourse correction maneuvers and MSFN uncertainties cause a 9-n. mi. dispersion in pericynthion altitude at LOI-1 ignition time as shown in table I. In fact, the effect of the errors upon the mean ignition time caused the maneuver to be performed 10 seconds earlier than nominal.

However, the most significant consequence of the translunar midcourse correction errors, combined with LOI-1 performance errors, is that they tend to increase the ΔV required for the maneuver. The 3σ deviation in the total ΔV gained was 34 fps which was caused primarily by targeting dispersions.

The 1.22 fps V_{gx} residual was caused by SPS thrust tailoff uncertainty.

Circularization Maneuver - LOI-2

Prior to the LOI-2 maneuver, the best estimate of the MSFN tracking of only one orbital pass was used to update the onboard computer. As might be expected, the MSFN dispersions increased the ΔV requirements for this maneuver. Results of the LOI-2 maneuver (table II) show that the mean of the required ΔV was 146.84 fps, which is approximately 8 fps more than nominally required. The 3σ dispersion of 42.87 fps shows that the required ΔV can be as much as 50 fps more than nominal. The statistics for the time of ignition are also partially indicative of the large MSFN uncertainties in altitude at this point, because time of ignition is based on altitude.

The LOI-2 maneuver is a relatively short spacecraft burn. As a result, the PGNCS digital autopilot does not have sufficient time to steer out all of the thrust vector mistrim. This error causes cross-axis velocity errors which can be detected as V_{gy} and V_{gz} residuals. The 3σ V_{gy} and V_{gz} residuals are 7.88 fps and 8.42 fps, respectively.

Transearth Injection Maneuver - TEI

The differences in the actual trajectory from the nominal trajectory at the TEI update time, when compounded by errors in the MSFN update, can cause large deviations in the TEI time of ignition. The maneuver can be almost 20 minutes later than nominally planned (table III). However, there is very little impact upon the ΔV requirement for this maneuver. A 13.23-fps 3σ dispersion exists in the total ΔV gained for this maneuver. Both targeting and spacecraft sensing errors contribute to this dispersion.

The V_{gx} residual shows that a 3.05-fps dispersion can occur. This dispersion results from SPS thrust tailoff uncertainty.

APS Burn to Depletion Maneuver

Results of the dispersion analysis of the APS burn to depletion maneuver are presented in table IV. The V_g residuals show that the targets are sufficiently biased to insure propellant depletion prior to a guided cutoff.

The large errors in the velocity parameters are caused primarily by initial misalinement of the AGS at ignition. This initial misalinement results primarily from 4 hours of PGNCS drift prior to alinement of the AGS with the PGNCS.

CONCLUSIONS

Based upon the dispersion analyses for the LOI-1, LOI-2, TEI, and the APS burn to depletion maneuvers, the following conclusions have been made.

1. No major problems were uncovered in the dispersion analysis.

2. MSFN inaccuracies in the pre-LOI-2 update are the primary contributors to the increase in ΔV cost for LOI-2. The required ΔV can be as much as 50 fps more than nominal.

3. Differences in the actual trajectory from the nominal trajectory combined with pre-TEI update errors can cause large deviations (20 min) in the time of ignition for TEI.

4. TEI can be retargeted with no significant increase in ΔV cost.

5. The ΔV targets for the APS burn to depletion maneuver are sufficiently biased to insure APS propellant depletion.

TABLE I.- LOI-1 MANEUVER SUMMARY

[IMU alinement time 75:13:17.55 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	0.00	0.00	0.00	Burn initiation g.e.t., hr:min:sec	76:08:17.55	76:08:6.73	-0:0:54.14 +0:0:17.24
	Postburn	169.64	169.94	7.08				
Perigee altitude, n. mi.	Preburn	59.30	59.37	9.07	Burn duration (not including ullage), sec	345.93	346.40	8.01
	Postburn	59.04	58.85	2.00				
Semimajor axis, n. mi.	Preburn	-2310.51	-2308.19	65.81	Actual total ΔV gained, fps	2866.16	2872.00	34.25
	Postburn	1052.85	1052.90	3.80				
Altitude, n. mi.	Preburn	84.01	85.56	12.96	Actual ΔV_X gained, fps	-2737.48	-2719.84	73.61
	Postburn	59.63	60.69	6.96				
Right ascension of the ascending node, deg	Preburn	200.60	200.59	7.01	Actual ΔV_Y gained, fps	43.69	43.49	7.92
	Postburn	199.06	199.12	6.44				
Inclination, deg	Preburn	174.75	174.74	0.28	Actual ΔV_Z gained, fps	-848.05	-916.54	277.14
	Postburn	174.32	174.32	0.32				
Inertial flight-path angle, deg	Preburn	-9.71	-10.15	2.05	V_{gx} residual, fps	-0.02	0.00	1.22
	Postburn	0.44	0.519	1.70				
Eccentricity	Preburn	1.432	1.432	0.010	V_{gy} residual, fps	0.00	0.00	0.00
	Postburn	0.053	0.053	0.003				
Spacecraft weight, lb	Preburn	93 133.0	93 133.0	218.7	V_{gz} residual, fps	0.00	0.00	0.00
	Postburn	70 115.2	70 066.7	374.1				
Inertial velocity, fps	Preburn	8250.37	8242.87	57.08	Main engine ΔV expended, fps	2866.16	2872.00	34.25
	Postburn	5478.34	5474.80	33.56				
True anomaly, deg	Preburn	343.52	342.78	3.48	RCS ΔV expended for trim and ullage, fps	0.00	0.00	0.00
	Postburn	8.97	68.22	17.37				

COMMENTS: The LOI-1 maneuver was targeted for a 60- by 170-n. mi. orbit, with no constraint for passage over the landing site considered in the targeting. However, the nominal plane change was applied. The tolerances on pericynthion and apocynthion were ±2 n. mi. The 7.08 n. mi. dispersion in apocynthion is caused primarily by the impact of initial MSFN inaccuracies on targeting. Translunar midcourse correction errors cause a higher ΔV requirement than nominal for LOI-1.

TABLE II.- LOI-2 MANEUVER SUMMARY

[IMU alinement time 79:38:23.55 g.e.t.]

Trajectory characteristics

Parameter		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	169.69	169.98	7.07
	Postburn	59.23	62.91	10.05
Perigee altitude, n. mi.	Preburn	59.02	58.82	2.08
	Postburn	58.93	56.58	6.39
Semimajor axis, n. mi.	Preburn	1052.85	1052.90	3.78
	Postburn	997.60	998.26	4.77
Altitude, n. mi.	Preburn	59.04	59.69	2.91
	Postburn	59.03	59.92	4.14
Right ascension of the ascending node, deg	Preburn	199.20	199.27	6.44
	Postburn	199.20	199.27	6.45
Inclination, deg	Preburn	174.32	174.32	0.32
	Postburn	174.33	174.32	0.33
Inertial flight-path angle, deg	Preburn	-0.011	-0.411	0.99
	Postburn	-0.008	-0.026	0.59
Eccentricity	Preburn	0.053	0.053	0.003
	Postburn	0.000	0.003	0.007
Spacecraft weight, lb	Preburn	70 115.2	70 066.7	374.1
	Postburn	69 159.9	69 054.9	495.3
Inertial velocity, fps	Preburn	5483.34	5480.02	17.25
	Postburn	5344.80	5341.84	23.37
True anomaly, deg	Preburn	359.91	324.27	280.73
	Postburn	352.85	205.37	266.52

Maneuver characteristics

	Nominal	Mean	3σ
Burn initiation g.e.t., hr:min:sec	80:32:00.88	80:28:53.91	-0:11:23.76 +0:07:31.18
Burn duration (not including ullage), sec	14.36	15.20	4.38
Actual total ΔV gained, fps	138.55	146.84	42.87
Actual ΔV_X gained, fps	-138.49	-136.54	15.92
Actual ΔV_Y gained, fps	0.00	0.00	0.38
Actual ΔV_Z gained, fps	0.45	-36.71	125.76
V_{gx} residual, fps	-0.01	-0.07	1.20
V_{gy} residual, fps	0.00	0.14	7.88
V_{gz} residual, fps	0.00	0.40	8.42
Main engine ΔV expended, fps	138.55	146.84	42.87
RCS ΔV expended for trim and ullage, fps	0.00	0.00	0.00

COMMENTS: The LOI-2 maneuver was targeted for a 60- by 60-n. mi. circular orbit, with a tolerance of 1 n. mi. on altitude. However, pre-LOI-2 tracking inaccuracies make it difficult to obtain a good circular orbit. Also, the cost in ΔV is increased. The V_{gy} and V_{gz} residuals are the cross-axis velocity errors caused by thrust vector mistrim.

TABLE III.- TEI MANEUVER SUMMARY

[IMU alinement time 126:56:14.55 g.e.t.]

Trajectory characteristics					Maneuver characteristics			
Parameter		Nominal	Mean	3σ		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	59.13	62.93	10.00	Burn initiation g.e.t., hr:min:sec	127:51:54.72	128:04:49.58	-0:18:46.81 +0:20:40.65
	Postburn	0.00	0.00	0.00				
Perigee altitude, n. mi.	Preburn	59.04	56.57	6.44	Burn duration(not including ullage), sec	155.06	154.74	3.86
	Postburn	58.93	56.70	2.83				
Semimajor axis, n. mi.	Preburn	997.60	998.26	4.77	Actual total ΔV gained, fps	3255.00	3256.41	13.23
	Postburn	-1771.13	-1708.77	24.72				
Altitude, n. mi.	Preburn	59.05	59.83	3.51	Actual ΔV_X gained, fps	3220.03	3221.99	13.48
	Postburn	63.27	64.04	2.97				
Right ascension of the ascending node, deg	Preburn	201.14	201.21	6.50	Actual ΔV_Y gained, fps	-236.39	-262.93	27.00
	Postburn	205.51	205.53	9.00				
Inclination, deg	Preburn	174.33	174.32	0.34	Actual ΔV_Z gained, fps	394.04	391.61	62.99
	Postburn	176.05	176.04	0.17				
Inertial flight-path angle, deg	Preburn	0.001	-0.001	0.65	V_{gx} residual, fps	-0.21	-0.23	3.05
	Postburn	4.178	4.179	0.34				
Eccentricity	Preburn	0.000	0.003	0.007	V_{gy} residual, fps	0.00	0.00	0.00
	Postburn	1.583	1.584	0.009				
Spacecraft weight, lb	Preburn	37 848.2	37 743.2	495.3	V_{gz} residual, fps	0.00	0.00	0.00
	Postburn	27 424.8	27 352.9	418.8				
Inertial velocity, fps	Preburn	5344.12	5342.32	11.46	Main engine ΔV expended, fps	3251.59	3253.00	13.23
	Postburn	8575.72	8574.54	14.42				
True anomaly, deg	Preburn	366.59	175.83	218.22	RCS ΔV expended for trim and ullage, fps	3.41	3.41	0.00
	Postburn	6.82	6.82	0.56				

COMMENTS: The TEI maneuver was targeted for burnout velocity magnitude (±2 fps), flight-path angle (±0.05°), and azimuth (±0.25°). The large deviation in time of ignition results primarily from the large MSFN inaccuracies.

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

[IMU alinement time 103:36:41.4 g.e.t.]

Trajectory characteristics				
Parameter		Nominal	Mean	3σ
Apogee altitude, n. mi.	Preburn	60.73	62.17	7.38
	Postburn	0.00	0.00	0.00
Perigee altitude, n. mi.	Preburn	57.43	56.95	6.09
	Postburn	53.23	53.27	4.17
Semimajor axis, n. mi.	Preburn	997.59	998.47	5.22
	Postburn	-1242.91	-1242.18	56.55
Altitude, n. mi.	Preburn	58.92	59.11	1.73
	Postburn	54.31	54.38	5.72
Right ascension of the ascending node, deg	Preburn	170.45	170.45	1.20
	Postburn	170.45	170.45	1.47
Inclination deg	Preburn	154.03	154.03	0.23
	Postburn	154.03	154.03	0.46
Inertial flight path angle, deg	Preburn	-0.094	-0.095	0.108
	Postburn	2.135	2.105	1.689
Eccentricity	Preburn	0.001	0.002	0.001
	Postburn	1.798	1.799	0.038
Spacecraft weight, lb	Preburn	7725.0	7725.3	34.77
	Postburn	5352.6	5352.6	1.00
Inertial velocity, fps	Preburn	5345.45	5346.85	9.63
	Postburn	8962.72	8963.50	49.56
True anomaly, deg	Preburn	275.55	290.77	112.26
	Postburn	0.93	3.27	2.61

Maneuver characteristics			
	Nominal	Mean	3σ
Burn initiation g.e.t., hr:min:sec	109:03:41.4	109:03:41.4	0.00
Burn duration (not including ullage), sec	211.95	211.86	8.34
Actual total ΔV gained, fps	3652.04	3652.46	45.17
Actual ΔV_X gained, fps	3484.40	3483.67	49.92
Actual ΔV_Y gained, fps	0.00	0.95	103.43
Actual ΔV_Z gained, fps	1093.77	1096.49	95.78
V_{gx} residual, fps	1347.96	1244.36	43.92
V_{gy} residual, fps	0.00	32.65	42.84
V_{gz} residual, fps	0.00	516.01	39.98
Main engine ΔV expended, fps	3652.04	3652.46	45.17
RCS ΔV expended for trim and ullage, fps	0.00	0.00	0.00

COMMENTS: The APS burn to depletion maneuver was an AGS controlled burn. The LM PGNCS was alined 5.5 hours prior to ignition. At 1.5 hours prior to ignition, the AGS was alined to the PGNCS. The V_g residuals are the results of a non-guided engine cut off.

APPENDIX A

COORDINATE SYSTEMS

APPENDIX A

COORDINATE SYSTEMS

In tables I through III, the statistics for inertial right ascension of the ascending node and orbital inclination are based on an initially rotating selenographic coordinate system which was made inertial at a ground elapsed time of $76^h 8^m 17.55^s$, that is, LOI-1 ignition time.

The actual velocity gained, ΔV_x, ΔV_y, and ΔV_z, presented in tables I through IV 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 ignition time

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

The ΔV residuals, V_{gx}, V_{gy}, V_{gz}, are in 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 (3σ DEVIATIONS)

APPENDIX B

ERROR SOURCE MAGNITUDES (3σ DEVIATIONS)

Source	CSM PGNCS[a]	LM PGNCS[a]	LM AGS[a]
Platform misalinement, deg	0.033	N/A	0.063[b]
Static gyro drifts, deg/sec	0.251×10^{-6}	[c]0.251×10^{-6}	0.168×10^{-3}
Input axis g-sensitive gyro drift, deg/sec/ft/sec^2	0.312×10^{-5}	N/A	0.193×10^{-5}
Spin reference axis g-sensitive gyro drift, deg/sec/ft/sec^2	0.195×10^{-7}	N/A	N/A
Gyro scale factor, ppm	N/A	N/A	N/A
Accelerometer misalinements, deg	0.018	N/A	N/A
Accelerometer biases, ft/sec^2	0.021	N/A	0.019
Accelerometer nonlinearity coefficient, sec^2/ft	348.0	N/A	300.0
	0.939×10^{-6}	N/A	0.939×10^{-6}
Attitude misalinement, deg	0.5	0.5	
Thrust tailoff uncertainty, sec	0.12	0.09	
Weight uncertainty, lb	218.7	36.00	
Thrust uncertainty, lb	441.9	121.2 (APS)	
I_{sp} uncertainty, sec	3.57	0.357 (APS)	
Thrust vector mistrim, deg	1.00	N/A	

[a]N/A indicates these errors were not modeled in this analysis.

[b]PGNCS inflight alinement error transmitted to the AGS.

[c]PGNCS drift rate prior to alinement of AGS to PGNCS.