THE LUNAR EXCURSION MODULE

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The Lunar Excursion Module is that portion of the Apollo Spacecraft which will land two astronauts on the lunar surface and return them to the command and service modules waiting in lunar orbit for the return trip to earth. The development of LEM resulted from NASA's selection of lunar orbit rendezvous as the most feasible method of achieving lunar landing in this decade. In November 1962, a contract was awarded to Grumman Aircraft for the development of LEM with actual go-ahead in January 1963. Since that time, the vehicle has progressed through its preliminary and detailed design phases and is now entering into the hardware development and integration test phase. Figure 1 shows a metal mock-up of LEM, which was presented to NASA for review last fall.

LEM is a two stage vehicle. The Descent Stage on the bottom has an engine for deboosting the vehicle from lunar orbit to touchdown and a landing gear to attenuate landing shock and act as a launch pad for subsequent takeoff. The Ascent Stage on top houses the two man crew and contains the equipment necessary to guide and control the vehicle through its nominal or abort mission trajectories. The Ascent Stage has its own engine for powering lift off from the lunar surface and rendezvous with the Command and Service Modules.

Figures 2 and 3 show the nominal LEM Mission. Separation from the CSM in its 80NM lunar orbit is accomplished after two of the three astronauts have entered LEM and completed a check out of all systems. The maneuver consists of a —X translation using the Reaction Control System. The LEM is then positioned for injection into a Hohmann descent orbit. This is accomplished by firing the 10,500 lb. thrust descent engine for approximately 30 seconds. The powered descent phase begins at an altitude of 50,000 feet after almost an hour of coasting. The first phase of powered descent provides the major braking maneuver down to about 11,000 feet. The second or Line of Sight phase involves a pitch over maneuver from the maximum braking attitude to a pitch angle of approximately 43° accompanied by a reduction in descent engine thrust. At this point the programmed landing site comes into the view of the astronauts, approximately seven miles away. Thrust is varied to reduce velocity from about 730 fps and a sink rate of 165 fps at 10,000 feet to take over conditions of approximately 60 feet per second forward and 15 fps down at 700 feet above the lunar surface. Below 700 feet the nominal mode allows manual takeover to achieve touchdown in a satisfactory area within the design limits of the landing gear which are 10 fps vertical velocity and 4 fps horizontal velocity.

Once on the lunar surface, the astronauts check to see that all systems are in a satisfactory condition for launch. When checkout is completed, the astronauts don their Portable Life Support System (PLSS) Backpacks and protective coveralls and take turns exploring the lunar surface on 3 hour cycles. The design lunar stay time is approximately 35 hours. At the end of the lunar stay period, with the CSM almost directly overhead, the Ascent Engine is fired for a burn of approximately 7 minutes. During this time the Ascent Stage is lifted vertically for 12 seconds and then directed through a pitch program which takes it to an altitude of approximately 50,000 feet at a velocity of 5583 fps. At this point the vehicle begins a coasting Hohmann transfer orbit to rendezvous with the CSM. Mid-course corrections are effected by firing the RCS thrusters to establish a collision course between the LEM and CSM. Beginning at about 5 miles range further RCS burns are made so that the relative velocity between the LEM and CSM is reduced to near zero at a few hundred feet. At this point the LEM is aligned nose to nose with the CSM. LEM then pitches forward 90 degrees and translates into a hard dock with the CSM. The two astronauts transfer into the CSM taking with them scientific data and lunar samples and the LEM Mission is completed.

The mission has been stated very simply. It is, in fact, a great deal more complex than anything performed to date in manned spacecraft. Yet none of these mission phases is so complicated that it could not be performed by man given adequate sensors, a stable vehicle, and sufficient fuel. Since one pound of weight in the Ascent Stage is equal to something in the order of 500 pounds of weight in the Apollo vehicle on the pad at Cape Kennedy, there is a critical trade-off between manual control and automaticity. As a consequence, the nominal LEM Mission provides for automatic descent, ascent, and rendezvous, where automation is more efficient, and manual landing and docking where human judgment and perception exceeds sensor capabilities.

I would like to describe the LEM Flight Control System, which performs these functions and discuss some of the development areas which are concerned with man's participation in the mission.

Figure 4 shows the basic FCS configuration. It has a primary guidance, navigation, and control path which meets all the mission completion and abort guidance, navigation and control requirements. It also contains an abort system which allows guidance and control of the vehicle to a safe rendezvous in the event of a serious prime guidance system malfunction. Emphasis is placed on the fact that there are two completely independent guidance and control paths between guidance sensors and propulsion units. Effectively, there are two separate paths for crew safety and one for mission completion. The propulsion units include a reaction control system for maneuvering the vehicle in attitude and through small translations, and the descent and ascent engines for major brake and boost operations.

The Primary System is composed of the following units:

A three gimbal Inertial Measurement Unit (IMU), which continuously measures spacecraft attitude and senses acceleration along its three axes. IMU gimbal angles, appropriately transformed, are displayed on the two spacecraft 3-axis attitude indicators (FDAI).

A one-power Alignment Optical Telescope (AOT) through which navigational stars can be sighted to align the IMU.

A Rendezvous Radar (RR), which measures range, range rate, and line-of-sight angle relative to the LEM by tracking a transponder on the CSM.

A four beam doppler Landing Radar (LR), which senses velocity and altitude with respect to the lunar surface.

A digital LEM Guidance Computer (LGC), which accepts inputs from the IMU, AOT, RR, LR, attitude controller, translation controller, and manual insertions on its own keyboard, and solves the navigation, guidance, steering, and stabilization equations. It then sends out RCS on-off, descent engine throttle, and descent engine gimbal drive commands to control the spacecraft flight path.

Abort Guidance and Control is effected by the Abort Guidance Section (AGS) and the Control Electronics Section (CES) using strap-down inertial sensors and a digital computer for guidance and navigation, and then achieving stabilization and control through an analog auto pilot. The strap-down inertial reference consists of three integrating rate gyros and three accelerometers which feed vehicle angular velocity and acceleration to the computer. The processed information is used for the remainder of the systems computations, navigation, guidance, steering, euler angles for displays, etc. The Abort Guidance System starts its navigational computations after it has been aligned in attitude, velocity, and position with the Primary G&N System. Abort guidance and steering is initiated only if the primary G&N has malfunctioned. Spacecraft stabilization and control in the abort guidance mode is accomplished by an autopilot whose basic functions are performed by analog computation in the Control Electronics Section. The CES is designed to accept signals from the AGS and from the crew to provide various automatic, semi-automatic, and manual modes of vehicle control for aborted missions. There is some possibility that this mode may allow mission completion if a primary system failure occurs near the lunar surface.

The CES also provides the necessary input signals and logic circuitry for control of RCS firing, ascent and descent engine on/off, and on/off/throttling respectively, and descent engine gimballing. It also has logic circuitry to allow optimum RCS jet selection in the event of individual jet failures.

All of these subsystems and components make up the integrated flight control system, which is designed to effect complete LEM attitude and flight path control during all phases of the mission with varying degrees of astronaut participation. With each of the guidance systems provided, primary and abort, there are several modes of operation available.

Let us consider the primary system during a typical mission phase — that of powered descent from initiation of the line of sight phase at about 10,000 ft. to touchdown (Figure 5). We are in the automatic mode of the primary system with all navigation, guidance, vehicle stabilization and control under the control of the LEM guidance computer. The Landing Radar is updating the inertial data with respect to altitude and velocity through a weighting process which brings in the full effect of the radar at 5,000 feet for altitude and about 100 feet for velocity. The landing site lies straight ahead depressed about 55 degrees below the LEM Z axis. Downward visibility of 65° allows the proposed landing site to be seen through the Landing Point Designator, a kind of gunsight etched on the pilots window. The computer display indicates the landing site coordinates on the LPD. As the LEM approaches the landing site and the lunar surface features are seen in greater detail, the pilot may see that the automatic trajectory is taking him toward a crater or other obstruction which would make landing impossible. He may then override the automatic system with his attitude controller in pilot yaw and slew the LPD to a safe landing area. He then reads off the new LPD coordinates and inserts these into the LGC. The system then guides the vehicle toward the new landing site.

At an altitude of about 700 feet, the pilot switches the system from "Auto" to "Attitude Hold". This places him in control of the vehicle through a digital auto pilot which will be discussed later. The descent engine is controlled by a Rate of Descent (ROD) switch mounted near the throttle. This switch, working through the LGC allows the pilot to increase or decrease vertical velocity by a small increment (1—2 fps) each time the switch is actuated. At takeover, the pilot uses the 3-axis attitude controller to pitch the vehicle forward from the 42° braking attitude to an upright or zero pitch attitude. At this point his forward velocity is 40-50 feet per second, his sink rate is 8-10 feet per second, and his nominal landing site is about 4500 feet ahead. Effectively, this works out to about 2500 feet since the moon is rotating at 15 fps against the direction of landing approach. His fuel or ΔV remaining for the landing maneuver allows about 3½ minutes of flight, giving him a landing footprint which is about 7400 feet on its longest, or straight ahead dimension. He then maneuvers the vehicle to a safe landing area within this foot print by using his attitude controller to control the direction of the thrust vector, as in most VTOL devices. Altitude rate is "bled-off" and horizontal velocities are nulled so that the vehicle arrives over the intended landing point with about 150 feet of altitude, zero horizontal velocity, and a sink rate of 4-5 fps. The vehicle is then lowered straight down holding horizontal velocities, pitch and roll attitudes, and 3-axis rates as close to zero as possible. This is essentially an instrument let down to accommodate possible dust obscuration. The last radar update of the inertial data takes place at about 100 feet, making it advisable to descend as smartly as possible below this altitude to avoid build-up of inertial errors. At 50 feet of altitude sink rate should be reduced to about 3.5 fps and the pilot's left thumb would be moved to the descent engine cut-off button (at the present time it appears advisable to shut down the descent engine prior to touchdown to avoid excessive pressure build-up in the engine nozzle and possible vehicle stability problems). A mechanical probe approximately 4 feet in length will extend below each landing gear to insure a positive indication of altitude before engine shutdown. When the probe contact light on the instrument panel comes on, the engine shut-off button is pressed, and the vehicle drops to the lunar surface as engine thrust tails off toward zero.

DIGITAL AUTOPILOT

The Digital Autopilot (DAP) is worthy of mention because the concept is relatively unique in piloted vehicles. A DAP for LEM became feasible a little over a year ago when it was decided that the larger Apollo Guidance Computer would be procured on a common usage basis for LEM. Increased computer capability made it possible to incorporate a digital autopilot which would allow more flexibility and sophistication in the choice of guidance laws. In addition to providing greater efficiency in the automatic guidance modes, the digital autopilot bypasses the Control Electronics Section and allows the analog autopilot of the Abort System to be a completely separate and redundant control path. The disadvantage in the digital autopilot lies in adapting the system for manual control. In an analog autopilot, or for that matter, a conventional airplane control system, all of the control system parameters are continuously sampled. In a digital autopilot such things as controller deflection, vehicle attitude rates, etc., can only be sampled intermittently at a rate dependent upon the capacity of the computer. Reaching a compromise between the infinite sampling rates which pilots find desirable, and the lower rates, which the computer can handle becomes a problem of simulation. A first cut at sampling rates was made during a docking simulation last spring.

The study was run on a fixed base, six degree-of-freedom analog simulator, which had been set up to investigate overhead docking techniques. The simulator incorporated a realistic LEM crew station and instrument panel with a projected television external display which provided a six degree-of-freedom view of the stabilized CSM through the front window of LEM. A TV monitor mounted above the overhead window picked up the same picture after LEM pitchover.

Docking techniques were optimized on an earlier study using an analog autopilot with continuous sampling of control system parameters. For the study in question, the analog computer was modified to simulate a digital autopilot with respect to attitude controller detent, and rate command input sampling. A digital autopilot rate threshold for "attitude hold" activation was also simulated.

Four pilots flew three docking runs in each of 11 different DAP configurations. Each configuration represented a different combination of the following variables:

DETENT SAMPLING	RATE COMMAND SAMPLING	RATE THRESHOLD
1 per second	3 per second	2.5 deg/sec
5 per second	6 per second	5.0 deg/sec
10 per second	10 per second	

In addition, each pilot flew three runs in a continuous sampling mode.

The overall effectiveness of each DAP configuration was measured in terms of propellant consumption, pilot comments, and manual control activity. The latter was a measure of the difficulty experienced in making small attitude corrections and the success in achieving a desired "attitude hold" condition.

Results of the study showed no significant difference in propellant consumption among the DAP configurations, or between any DAP configuration and the continuous system. As might be expected, there was good correlation between pilot comments and control activity. Low sampling rates were graded inferior to the higher rates, and measurements of stick efficiency and time delays supported these assessments.Sampling rates of 10 per second for the out of detent signal, and 6 per second for attitude rate command were considered optimum as a result of this limited simulation. A further refinement of sampling rates is planned on a lunar landing simulation presently underway. With respect to the rate threshold for activation of "attitude hold" there appeared to be little to choose between 2.5 and 5 degrees per second. Generally speaking, pilots like this value to be as low as possible to obviate annoying "overshoot and return."

CREW STATION EVALUATION

I had planned to continue with a detailed description of a rather sophisticated lunar landing simulation which we recently completed to verify our LEM touchdown envelope; complete with dust obscuration and complete system errors, randomized within 3 sigma limits, and the like. But simulation, at best, is dull sport for pilots. Instead, I should like to tell you why we have the astronauts standing in LEM, and what we are doing to keep them that way.

Several years ago, when we were hoping to get into the manned spacecraft business, we proposed building a vehicle with a cockpit not unlike those of airplanes, which we knew about. The astronauts were given two conventional looking aircraft seats to sit in, and four large picture windows with 24 square feet of glass to look through. Restraint was provided by seat belt and shoulder harness, which you can't argue with.

Not long after finding ourselves in the manned spacecraft business it became apparent that glass made inefficient structure. We also found it a poor medium for dealing with solar radiation.

There soon began an effort to reduce the size of the windows. In five or six iterations the windows were successively reduced in size to the present triangular windows, which are 1½ square feet each. With each reduction, the seats were moved forward and tilted in an effort to retain a satisfactory cone of visibility. Finally, someone decided that a seat was unnecessary at zero "g" and not essential at lunar gravity (1/6 "g"), and the seats came out at a weight saving of about 45 pounds each.

The present standing flight position has met with everyone's satisfaction, and it provides a cone of visibility from the design eye point of 65° downward, 10° upward, 95° outboard, and 15° inboard; better than most helicopters in the areas critical to landing.

With the removal of the seats, we lost the positive restraint of the seat belt and shoulder harness. Calculations have shown that landings within the LEM touchdown envelope may result in accelerations at the crew station of 5.9 "g's" vertically, and 2.9 "g's" horizontally, in combination. In addition, some form of restraint is necessary to insure that the astronaut is properly immobilized at his flight station during maneuvers at zero "g".

To investigate the landing impact problem, a mock-up of a single LEM flight station was placed on an inclined ramp, as shown in figure 6. Actually, this was the second test rig used in the program. The first was a single axis drop test vehicle. This is a bi-axial rig, which is kicked up the ramp by a pneumatic ram providing simultaneous application of vertical and horizontal acceleration. The philosophy used in developing a restraint system was to start with only hand grips for stability and the man's legs for impact attenuation. At the present time we have done extensive testing through an envelope of 4.5 "g's" vertically and 2 "g's" horizontally, and have arrived at a restraint system which adequately covers this regime. It consists of armrests which deflect on impact and contain the astronaut laterally, two hand grips which must be grasped before impact, and a harness to restrain him during rebound after impact. The harness, shown in Figure 7, is attached to inertia reels and also performs the function of zero "g" restraint. A "window washer" strap on the front of the harness is used to position the pilot for viewing through the overhead docking window.

Earlier versions of this harness have received extensive zero "g" testing in the reduced gravity KC-135.

This sums up this briefing on a few of the development phases of the Lunar Excursion Module. Some of the numbers will change, but hardware is starting to roll off the line, and nothing insurmountable appears to be standing in the way of a timely visit to the moon.

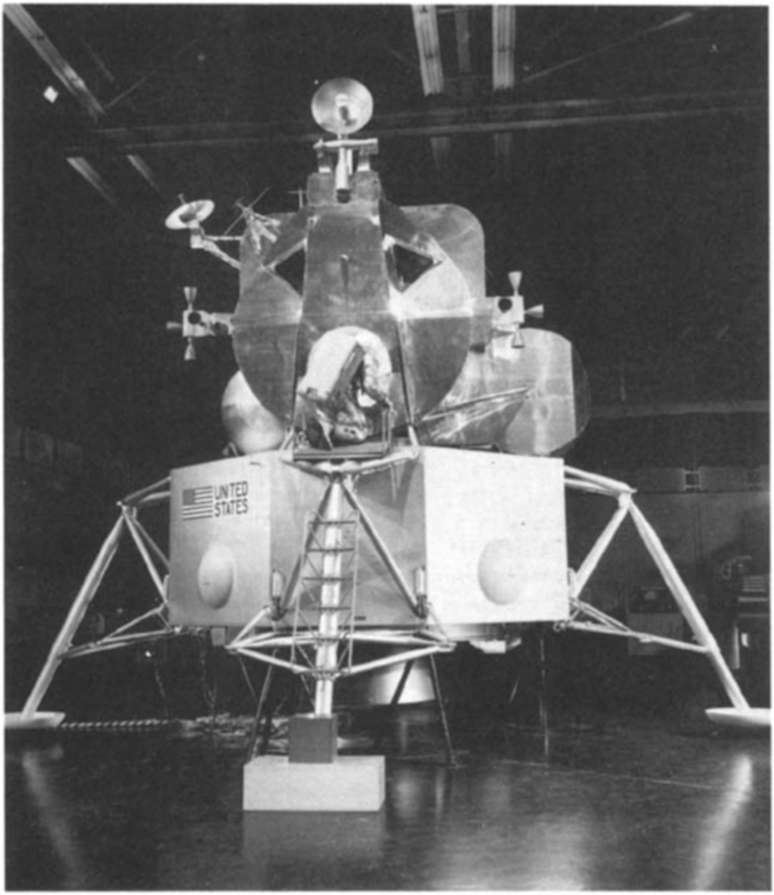
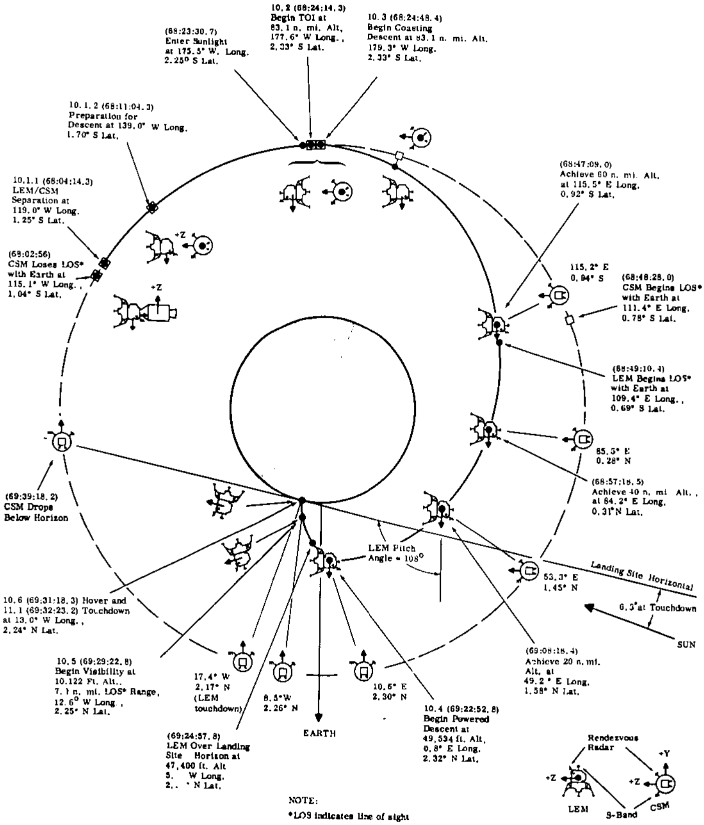
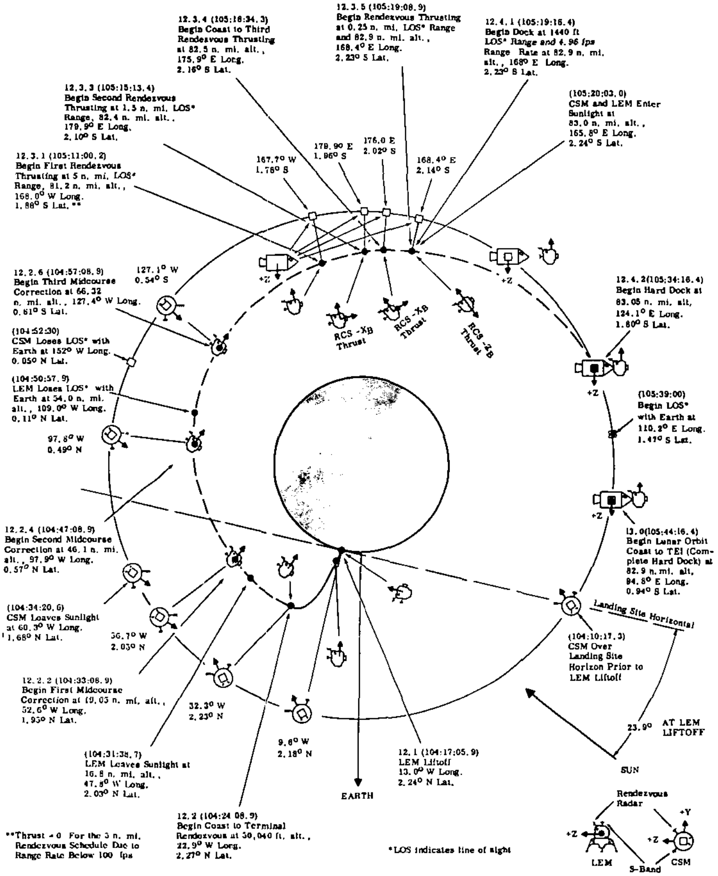


Figure 1



LEM Descent Phase Description

Figure 2



12.3.4 (105:18:34.3)
Begin Coast to Third Rendezvous Thrusting at 82.5 n. mi. alt., 175.9° E Long. 2.16° S Lat.

12.3.5 (105:19:08.9)
Begin Rendezvous Thrusting at 0.25 n. mi. LOS* Range and 82.9 n. mi. alt., 168.4° E Long. 2.23° S Lat.

12.4.1 (105:19:16.4)
Begin Dock at 1440 ft LOS* Range *and 4.96 fps* Range Rate at 82.9 n. mi. alt., 168° E Long. 2.23° S Lat.

12.3.3 (105:15:13.4)
Begin Second Rendezvous Thrusting at 1.5 n. mi. LOS* Range, 82.4 n. mi. alt., 179.9° E Long. 2.10° S Lat.

(105:20:03.0)
CSM and LEM Enter Sunlight at 83.0 n. mi. alt., 165.8° E Long. 2.24° S Lat.

12.3.1 (105:11:00.2)
Begin First Rendezvous Thrusting at 5 n. mi. LOS* Range, 81.2 n. mi. alt., 168.0° W Long. 1.88° S Lat. **

12.2.6 (104:57:08.9)
Begin Third Midcourse Correction at 66.32 n. mi. alt., 127.4° W Long. 0.61° S Lat.

12.4.2 (105:34:16.4)
Begin Hard Dock at 83.05 n. mi. alt, 124.1° E Long. 1.60° S Lat.

(104:52:30)
CSM Loses LOS* with Earth at 152° W Long. 0.05° N Lat.

(104:50:57.9)
LEM Loses LOS* with Earth at 54.0 n. mi. alt., 109.0° W Long. 0.11° N Lat.

(105:39:00)
Begin LOS* with Earth at 110.2° E Long. 1.47° S Lat.

12.2.4 (104:47:08.9)
Begin Second Midcourse Correction at 46.1 n. mi. alt., 97.9° W Long. 0.57° N Lat.

13.0 (105:44:16.4)
Begin Lunar Orbit Coast to TEI (Complete Hard Dock) at 82.9 n. mi. alt, 94.8° E Long. 0.94° S Lat.

(104:34:20.6)
CSM Leaves Sunlight at 60.3° W Long. 1.68° N Lat.

(104:10:17.3)
CSM Over Landing Site Horizon Prior to LEM Liftoff

12.2.2 (104:33:08.9)
Begin First Midcourse Correction at 19.05 n. mi. alt., 52.6° W Long. 1.95° N Lat.

(104:31:38.7)
LEM Leaves Sunlight at 16.8 n. mi. alt., 47.8° W Long. 2.03° N Lat.

12.1 (104:17:05.9)
LEM Liftoff
13.0° W Long.
2.24° N Lat.

12.2 (104:24 08.9)
Begin Coast to Terminal Rendezvous at 50,040 ft. alt., 22.9° W Long. 2.27° N Lat.

**Thrust = 0 For the 5 n. mi. Rendezvous Schedule Due to Range Rate Below 100 fps

*LOS indicates line of sight

LEM Ascent Phase Description

Figure 3

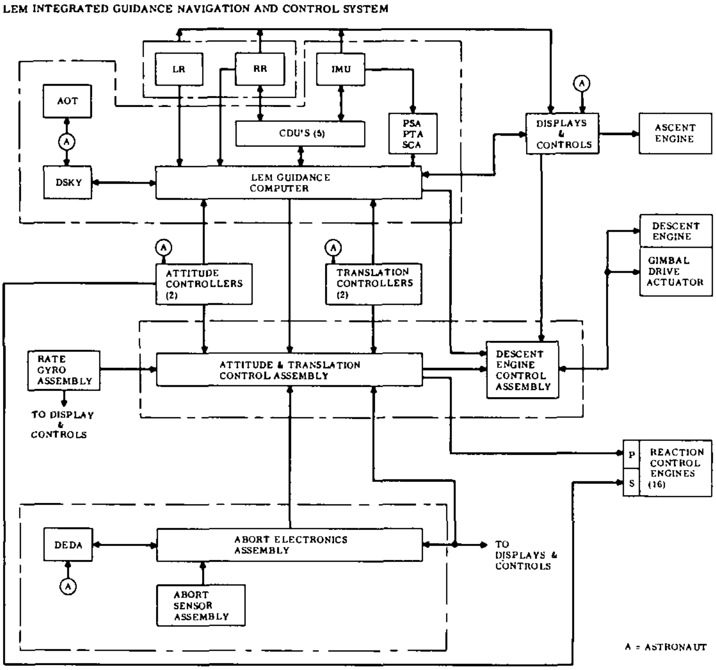


Figure 4

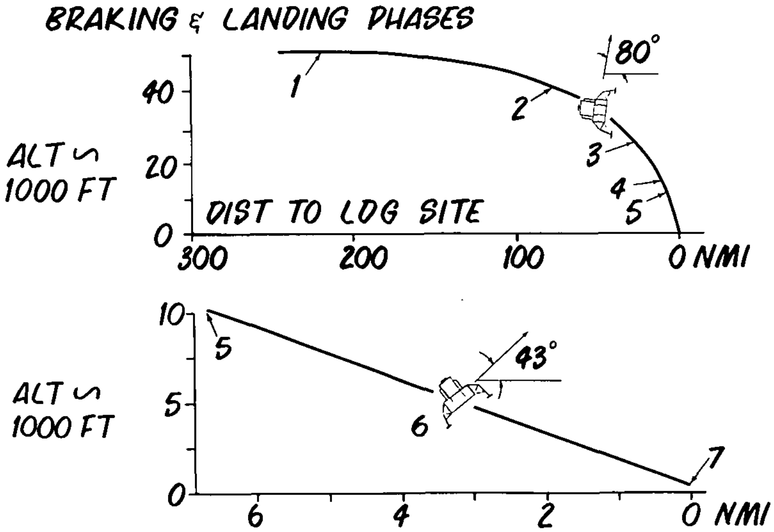


Figure 5

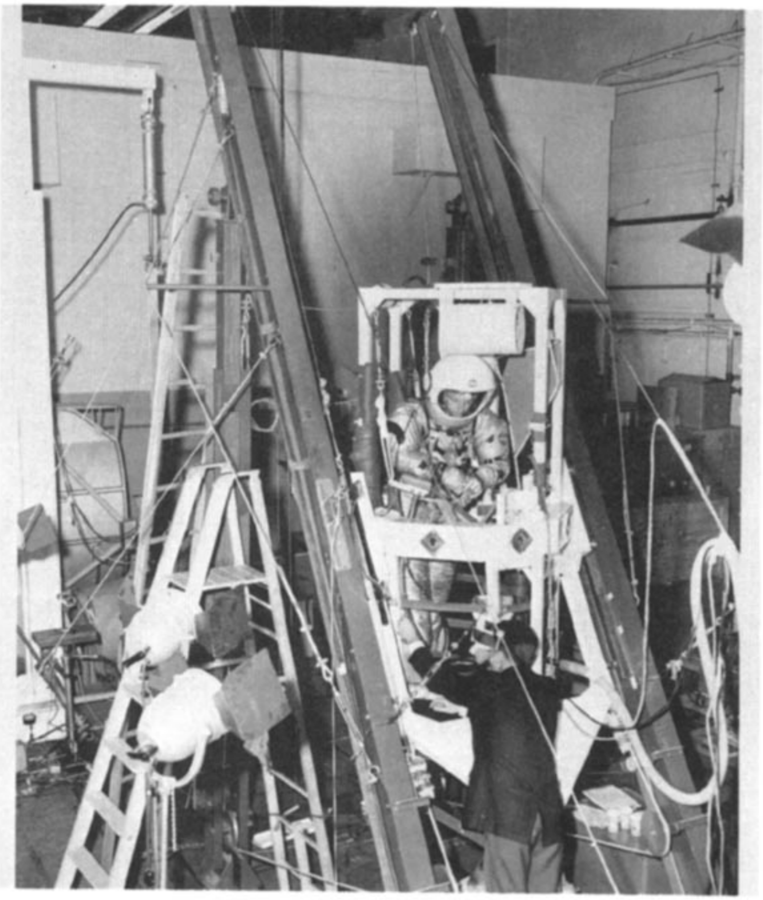


Figure 6

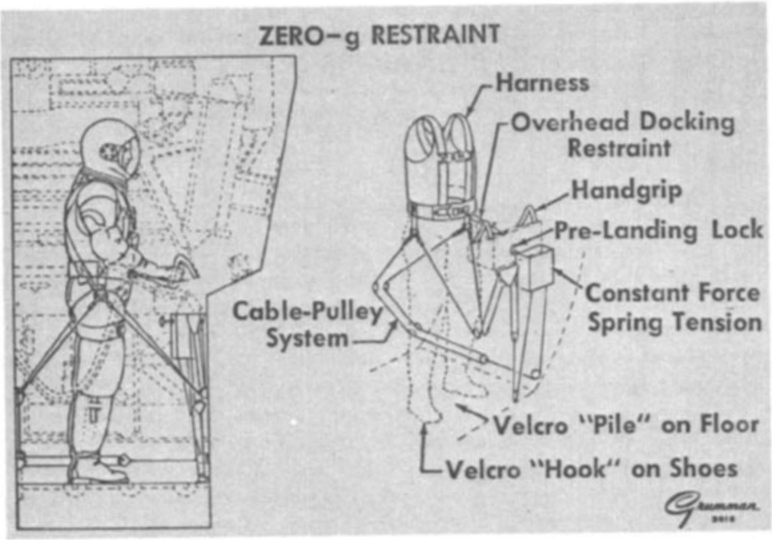

ZERO-g RESTRAINT
Harness
Overhead Docking Restraint
Handgrip
Pre-Landing Lock
Constant Force Spring Tension
Cable-Pulley System
Velcro "Pile" on Floor
Velcro "Hook" on Shoes
Grumman

Figure 7