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REPLY TO
ATTN OF: FM54 (71-143)

September 1, 1971

MEMORANDUM

TO: Informal Distribution

FROM: FM5/Planetary Mission Analysis Branch

SUBJECT: Postflight Analysis of CSM Maneuvers during Apollo 15

Introduction

The following analysis was made by the Maneuver Analysis Section of the Planetary Mission Analysis Branch. A brief summary of the enclosed information has previously been provided to the Postflight Analysis Group of the Mission Planning Support Office to be submitted as part of their report for inclusion in the MSC Mission Evaluation Report for Apollo 15.

All of the data, information, and comments found in this analysis were accumulated during this section's support in the Flight Dynamics SSR and MPL (Mission Planning Laboratory) during the mission.

Following is a narrative which generally summarizes the postflight analysis and real-time data which were gathered.

Translunar Injection

The SIVB onboard (IU) state vector was updated twice during earth orbit. A preliminary update was made through the Goldstone tracking station. Prior to this the accumulated error in the launch vehicle's onboard state vector exceeded acceptable values for both downrange and radial components. A final update which incorporated MSFN tracking during the stateside pass was uplinked through either Bermuda or Vanguard. This is the first mission in which an IU update was made.

TLI was performed in a near-nominal manner with actual ignition matching the real-time plan of 2:50:00.6 g.e.t. Prior to ignition, the real-time-planned ΔV and burn time were 10414.7 fps and 353.39 sec., respectively. Due to a slightly "hotter" J-2 engine than was expected, the actual burn time prediction was updated to be about 4 sec. shorter than planned midway through the burn.

After the maneuver was executed, the RTCC ephemeris was anchored on the best post-TLI state available--ICHU-13, the IU vector. Perilune conditions based on this vector are 139.27 n.m. altitude at 78:31:21 g.e.t. Translunar midcourse computations based upon ICHU-13 showed that a 3.7 fps MCC-1 maneuver (at TLI+9 hrs.) was required to return to the operational trajectory at LOI time.

Based on this preliminary analysis, it appears that the high degree of accuracy at TLI was attributable to the IU-navigation update made in earth orbit. The ΔV midcourse ΔV at TLI+9 hrs. is 23.3 fps; predicted MCC-1 ΔV before the IU-updates were made was on the order of 30 fps, assuming a perfectly executed TLI. It therefore appears that a very good navigation update was sent to the IU and that TLI was near-perfect in execution.

Transposition and Docking

Actual CSM separation from the IM/SIVB occurred at 3:22:24 g.e.t. which compares with 3:20:54 g.e.t. prelaunch. No problems were encountered during this phase and actual hard docking occurred at 3:33:48 g.e.t.

CSM/IM Separation from SIVB

Actual CSM/IM separation from the SIVB occurred as planned at 4:18:00 g.e.t. The actual ΔV applied was .5 fps as compared to a prelaunch plan of .3 fps. The resulting perilune altitude was lowered to 130.8 n.m. as compared to the prelaunch nominal 68. n.m.

MCC-1

The ΔV required at MCC-1 to reoptimize (BAP-4) the translunar trajectory was 2.8 fps as computed from CDC-1 approximately 2 hours before MCC-1. This 2.8 fps MCC-1 maneuver would grow to only 4.8 fps at MCC-2 time so the decision was made not to perform MCC-1.

SPS Burn Test/MCC-2

Shortly after TLI the Apollo 15 crew reported a malfunction which left the SPS thrust light on. To confirm that the SPS was usable, a test burn was to be performed at 28:40:00 g.e.t. The burn was made under SCS guidance. A MCC-2 maneuver based upon ACNX121 was computed with ignition at 28:40:00 and provided the ΔV and the attitude used for the SPS test burn. It was expected that a return-to-nominal type MCC-2 would be made at the nominal MCC-2 time.

The SPS test burn was performed at 28:40:22.5 g.e.t. with a total ΔV of 5.3 fps. The magnitude of the SPS test burn was very close to the

4.8 fps needed for the MCC-2. Hence no other maneuvers were required at this time. Perilune altitude after the burn was 63 n.m.

MCC-4

The vector used for computing the final real-time-planned MCC-4 maneuver was ACNX236 which had a closest approach time and altitude at the moon of 78:35:15 g.e.t. and 63.27 n.m., respectively. This perilune altitude, which was approximately 5 n.m. lower than the planned nominal, would result in the LOI processor rotating LPO-1 about 6° more than nominal which in turn would result in a rather large ΔV_z component (-28 fps) at DOI when the LDP processor is used. Because of the desire to eliminate this ΔV_z component at DOI, along with matching the Operational Trajectory (OT) g.e.t. times at the beginning of rev. 2 and at PDI, the decision was made to perform a BAP-4 MCC-4 maneuver of 5.4 fps. A MCC-4 maneuver of 1.9 fps would have been sufficient to correct the perilune altitude error and eliminate the resulting ΔV_z required at DOI, but would have done nothing to improve the rev. 2 crossing time or to match the PDI time with the OT. Another factor in favor of the more costly BAP-4 MCC-4 was that a 5.4 fps maneuver could be executed with the SPS while a 1.9 fps maneuver was below the SPS minimum impulse capability (~ 3 fps). The MCC-4 maneuver was executed on time at 73:31:14 g.e.t. Both the ΔV and burn time of the actual maneuver matched the planned values of 5.4 fps and .92 sec. indicating a very well executed maneuver. The vector used (CCHU24) to update the ephemeris immediately after MCC-4 showed a perilune altitude of 68.26 n.m. and a closest approach time of 78:35:06 g.e.t. Using the vector CCHU24 and running through LOI and DOI showed the following: 0.0 fps ΔV_z component at DOI, rev. 2 crossing at 80:40:35.17 g.e.t. was within 3 sec. of the OT value, PDI time of 104:28:55 g.e.t. matched the OT value to within 1 sec.

SIM-Door Jettison

Based upon the confirmed MCC-4 the spacecraft trajectory had a perilune altitude of 68.38 n.m. at 78:35:06 g.e.t. The SIM bay door was jettisoned at 74:06 g.e.t. and imparted less than .02 fps to the CSM/IM. A preliminary LOI maneuver pad which was very close to the OT was read up at 74:50 g.e.t.

Lunar Orbit Insertion

At 76:58 the "best available" state vector was ACNX275 which was based on fitting the previous 2 hrs. and 35 minutes of MSFN tracking (the tracking after the SIM-door jettison) with no apriori knowledge. Surprisingly, the corresponding perilune altitude was 69.71 n.m. with about a $.1^\circ$ change in inclination. The final LOI maneuver pad was computed using ACNX275 and voiced up at 77:33 g.e.t.

Shortly after LOS the final determination of the spacecraft trajectory gave perilune altitude as 68.75 n.m. with an inclination which was very close to the value from the confirmed MCC-4.

The LOI burn was executed perfectly--on time, and with zero velocity residuals in all three axes. However, the $.12^\circ$ error in inclination present in ACNX275 resulted in the post-LOI orbit being $.12^\circ$ out of plane from the desired value. It therefore appears that the perfect LOI execution was negated, insofar as achieving the proper planes, by the errors in the MSFN state on which the LOI targeting was based. Orbit shape after LOI was 170.1 by 57.7 n.m. as compared to the targeted 169.6 by 58.4 n.m.

DOI Maneuver

Nominally, DOI involves no plane change (ΔV_y) and is set up so that the radial component (ΔV_z) is near zero for ease of burn monitoring by the crew.

To recover from the error in the LPO orbit plane after LOI, a plane change was incorporated into the DOI maneuver. Beginning with the value of ΔV_y required to achieve the LLS using the "plane-change" and "circularization at a time" option of the LDPP, the FDO manually iterated on the components of the DOI maneuver. The final result was a 213.9 fps maneuver ($\Delta V_y = -48.0$ fps) which carried the IM over the LLS with a selenographic approach azimuth of 269.585° (nominal= 269.0°).

The DOI burn was on time and accurate enough that the burn itself was not trimmed. Orbit shape after the maneuver was 58.5 by 9.6 n.m., as compared to the planned 58.4 by 9.2 n.m.

DOI Trim

A DOI trim maneuver became necessary before the undocking of the CSM/IM because of a more rapid drop in perilune altitude than expected in the post-DOI orbit. Just prior to the trim maneuver, a perilune altitude of approximately 7 n.m. was noted, which was about 2 n.m. lower than expected at that time. The vector HSKX368 was used to compute the DOI trim maneuver which had an ignition time of 95:56:42.5 g.e.t. The planned ΔV and burn time of the maneuver were 3.1 fps and 20.36 sec., respectively. The actual maneuver was executed on time and achieved 3.2 fps in ΔV and 21.2 sec. in burn time. The resulting orbit achieved after the trim maneuver was 59.9 n.m. by 9.6 n.m.

CSM Circularization Maneuver

Two revs. prior to the lunar landing the CSM is placed in an orbit which will perturb into a 60 n.m. circular orbit at the nominal time of IM ascent.

The real-time plan called for a 68.3 fps SPS maneuver at 101:38:58 which would place the spacecraft in a 54.3 n.m. x 64.9 n.m. orbit. The actual burn was made on time and resulted in a 54.8 n.m. x 65.2 n.m. orbit.

LOPC

The lunar orbit plane change maneuver was computed from the vector NBEX555 with an ignition time at 165:11:32.0 g.e.t. The real-time-planned ΔV and burn time of the maneuver were 330.9 fps and 18.08 sec., respectively. The actual maneuver was executed on time and achieved 330.6 fps in ΔV and 18.06 sec. in burn time. Apolune and perilune of the resulting orbit were 64.5 n.m. and 53.6 n.m., respectively.

Shaping Maneuver and Subsatellite Jettison

The orbit shaping maneuver occurred on rev. 73 followed by the subsatellite jettison on rev. 74. The object of the shaping maneuver was to place the CSM in such an orbit that after jettison the estimated lifetime of the subsatellite's orbit would be greater than 1 year. The desired characteristics for the satellite orbit were the following:

$$h_a = 75 \pm 2 \text{ n.m.}$$

$$h_p = 55 \pm 2 \text{ n.m.}$$

$$\lambda_{pc} = 47^\circ W \text{ with an acceptable range of } 52^\circ W \text{ to } 37^\circ W$$

The force of the spring during jettison was simulated by a ΔV of 4 fps. Table 1 presents the comparison between the designed and actual shaping maneuver and jettison sequence. The shaping maneuver was performed well. The ignition was on time and the residuals were small. The jettison occurred 9 seconds late due to a signal delay that was not considered. The column of Table 1 labeled "confirmed" presents the resulting orbit for the confirmed jettison simulation. The final column of Table 1 presents the characteristics of the satellite orbit resulting from post-jettison tracking of the satellite.

Transearth Injection

The transearth injection (TEI) occurred near the end of rev. 74 at a g.e.t. of 223:48:45. The burn was targeted to the same end conditions as the premission TEI, namely, to the "end of mission" target line (EOM, $158^\circ W$) at 295 hours g.e.t. with a 40° ascending inclination. Forcing the inclination up to 40° cost 140 fps, and there had been some concern prior to the mission that this would not leave a sufficient ΔV reserve for weather avoidance in the event of large SPS

translunar midcourse maneuvers and/or low engine performance. However, the MPT indicated a post-TEI SPS ΔV reserve of approximately 430 fps, well above the required reserve for weather avoidance.

The planned burn of 3046.8 fps was generated on the CROX762 vector, which consisted of data from rev. 72 and rev. 73 up to the shape maneuver. The planned TEI frozen on a rev. 74 tracking vector (RIDX767) indicated a γ_{EI} of -6.76° which corresponds to a MCC-5 ΔV of .4 fps.

The execution of the TEI burn was near perfect, with trimmed \vec{V}_G residuals of $(-.2, +.6, +.2)$. The burn was on time, and the confirmed burn duration agreed with the planned. The executed TEI, based on confirming the burn with the trimmed \vec{V}_G residuals, indicated a γ_{EI} of -7.13° which corresponds to a MCC-5 ΔV of .9 fps. A post-TEI 2-hour tracking vector (RIDX788) indicated a γ_{EI} of -7.21° ; further tracking showed the spacecraft closer to the center of the corridor.

Column 1 of Table 2 shows the premission TEI based on the final Apollo 15 OT. Columns 2 and 3 show the preliminary and final planned maneuvers, while column 4 shows the final TEI frozen on the best pre-burn tracking vector. Column 5 shows the executed burn based on the confirmed \vec{V}_G residuals. The last column shows the entry conditions based on a tracking vector at TEI+5 hours.

Transearth Midcourses

Table 3 presents the entry and perigee conditions on several transearth state vectors as well as the targeted entry conditions. The entry conditions were initially steeper than the targeted γ of -6.50° and finally at MCC-7 time were shallower than nominal. At MCC-5 time the entry γ was -6.69° which would require a 0.3 fps maneuver to correct back to nominal. The maneuver threshold at MCC-5 is 1 fps. The MCC-6 vector predicted a nominal entry flightpath angle. Thus neither MCC-5 nor MCC-6 were performed. At MCC-7 time the entry γ had risen to -5.82° , and consequently the maneuver was now 5.6 fps and well outside the threshold limit.

The MCC-7 maneuver was executed and its characteristics are presented in Table 4. The maneuver was performed within the accuracy of the sensing instruments which resulted in no confirmation being performed. A post-MCC-7 vector, the final column of Table 3, verifies the accurate execution of MCC-7.

Conclusions

It appears that the high degree of accuracy at translunar injection was attributable to the IU-navigation update made in earth orbit, coupled with near-perfect execution of the burn itself.

The perfect LOI execution was negated, insofar as achieving the proper orbital plane, by the errors in the MSFN state on which the LOI targeting was based.

Perturbations from the spacecraft (PTC startup/stop, water dumps, etc.) caused the entry flightpath angle to change from -7.2° (after TEI) to -5.82° (at MCC-7 time).

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4 Enclosures

FM54/RSDavis:QAHolmes:GILNorbraten:RHSanders:jrh:8/30/71

Table 1.

Shaping Maneuver and Satellite Jettison Parameters

<u>Maneuver</u>	<u>Parameter</u>	<u>Units</u>	<u>Apollo 15 O.T.</u>	<u>Realtime Plan</u>	<u>Confirmed</u>	<u>Tracking</u>
Shape	Vector	-	-	NBEX744	NBEX744	TEXX467
	GETI	h:m:s	221:25:51.6	221:20:47.2	221:20:47.2	
	BT	sec	3.38	3.32	3.32	
	ΔV	fps	64.2	66.4	66.4	
Post Shape	h_a (a)	n. mi.	77.0	76.1	76.0	
	h_p (a)	n. mi.	56.9	54.3	54.3	
	λ_{pc}	deg	47.3198 W	47.8318 W	48.1284 W	
Jettison	GETI	h:m:s	222:36:12.7	222:39:27.0	222:39:36.0	234:48:43 ^(b)
	ΔV estim	fps	4.0	4.0	4.0	
Post-Jett	h_a (a)	n. mi.	77.5	76.5	76.3	75.1
(Satellite Orbit)	h_p (a)	n. mi.	57.6	55.1	55.1	57.3
	λ_{pc}	deg	42.6250 W	47.2097 W	47.4941 W	47.594 W
	period	sec.	7202	7185	7184	7188

(a) Altitudes measured above a lunar radius = 937.1680 n. mi.

(b) Time is g. e. t. of the vector

Table 2.

TEI COMPARISON TABLE

	<u>Final Prepermission O.T.</u>	<u>Planned (Preliminary TEI 74 Pad)</u>	<u>Planned (Final TEI 74 Pad)</u>	<u>Frozen on Rev 74 Vector</u>	<u>Confirmed</u>	<u>Post Burn Tracking Vector TEI + 5 Hrs</u>
Vector	-	NBEX744	CROX762	RIDX767	RIDX767	RIDX788
Ignition Time (GET)	223:46:06	223:48:44	223:48:45	223:48:45	223:48:45	-
(GMT)	237:20:06	237:22:45	237:22:46	237:22:46	237:22:46	-
TEI ΔV (fps)	3049.7	3047.7	3046.8	3046.8	3047.0	-
Burntime(min:sec)	2:17.8	2:21.6	2:21.2	2:21.2	2:21.2	-
Entry Time (GET)	294:58:20	294:58:11	294:58:05	294:58:02	294:57:45	294:57:43
Vr(fps)	36097	36097	36097	36097	36097	36097
λr (deg)	-6.49	-6.49	-6.49	-6.76	-7.13	-7.21
ir(deg)	40.0	40.0	40.0	40.0	40.0	40.0
Landing Time (GET)	294:11:50	295:11:39	295:11:34	-	-	-
ϕip (deg:min)	26:08 N	26:07 N	26:07 N	-	-	-
λip (deg:min)	158:00 W	157:59 W	157:59 W	-	-	-
hvp (n. mi.)	-	21.2	21.1	17.5	11.9	10.8
Perigee Time (GET)	-	295:00:25	295:00:20	295:00:22	295:00:12	295:00:10
MCC-5 ΔV	0.0	0.0	0.0	0.4	0.9	1.0

Table 3.

Entry and Perigee Conditions from Selected TEC States

<u>Parameter</u>	<u>Units</u>	<u>Planned TEI Target</u>	<u>Confirmed TEI</u>	<u>MCC5</u>	<u>MCC6</u>	<u>Pre MCC7</u>	<u>Entry</u>
Vector ID	-	-	RIDX 767	GWMX816	CRØX895	CRØX987	CRØX020
GET EI	h:m:s	294:58:5	294:57:45	294:58:6	294:58:37	294:59:11	294:58:54
V EI	fps	36097	36097.0	36097.1	36097.1	36097.2	36096.4
λ EI	deg	-6.50	-7.13	-6.69	-6.50	-5.82	-6.51
IR	deg	40.0	40.0	40.1	40.1	40.1	40.1
GET VP	h:m:s	295:0:20	295:0:12	295:0:24	295:0:52	295:1:11	295:1:9
H VP	n. mi.	21.1	11.9	18.4	21.1	30.1	21.0

Table 4.

Midcourse 7 Parameters

<u>Parameter</u>	<u>Units</u>	<u>Post-MCC7 Estimate</u>
Vector		CROX987
GET I	h:m:s	291:56:48
ΔV	fps	5.6
BT	sec	24.2
GET EI	h:m:s	294:58:55
VR	fps	36096
λ_R	deg.	-6.49
IR	deg.	40.1
GET L	h:m:s	295:12:24
Landing lat.	deg:min	26:8 N
Landing long.	deg:min	158:9 W