MSC-01562

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MSC INTERNAL NOTE NO. 70-FM-20

FEBRUARY 5, 1970

THE APOLLO 11 ADVENTURE

(This document supersedes 69-FM-270)

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

MSC INTERNAL NOTE NO. 70-FM-20

PROJECT APOLLO

THE APOLLO 11 ADVENTURE

February 5, 1970

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

CONTENTS

Section Page

PART I - THE ACCOMPLISHMENT 1-1

PART II - THE ROLE OF MPAD 2-1

PART III - AFTERTHOUGHTS 3-1

THE APOLLO 11
ADVENTURE

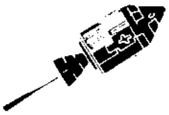
PART I
THE ACCOMPLISHMENT

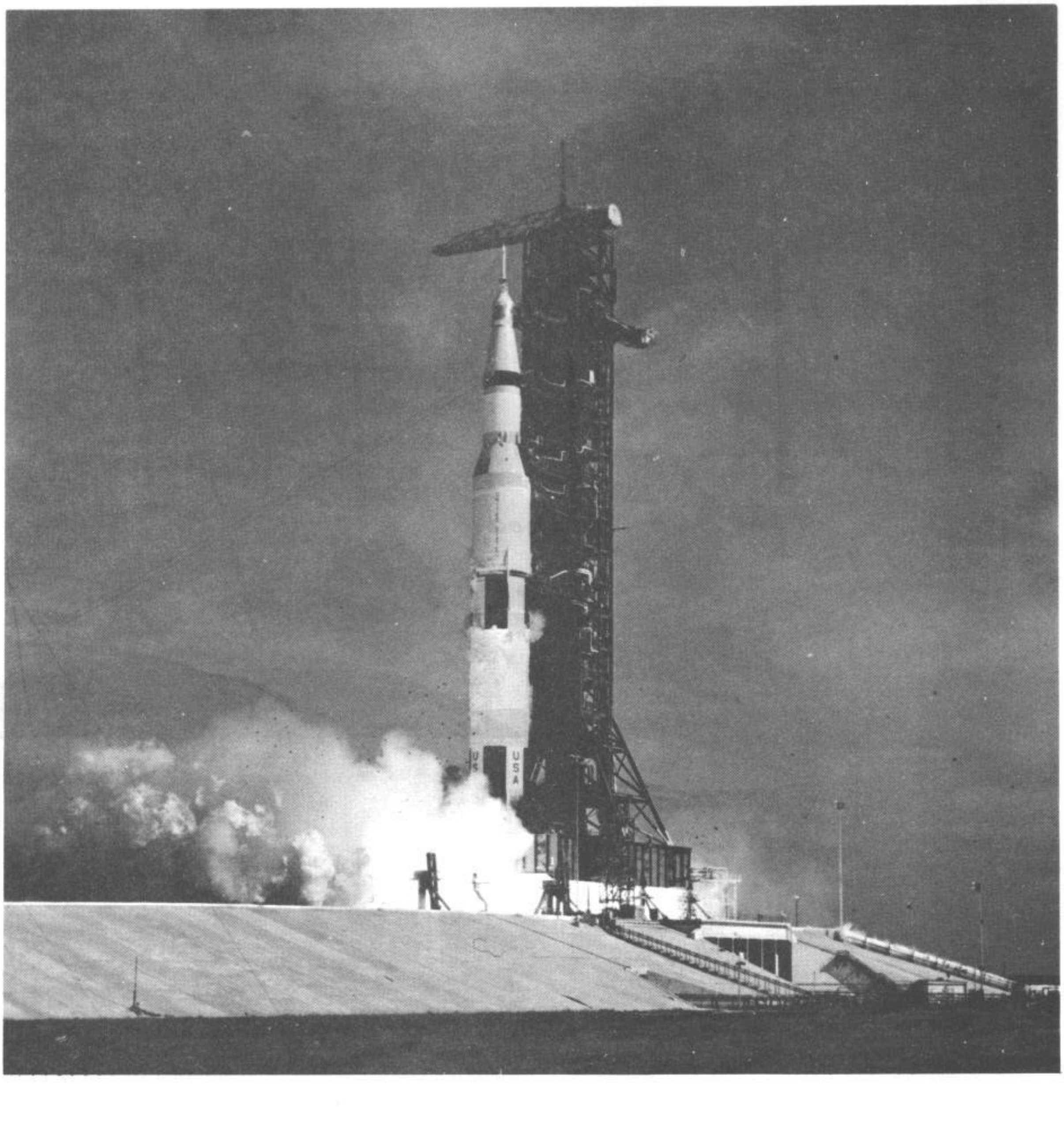
"I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth"......

John F. Kennedy

to Congress

May, 1961




USA

DAY 1

Day 1 of the Apollo 11 flight to the moon was Wednesday, July 16, 1969. Commander (CDR) Neil A. Armstrong, lunar module pilot (LMP) Edwin E. Aldrin, and command module pilot (CMP) Michael A. Collins began the 75-hour trip when the launch stage ignited at $13^h32^m00.78^s$ G.m.t. (8^h32^m a.m. c.d.t.). No unscheduled holds had occurred.

* *

00 00 03 17 CDR Tower's gone.

00 00 03 19 CC Roger. Tower.

00 00 03 28 CDR Houston, be advised the vision is GO today.

00 00 03 32 CC This is Houston. Roger. Out.

00 00 03 36 CDR Yes. They finally gave me a window to look out.

* *

At $11^m49.3^s$ g.e.t., they were in orbit. The Saturn V ignition, holddown release, and lift-off had been within the expected limits; the Saturn V systems performed at or near nominal. At insertion, the velocity and flight-path angle were 25 568 fps and 0.01°, respectively, and the S-IVB/CSM/LM vehicle was in a nominal earth parking orbit: 102.5-n. mi. apogee and 99.4-n. mi. perigee.

Telemetry data dropouts occurred during the Bermuda and USNS Vanguard station coverage of launch apparently because the CSM omni antenna D was not selected at the scheduled time. The crew attempted a brief television transmission over Goldstone during the first revolution to check out the TV camera. Because of the low elevation angle, the transmission was not received successfully. However, MILA later received approximately 1 minute of usable TV signal, which indicated that the system was operating satisfactorily.

At 1^h45^m g.e.t., the SM RCS quad B package temperature was low, 101° F instead of 122° F. The crew determined that the primary switch was still open. When the switch was closed, the temperature rose to normal.

Pretranslunar injection (TLI) checkout was conducted, and the S-IVB TLI maneuver began on time at $2^h44^m16.2^s$ g.e.t. The burn was nominal: it lasted 347.3 seconds and imparted a ΔV of 10 441 fps. End conditions were nominal for translunar coast on a free-return, circumlunar trajectory. At this time, it was predicted that the S-IVB/CSM/LM would come within 701.9 n. mi. of the moon at $75^h16^m23^s$ g.e.t. if no other burn occurred.

After TLI, four maneuvers were executed. The CSM was separated from the S-IVB/LM at approximately 3^h17^m g.e.t.; transposition occurred; and then the CSM docked with the LM by 3^h29^m. The LM/CSM was reported to be extracted from the S-IVB at $4^h16^m59.1^s$ g.e.t. A 19.7-fps SPS evasive maneuver was executed for 3.4 seconds on time at $4^h40^m01^s$. The ΔV was the desired amount, but the maneuver was slightly longer than had been planned. The result was a trajectory that would have taken the vehicle within 180.8 n. mi. of the moon at $75^h38^m22^s$. The 119-fps S-IVB slingshot maneuver began at approximately 5^h g.e.t. and resulted in a trajectory that successfully avoided both lunar impact and earth capture. The point closest to the moon was estimated to be approximately 1825 n. mi. and occurred at $79^h12^m30^s$ g.e.t.

* *

00 03 37 58 CC Roger. Could you give us comments on how the transposition and docking went? Over.

00 03 38 07 CMP I thought it went pretty well, Houston, although I expect I used more gas than I've been using in the simulation. The turnaround maneuver - I went PITCH ACCEL COMMAND and started to pitch up, and then when I put MANUAL ATTITUDE PITCH back to RATE COMMAND for some reason - it stopped its pitch rate, and I had to go back to ACCEL COMMAND and hit what I thought was an extra PROCEED on the DSKY. During the course of that, we drifted slightly further away from the S-IVB than I expected. I expected to be out about 66 feet. My guess would be around 100 or so; and therefore, I expect I used a bit more coming back in. But, except for using a little more gas - and I'd be interested in your numbers on that - everything went nominally.

* *

Communications were lost during transposition and docking because the spacecraft omni antennas were not changed during the maneuver. After docking, the high gain antenna was selected and communications were restored. The crew reported an anomaly on both the primary and secondary propellant isolation valves of RCS quad B at CSM separation. During transposition, docking, and ejection, more SM RCS propellant was used than had been planned.

Star-earth horizon navigation sightings proved difficult to obtain. The CM mission simulator at MSC was configured to reproduce the procedure in order to develop a fix to use Thursday. The scarcity of good sightings contributed to a higher than expected SM RCS propellant.

An unscheduled 16-minute television transmission was recorded at the Goldstone station beginning at $10^{h}32^{m}$ g.e.t. The tape was played back at Goldstone and was transmitted to Houston beginning at $11^{h}26^{m}$ g.e.t. The quality was excellent.

* *

(during TV transmission)

00 10 39 36 CMP Okay, Houston. You suppose you could turn the earth a little bit so we can get a little bit more than just water?

00 10 39 45 CC Roger, 11. I don't think we got much control over that. Looks like you'll have to settle for the water.

* *

At the planned time ($11^{h}30^{m}$ g.e.t.) of the first midcourse correction maneuver (MCC-1), the ΔV required was 17.1 fps and would increase to only 21.2 fps at the planned time of MCC-2 ($26^{h}45^{m}$ g.e.t.). Therefore, MCC-1 was cancelled.

Toward the end of the first day of flight, the oxygen flow rate was reading significantly lower than expected. It was suspected that the cabin oxygen enrichment purge was not progressing satisfactorily in comparison to previous missions. This condition could occur if a waste storage vent valve was closed or if the overdump line was restricted.

At $21^{h}28^{m}$ g.e.t., 6:00 c.d.t., July 17, 1969, the CSM/LM weight was 96 361 pounds, the velocity was 5667 fps, and the vehicle was 93 236 n. mi. from earth.

DAY 2

On the second day of the Apollo 11 flight, at approximately 26^h10^m g.e.t., the crew oriented the spacecraft for star-earth horizon navigation sightings. Omni A was the optimum antenna, and it was used for the first time.

* *

01 00 45 35	CMP	It's really a fantastic sight through that sextant. A minute ago, during that AUTO maneuver, the reticle swept across the Mediterranean. You could see all of North Africa, absolutely clear; all of Portugal, Spain, Southern France; all of Italy, absolutely clear. Just a beautiful sight.
01 00 45 54	CC	Roger. We all envy you the view up there.
01 00 45 59	CMP	But still no star.

* *

Because delay of MCC-2 until the time scheduled for MCC-3 would have made the ΔV prohibitive, MCC-2 was performed at $26^h44^m58^s$ g.e.t. The MCC-2 was a 3.1-second SPS burn. The ΔV was 20.9 fps. (A ΔV of 21.3 fps was planned.) Just before MCC-2, the high gain antenna (HGA) in the AUTO TRACK mode was selected for use, and high bit rate data were received continuously during the burn. Up- and down-link signal strength data agreed very well with predicted values for both the HGA and the omni antennas. The MCC-2 burn parameters appeared nominal, and perilune of the resultant trajectory was predicted to be 61.5 n. mi.

An unscheduled television transmission was received and recorded at Goldstone between 30^h28^m and 31^h18^m g.e.t. Because the spacecraft was in passive thermal control (PTC) and transmission was through omni antennae, the picture quality varied from fair to unusable. The picture quality of the scheduled transmission at 33^h59^m g.e.t., when the HGA was used, was good.

* *

01 10 14 14	CMP	I would have put on a coat and tie if I'd known about this ahead of time.
01 10 14 18	CC	Is Buzz holding your cue cards for you? Over.
01 10 14 25	CMP	Cue cards have a no. We have no intentions of competing with the professionals, believe me...

* *

On the second day of flight, the PTC mode worked nominally and spacecraft controls were within acceptable limits. A high oxygen flow rate through fuel cell 3 was experienced during the oxygen purge and activated the master caution and warning alarm. After purge and reset, the system returned to normal. Consumable usage rates remained within acceptable limits. The predicted closest approach to the moon by the S-IVB was 1825 n. mi. at 79^h13^m g.e.t.

At 6:00 c.d.t., 45^h28^m g.e.t., on July 18, 1969, the CSM/LM weight was 96 068 pounds, the velocity was 3653 fps, and the vehicle was 155 600 n. mi. from earth.

DAY 3

On the third day of the Apollo 11 flight, both MCC-3 (scheduled for the third day) and MCC-4 (scheduled for the fourth day) were cancelled. Both maneuvers would have required a very small ΔV, and the lunar orbit insertion (LOI) targeting could compensate for any residuals in perilune conditions. The MCC-3 was computed to be 0.83 fps at 53^h55^m g.e.t.; and MCC-4, to be 2.6 fps at 70^h55^m g.e.t. Slight changes in the LOI maneuvers (LOI-1 and LOI-2) resulted from performance of only one midcourse during translunar coast.

The crew began a 96-minute color television transmission at 55^h08^m g.e.t. An audience in North and South America, Japan, and Western Europe saw the Apollo 11 crew remove the probe and drogue, open the spacecraft tunnel hatch, and perform LM housekeeping. The picture quality and resolution were excellent.

* *

02 07 31 11	CC	We can see the LM umbilical connection quite well there, Buzz; we see you zooming in on one of the decals now. It's, "To reset, unlatch handle; latch behind grip and pull back two full strokes." That's about all we can make out.
31 35	LMP	Hey, you get an A+.
31 37	CC	Thank you very much, sir. At least I passed my eye test.
31 46	LMP	I'm standing six feet from it, Charlie, and you can read it better than I can. There's something wrong with the system.

* *

Cabin pressure during LM pressurization increased to approximately 5.5 psia. Surge tank pressure decay data were obtained when the direct oxygen valve was opened and indicated an oxygen flow rate of about

4.5 to 5.5 lb/hr. The oxygen flow meter was pegged at the upper limit (0.981 lb/hr) during this time, and the oxygen flow high caution and warning alarm was activated when the direct oxygen valve was opened.

The master alarm also occurred when the direct oxygen valve was positioned closed, and the oxygen flow was increasing from the upper limit. (This condition is abnormal, but it had occurred occasionally during tests at KSC.) The remaining environmental control system (ECS) parameters were normal. The water accumulator in the LM for the suit liquid cooling assembly was reported to have an indicator position of 1/4 inch to 3/8 inch into the green. This reading is indicative of approximately 16.5 psig and is well within the expected range for accumulator level. The actual initial ingress by the LM pilot occurred at 55^h38^m g.e.t.

* *

02 08 37 44	CC	Roger. Must be some experience. Is Collins going to go in and look around?
02 08 37 56	CDR	We're willing to let him go, but he hasn't come up with the price of a ticket yet.
02 08 38 01	CC	Roger. I'd advise him to keep his hand off the switches.
02 08 38 08	CDR	If I can get him to keep his hands off my DSKY it'd be a fair swap.

* *

The spacecraft passed into the moon's sphere of influence at $61^h39^m55^s$ g.e.t. The earth-referenced position and velocity were 186 436 n. mi. and 2990 fps, respectively. The corresponding moon-referenced values were 33 823 n. mi. and 3772 fps, respectively.

The CM ECS oxygen flow anomaly that appeared Wednesday seems to have been caused by a calibration shift toward the low end of the oxygen flow transducer. Because this measurement was not dependable, other measurements were used to provide comparable information. The condenser exit temperature on fuel cell 2 continued to fluctuate. It decreased approximately 1°F to 2°F every 5 minutes. (A similar condition occurred on fuel cell 2 during Apollo 10. The cause of the disturbance seems to be associated with the cooling fluid stream.)

Use of all consumables remained within predicted limits Friday. Propellant usage from the service module (SM) reaction control system (RCS) remained somewhat above preflight predictions. Temperatures which respond to passive thermal control were well within operational limits.

An updated calculation (69^h) predicted that the S-IVB point closest to the moon would be 2339 n. mi. at $79^h20^m35^s$ g.e.t.

At 6:00 c.d.t., 69^h28^m g.e.t., July 19, 1969, the CSM/LM weighed 96 012 pounds, moved with a velocity of 3973 fps (moon-referenced), and was 16 250 n. mi. from the moon.

DAY 4

On the fourth day of the Apollo 11 flight, the CSM/LM entered lunar orbit. (The MCC-4 scheduled for 75^h54^m g.e.t. had already been cancelled.) The SPS performed LOI-1 at $75^h49^m50.5^s$ g.e.t. This 2918-fps retrograde burn lasted 362 seconds and placed the spacecraft in an elliptical orbit with a 169.7-n. mi. apolune and a 60.0-n. mi. perilune. The SPS operated nominally during LOI-1 except for an apparent leak in the bank B gaseous nitrogen actuation system. After shutdown, the pressure stabilized, and there was no additional leakage.

* *

03 04 34 34	CDR	Apollo 11 is getting its first view of the landing approach. This time we are going over the Taruntius crater, and the pictures and maps brought back by Apollo 8 and 10 have given us a good preview of what to look at here. It looks very much like the pictures, but the difference between watching a real football game and watching it on TV. There's no substitute for actually being there.

* *

During the second revolution, at 78^h24^m g.e.t., the scheduled television broadcast began and continued for 34 minutes. Spectacular views of the lunar surface included the approach path to lunar landing site 2. A white spot at the bottom of the screen, first observed on Friday and attributed to a burn in the camera tube, was still present and was no longer expected to decrease in size.

* *

03 06 24 13	CC	Apollo 11, this is Houston. Affirmative. We are reading you loud and clear on voice and we have a good clear TV picture, a little bright crater in the - -
03 06 24 23	LMP	-- No, no, no --
03 06 24 24	CC	The bottom of the picture. I guess that's the spot on the tube.

* *

After two revolutions and a navigation update, the second SPS retrograde burn, LOI-2, was made at $80^h11^m36^s$. It lasted 17 seconds and changed the velocity by 159 fps. The resultant orbit had a 65.7-n. mi. apolune and a 53.8-n. mi. perilune. Because of the gaseous nitrogen leak, bank B of the SPS had been isolated after LOI-1, and LOI-2 was performed satisfactorily with bank A. All SPS parameters were nominal after the burn.

After LOI-2, initial acquisition of signal at Goldstone occurred at $80^h34^m03^s$ g.e.t., and two-way lock using the HGA was established at $80^h35^m07^s$ g.e.t. A problem occurred with the Goldstone update buffer, and an uplink handover to Hawaii was attempted at $80^h40^m15^s$; communications were lost for approximately 6 minutes. Apparently at handover, the HGA slewed off. Communications were reestablished at $80^h46^m12^s$ when the crew made an HGA reaquisition.

The crew reported at 81^h29^m that moisture was found on the aft bulkhead. This moisture had been found after SPS burns on previous missions and apparently was a reaction to acceleration.

After LOI-2, the crew transferred to the LM and performed various housekeeping functions, a voice and telemetry test, and an oxygen purge system test for about 2 hours. The LM functions and consumables checked out, and both LM Hasselblad and Maurer cameras were determined to be operational. Later, lunar landmarks were tracked; the landmarks were well spaced and of good quality. The following news report was later relayed to the crew.

* *

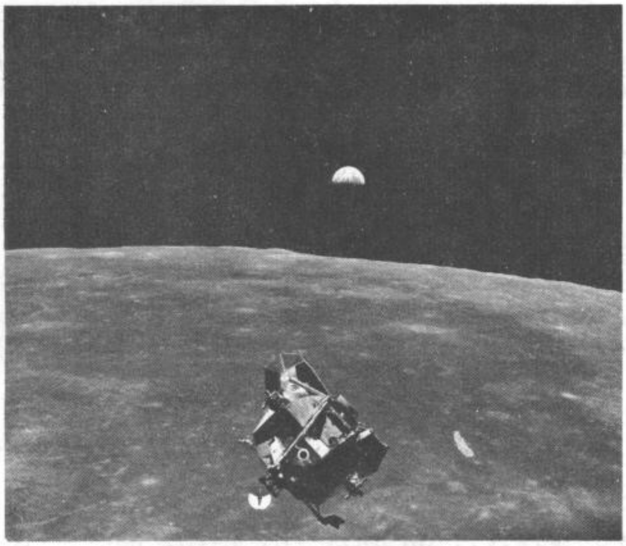
03 23 17 28	CC	Roger. Among the large headlines concerning Apollo 11 this morning, there's one asking that you watch for a lovely girl with a big rabbit. An ancient legend says a beautiful Chinese girl called Chang-O has been living there for 4000 years. It seems she was banished to the Moon because she stole some pills of immortality from her husband. You might also look for her companion, a large Chinese rabbit, who is easy to spot since he is always standing on his hind feet in the shade of a cinnamon tree. The name of the rabbit is not reported.
03 23 18 15	LMP	Okay. We'll keep a close eye out for the bunny girl.

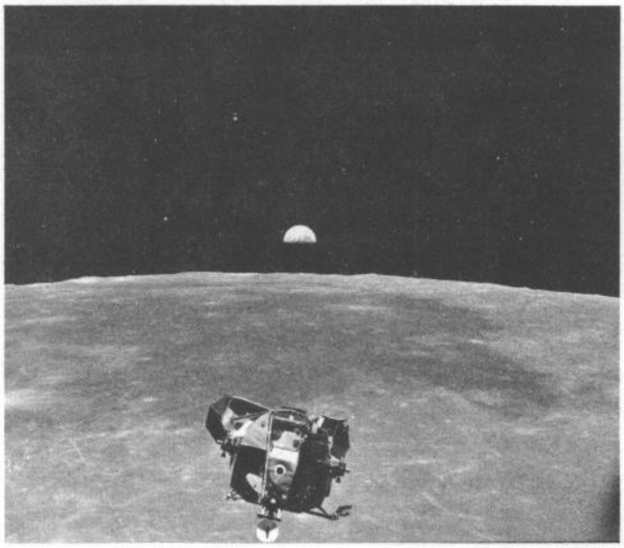
* *

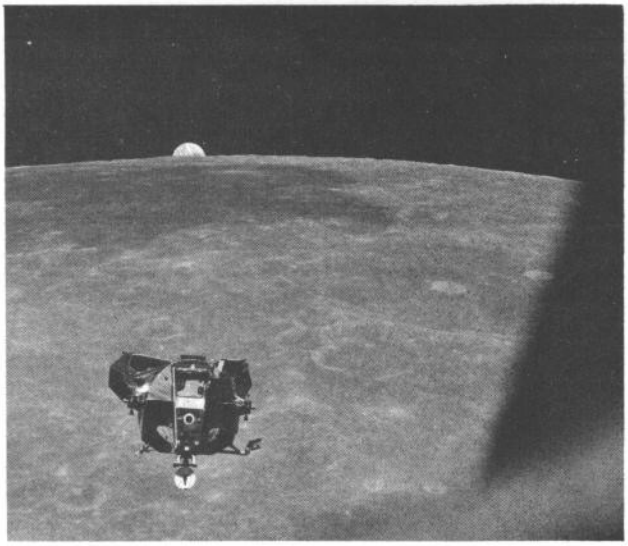
The CM ECS oxygen manifold pressure had been nominal throughout the mission and had responded properly to all oxygen demands. The oxygen flow transducer remained anomalous; its output apparently was as much as 3 lb/hr low. Flight crew checklist procedures were updated to provide alternate measurements. The CM was pressurized to approximately 15.2 psia before the LM pressure equalization valve was opened. The LM pressurization was normal, and the CM pressure decreased to 4.7 psia. The indicated oxygen overflow increased to 0.68 lb/hr as the cabin pressure regulator became active. These data suggested that the oxygen flow transducer was biased by 0.7 lb/hr toward the low end of the tranducer range.

Minor disturbances in fuel cell 2 condenser exhaust temperature continued to be observed, but no change in magnitude or period was noted.

At 6:00 c.d.t., 93^h28^m g.e.t., on July 20, 1970, the CM/LM weighed 70 321 pounds and was in a lunar orbit with a 64-n. mi. apolune and a 55.5-n. mi. perilune.







DAY 5

On day 5 of the Apollo 11 flight, the CDR and the LMP entered the LM at approximately 95^h20^m g.e.t. and thoroughly checked all LM systems in preparation for descent. The LM was undocked from the CSM at approximately 100^h12^m g.e.t. and stationkeeping began.

* *

04 04 18 01	CDR (Eagle)	Roger. Eagle is undocked.
04 04 18 03	CC	Roger. How does it look, Neil?
04 04 18 04	CDR (Eagle)	The Eagle has wings.

* *

At 100^h40^m g.e.t., the SM RCS was used to perform a small separation maneuver directed radially downward toward the center of the moon. The descent orbit insertion (DOI) maneuver was performed by a LM descent propulsion system (DPS) retrograde burn one-half revolution after LM/CSM separation, and the LM was placed in an elliptical orbit with a perilune of 8.5 n. mi.

The LM to Manned Space Flight Network (MSFN) communication system provided the voice and data required for the powered descent. Prior to the yaw maneuver, continuous steerable antenna AUTO-TRACK could not be maintained, and the aft omni had to be selected. After the yaw maneuver, the steerable antenna was required, and the antenna tracked perfectly through touchdown. The communication system performed nominally after landing except for an unexplained echo heard on the voice channel at the Mission Control Center during the EVA. Television through the Parks 210-foot antenna and EVA data through the MARS 210-foot antenna were good.

The LM powered descent initiation (PDI) maneuver was initiated at perilune of the descent orbit. The time of the maneuver was as planned.

During the final approach phase, the crew noted that the landing point toward which the spacecraft was headed was in the center of a larger crater which appeared extremely rugged. The crater contained boulders 5 to 10 feet in diameter and larger. Consequently, the crew elected to fly to a landing point beyond this crater. The additional maneuvering to translate beyond the rough terrain required manual attitude control and fine adjustments of the rate of descent in addition to high horizontal velocity. The final landing point was estimated to be nearly 4 miles down range from the planned point. Descent engine cutoff occurred at $102^{h}45^{m}45^{s}$ g.e.t. ($3^{h}17^{m}45^{s}$ p.m. c.d.t.) after probe contact indication. Onboard inertial system coordinates of the landing point were 0.69°N, 23.46°E. Exact coordinates were later determined to be 0.636°N and 23.50°E. This location was named Tranquility Base.

* *

04 06 28 08	CC	Eagle, Houston. If you read, you're GO for powered descent. Over.
04 06 28 18	CMP (COLUMBIA)	Eagle, this is Columbia. They just gave you a GO for powered descent.
04 06 28 22	CC	Columbia, Houston. We've lost them on the high gain again. Would you please - We recommend they yaw right 10 degrees and reacquire.
04 06 28 34	CMP (COLUMBIA)	Eagle, this is Columbia. You're GO for PDI and they recommend you yaw right 10 degrees and try the high gain again.
04 06 28 46	CMP (COLUMBIA)	Eagle, you read Columbia?
04 06 28 48	LMP (EAGLE)	Roger. We read you.
04 06 28 49	CMP (COLUMBIA)	Okay.
04 06 28 51	CC	Eagle, Houston. We read you now. You're GO for PDI. Over.
		. . .
04 06 29 23	CC	Eagle, Houston. Your alinement is GO on the AGS. On my Mark, 3 30 until ignition.
04 06 29 29	LMP (EAGLE)	Roger.
04 06 29 33	CC	Mark.

04 06 29 34	CC	3 30 until ignition.
04 06 29 38	LMP (EAGLE)	Roger. Copy. Thrust translation - four jets - Balance couple - ON. TTCA throttle - MINIMUM. Throttle - AUTO CDR. Prop button - RESET. Prop button. Okay. ABORT/ABORT STAGE - RESET. ATT CONTROL - three of them to MODE CONTROL. Okay, MODE CONTROL is set. AGS is reading 400 plus 1. Standing by for ...
		...
04 06 33 09	LMP (EAGLE)	... 10 ... 10 percent ...
04 06 33 41	CC	Columbia, Houston. We've lost them. Tell them to go aft OMNI. Over.
04 06 33 51	CMP (COLUMBIA)	They've lost you. Use the OMNI's again.
04 06 34 01	LMP (EAGLE)	...
04 06 34 05	CMP (COLUMBIA)	Say again, Neil?
04 06 34 07	LMP (EAGLE)	I'll leave it in SLEW. Relay to us. See if they have got me now. I've got good signal strength in SLEW.
04 06 34 13	CMP (COLUMBIA)	Okay. You should have him now, Houston.
04 06 34 16	CC	Eagle, we've got you now. It's looking good. Over.
04 06 34 23	CC	Eagle --
04 06 34 24	LMP (EAGLE)	- - descent looks good.
04 06 34 25	CC	Eagle, Houston. Everything is looking good here. Over.
04 06 34 29	LMP (EAGLE)	Roger. Copy.
		...
04 06 34 59	LMP (EAGLE)	AGS and PNGS agree very closely.
04 06 35 01	CC	Roger.

04 06 35 14	LMP (EAGLE)	Beta ARM. Altitudes are a little high.
		...
04 06 36 18	CDR (EAGLE)	Our position checks down range show us to be a little long.
04 06 36 21	CC	Roger. Copy.
		...
04 06 37 22	CC	Roger. You are GO - You are GO to continue powered descent. You are GO to continue powered descent.
04 06 37 30	LMP (EAGLE)	Roger.
04 06 37 35	CC	And, Eagle, Houston. We've got data dropout. You're still looking good.
04 06 38 04	LMP (EAGLE)	... PGNS. We got good lock-on. Altitude lights OUT. DELTA-H is minus 2 900.
04 06 38 18	CC	Roger. We copy.
04 06 38 20	LMP (EAGLE)	Got the Earth right out our front window.
04 06 38 23	CDR (EAGLE)	Houston, you're looking at our DELTA-H?
04 06 38 25	CC	That's affirmative
04 06 38 26	CDR (EAGLE)	PROGRAM ALARM.
04 06 38 28	CC	It's looking good to us. Over.
04 06 38 30	CDR (EAGLE)	It's a 1202.
04 06 38 32	LMP (EAGLE)	1202.
04 06 38 48	CDR (EAGLE)	Give us a reading on the 1202 PROGRAM ALARM.
04 06 38 53	CC	Roger. We got - We're GO on that alarm.
04 06 38 59	CDR (EAGLE)	Roger. P30.

04 06 39 01	CC	6 plus 25, throttle down - -
04 06 39 02	LMP (EAGLE)	Looks like about 820 -
04 06 39 03	CC	- - 6 plus 25, throttle down.
04 06 39 06	CDR (EAGLE)	Roger. Copy. 6 plus 25.
04 06 39 14	LMP (EAGLE)	Same alarm, and it appears to come up when we have a 1688 up.
04 06 39 17	CC	Roger. Copy.
04 06 39 23	CC	Eagle, Houston. We'll monitor your DELTA-H.
04 06 39 24	LMP (EAGLE)	... worked out beautifully.
		...
04 06 39 30	CC	Roger. DELTA-H is looking good to us.
04 06 39 34	LMP (EAGLE)	Ah! Throttle down - -
04 06 39 35	CDR (EAGLE)	Throttle down on time!
04 06 39 36	CC	Roger. We copy throttle down - -
04 06 39 37	LMP (EAGLE)	- - ... throttles down. Better than the simulator.
04 06 39 42	CC	Roger.
04 06 39 48	LMP (EAGLE)	AGS and PGNS look real close.
04 06 40 08	CC	At 7 minutes, you're looking great to us, Eagle.
		...
04 06 41 01	LMP (EAGLE)	Give us an estimated switchover time please, Houston.
04 06 41 05	CC	Roger. Stand by. You're looking great at 8 minutes.
		...
04 06 41 12	CC	Eagle, you've got 30 seconds at P64.

04 06 41 15	LMP (EAGLE)	... Roger.
04 06 41 27	CC	Eagle, Houston. Coming up 8 30; you're looking great.
04 06 41 35	LMP (EAGLE)	P64.
04 06 41 37	CC	We copy.
04 06 41 51	CC	Eagle, you're looking great. Coming up 9 minutes.
04 06 42 05	CDR (EAGLE)	Manual attitude control is good.
04 06 42 08	CC	Roger. Copy.
04 06 42 10	CC	Eagle, Houston. You're GO for landing. Over.
04 06 42 17	LMP (EAGLE)	Roger. Understand. GO for landing. 3000 feet. PROGRAM ALARM.
04 06 42 19	CC	Copy.
04 06 42 22	LMP (EAGLE)	1201
04 06 42 24	CDR (EAGLE)	1201.
04 06 42 25	CC	Roger. 1201 alarm. We're GO. Same type. We're GO.
04 06 42 31	LMP (EAGLE)	2000 feet. 2000 feet. Into the AGS, 47 degrees.
04 06 42 35	CC	Roger.
04 06 42 36	LMP (EAGLE)	47 degrees.
04 06 42 41	CC	Eagle, looking great. You're GO.
04 06 42 58	CC	Roger. 1202. We copy it.
04 06 43 01	LMP (EAGLE)	35 degrees. 35 degrees. 750. Coming down to 23.
04 06 43 07	LMP (EAGLE)	700 feet, 21 down, 33 degrees.
04 06 43 11	LMP (EAGLE)	600 feet, down at 19.

04 06 43 15	LMP (EAGLE)	540 feet, down at - 30. Down at 15.
04 06 43 26	LMP (EAGLE)	At 400 feet, down at 9.
04 06 43 29	LMP	... forward.
04 06 43 32	LMP (EAGLE)	350 feet, down at 4.
04 06 43 35	LMP (EAGLE)	30, ... one-half down.
04 06 43 42	LMP (EAGLE)	We're pegged on horizontal velocity.
04 06 43 46	LMP (EAGLE)	300 feet, down 3 1/2, 47 forward.
04 06 43 51	LMP (EAGLE)	... up.
04 06 43 52	LMP (EAGLE)	On 1 a minute, 1 1/2 down.
04 06 43 57	CDR (EAGLE)	70.
04 06 44 04	LMP (EAGLE)	Watch your shadow out there.
04 06 44 07	LMP (EAGLE)	50, down at 2 1/2, 19 forward.
04 06 44 13	LMP (EAGLE)	Altitude-velocity light.
04 06 44 16	LMP (EAGLE)	3 1/2 down, 220 feet, 13 forward.
04 06 44 23	LMP (EAGLE)	11 forward. Coming down nicely.
04 06 44 24	LMP (EAGLE)	200 feet, 4 1/2 down.
04 06 44 26	LMP (EAGLE)	5 1/2 down.
04 06 44 31	LMP (EAGLE)	160, 6 - 6 1/2 down.
04 06 44 33	LMP (EAGLE)	5 1/2 down, 9 forward. That's good.

04 06 44 40	LMP (EAGLE)	120 feet.
04 06 44 45	LMP (EAGLE)	100 feet, 3 1/2 down, 9 forward. Five percent.
04 06 44 51	LMP (EAGLE)	...
04 06 44 54	LMP (EAGLE)	Okay. 75 feet. There's looking good. Down a half, 6 forward.
04 06 45 02	CC	60 seconds.
04 06 45 04	LMP (EAGLE)	Lights on. ...
04 06 45 08	LMP (EAGLE)	Down 2 1/2. Forward. Forward. Good.
04 06 45 17	LMP (EAGLE)	40 feet, down 2 1/2. Kicking up some dust.
04 06 45 21	LMP (EAGLE)	30 feet, 2 1/2 down. Faint shadow.
04 06 45 25	LMP (EAGLE)	4 forward. 4 forward. Drifting to the right a little. Okay. Down a half.
04 06 45 31	CC	30 seconds.
04 06 45 32	CDR (EAGLE)	Forward drift?
04 06 45 33	LMP (EAGLE)	Yes.
04 06 45 34	LMP (EAGLE)	Okay.
04 06 45 40	LMP (EAGLE)	CONTACT LIGHT.
04 06 45 43	LMP (EAGLE)	Okay. ENGINE STOP.
04 06 45 45	LMP (EAGLE)	ACA - out of DETENT.
04 06 45 46	LMP (EAGLE)	Out of DETENT.
04 06 45 47	LMP (EAGLE)	MODE CONTROL - both AUTO. DESCENT ENGINE COMMAND OVERRIDE - OFF. ENGINE ARM - OFF.

04 06 45 52	LMP (EAGLE)	413 is in.
04 06 45 57	CC	We copy you down, Eagle.
04 06 45 59	CDR (TRANQ)	Houston, Tranquility Base here.
04 06 46 04	CDR (TRANQ)	THE EAGLE HAS LANDED.
04 06 46 06	CC	Roger, Tranquility. We copy you on the ground. You got a bunch of guys about to turn blue. We're breathing again. Thanks a lot.
04 06 46 16	CDR (TRANQ)	Thank you.

* *

The LM radar system performed nominally throughout descent. The landing radar acquired the lunar surface and provided altitude data when the slant range was 38 000 to 41 000 feet. Velocity data were provided when the slant range was 22 000 to 26 000 feet. As expected two velocity measurements were lost because of zero Doppler conditions in the vicinity of 100 to 300 feet. Landing radar continued down to an altitude of approximately 25 feet.

At 105^h g.e.t., the automatic evaporator inlet temperature apparently malfunctioned. The temperature measured at the evaporator outlet decreased to 31°F. The condition was corrected by cycling the control switch from AUTO to MANUAL and back to AUTO. Performance later returned to normal.

It was reported by the crew after lunar landing that the mission timer had malfunctioned. Initial efforts to correct this malfunction were not successful, but after EVA, the timer was successfully reactivated.

The LM tilted on the surface 4.5° from the vertical and yawed left 13°. The crew indicated that the landing site area contained numerous boulders of varying shapes and sizes. The surface color varied from very light to dark gray. From his window view, the CDR reported that he could see some boulders that were apparently fractured by engine exhaust and that the surface of these boulders appeared to be coated light grey while the fractures were much darker. At zero phase angle (between sun angle and viewing angle), the surface was reported to be almost white. A hill could be seen at approximately 0.5 mile to 1 mile in front of the LM.

Soon after lunar landing, the LM oxidizer and supercritical helium tanks then the fuel tanks were vented. When venting was completed, the fuel interface pressure began to rise rapidly. The vent valves were reopened, but the pressure rise was not stopped. While the oxidizer tank was being vented, the supercritical helium was also being vented through the oxidizer tank. The helium passes through a heat exchanger used to transfer heat from the fuel to the helium when the engine is firing. Because the engine was off, no fuel was flowing, and the cold helium froze the fuel in the heat exchanger. Heat soakback from the engine caused the fuel trapped between the frozen heat exchanger and the closed engine valve to expand, which produced the rapid pressure rise observed. Then, after approximately 1 hour, the heat exchanger thawed as it absorbed heat in the engine compartment.

The crew indicated that they could immediately adapt to the one-sixth gravity in the LM and moved very easily in this environment. Approximately 2 hours after landing, the crew requested that the extravehicular activity (EVA) be accomplished prior to the sleep period or about 4.5 hours earlier than originally scheduled. The rest period originally planned to occur prior to EVA was slipped until post-EVA and was added to the second sleep period.

After the postlanding checks, the LM hatch was opened at $101^h07^m35^s$ g.e.t. The CDR's first step on the moon occurred at $102^h24^m25^s$ g.e.t. ($9^h56^m25^s$ p.m. c.d.t.).

* *

04 13 23 38	CDR (TRANQ)	I'm at the foot of the ladder. The LM footpads are only depressed in the surface about 1 or 2 inches, although the surface appears to be very, very fine grained, as you get close to it. It's almost like a powder. Down there, it's very fine.
04 13 23 43	CDR (TRANQ)	I'm going to step off the LM now.
04 13 24 48	CDR (TRANQ)	THAT'S ONE SMALL STEP FOR A MAN, ONE GIANT LEAP FOR MANKIND.

* *

He made a brief check of the LM exterior and indicated that penetration of the footpads was only about 1 or 2 inches and that collapse of the struts was minimal. He reported sinking approximately 1/8 inch into the fine, powdery surface material, which adhered readily to his lunar boots in a thin layer. No crater was formed from the effects of the descent engine, and about 1 foot of clearance was observed between the engine bell and the lunar surface. The CDR also reported that it was quite dark in the shadows, which made it difficult for him to see his footing.

The CDR then collected a contingency sample of lunar soil from the vicinity of the LM ladder. He reported that, although the surface material was loose and soft he encountered very hard cohesive material as he dug down 6 to 8 inches.

* * *

04 13 34 56	CDR	It has a stark beauty all its own. It's like much of the high desert of the United States. It's different but it's very pretty out here.

* * *

The CDR photographed the LMP's egress and descent to the lunar surface. The CDR and LMP then unveiled and read the plaque mounted on the strut behind the ladder. Next, the CDR removed the TV camera from the descent stage, obtained a panorama, and placed the camera on its tripod in a position to view the subsequent surface EVA operations.

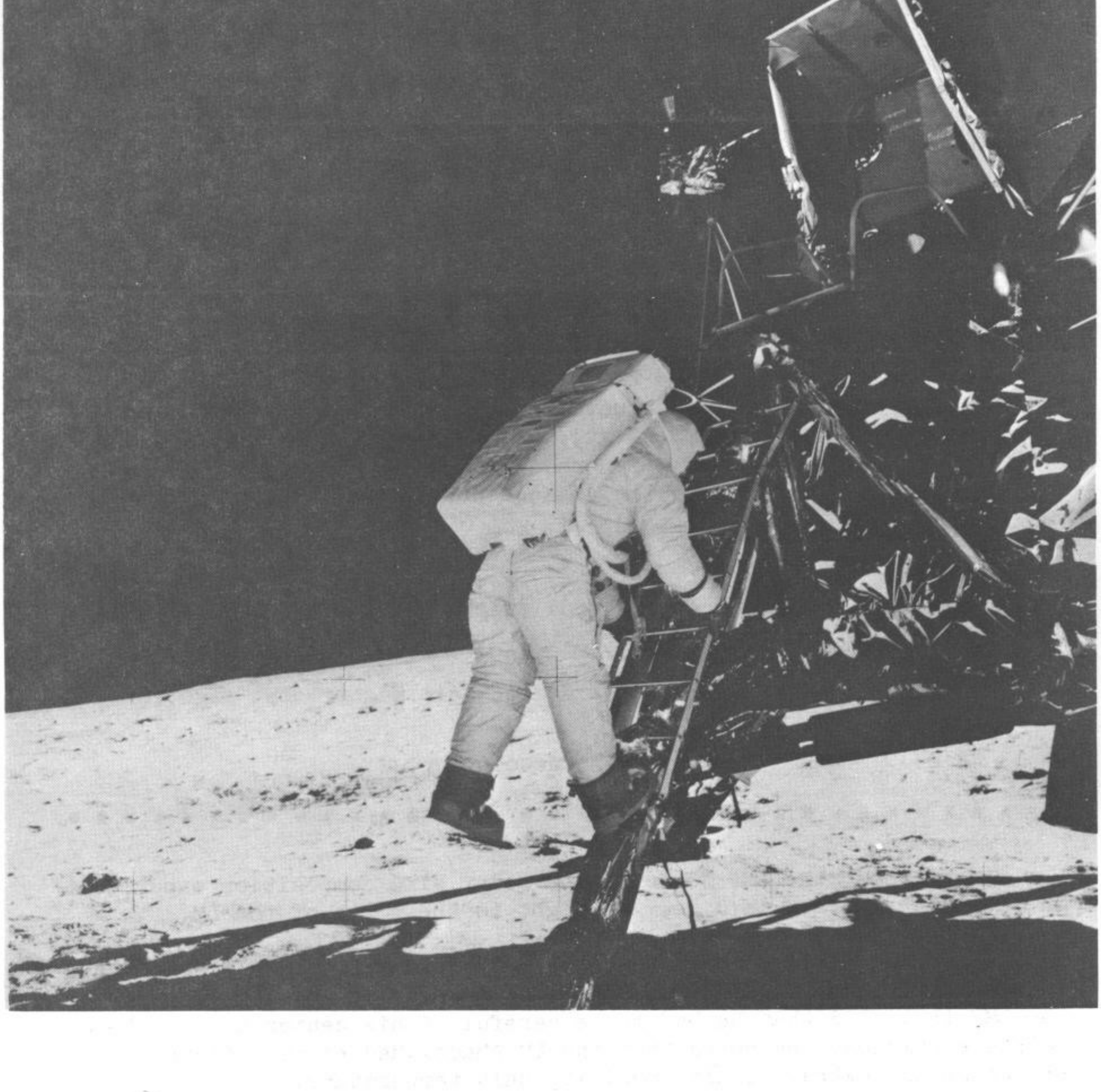
* * *

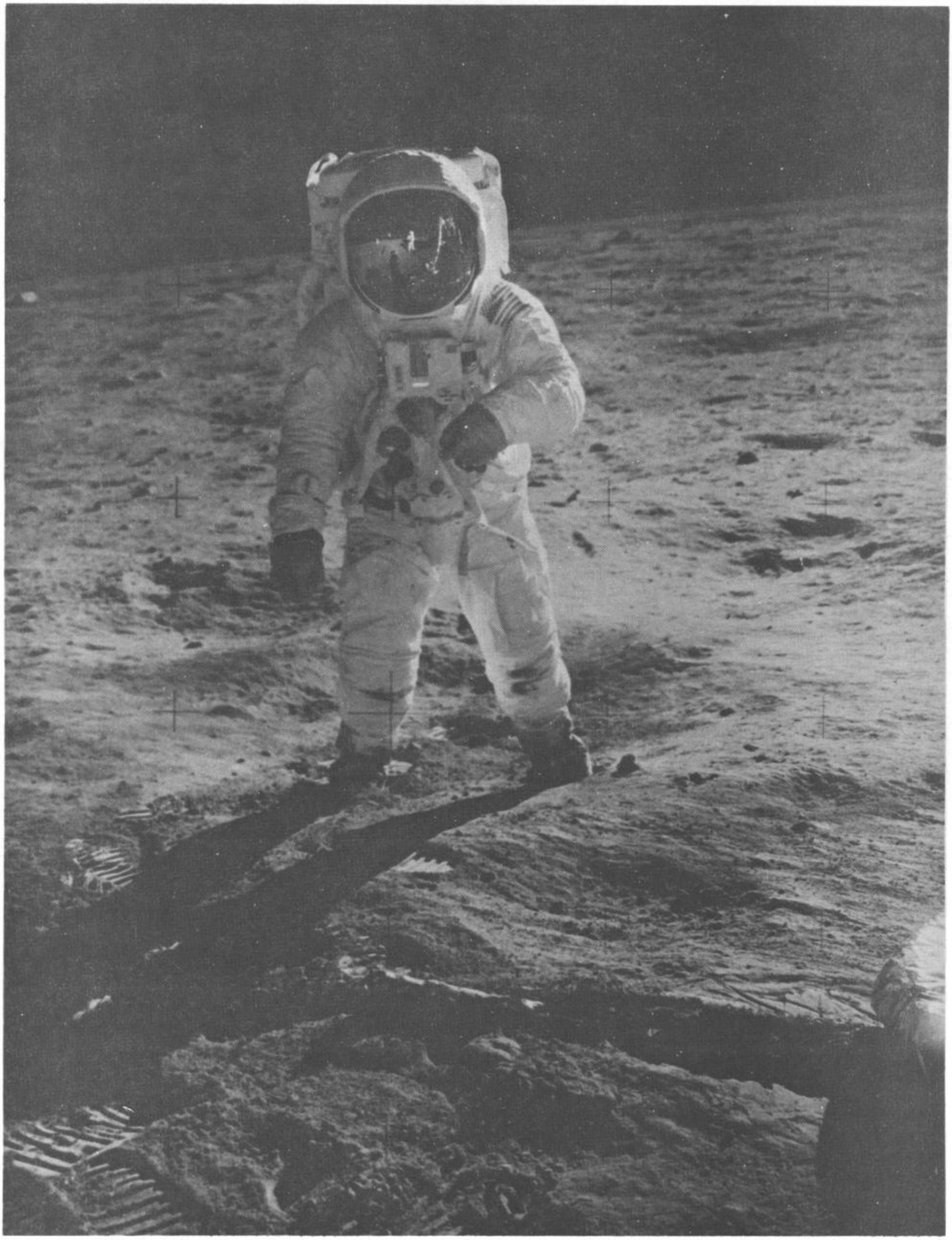
04 13 43 08	CDR	That's a good step. About a 3-footer.
04 13 43 16	LMP	Beautiful view!
04 13 43 18	CDR	Isn't that something! Magnificent sight out here.
04 13 43 24	LMP	Magnificent desolation.

* * *

As planned, the LMP deployed the solar wind composition experiment on the lunar surface in direct sunlight to the north of the LM.

Subsequently, the crew erected a 3-by 5-foot American flag on an 8-foot aluminum staff. During the ensuing environmental evaluation, the LMP indicated that he had to be careful of his center of mass to maintain balance. He noted that the LM shadow had no significant effect on his extravehicular mobility unit temperature.





* *

04 14 14 48	LMP	So-called kangeroo hop does work, but it seems that your forward mobility is not quite as good as - it is in the conventional - more conventional one foot after another.
04 14 15 06	LMP	It's hard saying what a sane pace might be. I think it's the one that I'm using now--would get rather tiring after several hundred... but this may be a function of this suit, as well as lack of gravity forces.

* *

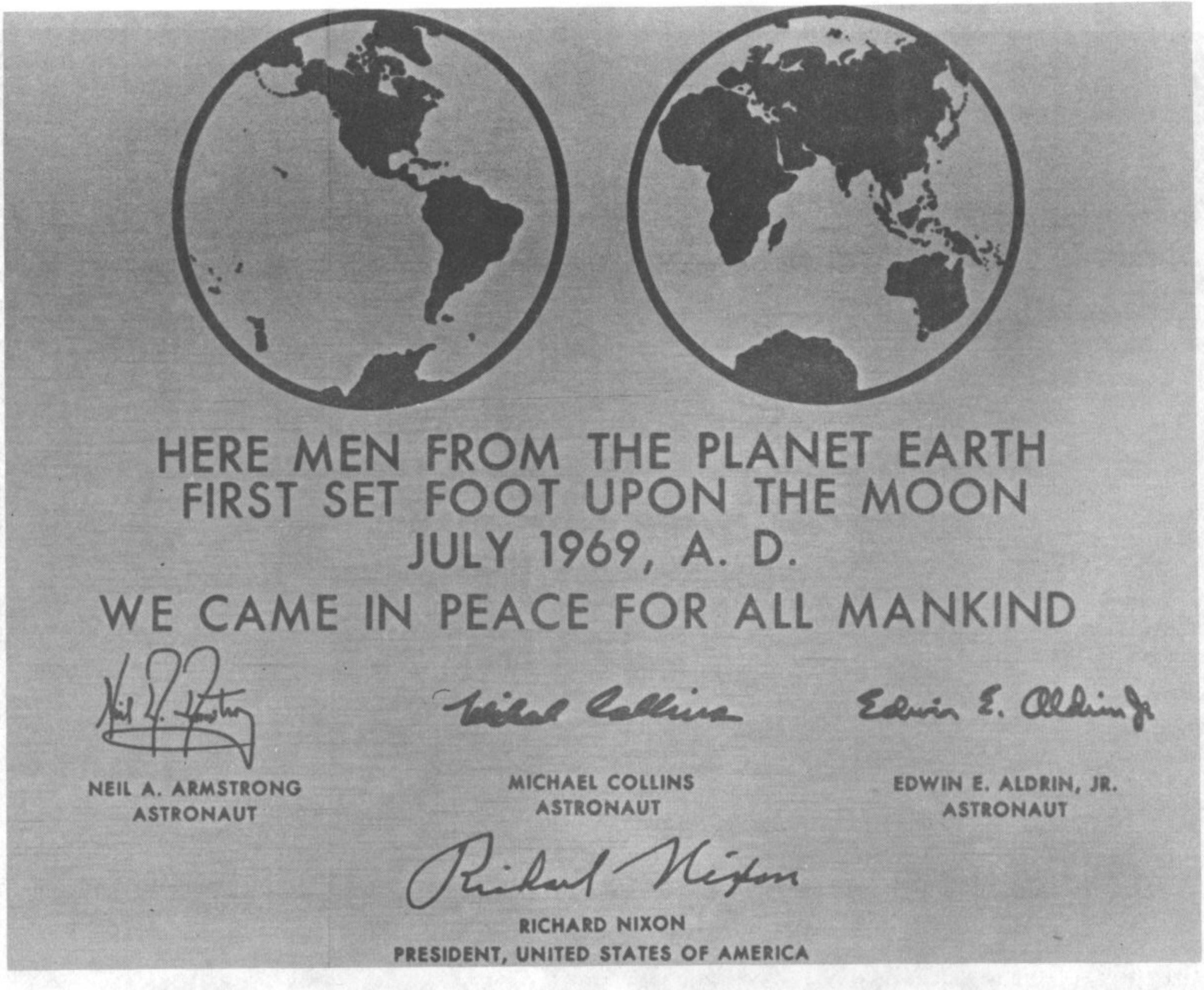
President Nixon conversed with Armstrong and Aldrin from the White House and conveyed his congratulations and good wishes.

* *

04 14 16 30	PRESIDENT NIXON	Neil and Buzz, I am talking to you by telephone from the Oval Room at the White House, and this certainly has to be the most historic telephone call ever made. I just can't tell you how proud we all are of what you ... for every American. This has to be the proudest day of our lives. And for people all over the world, I am sure they, too, join with Americans in recognizing what an immense feat this is. Because of what you have done, the heavens have become a part of man's world. And as you talk to us from the Sea of Tranquility, it inspires us to redouble our efforts to bring peace and tranquility to Earth. For one priceless moment in the whole history of man, all the people on this Earth are truly one; one in their pride in what you have done, and one in our prayers that you will return safely to Earth.

* *

The CDR collected a bulk sample of lunar surface material that consisted of assorted surface material and selected rock chunks. After the bulk sample collection, the crew inspected the LM and reported no discrepancies. The quads, struts, skirts, and antennae were satisfactory.



HERE MEN FROM THE PLANET EARTH
FIRST SET FOOT UPON THE MOON
JULY 1969, A. D.
WE CAME IN PEACE FOR ALL MANKIND

Michael Collins

Edwin E. Aldrin Jr

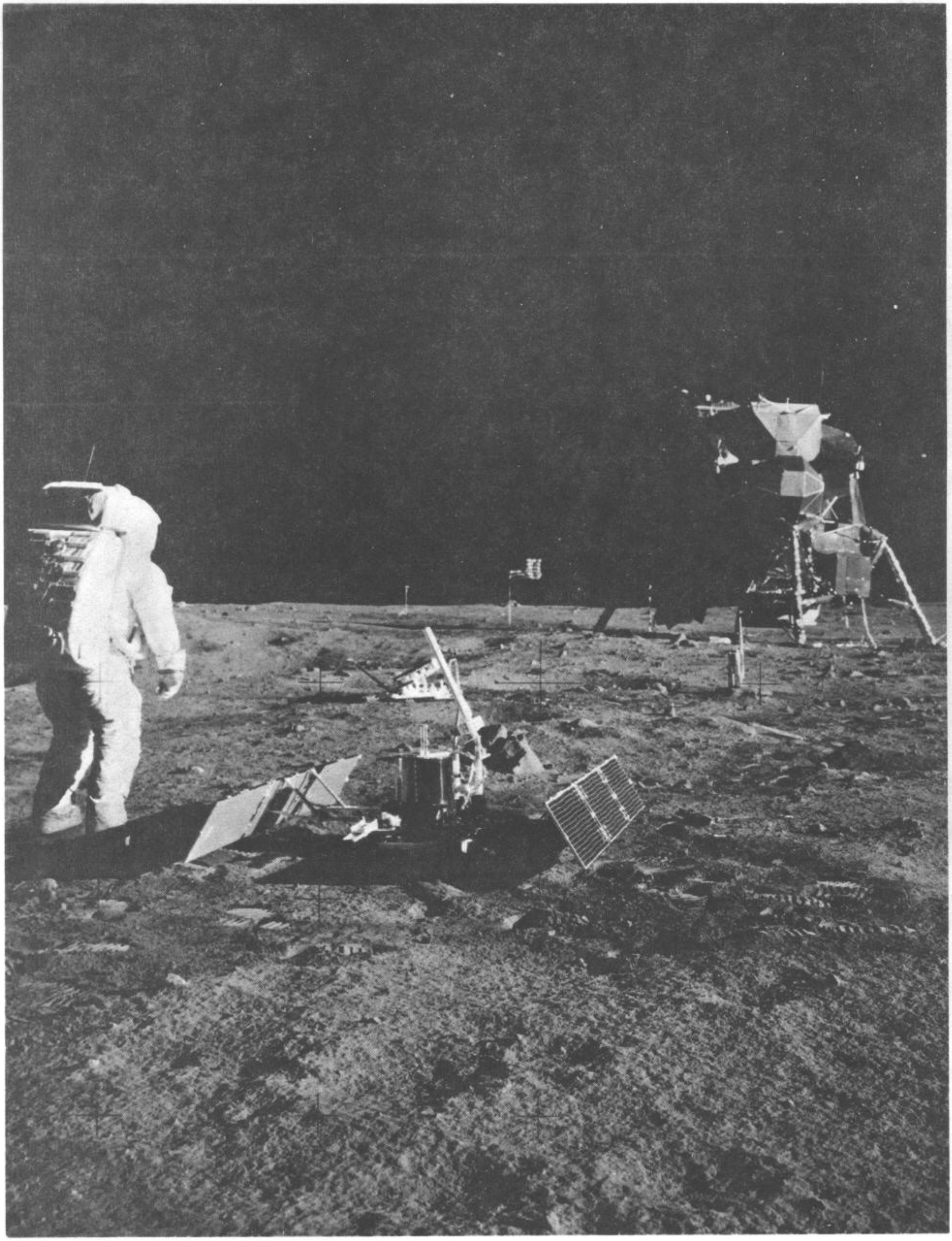
NEIL A. ARMSTRONG
ASTRONAUT

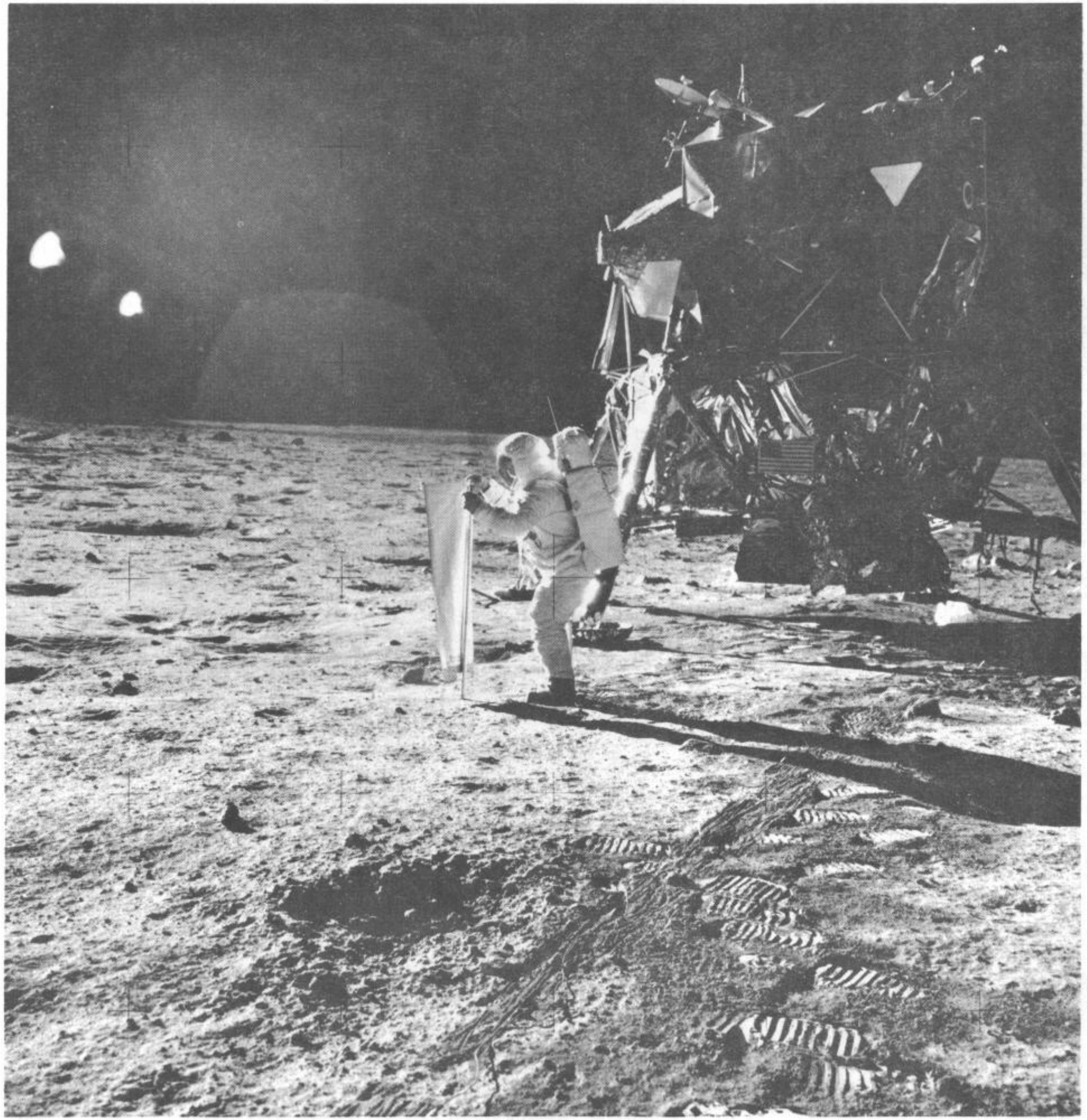
MICHAEL COLLINS
ASTRONAUT

EDWIN E. ALDRIN, JR.
ASTRONAUT

Richard Nixon

RICHARD NIXON
PRESIDENT, UNITED STATES OF AMERICA





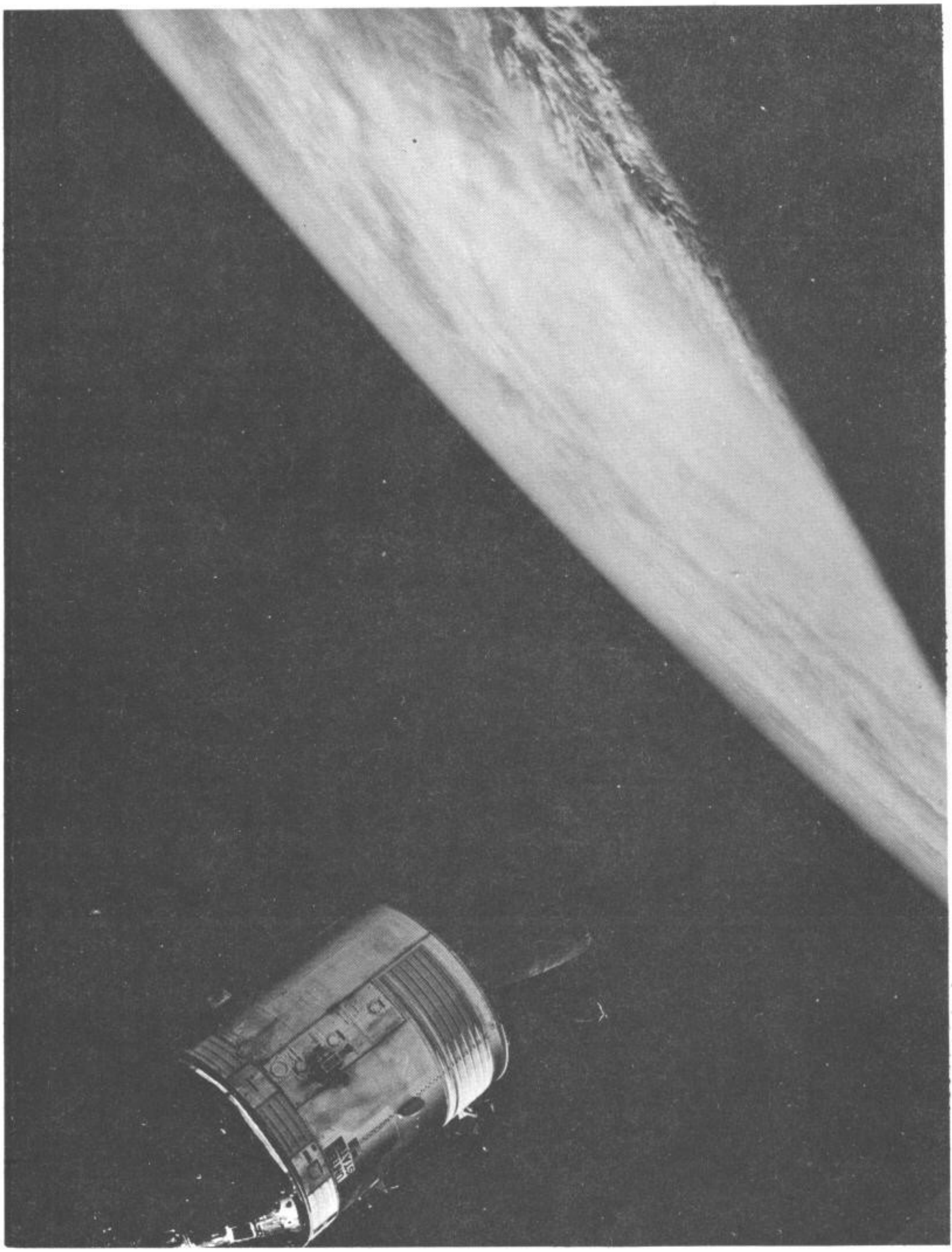
The passive seismic experiment package (PSEP) and laser ranging retro reflector were deployed south of the LM. Excellent PSEP data were obtained which included detection of the crewmen walking on the surface and later in the LM. The crew then collected more lunar samples until EVA termination, including two core samples and approximately 20 pounds of discretely selected material. The LMP had to exert a considerable force to drive the core tubes an estimated 8 to 9 inches into the lunar surface.

Throughout the EVA, TV provided continuous observation for time correlation of crew activity with telemetered data and voice comments and provided live documentation of this historically significant achievement. Lunar surface photography consisted of both still and sequence coverage with the Hasselblad camera, the Maurer data acquisition camera, and the Apollo lunar surface close-up camera. All EVA systems operated nominally during the EVA.

EVA termination, film and sample transfer, LM ingress, and equipment jettison occurred according to plan. The crew rested after post-EVA activities and prior to preparation for lift-off later in the day.

Flight crew performance during this period was outstanding. During the high activity events, bio-medical parameters were monitored carefully. From DOI to landing, the CDR's pulse rate went from 110 beats per minute to a maximum of 156. During the lunar surface activities, both crewmen had low pulse rates of 90 beats per minute. The LMP's maximum pulse rate was 125 while the CDR's pulse rate went to a maximum of 160 during the LM equipment transfer. None of the crew members had taken any medication.

At 6:00 c.d.t., 117^h28^m g.e.t., the LM was at Tranquility Base on the lunar surface. The CSM weighed 36 567 pounds and was in a lunar orbit with a 62.3-n. mi. apolune and a 56.8-n. mi. perilune.



DAY 6

The LM lifted off from the lunar surface on the sixth day of the Apollo 11 Mission at 124^h22^m g.e.t. It had been on the moon 21 hours 36 minutes.

* *

05 04 32 55	CDR (EAGLE)	Roger, Houston. The Eagle is back in orbit, having left Tranquility Base and leaving behind a - a replica from our Apollo 11 patch and the olive branch.

* *

The 437.9-second, 6071.1-fps acent propulsion system (APS) maneuver inserted the LM into a lunar orbit with a 45.2-n. mi. apogee and a 9-n. mi. perigee. After ascent at $125^h19^m34.7^s$, the rendezvous maneuver sequence began with the coelliptic sequence initiation (CSI). The LM docked with the CSM at $128^h03^m40^s$ after all rendezvous maneuvers were completed. The resultant orbit had a 62.6-n. mi. apolune and a 56.3-n. mi. perilune.

The LM communications were nominal through lunar ascent. The steerable antenna maintained lock and tracked through the APS burn, and uplink signal strength and temperature remained stable. Voice communications were excellent. The steerable antenna was used until a switch was made to omni antenna for a LM maneuver to a region beyond the steerable antenna limits.

After the LM was docked with the CSM, the CSM cabin pressure was increased. Calculations based on cabin pressure rise indicate that the flow rate was in excess of the required 0.6 lb/hr, and a positive flow was maintained from the CSM to the LM.

At 126^h g.e.t., the crew reported that they had selected the secondary lithium hydroxide cartridge because of erratic carbon dioxide (CO_2) readings. When erratic readings were also reported on the secondary cartridge, it was determined that the CO_2 sensor was probably erratic, and the CO_2 sensor circuit breaker was pulled. The primary cartridge was placed on line.

The ascent stage was jettisoned at $130^h09^m31.2^2$ g.e.t. Twenty minutes later, the CSM RCS performed a 7.1-second, 2.2-fps separation maneuver from the LM and entered a 62.6 by 54.7-n. mi. orbit. This event was moved up approximately 83 minutes earlier than indicated on the flight plan to assure no orbit perturbations because of LM RCS thrust activity. The LM was left in a powered up configuration.

The SPS performed the transearth injection (TEI) maneuver during the thirty-first lunar orbit at $135^h23^m42^s$ g.e.t. The maneuver lasted 151.4 seconds and resulted in a velocity change of 3279 fps. The total time in lunar orbit was 39 hours 34 minutes.

* *

05 15 35 14	CC	Hello, Apollo 11. Houston. How did it go?
05 15 35 22	CMP	Time to open up the LRL doors, Charlie.

* *

At 6:00 c.d.t., 165^h28^m g.e.t., the CSM weighed 26 000 pounds, was traveling 4900 fps, and was 130 300 n. mi. from earth.

DAY 7

At $148^{h}07^{m}22^{s}$ g.e.t., on the seventh day of the mission, Apollo 11 was 33 800 n. mi. from the moon and passed into the earth's sphere of influence. Distance from the earth was 174 000 n. mi., and velocity was 3994 fps with respect to the earth.

The MCC-5 was initiated at $150^{h}30^{m}$ g.e.t. The 11.2-second SM RCS burn produced a velocity change of 4.8 fps.

Communication was lost with the spacecraft for 51 minutes beginning at $151^{h}54^{m}$ g.e.t. The loss appeared to result from a combination of spacecraft maneuvering followed by a constant attitude. The signal strength received from the selected omni antenna was insufficient to permit selection of a favorable omni from the ground. Communication was regained by a gradual attitude change or by an antenna switch by the crew.

Communications were again lost for approximately 18 minutes beginning at $154^{h}21^{m}$ g.e.t. The spacecraft was in PTC during this time with ground switching between omni D and the HGA. It was determined later that the HGA was in the AUTO TRACK mode rather than the auto-reacquisition mode which would explain the communications failure.

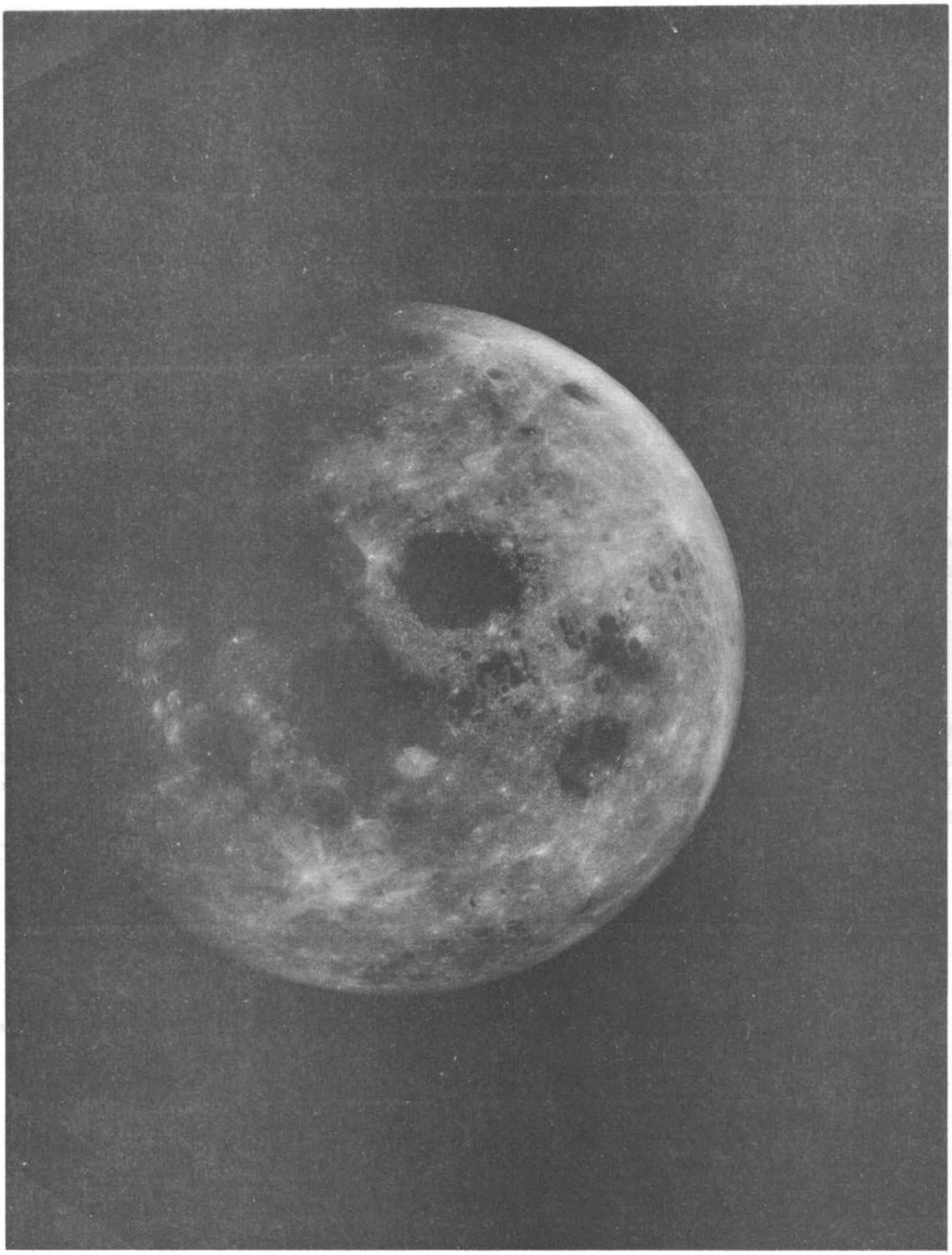
An 18-minute television transmission was initiated at $155^{h}36^{m}$ g.e.t. and produced good quality pictures. The crew demonstrated the effect of weightlessness on food and water and showed brief scenes of the moon and earth.

* * *

06 11 52 55	CMP	You have a picture now, Houston?
06 11 52 56	CC	That's affirmative. I refuse to bite on this one, though. You tell us.
06 11 53 02	CDR	Okay. This should be getting larger, and if it is, it's the place we're coming home to.

* * *

At 6:50 c.d.t., $165^{h}28^{m}$ g.e.t., the spacecraft was traveling at 4900 fps and was 130 000 n. mi. from earth.



DAY 8

The accuracy of the MCC-5 was such that the MCC-6 originally planned for 172:00 g.e.t. was not required. The MCC-6, if performed on schedule, would have required a differential velocity of only 0.4 fps.

A 12.5-minute television transmission was initiated at approximately 177^h32^m g.e.t. and produced good quality color pictures. The crew expressed sincere appreciation to all people who had helped make the Apollo 11 mission possible.

* *

07 22 22 36 CC ...Air Canada says it has accepted 2300 reservations for flights to the moon in the past 5 days. It might be noted that more than 100 have been made by men for their mothers-in-law...

* *

The predicted time to reach entry interface was 195^h03^m g.e.t., and the time to land was approximately 14 minutes later at 195^h17^m g.e.t. (11:49 p.m. c.d.t.).

The predicted flight-path angle was -6.49°, and entry velocity was 36 194 fps.

Because of deteriorating weather in the nominal landing area, the decision was made at 181^h30^m g.e.t. to move the target point down range 215 n. mi. to longitude 169°10'W, latitude 13°19'W.

Systems performance was nominal, and consumables usage remained within acceptable limits.

At 6:00 c.d.t., 189^h28^m g.e.t., the spacecraft was 40 500 n. mi. from earth and was traveling at 9735 fps.

DAY 9

The MCC-7, scheduled for 192^h06^m g.e.t. on the ninth day, was not performed. The ΔV required was 0.1 fps. Propellant was in good condition, and the crew was in high spirits.

* * *

08 01 08 18	CMP	It's a pleasure to be able to waste gas.
08 01 31 48	CMP	We can see the Moon passing by the window and it looks what I consider to be a correct size.

* * *

Predicted entry interface conditions at MCC-7 time were as follows: arrival, $195^h03^m05^s$ g.e.t.; velocity, 36 194.3 fps; and flight-path angle, -6.5°.

Entry interface was reached at 195^h03^m g.e.t. Weather in the prime recovery area was excellent. Visibility was 12 miles; wave height, 3 feet; and wind, 16 knots.

The CM and SM separated at $194^h49^m19^s$ g.e.t., and entry interface (400 000 ft) occurred at $195^h03^m06^s$ g.e.t. The entry velocity was 36 194 fps and the flight-path angle was -6.48°.

Visual contact of the spacecraft was reported at 195^h06^m g.e.t. Drogue and main parachutes deployed normally. Landing occurred approximately 14 minutes after entry interface at 195^h18^m g.e.t. ($11^h50^m35^s$ c.d.t.).

* * *

08 03 17 48	SWIM 1	Roger. This is SWIM 1, Apollo 11.
08 03 17 54	CDR	Roger. 300 feet.
08 03 17 56	SWIM 1	Roger. You're looking real good.
08 03 18 18	SWIM 1	SPLASHDOWN!

* * *

The landing point was in the mid-Pacific, approximately 169°W longitude by 13:18°N latitude, about 13 n. mi. from the prime recovery ship USS HORNET. The CM landed in the stable 2 position. Flotation bags were deployed to right the CM into stable 1 position at $195^h25^m10^s$. The crew reported that they were in good condition.

After landing, the recovery helicopter dropped swimmers who installed the flotation collar to the CM. A large, seven-man raft was deployed and was attached to the flotation collar. Biological isolation garments (BIG's) were lowered into the raft, and one swimmer donned a BIG while the astronauts donned BIG's inside the CM. Two other swimmers moved upwind of the CM on a second large raft. The postlanding ventilation fan was turned off, the CM was powered down, and the astronauts egressed and helped the swimmer close the CM hatch. The swimmer then decontaminated all garments, the hatch area, the collar, and the area around the postlanding vent valves.

The helicopter recovered the astronauts. After landing on the recovery carrier, the astronauts and a recovery physician entered the mobile quarantine facility (MQF).

President Nixon, aboard USS HORNET, spoke to the crew members by intercommunications and congratulated them for this stupendous feat.

The flight crew, recovery physician, and recovery technician remained inside the MQF until it was delivered to the Lunar Receiving Laboratory (LRL) in Houston, Texas. (This delivery occurred on July 27.)

After the helicopter picked up the crew, the CM was retrieved and placed in a dolly aboard the recovery ship. It was then moved to the MQF and mated to the transfer tunnel. From inside the MQF/CM containment envelope, the MQF engineer began postretrieval procedures (removal of lunar samples, data, equipment), passing the removed items through the delivery to the LRL.

The sample return containers (SRC), film, and data were flown to Johnson Island by fixed wing aircraft from USS HORNET. The two SRC's were then flown by separate aircraft to Houston for transport to the LRL.

APOLLO 11 MANEUVER SUMMARY

(a) Translunar maneuver summary

Maneuver	Ground elapsed time at ignition, hr:min:sec, g.e.t.			Burn time, sec			Velocity change, fps			Time of closest approach, hr:min:sec, g.e.t.			Height at closest approach, n. mi.		
	Prelaunch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Prelaunch plan	Real-time plan	Actual	Prelaunch plan	Real-time plan	Actual
TLI (S-IVB)	2:44:15.3	2:44:16.2	2:44:16.2	349.5	347.5	347.3	10 451.2	10 435.9	10 441.0	75:24:06.1	75:04:28	75:16:24	346.5	854.1	701.9
Evasive maneuver (SPS)	4:39:44.9	4:39:44.9	4:40:01.0	2.8	2.8	3.4	19.7	19.7	19.7	75:57:39.4	75:40:35.2	75:38:22	59.8	335.0	179.7
MCC-1 (SPS)	11:45:00	11:30:00	N.P. (Not performed)	0.0	2.4	N.P.	0.0	17.3	N.P.	75:57:39.4	75:53:49.0	N.P.	59.8	60.0	N.P.
MCC-2 (SPS)	26:45:00	26:44:58	26:44:58	0.0	3.0	2.9	0.0	21.3	20.9	75:57:39.4	75:53:49.0	75:53:46	59.8	60.0	62.8
MCC-3	53:55:00	53:55:00	N.P.	0.0	8.0	N.P.	0.0	.8	N.P.	75:57:34.4	75:53:49.0	N.P.	59.8	60.0	N.P.
MCC-4	70:55:00	70:55:00	N.P.	0.0	21.6	N.P.	0.0	2.6	N.P.	75:57:34.4	75:53:49.0	N.P.	59.8	60.1	N.P.

Maneuver	Ground elapsed time at ignition, hr:min:sec, g.e.t.			Burn time, sec			Velocity change, fps			Resultant apolune/perilune, n. mi.		
	Prelaunch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual
Lunar orbit insertion	75:54:28.4	75:49:49.6	75:49:49.6	358.9	362.1	362.1	2924.1	2917.3	2917.5	169.8/59.7	169.1/61.1	168.8/61.3
Lunar orbit circularization	80:09:29.7	80:11:36.0	80:11:36.0	16.4	17.0	17.0	157.8	159.2	158.8	65.6/53.6	65.7/53.7	65.7/53.8
CSM/LM separation	100:39:50.4	100:39:50.0	100:39:50	8.0	8.0	8.2	2.5	2.5	2.6	63.1/55.6	64.0/56.0	63.7/55.8
Descent orbit insertion	101:38:48.0	101:36:14.1	101:36:14.1	28.0	29.8	29.8	74.0	76.4	76.4	60.0/ 8.2	57.2/ 8.5	57.2/ 8.5
Powered descent initiation	102:35:13.0	102:33:04.4	102:33:04.4	714.0	712.7	712.6	6775.0	6776.0	6775.8	0.0/ 0.0	0.0/ 0.0	0.0/ 0.0
CSM plane change	107:05:33.4	106:05:00	N.P.	.8	.8	N.P.	16.6	15.0	N.P.	63.1/55.6	64.0/56.0	N.P.
Ascent	124:23:26.0	124:22:00.0	124:22:00.0	437.9	439.4	439.9	6060.2	6070.2	6070.1	45.0/ 9.9	45.2/ 9.0	45.2/ 9.0
Coelliptic sequence initiate	125:21:19.1	125:19:34.7	125:19:34.7	44.8	48.5	47.0	49.4	53.2	51.5	45.7/44.9	47.1/45.5	48.6/45.3
LM plane change	125:50:28.0	126:12:33	N.P.	0.0	1.0	N.P.	0.0	.2	N.P.	45.7/44.9	47.0/45.5	N.P.
Constant delta altitude	126:19:37.0	126:17:46.0	126:17:46.0	2.0	18.2	18.1	4.5	20.0	19.9	45.1/42.8	47.0/40.9	47.0/40.9
Terminal phase initiate	126:58:08.4	126:57:00	127:03:30.8	22.2	22.7	22.8	24.6	25.1	25.3	61.2/42.6	61.1/43.9	61.2/43.9
Terminal phase finalize	127:40:37.7	127:39:34.2	127:45:54	28.3	28.4	28.4	31.4	31.5	31.4	59.5/59.0	62.6/56.6	62.2/56.6
CSM/LM separation	131:53:04.7	130:30:00	130:30:00	3.2	6.5	7.1	1.0	2.0	2.2	59.6/59.0	62.6/54.7	62.6/54.7

APOLLO 11 MANEUVER SUMMARY - Concluded

(c) Transearth maneuver summary

Maneuver	Ground elapsed time at ignition hr:min:sec, g.e.t.			Burn time, sec			Velocity change, fps			Velocity (fps) at EI, fps			Flight-path angle at EI, deg		
	Prelaunch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Pre-launch plan	Real-time plan	Actual	Prelaunch plan	Real-time plan	Actual	Prelaunch plan	Real-time plan	Actual
TEI[a] (SPS)	135:24:33.8	135:23:41.6	135:23:42.0	149.1	147.9	150.0	3292.7	3283.6	3278.8	36 194.3	36 194.3	e	-6.50	-6.50	e
MCC-5[b]	150:24:00	150:29:54.5	150:29:54.5	0.0	11.0	10.8	0.0	4.8	4.7	36 194.3	36 194.3	36194.3	-6.50	-6.51	-6.46
MCC-6[c]	172:00:00	172:00:00	N.P.	0.0	1.1	N.P.	0.0	.4	N.P.	36 194.3	36 194.3	N.P.	-6.50	-6.51	N.P.
MCC-7[d]	192:06:00	192:06:00	N.P.	0.0	.5	N.P.	0.0	.1	N.P.	36 194.3	36 194.3	N.P.	-6.50	-6.50	N.P.

[a] g.e.t. to entry interface was 195:05:03.5 for prelaunch and real-time plans.

[b] g.e.t. to entry interface was 195:05:03.5 for the prelaunch plan and 195:03:06 for the real-time plan;the actual time was 195:03:08.

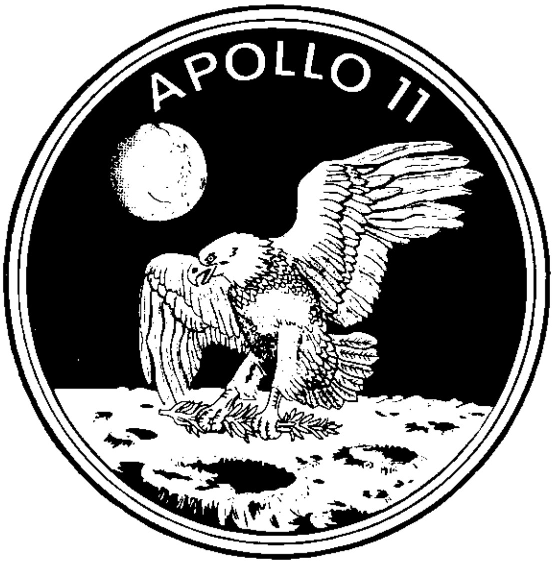
[c] g.e.t. to entry interface was 195:05:03.5 for the prelaunch plan and 195:03:04 for the real-time plan.

[d] g.e.t. to entry interface was 195:05:03.5 for the prelaunch plan and 195:03:05 for the real-time plan.

[e] No entry; vacuum perigee over 66 n. mi.

Task Accomplished.....

July, 1969

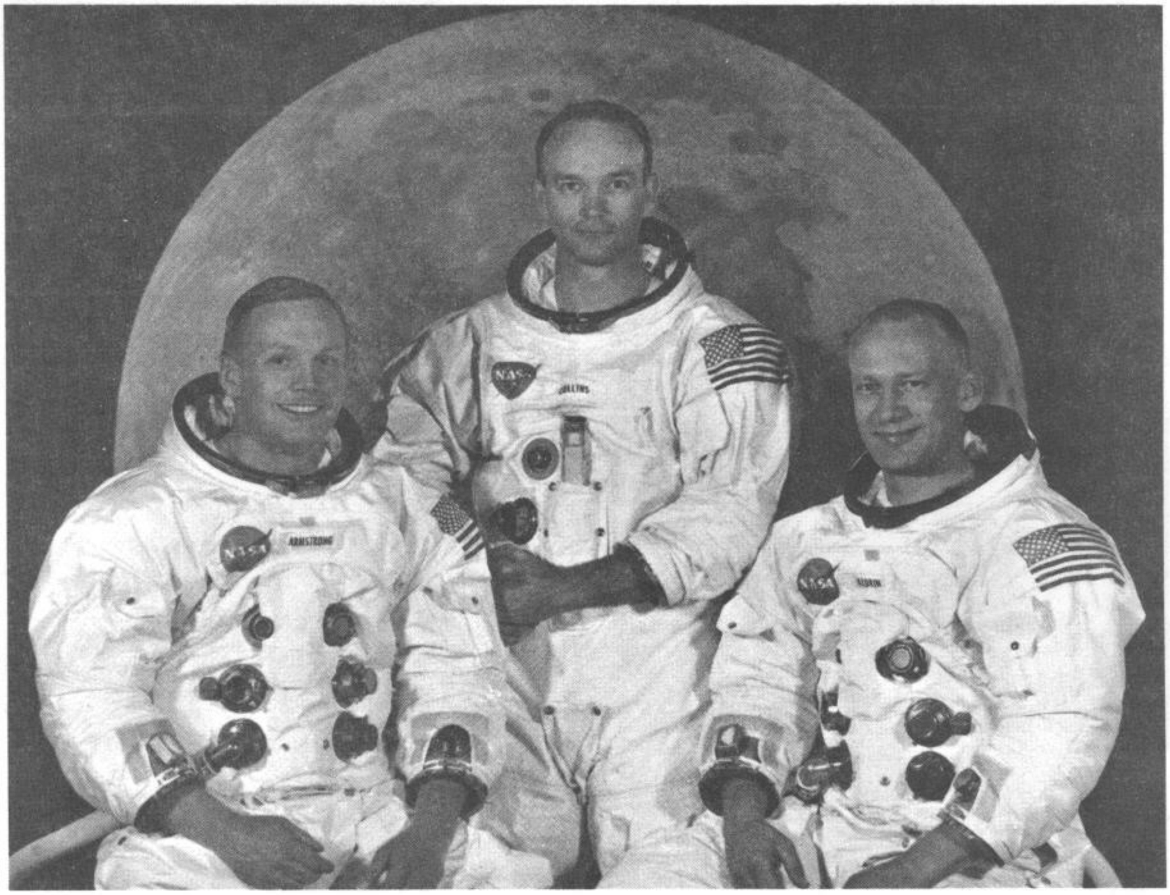


NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

2084

PART II

THE ROLE OF MPAD



PRIME CREW OF FIFTH MANNED APOLLO MISSION

NEIL A. ARMSTRONG MICHAEL COLLINS EDWIN E. ALDRIN, JR.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS 77058

IN REPLY REFER TO: CB

TO : Mission Planning and Analysis Division

FROM : The Apollo 11 Crew

SUBJECT: The lunar landing

It has been a rare pleasure for us, over a space of several years, to work with all of you in MPAD. Your imaginative and careful work throughout each new step of space exploration made a success of the flights before ours, and gave us great confidence as we set out toward a lunar landing.

In flight we found it worked just like you said, but then that was no surprise, as we had become accustomed to the precision of your trajectories and analyses.

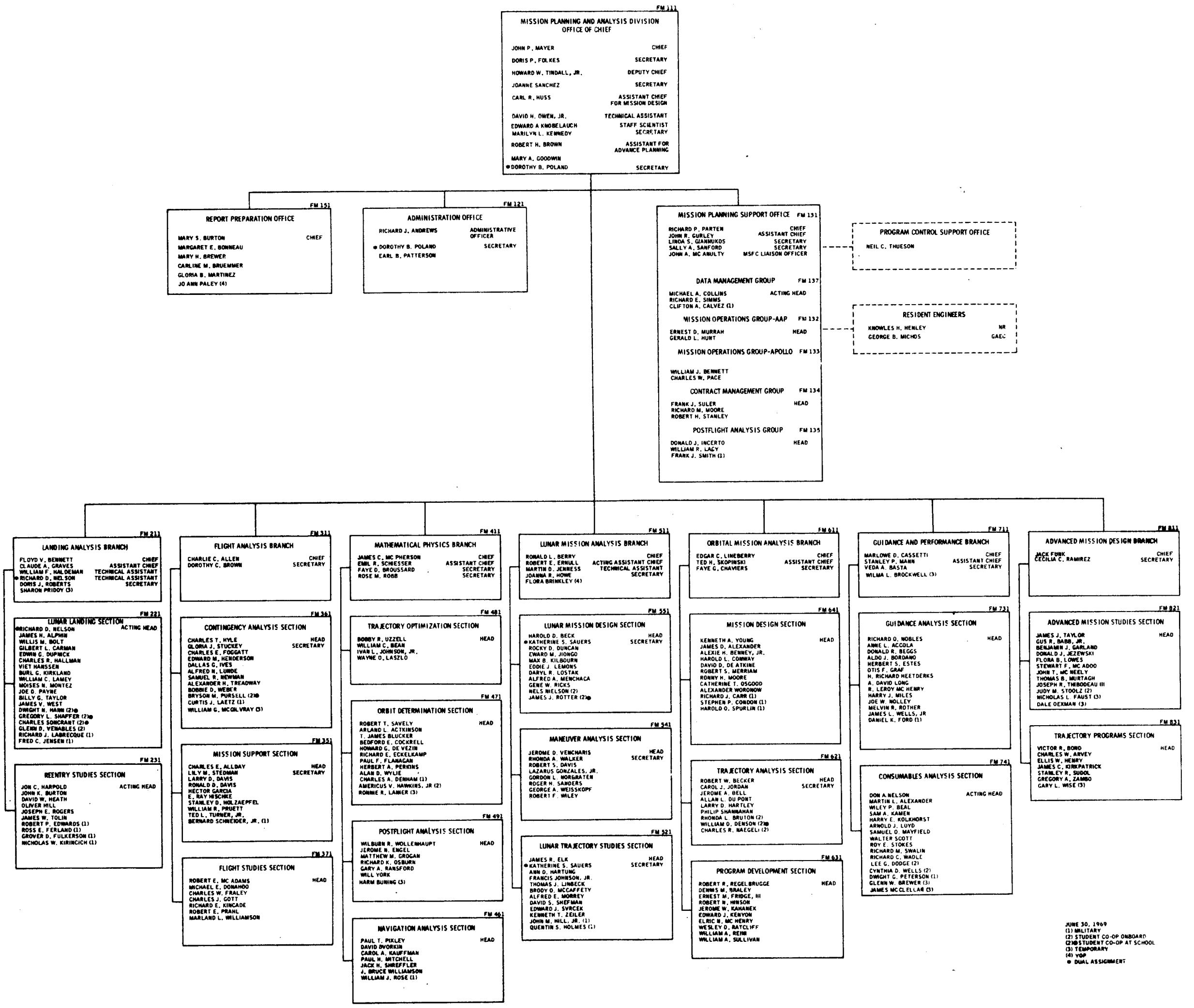
We are looking forward to watching you plan bigger and better things for the future.

Sincerely,

Neil A. Armstrong
NASA Astronaut

Michael Collins
Michael Collins
Colonel, USAF
NASA Astronaut

Edwin E. Aldrin
Edwin E. Aldrin
Colonel, USAF
NASA Astronaut



FM 111
MISSION PLANNING AND ANALYSIS DIVISION OFFICE OF CHIEF

JOHN P. MAYER	CHIEF
DORIS P. FOLKES	SECRETARY
HOWARD W. TINDALL, JR.	DEPUTY CHIEF
JOANNE SANCHEZ	SECRETARY
CARL R. HUSS	ASSISTANT CHIEF FOR MISSION DESIGN
DAVID H. OWEN, JR.	TECHNICAL ASSISTANT
EDWARD A KNOBELAUCH	STAFF SCIENTIST
MARILYN L. KENNEDY	SECRETARY
ROBERT H. BROWN	ASSISTANT FOR ADVANCE PLANNING
MARY A. GOODWIN	
●DOROTHY B. POLAND	SECRETARY

FM 151
REPORT PREPARATION OFFICE

MARY S. BURTON	CHIEF
MARGARET E. BONNEAU	
MARY H. BREWER	
CARLINE M. BRUEMMER	
GLORIA B. MARTINEZ	
JO ANN PALEY (4)	

FM 121
ADMINISTRATION OFFICE

RICHARD J. ANDREWS	ADMINISTRATIVE OFFICER
● DOROTHY B. POLAND	SECRETARY
EARL B. PATTERSON	

MISSION PLANNING SUPPORT OFFICE FM 131

RICHARD P. PARTEN	CHIEF
JOHN R. GURLEY	ASSISTANT CHIEF
LINDA S. GIANNUKOS	SECRETARY
SALLY A. SANFORD	SECRETARY
JOHN A. MC ANULTY	MSFC LIAISON OFFICER

DATA MANAGEMENT GROUP FM 137

MICHAEL A. COLLINS	ACTING HEAD
RICHARD E. SIMMS	
CLIFTON A. CALVEZ (1)	

MISSION OPERATIONS GROUP-AAP FM 132

ERNEST D. MURRAH	HEAD
GERALD L. HUNT	

MISSION OPERATIONS GROUP-APOLLO FM 133

WILLIAM J. BENNETT
CHARLES W. PACE

CONTRACT MANAGEMENT GROUP FM 134

FRANK J. SULER	HEAD
RICHARD M. MOORE	
ROBERT H. STANLEY	

POSTFLIGHT ANALYSIS GROUP FM 135

DONALD J. INCERTO	HEAD
WILLIAM R. LACY	
FRANK J. SMITH (1)	

PROGRAM CONTROL SUPPORT OFFICE

NEIL C. THUESON

RESIDENT ENGINEERS

KNOWLES H. HENLEY	NR
GEORGE B. MICHOS	GAEC

FM 211
LANDING ANALYSIS BRANCH

FLOYD V. BENNETT	CHIEF
CLAUDE A. GRAVES	ASSISTANT CHIEF
WILLIAM F. HALDEMAN	TECHNICAL ASSISTANT
●RICHARD D. NELSON	TECHNICAL ASSISTANT
DORIS J. ROBERTS	SECRETARY
SHARON PRIDDY (3)	

FM 221
LUNAR LANDING SECTION

●RICHARD D. NELSON	ACTING HEAD
JAMES H. ALPHIN	
WILLIS M. BOLT	
GILBERT L. CARMAN	
EDWIN G. DUPNICK	
CHARLES R. HALLMAN	
VIET HANSSEN	
BURL G. KIRKLAND	
WILLIAM C. LAMEY	
MOISES N. MONTEZ	
JOE D. PAYNE	
BILLY G. TAYLOR	
JAMES V. WEST	
DWIGHT N. HANN (2)●	
GREGORY L. SHAFFER (2)●	
CHARLES SONCRANT (2)●	
GLENN D. VENABLES (2)	
RICHARD J. LABRECQUE (1)	
FRED C. JENSEN (1)	

FM 231
REENTRY STUDIES SECTION

JON C. HARPOLD	ACTING HEAD
JOHN K. BURTON	
DAVID W. HEATH	
OLIVER HILL	
JOSEPH E. ROGERS	
JAMES W. TOLIN	
ROBERT P. EDWARDS (1)	
ROSS E. FERLAND (1)	
GROVER D. FULKERSON (1)	
NICHOLAS W. KIRINCICH (1)	

FM 311
FLIGHT ANALYSIS BRANCH

CHARLIE C. ALLEN	CHIEF
DOROTHY C. BROWN	SECRETARY

FM 361
CONTINGENCY ANALYSIS SECTION

CHARLES T. HYLE	HEAD
GLORIA J. STUCKEY	SECRETARY
CHARLES E. FOGGATT	
EDWARD M. HENDERSON	
DALLAS G. IVES	
ALFRED N. LUNDE	
SAMUEL R. NEWMAN	
ALEXANDER H. TREADWAY	
BOBBIE D. WEBER	
BRYSON M. PURSELL (2)●	
CURTIS J. LAETZ (1)	
WILLIAM G. MCGILVRAY (3)	

FM 351
MISSION SUPPORT SECTION

CHARLES E. ALLDAY	HEAD
LILY M. STEDMAN	SECRETARY
LARRY D. DAVIS	
RONALD D. DAVIS	
HECTOR GARCIA	
E. RAY HISCHKE	
STANLEY D. HOLZAEPFEL	
WILLIAM R. PRUETT	
TED L. TURNER, JR.	
BERNARD SCHNEIDER, JR. (1)	

FM 371
FLIGHT STUDIES SECTION

ROBERT E. MC ADAMS	HEAD
MICHAEL E. DONAHOO	
CHARLES W. FRALEY	
CHARLES J. GOTT	
RICHARD E. KINCADE	
ROBERT E. PRAHL	
MARLAND L. WILLIAMSON	

FM 411
MATHEMATICAL PHYSICS BRANCH

JAMES C. MC PHERSON	CHIEF
EMIL R. SCHIESSER	ASSISTANT CHIEF
FAYE D. BROUSSARD	SECRETARY
ROSE M. ROBB	SECRETARY

FM 481
TRAJECTORY OPTIMIZATION SECTION

BOBBY R. UZZELL	HEAD
WILLIAM C. BEAN	
IVAN L. JOHNSON, JR.	
WAYNE O. LASZLO	

FM 471
ORBIT DETERMINATION SECTION

ROBERT T. SAVELY	HEAD
ARLAND L. ACTKINSON	
T. JAMES BLUCKER	
BEDFORD E. COCKRELL	
HOWARD G. DE VEZIN	
RICHARD E. ECKELKAMP	
PAUL F. FLANAGAN	
HERBERT A. PERKINS	
ALAN D. WYLIE	
CHARLES A. DENHAM (1)	
AMERICUS V. HAWKINS, JR (2)	
RONNIE R. LAMER (3)	

FM 491
POSTFLIGHT ANALYSIS SECTION

WILBURN R. WOLLENHAUPT	HEAD
JEROME N. ENGEL	
MATTHEW M. GROGAN	
RICHARD K. OSBURN	
GARY A. RANSFORD	
WILL YORK	
HARM BUNING (3)	

FM 461
NAVIGATION ANALYSIS SECTION

PAUL T. PIXLEY	HEAD
DAVID DVORKIN	
CAROL A. KAUFFMAN	
PAUL H. MITCHELL	
JACK H. SHREFFLER	
J. BRUCE WILLIAMSON	
WILLIAM J. ROSE (1)	

FM 511
LUNAR MISSION ANALYSIS BRANCH

RONALD L. BERRY	CHIEF
ROBERT E. ERNULL	ACTING ASSISTANT CHIEF
MARTIN D. JENNESS	TECHNICAL ASSISTANT
JOANNA R. HOWE	SECRETARY
FLORA BRINKLEY (4)	

FM 551
LUNAR MISSION DESIGN SECTION

HAROLD D. BECK	HEAD
●KATHERINE S. SAUERS	SECRETARY
ROCKY D. DUNCAN	
EWARD M. JIONGO	
MAX B. KILBOURN	
EDDIE J. LEMONS	
DARYL R. LOSTAK	
ALFRED A. MENCHACA	
GENE W. RICKS	
NELS NIELSON (2)	
JAMES J. ROTTER (2)●	

FM 541
MANEUVER ANALYSIS SECTION

JEROME D. VENCHARIS	HEAD
RHONDA A. WALKER	SECRETARY
ROBERT S. DAVIS	
LAZARUS GONZALES, JR.	
GORDON L. NORBRATEN	
ROGER H. SANDERS	
GEORGE A. WEISSKOPF	
ROBERT F. WILEY	

FM 521
LUNAR TRAJECTORY STUDIES SECTION

JAMES R. ELK	HEAD
●KATHERINE S. SAUERS	SECRETARY
ANN D. HARTUNG	
FRANCIS JOHNSON, JR.	
THOMAS J. LINBECK	
BRODY O. MCCAFFETY	
ALFRED E. MORREY	
DAVID S. SHEFMAN	
EDWARD J. SVRCEK	
KENNETH T. ZEILER	
JOHN M. HILL, JR. (1)	
QUENTIN S. HOLMES (1)	

FM 611
ORBITAL MISSION ANALYSIS BRANCH

EDGAR C. LINEBERRY	CHIEF
TED H. SKOPINSKI	ASSISTANT CHIEF
FAYE G. CHAVIERS	SECRETARY

FM 641
MISSION DESIGN SECTION

KENNETH A. YOUNG	HEAD
JAMES D. ALEXANDER	
ALEXIE H. BENNEY, JR.	
HAROLD L. CONWAY	
DAVID D. DE ATKINE	
ROBERT S. MERRIAM	
RONNY H. MOORE	
CATHERINE T. OSGOOD	
ALEXANDER WORONOW	
RICHARD J. CARR (1)	
STEPHEN P. CONDON (1)	
HAROLD O. SPURLIN (1)	

FM 621
TRAJECTORY ANALYSIS SECTION

ROBERT W. BECKER	HEAD
CAROL J. JORDAN	SECRETARY
JEROME A. BELL	
ALLAN L. DU PONT	
LARRY D. HARTLEY	
PHILIP SHANNAHAN	
RHONDA L. BRUTON (2)	
WILLIAM O. DENSON (2)●	
CHARLES R. NAEGELI (2)	

FM 631
PROGRAM DEVELOPMENT SECTION

ROBERT R. REGELBRUGGE	HEAD
DENNIS M. BRALEY	
ERNEST M. FRIDGE, III	
ROBERT N. HINSON	
JEROME W. KAHANEK	
EDWARD J. KENYON	
ELRIC N. MC HENRY	
WESLEY D. RATCLIFF	
WILLIAM A. REINI	
WILLIAM A. SULLIVAN	

FM 711
GUIDANCE AND PERFORMANCE BRANCH

MARLOWE D. CASSETTI	CHIEF
STANLEY P. MANN	ASSISTANT CHIEF
VEDA A. BASTA	SECRETARY
WILMA L. BROCKWELL (3)	

FM 731
GUIDANCE ANALYSIS SECTION

RICHARD O. NOBLES	HEAD
ANNE L. ACCOLA	
DONALD R. BEGGS	
ALDO J. BORDANO	
HERBERT S. ESTES	
OTIS F. GRAF	
H. RICHARD HEETDERKS	
A. DAVID LONG	
R. LEROY MC HENRY	
HARRY J. MILES	
JOE W. NOLLEY	
MELVIN R. ROTHER	
JAMES L. WELLS, JR	
DANIEL K. FORD (1)	

FM 741
CONSUMABLES ANALYSIS SECTION

DON A. NELSON	ACTING HEAD
MARTIN L. ALEXANDER	
WILEY P. BEAL	
SAM A. KAMEN	
HARRY E. KOLKHORST	
ARNOLD J. LOYD	
SAMUEL O. MAYFIELD	
WALTER SCOTT	
ROY E. STOKES	
RICHARD M. SWALIN	
RICHARD C. WADLE	
LEE G. DODGE (2)	
CYNTHIA D. WELLS (2)	
DWIGHT G. PETERSON (1)	
GLENN W. BREWER (3)	
JAMES MC CLELLAN (3)	

FM 811
ADVANCED MISSION DESIGN BRANCH

JACK FUNK	CHIEF
CECILIA C. RAMIREZ	SECRETARY

FM 821
ADVANCED MISSION STUDIES SECTION

JAMES J. TAYLOR	HEAD
GUS R. BABB, JR.	
BENJAMIN J. GARLAND	
DONALD J. JEZEWSKI	
FLORA B. LOWES	
STEWART F. MC ADOO	
JOHN T. MC NEELY	
THOMAS B. MURTAGH	
JOSEPH R. THIBODEAU III	
JUDY M. STOOLZ (2)	
NICHOLAS L. FAUST (3)	
DALE OEXMAN (3)	

FM 831
TRAJECTORY PROGRAMS SECTION

VICTOR R. BOND	HEAD
CHARLES W. ARVEY	
ELLIS W. HENRY	
JAMES C. KIRKPATRICK	
STANLEY R. SUDOL	
GREGORY A. ZAMBO	
GARY L. WISE (3)	

JUNE 30, 1969
(1) MILITARY
(2) STUDENT CO-OP ONBOARD
(2)● STUDENT CO-OP AT SCHOOL
(3) TEMPORARY
(4) VOP
● DUAL ASSIGNMENT

Bill Tindall.
Joanne Sanchez

Carl R. Huss

THE MISSION PLANNING AND ANALYSIS DIVISION

Mary Ann Goodwin

Doris Folkes

Bob Brown

Marilyn Kennedy

David Owen

William J. Bennett

Horace L. Hunt

Charles Pace

Linda Giannukos

Sally Sanford

Linda DeCorte

Frank J. Smith

THE MISSION PLANNING

SUPPORT OFFICE

Buck Simmons

John McAnulty

R.P. Porter

E. Dixon Murrah

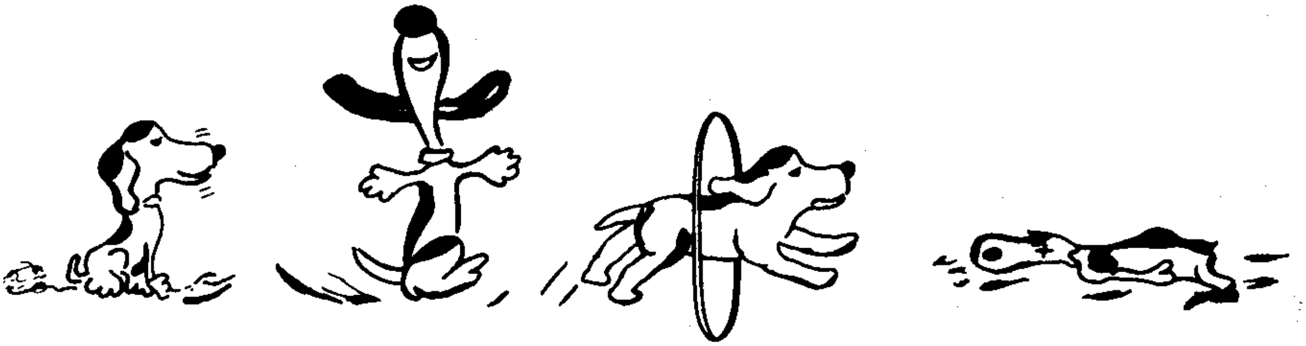
Michael A. Collins Jr

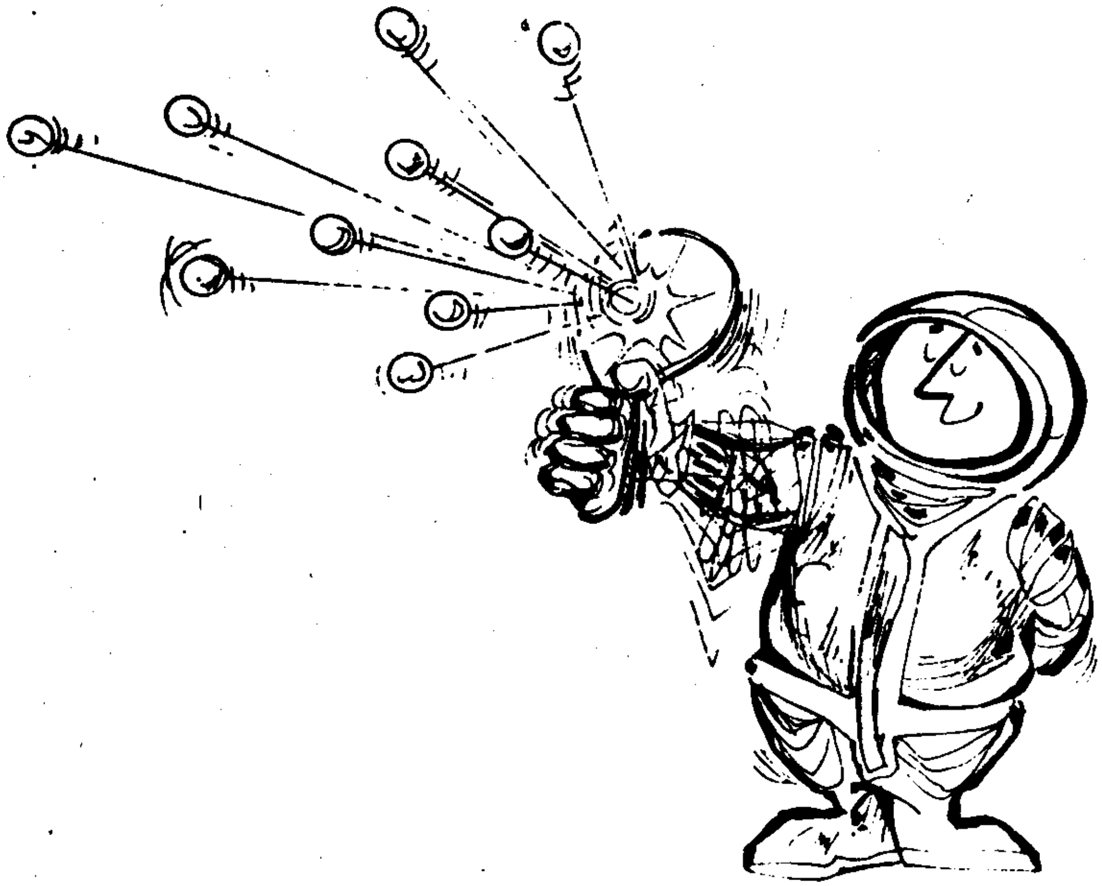
Bob Lacy

Robert Stanley

George Nichols

PRESENTING THE "G" MISSION TRAVELING DOG SHOW

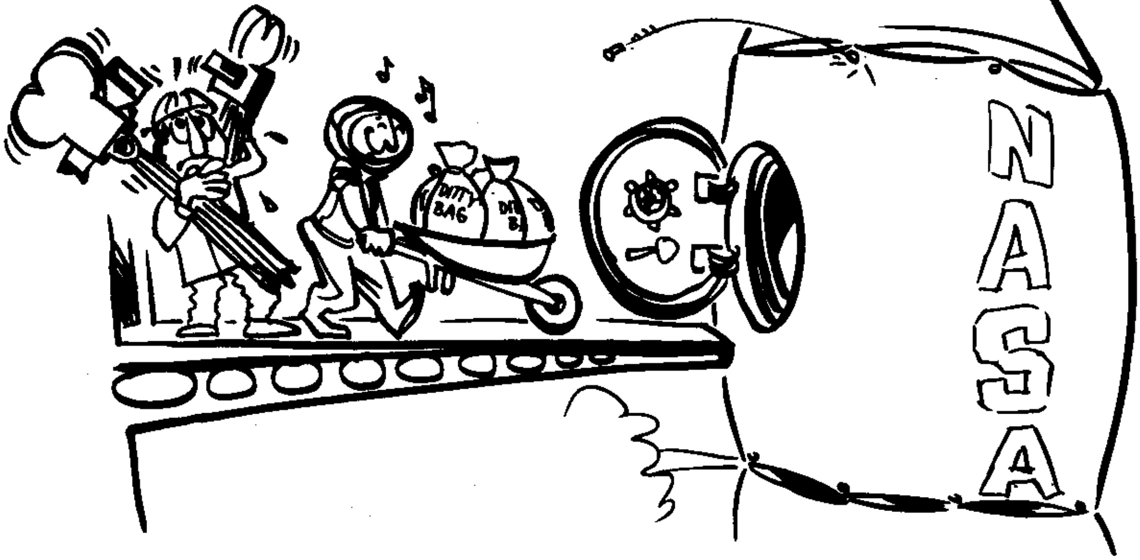




MISSION
COORDINATION

DATA MANAGEMENT

PRELAUNCH SPACECRAFT WEIGHT CHANGES

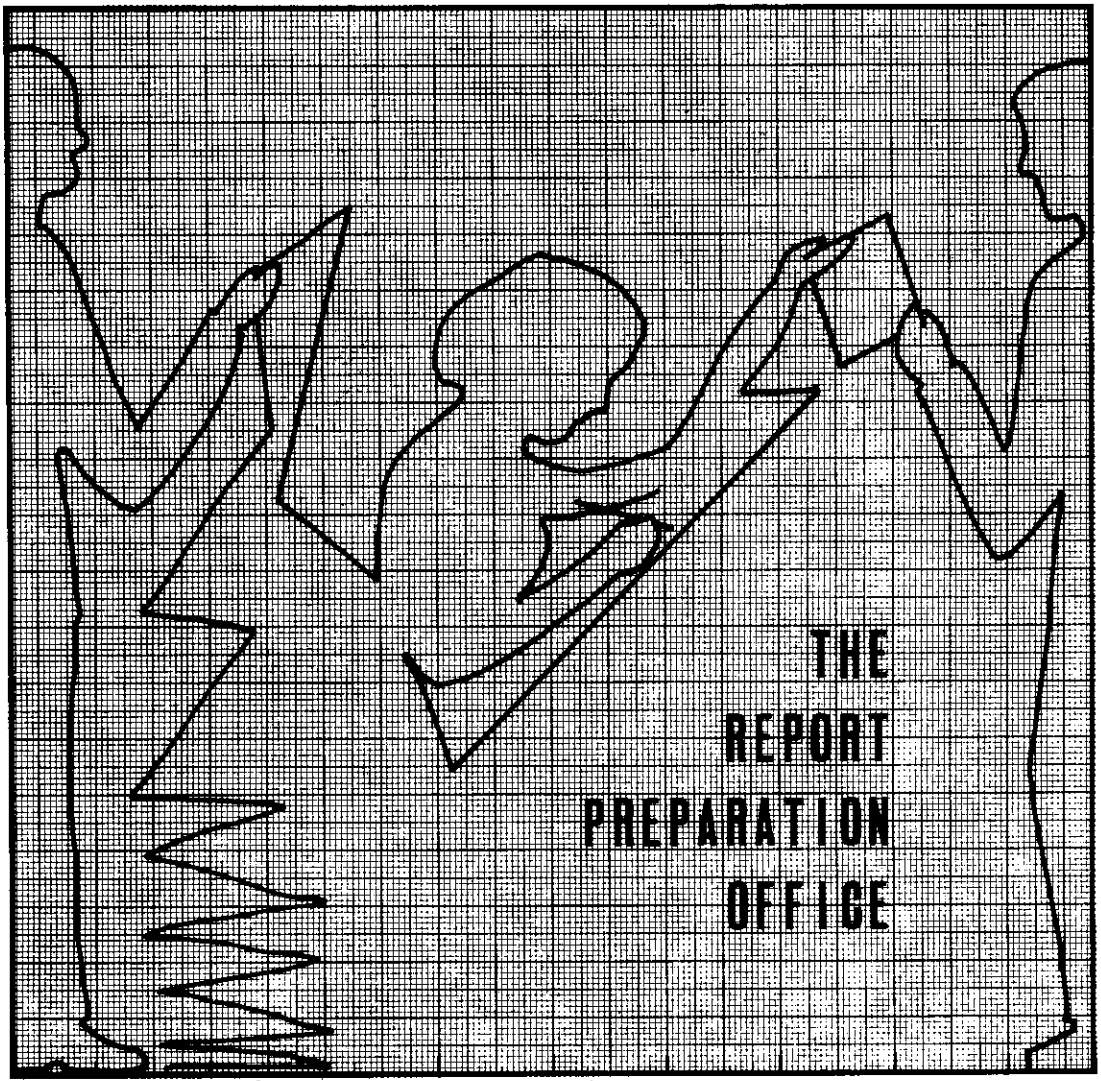


R. J. 'Andy' Andrews

Dorothy B. Poland

THE ADMINISTRATION OFFICE

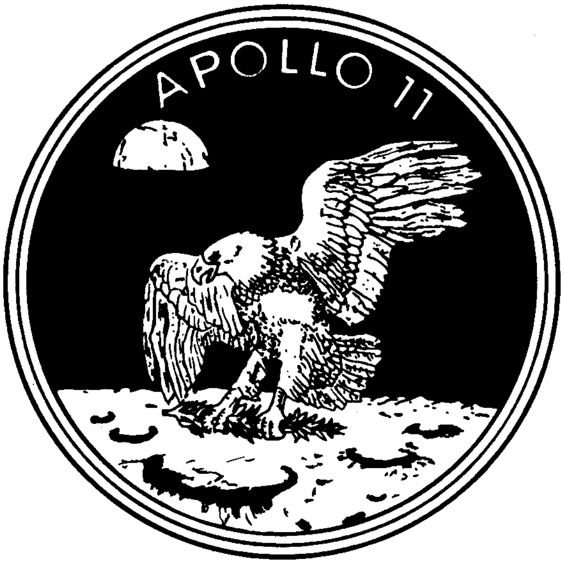
Earl Patterson



Mary Shy Burton Margaret Bousseau Mary Brewer Carlie Bruemmer Gloria B. Martinez

While working with data from various MPAD areas, the math aides realized that the earth-moon-sun geometry was depicted incorrectly on the official Apollo 11 insigne. This inaccuracy was corroborated by actual photographs taken during the Apollo 11 flight.

A correct version (courtesy of the math aides) is depicted below.



Joyce Broussard

Werdna Gray

Priscilla L. Nichols

Dale Langford

Jolene Wellborn

Wilma Watson

Cherie Black

Patt Smith

michele Tilley

Gwen Covington

Sylvia L. Parks

Rebecca Werner

Patsy Moore

Charles Jakob

ITT/FEC PUBLICATION SUPPORT

Linda Camp

Laura L. Wilson

Jewel C. Harwell

"Judy" Stevens

Mickey Gentry

John King

Pat Sims

Susan Ruff

Gracia Mittelsted

Connie Hinson

Sam Faicki

Linda Holt

Retha Hanson

Sue Garman

Linda Holden

Beverly Hatcher

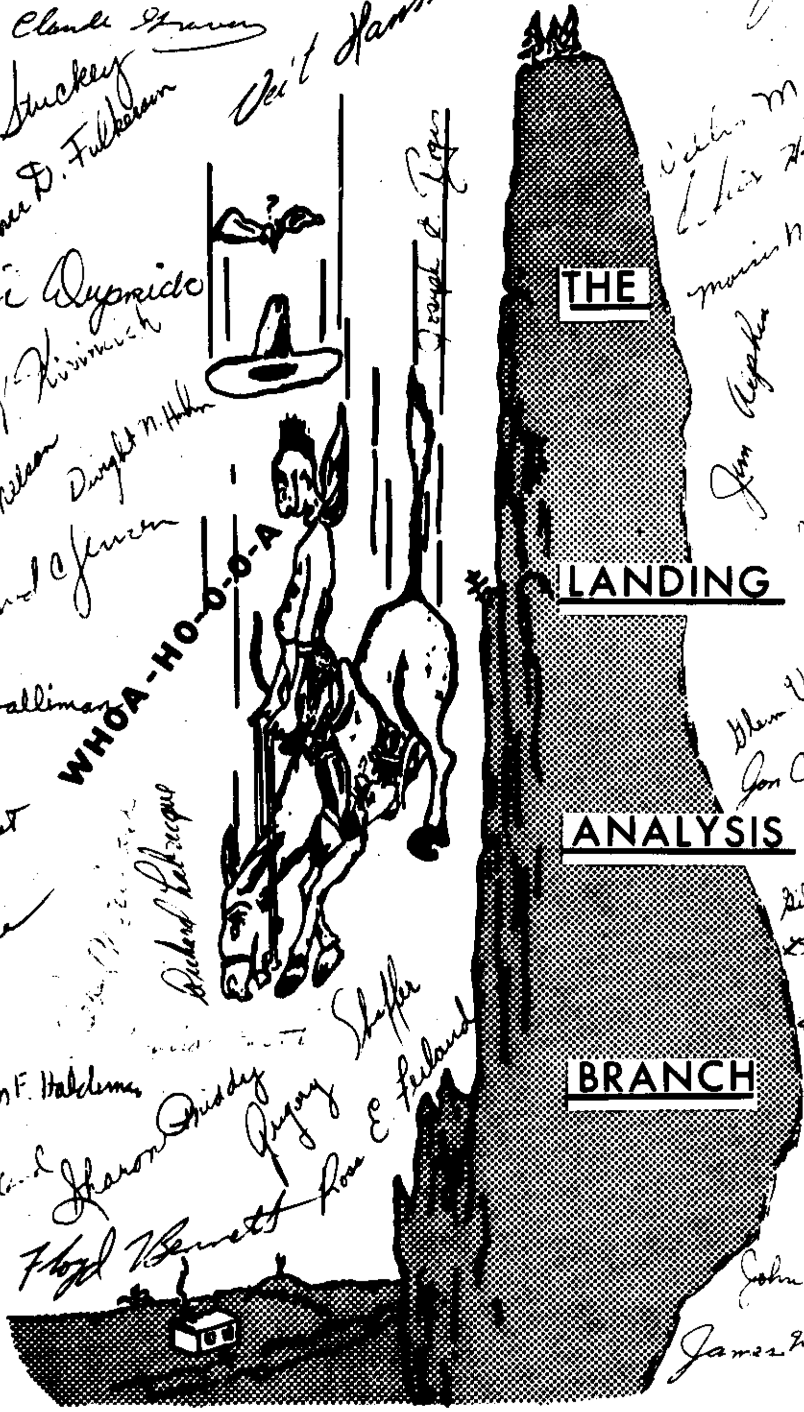
Paula Routledge

Paul Sude

Toni Burgin

Anita M. Terry

Kay McKaughan



Claude Graves
Gloria Stuckey
Grace D. Fulkerson
Cecil Hansen
Edwin Dupricdo
Nicholas McKinnich
Richard D. Nelson
Dwight N. Hahn
Fred C Jensen
Charles Halliman
James V. West
Don Payne
Richard Laberge
William F. Haldeman
Sharon Griddy
Gregory Shaffer
Ross E. Leland
Floyd V. Bennett
Joseph E. Rigas

Doris J. Roberts
William M. Bolt
Clair Hill
Maurice N. Montez
Jim Aughey
Charles Sonerant
Glen Venables
Jon C Harpold
Gilbert Carman
Bill Taylor
William J. Feeney
John K. Burton
James W. Tolin Jr

THE LANDING ANALYSIS BRANCH

The designated responsibilities of the Landing Analysis Branch are mission planning and analysis related to descent to and ascent from the surface of gravitational bodies with consideration given to thrust-controlled flight and aerodynamically controlled flight as required. This branch consists of two sections: the Lunar Landing Section, composed of a descent group and an ascent group; and the Reentry Studies Section.

LUNAR LANDING SECTION

Specific tasks which must be performed to produce a final lunar module descent/ascent mission design include powered flight trajectory analysis, guidance analysis, systems analysis, guidance and flight monitoring procedures development, and real-time mission support. Initially, computational capability had to be developed to conduct the required analyses. Results of the analyses conducted appeared in the Apollo 11 mission documents including the reference trajectory, the operational trajectory, dispersion documents, and revisions to each.

The result of 2 years of detailed planning and analysis by this section was the successful accomplishment of the first manned lunar landing on July 20, 1969, and ascent to lunar orbit on July 21, 1969. The documented results of this effort were used as a basis for the premission plan (operational trajectory) for Apollo 11.

The sequence of events leading to a lunar landing from lunar orbit are the following: CSM/LM undock, CSM separation, descent orbit injection (DOI), and the powered descent. Undocking occurs during the thirteenth orbit after the circularization maneuver (LOI-2). Approximately 30 minutes later, the CSM performs a separation maneuver. One-half orbit after separation, the DOI maneuver is performed to place the LM on a Hohmann transfer orbit that will transfer it from the near 60-n. mi. circular parking orbit to a low altitude of 50 000 feet. The powered descent maneuver is initiated near the 50 000-foot perilune of the descent transfer orbit and consists of three operational phases: braking, for efficiency; approach, for crew visibility; and landing, for takeover of manual control to landing on the lunar surface. The transition from braking to approach phase is termed high gate, and the transition from approach to landing phase is termed low gate. Details of the premission plan for lunar descent from descent engine ignition to landing are shown in figure 1.

The sequence of events that lead to insertion into lunar orbit after launch from the surface are as follows: prelaunch preparation, ignition/staging, vertical rise, pitchover, and insertion upon completion of powered flight. Prelaunch preparation nominally begins approximately 2 hours prior to lift-off and includes checkout of the various systems to assure that each is ready for launch. Separation occurs at ascent engine ignition; the ascent stage begins vertical rise and leaves the descent stage on the lunar surface. After the vertical phase is completed, the vehicle pitches over into the attitude required to begin the near optimum ascent-to-insertion trajectory. When targeted insertion conditions are met, the ascent engine cuts off, and the vehicle is in the desired coasting orbit to begin rendezvous preparations. Details of the lunar module ascent to insertion are shown in figure 2.

Propellant utilization calculations and allowables, termed ΔV budget, received much time and attention during the Apollo 11 lunar landing planning effort. Propellant is a highly critical consumable and can determine the success of the mission. A typical set of ΔV budget figures, one result of many updates and revisions, is shown in figure 3 and in tables I and II.

Development of procedures and techniques to monitor critical systems and to assess flight progress, both by the crew on board the vehicle and by the ground flight control personnel, received much attention. It seemed as if all of MSC and a large contractor force were involved in this effort, and its importance cannot be overemphasized. The Landing Analysis Branch led the procedures and techniques development effort for lunar module descent and ascent. Typical results of this effort are shown by the flow charts in figure 4 for descent and in figure 5 for ascent. Full detail of the results of these tasks are published in various volumes of the Apollo Mission Techniques documents.

The problem of backup manual control for aborts from descent to or ascent from the lunar surface were also studied in a series of meetings. If both the primary and abort guidance systems should fail, some manual control technique was desired by which safe orbit conditions could be achieved. The manually controlled attitude angles and duration at each attitude that resulted from the study are shown in figure 6. This figure was available to the ground flight control personnel during Apollo 11 and would have been used to obtain the desired attitudes to be relayed to the crew if manual control had become necessary.

Both real-time events and postflight analyses show that the actual descent trajectory was very close to the nominal automatic trajectory down to the point of entry into program 66. The DOI maneuver was executed with very small residuals which were burned to zero in the radial and down-range directions. The DPS ignition was performed on time, and postflight data indicate that the thrust-to-weight ratio was very close to nominal. The windows-up maneuver was initiated very close to the expected time, but the execution was longer than expected because of a misplaced rate scale switch. Landing radar altitude and good velocity data signals were achieved while the SC was still in the transient state at a yaw angle of approximately 20°. The good velocity data were earlier than expected. The throttle recovery was achieved within 1 second of preflight predictions. High gate altitude and altitude rates were slightly lower than nominal. Normally, the crew would evaluate the landing area soon after the pitch maneuver at high gate. However, because of program alarms, Commander Armstrong delayed this evaluation until an altitude of approximately 3000 feet. It became apparent that the target point was an undesirable landing area. P66 was entered at approximately 400-feet altitude, and the trajectory was translated down-range approximately 1100 feet from the targeted landing area. The total flight time was extended an additional 40 seconds from the normal time for an automatic landing.

. The typical ground monitoring charts presented in figures 7 and 8 show comparisons of actual and premission planned parameters. The departure from the nominal trajectory after manual control was assumed is shown in figure 7. The near nominal performance of the DPS engine is shown in figure 8. Analog strip charts of pertinent descent parameters (fig. 9) also indicate the near nominal descent trajectory. The combined effect of an initial down-range position error and the additional down-range manually controlled translation to a smooth landing area appear in figure 10 as a miss from the nominal landing site, but the actual landing point was within the premission predicted landing ellipse.

The point marked initiate P66 indicates the point at which the commander assumed attitude and rate-of-descent control to deviate from the landing point to which the automatic guidance P64/P65 was steering (a boulder field area around West Crater). The P66 initiation occurred at an altitude of 410 feet and 2 minutes 18 seconds prior to landing. The crater designated in figure 10(b) as PHOTO AS11-40-5955 indicates the large crater photographed by the crew during EVA on the surface.

Lift-off and ascent from the lunar surface was also very near the nominal. Insertion into the target orbit was well within expected tolerances. Comparisons of the actual and preplanned trajectory parameters are shown in figures 11 and 12; near nominal conditions are indicated. The ascent analog strip charts (figs. 13 and 14) also indicate the near nominal ascent trajectory.

The preceding paragraphs indicate the type and magnitude of work done by the Lunar Landing Section in premission planning, in mission support, and in postflight analysis. The figures presented are taken from various documents published by section personnel. Many long days and much overtime work willingly volunteered by the members of the section enhanced the success of the first lunar landing mission. The quality of their work and attention to detail was a significant factor in the overwhelming success of the Apollo 11 mission in July 1969.

TABLE I.- LM DESCENT DELTA V BUDGET (SEPTEMBER 1968)

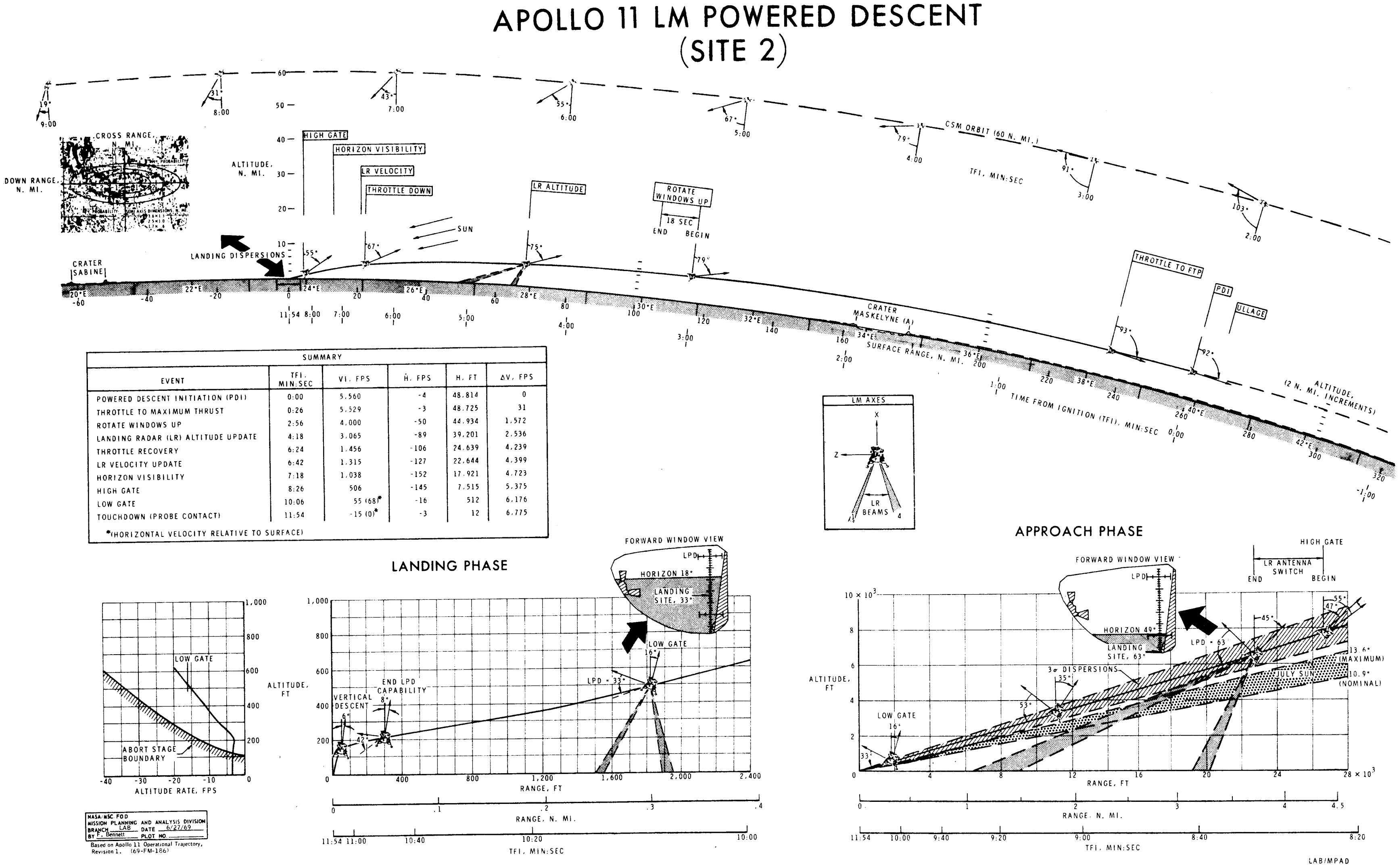
<table>
<tr><th rowspan="2">Item</th><th colspan="4">Phase ΔV, fps</th><th rowspan="2">Total ΔV, fps</th></tr>
<tr><th>Descent transfer</th><th>Braking</th><th>Final approach</th><th>Landing</th></tr>
<tr><td>Nominal</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Automatic guidance</td><td>71</td><td>5312</td><td>887</td><td>402</td><td>6672</td></tr>
<tr><td>Manual guidance</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Landing site redesignation</td><td>--</td><td>--</td><td>60</td><td>--</td><td rowspan="2">325</td></tr>
<tr><td>Manual maneuvering (50 sec)</td><td>--</td><td>--</td><td>--</td><td>265</td></tr>
<tr><td>Nominal ΔV</td><td></td><td></td><td></td><td></td><td>6997</td></tr>
<tr><td>Dispersions (RSS)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>CSM orbital altitude</td><td colspan="2">30</td><td>--</td><td>--</td><td rowspan="5">±119</td></tr>
<tr><td>CSM orbital plane</td><td>--</td><td>10</td><td>--</td><td>--</td></tr>
<tr><td>LM navigation</td><td>--</td><td>40</td><td>--</td><td>60</td></tr>
<tr><td>DPS thrust at FTP</td><td>--</td><td>40</td><td>--</td><td>--</td></tr>
<tr><td>Manual control</td><td>--</td><td>--</td><td>--</td><td>80</td></tr>
<tr><td>Total descent budget, fps</td><td></td><td></td><td></td><td></td><td>6997 ± 119</td></tr>
</table>

TABLE II.- LM ASCENT DELTA V BUDGET (SEPTEMBER 1968)

Item	ΔV, fps
Nominal[a]	
Inplane launch into 10- by 30-n. mi. orbit	6032
Out-of-plane allowance (0.5°)	18
Nominal ΔV	6050
Contingency bias	
PGNCS/AGS switchover	40
Nominal + bias	6090
Dispersions (RSS)	
PGNCS	10
Thrust	8
Total dispersions	±12.8
Total ascent budget,[b] fps	6090 ± 12.8

[a] $T/W = 0.3316$.

[b] $\Delta V_{asc} = 7659.6 - 8170.0 \left(\frac{T}{W_0}\right) + 10\,000.0 \left(\frac{T}{W_0}\right)^2$.



APOLLO 11 LM POWERED DESCENT
(SITE 2)

SUMMARY					
EVENT	TFI, MIN:SEC	VI, FPS	Ḣ, FPS	H, FT	ΔV, FPS
POWERED DESCENT INITIATION (PDI)	0:00	5,560	-4	48,814	0
THROTTLE TO MAXIMUM THRUST	0:26	5,529	-3	48,725	31
ROTATE WINDOWS UP	2:56	4,000	-50	44,934	1,572
LANDING RADAR (LR) ALTITUDE UPDATE	4:18	3,065	-89	39,201	2,536
THROTTLE RECOVERY	6:24	1,456	-106	24,639	4,239
LR VELOCITY UPDATE	6:42	1,315	-127	22,644	4,399
HORIZON VISIBILITY	7:18	1,038	-152	17,921	4,723
HIGH GATE	8:26	506	-145	7,515	5,375
LOW GATE	10:06	55 (68)*	-16	512	6,176
TOUCHDOWN (PROBE CONTACT)	11:54	-15 (0)*	-3	12	6,775

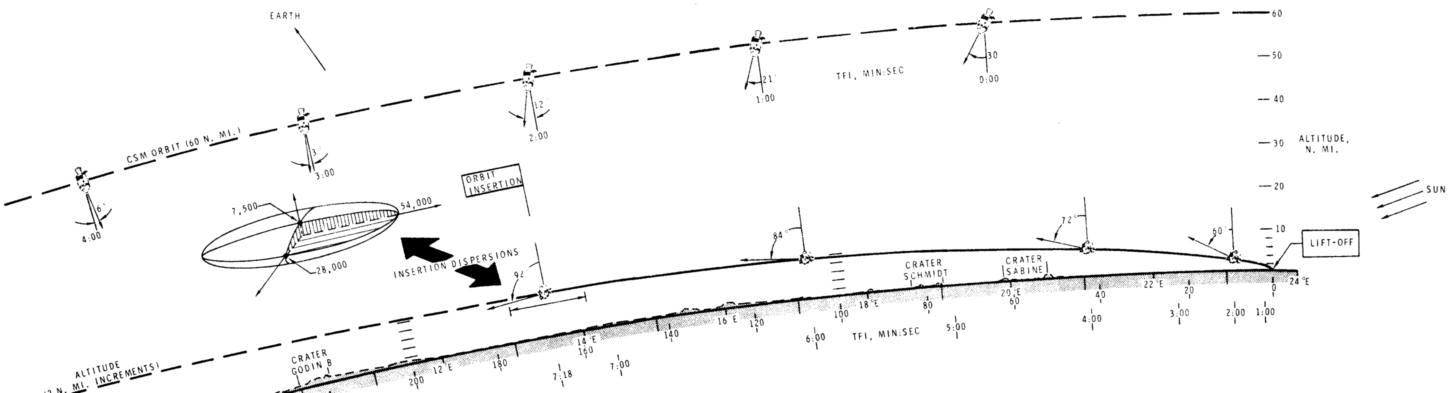
*(HORIZONTAL VELOCITY RELATIVE TO SURFACE)

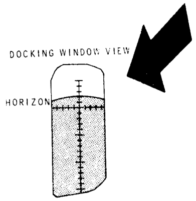
NASA/MSC FOD
MISSION PLANNING AND ANALYSIS DIVISION
BRANCH LAB DATE 6/27/69
BY F. Bennett PLOT NO.
Based on Apollo 11 Operational Trajectory, Revision 1. (69-FM-186)

Figure 1.- Premission plan for descent to lunar surface.

APOLLO 11 LM POWERED ASCENT

(SITE 2)

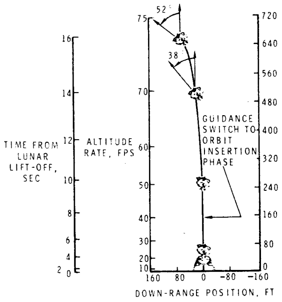


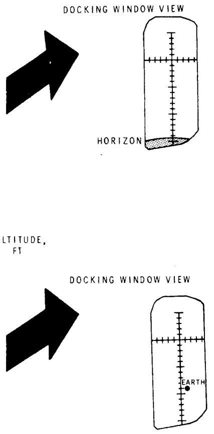


SUMMARY								
					LM - CSM RELATIVE			
EVENT	TFI, MIN:SEC	INERTIAL VELOCITY, FPS	ALTITUDE RATE, FPS	ALTITUDE, FT	RANGE, N. MI.	RANGE RATE, FPS	PHASE ANGLE, DEG	LOOK ANGLE, (LOCAL VERTICAL) DEG
LIFT-OFF	0:00	15	0	0	80	3,531	3.2	44
END OF VERTICAL RISE	0:16	77	75	659	90	3,866	4.1	51
	2:00 4:00 6:00	1,010 2,412 4,165	168 183 111	13,892 35,910 54,298	159 224 259	3,837 2,617 911	8.8 12.9 15.1	74 83 87
ORBIT INSERTION	7:18	5,536	32	59,977	262	-449	15.3	87

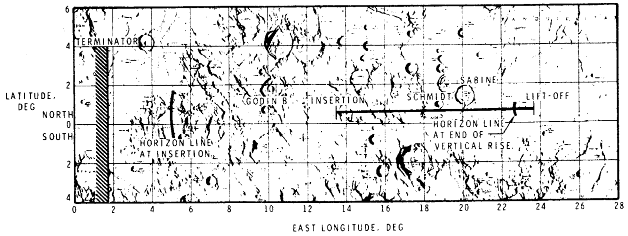
h_p = 55,000 FT
h_a = 45 N. MI.
η = 18°
γ = .33°
ΔV = 6,060 FPS

VERTICAL RISE PHASE





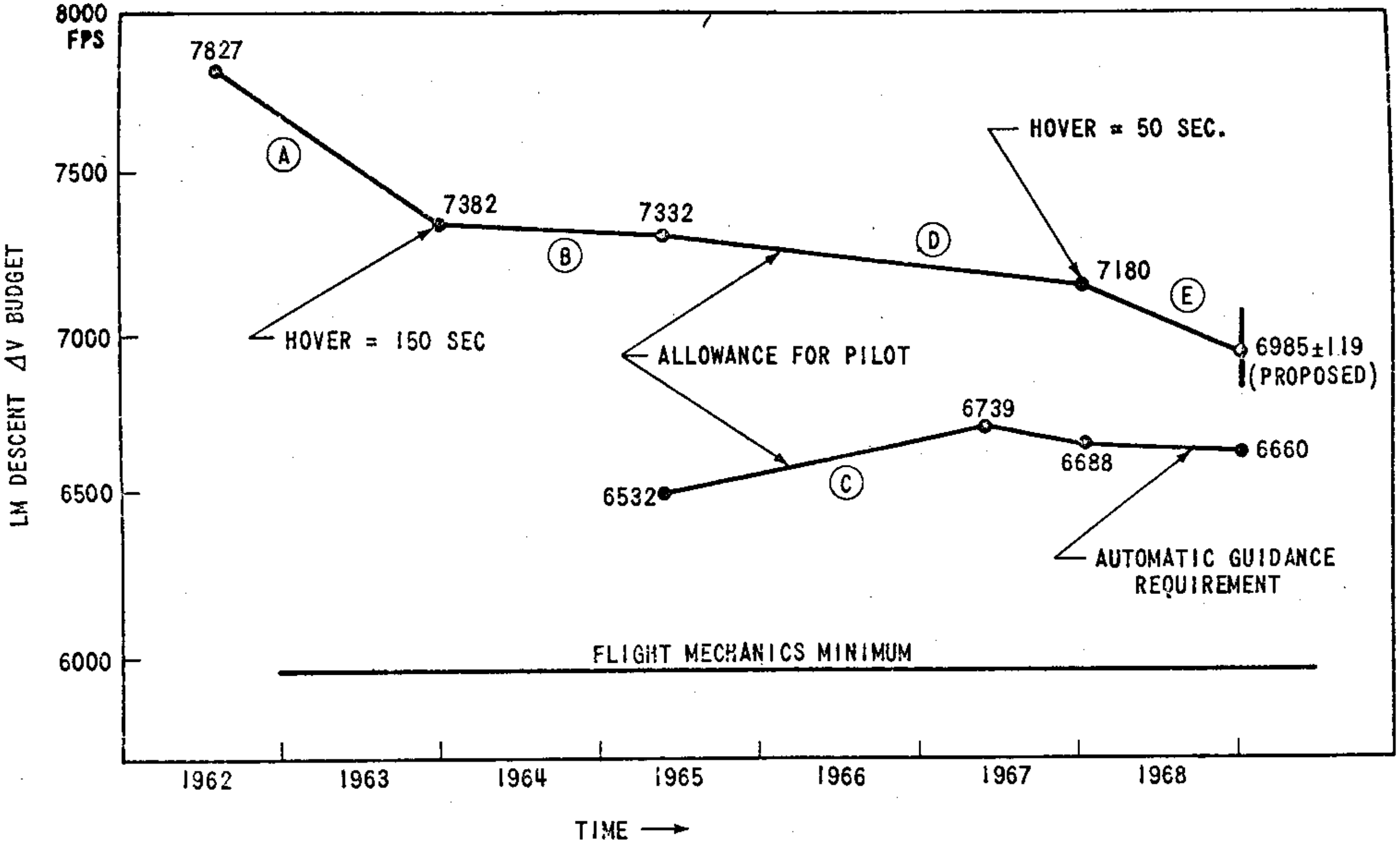
LM GROUNDTRACK



NASA/MSC/FOD
MISSION PLANNING AND ANALYSIS DIVISION
BRANCH LAB DATE 6/30/69
BY V. Hanssen PLOT NO. ______

Based on Apollo 11 Operational Trajectory, Revision 1. (69-FM-186)

Figure 2.- Premission plan for ascent from lunar surface.



A. CHANGE FROM EQUIPERIOD TO HOHMANN TRANSFER ORBIT

B. REFINEMENTS FROM GUIDED SIMULATIONS

C. LM-DPS PROBLEMS REQUIRE NOMINAL THROTTLE DOWN ~ 120 SEC BEFORE HIGH GATE

D. CSM ORBITAL ALTITUDE REDUCED TO 60 NMI; REDUCED REDESIGNATION

E. DISPERSIONS RSS'd STATISTICALLY WITH Isp & PROPELLANT DISPERSIONS

Figure 3.- LM descent ΔV history.

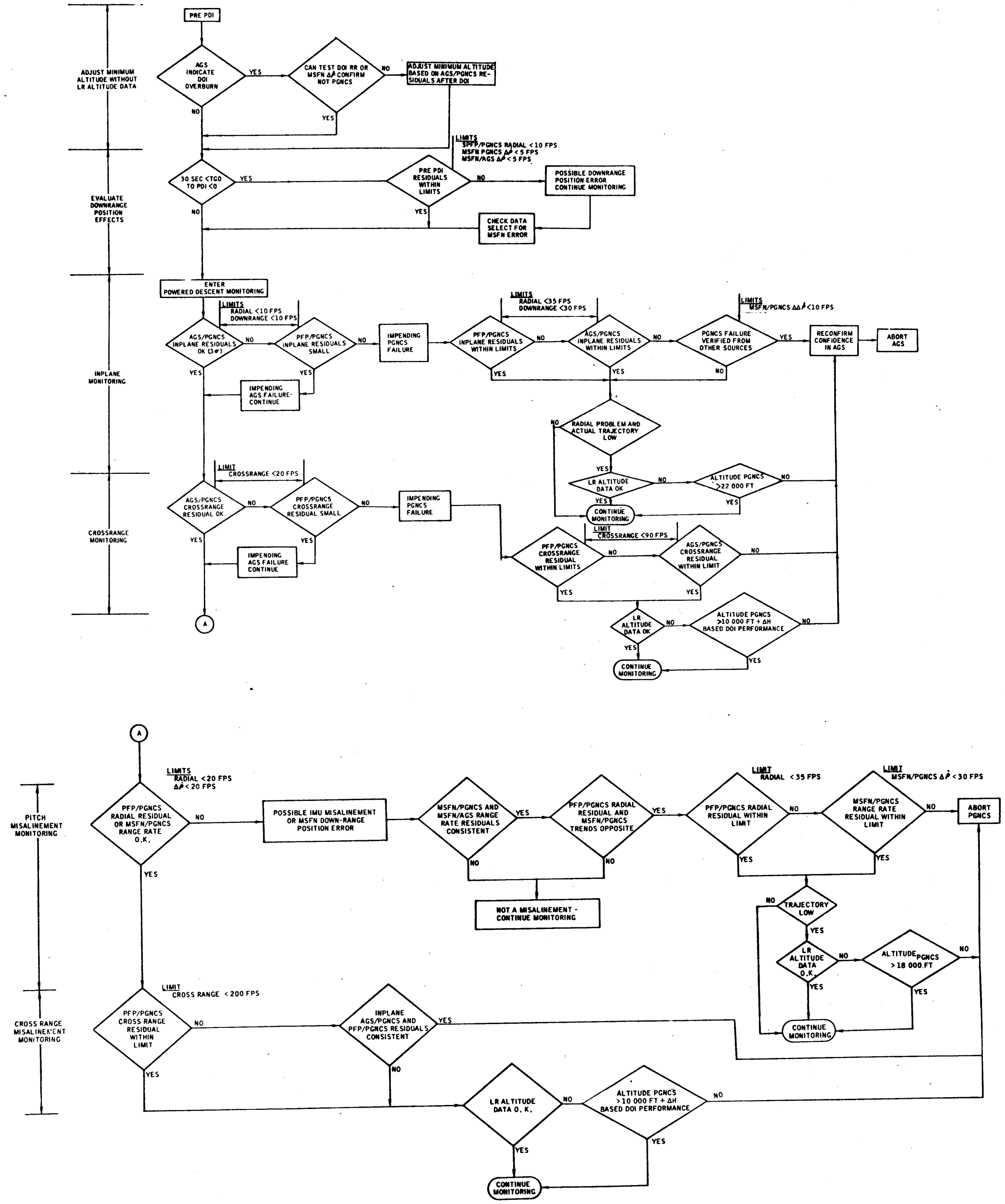
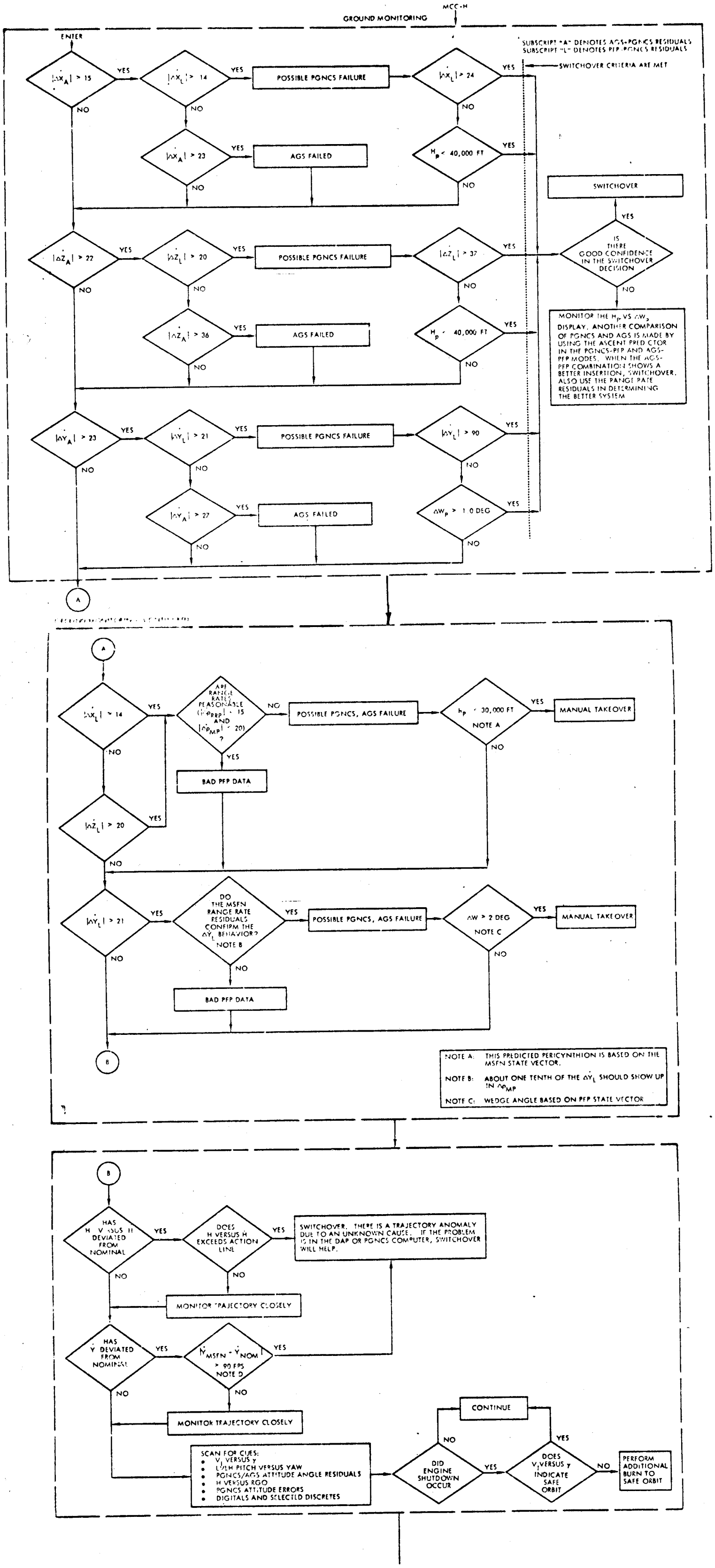


Figure 4.- MCC velocity residual monitoring.



NOTE A: THIS PREDICTED PERICYNTHION IS BASED ON THE MSFN STATE VECTOR.

NOTE B: ABOUT ONE TENTH OF THE $\Delta \dot{Y}_L$ SHOULD SHOW UP IN $\Delta \dot{\rho}_{MP}$

NOTE C: WEDGE ANGLE BASED ON PFP STATE VECTOR

Figure 5.- Procedures and techniques for LM ascent.

NOTE D: Y_{NOM} IS READ FROM CHARTS THAT RELATE Y TO THE OUT-OF-PLANE DISTANCE TO BE TRAVERSED DURING ASCENT

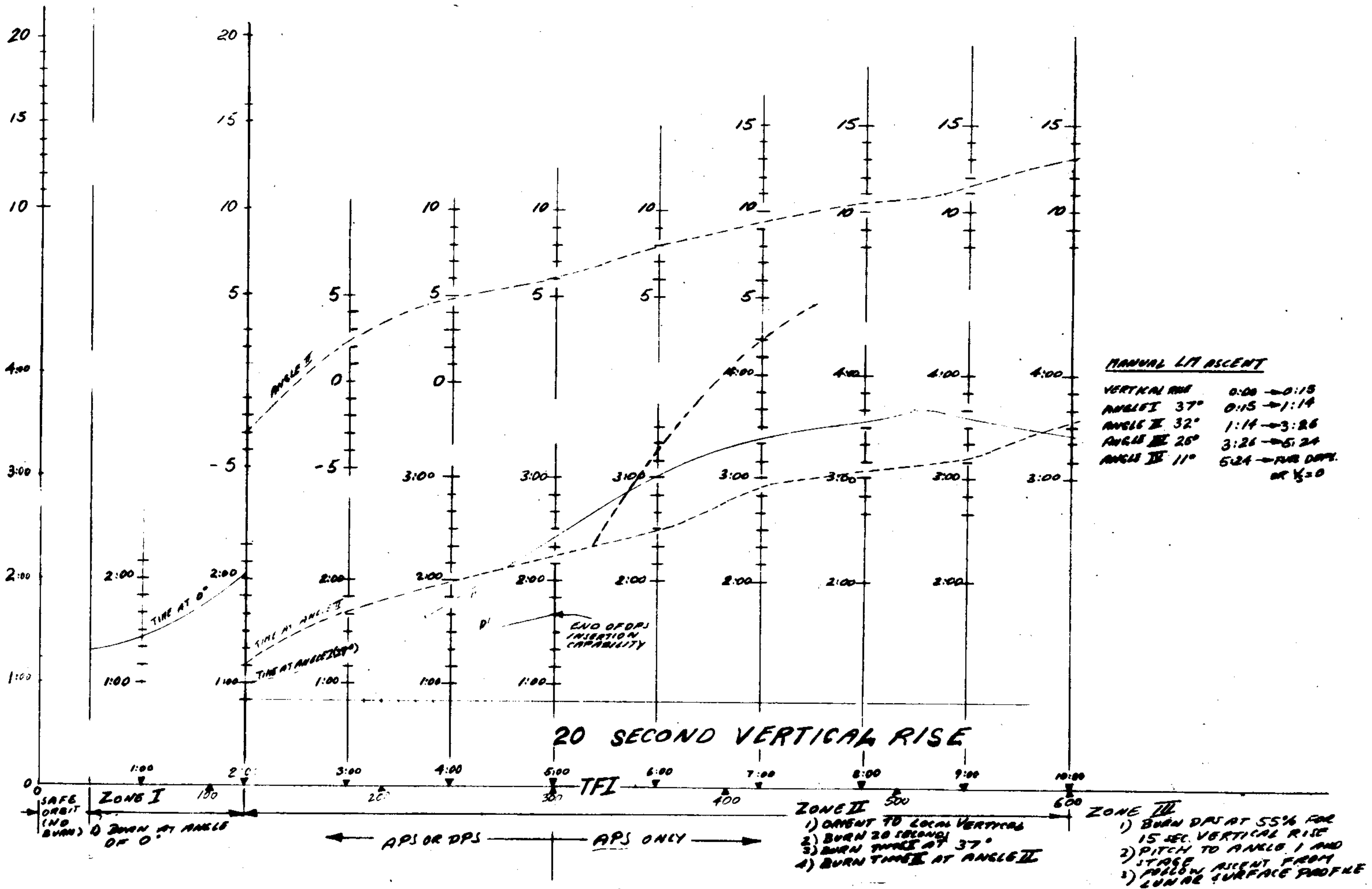


Figure 6.- Manually controlled attitude angles.

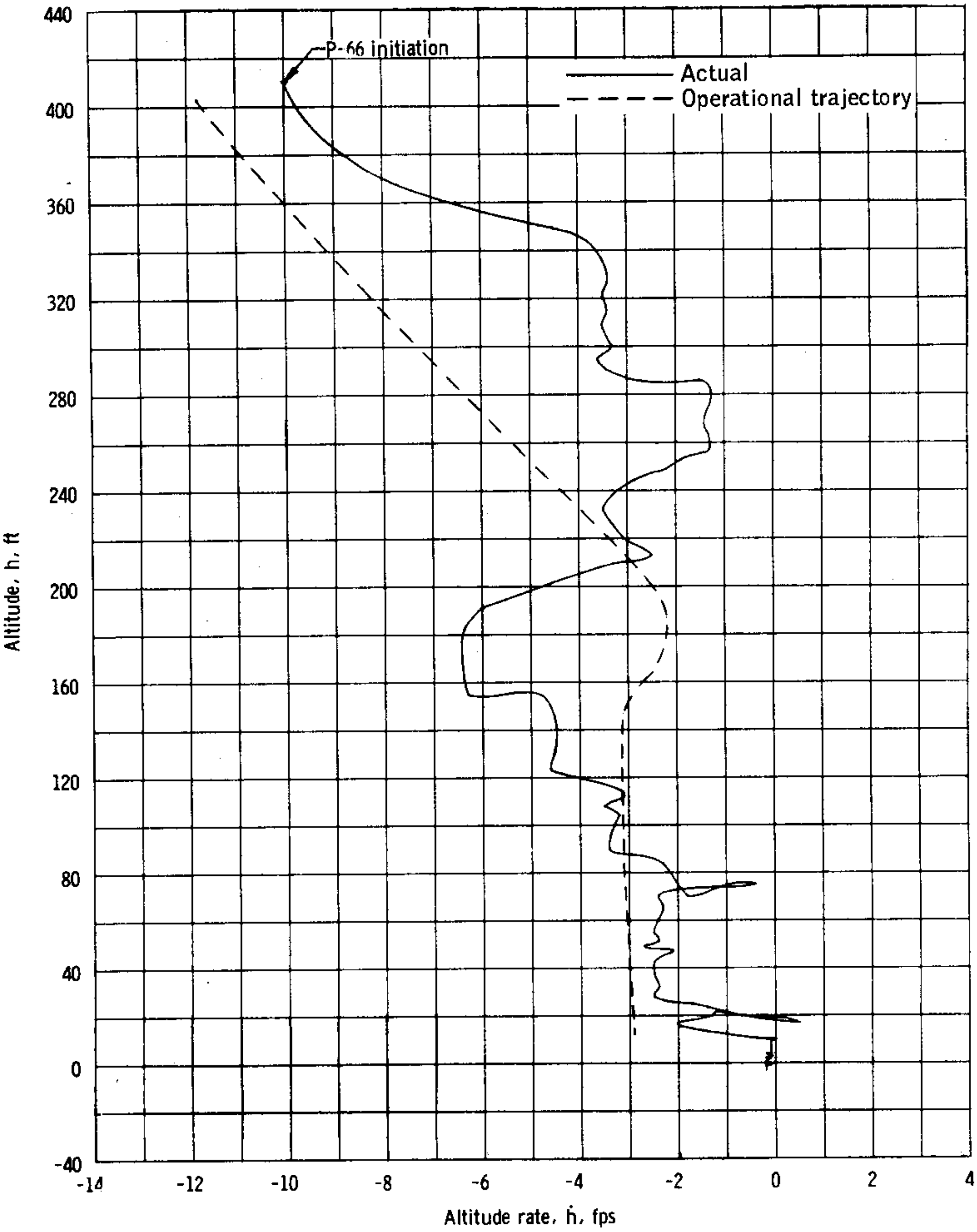


Figure 7.- Altitude versus altitude rate during the landing phase.

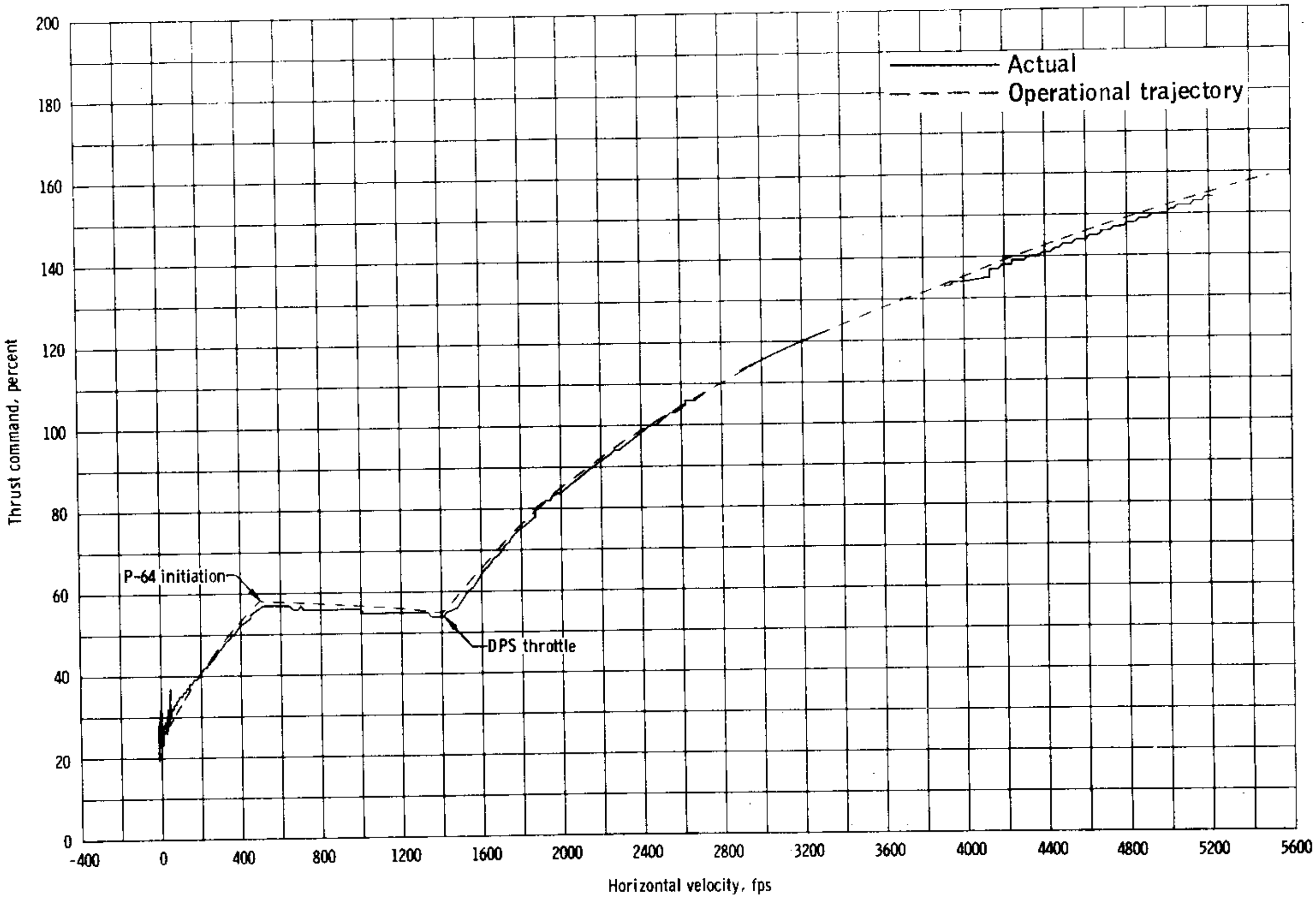
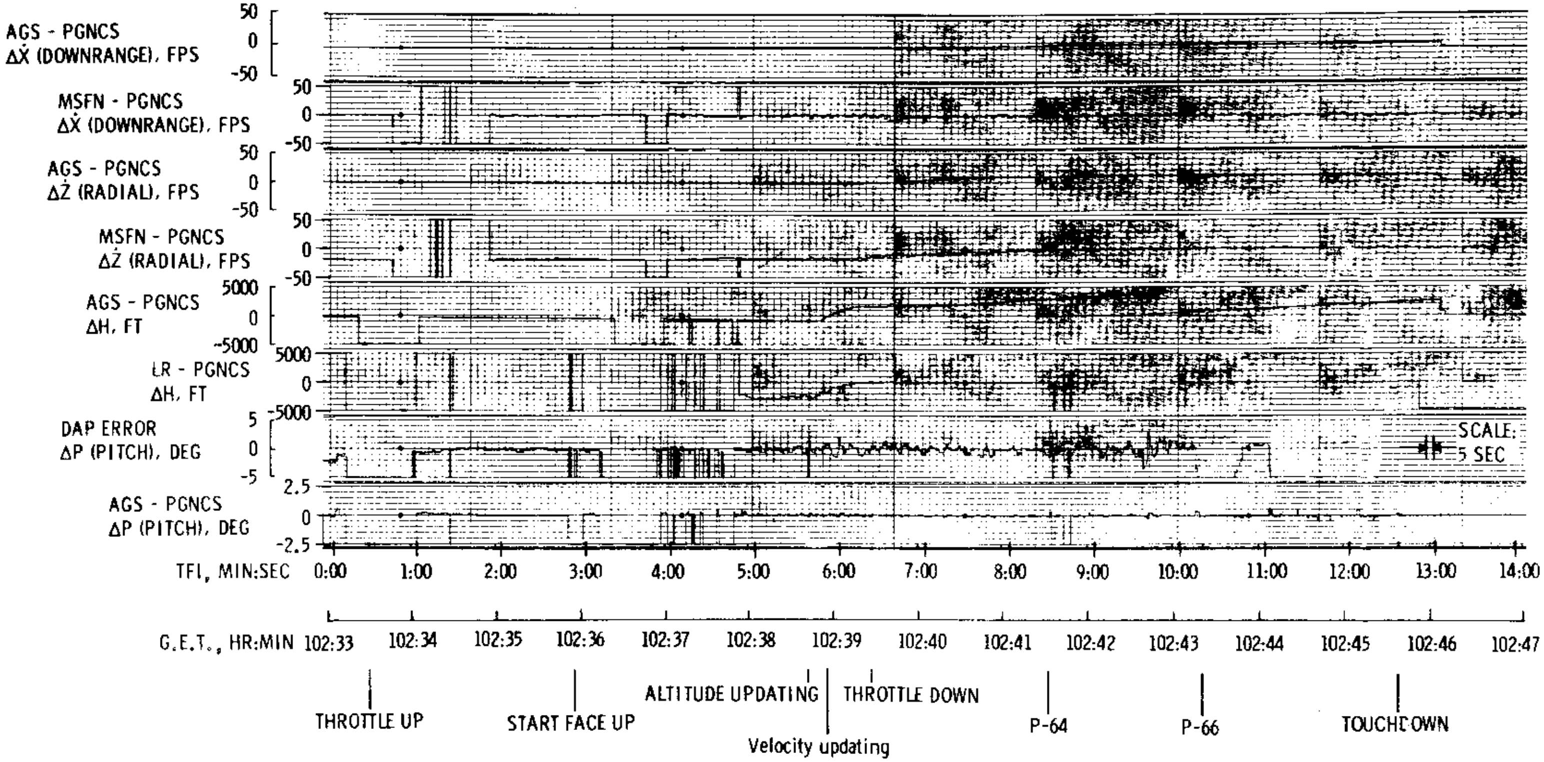
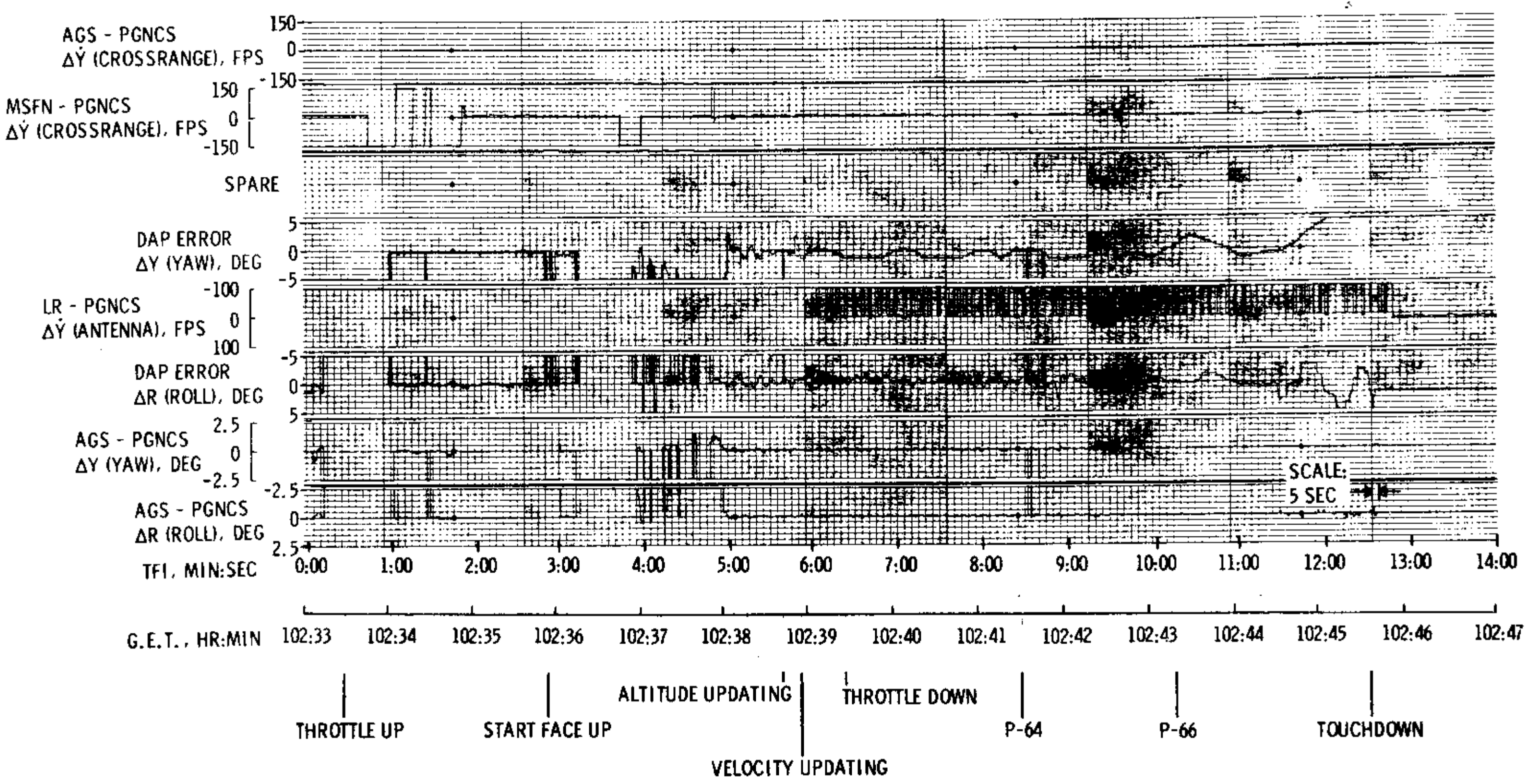


Figure 8.- Percent commanded thrust versus horizontal velocity.



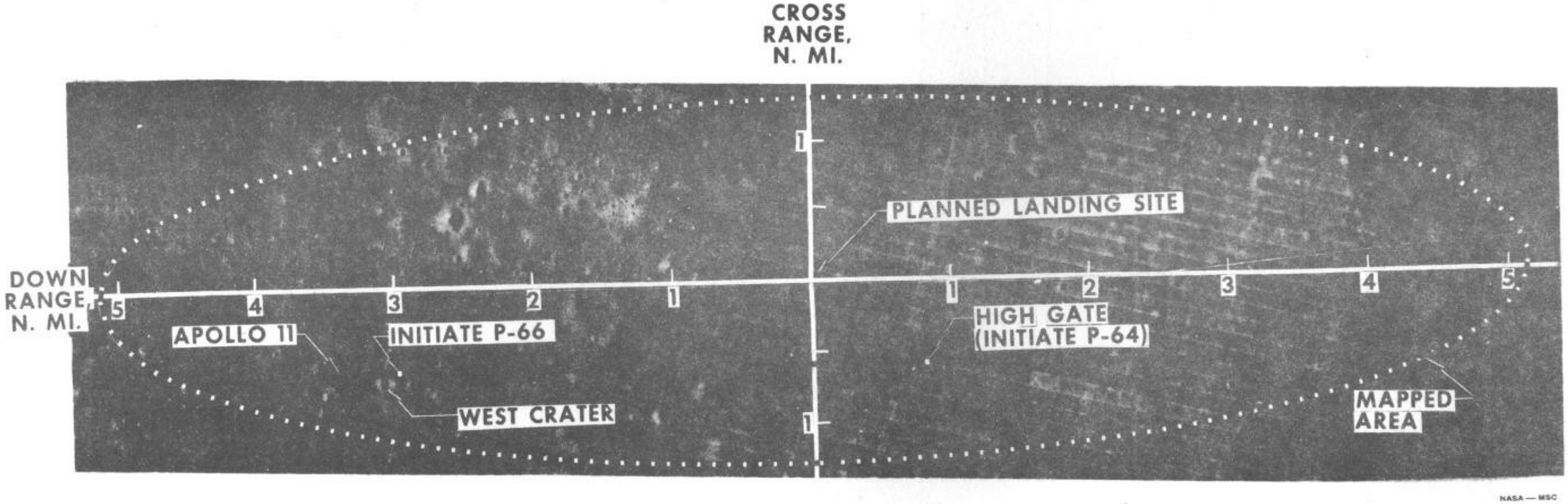
(a) Inplane.

Figure 9. - Apollo 11 descent strip charts.



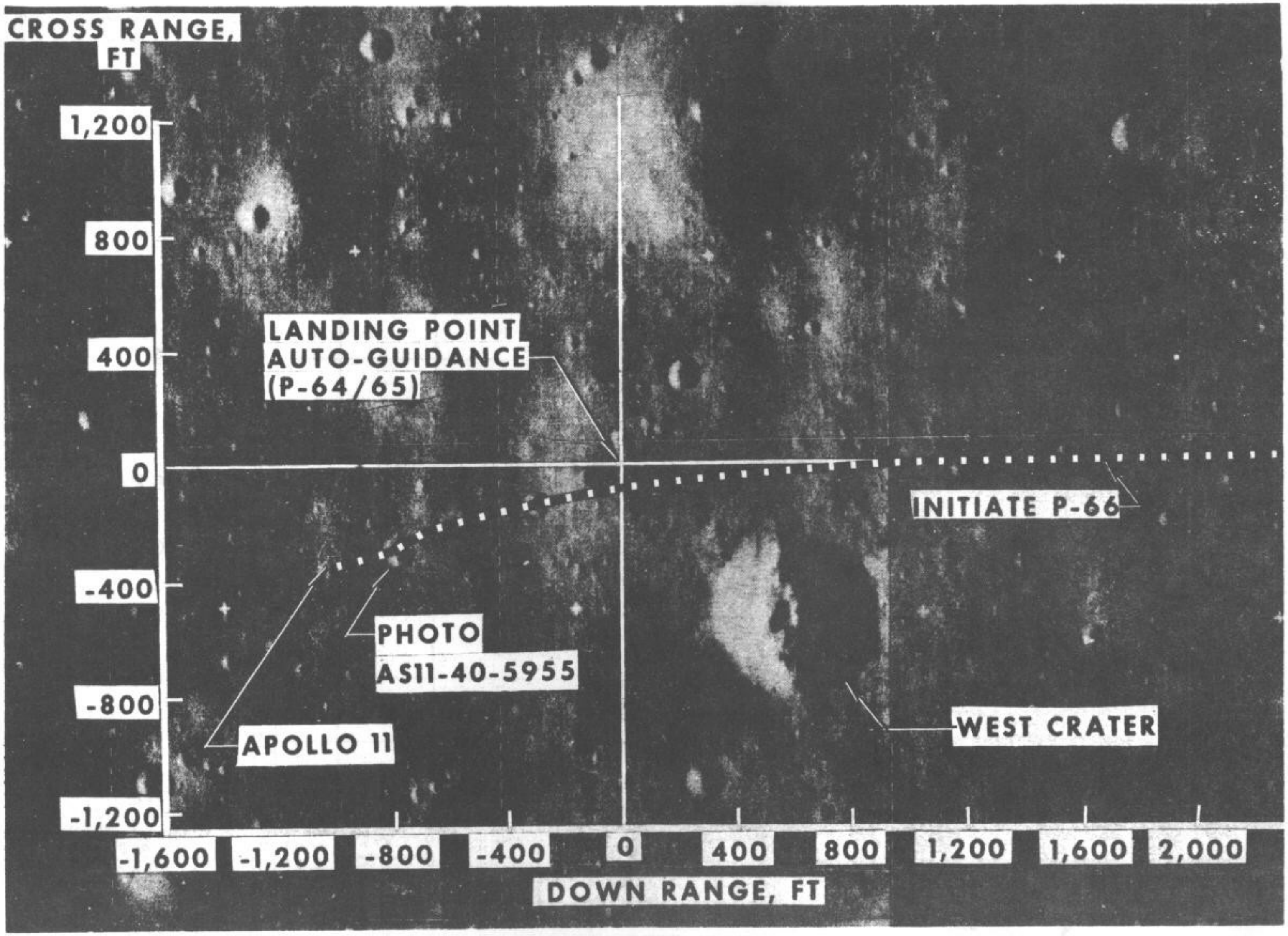
(b) Out-of-plane.

Figure 9.- Concluded.



(a) Landing ellipse.

Figure 10.- Apollo 11 lunar landing site.



(b) Landing phase groundtrack.

Figure 10.- Concluded.

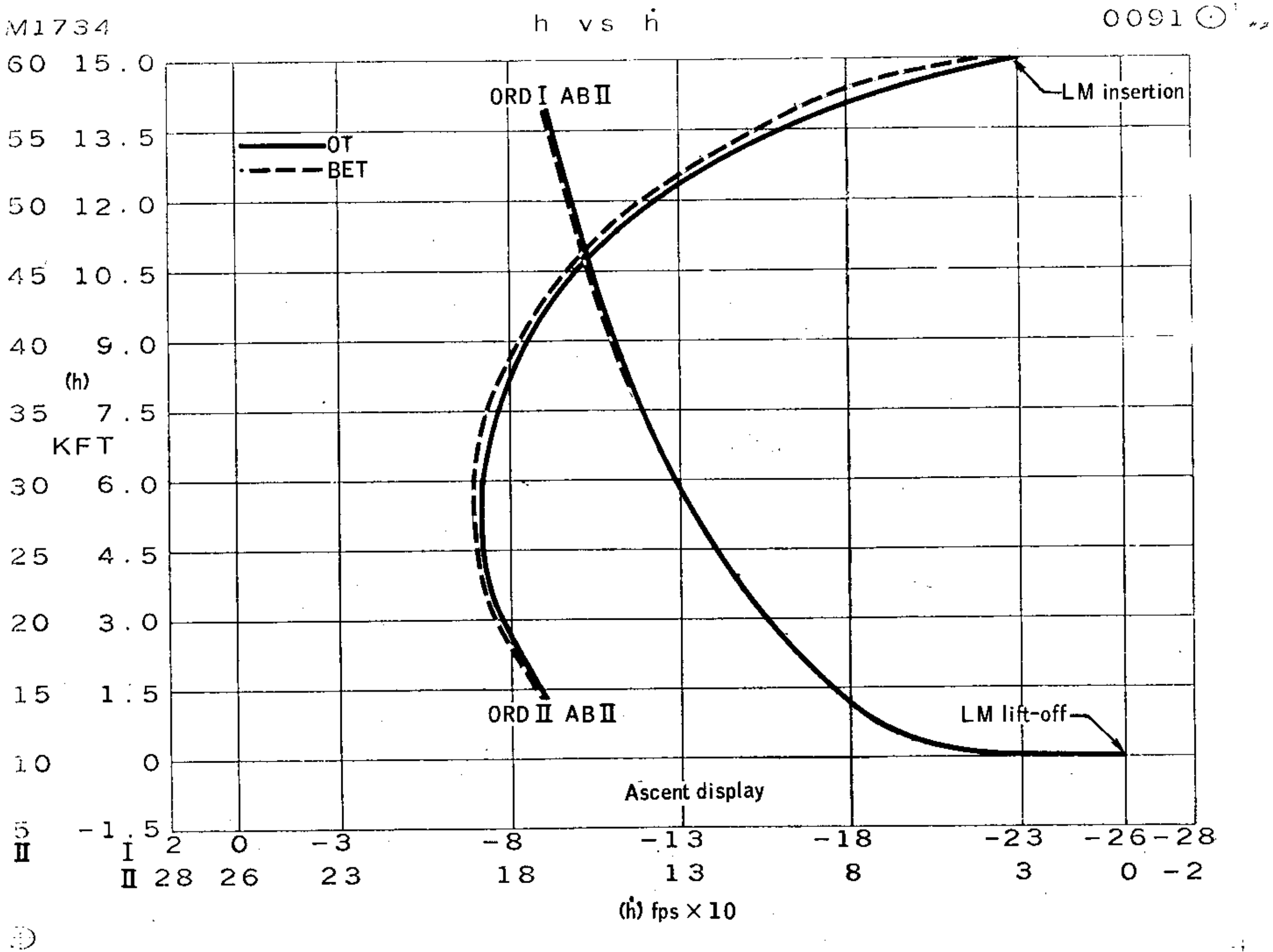


Figure 11.- LM altitude versus LM ascent rate.

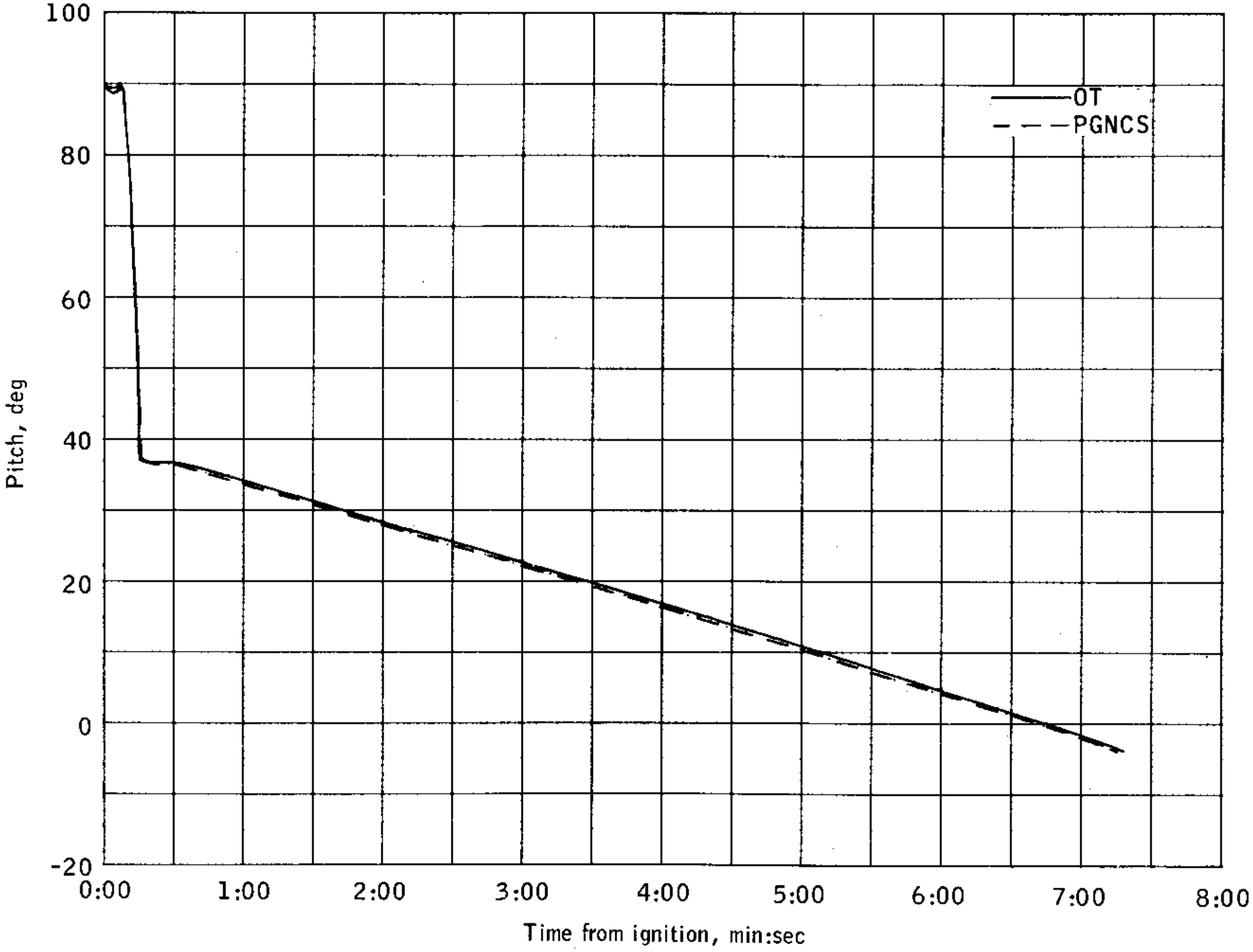


Figure 12.- Pitch attitude history.

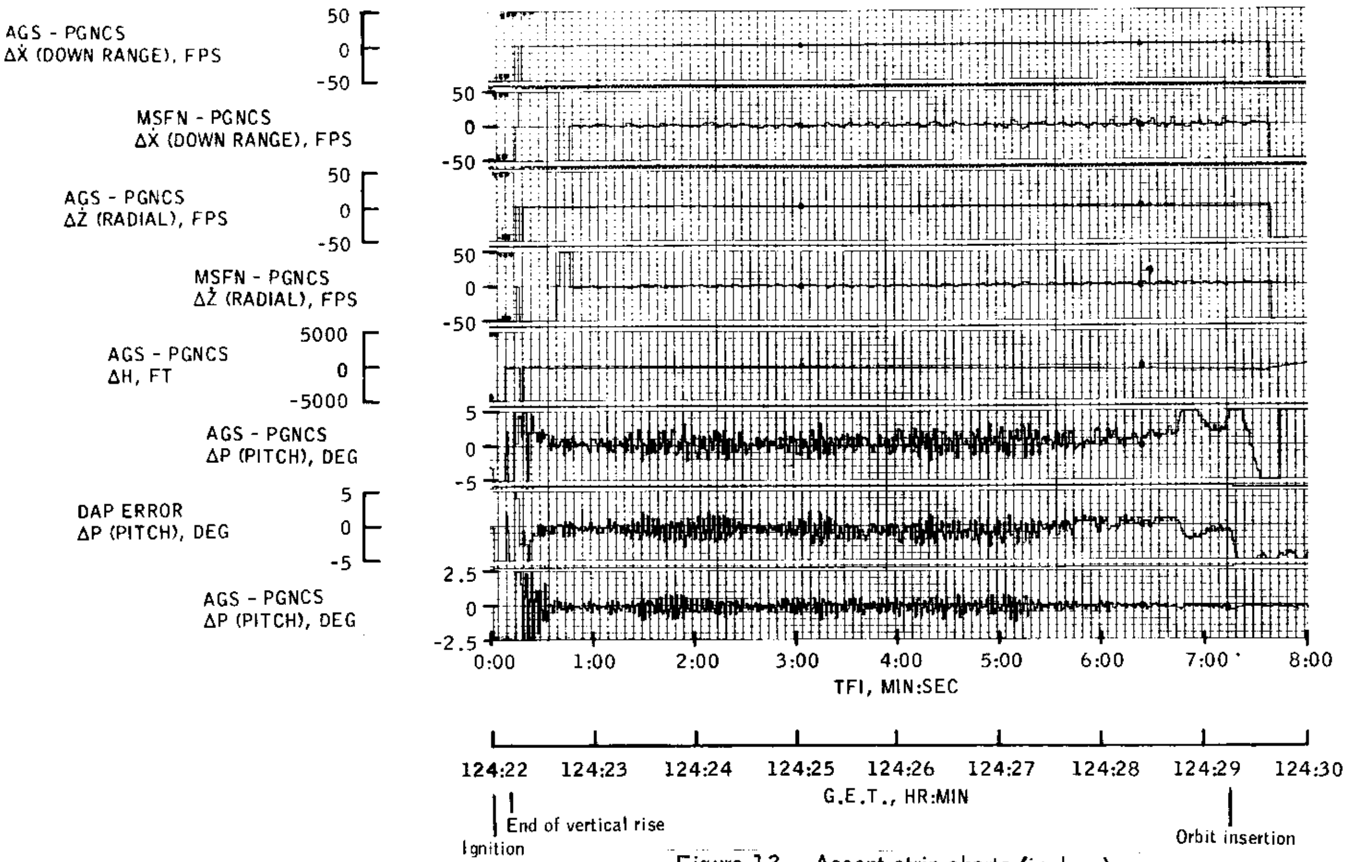


Figure 13.- Ascent strip charts (inplane).

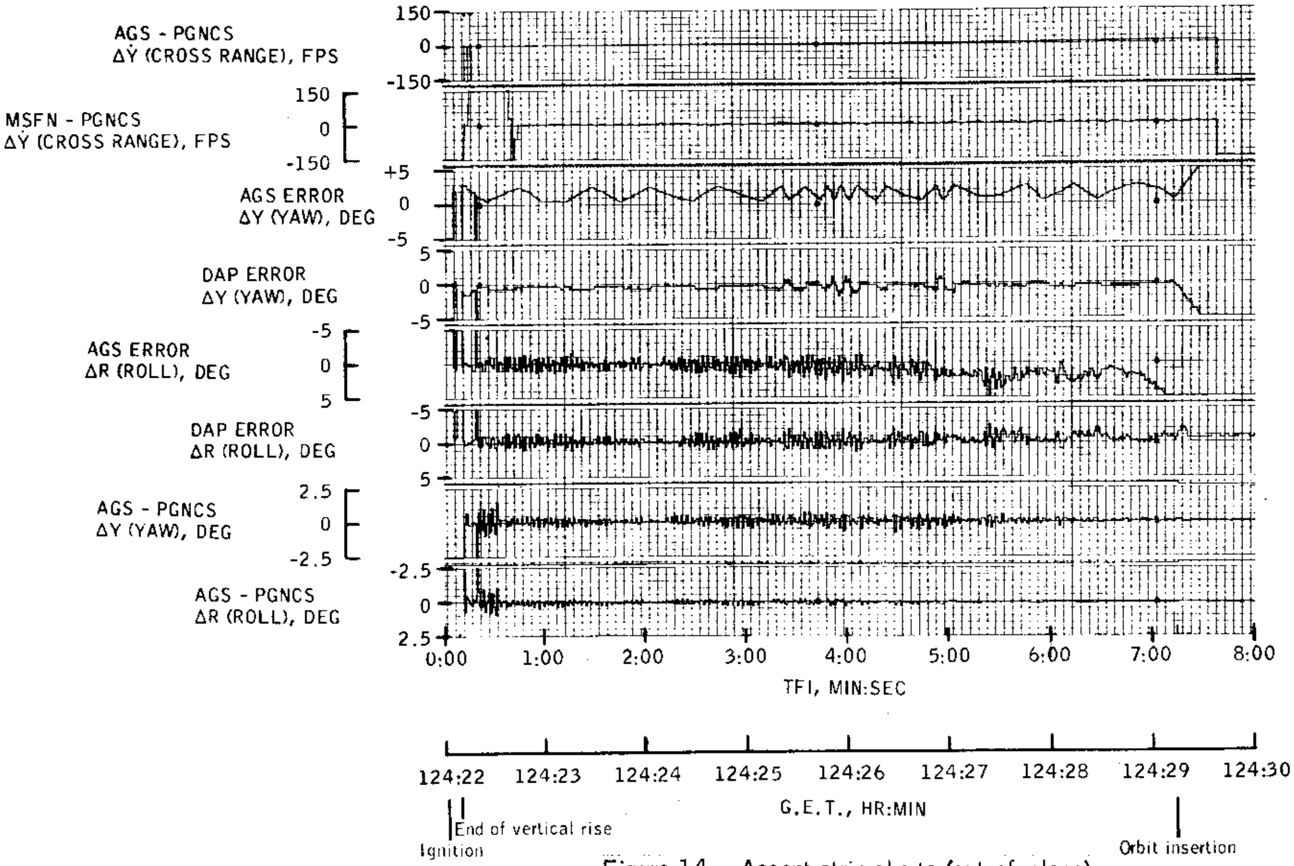


Figure 14.- Ascent strip charts (out-of-plane).

REENTRY SECTION

Atmospheric reentry includes the passage of the command module (CM) through the earth's atmosphere and the safe arrival of the CM at a predetermined geographical location. The passage of the CM through the earth's atmosphere involves problems related to crew safety and accurate trajectory control. The first problem (crew safety) can be divided into three areas: (1) heating, (2) excessive gravitational forces, and (3) skipping out of the atmosphere. Aerodynamic heating is produced when the CM, moving at supersonic speeds, penetrates the atmosphere. The air cannot move fast enough to make way for the moving body and is therefore compressed, which causes the air to be heated up. Enough heat is produced to ionize the air around the CM which produces a barrier to radio communication. The problem of heating is solved by the use of a protective covering of ablative material dissipates heat by melting and vaporizing at the surface. The heat is removed by the loss of the vaporized portion of the heat shield.

The second and third problems concerning crew safety may be best explained by figure 1. In this figure, the CM is shown penetrating the top of the earth's atmosphere at specified angles to a local tangent line. If the CM's direction of motion were along line A, the spacecraft would be penetrating the atmosphere at a steep angle and would pull excessive g-forces, thus endangering the crew. If the CM's direction of motion were along line B or shallower, the spacecraft would literally skip out of the atmosphere. This condition is analagous to skipping a stone across a body of water by throwing the stone at a low or shallow angle with respect to the surface of the water. The desired reentry penetration angle lies between lines A and B, such as line C. When the spacecraft enters at this angle, it is subjected to neither excessive g-forces nor skips out of the atmosphere. The reentry penetration angle is controlled along the return to earth leg by making midcourse corrections to the trajectory. The width of the angle between lines A and B is about 2° and is known as the reentry corridor. The reentry corridor for Apollo 11 is shown in figure 2.

The second basic problem, once the spacecraft has safely penetrated the earth's atmosphere, is to guide the spacecraft to a predetermined landing point. This is accomplished by controlling aerodynamic lifting forces on the CM by rolling the spacecraft about an axis parallel to the direction of motion through the use of small reaction control system thrusters. By modulating this lifting force the CM's lateral and horizontal direction of motion is controlled. The direction in which to roll the spacecraft is determined by an onboard computer which in turn automatically maneuvers the spacecraft to that roll attitude. The CM's motion is eventually slowed by the atmospheric drag to a point where parachutes are deployed and the spacecraft floats to a landing at the target point.

Figure 3 shows the Apollo 11 landing point capability (footprint) on the surface of the earth. Premission, the Apollo entry was to be flown by the guidance and control system to a 1285-n. mi. target (from entry interface to splashdown). However, bad weather conditions developed about 12 hours before entry. Therefore, it was necessary to utilize the entry guidance capability to increase the entry range in order to overfly the bad weather. It was decided in real time to increase the range to 1500 n. mi. The resultant entry ground track and landing point are illustrated in figure 3.

The service module was jettisoned on schedule and at entry interface the CM was on a trajectory near the center of the corridor as shown in figure 2. The entry velocity and flight-path angle were 36 194 fps and -6.48°, respectively. Figure 4 presents the altitude range profile flown on the Apollo 11 mission. This figure, along with table I, presents the significant events for the Apollo 11 entry. Figure 5 presents the velocity load factor profile as sensed by the entry monitoring system. The trace indicates an initial peak load factor of 6.7g and a final phase peak load factor of 6.1g.

The computer indicated a landing at 169°9'W longitude and 13°18'N latitude, which is 1.69 n. mi. from the desired target point.

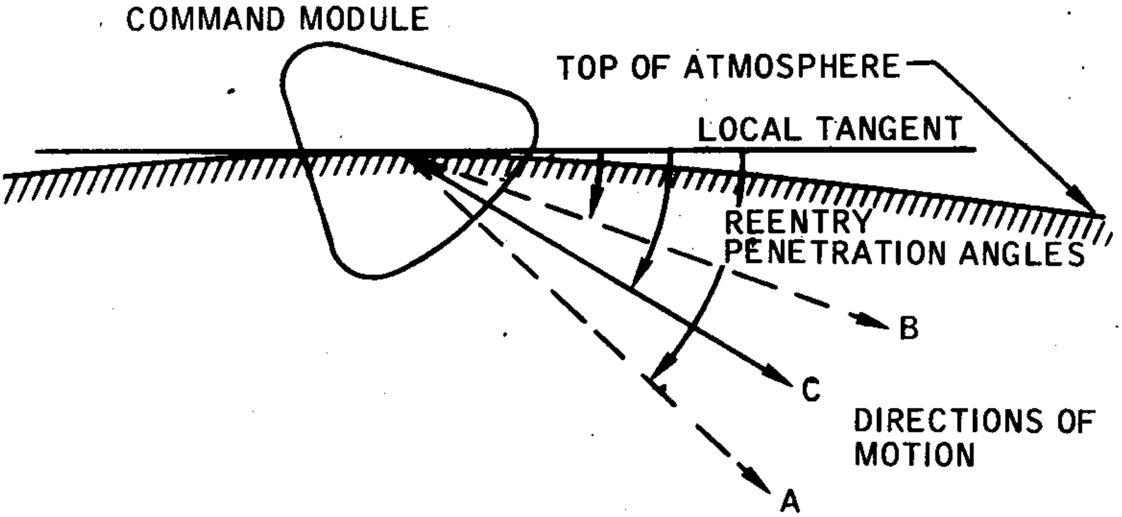


Figure 1.- Command module penetrating the earth's atmosphere.

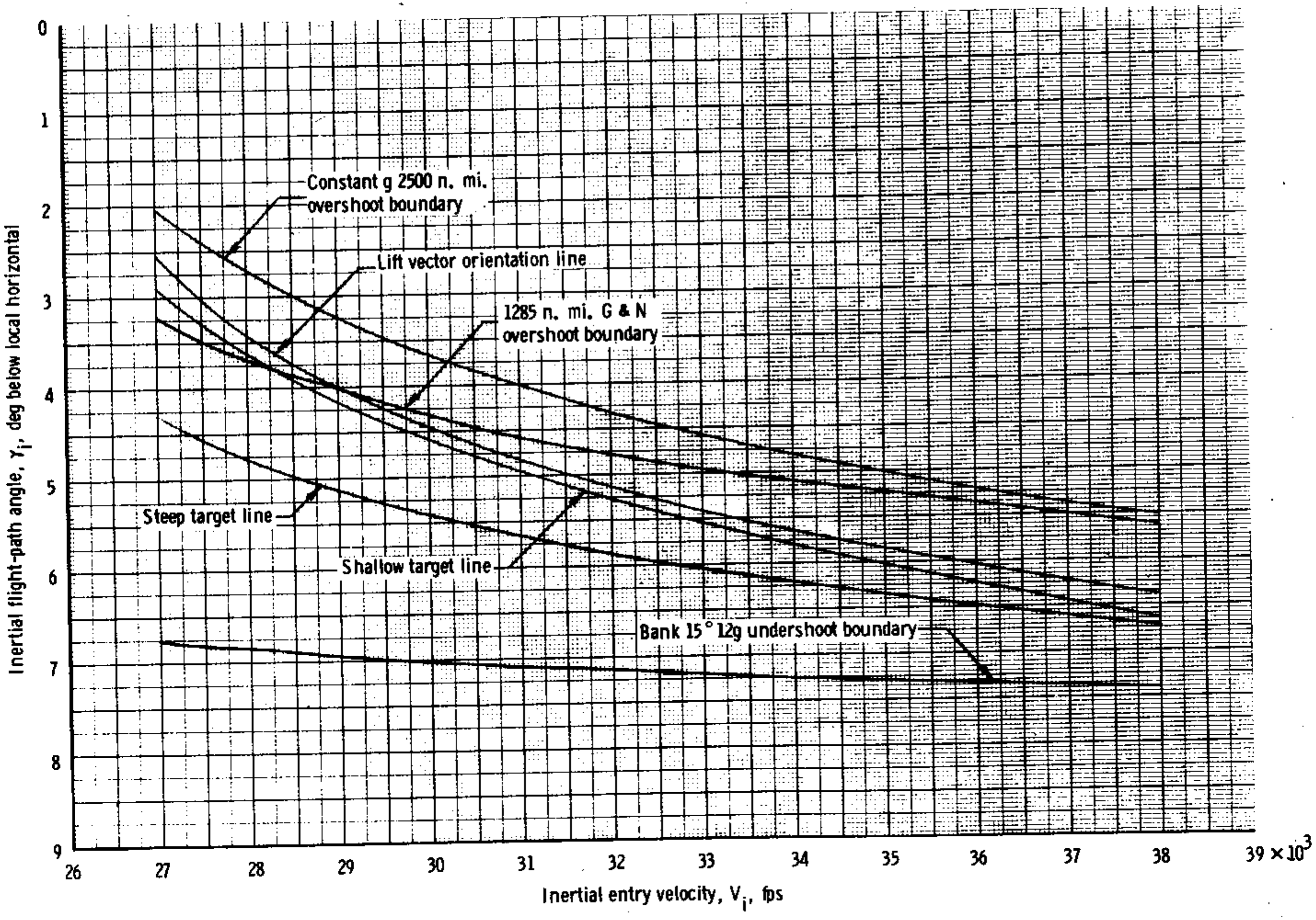


Figure 2.- Reentry corridor.

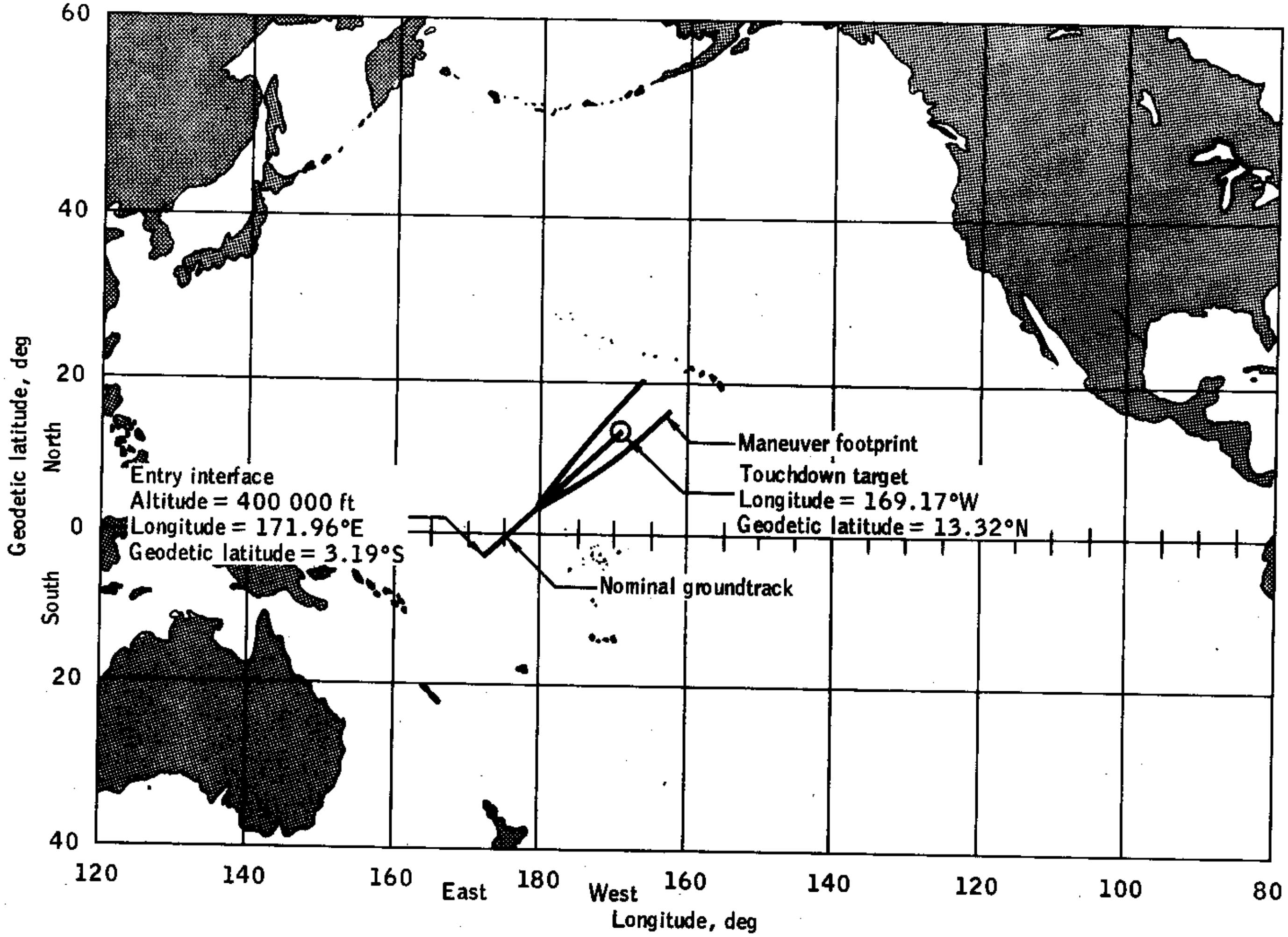


Figure 3.- Maneuver footprint and nominal groundtrack.

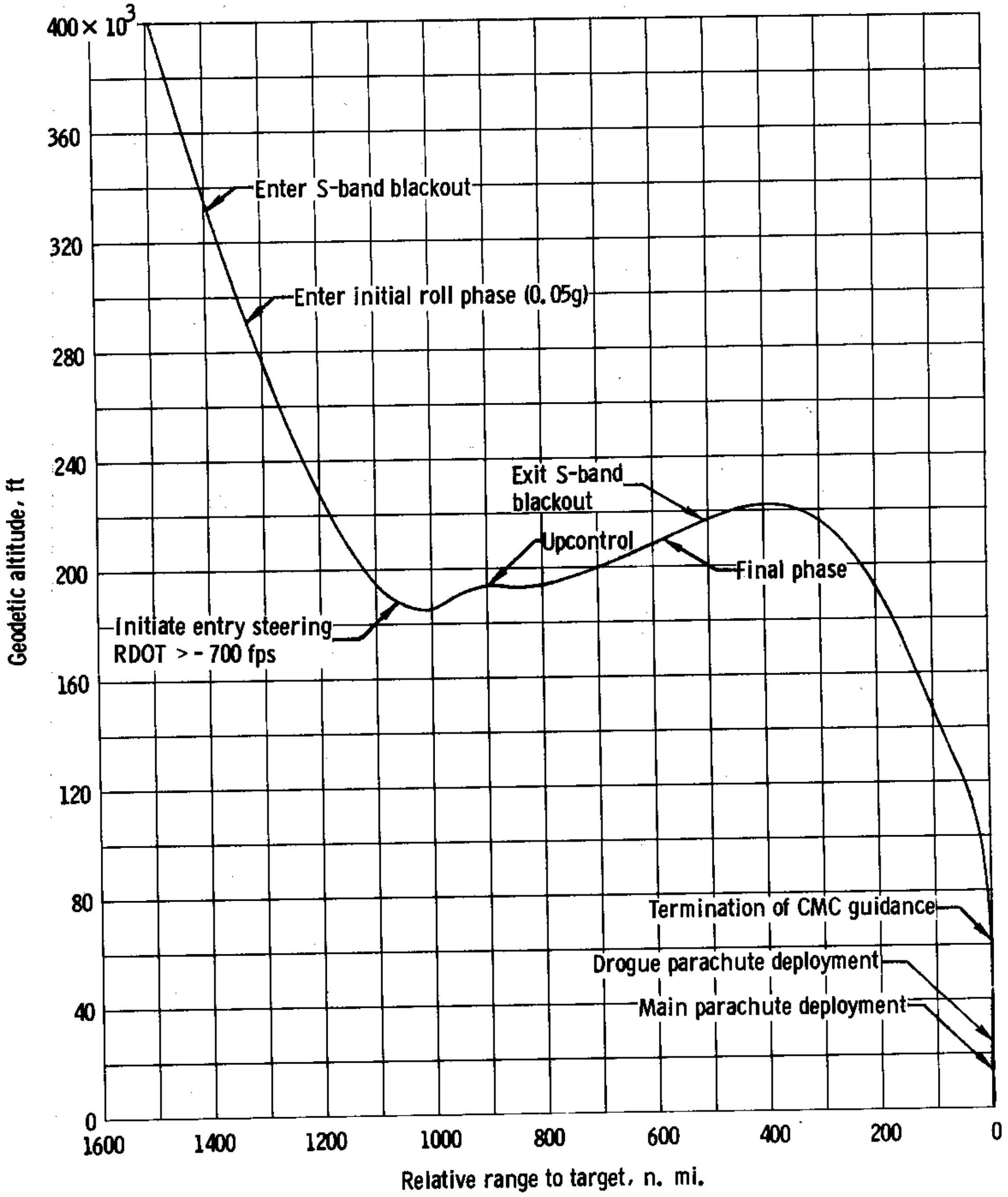


Figure 4.- Apollo 11 reentry trajectory profile.

TABLE I.- SIGNIFICANT EVENTS DURING ENTRY

Event	Time from lift-off, hr:min:sec	Time from 400 000 ft, min:sec
Entry	195:03:06	0:00
Enter S-band communications blackout	195:03:24	0:18
Enter C-band communications blackout. Load factor = 0.05g	195:03:35	0:29
Maximum heating rate	195:04:14	1:08
Guidance initiate at RDOT = -700 fps	195:04:22	1:16
Maximum load factor	195:04:26	1:20
Exit C-band communications blackout	195:05:51	2:45
Exit S-band communications blackout	195:06:37	3:31
Maximum load factor (second)	195:09:22	6:16
Termination CMC guidance	195:10:56	7:50
Drogue parachute deploy	195:11:59	8:53
Main parachute deploy	195:12:46	9:40
Splashdown	195:17:42	14:36

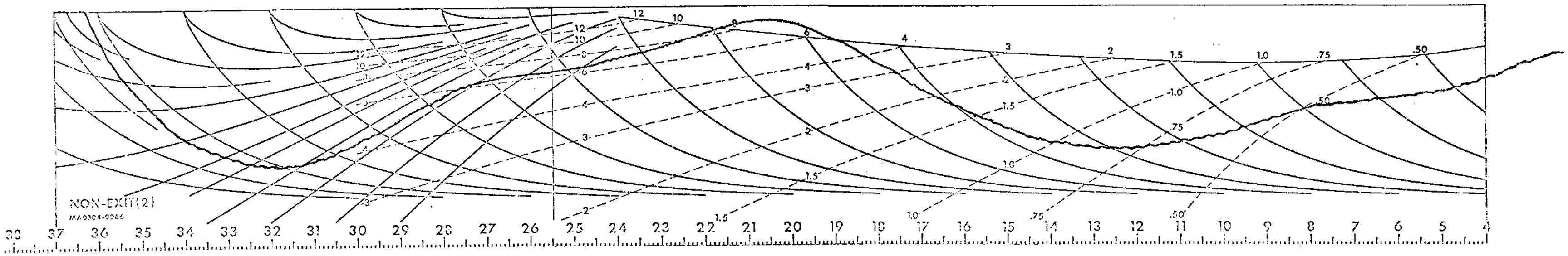


Figure 5.- Actual Apollo 11 EMS scroll.

Bobbie D Weber E. M. Henderson

Bernard A. Schneider Jr.

Curtis J. Laetz Ted L. Turner, Jr.

Alex H. Treadway Ron D. Davis

Ray Wiecke

Charles W. Fraley

Gloria Stuckey

Alfred N. Gunder Chuck Foggatt

Hector Garcia Jr.

Lily M. Stedman

Stan Holzapfel

THE FLIGHT ANALYSIS BRANCH

Charlie C. Allen Dorothy C. Brown

Charles E. Allday

Samuel R. Newman Larry D. Davis

Dallas G. Ives William R Pruett

Michael E. Donahoo

Charles F. Hyle Charles J. Gott

William G. McGilvray Marland L. Williamson

Richard E Kincade Robert E. Prahl

Robert E. McAdams

THE FLIGHT ANALYSIS BRANCH

The functions of the Flight Analysis Branch are to establish operational procedures and data to support the mission trajectories, to assure flight safety, and to support the real-time command and control function. The required activities include the development of launch, orbital, TLI, LOI, and TEI abort plans to assure flight crew safety; the development of range safety plans; the conducting of orbital debris studies to insure low casualty probabilities; the development of operational vehicle separation sequences and maneuver constraints to reduce the recontact hazards; the development of real-time decision logic and displays to support the flight crew and RTCC functions; and the establishment of the requirements and managing the functions of the RTACF for the support of the mission.

The Flight Analysis Branch consists of three sections: the Contingency Analysis Section with responsibility for abort analysis functions, the Mission Support Section with responsibility for inflight operational support, and the Flight Studies Section with trajectory and systems analysis responsibilities.

CONTINGENCY ANALYSIS SECTION

To insure the high confidence level required by the Apollo Lunar Landing Program, a practical return-to-earth abort capability must be defined throughout the various mission phases. Definition of this capability and implementation of the associated techniques into the mission planning and crew training activities are the major functions of the Contingency Analysis Section. In general, spacecraft and operational constraints are superimposed on safe return-to-earth trajectory requirements. The resultant interaction has led to the evolvement of several distinct abort techniques and powered flight monitoring procedures. These techniques and procedures are combined to ensure that a safe return-to-earth capability exists throughout the spectrum of anticipated contingency conditions.

An overview of the contingency plan including crew and ground monitoring limits as well as abort techniques are summarized in figure 1 for each mission phase.

Many contingencies, were provided for with the development of charts carried in the spacecraft by the flight crew. Five Contingency Analysis Section work areas were represented by such onboard crew charts. Typical examples from the launch abort, TLI monitor, TLI abort, LOI monitor and LOI abort work areas are shown in figures 2 through 6.

Although the probability that an Apollo mission will have to be aborted in low, the confidence level in the lunar landing program has been greatly enhanced by the provision of carefully planned contingency procedures.

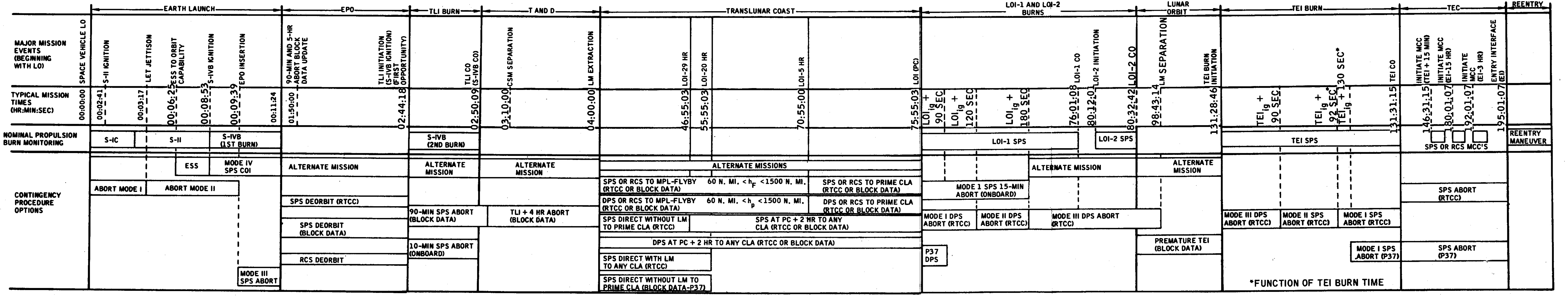


Figure 1.- The relationshipof the nominal Apollo 11 mission events and the operational abort modes.

Crew chart 1. - Launch abort curves.
Henderson/FAB/MPAD
6/27/69
Final data.

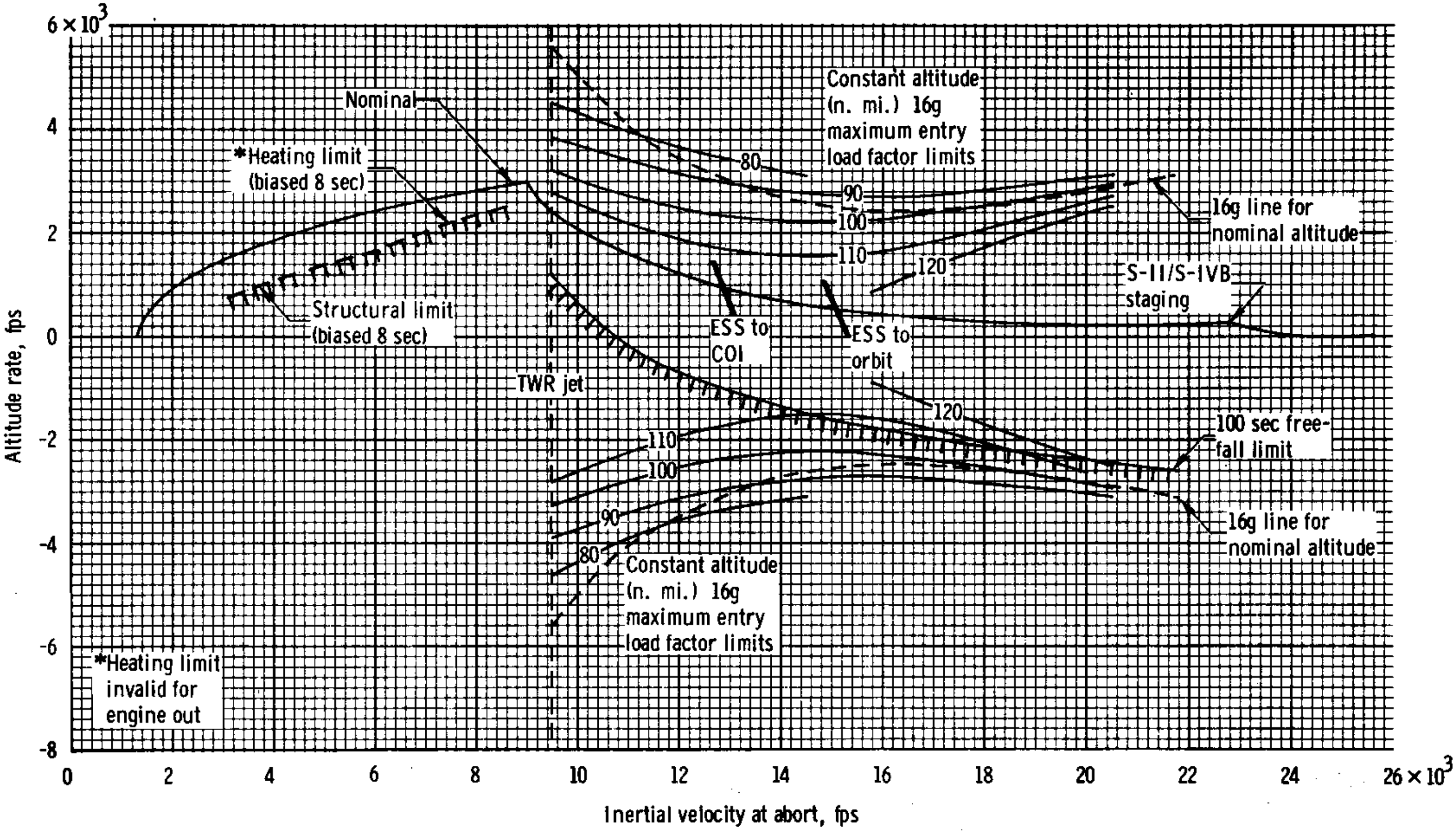


Figure 2.- Launch abort curves.

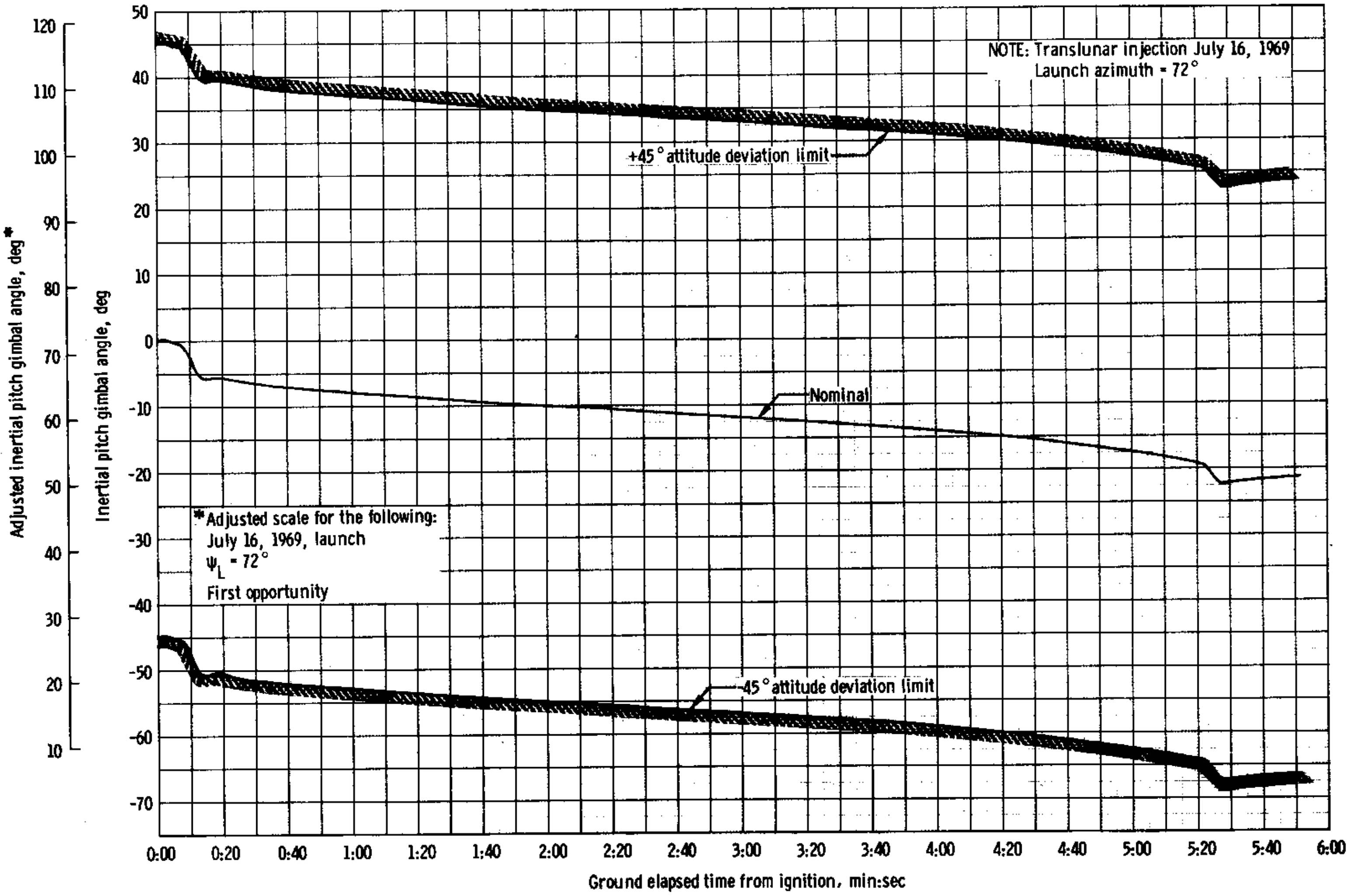


Figure 3.- TLI pitch gimbal angle history and attitude deviation limits for first opportunity.

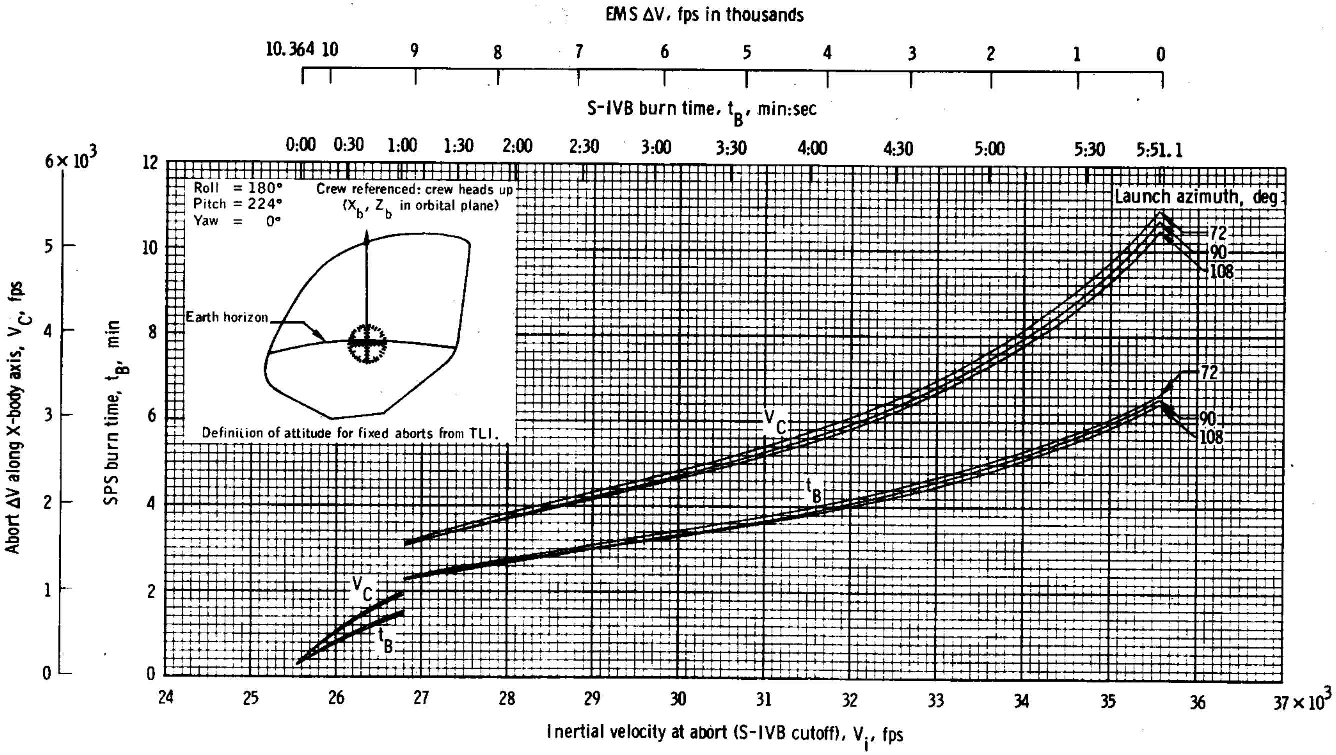


Figure 4.- Abort delta velocity and SPS burn time as functions of inertial velocity at abort for fixed-attitude aborts from TLI.

SEG	24	26	29	32	34	43	44	113	114	117	118
X	-14	21	14	12	-21	-24	-24	-16	-23	-16	-18
Y	-20	-15	0	16	12	-22	-10	-24	-16	-16	-14

SEG	119	120	121	122	123	124	128	131	133	135	142
X	21	-2	-15	2	-13	10	19	24	-19	-16	13
Y	-22	-19	-14	-17	-11	-14	-9	-7	0	0	15

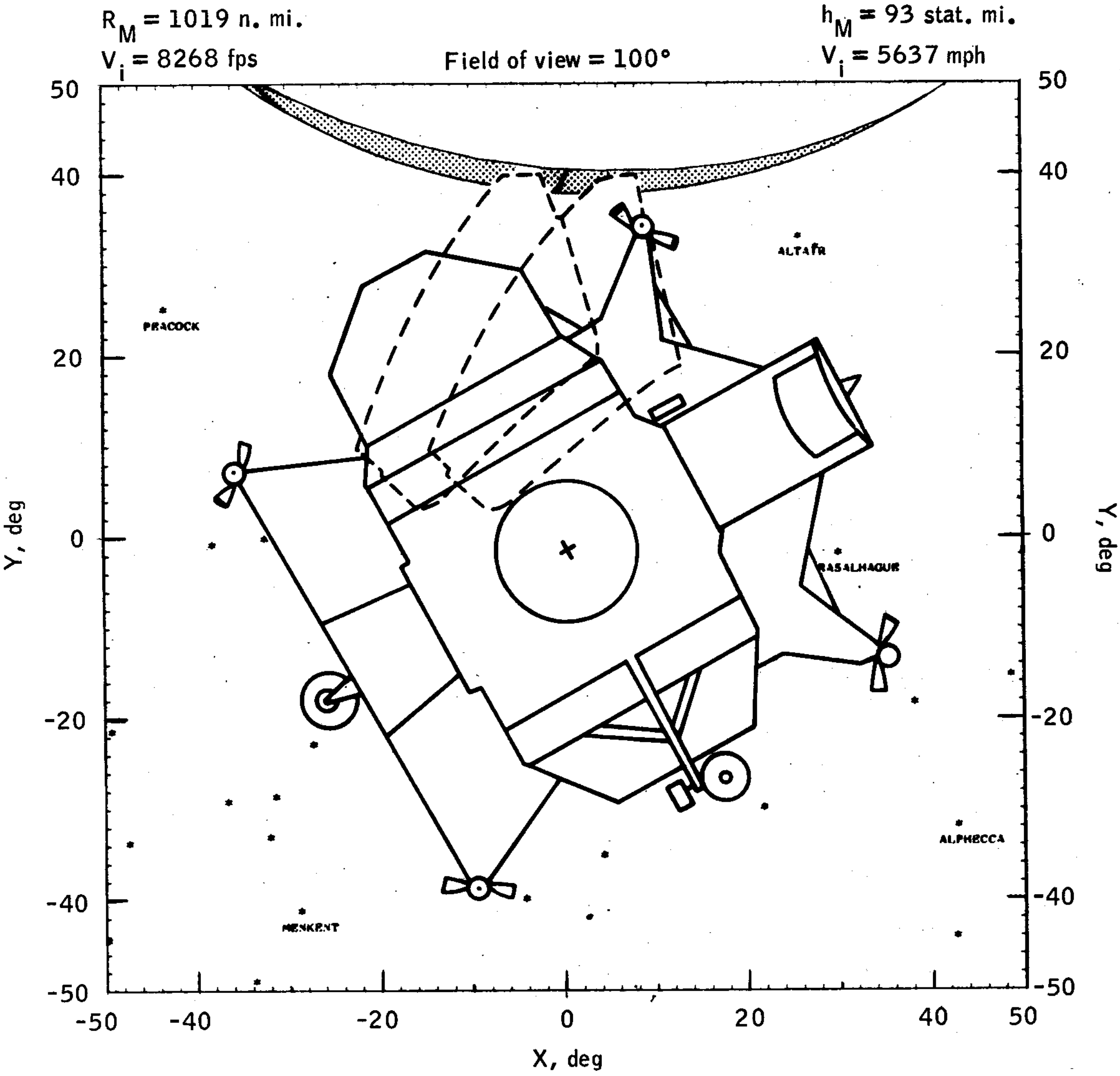
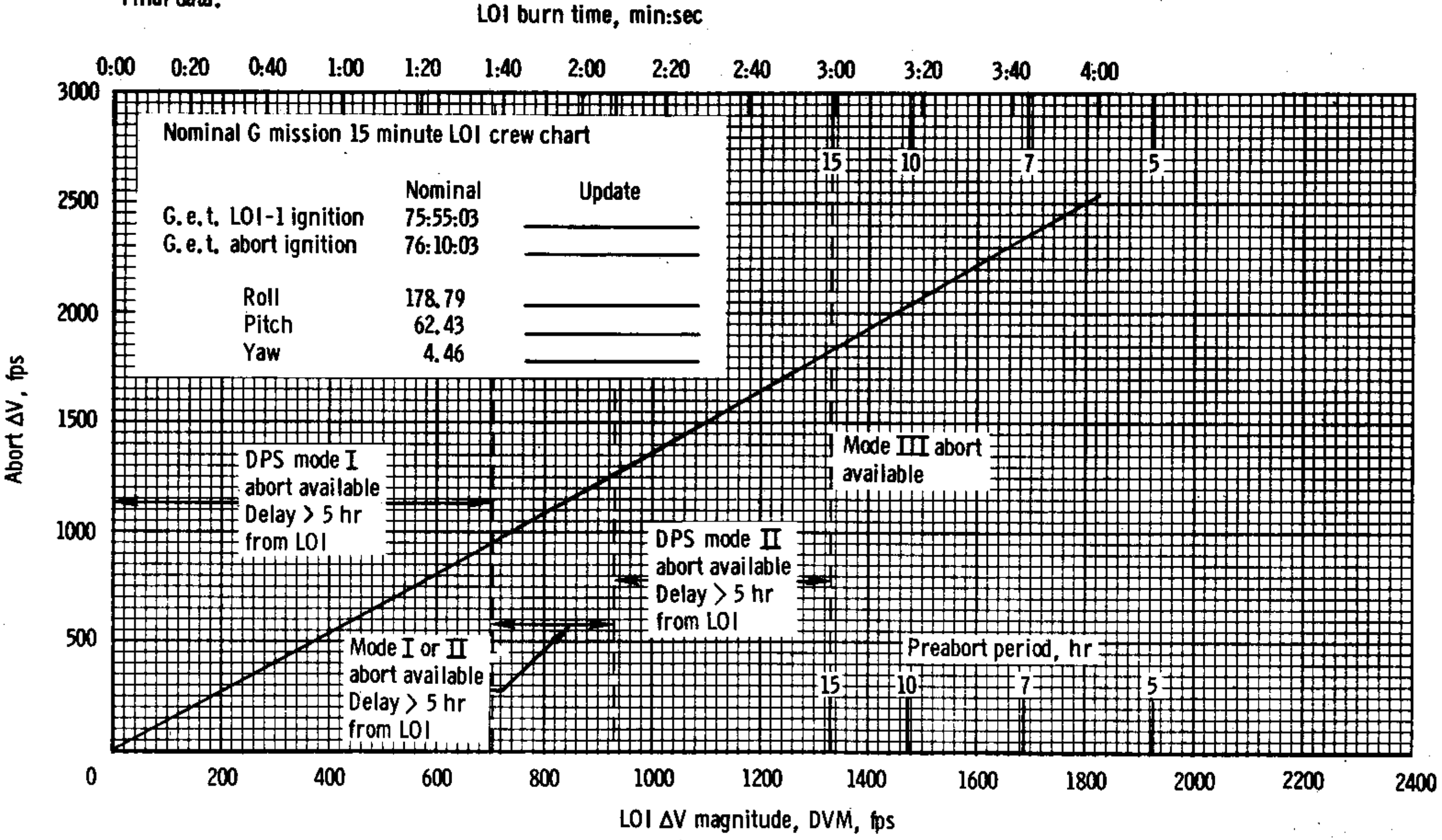


Figure 5.- Beginning of lunar orbit insertion burn, g.e.t. = 75:55:02.8.

Crew chart 5.- Nominal LOI 15 minute abort CSM/LM.
Foggatt/FAB/MPAD
6/27/69
Final data.



Nominal G mission 15 minute LOI crew chart

	Nominal	Update
G.e.t. LOI-1 ignition	75:55:03	________
G.e.t. abort ignition	76:10:03	________
Roll	178.79	________
Pitch	62.43	________
Yaw	4.46	________

Figure 6.- Nominal LOI 15 minute abort CSM/LM.

FLIGHT STUDIES SECTION

The members of the Flight Studies Section investigated the topics of separation and recontact, orbital debris, and range safety for the first lunar landing mission.

Separation techniques and procedures were analyzed, and in some cases defined, to insure there would be no recontact between manned vehicles and unmanned jettisoned configurations. All phases of the mission, from lift-off to landing were evaluated for the nominal, abort, and alternate mission cases.

Two areas of separation required more extensive studies than other separation cases. These areas include (1) the nominal CSM/LM ejection and the CSM SPS evasive maneuver from the S-IVB and (2) the nominal LM ascent stage jettison in lunar orbit.

The analysis for the first major area of concern determined that the planned SPS evasive maneuver burn was sufficient to preclude a recontact with the S-IVB. The LM ejection and CSM SPS evasive maneuver are defined in table I, and are pictorially represented in figure 1. The motion of the CSM/LM relative to the S-IVB for the nominal SPS evasive maneuver is presented in figure 2. The adequacy of these separation procedures was verified by real-time calculations.

Studies conducted for the second major area of concern determined that the planned LM ascent stage jettison attitude and separation ΔV were sufficient to avoid recontact with the CSM prior to TEI. Two LM ascent stage jettison sequences were evaluated. In the first sequence, the ascent stage was jettisoned along the local horizontal (fig. 3). In the second sequence, the LM ascent stage is jettisoned 45° above the local horizontal (fig. 4). The relative motion of the LM with respect to the CSM from jettison to TEI for the first sequence is shown in figure 5. The separation distances for the second sequence are somewhat larger than those shown in figure 5. No near collisions after LM ascent stage jettison were observed during the mission.

Separation procedures for abort and alternate missions were defined in collaboration with the Flight Control Division and the Flight Crew Support Division. Launch, earth orbit, TLI, TLC, lunar orbit, TEC, and entry phases were evaluated. In addition to these separation and recontact analyses, gimbal angles were generated to be used by the crew to view the S-IVB during the evasive maneuver and to view the LM ascent stage after jettison.

Earth entry of spacecraft debris was analyzed to determine the probability that a casualty would result from the nominal mission. The jettisoned SLA panel trajectories were calculated to predict those panels which would return, the probable impact areas of these panels, and the casualty expectations associated with the surviving debris of these panels.

The nominal CM/SM separation was also analyzed to predict the trajectory of the SM after separation and the landing area for the SM debris. The orbital debris analysis was performed based on the CM/SM separation sequence presented in table II and the separation attitudes defined in figure 6. Preflight calculations and real-time monitoring indicated that there was enough SM RCS fuel remaining for a burn of approximately 400 seconds. If the SM remained stable throughout the burn, a burn of this duration initiated at the attitude shown in figure 6 would have resulted in the SM's grazing the earth's atmosphere and skipping out into orbit in excess of 500 000 n. mi.

However, because tracking data from the Apollo 10 mission had shown that the separation ΔV was greatly reduced for that mission and because it was indicated that this reduction was caused by instability during the burn, it was assumed that the SM would also become unstable at some point during the burn for the Apollo 11 mission. Therefore, the SM impact points and casualty expectations were determined for the most probable separation ΔV range (5 fps to 120 fps).

The Airborne Launch Optical Tracking System (ALOTS) filming of the SM breaking up and visual observation by the crew of the SM 5 minutes after separation verified that the SM did not remain stable during the burn. If the SM had remained stable, the SM would never have reached the breakup altitude and, as shown in figures 6 and 7, the crew would never have seen the SM prior to entry interface (the SM would have been above and in front of the CM -X-axis). As the result of this SM motion after separation, steps are being taken to change the separation sequence for the Apollo 13 mission to insure that the SM burn is terminated prior to the time the SM would become unstable.

The LET nominal impact and 3σ dispersion impact data were generated and provided to the KSC in fulfillment of the Air Force Eastern Test Range (AFETR) range safety requirements. The effect of launch vehicle destruct action on the Apollo spacecraft was also required by the AFETR and was supplied prior to the mission.

TABLE I.- LM EJECTION AND CSM SPS EVASIVE MANEUVER

Time, after CSM/LM ejection, hr:min:sec	Event
00:00:00	CSM/LM is ejected from the S-IVB (TLI cutoff plus 1^h20^m or $4^h09^m44.8^s$ g.e.t. for July 16, 1969, nominal launch). Spring actuator ΔV is approximately 0.8 fps for a 48-percent efficiency.
00:00:05	Initiate CSM RCS -X translation. No change in spacecraft attitude.
00:00:08	Terminate CSM RCS -X translation. ΔV = 0.4 fps. Total ejection ΔV = 1.2 fps.
00:00:21.5	The spacecraft will have translated 25 ft based on a minimum spring efficiency of 48 percent. After ejection, begin orientation to the SPS evasive maneuver attitude: pitch = -75° and yaw = 0°. The roll angle will be approximately 57° to view the S-IVB in the left side window. If the S-IVB LH_2 propulsive vent fails to close after TLI and cannot be closed prior to LM ejection, it will be necessary for the spacecraft to orient to the SPS evasive maneuver attitude and to perform a 5-sec +X RCS translation prior to 5 min after ejection. The nominal evasive maneuver would still occur as planned. If no action were taken, an 8-lb propulsive vent would cause the S-IVB to recontact the spacecraft approximately 6 min after ejection.
00:30:00	Initiate the SPS evasive maneuver ($4^h39^m44.8^s$ g.e.t. for a nominal July 16, 1969 launch). ΔV = 19.7 fps.

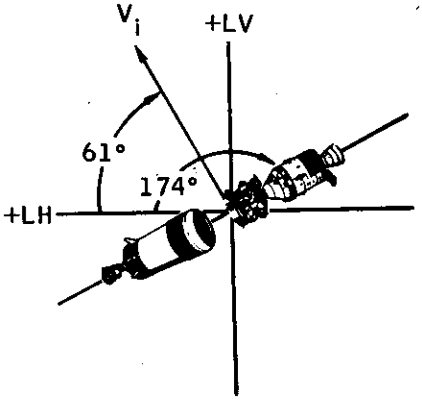
TABLE I.- LM EJECTION AND CSM SPS EVASIVE MANEUVER - Concluded

Time, after CSM/LM ejection, hr:min:sec	Event
00:40:00	At TLI cutoff plus 2^h00^m, initiate the TB8 sequence. Continuous S-IVB LH_2 propulsive vent ON. S-IVB orients to the dump attitude: pitch 218°, yaw 0°, roll 170° with respect to the LM for a July 16, 1969, launch.
00:52:00	Initiate LOX dump (TLI plus 2^h12^m).
00:53:48	Terminate LOX dump (TLI plus $2^h13^m48^s$). ΔV = 52.5 fps.
01:26:40	Initiate S-IVB attitude propulsion system burn (TLI plus $2^h46^m40^s$).
01:31:20	Terminate S-IVB attitude propulsion system burn (TLI plus $2^h51^m20^s$). Attitude propulsion system burn ΔV = 39.4 fps. Continuous vent ΔV = 6.6 fps. Total slingshot ΔV = 98.5 fps (30 m/sec).

TABLE II.- NOMINAL CM/SM SEPARATION PROCEDURES

Time, hr:min:sec, g.e.t.	Event
194:48:04	At t_{ff} = 17 minutes, the CSM performs the IMU alinement attitude check. The IMU alinement check is performed with CSM heads down, +X-axis alines 31.7° above the LOS to the backward horizon in the orbital plane (0° yaw). The CSM then yaws 45° north and holds this attitude for SM separation.
194:50:04	At t_{ff} = 15 min, the CM jettisons the SM and then orients to the entry attitude. Total relative ΔV imparted immediately at SEP is approximately 1.5 fps.

CSM/LM EJECTION ATTITUDE AT TLI C/O + $1^{h}20^{m}$



LVLH SPACECRAFT ATTITUDE

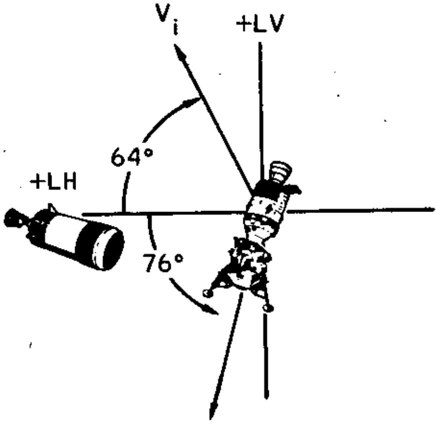
P = -006.2
Y = -040.3
R = -060.0

- ● EXECUTE CSM/LM EJECTION
- ● AT 5 SECONDS AFTER EJECTION PERFORM CSM -X RCS FOR 3 SECONDS
- ● TOTAL $\Delta V \cong 1.2$ FPS FOR 48% EFFICIENT SPRING EJECTION

SPACECRAFT GIMBALS

R (OGA) = -056.9
P (IGA) = -073.9
Y (MGA) = -040.6
PAD REFS. (ref. 1)

SPS EVASIVE MANEUVER ATTITUDE AT TLI C/O + $1^{h}50^{m}$



LVLH SPACECRAFT ATTITUDE

Y = 000
P = -076.2
R = 056.8

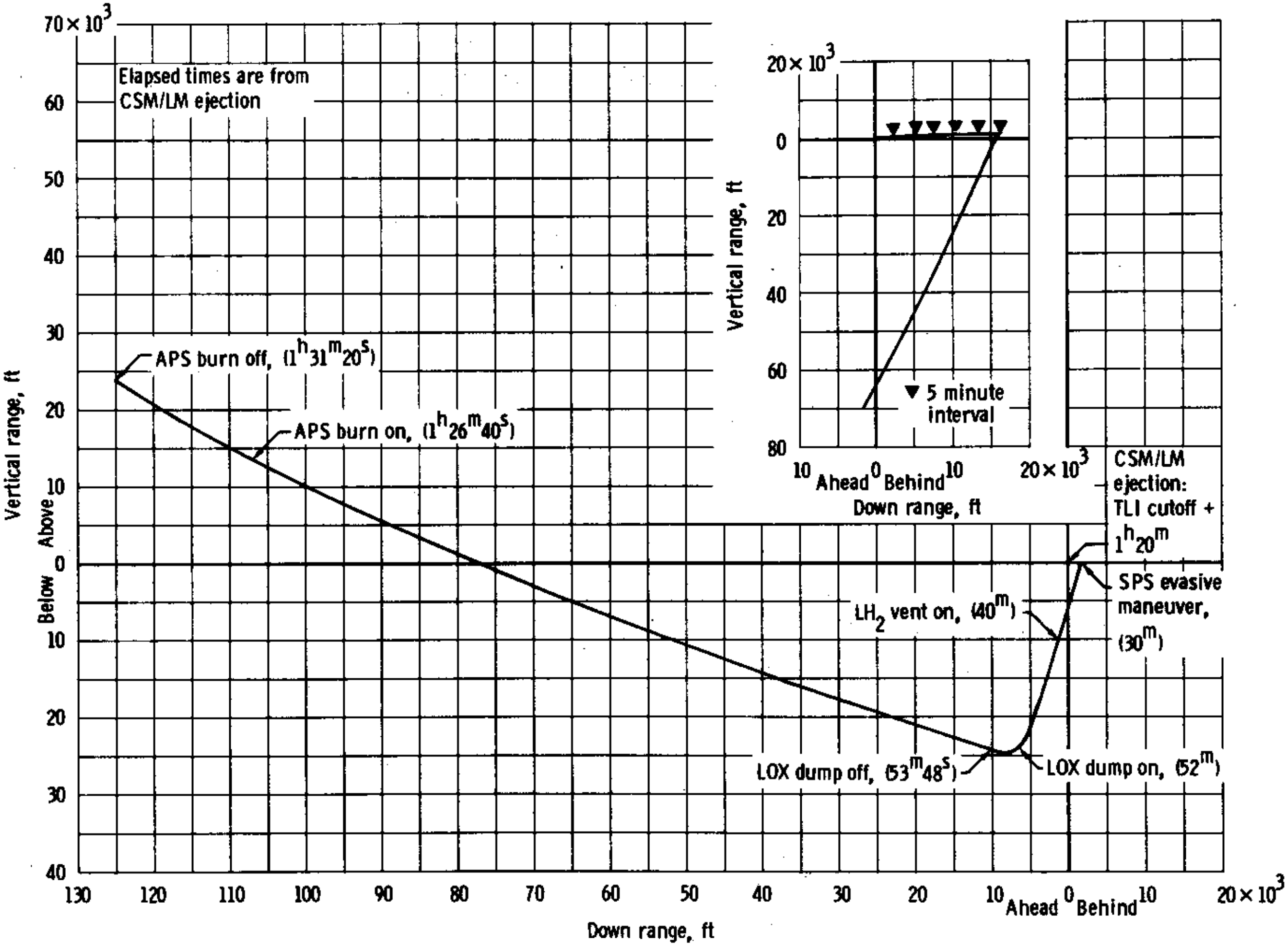
- ● AFTER CSM/LM EJECTION ORIENT TO SPS EVASIVE MANEUVER ATTITUDE
- ● PERFORM SPS BURN AT 30 MINUTES AFTER EJECTION FOR

$\Delta V_X = 5$ FPS
$\Delta V_Y = 0$ FPS
$\Delta V_Z = 19$ FPS
TOTAL $\Delta V = 19.7$ FPS
$\Delta T = 2.8$ SECONDS

SPACECRAFT GIMBALS

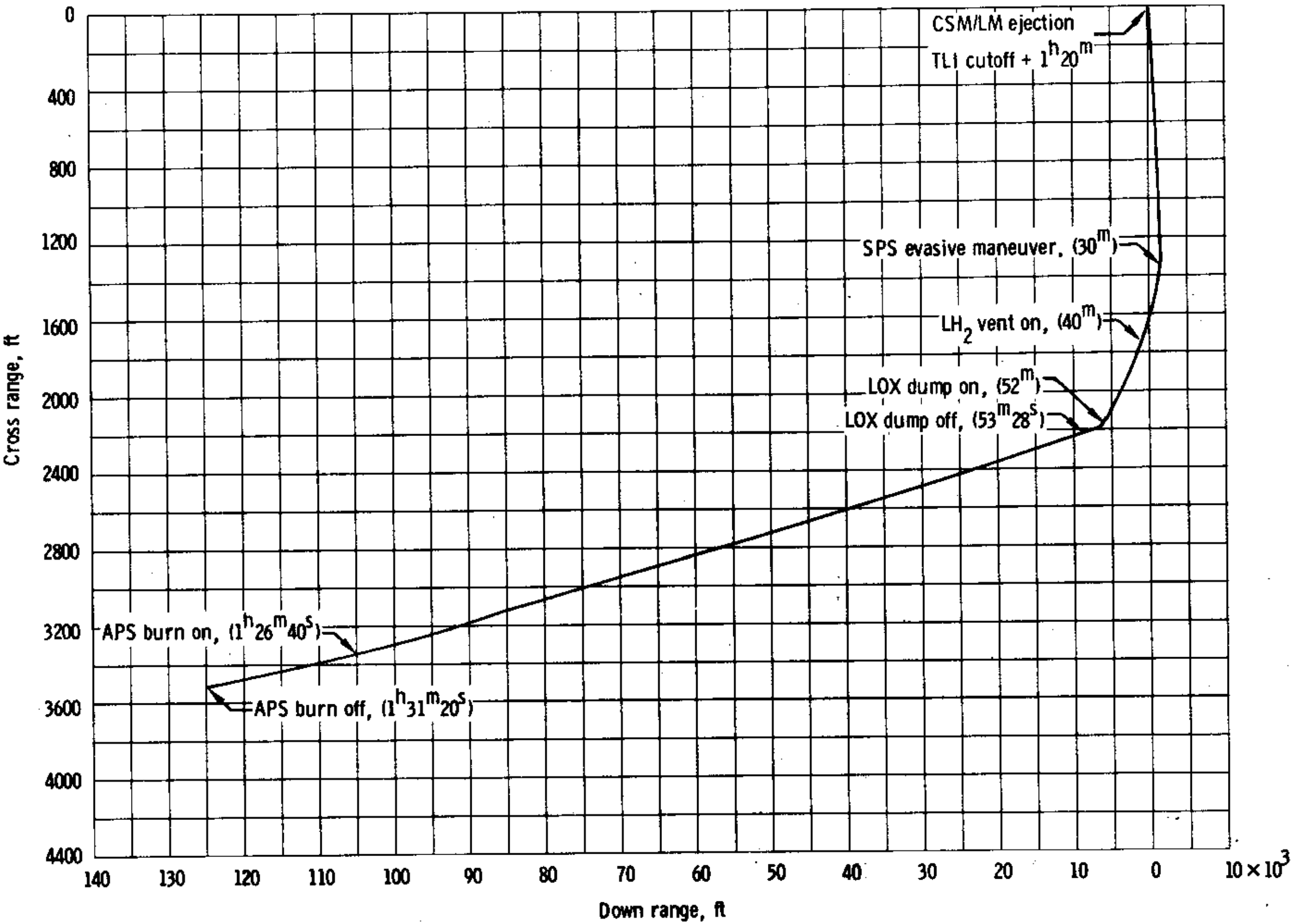
R (OGA) = 056.9
P (IGA) = -147.7
Y (MGA) = -003.2
PAD REFS. (REF.)

Figure 1.- Nominal CSM/LM ejection and SPS evasive maneuver.



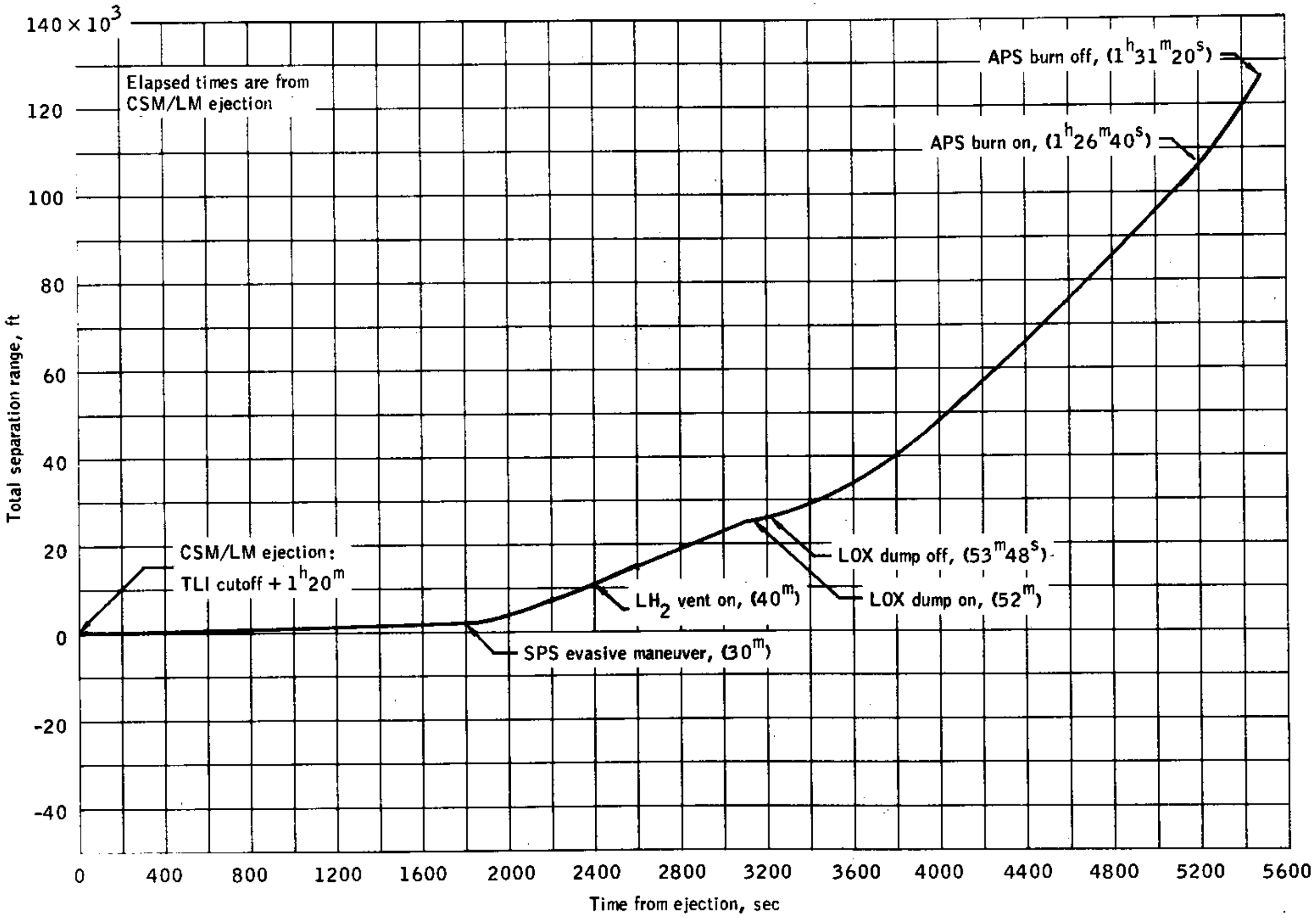
(a) Down range versus vertical range.

Figure 2.- Motion of the CSM/LM relative to the S-IVB for the nominal SPS evasive maneuver, July 16 launch.



(b) Down range versus cross range.

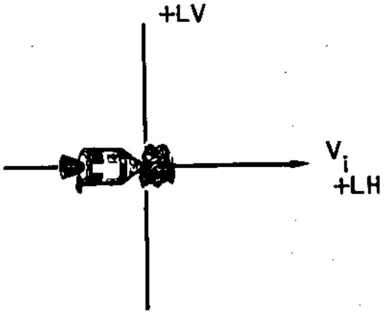
Figure 2.- Continued.



(c) Range versus time.

Figure 2.- Concluded.

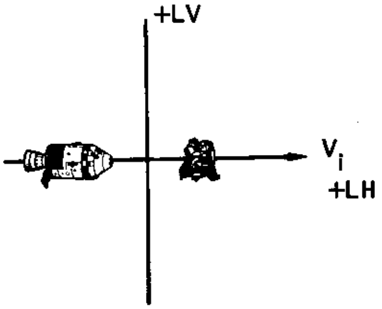
LM ASCENT STAGE JETTISON ATTITUDE



LVLH SC ATTITUDE

Y = 000
P = 000
R = 000

JETTISON LM ASCENT STAGE

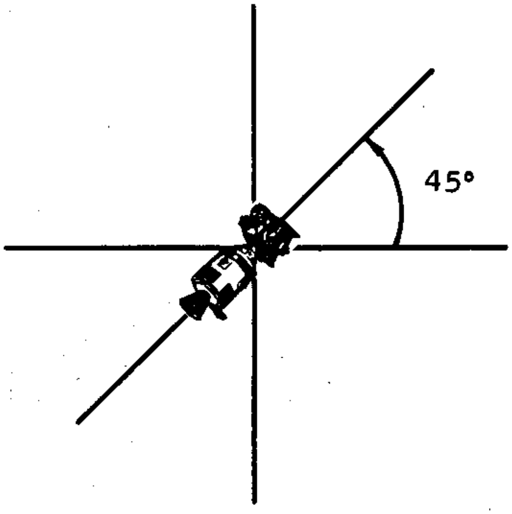


SPACECRAFT GIMBALS

R (OGA) = 000
P (IGA) = -019.7
Y (MGA) = 000
L/O REFS (ref. 4)

- PERFORM CSM -X RCS RETROGRADE FOR NET ΔV = 1 FPS
- TEI PERFORMED 1 3/4 ORBITS LATER

Figure 3.- CSM/LM ascent stage separation and jettison along the local horizontal.



- JETTISON LM
- PERFORM CSM -X RCS RETROGRADE FOR NET $\Delta V = 1.5$ FPS
- TEI PERFORMED 1 3/4 ORBITS LATER

Figure 4.- LM ascent stage jettison 45° above the local horizontal.

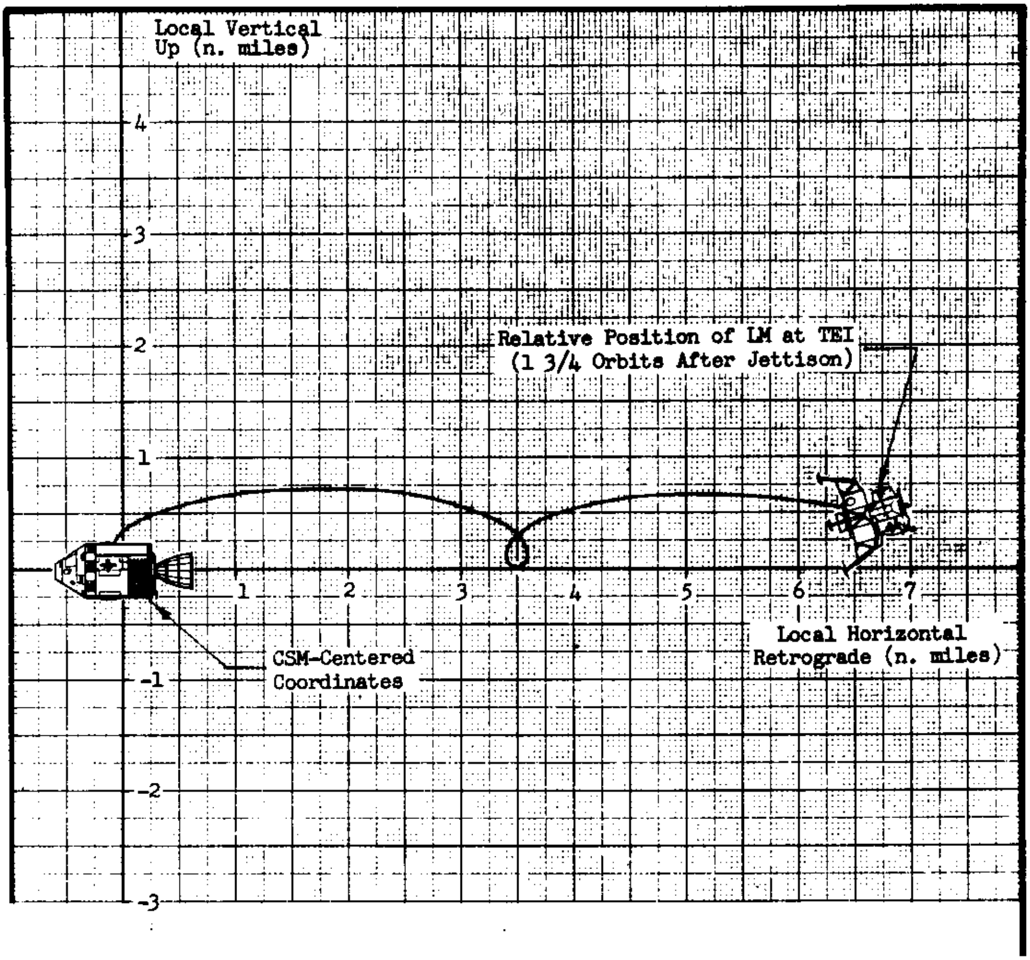
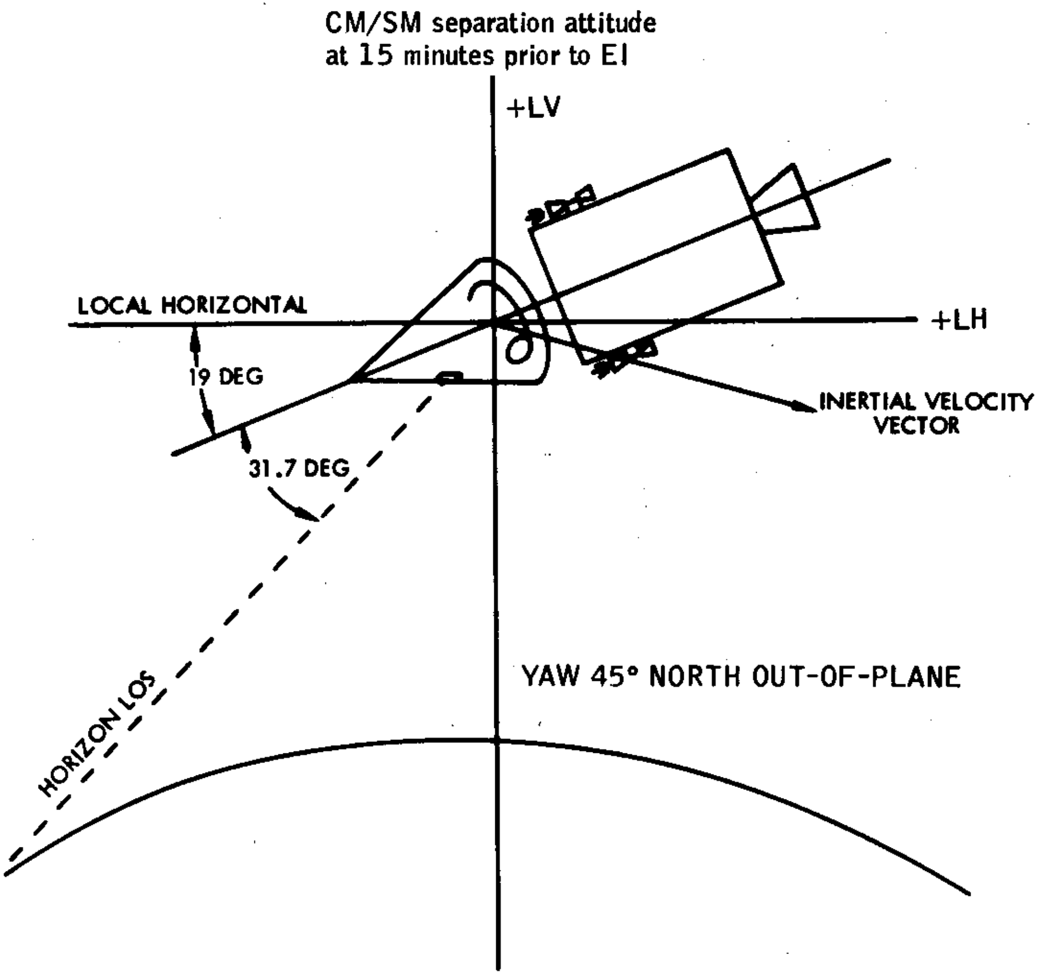


Figure 5.- Relative motion for LM jettison prior to nominal TEI (Mission G).



LVLH SC ATTITUDE

P = 161
Y = -045
R = 000

SC GIMBALS

R (OGA) = 000
P (IGA) = -088.2
Y (MGA) = -045

ENTRY REFS

(ref. 1)

- AT t_{ff} = 17 MIN CSM IS AT ATTITUDE SHOWN
- CSM THEN YAWS 45° NORTH OUT-OF-PLANE AND JETTISONS THE SM AT t_{ff} = 15 MINUTES
- CSM THEN ORIENTS TO ENTRY ATTITUDE

SC GIMBALS AT EI

R (OGA) = 000
P (IGA) = 156
Y (MGA) = 000

Figure 6.- Nominal CM/SM separation attitudes.

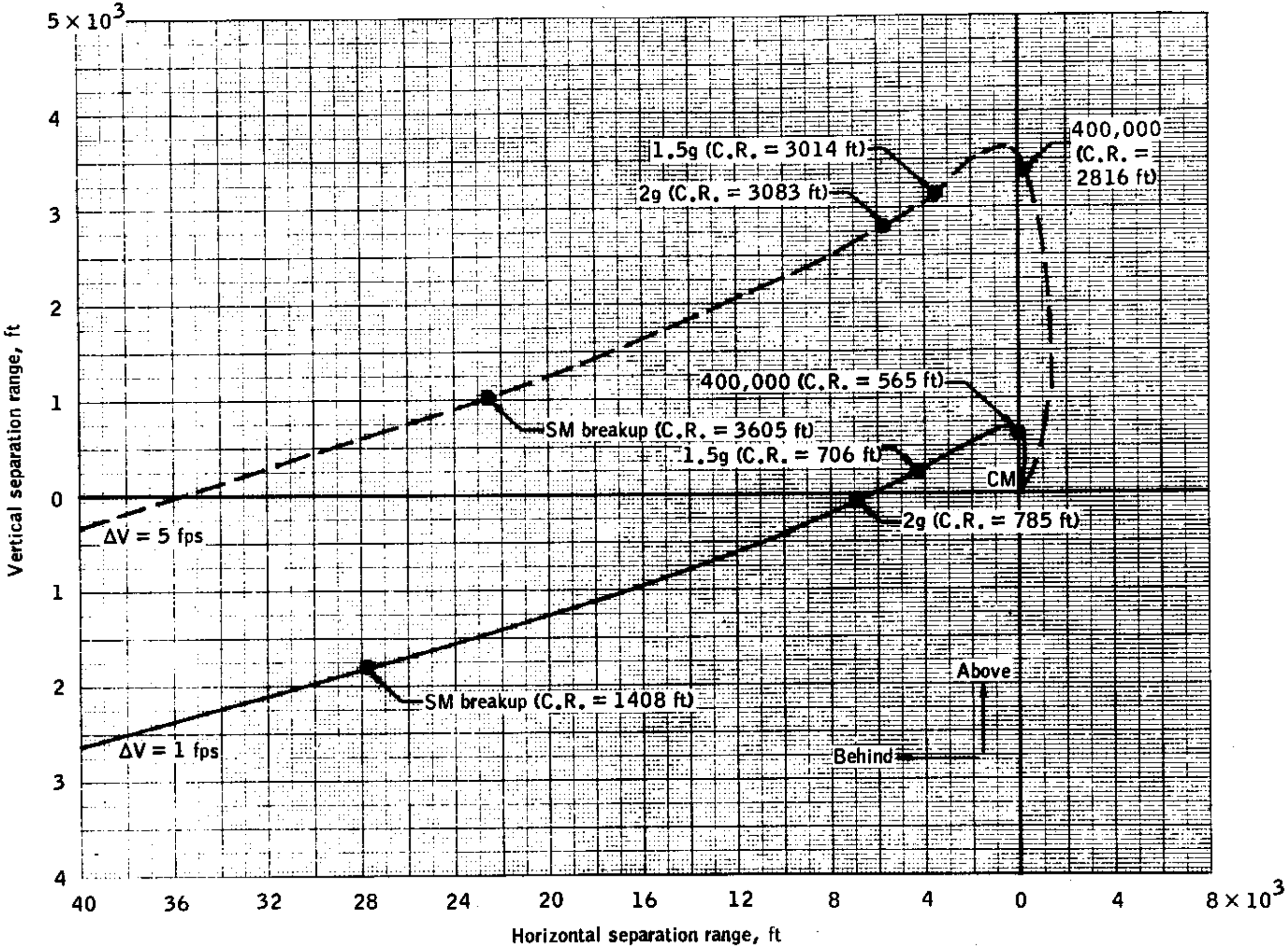


Figure 7.- SM motion relative to the CM for nominal entry from TEC (SM separation ΔV's of 1 and 5 fps).

MISSION SUPPORT SECTION

The Mission Support Section is responsible for the management, planning, and operation of the Real-Time Auxiliary Computing Facility (RTACF). Flight preparation began with the appointing of an Operational Support Team and the development of computer processors to satisfy the RTACF computing requirements. Thirty-eight team members from the Mission Support Section and its contractor support organizations began program verification and training shortly after the Apollo 10 mission. During this preparation period, sixteen simulations were supported during which compatibility checks were made with the RTCC and mission tapes and high-speed drum files were constructed.

During the mission, six hundred and thirty-seven data requests were satisfied for the RTACF requestors. The following is a list of the computational capability that existed in the RTACF in support of the Apollo 11 mission.

a. Mode I abort (wind data) - The mode I abort computation provides predicted mode I impact points based on the current KSC wind profile.

b. CSM structural analysis - CSM structural analysis computation determines the structural load that the CSM will encounter during the launch phase, based on the current KSC wind profile.

c. Lift-off REFSMMAT - The lift-off REFSMMAT computation given the onboard REFSMMAT used until the IMU is realined in orbit.

d. Mass properties - Mass properties computations include the following.

1. Weight-c.g. tables - used by the RTACF and RTCC trajectory processors to compute pitch and yaw trim angles

2. Entry aerodynamics - used in the RTACF and RTCC entry processors

3. DAP load

e. Constants update - The constants update represents computations required to update RTACF constants such as mass properties tables, aerodynamic tables, and thrust parameters.

f. Translunar midcourse - The translunar midcourse processor computes a midcourse maneuver designed to return the spacecraft to the desired trajectory for either a LOI maneuver or a free-return flyby. Certain RCS optimization computations are available only in the RTACF program.

g. Transearth midcourse - The transearth midcourse processor computes a midcourse maneuver designed to return the SC to the desired entry trajectory.

h. Return to earth - RTE computations provide time of an abort maneuver, ΔV, burn attitudes, time of entry interface, and time of landing for a specified recovery area. Additional data such as maximum g, velocity and flight-path angle at entry interface are also available.

i. LOI - The LOI is the computation of the lunar orbit insertion maneuver.

j. ARRS - The ARRS is a generalized rendezvous program that consists of the following.

1. General purpose maneuver processor computes impulsive maneuver at a point to achieve desired conditions

2. Two-impulsive and terminal phase processor - computes two impulsive maneuvers by specifying point and final conditions

3. Mission plan table processor - computes finite burn to achieve a given orbit

4. Relative print routine - computes relative quantities between two vehicles

5. Tracking routine - computes tracking station coverage during a given period of time

6. CSM insertion rescue computation routine

7. Ascent - computes LM powered ascent

8. LPD - simulates LM powered descent

9. Launch window - computes LM lift-off time

k. Maneuver confirmation - Maneuver confirmation refers to the application of nonnominal components of ΔV (residuals) from a particular SC maneuver to the nominal maneuver target to determine the actual SC trajectory.

l. Maneuver evaluation - The maneuver evaluation processor computes a maneuver that is equivalent to a maneuver which has been performed. A preburn vector and a postburn vector are propagated to the impulsive maneuver time. At this point, the equivalent SC attitudes and external ΔV components are computed.

m. Groundtracks - Groundtracks are time histories of latitude, longitude, altitude, and revolution number of the SC referenced either to the earth or to the moon.

n. Generation of ephemeris tape - The ephemeris tape was used in conjunction with downlinked telemetry gimbal angles for SC antenna and thermal evaluations.

o. Telescope look angles - Telescope look angle computation provides right ascension and declination of the SC for several observatories. This information was provided for the following sites.

1. Denver Museum of Natural Science, Denver, Colorado
2. Jodrell Bank Observatory, London, England
3. Manned Spacecraft Center, Houston, Texas, Building 16
4. Leuschner Observatory, Berkeley, California

p. Relative motion - This processor computes range, range rate, elevation and azimuth between two vehicles.

q. Entry data for Track Controller - Entry data for the track controller involves the computation of the following data.

1. Pointing data for the SM (used to track the SM during entry)
2. Pointing data for the entry ship (used to determine the optimum location for the entry ship)
3. Time and position of the entry fireball (used to photograph the entry fireball)

r. Entry time histories - This subroutine computes a time history of significant entry events.

s. Crew chart update - The crew chart update is the computation of attitudes and abort maneuver ΔV required immediately after TLI or LOI-1 cutoff.

t. Vector conversion

u. Checkout monitor - The checkout monitor is a table that displays orbital parameters at a specified time. These parameters include a state vector in the mean Besselian coordinate system as well as spherical elements.

v. Space digitals - This display provides trajectory data at h_{pc}, EI, and other selected points.

w. Radar delay time - The delay time (slant range) is a computation of slant range from a selected site to the SC and delay time for a radio signal to travel from the site to the SC.

x. Time to fire (deorbit time)

1. CLA/ARS - determination of deorbit burn or entry or both to hit a specified target

2. Block data - a set of deorbit times and events sent to the crew for emergency use

y. Apollo generalized optics program - The AGOP is used to compute the following data.

1. Cislunar navigation (star/landmark and star/horizon sighting information)

2. Reference body locations

3. Passive thermal control attitude definition

4. Pitch angle to lunar terminator or horizon (for LOI alinement check); this information was available only from the RTACF

z. Earth-sun-moon look angles - The ESM is the computation of look angles from the SC to the earth, the moon, and the sun. The results were used for communication and thermal analysis during the Apollo 10 mission.

aa. LTP/ORION - These programs determine the accuracy and validity of the onboard navigation sightings and the MSFN tracking.

bb. CSM SEENA - The LM and CSM SEENA programs compute electrical capability, energy drain, and energy remaining for any configuration.

cc. LM and CSM MRS - The MRS programs compute a complete RCS propellant budget based on the current flight plan.

dd. PVT - The PVT processor determines the amount of SM RCS propellant remaining and how much is usable.

ee. Model data - These data, which include state vector, REFSMMAT, gimbal angles, and other trajectory data, are computed for each maneuver and are used to aline a spacecraft attitude model.

ff. Solar Particle Alert Network (SPAN) data reduction - SPAN data reduction is the reduction of data received from the Solar Partical Alert Network. The data are used to determine if solar activity might endanger the safety of the crew.

gg

gg. Radiation - The radiation computation is a time history of radiation dose and dose rate for a specified time period.

hh. Postflight Analysis Office computations - PFAO computation of various trajectory parameters are used by PFAO to prepare data summaries for NASA Headquarters.

ii. Radar tracking - Radar tracking is a computation of look angles from a ground site to the SC. These data were used primarily by the Public Affairs Officer for release to the general public.

jj. Attitude definition - Computation of spacecraft attitude for a specific maneuver or event.

kk. FDO orbit digitals - The FDO orbit digitals provide orbital parameters based on current orbit or projected orbit.

ll. HOPE - HOPE provides state vector propagation and comparison to determine landing site offset.

mm. PAO - The PAO computation consists of data for SC sighting, press releases, and news conferences.

nn. Navigation update - This computation provides a state vector in the correct units to update the S-IVB, CSM, LGC, or AGS computers

oo. Work schedule processor - The work schedule processor computations include the following.

1. Radar ACQ and LOS data
2. SC daylight/darkness data
3. Moon rise/moon set data

4. Orbital events

5. Landmark sighting

6. Star ACQ and LOS data

7. Closest approach data

8. Pointing data

pp. DOI (DAMP) - This computation simulates the LM powered descent

qq. PDAP - The PDAP program simulates powered descent aborts every 20 seconds along the nominal LM descent trajectory.

rr. Lifetime - The lifetime processor determines the orbital lifetime of a particular vehicle.

ss. LOI GO/NO-GO computation is an evaluation of the velocity component difference between the command module computer (CMC) and the instrument unit (IU) during TLI. This evaluation is used to determine whether the CMC is GO/NO-GO for LOI.

In addition to controlling the RTACF operation, the section provided the technical point of contact to the North American Air Defense Command, generated the contingency deorbit data which was loaded onboard the spacecraft, provided verification of the RTCC abort program, time-to-fire program, and Lunar Surface Alinement Display, and provided all spacecraft optics computations for the flight crew simulator data packs. A complete return-to-earth capability was developed and tested at Bellcomm in Washington, D. C., in support of the Emergency Mission Control Center. This capability could have been used by the flight control team in the event of any loss of the Houston Mission Control Center.

Will York

Bobby R. Uzzell

Cliff Bean

Jack Shuffler

Gary Langford

Robert T. Sawdy

Aland L. Atkinson

William J. Rose

Jim McPherson

Emily Schriever

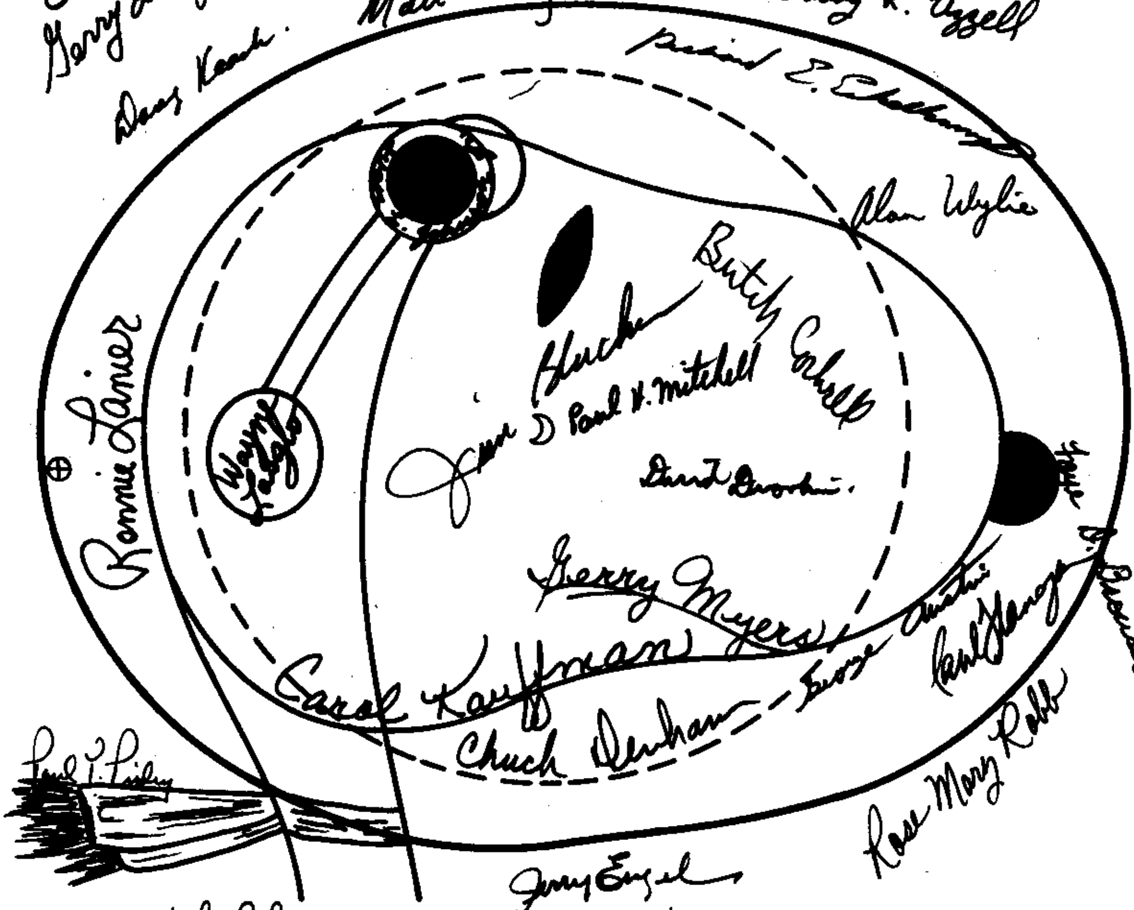
Dick Osburn

Gerry deVajin

Matt Grogan

Bobby R. Uzzell

Doug Kauch



Alan Wylie

Butch Gabrell

Jim Fletcher

Paul H. Mitchell

Jim D

David Brookin

Ronnie Lanier

Wayne Tailor

Gerry Myers

Carol Kauffman

Chuck Denham

George Austin

Carl Hanzo

Rose Mary Robb

Paul T. Pinley

Jerry Engel

Hal Perkins

THE MATHEMATICAL PHYSICS BRANCH

APOLLO LUNAR ORBIT NAVIGATION ACCURACIES

The following is a short review of lunar orbit navigation accuracies associated with the location of the lunar module (LM) at the beginning of the powered descent.

Pre-Apollo 8

Langley lunar orbiter 3 (LLO3) data processing prior to Apollo 8 led to the selection of a triaxial model of the moon's gravitational field. The plan for Apollo 8 was to compute the orbit from MSFN tracking data (Doppler) obtained from several sites during a single pass of the spacecraft across the front of the moon.

The expected accuracy for altitude and down-track and cross-track positions for Apollo 8 based on LLO3 experience is given in table I, line 1. The accuracies are given for two revolutions of prediction because during Apollo 11 it was necessary for the last tracking data used to be two revolutions prior to landing.

Apollo 8

The accuracy experienced during Apollo 8 was approximately the same as predicted for radius and cross-track position. However, larger than expected errors occurred when down-track position was predicted with one pass fits (table I, line 2).

Pre-Apollo 10

Much was learned from Apollo 8 navigation experience both during and after the flight. The same prediction errors occurred when any pass was fit and used to predict a fixed time forward. The repeatability of the errors eventually led to a number of significant changes in navigation procedures for Apollo 10. These changes included the use of the R2 potential model, the procedure to fit two passes of tracking data instead of just one, and the development of empirical procedures for descent targeting. The R2 model reduced eccentricity prediction errors by two thirds. This change resulted in better radius prediction accuracy which was critical for lunar landing. The better eccentricity prediction decreased the local error in two-pass fits to acceptable levels. The two-pass fits, in turn, eliminated the orbital period error which drastically decreased errors in predictions of down-track positions. The accuracy which was expected for Apollo 10 is given in table I, line 3.

Apollo 10

The R2 model predicted eccentricity, perilune, and apolune as expected. The two-pass fit technique reduced down-track position errors as expected. Orbital plane motion was different than predicted with either the R2 or triaxial moon models. Instead of remaining nearly inertially fixed with the moon rotating one deg/per rev under the orbit, the orbital plane swung around with the moon. This effect was not experienced in any of the previous orbital flights around the moon because they were inclined to the moon's equator by 12° or more. Apollo 10 was nearly equatorial, which enabled the moon's gravitational field to move the orbital plane differently. As a result of the unexpected plane motion, the actual groundtrack shifted south of the desired site by approximately 5 n. mi. by the time the spacecraft was ready to simulate the elliptical descent orbit. This miss distance was detected in real time through the use of one-pass fits for plane determination as planned premission. Two-pass fits were used only to determine inplane elements because they were less accurate than one-pass fits for plane determination.

In addition to the orbital plane motion errors, there was an unexpected 18 000-foot down-track position error at closest approach on the descent orbit. This error was believed to be caused by translational forces exerted by the spacecraft during the last few revolutions prior to descent orbit insertion. Investigations of uncoupled attitude maneuvers showed that these small translations were of the right magnitude but did not fully account for the total error. In any event, it was not possible to remove any of the numerous suspected sources in the short time prior to Apollo 11.

Accuracies achieved on Apollo 10 and expected on Apollo 11 during intervals of no unmodeled translational forces are presented in table I, lines 4 and 5, respectively.

Apollo 11

The procedures used during Apollo 11 were nearly the same as for Apollo 10 because the orbits were the same. One-pass fits were used to determine orbital plane and two-pass fits were used to determine inplane elements. For the rev 14 descent, the LM used a position and velocity vector based on fitting passes 11 and 12 MSFN Doppler data for inplane elements and on pass 12 data for plane determination.

For Apollo 11, the determination of orbital plane at the time of tracking (no prediction) was less accurate than for Apollo 10. The one-pass fits resulted in five times more random variation in cross-track position (2000 ft for Apollo 10 to 10 000 ft for Apollo 11), and all the solutions were biased by about 10 000 feet at the longitude of landing site 2. These errors were determined in real time through the use of excellent landing site tracking with the CM optics as planned and did not contribute directly to landing inaccuracies. The LM landed 4500 feet south of the desired landing point because of an inaccurate empirical determination of cross-track position prediction errors which resulted from the noisy plane determinations. Improved procedures should reduce this error for Apollo 12. The 22 300-foot down-track position error at powered descent initiation (PDI) was larger than expected (table II). This error most probably resulted from unmodeled translational forces which occurred during the last few revs before landing. Actual accuracies achieved during Apollo 11 without unmodeled forces are given in table I, line 6.

TABLE I.- ONE-SIGMA ACCURACY WHEN PREDICTING FORWARD TWO REVOLUTIONS

[In absence of spacecraft translational force]

	Altitude above moon, ft	Down-track distance relative to landing site, ft	Cross-track distance relative to landing site, ft
Expected on Apollo 8	2400	8 500	1100
Achieved on Apollo 8	3000	30 000	1100
Expected on Apollo 10	1100	6 000	1100
Achieved on Apollo 10	360	3 500	4000
Expected on Apollo 11	680	3 500	1100
Achieved on Apollo 11	360	1 300	4000

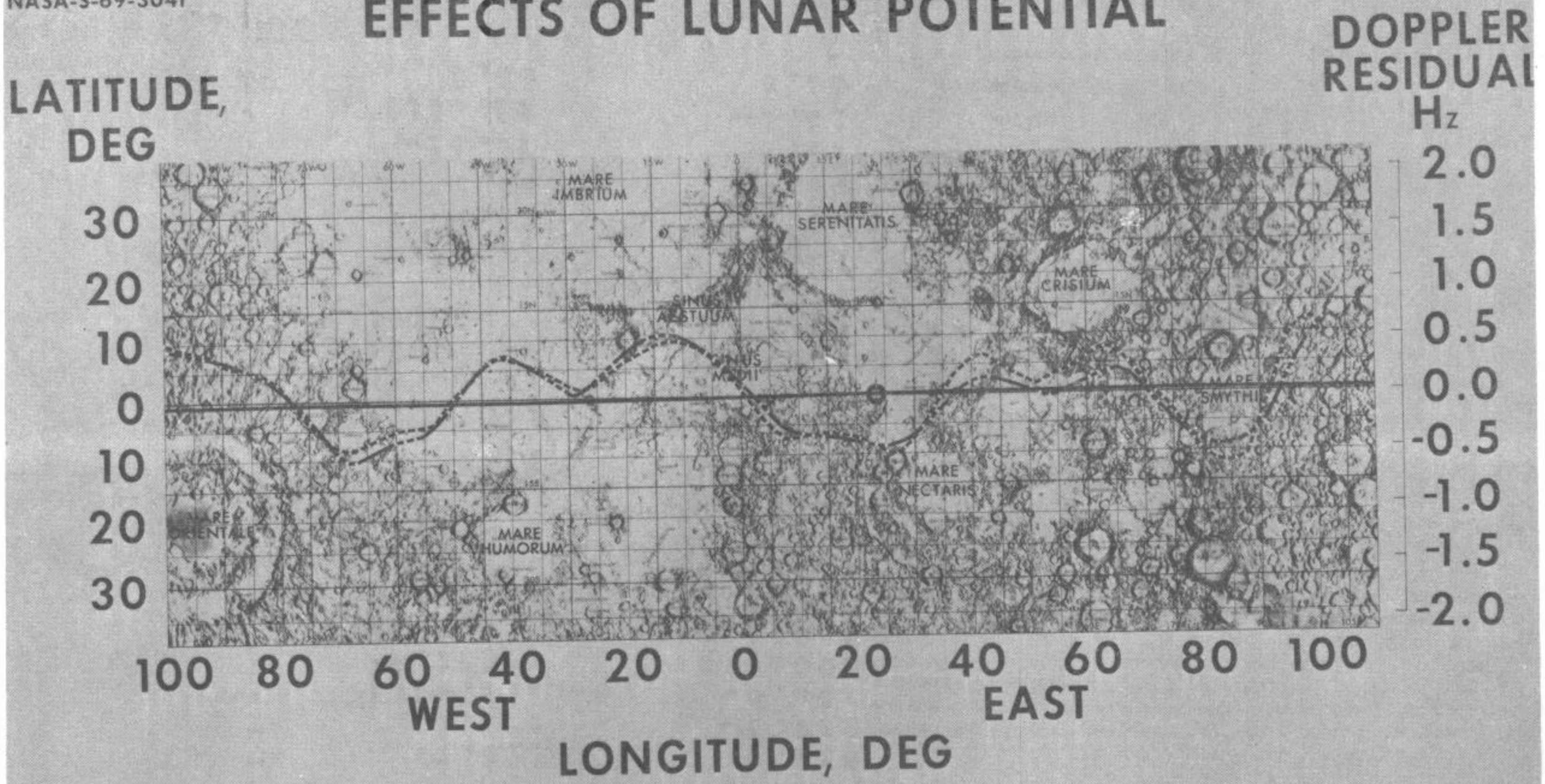
TABLE II.- APOLLO 11 ACCURACY OF LM KNOWLEDGE OF ITS POSITION AT PDI RELATIVE TO THE LANDING SITE

Altitude, ft	460
Down-track distance, ft	22 300
Cross-track distance, ft	4 600

NASA-S-69-3041

MPAD 5770 S

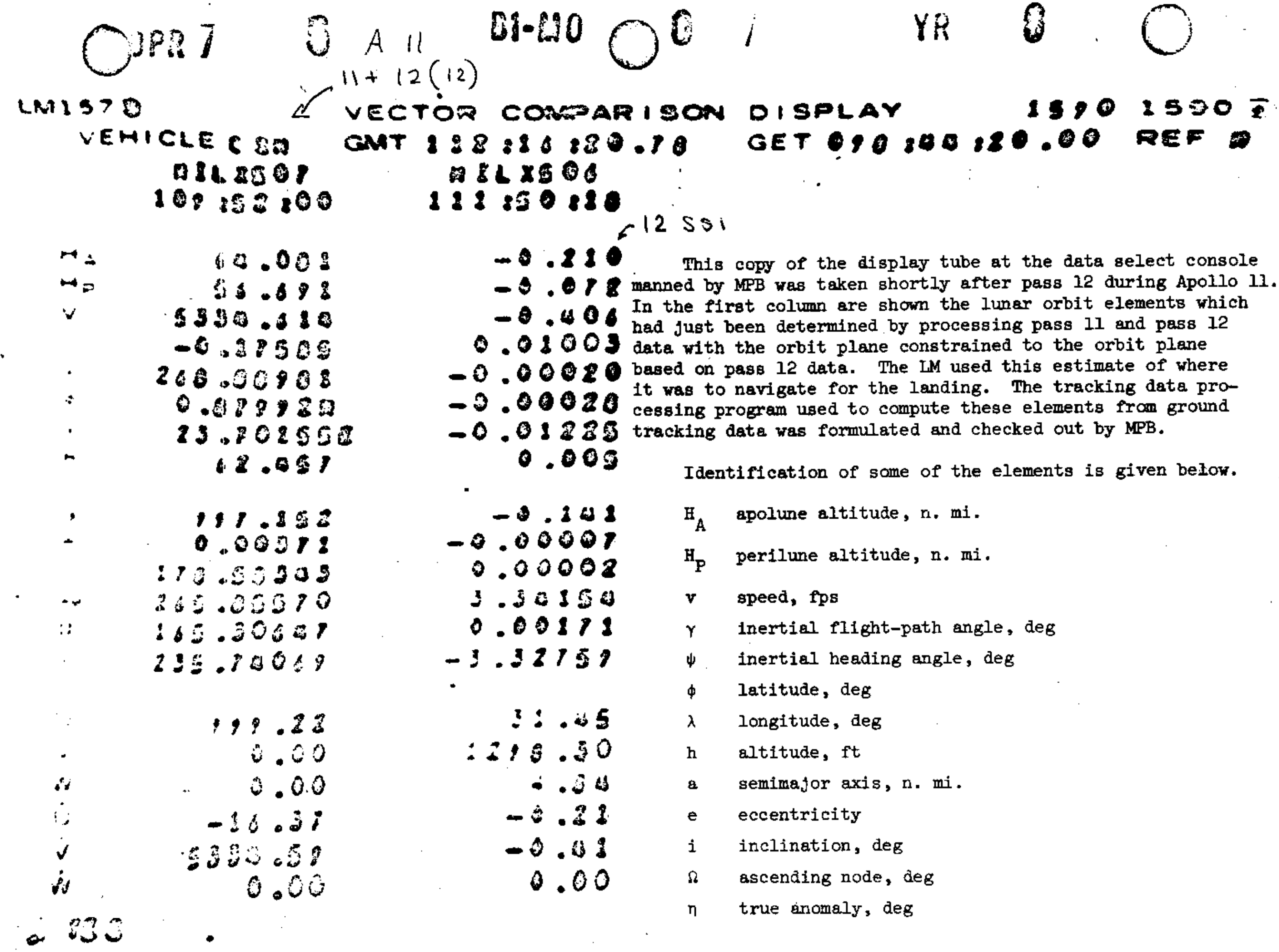
EFFECTS OF LUNAR POTENTIAL



--------- APOLLO 10-28TH REVOLUTION

---—--- APOLLO 11-20TH REVOLUTION

⊕ LANDING SITE 2

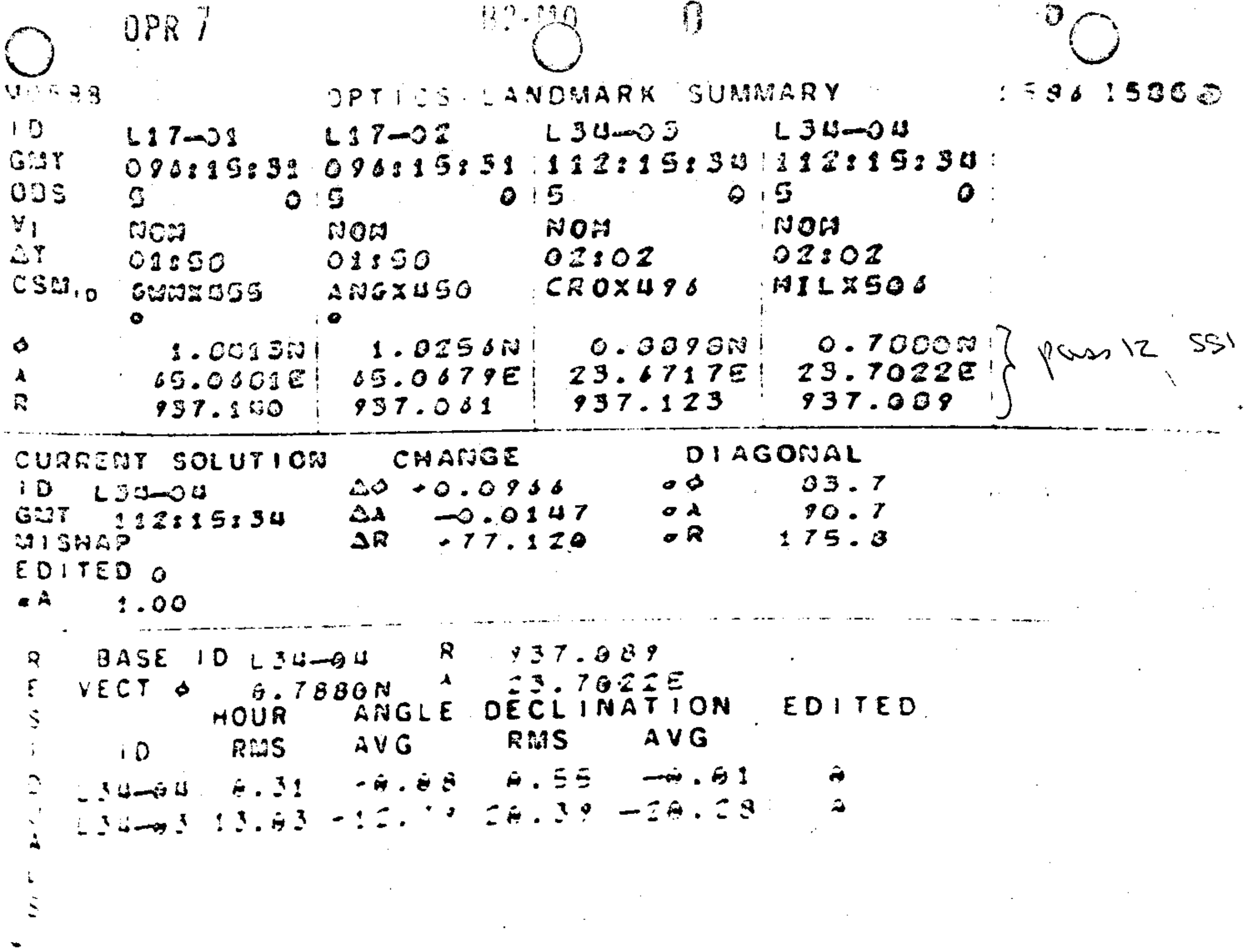


```
JPR 7   3 A 11   D1-110   0 /          YR   0
                  11+12(12)
LM1570             VECTOR COMPARISON DISPLAY          1570 1590
   VEHICLE CSM     GMT 128:16:20.78     GET 070:00:20.00   REF 0
        01L2S07            01LXS06
      109:52:00          111:50:18
                                   12 SS1
HA          60.001           -0.210
HP          56.691           -0.078
V         5390.618           -0.406
          -0.37509          0.01003
         268.00983         -0.00020
          0.879920         -0.00020
         23.702558         -0.01225
            62.051            0.009

           111.152           -0.141
           0.00371         -0.00007
         178.55305          0.00002
         265.05570          3.30150
         165.30647          0.00171
         235.70049         -3.32759

            111.22            31.45
              0.00          1218.50
              0.00             4.54
            -16.37            -0.21
V          5390.59            -0.01
              0.00             0.00
033
```

This copy of the display tube at the data select console manned by MPB was taken shortly after pass 12 during Apollo 11. In the first column are shown the lunar orbit elements which had just been determined by processing pass 11 and pass 12 data with the orbit plane constrained to the orbit plane based on pass 12 data. The LM used this estimate of where it was to navigate for the landing. The tracking data processing program used to compute these elements from ground tracking data was formulated and checked out by MPB.

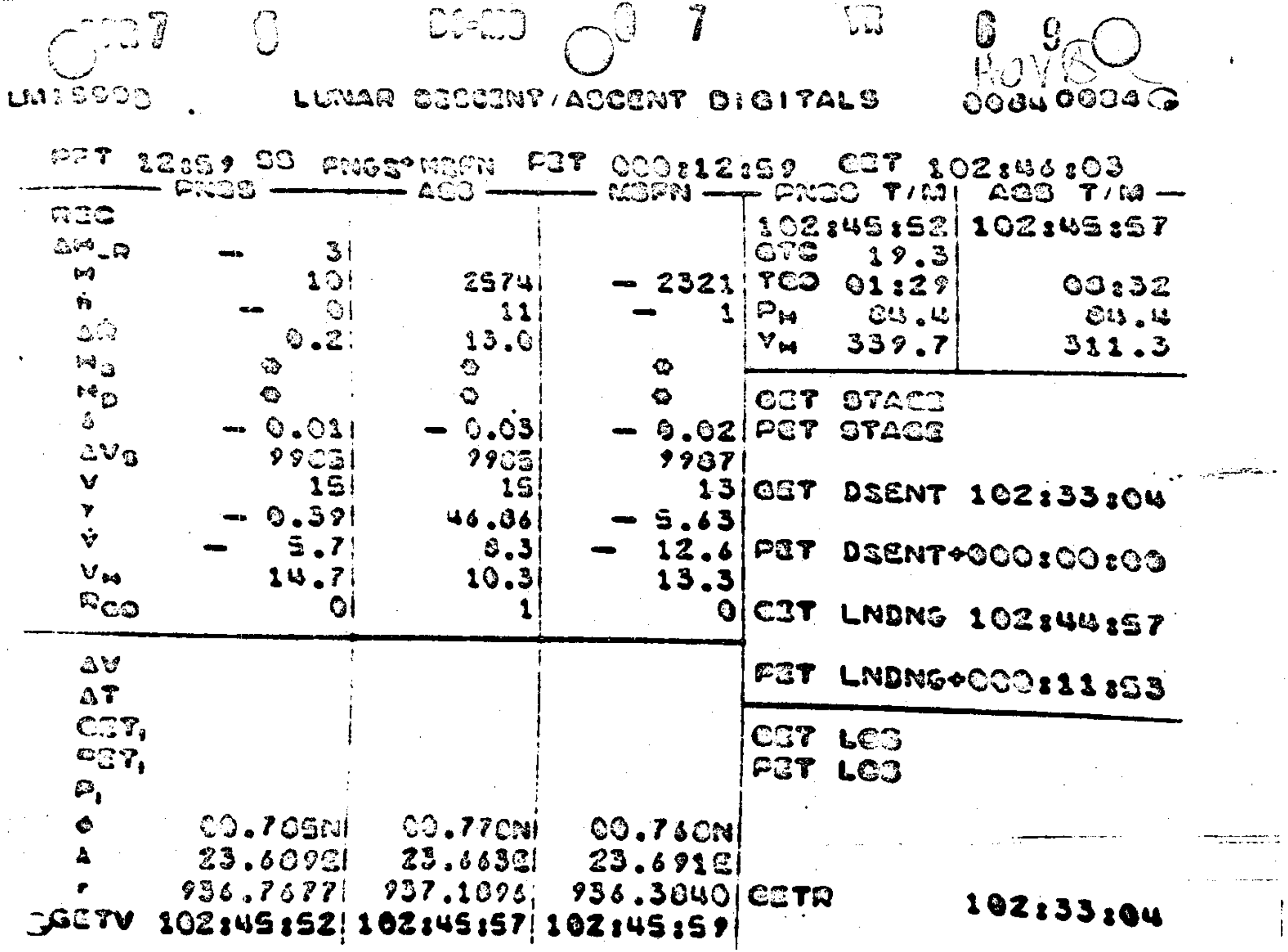
Identification of some of the elements is given below.

H_A	apolune altitude, n. mi.
H_P	perilune altitude, n. mi.
v	speed, fps
γ	inertial flight-path angle, deg
ψ	inertial heading angle, deg
ϕ	latitude, deg
λ	longitude, deg
h	altitude, ft
a	semimajor axis, n. mi.
e	eccentricity
i	inclination, deg
Ω	ascending node, deg
η	true anomaly, deg



```
      OPR 7
V0598                 OPTICS LANDMARK SUMMARY                1596 1536
ID     L17-01       L17-02       L34-03       L34-04
GMT    096:15:31    096:15:51   112:15:34   112:15:34
ODS    S        0   S        0   S        0   S        0
V1     NOM          NOM          NOM          NOM
ΔT     01:50        01:50        02:02        02:02
CSMID  GWNX055      ANGX450      CROX496      MILX506
       0            0
φ         1.0013N      1.0256N     0.8898N      0.7880N  } pass 12 SS1
λ        65.0601E     65.0679E    23.6717E     23.7022E  }
R        937.180      937.061     937.123      937.089   }

CURRENT SOLUTION       CHANGE               DIAGONAL
ID  L34-04          Δφ +0.0966          σφ      83.7
GMT  112:15:34      Δλ  -0.0147         σλ      90.7
MISMAP              ΔR +77.120          σR     175.8
EDITED 0
σA       1.00

R    BASE ID L34-04        R    937.089
E   VECT φ     0.7880N     λ    23.7022E
S            HOUR    ANGLE  DECLINATION    EDITED
I     ID     RMS     AVG     RMS     AVG
D   L34-04   0.31   -0.08    0.55   -0.01     0
U   L34-03  13.03   -12.    20.39  -20.28     0
A
L
S
```

This copy of the display tube at the data select support console shows the latitude ϕ, longitude λ, and radius R for the location of the landing site. The values 0.7880N, 23.7022E, and 937.089 were obtained by use of a fit to pass 12 MSFN data to locate the CM and the CM sextant tracking of the landing site landmark. These numbers were given to the LM which used them to navigate down to the moon's surface. (The radius was first adjusted slightly to account for prediction errors.) The RTCC processor used to compute these values was formulated and checked out by MPB.

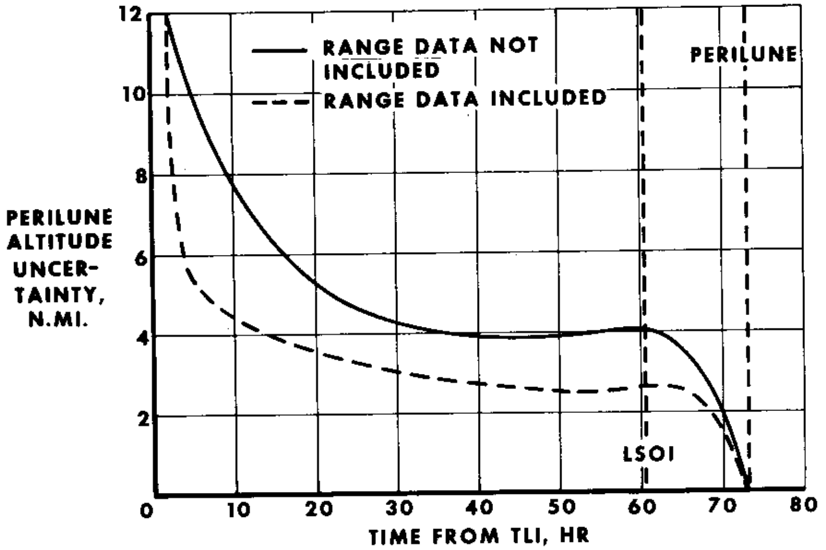


```
LM1 5003          LUNAR DESCENT/ASCENT DIGITALS              0004 0034

 RFT 12:59 55  PNGS-MSFN  PET 000:12:59   GET 102:46:03
 ------ PNGS -------- AGS -------- MSFN --- PNGS T/M | AGS T/M ---
 REC                                       |102:45:52|102:45:57
 ΔH_R       -      3|                      |GTC  19.3|
  H               10|      2574|    - 2321 |TGO 01:29|      00:32
  Ḣ          -     0|        11|    -    1 |P_H  84.4|       84.4
  ΔḢ             0.2|      13.0|           |Y_H 339.7|      311.3
  H_S          0           0          0    ---------------------
  H_D          0           0          0    |GET STAGE
  δ         - 0.01|     - 0.03|   - 0.02  |PET STAGE
  ΔV_B         9905|      9905|      9987 |
  V              15|        15|        13 |GET DSENT 102:33:04
  γ         - 0.39|      46.06|   - 5.63  |
  V̇        -    5.7|       8.3|   - 12.6  |PET DSENT+000:00:00
  V_H           14.7|      10.3|      13.3 |
  R_CO             0|         1|         0 |GET LNDNG 102:44:57
 -------------------------------------------
  ΔV                                       |PET LNDNG+000:11:53
  ΔT                                       ---------------------
  GET_I                                    |GET LGS
  PET_I                                    |PET LGS
  P_I
  φ        00.705N|   00.770N|   00.760N |
  λ        23.609E|   23.663E|   23.691E |
  r       936.7677|  937.1096|  936.3040 |GETR         102:33:04
 GETV    102:45:52|102:45:57|102:45:59 |
```

This copy of the RTCC display tube at the data select support console shows elements computed by the LM primary (PNGS) and backup (AGS) navigation systems and the RTCC powered flight processor (MSFN). These elements were recorded while the LM was hovering 10 feet above the moon (PNGS H). The speed V of 15 fps is caused by the moon's rotational rate. The estimates of latitude ϕ, longitude λ, and radius R at the bottom were used to compute the first estimates of where the LM landed. The powered flight processor was formulated and checked out by MPB and TRW.

APOLLO 11

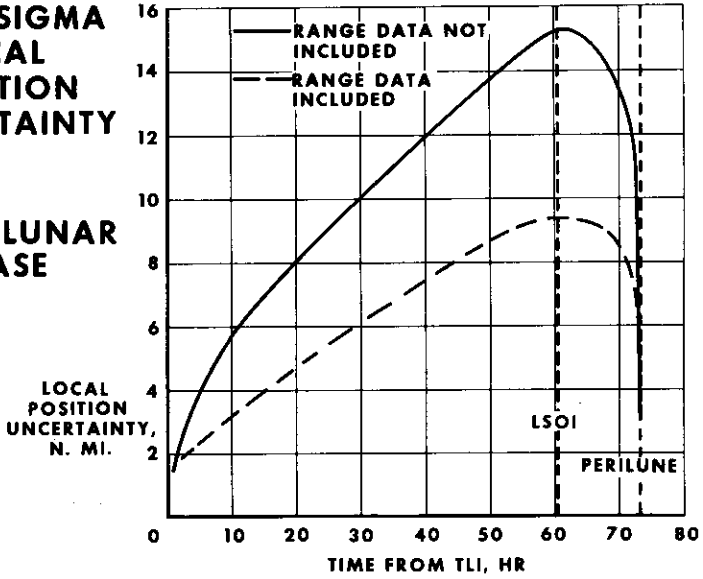
THREE-SIGMA PREDICTED PERILUNE ALTITUDE UNCERTAINTY - TRANSLUNAR PHASE



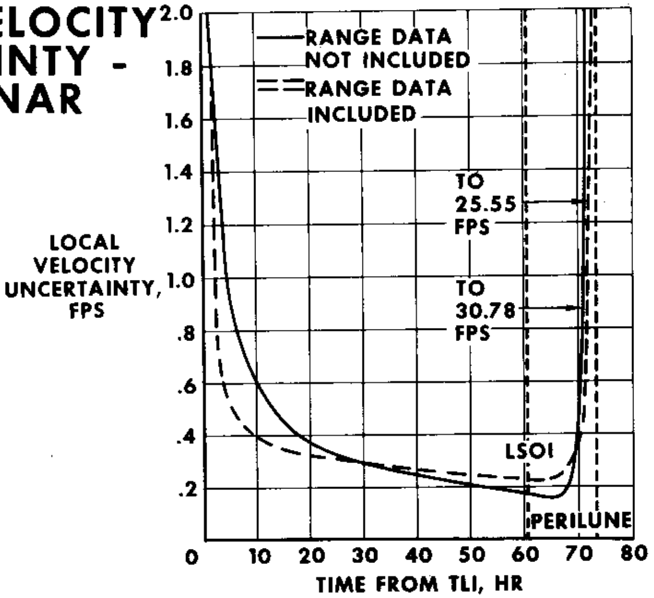
APOLLO 11

THREE-SIGMA LOCAL POSITION UNCERTAINTY

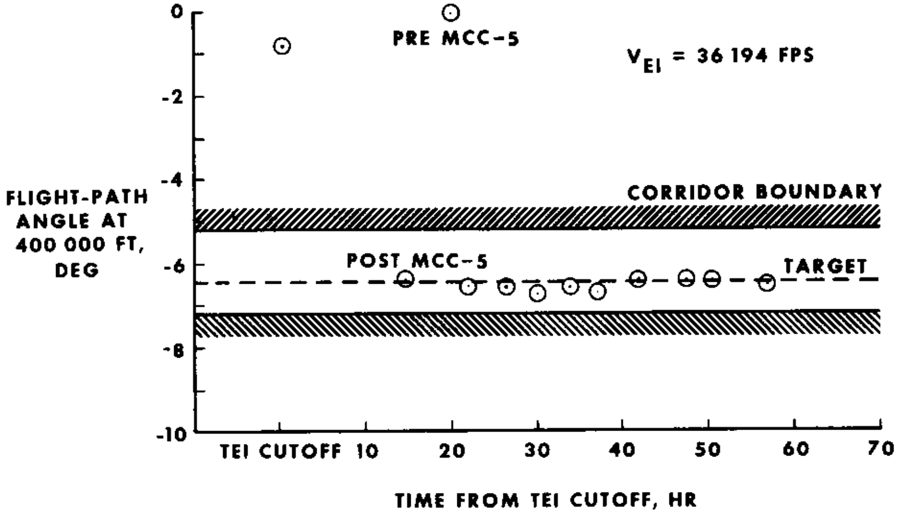
TRANSLUNAR PHASE



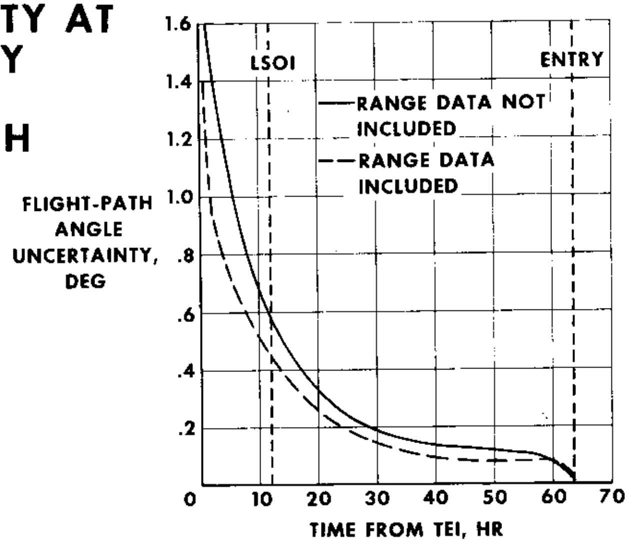
APOLLO 11 THREE-SIGMA LOCAL VELOCITY UNCERTAINTY - TRANSLUNAR PHASE



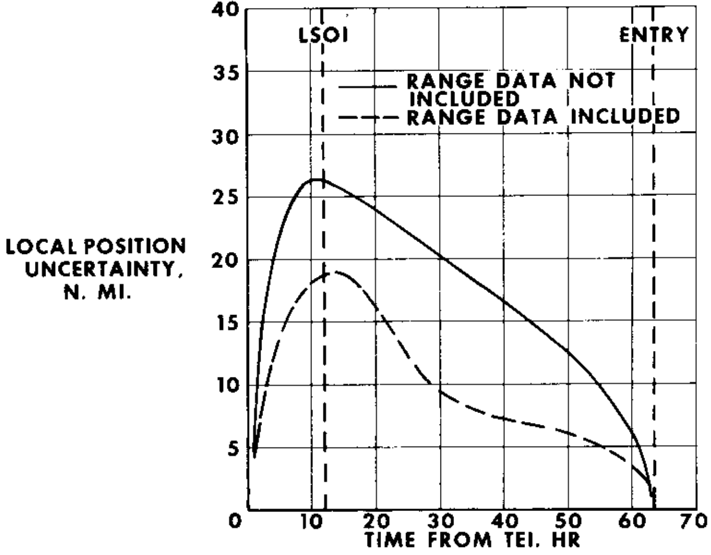
APOLLO 11
ENTRY INTERFACE CONDITIONS



APOLLO 11
THREE-SIGMA PREDICTED FLIGHT-PATH ANGLE UNCERTAINTY AT FIXED ENTRY RADIUS - TRANSEARTH PHASE

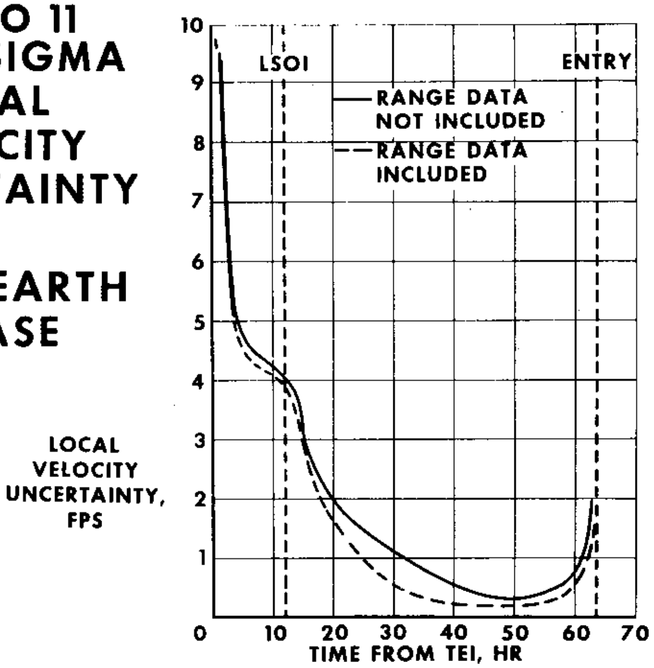


APOLLO 11
THREE-SIGMA LOCAL POSITION UNCERTAINTY-TRANSEARTH PHASE



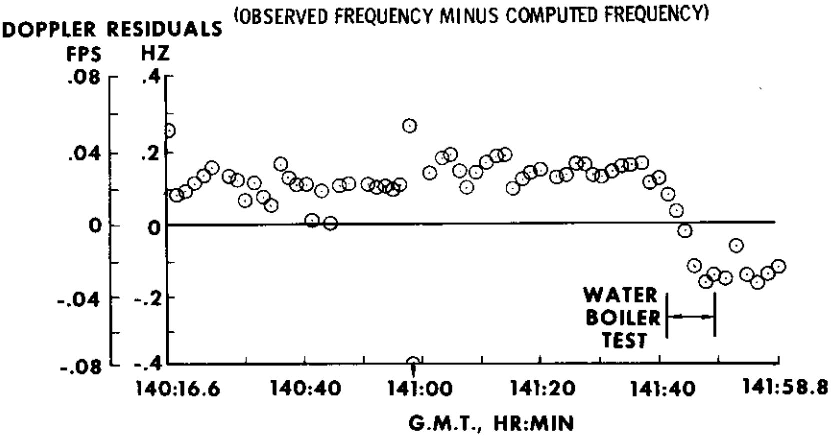
APOLLO 11 THREE-SIGMA LOCAL VELOCITY UNCERTAINTY

TRANSEARTH PHASE

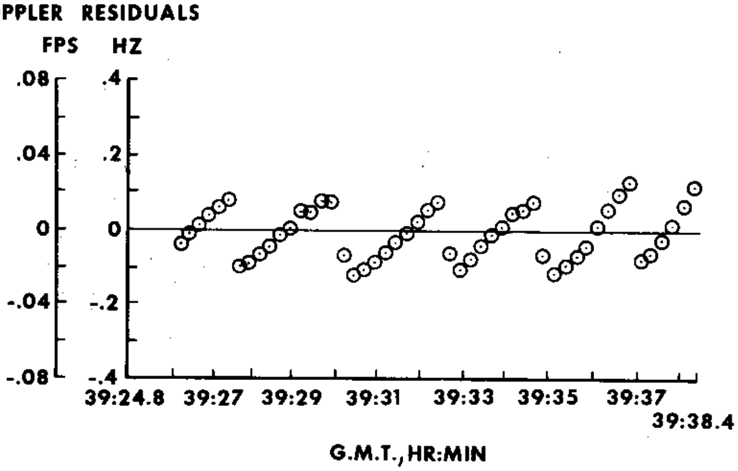


APOLLO 8 TRANSEARTH COAST DOPPLER MEASUREMENT SENSITIVITY TO SPACECRAFT VENTING

(OBSERVED FREQUENCY MINUS COMPUTED FREQUENCY)

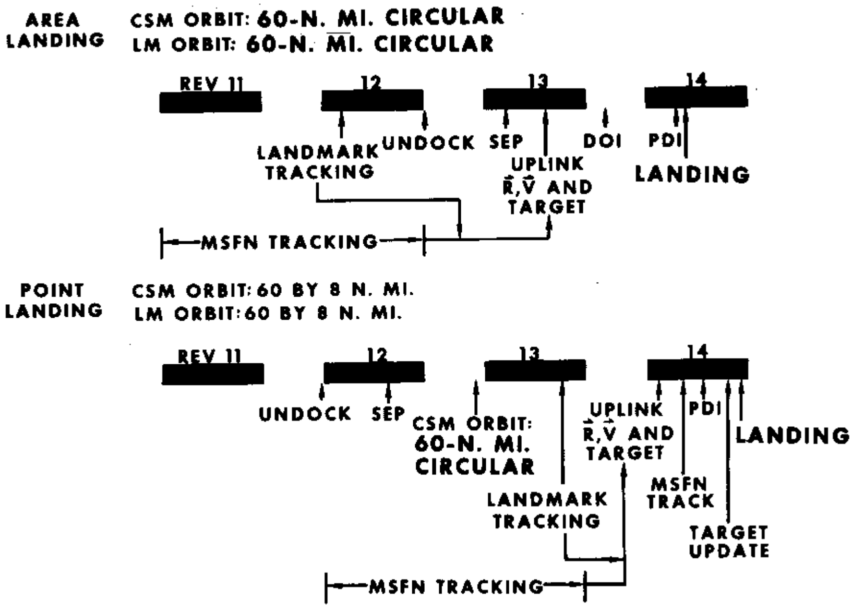


APOLLO 10 TRANSEARTH COAST DOPPLER MEASUREMENT SENSITIVITY TO SPACECRAFT MOTION

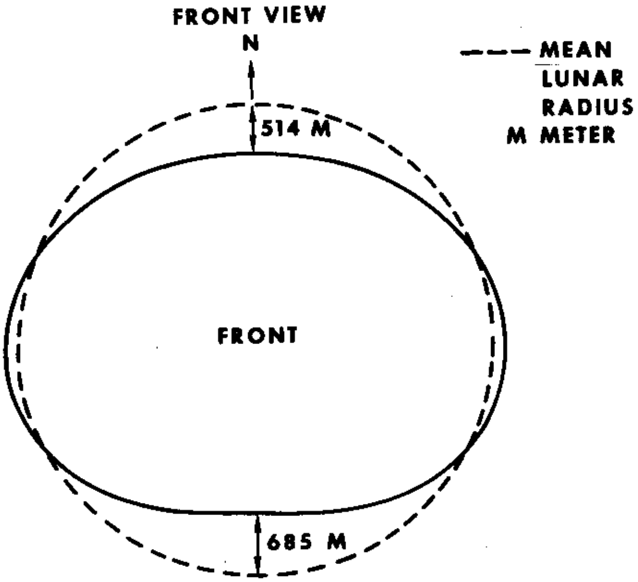


Spacecraft antenna motion during passive thermal control (0= 0.3 deg/sec

APOLLO NAVIGATION TIMELINES



R2 MOON MODEL



R2 model

$C20 = -2.07108 \times 10^{-4}$

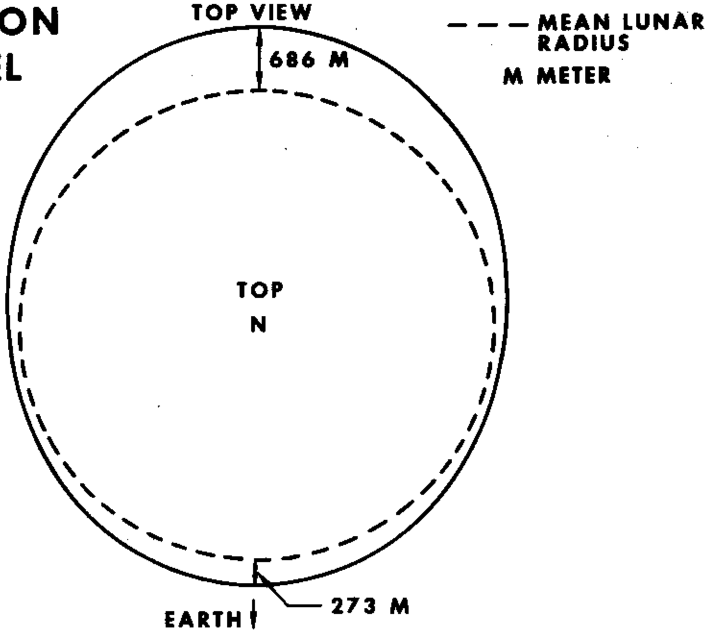
$C30 = 0.21 \times 10^{-4}$

$C22 = 0.20716 \times 10^{-4}$

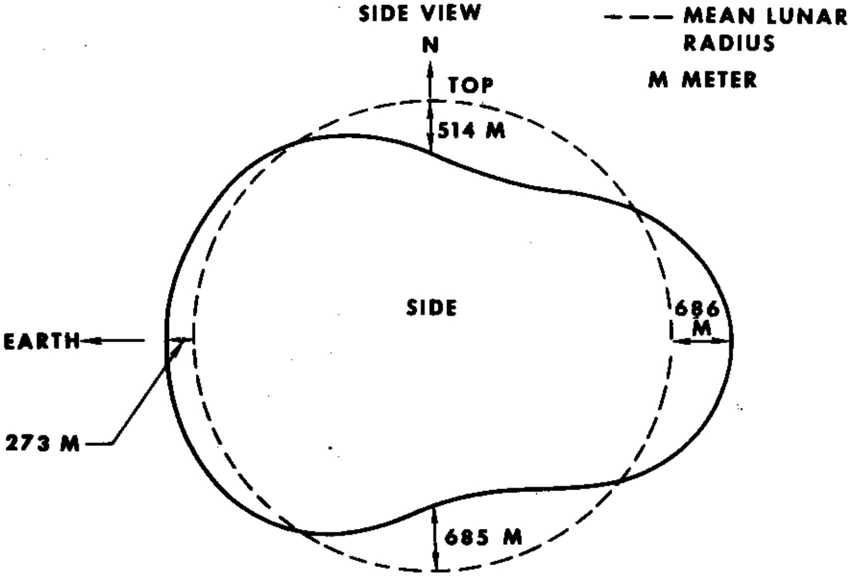
$C31 = 0.34 \times 10^{-4}$

C20 and C22 are based on astronomical observations. C30 and C31 are based primarily on Lunar Orbitor 3 (70 by 170 n. mi.) mean orbit element rates over a 40-day period.

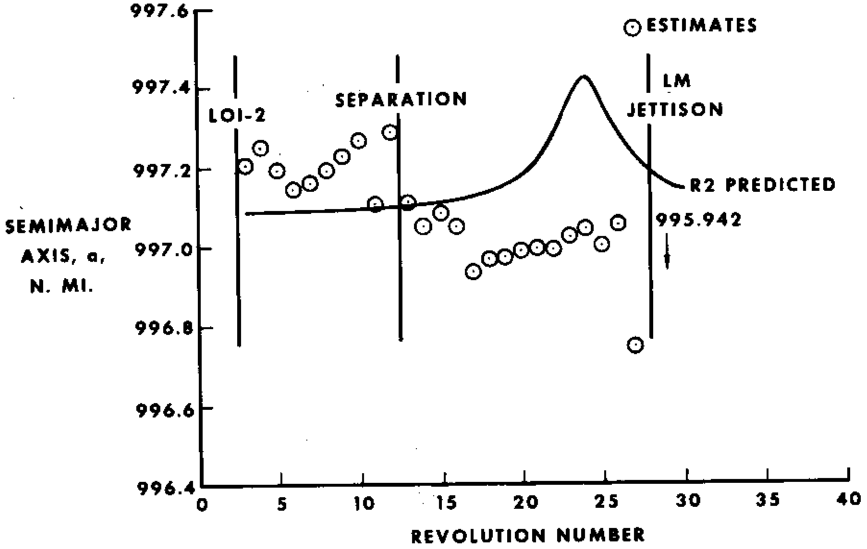
R2 MOON MODEL



R2 MOON MODEL

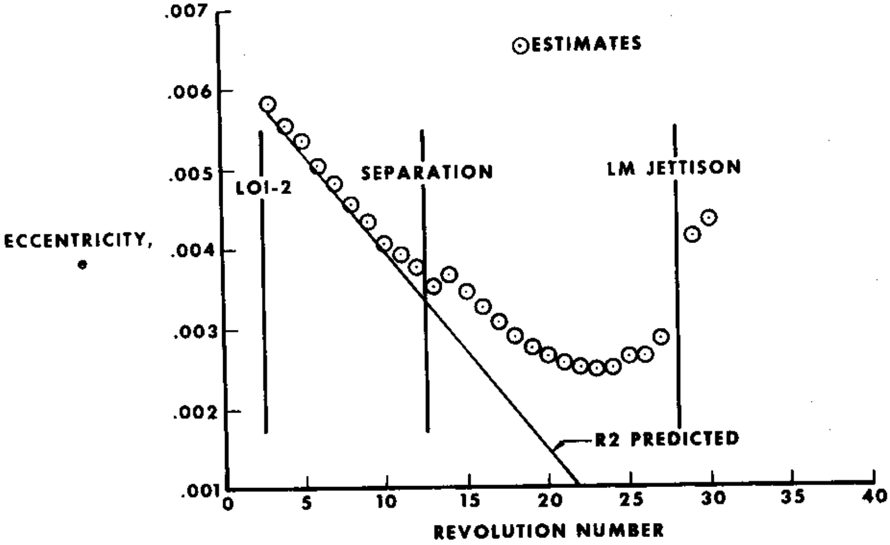


APOLLO 11 SEMIMAJOR AXIS HISTORY



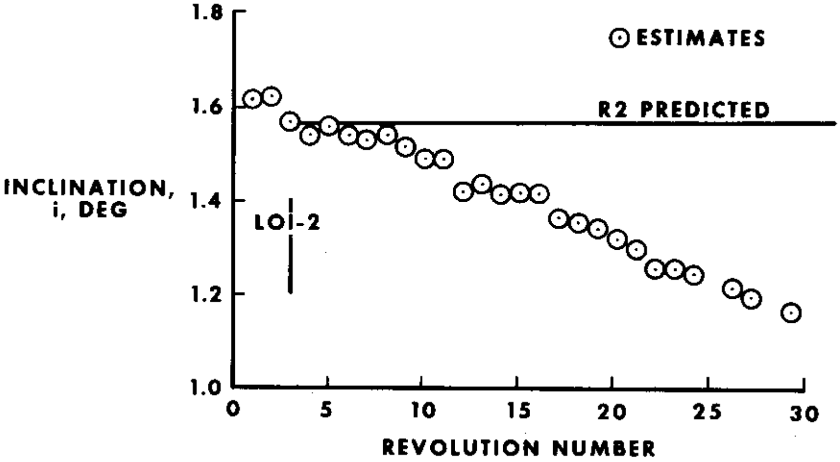
Separation maneuver is not included in R2 prediction.
Hump in R2 prediction at rev 24 results from R2 model; that is, longitude of perilune is on earth-moon line, and, in this region, R2 has a lump or bulge.
Estimates are based on one-pass no a priori orbit solutions using R2 model.

APOLLO 11 ECCENTRICITY HISTORY

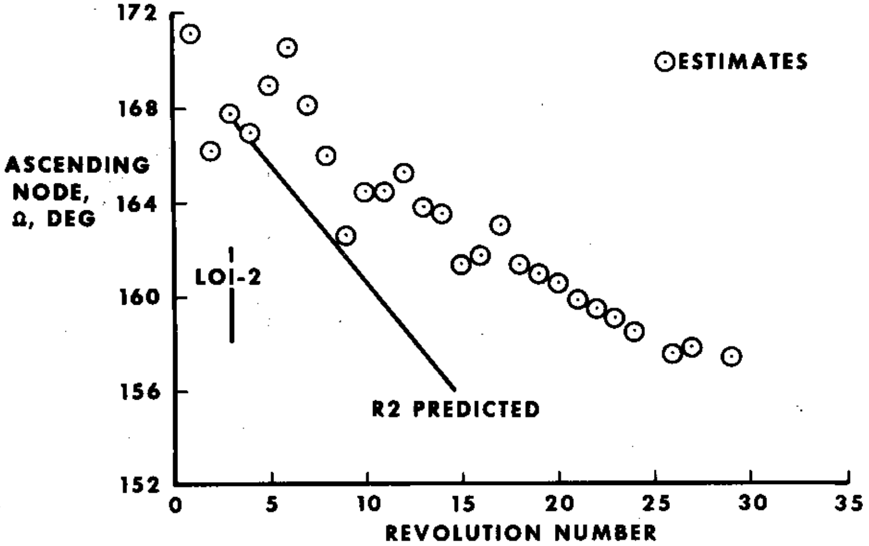


Separation maneuver is not included in R2 prediction.

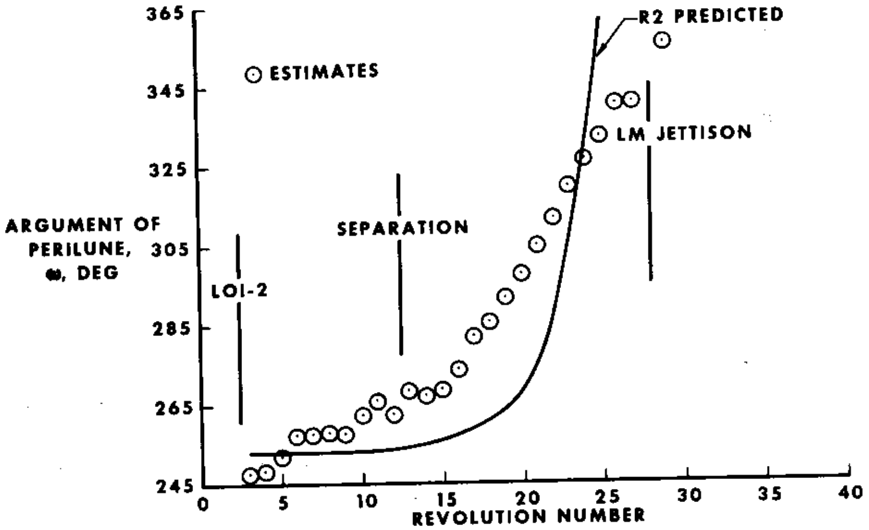
APOLLO 11 SELENOGRAPHIC INCLINATION HISTORY



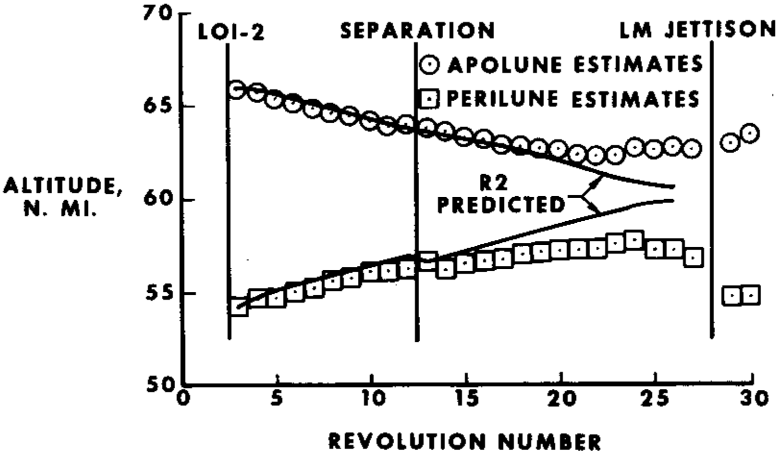
APOLLO 11
SELENOGRAPHIC ASCENDING NODE HISTORY



APOLLO 11 ARGUMENT OF PERILUNE HISTORY

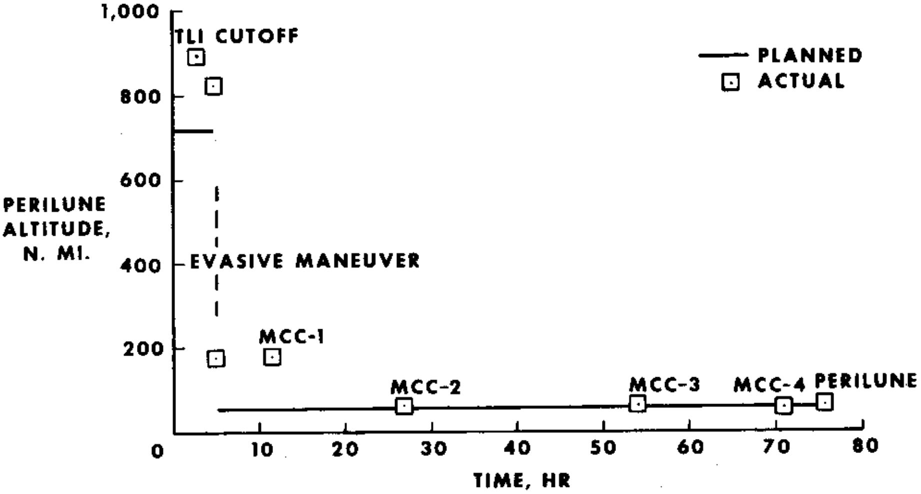


APOLLO 11 APOLUNE-PERILUNE HISTORY

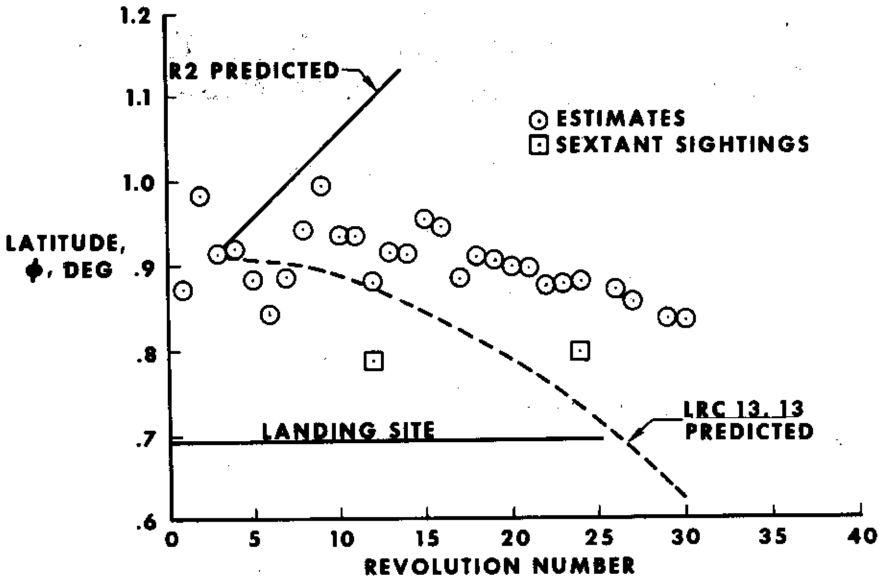


Separation maneuver is included in R2 prediction. Deviation between estimates and prediction after 12 revolutions is a result of the inaccuracy of the R2 model; however, it is still the best model for apolune-perilune prediction.

APOLLO 11
PERILUNE ALTITUDE HISTORY



APOLLO 11 CSM LATITUDE HISTORY



APOLLO 11 ERROR IN LOCATION OF LM RELATIVE TO LANDING SITE

	REVOLUTION 12	REVOLUTION 13	PDI
LATITUDE	300 FT	2 600 FT	4 600 FT
LONGITUDE	1 300 FT	7 800 FT	22 300 FT
RADIUS	300 FT	400 FT	460 FT

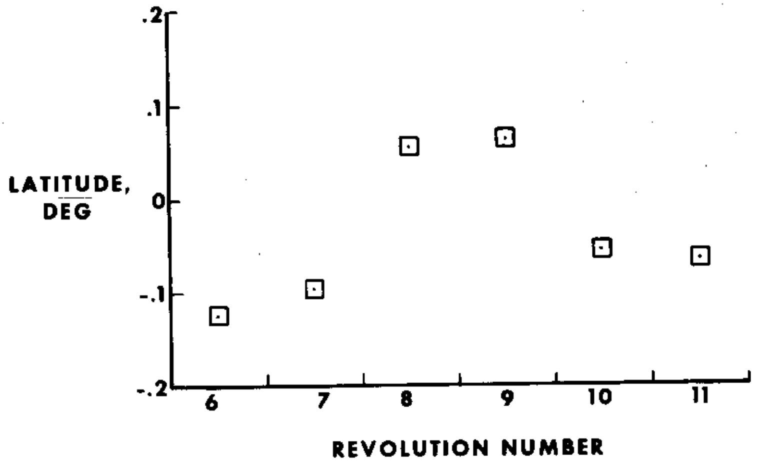
Error in latitude results from not accounting for two-rev plane propagation error in R2 model. Longitude error is explained on next figure.

POSSIBLE REASONS FOR APOLLO 11 DOWN-TRACK LANDING SITE MISS

- UNCOUPLED ATTITUDE MANEUVERS
- UNDOCKING
- DOI EXECUTION ERROR
- LM VENTING
- RCS TEST FIRINGS

APOLLO 11 TWO-REVOLUTION LATITUDE PROPAGATION ERROR

(LOCAL ONE-PASS SOLUTION MINUS TWO-PASS PROGAGATED SOLUTION)

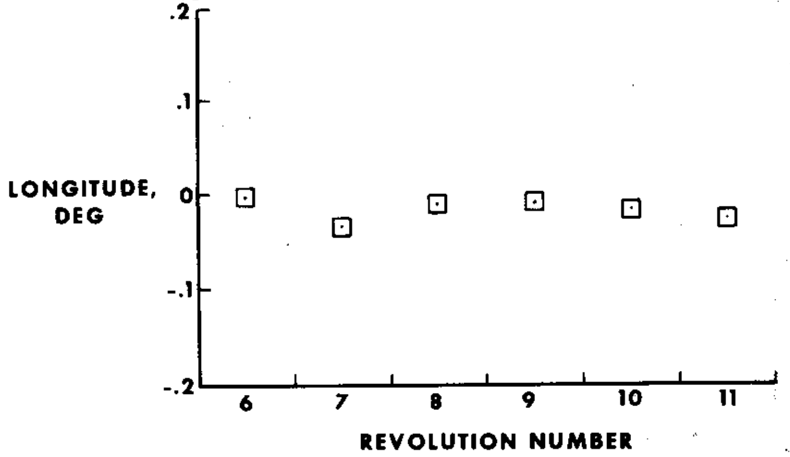


Average propagation error = -0.029° ± 0.090°. This correction is not applied because of large uncertainty which is in turn primarily caused by errors in local estimates.

On lunar surface, 0.1° ≈ 10 000 ft.

APOLLO 11 TWO-REVOLUTION LONGITUDE PROPAGATION ERROR

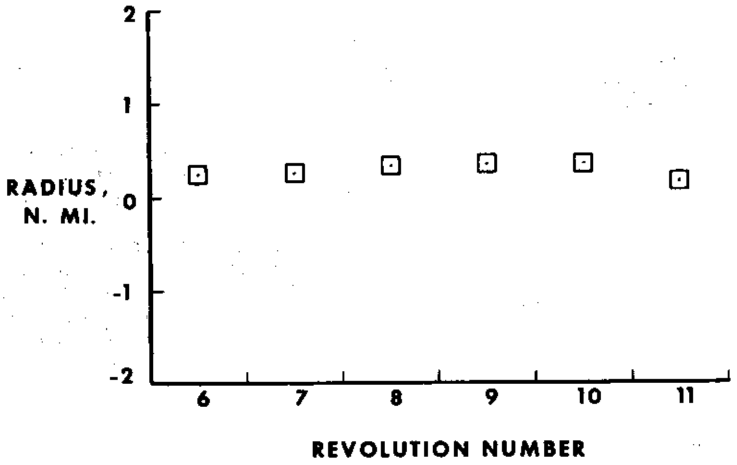
(LOCAL ONE-PASS SOLUTION MINUS TWO-PASS PROPAGATED SOLUTION)



Average two-rev propagation error = -0.008° ± 0.010°. This correction is not applied because value was less than uncertainty.

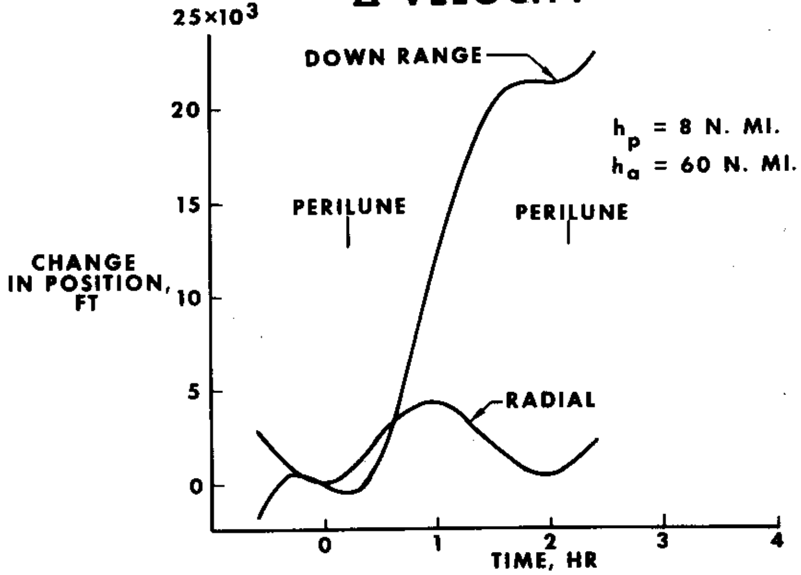
APOLLO 11 TWO-REVOLUTION PROPAGATION ERROR IN RADIUS

(LOCAL ONE PASS SOLUTION MINUS TWO-PASS PROPAGATED SOLUTION)



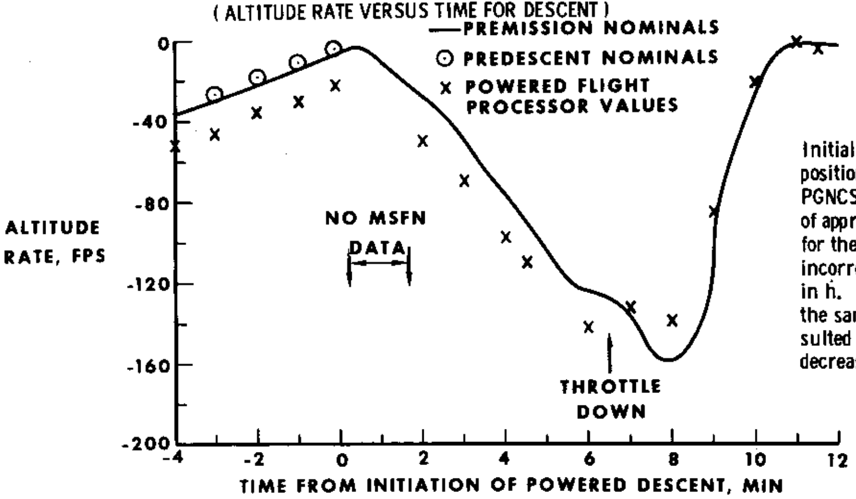
Average two-rev propagation error = 1900 ± 300 ft. This correction was applied.

EFFECT OF 1-FPS DOWN RANGE Δ VELOCITY



APOLLO 11
COMPARISON OF POWERED FLIGHT MSFN PROCESSOR VALUE OF LM ALTITUDE RATE FOR DESCENT TO NOMINAL

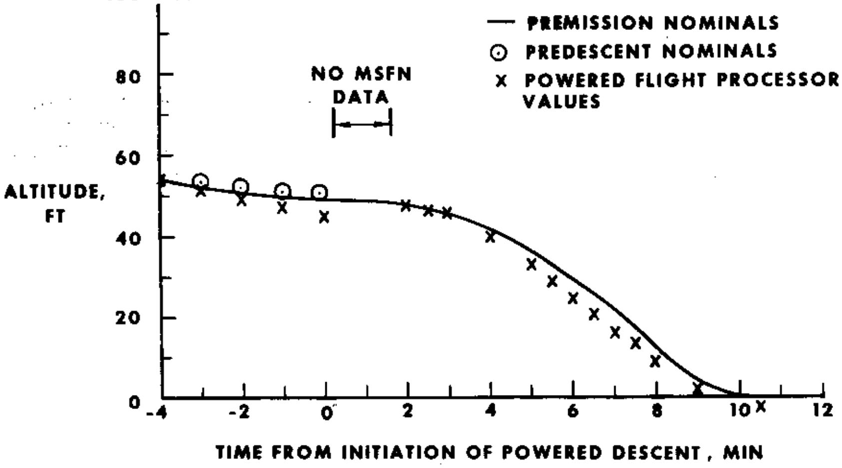
(ALTITUDE RATE VERSUS TIME FOR DESCENT)



Initial bias in $\dot{h}$ indicates down-range position error in vector used to initialize PGNCS, AGS, and the MSFN processor of approximately 20 000 ft. Filter solves for the correct velocity which, with the incorrect position, causes the deviation in $\dot{h}$. When the filter is restarted to PGNCS, the same conditions occurred which resulted in the same error in $\dot{h}$. Error decreases as velocity decreases.

APOLLO 11
COMPARISON OF POWERED FLIGHT MSFN PROCESSOR VALUE OF LM ALTITUDE FOR DESCENT TO NOMINAL

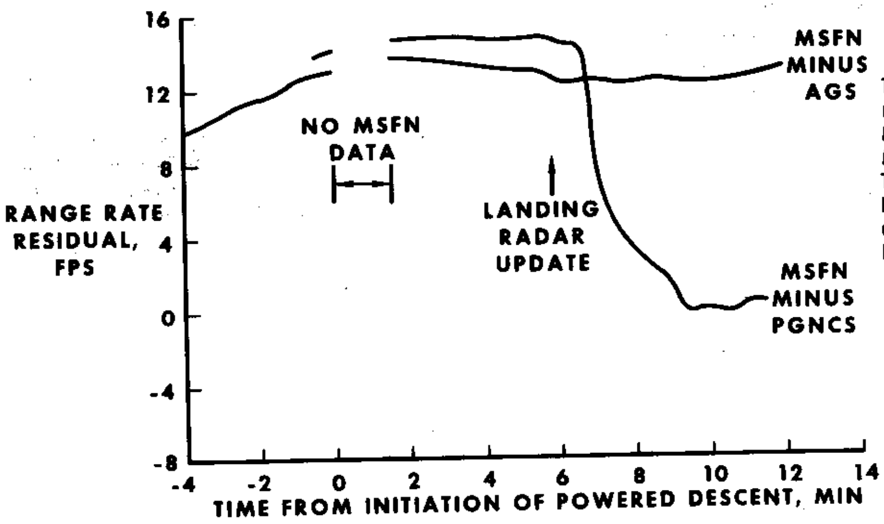
(ALTITUDE VERSUS TIME FOR DESCENT)



The error in down-range position resulted also in a bias on altitude.

APOLLO 11 DESCENT RANGE RATE RESIDUALS

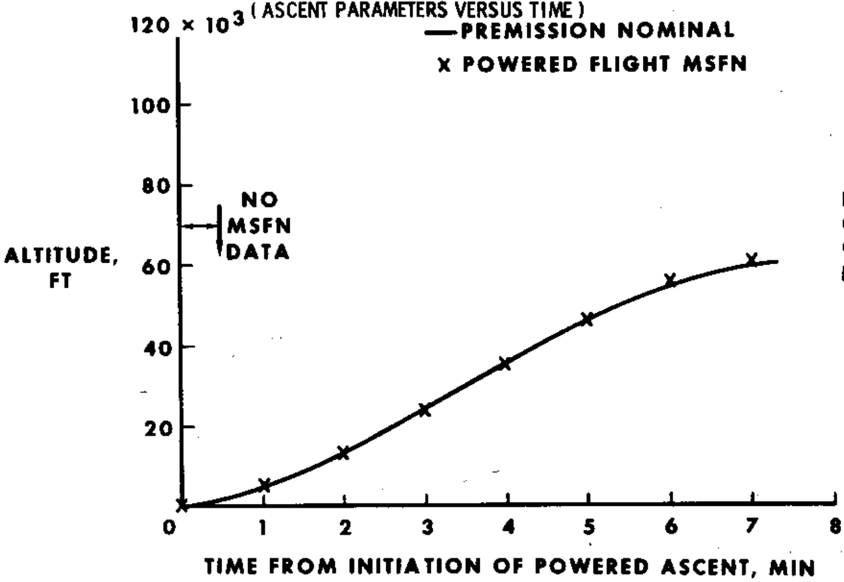
(RANGE RATE RESIDUALS FOR DESCENT)



The performance of the line-of-sight range rate residual processor for MSFN versus PGNCS residuals and MSFN versus AGS residuals is shown. The residuals for MSFN versus PGNCS became negligible after the PGNCS estimate of velocity was updated by landing radar.

APOLLO 11
POWERED FLIGHT MSFN PROCESSOR

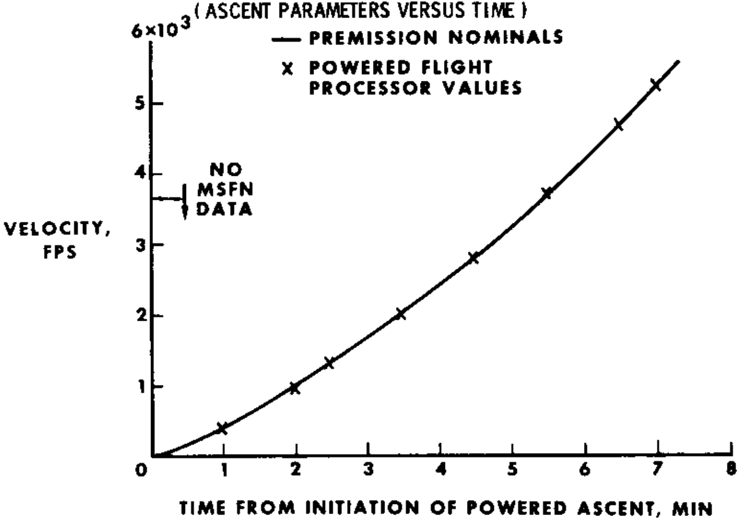
(ASCENT PARAMETERS VERSUS TIME)



Except during the time of no MSFN data, both the filter and the line-of-sight range rate residual processor performed nominally.

APOLLO 11 COMPARISON OF POWERED FLIGHT MSFN PROCESSOR VALUE OF LM VELOCITY FOR ASCENT TO NOMINAL

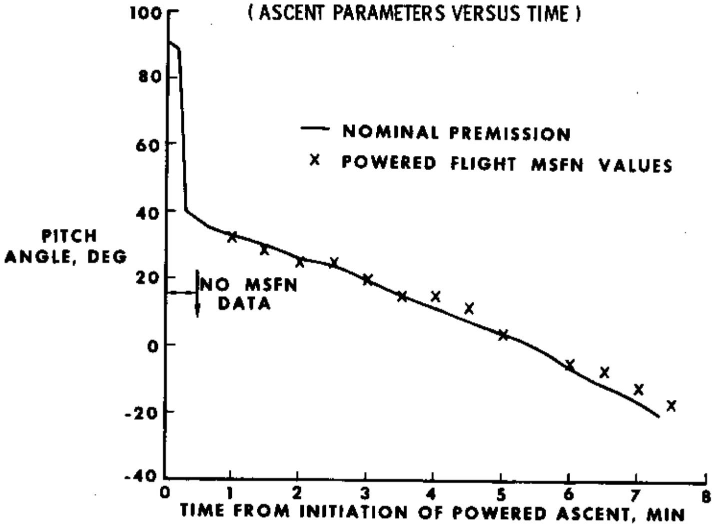
(ASCENT PARAMETERS VERSUS TIME)



Except during the time of no MSFN data, both the filter and the line-of-sight range rate residual processor performed nominally.

APOLLO 11 COMPARISON OF POWERED FLIGHT MSFN PROCESSOR VALUE OF LM PITCH ANGLE FOR ASCENT TO NOMINAL

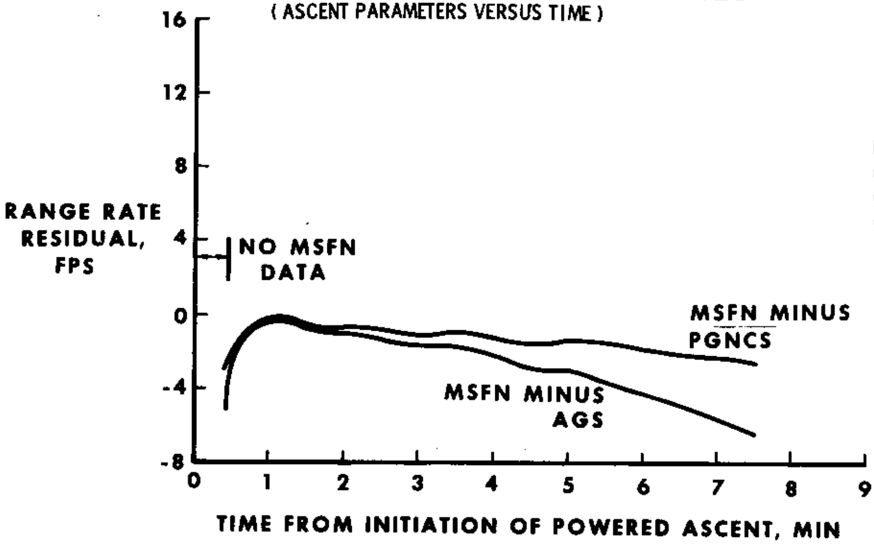
(ASCENT PARAMETERS VERSUS TIME)



Except during the time of no MSFN data, both the filter and the line-of-sight range rate residual processor performed nominally.

APOLLO 11
ASCENT RANGE RATE RESIDUALS

(ASCENT PARAMETERS VERSUS TIME)



Except during the time of no MSFN data, both the filter and the line-of-sight range rate residual processor performed nominally.

J.R. ELK

Tom Linbeck

Fran Johnson

Ed Surak

Mike Hill

Martin D. Jenness

Gene W Rich

Rhonda Walker

Dave S Schaffer

Hal Beck

Ronald L. Berry

Roger H. Sanders

Ken Ziehe

Jimmie D. Yencharis

George A. Weisskopf

Eddie Lemons

THE LUNAR MISSION ANALYSIS BUNCH

Sauers

Daryl R. Sostak

Alfred A. Menchaca

Kathy

Neal J. Nielsen

Bob Wiley

Robert Ernull

Robert S Davis

Oniel McCafferty "Moe"

Lazarus Gonzales, Jr.

Rocky Duncan

Doc Tick

Ann D Hartung

Gordon Lee Nolnatin

Quentin A. Holmes

Max B. Kilbourn

Joanna Howe

E. M. Jingo

THE LUNAR MISSION ANALYSIS BRANCH

In 1961, the Lunar Trajectory Section of the Mission Analysis Branch, which has become the Lunar Mission Analysis Branch, started to develop the computer programs and trajectory analysis techniques required to conduct a lunar landing mission. Since that time, many thousands of manhours have contributed to the successful completion of a manned lunar landing mission. The major contributions of the Lunar Mission Analysis Branch to the conduct of Apollo 11 were as follows: conducted preflight targeting scans; determined the launch window; supplied the Marshall Space Flight Center with the S-IVB targeting to obtain the proper translunar trajectory; established the midcourse correction, lunar orbit insertion, and transearth injection procedures and real-time targeting logic; and managed the formulation, implementation, and verification of the RTCC programs required to support the manned lunar landing mission. A brief sketch of lunar mission design criteria from determination of the launch windows through final implementation of the RTCC processors is presented in the following discussion and figures.

FREE-RETURN TRAJECTORIES

In figure 1, the initial trajectory of the spacecraft is shown placed well ahead of the moon at time of launch. Nominally, the velocity of the vehicle at translunar injection will be free return which means that, as the vehicle passes behind the moon, the lunar gravitation will deflect the trajectory back toward the earth into a safe entry corridor.

If the velocity at translunar injection is slightly below that required for a free-return trajectory, the moon will deflect the trajectory too much and, without a midcourse correction, the vehicle would return to a perigee altitude well above the atmosphere and thus there would be no entry. This situation is illustrated by the slow trajectory in figure 1.

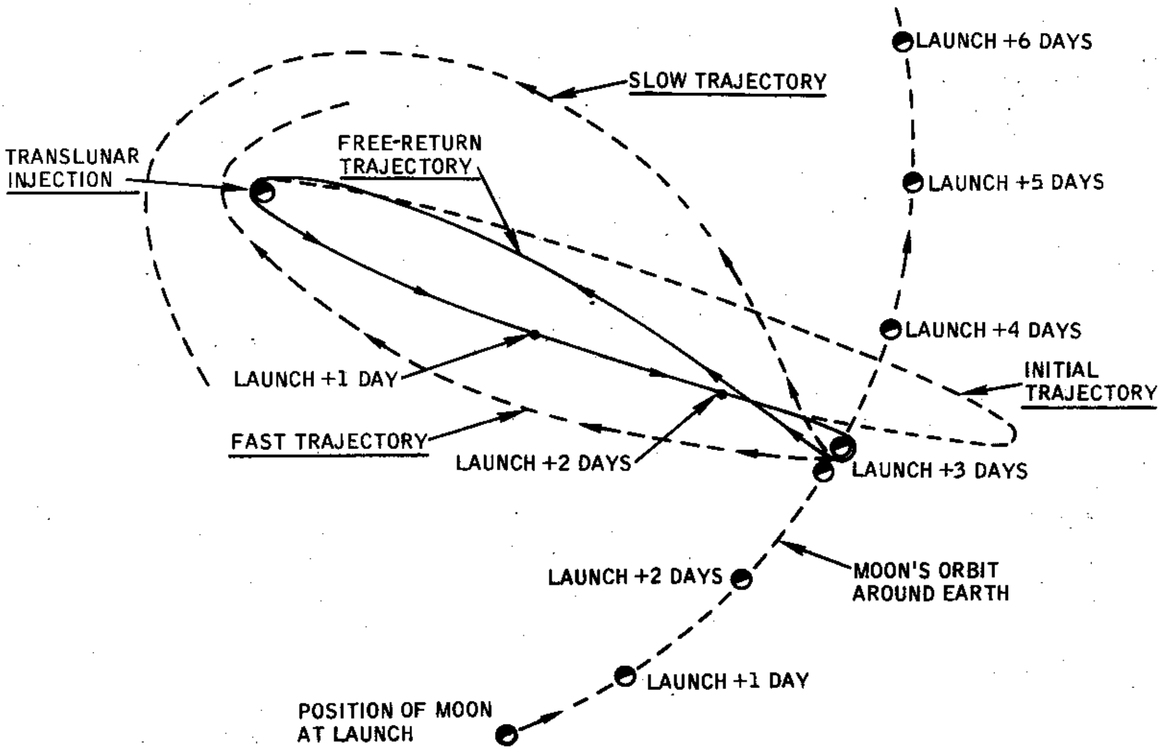
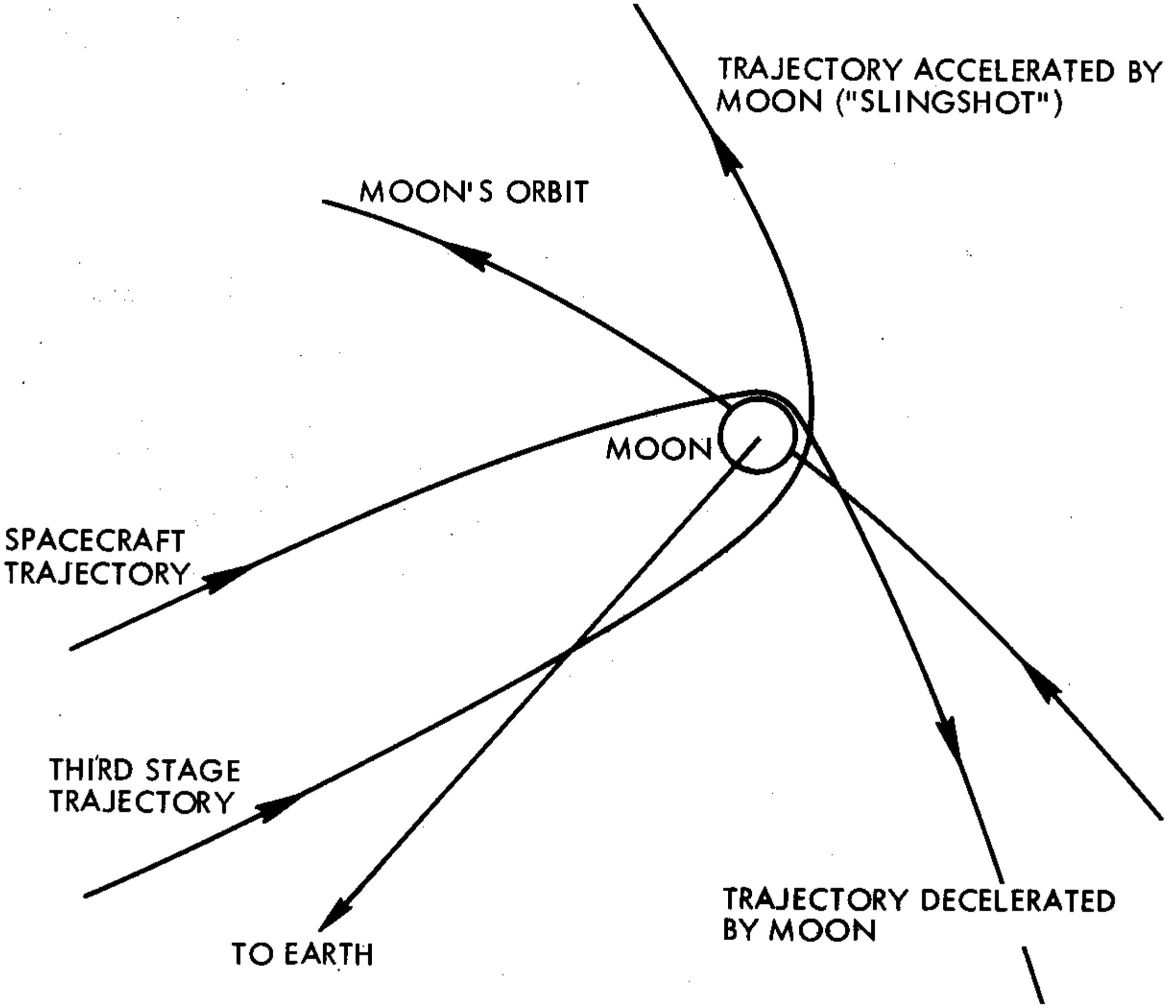


Figure 1.- Geometry of a free-return trajectory.

If the velocity at translunar injection is greater than the velocity required for a free-return trajectory, the spacecraft would not be deflected enough by the moon and would approach the earth from the opposite side, similar to the fast trajectory shown in figure 1. The precision at translunar injection required to accomplish the return to earth within the 20-mile limit required for safe capture is staggering. Because this precision far exceeds what can be expected from the launch vehicle, a number of small midcourse maneuvers are planned to correct the errors.

If the velocity at translunar injection were very much slower than the velocity required for a free-return trajectory, the spacecraft would pass around the trailing edge of the moon as opposed to the leading edge as illustrated by the third stage (S-IVB) trajectory in figure 2. Inertially, the S-IVB stage is slower than the CSM and, therefore, arrives at the moon later; thus, the moon has had time to get ahead of the approach path. Instead of being deflected back toward the earth as is the spacecraft trajectory, the trajectory of the S-IVB is deflected away from the earth in the direction of the moon's motion. This deflection will accelerate the S-IVB to an escape trajectory with respect to the earth and will place it in a solar orbit. The process of slowing the S-IVB after spacecraft separation is accomplished by venting the residual propellant out of the fuel tanks and is called an S-IVB blow-down.



LAUNCH WINDOW CONSIDERATIONS

There are a number of considerations which determine the unique time period called the launch window from which the lunar mission is flown. These considerations are as follows.

a. Daylight launch from Kennedy Space Center

b. Launch azimuth (direction) from Kennedy Space Center restricted from 72° to 108° from north

c. Translunar injection to occur over the Pacific Ocean (as opposed to the Atlantic Ocean)

d. Low sun elevation angles at the lunar landing site

e. Goldstone, California radar coverage of the lunar landing phase

f. Daylight earth landing in the prime recovery area

The time of lunar landing is almost uniquely determined by the location of the lunar landing site and by the acceptable sun elevation-angle range. Low sun elevation angles from 5° to 14° are required to create visible shadows of the craters to aid the crew in viewing the lunar terrain (fig. 3).

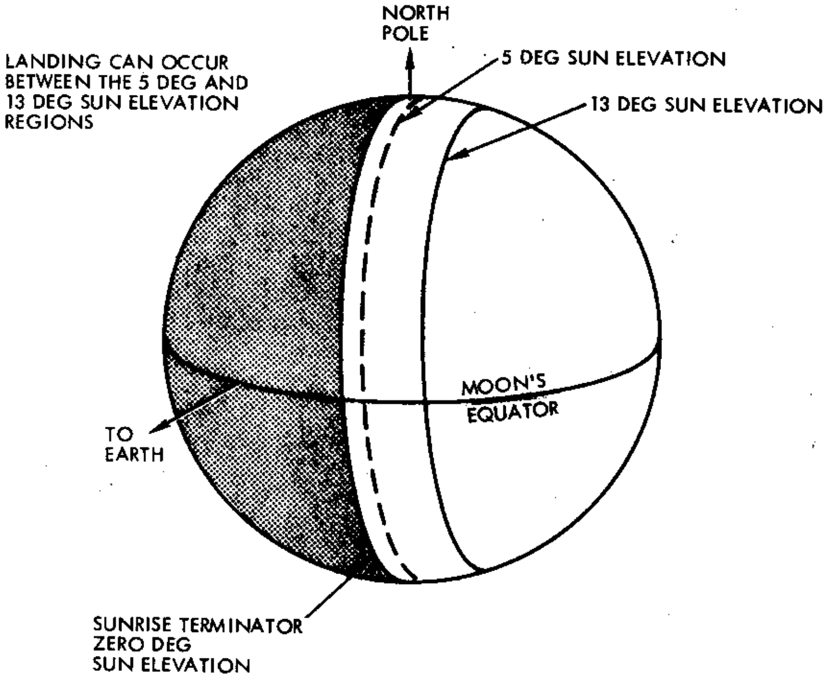


Figure 3. Sun elevation angle for lunar landing.

This lighting is equivalent to an early morning sunrise at the landing site. Because lunar sunlight incidence changes 0.5° per hour (as opposed to 15° per hour on the earth), the above elevation angle restriction establishes a 16-hour period which recurs approximately every 29.5 days, when the landing should be attempted. A backwards calculation of the total amount of time required for launch from earth, for flight to the moon, and for preparation for landing will establish the earth day of launch.

Because there are several candidate landing sites, there are several days of launch opportunity available. The most easterly landing site, where the proper lighting conditions will occur first, is assigned to the first opportunity. If, for some reason, the mission is not flown at this opportunity, a site further west will be selected for a later day. With the five candidate lunar landing sites illustrated in figure 4, an 8-day period of launch opportunity is established. An opportunity does not occur every day, but within the 8-day period, five launch opportunities will occur, one for each candidate landing site.

When the landing site and appropriate day of launch have been selected, it is necessary to determine the time of launch. The two major considerations involved are the acceptable launch azimuth (direction) range from the Kennedy Space Center and the location of the moon at spacecraft arrival. The geometry of the launch window as seen by an observer in space is presented in figure 5. The north pole, the equator, and the Kennedy Space Center latitude are included in the drawing. Because the earth rotates about the north pole one revolution each day (15° per hour), the launch site would rotate in the minor circle (labled KSC latitude) at the same rate. Also illustrated on the figure is the orbital plane of the moon about the earth, the expected location of the moon at spacecraft arrival, and the lunar antipode (the opposite direction of the moon). As viewed from inertial space, the moon moves relatively slowly about the earth (one revolution every 27.32 days or approximately 0.5° per hour). It is necessary for the spacecraft to be launched into an orbital plane that contains the position of the moon and its antipode at spacecraft arrival. Because the direction of launch is restricted[a] from 72° to 108° east of north, launch can occur only when the direction of launch is within the required range to intercept the moon. The 72° launch azimuth is always the first opportunity; and as the launch site rotates to the east, the launch direction moves from northeast to east and to southeast until the 108° launch azimuth restriction is encountered The 36° band of launch azimuth allows approximately a 4-hour, 30-minute period of launch opportunity. This period is called the daily launch window.

---

[a] This restriction is made primarily for crew safety and spacecraft to ground communication reasons.

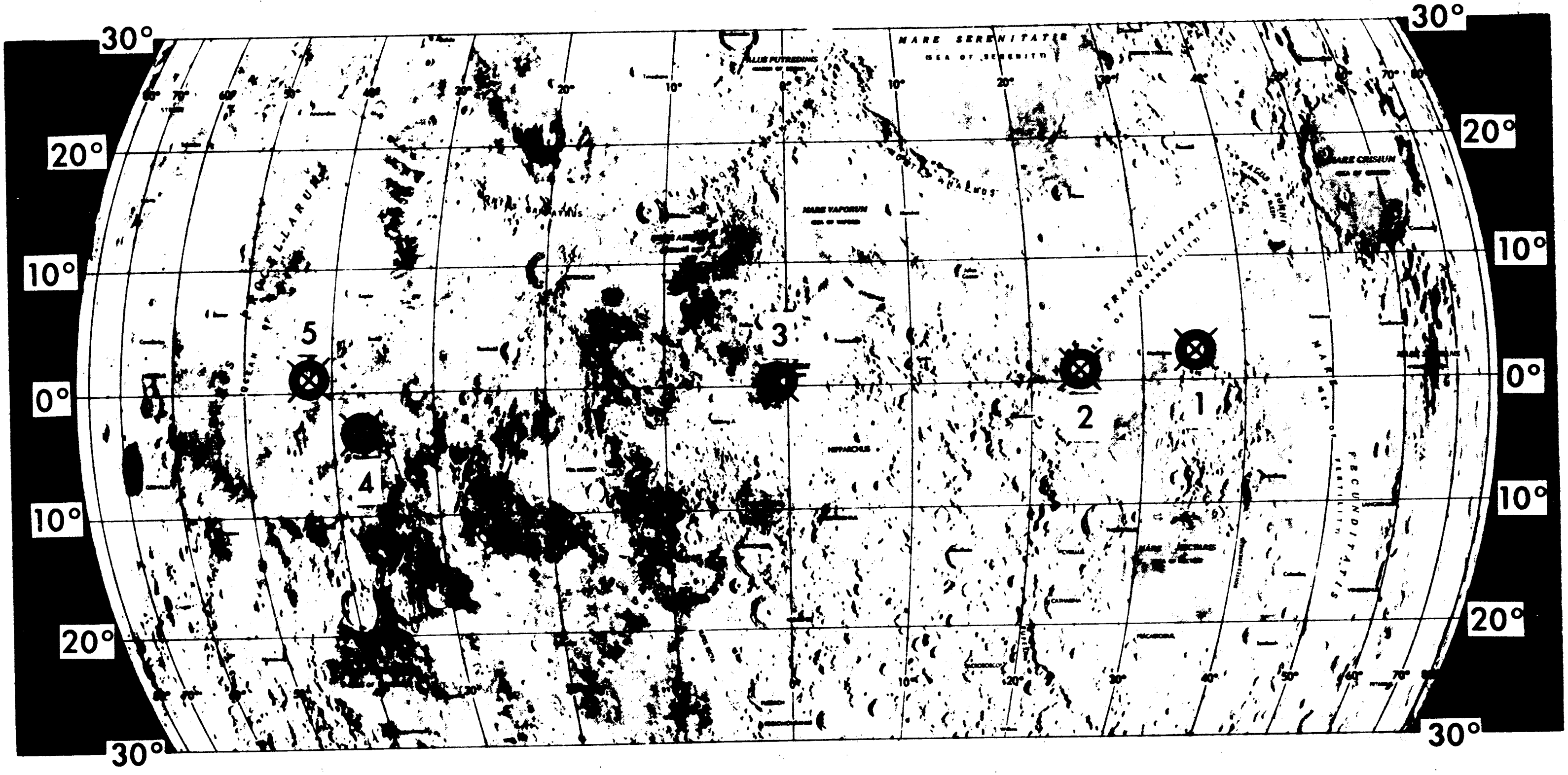


Figure 4.- Apollo candidate lunar landing sites.

also indicated in this figure. With a far eastern lunar landing site, earth landing occurs in the early morning before sunrise (this was the case with the Apollo 8 mission); while for a near central site, earth landing occurs in the morning. Finally, for lunar landing sites to the west, afternoon earth landings can be expected.

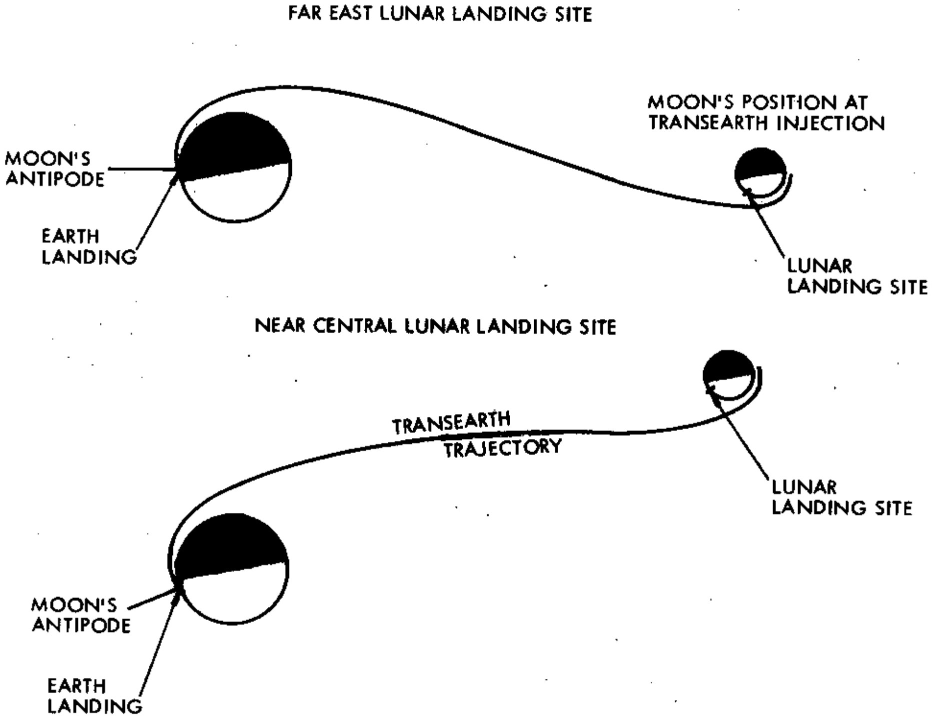


Figure 6. Daylight at earth landing.

SPECIFIC APOLLO 11 LAUNCH WINDOW DESIGN CONSIDERATIONS

The primary mission design ground rules which dictated the Apollo 11 launch window are shown in figure 7. Note that for the monthly window considerations, even though the five landing sites shown in figure 4 were available to provide four different launch days, the Apollo 11 requirement was for only 3 launch days or three landing sites per month chosen from the five available sites. Site 1 was eliminated from consideration because of undesirable terrain and the resultant night landing upon earth return. This latter decision was actually made prior to Apollo 11 so that the Apollo 10 mission would be compatible with Apollo 11.

Sites 2 and 3 were retained but an either/or option remained for sites 4 and 5 to be decided by launch window trajectory scans. These scans showed site 5 to be superior to site 4 from an SPS performance standpoint; therefore, site 4 was eliminated and site 5 retained. Thus, the final three sites selected for the Apollo 11 launch window were Apollo sites 2, 3, and 5.

The preferred lighting at lunar landing for Apollo 11 was low 5° to 14°, as mentioned in the general considerations. This requirement resulted in an allowable lunar arrival time period of ≈18 hours during the month for each of the three sites.

The fourth Apollo 11 design guideline listed in figure 7 was to constrain the translunar trajectory such that if the SPS were to fail for LOI ignition, the trajectory could be corrected to an earth return with a backup propulsion system either the SM RCS or the LM DPS. The preferred type of trajectory to satisfy this constraint was the free-return as shown in figure 8. This trajectory is so near a safe return to earth that it is easily correctable with only the SM RCS.

However, if it were necessary to satisfy the other guidelines, a hybrid profile could have been used as shown in figure 9. This type of profile consists of translunar injection onto a high-altitude perilune free-return trajectory followed by a midcourse correction onto a nonfree-return trajectory with a 60-n. mi. perilune altitude. The nonfree-return trajectory for Apollo 11 was constrained such that it could be corrected to a safe earth return with the LM DPS if the SPS failed at LOI ignition.

The daylight earth landing guideline was satisfied by deletion of far eastern sites as possible lunar landing sites, as mentioned earlier.

(a) Monthly

- 3 LAUNCH DAYS PER MONTH WITH AT LEAST 44 HR SPACING
- USE 3 OUT OF THE 5 CANDIDATE LUNAR LANDING SITES
- DESIRED LUNAR LIGHTING
    - 5° TO 14° AT LANDING
- TRANSLUNAR TRAJECTORY CORRECTABLE TO AN EARTH RETURN WITHOUT SPS
- DAYLIGHT EARTH LANDING

(b) Daily

- 72° TO 106° LAUNCH AZIMUTH
- PACIFIC INJECTION
- DAYLIGHT LAUNCH
- GOLDSTONE 210 FT COVERAGE OF LUNAR LANDING

Figure 7.- Apollo 11 launch window operational guidelines.

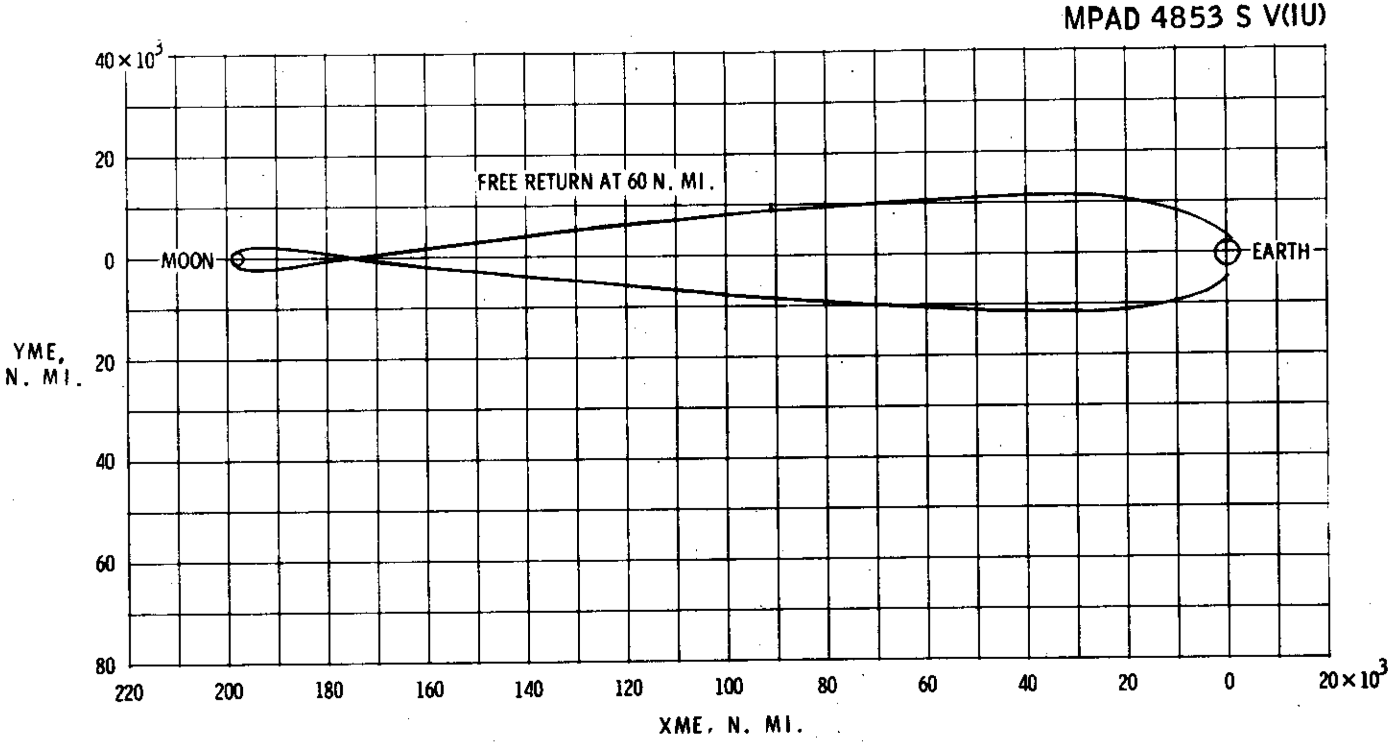
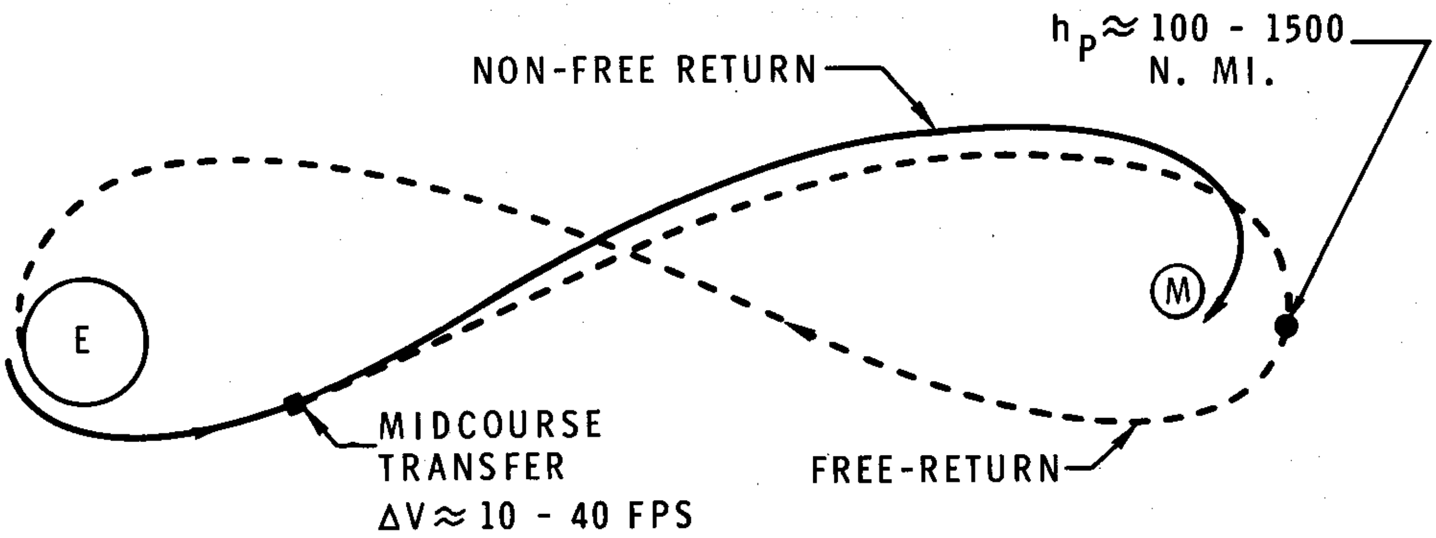


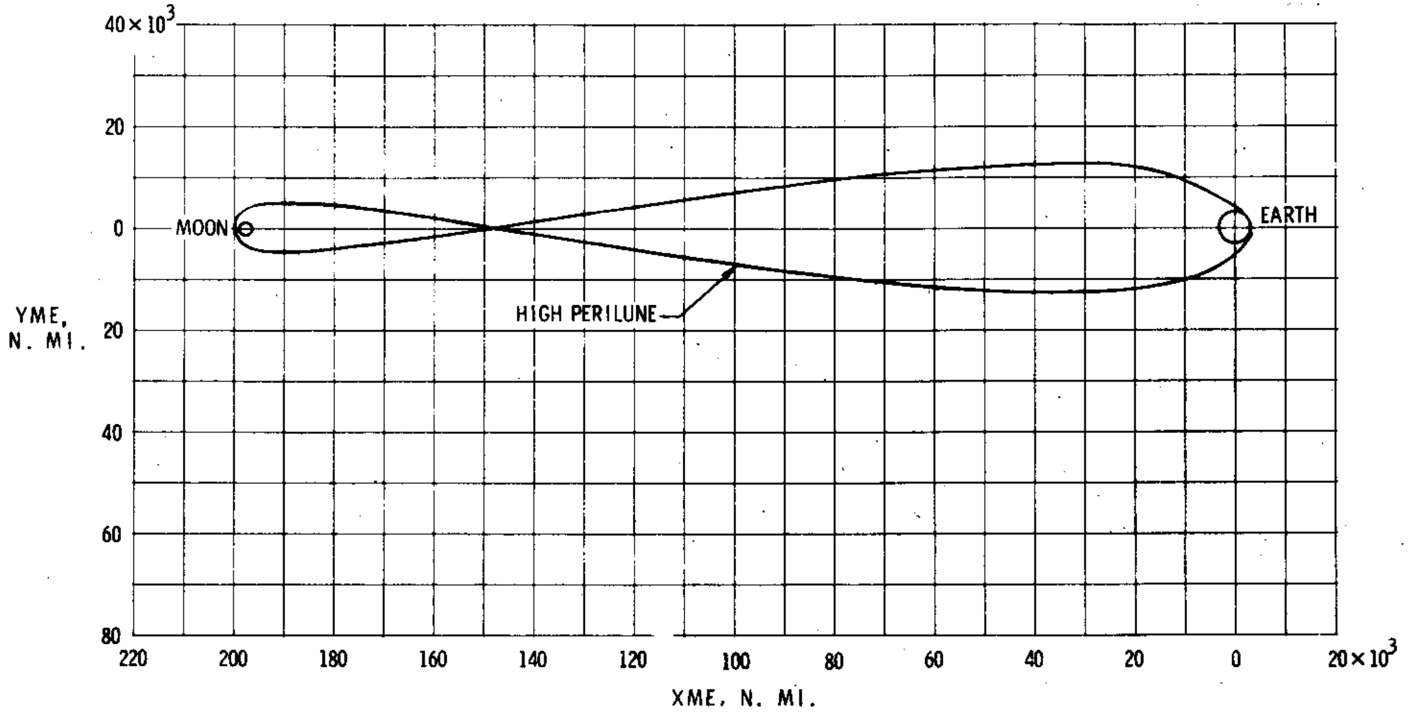
Figure 8.- Standard free-return profile.

MPAD 4803 S (IU)



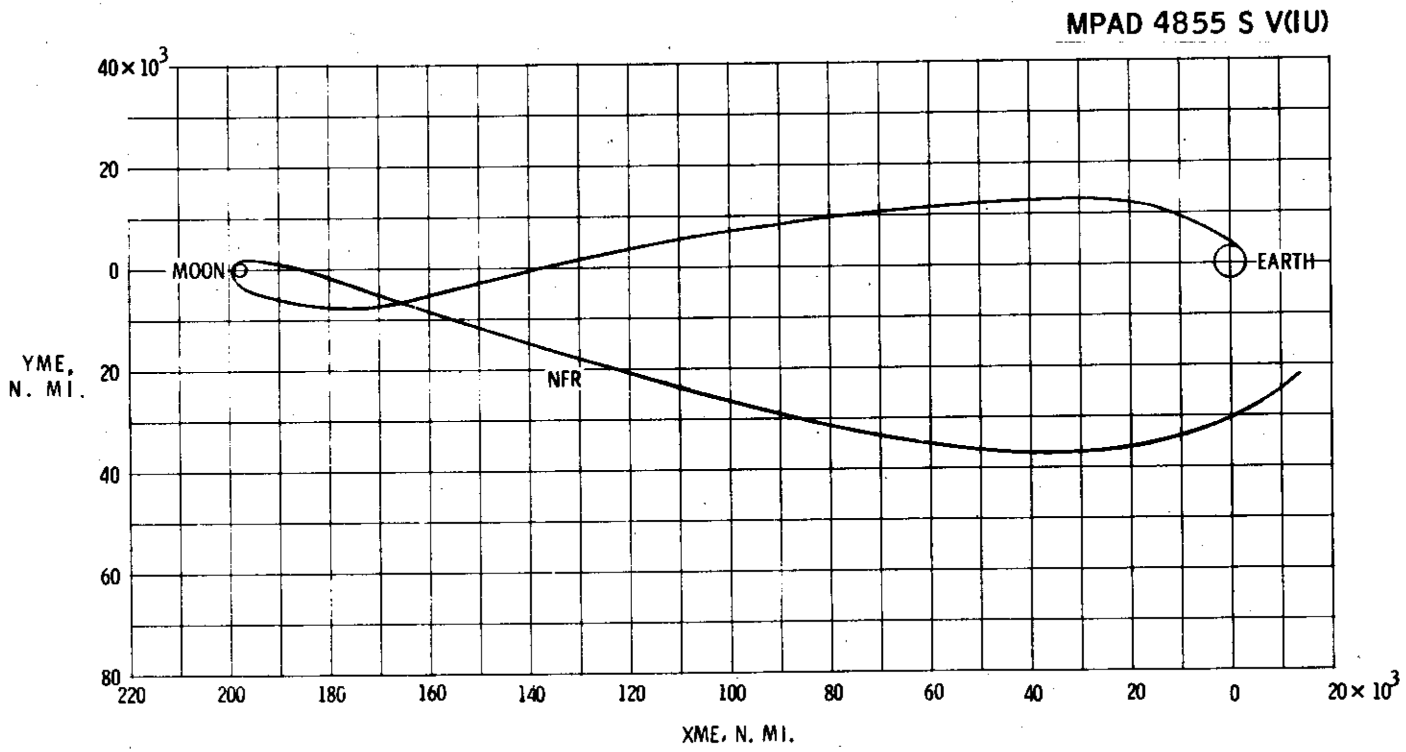
(a) Complete profile.

Figure 9.- Hybrid lunar profile.



(b) High-altitude perilune free-return profile of hybrid.

Figure 9.- Continued.



(c) Non-free-return profile.

Figure 9.- Concluded.

The guidelines used to establish the daily launch window are also listed in figure 7. The available launch azimuth spread was limited to 106° for Apollo 11 because of constraints on range safety from pad 39A.

The requests for a Pacific injection and a daylight launch coincided and were compatible for the Apollo 11 launch months and, therefore, presented no problem.

A new guideline that resulted from the Apollo 10 communications problems during the LM low-altitude pass was that the Goldstone 210-foot antenna should track during the lunar landing maneuver (PDI to landing). This 210-foot dish was to provide communications backup if a loss of high-gain occurred. This new Goldstone requirement which was added late, was found to be incompatible with the originally defined launch window. The launch window and trajectory changes caused by this late requirement are discussed in the following section.

RESULTANT APOLLO 11 LAUNCH WINDOW

In the following table are shown the significant data for the originally defined Apollo 11 launch window for the 3-month period from July through September 1969. Note that the free-return profile could only be used for the first two launch days in July; all other launch days were required to use the hybrid profile to satisfy the lunar lighting requirement. The corresponding TLI ignition loci for the July launch window are shown in figure 10.

As mentioned in the previous section, this launch window was not compatible with the new Goldstone 210-foot dish requirement. Data in figure 11 summarize this incompatibility and the changes to the launch window which remedied the situation. For the first launch day in July (July 16), the only change required was to add one additional rev in lunar orbit between LOI and DOI. However, for the other two launch days, a combination of a daily launch window slip coupled with a nonoptimum midcourse maneuver to slow down the trajectory was required besides the one additional rev. The change in the lunar lighting caused by these launch window changes is shown in figure 12. A bar chart is presented in figure 13 to show the altered launch window for July.

In figure 14, a schmatic is presented of the nominal Apollo 11 mission; that is, the mission which would be flown if lift-off occurred at the beginning of the launch window on July 16, with a 72° launch azimuth at the first injection opportunity. As it turned out, the nominal mission was the one that was flown; that is, lift-off was on time.

APOLLO 11 LAUNCH WINDOW CONFIGURATION[a]

Date	Parameter	Relative launch day						
		1	2	3	4	5	6	7
July 16-21	Launch date	16		18			21	
	Daily launch time, e.d.t (72°-108°)	9:32-13:54		9:38-14:02			10:09-14:39	
	Site/profile	2/fr		3/fr			5/hyb	
	Lunar ltg, deg (72°-1 to 108°-2)	9.9-12.6		8.3-11.0			6.3-9.0	
	Lunar approach azimuth, deg	-91.0		-89.0			-86.0	
	Lunar orbit inclination, deg	1.2		1.1			4.4	
	Total mission time, day:hr	8:3		8:5			8:8	
	Nominal SPS ΔV reserves, fps (72°-1)	1700		1550			1750	
	Contingency SPS ΔV reserves, fps (72°-1)	1000		950			1100	
Aug 14-20	Launch date	14		16				20
	Daily launch time, e.d.t (72°-108°)	7:51-12:15		8:04-12:31				10:05-14:47
	Site/profile	2/hyb		3/hyb				5/hyb
	Lunar ltg, deg (72°-1 to 108°-2)	6.2-8.9		6.2-8.9				9.0-12.0
	Lunar approach azimuth, deg	-91.0		-89.0				086.0
	Lunar orbit inclination, deg	1.2		1.1				4.4
	Total mission time, day:hr	8:5		8:7				8:8
	Nominal SPS ΔV reserves, fps (72°-1)	1600		1750				1300
	Contingency SPS ΔV reserves, fps (72°-1)	1300		1350				500
Sept 13-18	Launch date	13		15			18	
	Daily launch time, e.d.t (72°-108°)	6:17-10:45		7:04-11:39			11:31-16:14	
	Site/profile	2/hyb		3/hyb			5/hyb	
	Lunar ltg, deg (72°-1 to 108°-2)	6.8-9.6		6.3-9.2			6.8-9.7	
	Lunar approach azimuth, deg	-91.0		-89.0			-78.0	
	Lunar orbit inclination, deg	1.2		1.1			12.1	
	Total mission time, day:hr	8:7		8:8			8:6	
	Nominal SPS ΔV reserves, fps (72°-1)	1600		1500			1050	
	Contingency SPS ΔV reserves, fps (72°-1)	900		800			500	

---

[a] Data shown are approximate.

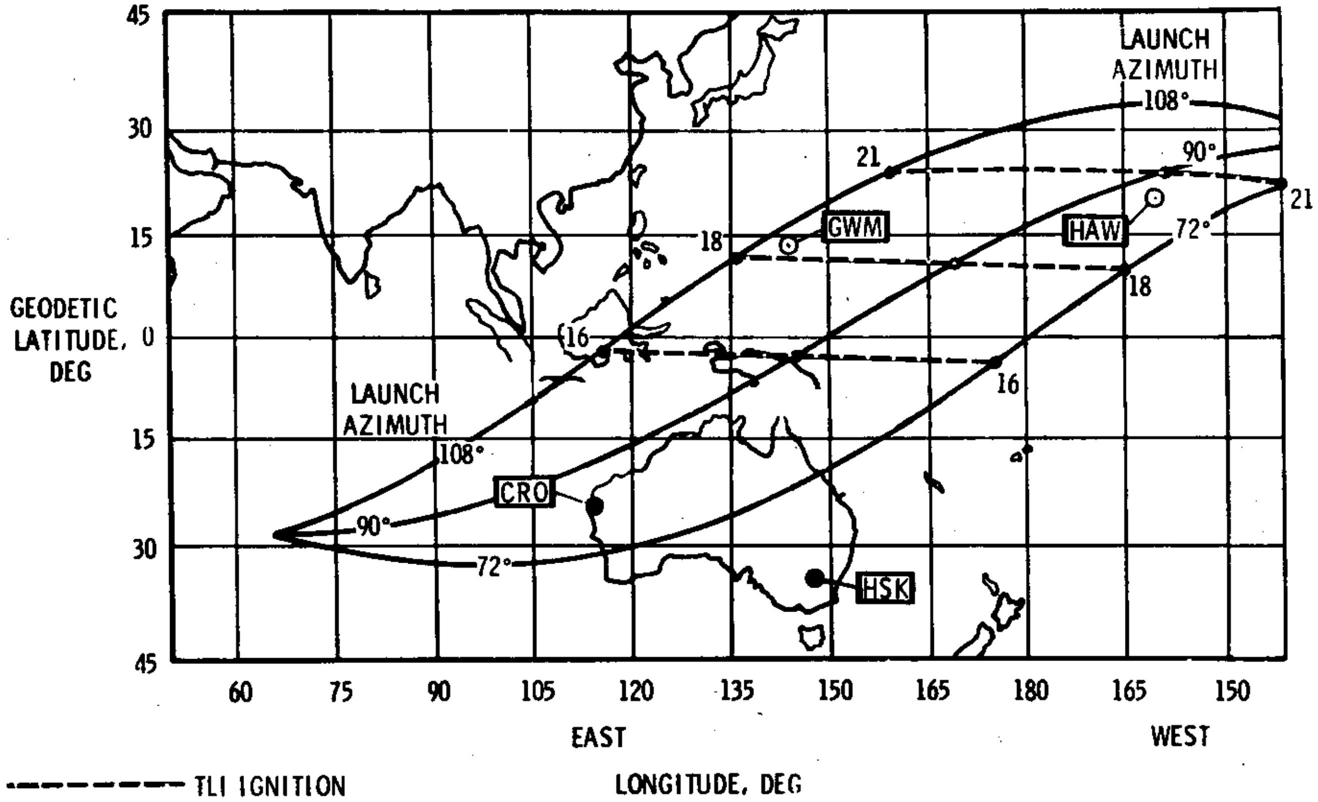


Figure 10.- Translunar injection positions.

MPAD 5435 S (IU)

	JULY		
	16	18	21
DELAY REQUIRED WITH CURRENT TIMELINE, HR:MIN	1:05	5:20	5:30
DELAY REQUIRED WITH ONE EXTRA LPO REV, HR:MIN	0	3:20	3:30
TLMCC ΔV REQUIRED WITH 2 1/2 HR LAUNCH WINDOW AND ONE EXTRA REV, FPS		TLI + 9^h 90 TLI + 24^h 130	TLI + 9^h 100 TLI + 24^h 140
LAUNCH AZIMUTH RANGE FOR 2 1/2 HR WINDOW, DEG	72 108	89 108	94 108

Figure 11.- Launch window effect for 210-foot PDI coverage.

	JULY			AUGUST			SEPTEMBER		
	16	18	21	14	16	20	13	15	18
LIGHTING RANGE WITH CURRENT PROFILE, DEG	9.8 ↕ 12.6	8.3 ↕ 11.0	6.3 ↕ 9.0	6.1 ↕ 8.9	6.1 ↕ 8.9	8.3 ↕ 11.3	6.7 ↕ 9.4	6.3 ↕ 9.1	6.7 ↕ 9.6
LIGHTING RANGE WITH ADJUSTMENT FOR 210 FT COVERAGE, DEG	10.8 ↕ 13.6	11.0 ↕ 12.0	9.0 ↕ 10.0	—	—	—	TO BE DETERMINED		

Figure 12.- Effect on lighting at lunar landing.

MPAD 5589 S (IU)

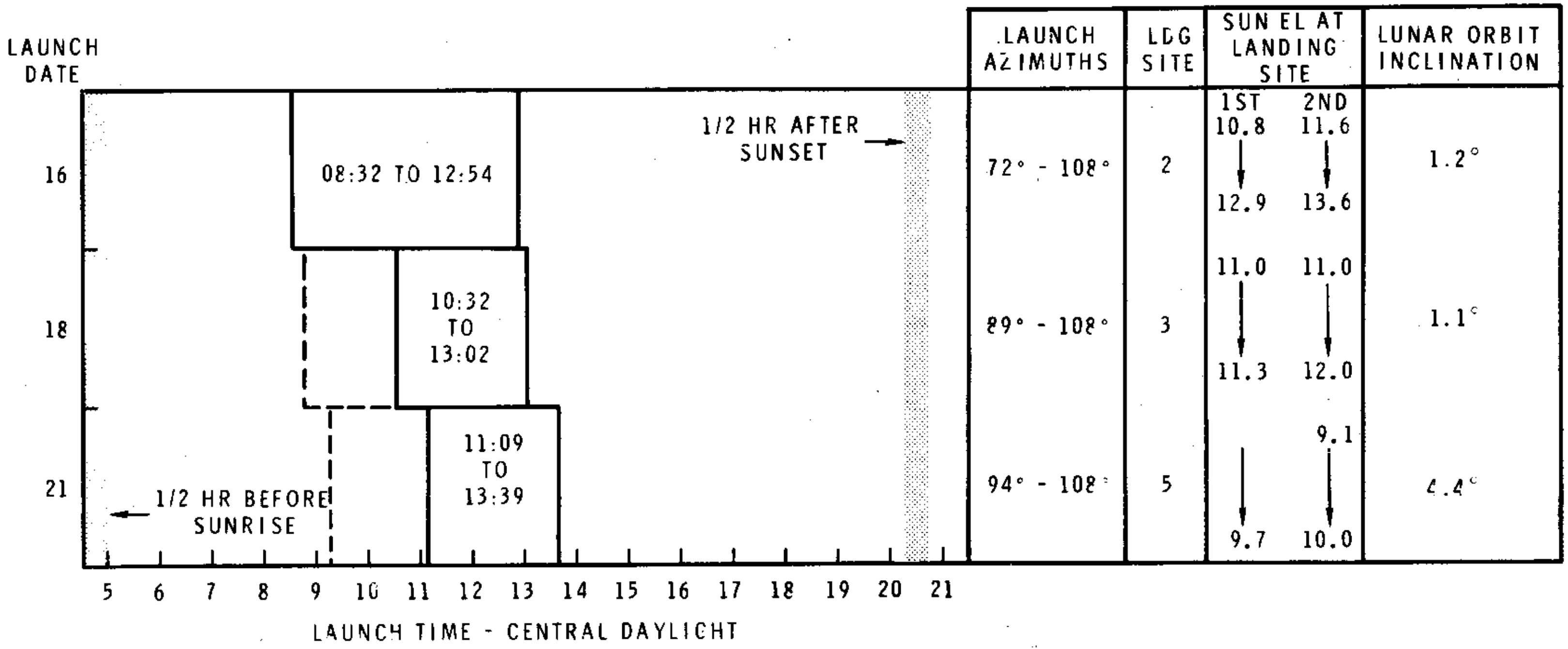


Figure 13.- July launch window configuration.

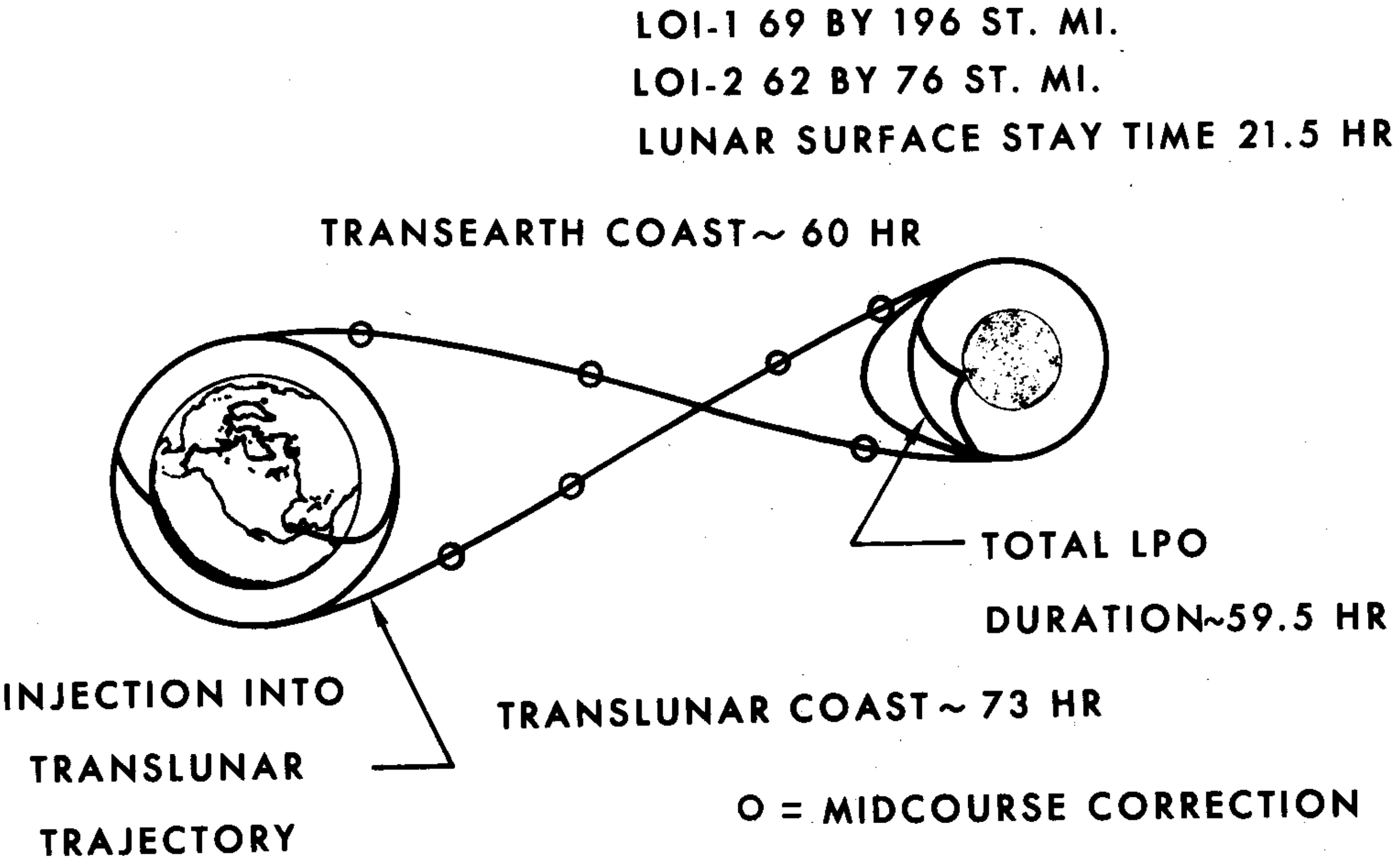


Figure 14.- Mission profile.

REAL-TIME TARGETING

General functional flow charts of the RTCC lunar mission targeting processors developed by LMAB personnel are shown in figures 15, 16, and 17.

The translunar midcourse, the lunar orbit insertion, and the return to earth targeting processors are given in the three figures. A summary of the actual real-time targeting and the results for Apollo 11 are also included. Because translunar injection was targeted jointly with MSFC, a discussion of that manuver is also presented.

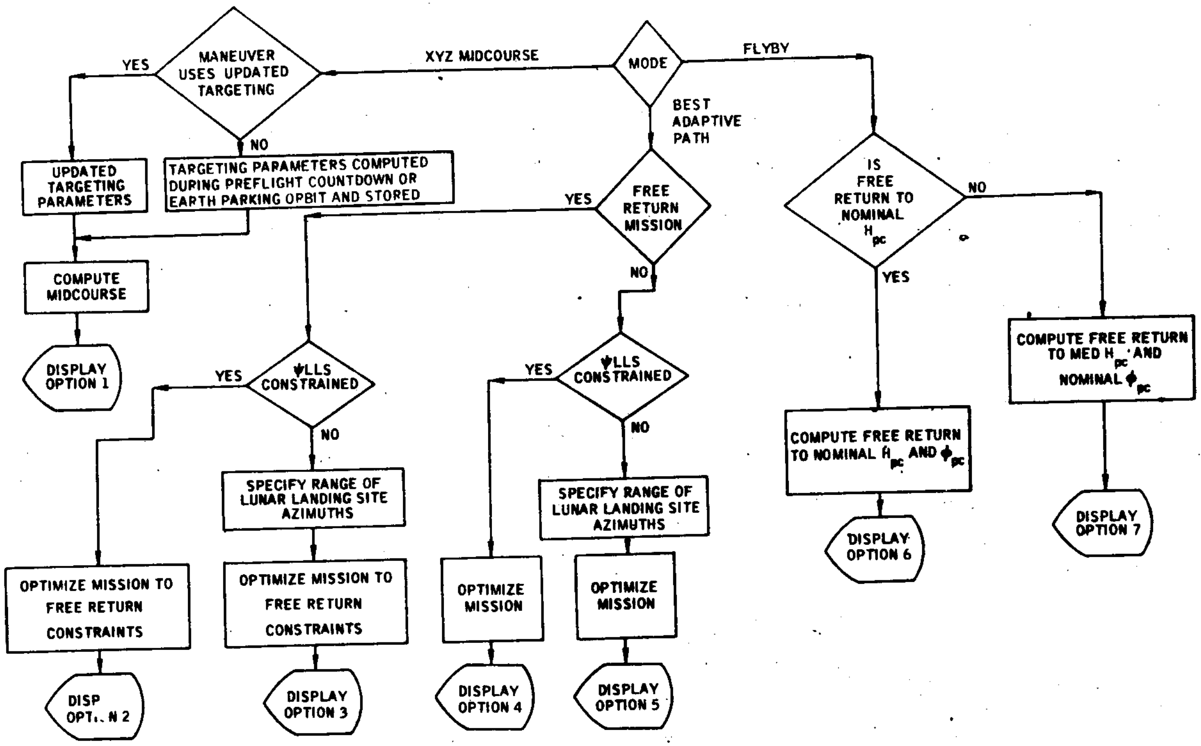


Figure 15.- RTCC translunar midcourse processor.

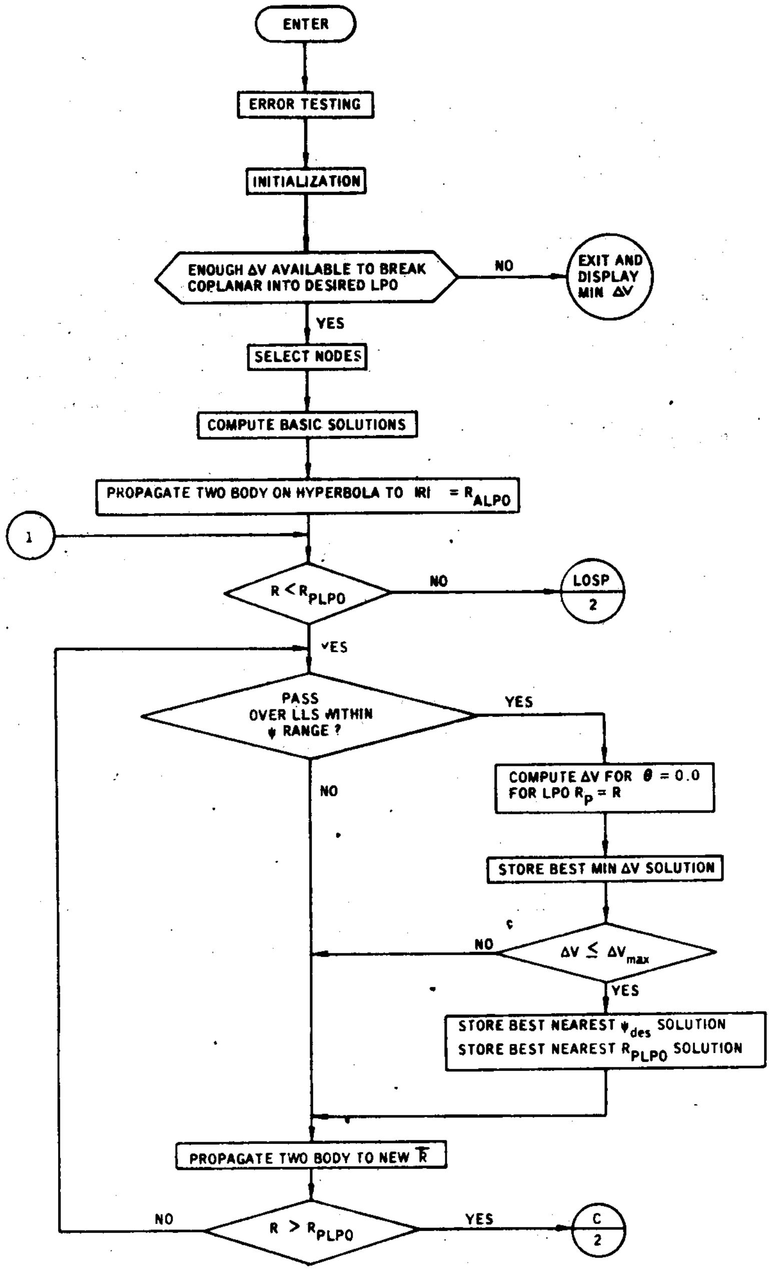


Figure 16.- RTCC lunar orbit insertion processor.

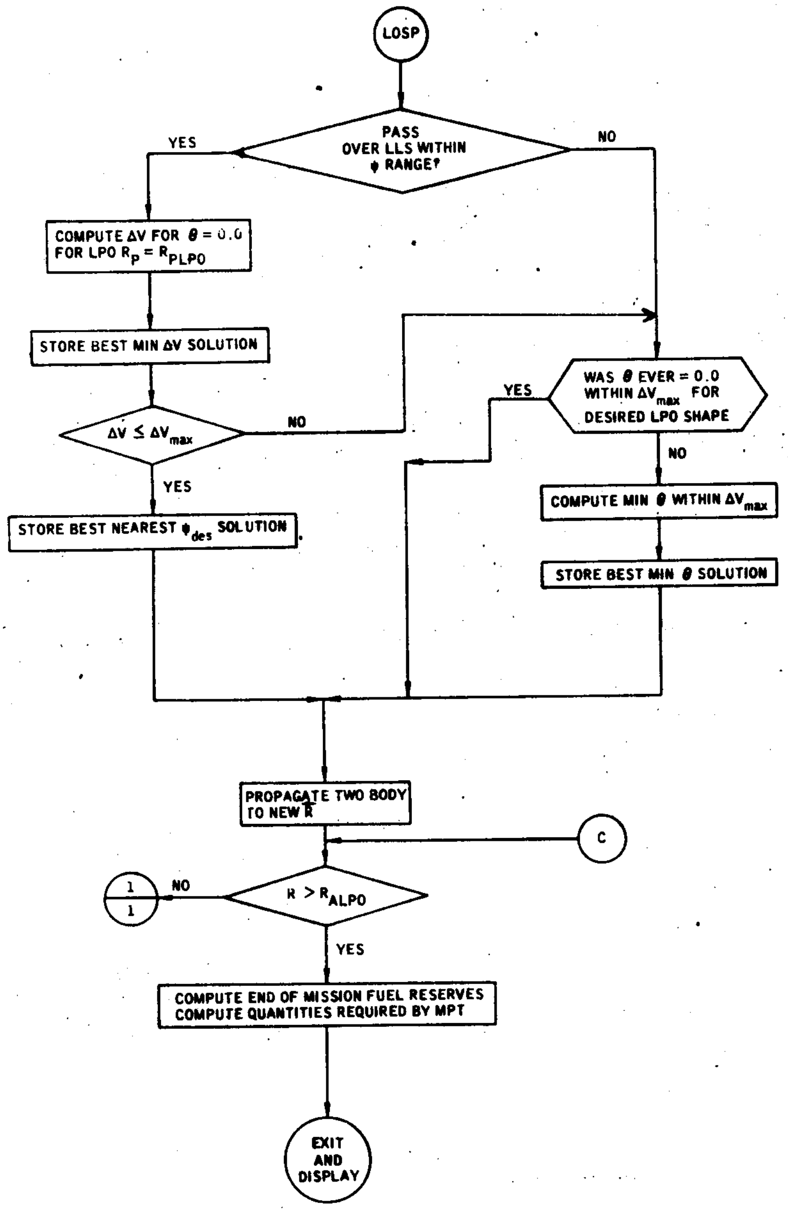


Figure 16.- Concluded.

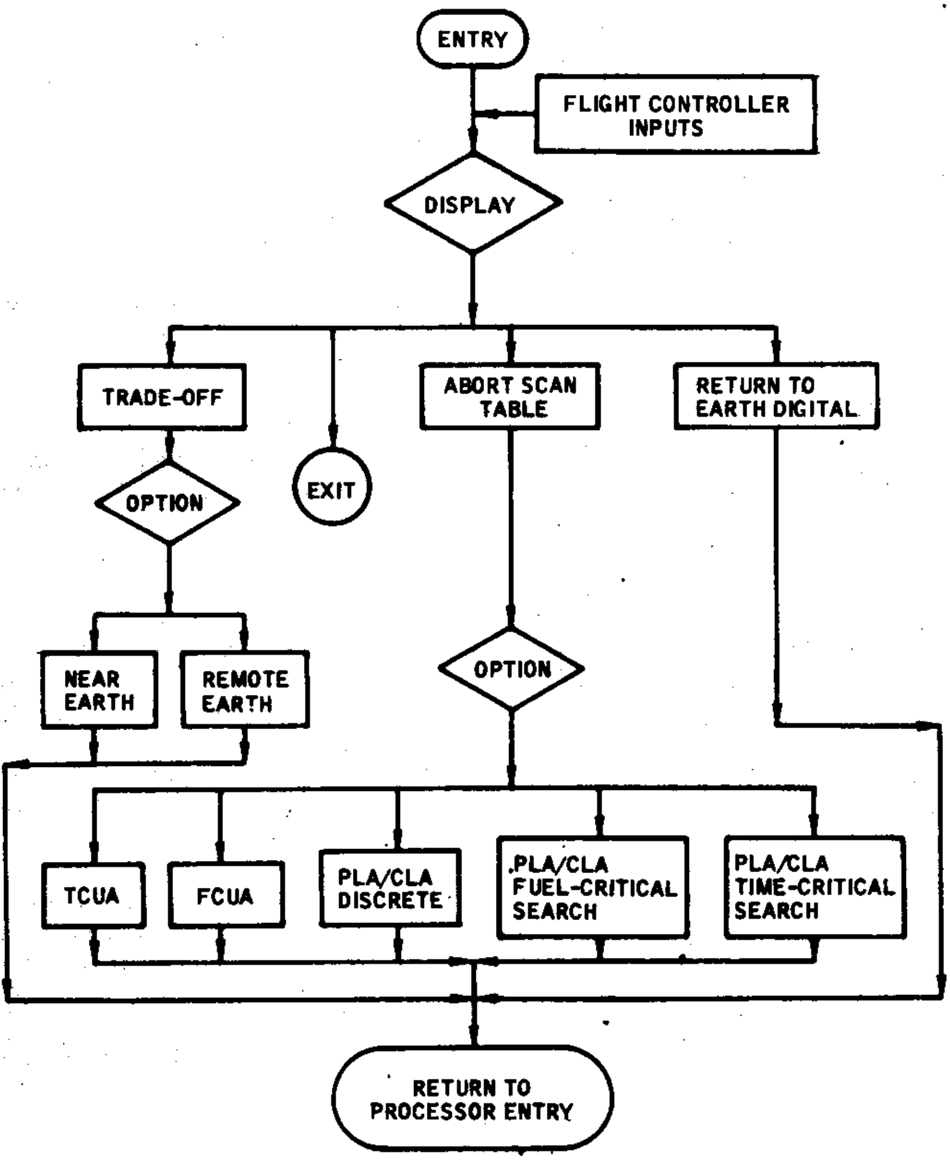


Figure 17.- Return to earth abort processor displays and display options.

TRANSLUNAR COAST

Translunar Injection

Although postflight analysis of TLI is primarily the responsibility of MSFC, some of the data generated from the SC best estimate of trajectory (BET) should be noted. Perilune altitude after TLI was 896.3 n. mi., based on the SC BET. This value compares with the perilune altitude of 718.9 n. mi. based on the nominal operational trajectory. This miss in the nominal perilune altitude is representative of approximately 1.6 fps accuracy in the maneuver, based on the sensitivities in the given reference.

Free-return conditions after TLI indicated a definite capture of the spacecraft with a flight-path angle at the entry interface of -64.06°.

Shortly after TLI, MCC-1 was computed with the LV IU vector and assuming a nominal evasive maneuver. At TLI plus 9 hours, the midcourse ΔV was 20.1 fps as compared to a preflight nominal value of 0.0 fps.

SC Ejection and Evasive Maneuver

The effect of SC ejection was fairly small; perilune altitude was changed from 896.3 n. mi. to 827.2 n. mi. If a nominal evasive maneuver had been performed on the postejection trajectory, resultant perilune altitude would have been 167.7 n. mi. The BET indicates that the postevasive trajectory actually yielded a perilune altitude of 180.8 n. mi. This value represents an error of approximately 0.24 fps in the most critical direction during the evasive maneuver.

The effective error in the evasive maneuver compensates for a portion of the error in TLI so that the predicted MCC-1 ΔV was reduced from the pre-evasive estimate. After the evasive maneuver, the required MCC-1 ΔV at TLI plus 9 hours was 17.1 fps which increased to only 21.2 fps at MCC-2 (TLI plus 24 hr). Because of the small cost in delaying the midcourse, it was decided to perform the maneuver at TLI plus 24 hours.

Midcourse Correction

The only necessary translunar midcourse correction was executed approximately 24 hours after TLI. The BET indicates a perilune altitude of 61.5 n. mi. after maneuver.

Two midcourse ΔV's were computed at MCC-2 cutoff time for this analysis to estimate the accuracy of the maneuver. The required ΔV for the best adaptive path (BAP) targeted midcourse was 0.48 fps. However, to correct only the altitude error at perilune would have required 0.08 fps.

Also, note that the free-return conditions after the maneuver indicate a flight-path angle at entry of -10.25°. It would have taken a very small ΔV (<1 fps) anywhere along translunar coast to return this to the center of the corridor.

Other Midcourses

Two other opportunities existed for midcourse corrections on translunar coast: a possible MCC-3 at LOI minus 22 hours and a possible MCC-4 at LOI minus 5 hours. Neither maneuver was performed for the following reasons. The predicted midcourse ΔV for an S, Y, Z, T targeted MCC-3 was computed to be 1.14 fps. If MCC-3 were not performed, a midcourse ΔV of only 5.83 fps (X, Y, Z, T targets) would be required at the last possible midcourse time, LOI minus 5 hours. Also, if only perilune altitude was desired to be controlled at the last midcourse point (MCC-4), only a 0.4-fps maneuver would have been needed. On the basis of this rather low ΔV for MCC-4 and the fact that LOI-1 targeting could easily control the error in perilune altitude, it was decided to scrub MCC-3 and MCC-4.

The BET indicates a perilune altitude of 60.5 n. mi. at 5 hours prior to LOI-1.

Lunar Orbit Insertion

LOI targeting remains fairly constant for the two state vectors considered from the BET; the states are at MCC-2 cutoff and at planned MCC-3 (LOI minus 22 hr). The final RTCC display also yielded very nearly the same targeting resutls as the BET did. Total ΔV planned for LOI-1 was approximately 2905 fps from the RTCC and 2906 fps from the BET. Altitude at the node was 63.1 n. mi. from the BET as opposed to 62 (±0.5) n. mi. generated in real time. The effect of the mismatch is a 2.5° rotation in the line of apsides of the target ellipse (12° real time compared to 14.5° from the BET).

Because of the observed lunar orbit perturbations in Apollo 10 which resulted in an error in passing over the desired lunar landing site, it was decided on Apollo 11 to bias the desired landing site by $\Delta\phi$ and $\Delta\Psi$ to minimize the error that results from these perturbations.

Targeting LOI-1 from GWMX 365 gave a $\Delta\phi$ and $\Delta\Psi$ from the biased landing site of 0.0033° and 0.0061°, respectively. These values relate to an out-of-plane angle (δ_{op}) from the desired LLS of 0.38°. An update to ACNX 374 (frozen LOI-1) gave $\delta_{op} = 0.41°$. An update to ANGX 389 and confirmation of the maneuver gave a δ_{op} of 0.52°. With ANGX 389, $\Delta\phi$ at the LLS (from biased value) was 0.1419° and $\Delta\Psi$ was 0.0178°.

The perilune altitude of the lunar parking orbit was determined real time (final value 61.0 n. mi.) to insure intersection of the desired LOI-2 lunar parking orbit with 3σ dispersions and to minimize the ΔV required for LOI-2. If the BET vector had been used to target LOI-1, a 61.4-n. mi. h_pLPO would have been recommended instead of the 61.0-n. mi. h_pLPO used. This technique would have prevented an increase in the LOI-2 ΔV needed.

The ability to perform a DPS return-to-earth maneuver from the initial LPO was verified. The DPS ΔV capability was computed to be 120 fps more than was actually needed. The SPS ΔV remaining after TEI was computed to be slightly greater than 1700 fps. Pitch drift monitoring studies made during translunar coast prior to LOI-1 showed that the minimum perilune altitude constraint would not be violated for LOI-1.

The LOI-1 cutoff state from the BET indicates a near nominal LOI-1 maneuver. The resultant LPO from the burn was 60.0 by 169.7 n. mi. Inclination and node of the resultant orbital plane were very close to nominal.

TRANSEARTH COAST

Transearth Injection Burn (Targeting)

Targeting for the TEI burn was essentially optimum. Ignition time in the RTCC was 15.79 seconds later than the fuel optimum t_{IG} based upon the BET; the RTCC planned ΔV was 3281 fps as compared to 3280 fps for the BET. The TEI solution based upon the BET vector and computed at the RTCC planned ignition time compares quite favorably to the RTCC solution. The ΔV's for the maneuver match to within 0.3 fps, and the landing points of the two are within 1.2 n. mi. of each other.

The TEI maneuver was not performed as well as the corresponding maneuver on Apollo 10. The BET TEI cutoff vector when propagated to earth by use of the RTCC programs and displays yields no entry interface. Perigee altitude for this vector is 69.4 n. mi. whereas the nominal perigee altitude for this transearth coast is 20.4 n. mi. The perigee altitude predicted in the RTCC from the confirmed TEI maneuver (GDSX 657) was 33.2 n. mi. (γEI = -5.51). The 10-hour (approximate) tracking vector (MADX 684) predicted a perigee altitude of 66.2 n. mi. Projection of MCC-5 back to TEI yields a ΔV error of approximately 2 fps in the TEI maneuver.

Midcourse Correction 5

At MCC-5 time, approximately TEI plus 15 hours, the predicted perigee altitude was 66.0 n. mi. (ANGX 690). The midcourse correction maneuver based upon this vector required a ΔV of 4.8 fps. The BET vector predicted a midcourse of 5.1 fps. Thus, MCC-5 was executed. The confirmed MCC-5 (based upon ANGX 965) resulted in a ΔV of 4.7 fps and a predicted γ_{EI} of -6.46°. The BET MCC-5 cutoff vector predicted a γ_{EI} of -6.46°.

An indication of the accuracy of MCC-5 is the MCC-5 solution based upon the BET MCC-5 cutoff vector. The ΔV for this MCC-5 evaluation maneuver was 0.06 fps.

Midcourse Correction 6

The predicted γ_{EI} at approximately EI minus 23 hours, MCC-6 time, was -6.74° for the BET vector. The RTCC was predicting a γ_{EI} of -6.48° (RIDX 769). The corresponding ΔV's were 0.53 fps and 0.05 fps, respectively. This midcourse was not executed.

Midcourse Correction 7

At EI minus 3 hours, the BET predicted γ_{EI} to equal -6.55° whereas the RTCC (GWMX 845) predicted -6.49°. The BET MCC-7 cost was 0.42 fps, while the RTCC cost was 0.1 fps. This midcourse also was not executed.

Phil Shannahan

Allan L. DuPont

Edward J. Fenyon

Faye Chaviers

Bill Reini

Carol Jordan

Dennis Braley

Bob Becker

THE ORBITAL MISSION
ANALYSIS BRANCH

Alex Woronow

Ted H. Skopinski

Ronny H. Moore

Stephen P. Condon

Lineberry

Dick Carr

Robert S. Merriam

Harold Spencer

William A. Sullivan

Dave Alexander

Jerome A. Bell

Robert N. Hinson

James W. Kirkland

Charles R. Naegeli

Ernest M. Fridge

Cathy Osgood

Larry Hawthorne

Bob (R³) Regelbrugge

Ken Young

THE ORBITAL MISSION ANALYSIS BRANCH

Development of the nominal rendezvous for the lunar landing began early in 1963 with the direct ascent technique. The entire development included ten phases: the first five phases took about a year each to develop; the last five were developed within the year preceding the Apollo 11 mission. The advantages and problems realized at the time of the development of each phase are presented below.

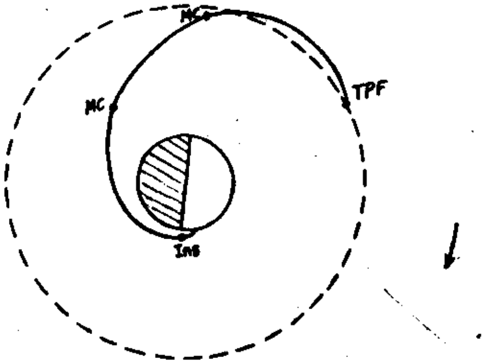
Phase 1 - Direct Ascent

The basic characteristics of the direct ascent phase are as follows.

a. Variable powered ascent; the objective is to insert on intercept trajectory

b. Variable transfer angle (insertion-to-intercept) depending on lift-off time within launch window of approximately 5 minutes duration.

c. Variable-time midcourses (plane change included)



The problems that were realized during the development of this phase of the mission are as follows.

a. Variable final approach angle; involved extremely complex crew monitoring and backup techniques

b. Practically no ground support for rendezvous

Phase 2 - Standard Insertion Parking Orbit with Standard Direct Intercept at Variable Time

There are two basic characteristics of phase 2.

a. Standard powered ascent into 50 000-foot circular parking orbit

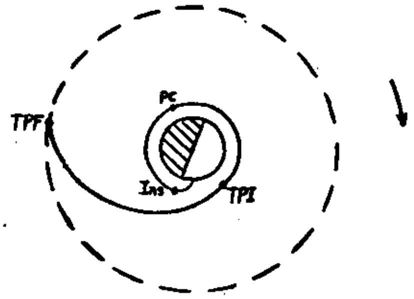
b. Standard direct intercept (approximately 160° terminal phase transfer) initiated at variable time (when required phase angle occurred) as function of lift-off time within launch window

Several new advantages became evident during development.

a. Standard final approach angle

b. Plane change prior to terminal phase at common node

c. Increased ground support capability



The problems realized during the development include the following.

a. Variable TPI time and, therefore, nonstandard lighting for terminal phase

b. Braking maneuvers marginal for RCS, which should be used for braking to avoid loss of visual contact

Phase 3 - Direct Coelliptic Sequence

The basic characteristics of the direct coelliptic sequences are as follows.

a. Variable insertion velocity as function of lift-off time within launch window

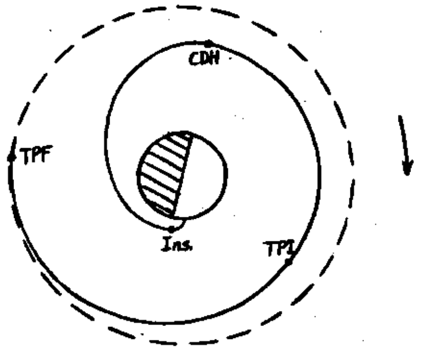
b. Coelliptic maneuver at variable-height apolune after insertion; therefore, variable coelliptic Δh

c. TPI theoretically at fixed time regardless of lift-off time within launch window (150° terminal phase transfer)

Two new advantages became evident.

a. Fixed TPI time, theoretically

b. Braking maneuvers always within what was then considered RCS capability



Two problems were realized during the development.

a. Variable powered ascent involved complex monitoring techniques before and after insertion

b. If powered ascent dispersions occur, large slips in TPI time are required to retain standard TPI conditions

Phase 4 - Original CSI-CDH Coelliptic Sequence

There are five basic characteristics of the original CSI-CDH coelliptic sequence.

a. Standard insertion orbit (30 by 10 n. mi.)

b. Horizontal CSI at 30 minutes after insertion

c. CDH at resultant apolune (as function of launch window) after CSI

d. TPI approximately over landing site

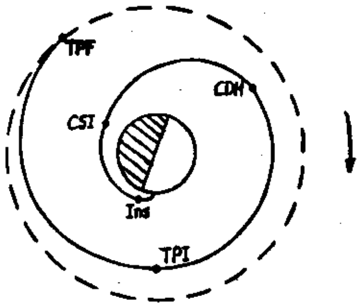
e. Terminal phase transfer angle of 140°

Three new advantages became evident.

a. Standard conditions around insertion

b. Better control of TPI time (less sensitive to insertion dispersions) because of phasing maneuver (CSI)

c. Optimum ΔV usage (horizontal CDH) because of CDH at apolune (assuming circular CSM orbit)



Two new problems were realized.

a. Lack of optimum terminal phase lighting

b. Lack of most desirable terminal phase transfer angle for line-of-sight control

Phase 5 - Same Coelliptic Sequence as for Phase 4, but with Optimized Terminal Phase

The basic characteristics of phase 5 are the same as for phase 4 except for the following.

a. TPI at 20 minutes prior to darkness

b. Terminal phase transfer angle of 130°

The new advantages discovered during development of this phase are as follows.

a. Optimum terminal phase lighting

b. Optimum braking line-of-sight control

The problems that were realized are the following.

a. Slim LM RCS margin for larger coelliptic Δh's

b. Relative ranges after insertion greater than RR spec limit for lift-offs later than approximately 1 minute after ontime lift-off

Phase 6 - Same Coelliptic Sequence as for Phase 5, but with CSM in 60-n. mi. Circular Orbit

The basic characteristics for phase 6 are the same as for phase 5 except for the following.

a. No nominal LM launch window; the philosophy was adopted that LM lift-off most probably would not occur more than a few seconds later than nominally planned

b. Shorter Δt's between CSI and CDH and between CDH and TPI

Several new advantages were noted.

a. Larger LM RCS margin because of lower CSM orbit and smaller coelliptic Δh's

b. Relative ranges well within RR spec limit for nearly nominal lift-off

c. Nearly standard maneuver timeline for nearly nominal cases (because of no nominal launch window)

Two new problems were realized during development of phase 6.

a. Insertion-to-CSI Δt too short for needed platform alinements and required VHF/sextant tracking

b. Need for plane change capability somewhere between insertion and TPI to avoid possible large out-of-plane maneuvers during terminal phase

Phase 7 - Extended CSI-CDH Coelliptic Sequence

Basic characteristics of the extended CSI-CDH coelliptic sequence are as follows.

a. Insertion-to-CSI Δt = 50 minutes

b. Resultant CSI-to-CDH Δt = 50 minutes

c. Separate plane change maneuver scheduled at 90° prior to CDH, with plane change to be completed at CDH

d. TPI necessarily moved to midpoint of darkness because of pre-CDH timeline; not optimum lighting, but second choice

The following advantages were discovered during development.

a. More accurate CSI because of alinement, and more tracking prior to CSI

b. Nearly coplanar terminal phase because of pre-TPI plane change capability

c. Maneuver timeline not so rushed

Problems realized during development are as follows.

a. Certain dispersions caused sharp decrease in CSI-to-CDH Δt if CDH occurred at first apsis after CSI

b. Plane change completion at CDH could cause mainly out-of-plane ΔV vector

Phase 8 - CSI-CDH Coelliptic Sequence with Controlled CSI-to-CDH Δt

Several basic characteristics were determined for phase 8.

a. CSI at apolune after insertion (Δt = 55 min) to avoid large radial component at CDH

b. CDH always half period (essentially 180°) after CSI

c. CDH nearly horizontal burn unless radial dispersion occurs at insertion

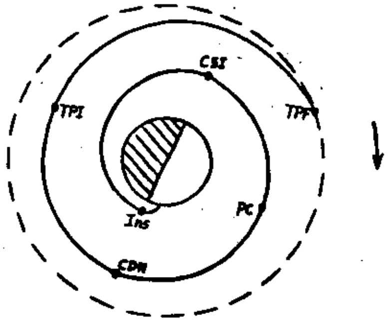
d. Plane change beginning at CSI

e. TPI at midpoint of darkness

New advantages of phase 8 are as follows.

a. CSI-to-CDH timeline nearly fixed

b. More favorable plane change procedure



It was realized during development that the relative range was too large at the beginning of the VHF tracking period between insertion and CSI.

Phase 9 - Same Coelliptic Sequence as for Phase 8, Except with Insertion Orbit 45 by 10 n. mi.

The basic characteristics of phase 9 are the same as for phase 8, with the following exceptions.

a. Standard insertion orbit of 45 by 10 n. mi.

b. Nominally, CSI at desired coelliptic Δh of 15 n. mi.

c. Nominally, CDH near-zero ΔV

d. TPI at midpoint of darkness, approximately 33 minutes after CDH

One new advantage was discovered during development of this phase: the relative range was within VHF spec limit (approximately 200 n. mi.) at the beginning of the pre-CSI tracking period.

Only one new problem was realized. The CDH-to-TPI Δt (with a possible slip in TPI) was too short for the required crew activities.

Phase 10 - Apollo 11 CSI-CDH Coelliptic Sequence (with radial component at insertion)

The basic characteristics of phase 10 are as follows.

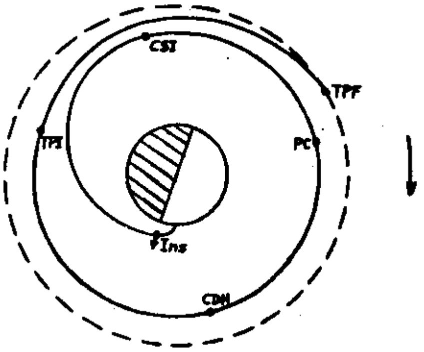
a. Radial component (30 fps up) at insertion (10 n. mi.), insertion orbit of 45 by 9 n. mi.

b. CSI at apolune after insertion (Δt = 51 min)

c. CDH one-half period after CSI

d. TPI at midpoint of darkness, approximately 37 minutes after CDH

An increased CDH-to-TPI Δt was the only advantage discovered during the development of this phase.



There are still several unsolved problems.

a. Terminal phase lighting not most favorable

b. Radial components at CDH if certain dispersions occur

c. Slim APS powered ascent margin

d. Longer than desirable insertion-to-rendezvous Δt

APOLLO 11 RENDEZVOUS

Maneuver	Δt from insertion to burn init., min	Δt from previous maneuver, min	ΔV, fps	Burn duration, sec	Burn attitude at burn init., deg	RCS thruster, usage	Resultant orbit, apo/per, n. mi.
CSI	51.0	51.0	50.1	45.0	0.0	+Z, two-jet	45.2/44.4
PC	80.0	29.0	0.0	0.0	0.0	±Y, two-jet	45.2/44.4
CDH	109.0	29.0	2.2	2.0	90.0	+Z, two-jet	45.2/45.0
TPI	146.0	37.0	24.7	22.1	26.5	+Z, two-jet	60.8/45.0
TPF	188.5	42.5	31.5	28.0	305.5	-Z, two-jet	60.2/59.3

PERTINENT QUESTIONS AND ANSWERS CONCERNING RENDEZVOUS DESIGN FOR LUNAR LANDING MISSION

Q - Why is the nominal parking orbit for the CSM approximately 60 n. mi. circular?

A - Not higher because of LM RCS ΔV budget; not lower because of the phasing situation for powered descent aborts.

Q - Why is LM insertion at 60 000 feet (instead of 50 000 ft)?

A - Allows larger safety margin relative to dispersion, especially for powered descent aborts.

Q - Why is LM insertion orbit apolune at 45 n. mi. (instead of 30 n. mi.)?

A - Affords relative range within VHF tracking capability ($R <$ ~200 n. mi.) at beginning of scheduled pre-CSI VHF/sextant tracking period.

Q - Why is there a radially upward ΔV component at LM insertion?

A - Increases Δt between CDH and TPI by decreasing Δt between insertion and CSI (CSI is at apolune after insertion); the Δt between CSI and CDH is essentially fixed.

Q - Why not increase CDH-to-TPI Δt simply by delaying TPI?

A - A later TPI (nominally) could result in extremely unfavorable lighting conditions at final approach, assuming a 3σ dispersed TPI delay.

Q - Why is CSI at LM apolune (instead of prior to apolune)?

A - To avoid large radial ΔV component at CDH for nominal case; CDH is an RCS burn.

Q - Why not apply a larger radial ΔV component at LM insertion, and therefore afford a larger increase in CDH-to-TPI Δt?

A - A radial ΔV component larger enough to significantly affect the timeline could result in unsafe perilune if approximately 3σ dispersions occur at insertion.

Q - From a procedures standpoint, why is Δt between insertion and CSI approximately 50 minutes?

A - Affords sufficient time for platform alinements, tracking periods, and prethrust activities.

Q - Why is CSI a horizontal-thrusting burn?

A - Avoids decrease in perilune altitude, which is already at approximately 9 n. mi.

Q - What value is allowed to vary (with dispersions) in exchange for constraining CSI to be horizontal?
A - Coelliptic Δh will vary with dispersions.

Q - Why is there a plane change capability after insertion but prior to terminal phase?
A - Insertion out-of-plane ΔV dispersion within 3σ (35 fps) could present the following major problems in terminal phase: complicated elevation angle reference at TPI, nonnominal approach, and large ΔV magnitudes during braking.

Q - Why start the plane change at CSI [and finish it at a separate plane change between CSI and CDH (PC)] if sufficient information is obtained by CSM?
A - More economical than starting plane change at PC and finishing it at CDH because CSI is a larger inplane burn than CDH.

Q - Why is the out-of-plane situation determined by CSM?
A - CSM's sextant angle measurements are significantly more accurate than those of the LM's rendezvous radar.

Q - Why is the half-period (~180°) option used for CSI-to-CDH transfer?
A - Essentially fixes the CSI-to-CDH Δt and therefore also the CSI-to-PC Δt and the PC-to-CDH Δt. If CDH-at-first apsis option were used, the CSI-to-CDH Δt could decrease sharply with certain insertion dispersions.

Q - Why is the nominal coelliptic Δh = 15 n. mi.?
A - Large enough to avoid closing-detection problems and small enough to avoid excessive ΔV usage for expected dispersions (approximately ±5 n. mi. variation in Δh).

Q - Why is TPI at the midpoint of darkness?
A - Acceptable tradeoff between lighting for pre-TPI sextant tracking and lighting for final approach.

Q - Why is TPI not at the most favorable position relative to lighting (20 min prior to darkness)?
A - Because of the required Δt's prior to TPI (insertion-to-CSI Δt and CSI-to-CDH Δt), CDH actually occurs after 20 minutes prior to darkness.

Q - Why is TPI a line-of-sight burn (i.e., the thrust vector along the line of sight to the target vehicle)?
A - Affords manual backup technique.

Q - Why is TPI targeted on a fixed elevation angle?

A - Because line-of-sight burn elevation angle varies only slightly with variations in Δh; also, elevation angle is a convenient input parameter.

Q - Why is the terminal phase 130° for CSM travel?

A - Optimum for line-of-sight control during braking; also, a tradeoff between inplane and possible out-of-plane ΔV costs (the shorter the transfer, the higher the inplane cost; the closer the transfer to 180°, the higher the possible out-of-plane costs for a given dispersion).

Q - Why are RCS Z-axis thrusters used for rendezvous maneuvers (instead of X-axis)?

A - Avoids breaking rendezvous radar lock; also, APS interconnect (which requires Z-axis thrusters) is not applicable for LLM nominal rendezvous because APS tanks are nearly empty.

Don A. Nelson

Roy E. Stokes

Richard M. Scales

Wilma Brockwell

R. Larry McHenry

Marlowe Cassetti

Otis F. Graf Jr.

Anne Accola

Richard O. Nobles

H Richard Hertzberg

Samuel O. Mayfield

Dwight G. Peterson

Cynthia Wells

THE GUIDANCE AND PERFORMANCE BRANCH

Wiley Beal

Harry E. Kolkhorst

Daniel K. Ford

Melvin Rothert

Don Beggs

Herbert A. Estes

David Long

Joe W. Holley

Carol Jordan

Aldo John Bordano

Wells

Martin L Alexander

Jim Walls

Harry Miles

Lee Dodge

Richard C. Wallace

Arnold Loyd

GUIDANCE ANALYSIS SECTION

One of the most significant contributions of the Guidance Analysis Section to the first lunar landing mission (Apollo 11) was the definition of the ground guidance monitoring philosophy and procedures for the powered flight maneuvers. The monitoring consists of evaluation of the guidance systems during the following maneuvers.

a. Evaluation of the command/service module (CSM) and Saturn guidance systems during the launch into earth orbit for a committment to the translunar injection (TLI) maneuver

b. Evaluation of the CSM systems during the TLI maneuver for a committment to the lunar orbit maneuver

c. Evaluation of the lunar module (LM) primary guidance system (PGNS) and abort guidance systems (AGS) during the lunar descent for descent abort and guidance switchover decisions

d. Evaluation of the LM PGNS and AGS during the lunar ascent for a guidance switchover decision

The evaluation consists of assessment of the performance of the various guidance systems primarily from comparison of their navigation and attitude references. The comparisons were generated in component form and were displayed on two analog recorders. The comparisons of the navigation systems were performed with a minimum of three independent systems. The systems consist of the primary guidance system, the backup or monitoring system (AGS), and a groundtrack system based on Manned Space Flight Network (MSFN) data. A typical example of the comparisons performed is shown in figures 1 and 2 for the lunar ascent maneuver. The following list indicates the data presented in the two figures.

a. Ascent pitch chart (fig. 1)

Channel 1: $\Delta\dot{X}$, fps, AGS-PGNS (down-range velocity difference)
Channel 2: ΔX, fps, MSFN-PGNS (down-range velocity difference)
Channel 3: $\Delta\dot{Z}$, fps, AGS-PGNS (radial velocity difference)
Channel 4: $\Delta\dot{Z}$, fps, MSFN-PGNS (radial velocity difference)
Channel 5: ΔH, ft, AGS-PGNS (attitude difference)
Channel 6: ΔP, deg, AGS (attitude error)
Channel 7: ΔP, deg, PGNS (attitude error)
Channel 8: P, deg, AGS-PGNS (attitude difference)

b. Ascent yaw chart (fig. 2)

Channel 1: $\Delta\dot{Y}$, fps, AGS-PGNS (out-of-plane velocity difference)
Channel 2: $\Delta\dot{Y}$, fps, MSFN-PGNS (out-of-plane velocity difference)
Channel 3: ΔY, deg, AGS (attitude error)
Channel 4: ΔY, deg, PGNS (attitude error)
Channel 5: ΔR, deg, AGS (attitude error)
Channel 6: ΔR, deg, PGNS (attitude error)
Channel 7: Y, deg, AGS-PGNS (attitude difference)
Channel 8: R, deg, AGS-PGNS (attitude difference)

An evaluation of the data presented in figures 1 and 2 indicates that the performance of the three systems (PGNS, AGS, and MSFN) was very satisfactory, which was characteristic of the performance of all guidance systems during all powered flight maneuvers for the Apollo 11 mission.

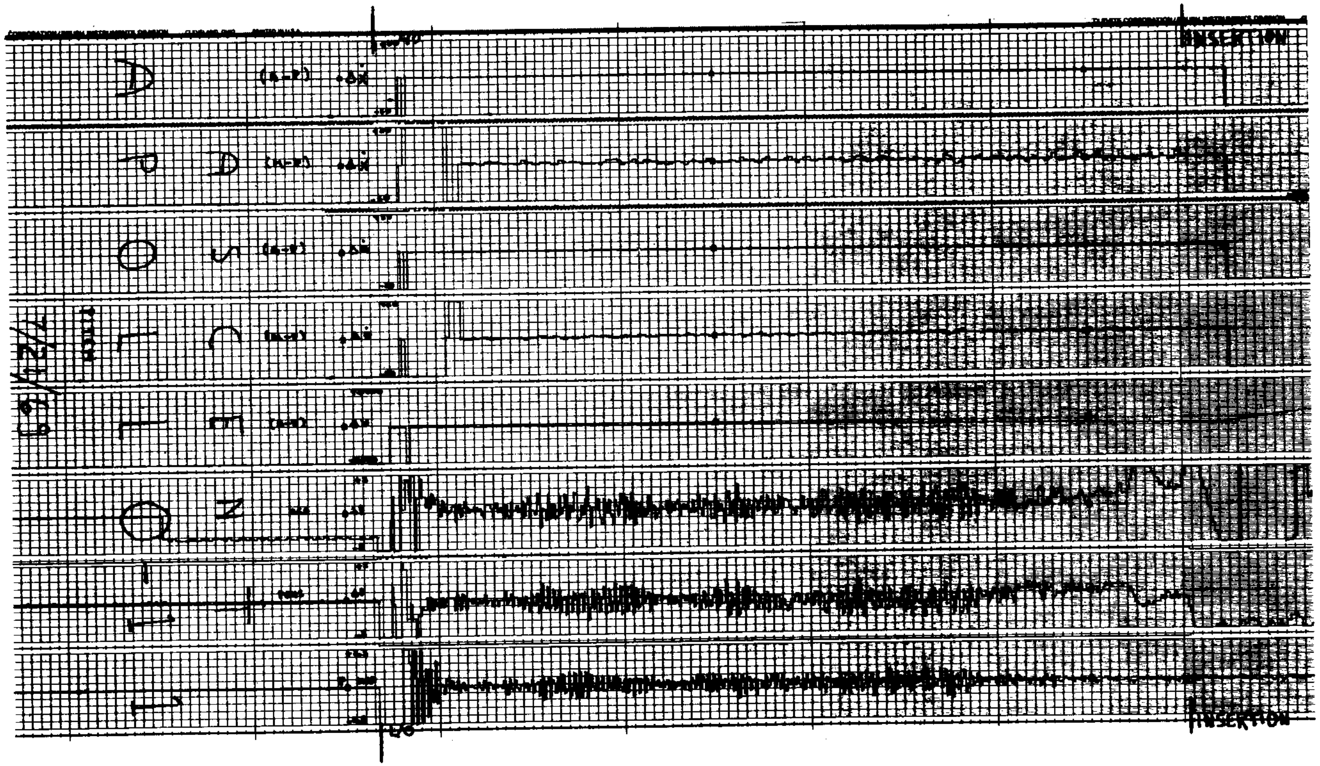


Figure 1.- Ascent pitch chart.

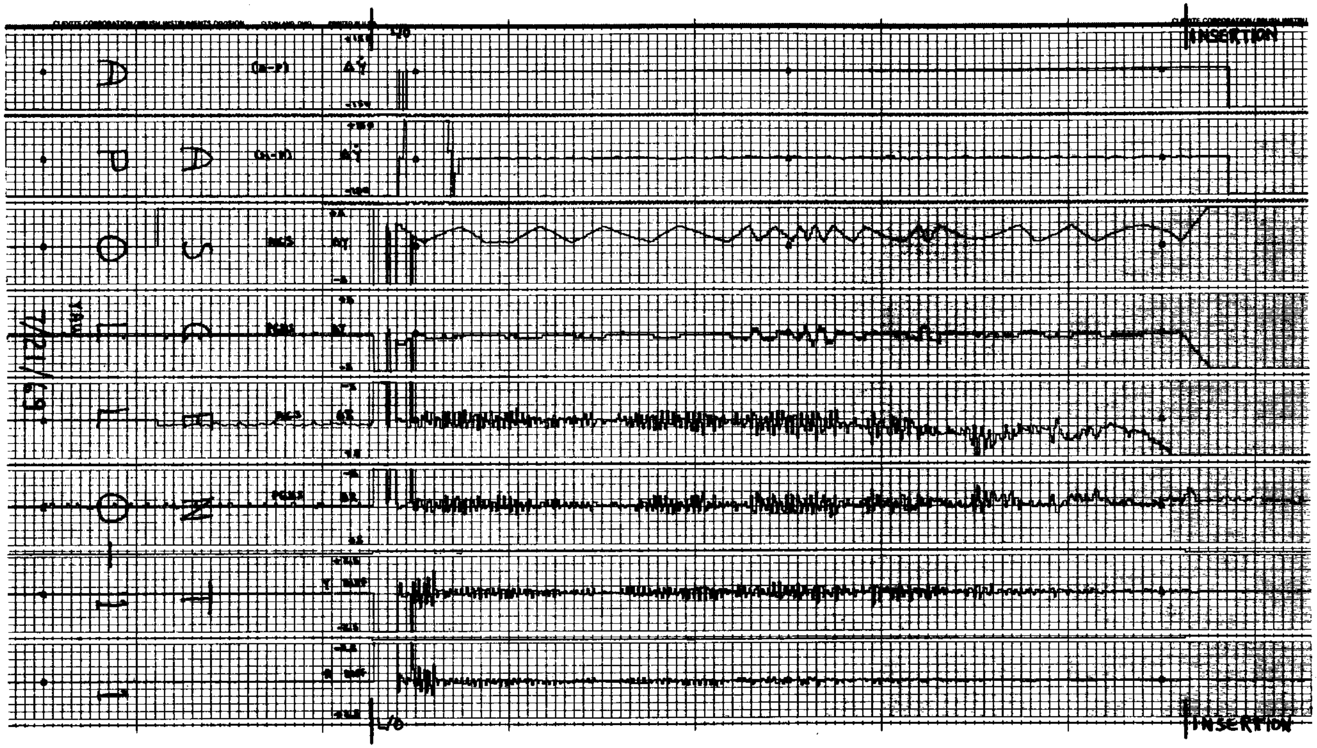


Figure 2.- Ascent yaw chart.

CONSUMABLES ANALYSIS SECTION

Many problems are associated with the consumables subsystem. The first one is to determine which problems are critical and how they can be defined and then integrated into the total mission planning cycle. A listing of the consumables subsystems considered significant to Apollo mission planning is presented in table I.

To conduct analyses for a mission plan, the following information is usually required.

a. Trajectory - The proposed trajectory provides primarily the maneuver times and magnitudes, the attitude of the vehicles, and the basic chronological sequence of events.

b. Flight plan - Many spacecraft operations and functions, such as electrical and environmental control, affect the consumables subsystems but have little or no effect on the trajectory. The flight plan provides information about the times that the various subsystems are used and also about methods used to activate and deactivate them.

c. System/subsystem/component performance data - These performance data are obtained usually from data books provided for this purpose or from actual flight data of the equipment.

d. Constraints and considerations - To insure crew safety and to provide a common understanding among all parties concerned, certain ambiguities must be defined. A set of acceptable assumptions evolves from the analyses that are performed. Consideration is given to certain conditions, for example, the amount of loaded propellant which remains trapped in the lines and is not available for use. Many constraints that are necessary for consistency have been suggested and have been accepted as essential until invalidated.

With the previous information, the computer programs are written for the basic mission timeline and the various consumables analyses are conducted and appropriate information is included in the mission plan. An iteration loop is required to feed back out-of-tolerance conditions and to provide for the updating that is inevitably required.

For Apollo 11, the lunar landing mission, a complete and thorough consumables subsystem analysis was conducted for the nominal, alternate, and contingency profiles. In addition and of equal significance, the Consumables Analysis Section (CAS) conducted many special studies to answer specific questions and to explore questionable areas. The following illustrate the nature of these vital contributions.

a. It was determined that the LM descent batteries were the limiting factor in the length of lunar staytime. Further analysis was performed to determine the maximum length of staytime possible.

b. It was determined that during the transearth return the LM ascent stage could back up communications by maintaining operation of the S-band steerable antenna heater and the ECA's at all times and by operating the actual communications equipment when transmission and reception were desired.

c. Special emphasis was placed on the descent stage water budget because it is the only environmental control system consumables that could be off-loaded to permit additional fuel to be loaded.

d. The steam vented by the ECS evaporator to reject heat from the spacecraft was found to produce a noticeable thrust during the Apollo 8 mission. An effort was made to define the effect on the LM so that it could be included in the mission plan.

e. The preferred abort technique following an SPS failure during the LOI burn was as follows: jettison of the SM, power-up of essential LM equipment and necessary CM equipment, and performance of a docked DPS burn in the CM/LM configuration. After considerable study, it was determined that sufficient LM consumables exist to permit SM jettison prior to a docked DPS abort burn.

f. Extensive postflight correlation was conducted on the CSM ECS primary radiator performance. This computer simulation model is very complicated because it involves many parameters, equipment usage, and the inherent individual radiator characteristics. The Apollo 11 predictions were made quickly and accurately by use of the techniques and the computer model developed.

g. The unexpected CO_2 partial pressure profile seen in the flight of LM-4 resulted in concern as to the profile to expect for LM-5. A study was conducted to determine the amount of LiOH required to complete the LM portion of the Apollo 11 mission, and it was found that acceptable CO_2 levels could be maintained for even the low-performance cases.

h. By careful study of the DPS propellant time-history profile, a set of background vocal cues was developed to keep the crew advised of their fuel status during the lunar descent phase.

A significant effort has been expended by the Consumables Analysis Section to develop computer simulations of the critical subsystems to evaluate their individual performance and their interaction in some cases. This additional capability has been used to a limited extent to conduct parametric studies on contingency and alternate mission situations.

The results shown in table I are indicative of the accuracy of the consumables subsystem analyses.

CONSUMABLES PREDICTION ACCURACY FOR APOLLO MISSION 7 - 11

Item	Mission				
	Apollo 7	Apollo 8	Apollo 9	Apollo 10	Apollo 11
	Percentage of deviation[a]				
CSM oxygen	-16	-9	-3	--	-2
CSM hydrogen	-6	-7	-1.5	+6	-2
CM RCS propellant	8.7	1.8	2.4	+4	+1
SM RCS propellant	+6	--	-16	-24	--
SPS propellant	+4.6	1.2	+2.5	--	--
LM descent electrical power system	b	b	-20	+1	-5
LM ascent electrical power system	b	b	-17	-3	+2
LM descent water	b	b	-6	--	--
LM ascent water	b	b	-21	--	--
LM descent oxygen	b	b	-10	--	-16
LM ascent oxygen	b	b	-5	-19	-20
DPS propellant	b	b	--	--	+3
APS propellant	b	b	--	--	+2
LM RCS propellant	b	b	-10	-5	+10

[a] A negative deviation indicates that actual usage was less than budgeted. Where no deviation is indicated, actual usage is within one percent of the budget. The deviation percentage is computed by computation of

$$\frac{\text{actual usage - predicted usage}}{\text{usable consumable}}$$

[b] Spacecraft not flown with mission.

Benjamin J. Garland

Donald Jezewski

Joseph R. Thibodeau III

Victor R. Bond

Howard M. Adler

JoAnn Patrick

Jack Funk

John T. McNeely

James T. Taylor

THE ADVANCED MISSION DESIGN BRANCH

Thomas B. Murtagh

Flora Bryan Lowes

Gregory A. Zembo

Ellis W. Henry

S. R. Sudol

Judith M. Stoly

Charles W. Avery

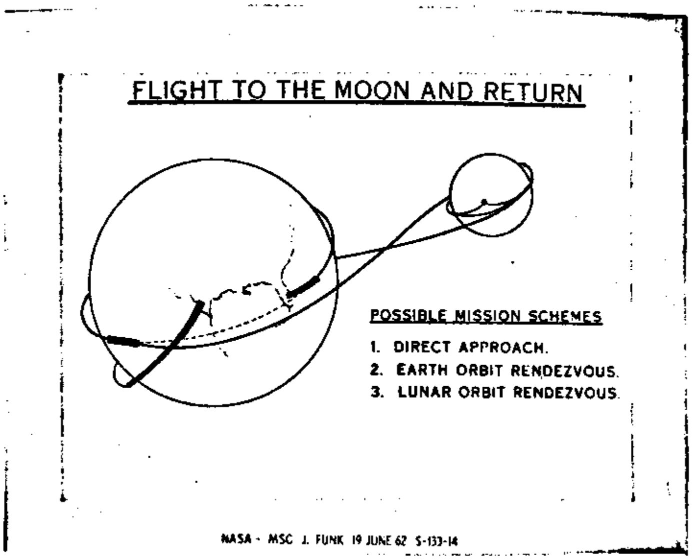
Nicholas S. Faust

Cecilia Ramirez

Gus R Babb

ADVANCED MISSION DESIGN BRANCH

In the beginning, there were three possible approaches to the lunar landing mission, and these are indicated in the following figure.



NASA - MSC J. FUNK 19 JUNE 62 S-133-14

Originally, the direct approach was favored by the Space Task Group (STG), and the original contract to North American Aviation (NAA) indicates that this mode was favored by the MSFC. The lunar orbit rendezvous mode was suggested by the Langley Research Center. After several months of study, the Space Task Group switched the direct approach to the lunar orbit rendezvous mode and initiated a three-way battle among STG, NAA, and MSFC as to which approach was technically best.

A ΔV budget that was to be used in the study of the lunar orbit rendezvous and direct modes is presented in the following memo. The earth orbit rendezvous mode was a variation of the direct mode which allowed two boosters instead of one to be used.

NASA - Manned Spacecraft Center
Houston, Texas
July 10, 1962

MEMORANDUM for Chief, Spacecraft Research Division

Subject: Meeting at NAA on velocity requirements for LEM and direct lunar landing missions

1. Attending the subject meeting were Messrs. Earl Cole, Leonard Rider, and Robert Kakuske of NAA; Calvin Perrine, Morris Jenkins, Ted Skopinski, and the writer of NASA-MSC.

2. After much discussion about ground rules flexibility, etc., a table of velocities for both the LEM and direct lunar landing mission was put together which tentatively both NAA and NASA could agree on as being a basis for comparison of the two modes. These velocities are given in the enclosed table.

3. It was indicated that a 10% reserve was to be added to the velocities in the table for weight estimates. Preliminary estimates of the weights based on velocities of enclosed table with 10% reserve indicated that a 25,000-lb LEM with a 3,000-lb adapter would require a C-5 payload of 84,500 lbs to escape. For the direct approach the escape weight would be about 185,000 lbs.

4. It is apparent that the direct approach is marginal with 10% reserve, so NAA is planning on presentation of weights as a function of percent margin in order to keep the direct approach alive.

Jack Funk
Head, Astromechanics Section

JF:nca

RGC

Enc:
Table: Velocities for Lunar
Landing Mission Orbit Altitude
about Moon 80 N. Mi.

VELOCITIES FOR LUNAR LANDING MISSION
ORBIT ALTITUDE ABOUT MOON 80 N.MI.

		LOR		EOR	
	Item	Velocity	Module	Velocity	Module
1.	Translunar midcourse	300	SM	300	LEM
2.	Retro from circumlunar to lunar orbit	3130	SM	3130	LEM
3.	Lunar orbit plane change of 6° simultaneously with retro maneuver	100	SM	100	LEM
4.	Total V_1 for SM	3530	SM	3530	
5.	Separation of LEM	5	LEM		
6.	Lunar orbit to equal period LOR or Hohmann EOR. Pericynthion Alt. 50,000 ft.	373	LEM	123	LEM
7.	Descent to surface from 50,000 100 ft/sec 1000 ft alt. LOR 450 ft/sec 2000 ft alt. EOR	5961	LEM	5330	LEM
8.	Total LEM	9			
9.	Descent from 450 ft/sec 2000 ft alt. to hover EOR			501	LSM
10.	Hover Translate and touchdown	700	LEM	715	LSM
11.	Total LEM down	7026	LEM		
12.	Total LSM			1216	LSM
13.	Launch to circular 50,000 ft. orbit	5885	LEM	5980	SM
	a. additional for abort from landing	100			
14.	2° plane change LEM	75	LEM		
15.	Rendezvous from 50,000 ft circular orbit	196	LEM		
16.	Total LEM launch	6256	LEM		

	Item	LOR Velocity	LOR Module	EOR Velocity	EOR Module
17.	Lunar orbit to transearth	3690	SM	3592	SM
18.	Transearth midcourse	300	SM	300	SM
19.	Addition for CM pickup of LEM from descent orbit can be used for orbit's maneuver if LEM makes landing	522	SM		
20.	Total V_2 SM-LOR	4365	SM		
21.	Total SM-EOR			9872	SM

The decision was made in favor of the lunar orbit rendezvous mode at a high level meeting attended by the President of the United States of America, and almost immediately there was a call for a ΔV budget so that the size of the system tanks could be determined. The first proposed ΔV budget for the Apollo system is shown in figure 2.

Studies on the phases of the mission which were independent of the mode had been completed earlier so that considerable information was available for input to the system design requirements, for example, results of the study shown in figure 3. Before the completion of this study in July 1961, the relation between L/D, corridor depth, and controllable range was unknown. There was not even a good definition of controllable range. The primary reason for the lack of knowledge about the phase was that guidance equations with which to conduct the studies were still being developed. The study illustrated by figure 3 was conducted without guidance equations by use of a roll switching at the bottom of the pullup. The 12 000-mile entry range with an L/D of 0.5 was unexpected.

It was necessary to develop some type of mission planning program to analyze the ΔV requirements. It was apparent that a fast mission planning technique was needed for the preliminary mission development. In the fall of 1962, Ellis Henry and Tom Gibson wrote a matched conic mission planning program which was used to analyze the mission requirements for the Apollo mission. This program was a major breakthrough in the mission planning area. The slides shown in figure 4 were used in a presentation to the NASA Management Council in May 1963.

During the early stages of development, information on lunar descent trajectories was almost nonexistent. At first, MSFC launch programs were used to calculate landing trajectories. While this program was sufficient for launches from the lunar surface, it would not converge on optimum landing trajectories. Don Jezewski was assigned the task of developing an analytical optimum lunar landing program based on a flat moon approximation. This program was used to calculate the optimum lunar landing results shown in figure 5 from which the engine design characteristic T/W = 0.4 was obtained. The initial LM descent ΔV budgets were obtained by adding 10 percent to these results.

VELOCITY REQUIREMENTS FOR LUNAR LANDING MISSION - LUNAR ORBIT RENDEZVOUS MODE

$T/W_0 = 0.4$

RENDEZVOUS ORBIT ALTITUDE, n.mi.	60	80	100
1. TRANSLUNAR MIDCOURSE GUIDANCE CORRECTIONS	300	300	300
2. CIRCUMLUNAR TO LUNAR ORBIT	3157	3130	3117
3. LUNAR ORBIT PLANE CHANGE	100	100	100
4. SEPARATION OF LEM FROM CSM	5	5	5
5. CIRCULAR TO EQUAL – PERIOD ORBIT. 50,000 FT. PERICYNTHION ALTITUDE	275	373	465
6. DESCENT TO SURFACE OF MOON (h=500 FT., γ=0, V = 50 fps	5961	6011	6066
7. HOVER TRANSLATION AND TOUCHDOWN	700	700	700
8. LAUNCH TO 50,000 FT. CIRCULAR ORBIT	5985	5985	5985
9. RENDEZVOUS FROM 50,000 FT. CIRCULAR ORBIT	144	196	248
10. LUNAR ORBIT TO TRANSEARTH	3710	3690	3670
11. TRANSEARTH MIDCOURSE GUIDANCE CORRECTIONS	300	300	300
12. CM PICKUP OF LEM	350	476	613

NASA - MSC J. FUNK 19 JULY 62 S-133-9

As the project progressed, the personnel of the AMDB were involved in the onboard guidance computer program. The initial step in the development of the LM descent guidance program was a study by Victor Bond, called Linear Acceleration Guidance Scheme For Landing and Launch Trajectories In A Vacuum [NASA TN D-2684 (Feb. 1965)]. This work was continued by MIT and developed into quadratic guidance so that the terminal end of the trajectory could be shaped for better crew visibility. Work progressed smoothly until the Apollo project office announced that the high end throttling of the descent engine was to be dropped and the descent guidance equation would have to be modified to operate with fixed thrust during most of the burn. The following task statement suggested the solution that was actually used. This study task was assigned to both Theoretical Mechanics Branch (TMB) and MIT at the same time.

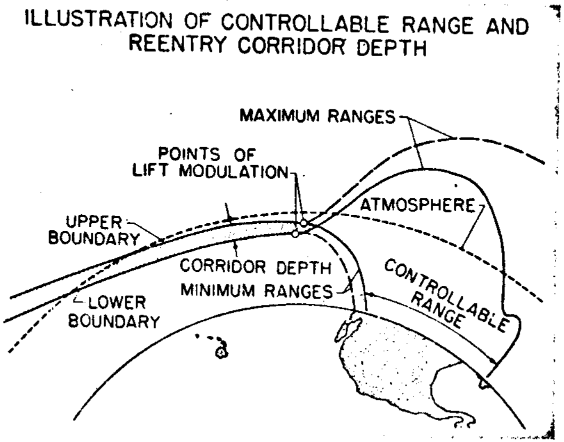
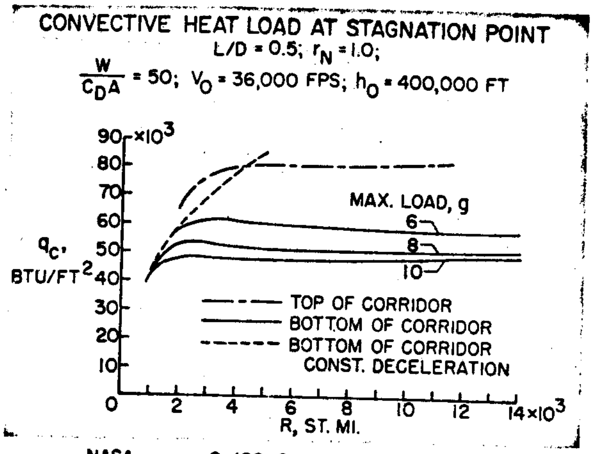


ILLUSTRATION OF CONTROLLABLE RANGE AND REENTRY CORRIDOR DEPTH

NASA S-102-1 FUNK 7/18-20/61

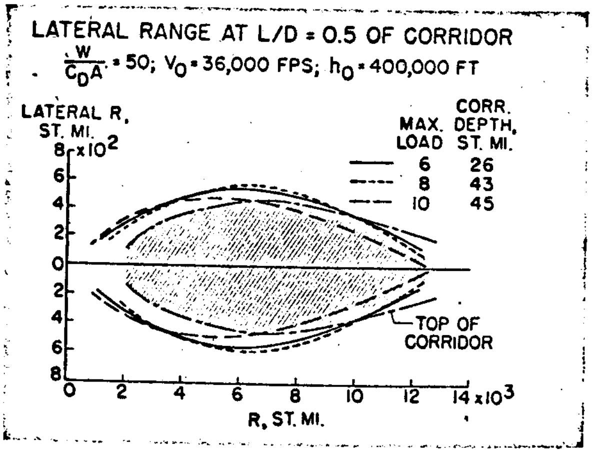
2



CONVECTIVE HEAT LOAD AT STAGNATION POINT

$L/D = 0.5$; $r_N = 1.0$; $\frac{W}{C_D A} = 50$; $V_0 = 36,000$ FPS; $h_0 = 400,000$ FT

NASA S-102-6 FUNK 7/18-20/61

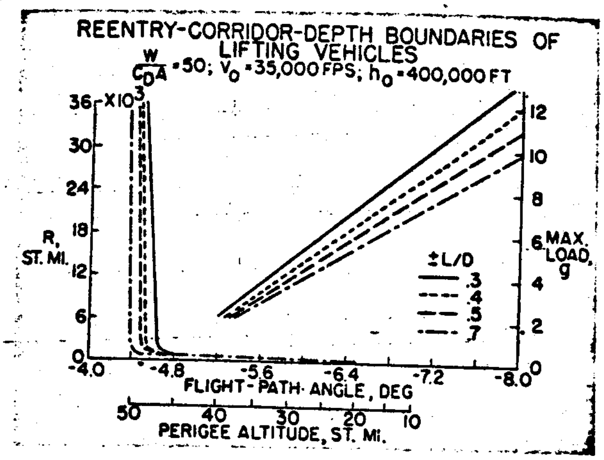


LATERAL RANGE AT L/D = 0.5 OF CORRIDOR

$\frac{W}{C_D A} = 50$; $V_0 = 36,000$ FPS; $h_0 = 400,000$ FT

NASA S-102-5 FUNK 7/18-20/61

4



REENTRY-CORRIDOR-DEPTH BOUNDARIES OF LIFTING VEHICLES

$\frac{W}{C_D A} = 50$; $V_0 = 35,000$ FPS; $h_0 = 400,000$ FT

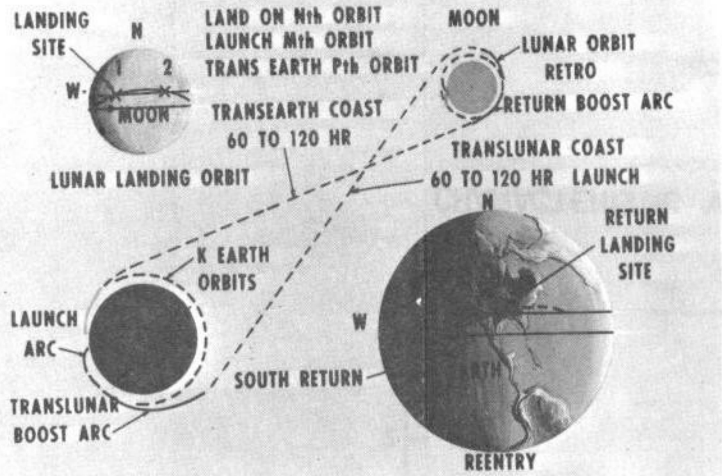
NASA S-102-2 FUNK 7/18-20/61

Figure 3.-

Development of entry range control and entry vehicle design requirements presentation July 18-20, 1961.

1

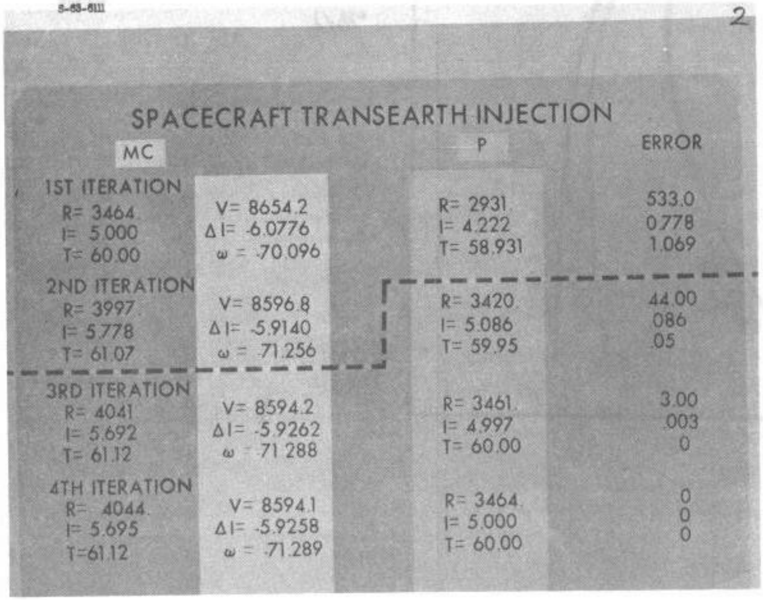
APOLLO MISSION ANALYSIS PROGRAM



NASA-MSC J FUNK 8 FEB 63 S-133-31

NASA
S-63-6111

2



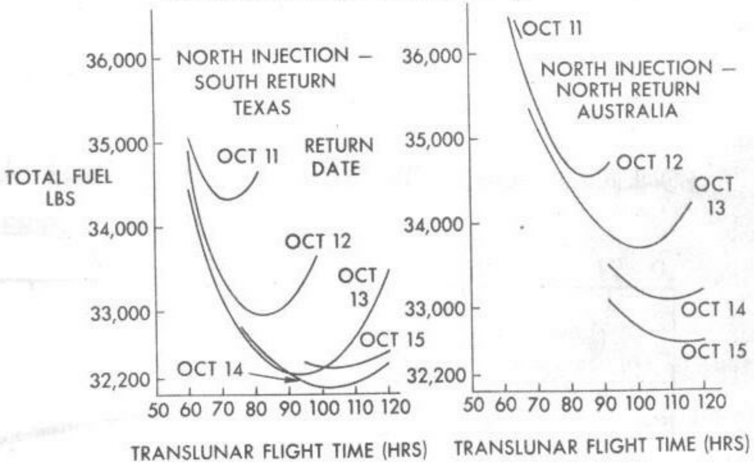
SPACECRAFT TRANSEARTH INJECTION

MC		P	ERROR
1ST ITERATION R= 3464. I= 5.000 T= 60.00	V= 8654.2 ΔI= -6.0776 ω = -70.096	R= 2931. I= 4.222 T= 58.931	533.0 0.778 1.069
2ND ITERATION R= 3997. I= 5.778 T= 61.07	V= 8596.8 ΔI= -5.9140 ω = -71.256	R= 3420. I= 5.086 T= 59.95	44.00 .086 .05
3RD ITERATION R= 4041 I= 5.692 T= 61.12	V= 8594.2 ΔI= -5.9262 ω = -71.288	R= 3461. I= 4.997 T= 60.00	3.00 .003 0
4TH ITERATION R= 4044. I= 5.695 T=61.12	V= 8594.1 ΔI= -5.9258 ω = -71.289	R= 3464. I= 5.000 T= 60.00	0 0 0

APOLLO LUNAR LANDING MISSION OCT 4, 1967
TO -28.5° LON, 0° LAT

3

ESCAPE WEIGHT 87,000 LBS LEM 25,000 LBS
MID'COURSE Δ V 300–300 FT/SEC I_{SP} 319

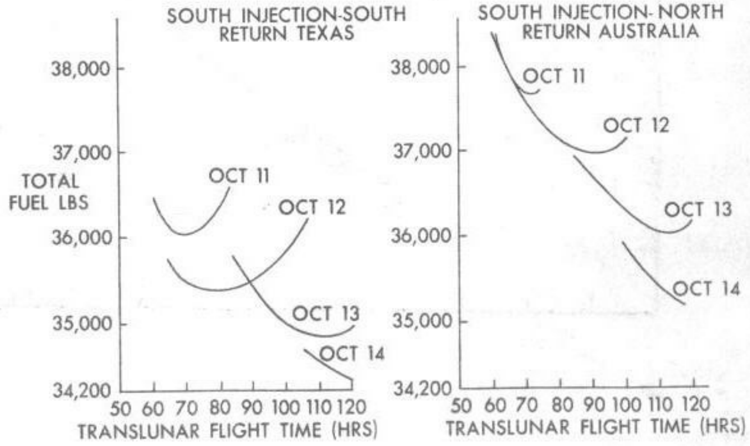


NASA-MSC J FUNK 8 FEB 63 S-133-32

APOLLO LUNAR LANDING MISSION OCT 4, 1967
TO- 28.5° LON, 0° LAT

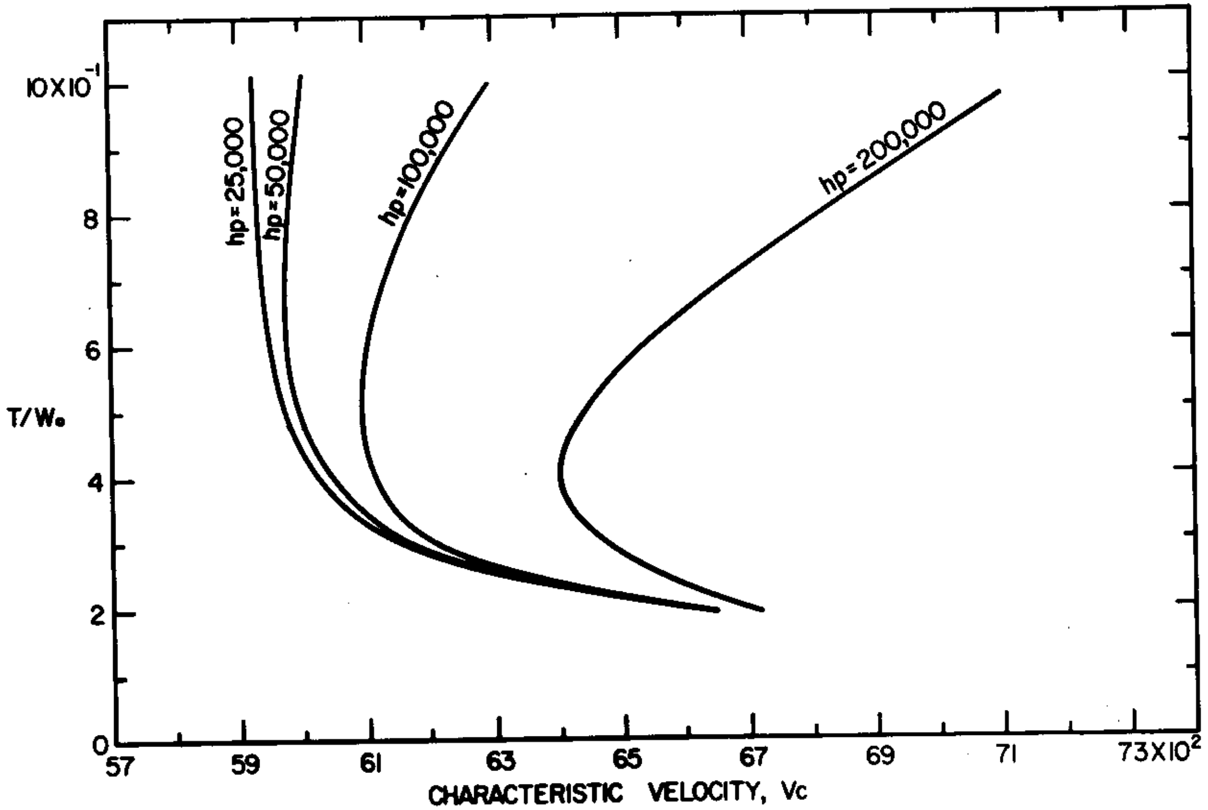
4

ESCAPE WEIGHT 87,000 LBS LEM 25,000 LBS
MIDCOURSE Δ V 300–300 FT/SEC I_{SP} 319



NASA-MSC J FUNK 8 FEB 63 S-133-33

Fig 5



CHARACTERISTIC VELOCITY FOR OPTIMUM VERTICAL LUNAR LANDINGS

NASA-MSC JACK FUNK APRIL 4,1962 S-133-3

TMB TASK DESCRIPTION 1

Assignments, object, and study plan are included in the evaluation of effects of engine throttle limits on primary descent guidance.

Assignments

Don Jezewski	One fourth
Tom Price	Full

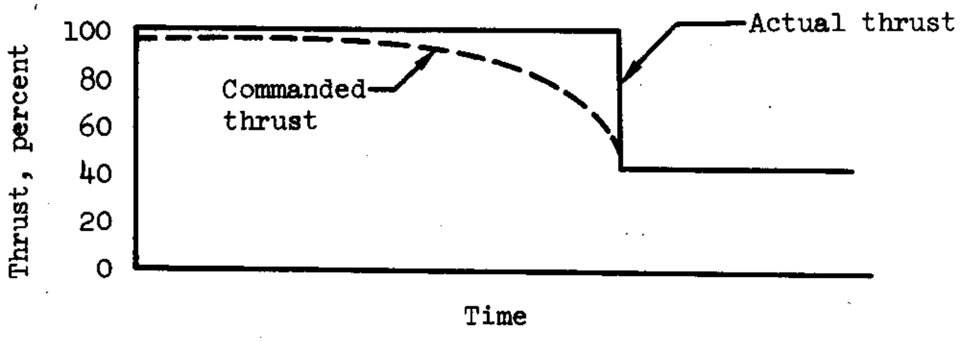
Object

a. To modify existing guidance equations or to develope new guidance equations to control the LEM landing descent with a descent engine that can only be operated at 100 percent throttle or throttled between 60 percent and 10 percent

b. To determine fuel penalties and trajectory characteristics resulting from fixed throttle operation over a portion of the descent

Study Plan

The plan is based on the operation of existing steering equations in a fixed throttle mode. The landing descent trajectory will be designed on the basis of 97 percent rated thrust. The main engine throttle will be held at a constant 100 percent, which will result in a command thrust history as shown.



PART III

AFTERTHOUGHTS

VOYAGE TO THE MOON

By Archibald MacLeish

Presence among us,
        wanderer in our sky,
dazzle of silver in our leaves and on our
water silver,

        O
silver envasion in our fartherest thought-
"the visiting moon" . . . "the glimpses of the moon" . . .

and we have touched you!

                            From the first of time,
before the first of time, before the
first men tasted, we thought of you.
You were a wanderer to us, unattainable,
alonging past the reach of longing,
a light beyond our light, our lives - perhaps
a meaning to us. . .

                            Now
our hands have touched you in your depth of night.

Three days and three nights we journeyed,
steered by fartherest stars, climbed outward,
crossed the invisible tide-rip where the floating dust
falls one way or the other in the void between,
followed that other down, encountered
cold, faced death - unfathomable emptiness. . .

Then, the fourth day evening, we descended,
Made fast, set foot at dawn upon your beaches,
sifted between our fingers your cold sand.

We stand here in the dusk, the cold, the silence. . .

and here, as at the first of time, we lift our heads.
Over us, more beautiful than the moon, a
moon, a wonder to us, unattainable,

alonging past the reach of longing,
a light beyond our light, our lives -- perhaps
a meaning to us . . .

O, a meaning!

over us on these silent beaches the bright
earth,
presence among us

"Houston, Tranquility Base here . . .

THE EAGLE HAS LANDED"

Astronaut Neil Armstrong
(Landing on the Moon 7-20-69)

Now that the Apollo 11 astronauts have landed on the moon and returned safely to earth, a national commitment to greatness, made early in the decade, has been met.

This, then, is a time of achievement. It is a time when people of good will around the world applaud the pioneers of space. And, the people of Houston, especially, are deeply committed to the conquest of space.

We have profound admiration for the entire space team--the administrators, the engineers and the technicians as well as the astronauts and their families.

We have worked with them and played with them. We have studied with them and worshipped with them. We have shared the crisis of tragedy and the triumph of achievement with them.

We have found them deeply dedicated, highly capable, and intensely human.

Ten years ago, the exploration of space existed for most of us only in the realm of science fiction. But increasingly, during the decade, we have experienced the exciting possibilities along that fantastic frontier that floats above us.

To the genuine revolutions in human achievement that are honored in history's hall of fame, we can already add with assurance the exploration of space.

Every age has its world of tomorrow, and ours is found in the ocean of space. Today's Marco Polos and Christopher Columbuses and Charles Lindberghs ride millions of pounds of thrust beyond the earth's influence to the unfriendly terrain of the moon.

Not all, of course, have recognized the signifiance of this new adventure. The same type of people who questioned Galileo, Columbus, surgery, the steam engine, railroads and the airplane are now questioning space exploration--simply because their minds do not comprehend its portent.

The engineering basis of heavier-than-air flights was laid in the early 19th century, but in 1896, Lord Kelvin, great British research physicist, said, "I have not the smallest molecule of faith in aerial navigation other than ballooning."

After the Wright brothers had been making successful airplane flights for five years, the British Secretary of War said, "We do not consider the airplane will be of any possible use for war purposes."

We should remember that history has dealt harshly with the doubters of human progress, whether it be in surgery, wireless communication, aviation or other fields of achievement.

The full impact of the space program will unfold over a period of time. Now that man has slipped the leash on his earthly environment, the future holds promise for completely new frontiers for pioneering.

The search for knowledge and the development of complex skills which the space program has motivated cannot be adjourned. This interdisciplinary exploration is revealing secrets at the heart of the universe as well as out in the skies. The new knowledge can be applied to some of the age-old needs of man as well as to some of his more recent dilemmas, as the thoughts and actions of mankind are being led into new channels of great wisdom.

It is impossible for us to think of so signal a victory in space and not reflect upon our outlook on the more mundane challenges here on Earth.

Our urban crisis as well as other pressing domestic issues, our international tensions, will be solved only as men's thinking is opened to a more perceptice recognition of these problems and to the possibilities of settling them. No man, no nation, no race, can fail to think of such problems more deeply and with greater confidence and understanding as a result of men having visited the lunar surface.

To find solutions to our complex and interrelated problems of today and tomorrow, we can draw increasingly upon data processing and the systems approach of the type that management technical groups have developed in our space program.

There are some events that are beyond the power of words to describe, and landing on the moon by earthlings who return to Earth to tell us about it falls into this category. When this is linked to the miracles of television and all the other sciences and technologies involved, we stand in awe at mankind's applications of his intelligence.

In the long run it may well be that the chief contributions of space pioneering and exploration will not be the fields of science and technology at all but rather in the fields of human relations and of the spirit. It may well be that we are developing channels of understanding and unification far deeper and moore important than politics or diplomacy.

This was expressed by Archibald MacLeish in his comments on the Apollo 8 success, when he said, "To see the earth as it truly is, small and blue and beautiful in that silence where it floats, is to see ourselves as riders on the earth together, brothers on that bright loveliness in the eternal cold--brothers who know now they are truly brothers."

Time after time during the Mercury, Gemini and Apollo flights, and more particularly during the more recent flights as the Astronauts have looked across the lunar distance toward the agate Earth, our thoughts have turned to God, and each of us has found new spiritual meanings in our own lives.

Now that dauntless astronauts have strolled the moon's desolation; and, as man's ancient dream of direct contact with this celestial body is transformed into reality, human life, inescapably, will take on new dimensions.

-Marvin Hurley

Marvin Hurley, Executive Vice-President of the Houston Chamber of Commerce; Houston Magazine, August 1969.

SPINOFFS FROM SPACE

By Keith Elliott

> "Can this wonderful journey ever lead to any pratical result? Reflect a moment on the audacious go-aheadiveness of the Yankee . . ."
>
> --Jules Verne, From the Earth to the Moon

Back in 1865 Jules Verne, that canny French fictioneer and prophet, foresaw with incredible accuracy Man's most awesome reach, his quest for the moon. He even called the shot, targeting his imaginary moon probe from a site not far from Cape Kennedy. And he prophesied the use of a solid propellant in the mission, too. Gunpowder.

Well, even Jules Verne couldn't call them all. And he begged completely the question of whether "any practical result" might derive from Man's boldest venture. Yet practical benefits already achieved from America's space efforts are as dramatic in many ways as the moon landing itself.

For instance, space research is playing an increasingly significant role in the field of medicine. Dr. Denton Cooley, the famed Houston heart surgeon, uses a device developed by the National Aeronautics and Space Administration to monitor heart-transplant patients after surgery. Perfected at the University of Minnesota School of Medicine under a NASA contract, the device can gauge externally the volume of blood being pumped by a human heart.

Small biosensors used to monitor the physical condition of astronauts during flight are now being manufactured by Corbin-Farnsworth of Palo Alto, Calif., for use in hospitals throughout the nation. Pasted on chests of heart patients, the biosensors broadcast heart data to a nurse at a central console, permitting her to monitor the condition of many patients at once.

A computer technique used by NASA's Jet Propulsion Laboratory to improve TV pictures of the moon and Mars is now being used to clarify medical X-ray photographs. And a sensitive meter developed by NASA engineers to detect the impact of micrometeorites on spacecraft has spun off two earthly advances. One is a device that can measure the heartbeat of a chick embryo; the Federal Drug Administration is using it to test the effects of certain drugs. The other is a new medical tool that measures infinitesimal muscle tremors; it is helping physicians in diagnosing neurological ailments, such as Parkinson's disease, and during delicate neurosurgery.

Clearly, mankind is beginning to reap terrestrial rewards from his $44 billion investment in space. And "the process is just now accelerating," according to NASA's Dr. Richard L. Lesher. As chief of Technology Utilization--the NASA arm which seeks to apply space techniques and knowledge to the general welfare--Lesher insists "it is still too early to expect many specific transfers of space technology to other sectors of the economy."

He adds: "Since the economists tell us that the total innovative process requires somewhere between 10 and 20 years, it follows that the bulk of the commercially useful returns from the first decade of investment in space research and development will be dramatically harvested in the 1970's.

The best is yet to come, then. Nevertheless, Dr. Lesher's office can cite hundreds of spin-offs from space that have occurred already. Among them:

An electromagnetic hammer which makes metal flow like soft plastic, allowing the smoothing and shaping of metals without weakening them. Invented by builders of giant rockets at the Marshall Space Flight Center in Alabama, the new tool is widely used now in shipbuilding and auto manufacture.

A badge-sized hydrogen gas leak detector, developed for rocket engine testing by North American Aviation, is now being marketed as a battery gas leak detector for, among others, small boat owners.

In South Carolina, high-speed textile looms are being monitored electronically with equipment installed by Space Craft, a contractor on the moon vehicle team that is now using space-learned savvy to diversify on Earth.

An unusually tough coating developed for spacecraft is the basis for a new long-wearing paint now on sale in the nation's retail stores.

Several lines of processed foods originally conceived for astronaut diets aloft can now be found on supermarket shelves. They can also be found among GI field rations.

A six-legged vehicle proposed by a NASA contractor for unmanned exploration of the moon has been redesigned as "the wheel-less wheel chair" for crippled children. The powered walking chair, simple to operate, is being used in a number of children's hospitals. It can cross rough terrain, climb and descend stairs, and has been described by at least one satisfied user as "groovy."

Pyrolitic graphite, an insulating material for nuclear-powered rockets, is now being used to line the bowls of pipes for a cool smoke down to the last puff. What's more, graphite-lined pipes can be washed with soap and water.

At least 25 state highway departments are using NASA data in programs to cut down, through new surfacing techniques, wet-weather accidents due to "hydroplaning." NASA's findings have been employed in the surfacing of runways at 15 big-city airports, too, following its depth research into the causes of aircraft landing accidents on rainy days.

A sight switch developed for astronauts has been adapted to powered wheel chairs, enabling paralyzed people to control their movements by simple sidewise eye movements. In other applications, the same switch enables immobilized patients to signal a nurse or to turn appliances on and off.

The list goes on and on. And nobody has a complete list.

Elliott, Keith: "Spinoffs from Space." Oilways, number 3, 1969.