NASA TECHNICAL
MEMORANDUM

NASA TM X-58036
December 1969

FLIGHT CONTROL OF THE APOLLO LUNAR-LANDING MISSION

Presented to
the Eighth International
Symposium on Space Technology and Science
Tokyo, Japan, August 25, 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

NASA TM X-58036

FLIGHT CONTROL OF THE APOLLO LUNAR-LANDING MISSION

M. P. Frank
Manned Spacecraft Center
Houston, Texas

FLIGHT CONTROL OF THE APOLLO LUNAR-LANDING MISSION

M. P. FRANK*

ABSTRACT

The purpose of the paper is to provide the reader with insight into the functions and activities carried out in the Mission Control Center and into the procedures used for controlling the Apollo lunar-landing mission.

To provide the proper background, the first part of the paper consists of a functional description of the worldwide tracking and data acquisition network, of the Mission Control Center, and of their capabilities in providing the necessary data from the spacecraft and flightcrew to the flight control team in the Mission Control Center. The flight control organization and the technical disciplines involved are discussed. A detailed description of the flight control activities and of the data and information transferred between the flightcrew and the ground controllers is given for particular phases of the mission. Emphasis is placed on the navigation and guidance aspects, but the systems-monitoring and consumables-analysis activities are also discussed.

INTRODUCTION

The successful completion of the first Apollo lunar-landing mission was a spectacular achievement in many ways, not the least of which was the relatively trouble-free manner in which the entire operation was accomplished. This smoothness was achieved as a result of experience gained from the preceding four manned missions. The purposes of the development flights were to verify spacecraft hardware design and to demonstrate operational techniques required to accomplish lunar landing and return. Operational concepts developed earlier were tested, evaluated, and occasionally modified during the preliminary missions; and the functions and activities carried out in the Mission Control Center (MCC) during the landing mission evolved from this process.

The purpose of this paper is to provide the reader with insight into the MCC functions and activities and into the procedures used for controlling the Apollo lunar-landing mission which consists of several phases. The step from one phase to the next represents a major decision point which leads to a higher mission plateau, as illustrated in figure 1, and the decision to take each step to a higher plateau is made only after a careful assessment of the status of the spacecraft by the flightcrew and the MCC. The mission profile is summarized by figure 2.

---

*Flight Director, NASA Manned Spacecraft Center, Houston, Texas 77058, U.S.A.

A description of the Manned Space Flight Network (MSFN), of the MCC, and of the capabilities of MSFN and MCC in providing the necessary data to the flight control team is presented. The flight control organization and functional responsibilities are discussed, and a description of the MCC activities in support of the lunar-landing phase is given, with special emphasis being placed on the navigation and guidance aspects.

THE MANNED SPACE FLIGHT NETWORK AND THE MISSION CONTROL CENTER

The worldwide ground operational support systems network is composed of facilities located at the launch site, at remote land-based sites, aboard tracking ships, and on aircraft. This network performs four basic types of communication vital to mission success: tracking, telemetry, command, and spacecraft-to-ground voice communications.

The stations in the MSFN (fig. 3) are distributed around the world to provide as much earth orbit trajectory coverage as possible. Continuous coverage is obtained once the spacecraft reaches an altitude of 10 000 nautical miles. Flight control personnel are not deployed to the various stations of the MSFN; only the personnel required to operate and maintain the communications equipment are located there. The MSFN stations can be thought of as remotely operated relay links between the spacecraft and the MCC. The NASA Communications Network (NASCOM) (fig. 4) links the stations by landlines, submarine cables, radio, microwave, and the satellite communications network that uses Intelstat II.

During manned space flight, the MCC (located at Houston, Texas) is the focal point of the MSFN. The MCC consists of four basic operational systems: the display/control system, the real-time computer complex (RTCC), the communications command and telemetry system, and the voice communications system (fig. 5).

Data and communications from the spacecraft are received at the remote stations and relayed to the MCC by way of the NASA Goddard Space Flight Center and the NASCOM. Upon reaching the MCC, spacecraft telemetry parameters are identified, converted to appropriate engineering units, and routed to the display system which groups the parameters in preestablished formats and makes the data selectively available to the flight controllers by the digital television system, by chart recorders, or by projection plotboards. The data processing is automatically performed by systems employing Univac 494 computers and an IBM 360/75 computer. All digital displays are completely updated every 2 seconds when data are being received from the spacecraft. The time interval from receipt of telemetry at the remote station to display of data in the MCC is approximately 5 seconds.

Tracking data reach the MCC by the same route as the telemetry data. The raw data are examined for consistency by tracking data analysts, are automatically corrected for individual station biases, and are processed by the orbit-determination program in the RTCC. The RTCC uses an IBM 360/75 digital computer with expanded core storage to process and format the telemetry data, to process the tracking data for orbit determination, and to perform many other calculations necessary for flight control. An additional machine stands by at all times to be brought on line should a failure occur in the operating machine.

Two types of commands are sent to the spacecraft from the MCC: coded discrete commands, which configure the spacecraft communications equipment; and data loads, which are inserted directly into the spacecraft onboard computer. All commands to be sent to the spacecraft are loaded into the remote-site command processors by personnel in the MCC coordinating with the remote-site station operators, and each command is automatically checked by the system to ensure that the command is identical to that specified in the MCC. The command is transmitted to the spacecraft from the remote site by the flight controller in the MCC. The commands received by the spacecraft are automatically checked to verify that they are valid. By way of telemetry, the flight controller sending the data checks the data loaded into the spacecraft computer.

The voice communications system is composed of multiple, multistation networks. The networks are configured to link the flight controllers, MCC support personnel, and network station controllers in order to provide optimum support of the mission operations.

The MCC has dual facilities and equipment, providing the capability to conduct combinations of simultaneous real-time missions, simulation exercises, or system checkout. This capability makes it possible to conduct an actual Apollo flight from each control area at the same time, or to simultaneously train flight operations teams.

FLIGHT CONTROL FUNCTIONS AND ORGANIZATION

The Apollo spacecraft design enables the flightcrew to abort the mission and return to earth without any outside aid, but design of a spacecraft with the onboard capability of performing a complete lunar-landing mission was beyond the reach of the state of the art in this decade. Ground support in several forms is mandatory, and a distinct difference is made between the prelaunch support provided by the launch-control center at Cape Kennedy and the post-lift-off support directed by the MCC. Only the inflight support from the MCC will be discussed in this paper.

The flight control personnel in the MCC are charged with the overall responsibility of directing and controlling mission operations of the manned space-flight program of the United States. The flight control team, under the leadership of the Flight Director, is specifically responsible for the development of the mission operations plan and for the detailed conduct of the mission. The Flight Director determines the priority of the flight plan activities and may take any action necessary for flight safety or for the successful completion of the mission. The Flight Director has the responsibility for the decision to continue with the nominal flight plan, to select an alternate mission plan, or to abort the mission. To assure the intelligent exercise of this authority, a vast amount of data is processed and analyzed in the MCC. The intelligence that results from this data analysis equips the MCC to perform many functions not inherent in the basic command and control responsibility in support of the flightcrew activities.

Manned Spacecraft Center management control is exercised through two different methods. One method is through the approval of the Flight Mission Rules document (published before the flight by the flight control team) and the second is by direct consultation with the Flight Director during the mission.

The Flight Mission Rules contains the basic mission control philosophy, the priorities for alternate missions, and the description of courses of action to be followed for system failures and other contingencies. This document is reviewed by management, and concurrence with the contents by the Apollo Program Manager and the Director of Flight Operations constitutes management direction to conduct the flight as planned.

The Apollo Program Manager, the Mission Director from Center Headquarters, and the Director of Flight Operations of the NASA Manned Spacecraft Center, representing top-level NASA management, are present in the Mission Operations Control Room (MOCR) during the active phases of the mission. If time permits, the managers are consulted by the Flight Director on any questions involving the alteration or deletion of mission objectives or planned activities. When time does not allow this consultation, the Flight Director alone is responsible for these decisions.

The focal point of the flight control activity is the MOCR, where the key members of the flight control team are located. The team is functionally organized in accordance with the technical disciplines represented within the MOCR to provide several levels of data evaluation and decisionmaking responsibility within each discipline (fig. 6). Each flight controller in the MOCR, with the exception of the spacecraft communicator, is the leader of a team of specialists. These specialist teams are located in the Staff Support Rooms (SSR) adjacent to the MOCR. A separate SSR for each flight control functional category exists, and each has the same display and communication equipment that is available to the flight controllers in the MOCR. In addition, SSR teams are equipped with chart recorders and closed-circuit television cameras for displaying data generated in the SSR to the MOCR. Each SSR team is staffed with experts for support of a specific MOCR position, and these experts perform data analysis, analyze long-term performance trends, compare these trends with base-line data, and relay this information, along with recommendations, to the MOCR personnel. The basic flight control functional categories are navigation and trajectory control, systems analysis and management, flight planning, aeromedical support, network management, and recovery planning.

Navigation and Trajectory Control

Because of the precise navigation accuracies required in order to complete the lunar-landing mission, the MCC, with its ground-based system of tracking stations and large digital computers, was given the primary responsibility for performing navigation computations for all phases of the mission, except for the rendezvous in lunar orbit. The navigation information in the form of a spacecraft state vector (position and velocity at a given time) is periodically transmitted to the spacecraft computer. With these periodic updates, the spacecraft computer is capable of navigation and guidance accuracies acceptable for performing powered flight maneuvers and reentry.

The spacecraft navigation and guidance system, with its inertial platform, sextant, and computer, is also used to provide navigation updates on a limited basis. However, the onboard capability is reserved primarily to provide a backup to the ground-based system so that the crew could return safely to earth if communications with the ground were lost. Onboard navigation sightings of the landing site by the spacecraft in lunar orbit may be combined with the MSFN tracking data to more accurately locate the lunar-landing site relative to the spacecraft orbit. These onboard sightings are used to improve the landing accuracy of the lunar module (LM).

During the rendezvous in lunar orbit, the relative navigation of the LM to the command and service module (CSM) is performed on board. The relative motion between the two spacecraft is more accurately determined by the rendezvous radar in the LM and by the very-high-frequency ranging and optical tracking complement in the CSM than can be determined by ground-based radar at the lunar distance. However, the initial state vectors prior to initiation of the rendezvous are supplied by the MCC.

Considerations other than accuracy exist that enhance the concept of primary ground-based navigation. The crew activities required in order to perform the optical sightings are time consuming. If the flightcrew had this responsibility, a significant part of each day would be spent performing optical sightings. Perhaps of even more importance is the amount of service-module reaction-control-system (RCS) propellant that would need to be allocated for maneuvering the spacecraft if the navigation sightings must be performed on board.

In addition to navigation computations, the MCC performs the targeting computations for most powered flight maneuvers. For the CSM, these maneuvers are the transearth and translunar midcourse corrections, the maneuvers that place the spacecraft in lunar orbit (lunar orbit insertion (LOI)) and send the spacecraft back to earth out of lunar orbit (transearth injection (TEI)), and the lunar orbit plane change performed by the CSM while the LM is on the lunar surface. The target parameters are in the form of a velocity change to be made $\overline{\Delta V}$ and a time to initiate the change. The MCC-computed targeting for the LM consists of these parameters for descent orbit insertion (DOI), the landing-site coordinates for the landing maneuver, and the time to initiate maneuvers in the rendezvous sequence. The target parameters are relayed to the spacecraft and inserted into the onboard computer. The spacecraft guidance system then controls the spacecraft as necessary to achieve the desired trajectory change.

Trajectory targeting is essentially a matter of determining the best trajectory for accomplishing the mission objectives. Each possible solution is evaluated in terms of system and operational constraints, propellant requirements, and probability of successfully accomplishing the mission. Once the selection of the desired trajectory change has been made by the MCC, the target parameters for the maneuver to achieve the desired trajectory are computed by special processors in the RTCC and relayed to the spacecraft.

The fact that targeting for the maneuvers is not done by the spacecraft does not reduce the probability of a successful mission since communication with the ground is mandatory for continuing with a nominal mission. Appropriate target data for transearth injection and LM lift-off are provided to the crew for every lunar orbit as far in advance as necessary to ensure that sufficient information is always available on board to provide a safe return if communications with the ground is lost. Navigation data are updated at necessary intervals for this same purpose.

Systems Analysis and Management

Spacecraft and launch vehicle systems engineering personnel comprise a large percentage of the flight control team in the MCC. Much of the total ground-support effort is devoted to the category of spacecraft systems analysis and management, and various roles are played by the MCC. These include routine monitoring of system parameters available on the telemetry, aiding the flightcrew in troubleshooting and correcting system problems, and updating predictions of system performance based on inflight data.

Monitoring of spacecraft systems data is one of the more important tasks of the MCC. The key parameters which can be used to evaluate systems performance are measured in the spacecraft and telemetered to the MCC for display in real time to the flight controllers. Whereas the flightcrew is frequently unable to keep a close watch on all spacecraft systems, either because they are too busy with other tasks or because they are sleeping, sufficient personnel are assigned in the MCC to provide close monitoring of all the data 24 hours a day. The MCC also has a capability to record and edit data and to make the data readily available for replay and study. Trend plots can be generated to show how a parameter has behaved over a period of time, and parameters can be grouped to immediately show the total performance of systems.

The purpose of the monitoring is to evaluate the performance of the systems. If a system is behaving abnormally, the data can be used to analyze the problem and to evaluate the attempts to correct or compensate for it. The MCC also has a major role in this troubleshooting activity. Spacecraft system engineers are available to flight controllers in the MCC for direct consultation and for specific investigative assignments during the mission. These personnel in many cases have either designed, built, or tested the system and they possess the depth of knowledge that can only be obtained through this experience. The MCC support in troubleshooting system problems is significant from two aspects: first, from the availability of a large amount of data for evaluation and, second, from the availability of systems experts to analyze the data and suggest corrective action.

Systems monitoring during the launch to earth orbit and the lunar landing has a special characteristic. During these phases, if problems develop, the decision to continue or to abort must be made immediately; there is no time for troubleshooting or for discussion with the crew. The flight controllers and the crew must be able to quickly recognize the situation and to know the proper immediate course of action. For these phases, detailed premission operations rules are defined which specify the type of failures that require immediate aborts. Special attention is given to these phases in the training periods prior to flight.

The third major activity in spacecraft systems management concerns performance prediction based on performance observed. Prior to launch, the spacecraft is loaded with consumable commodities which are used by the various systems throughout the mission. Examples are the propellants used by the main propulsion and reaction control systems, the cryogenic hydrogen used by the fuel cells in the generation of electricity, the cryogenic oxygen used by the fuel cells and for cabin pressurization and crew metabolic consumption, the electrical energy stored in the batteries, and water used for crew consumption and evaporative cooling of spacecraft systems.

The amount of a given consumable that is loaded is limited by spacecraft storage capacity, and in some cases, by the weight-carrying capacity of the launch vehicle or spacecraft. The amount of a consumable that must be carried is computed from preflight system performance estimates and from previous flight history. However, these performance estimates are not perfect.

A performance variation between spacecraft exists, and a particular spacecraft may perform a little differently in orbit than it performed in the test chamber. In addition, system degradation which can occur in flight can cause a decrease in the operating efficiency that results in a consumable being used at a greater rate than expected.

The MCC personnel continuously monitor the amount of each consumable remaining on board the spacecraft and the rate of consumption. The quantity remaining in the spacecraft is compared to the preflight prediction. If the differences cannot be attributed to a nonstandard use of the system, the system performance is assumed to be different from the preflight predictions. Estimates of remaining mission requirements are then computed, based on the revised performance of the system. If the predictions indicate that a system does not have enough of a consumable remaining to complete the nominal mission, then a contingency course of action must be devised. This contingency action may be to simply eliminate all nonessential use of the system and continue with the planned mission, or it may entail an immediate abort or selection of an alternate mission plan with lesser objectives. If a shortage occurs, the decision is made and the action taken is based on the consumables analysis and prediction performed by the MCC.

Flight Planning

The flight plan, which is followed by the crew during the mission, is in reality a schedule of activities the crew is to perform. The flight plan lists, at the appropriate time in the mission, the major events and the general crew activities required to prepare for and accomplish these events. The flight plan also contains the routine activities, such as the periodic system checks and maintenance, and the navigation sighting schedules for the entire mission from lift-off to splashdown. Frequently, unscheduled events that occur during a mission cause changes in the flight plan. Activities may be added, deleted, or rescheduled. If changes occur, a revision to the crew's activity schedule must be made, and the impact on the mission must be evaluated. This activity planning is performed by the MCC and relayed to the crew in the form of flight plan updates.

Aeromedical Support

The primary role of the MCC is to anticipate crew physiological problems and to give advice for preventing their occurrence. A secondary but important role is data gathering for evaluation of man's capabilities to function in the space environment.

The physical condition of the crew is monitored by the Flight Surgeon and his staff in the MCC. This is accomplished through the telemetered heart- and respiration-rate data derived from biosensors attached to the crewmen and through periodic voice reports from the crew. During extravehicular activities, the system data from the extravehicular mobility unit are also of special interest to the medical personnel.

In addition, the MCC assists in evaluating the space environment. Stations around the world that comprise the Solar Particle Analysis Network provide continuous monitoring of solar radiation. The reports from these stations are collected and analyzed in the MCC to determine if a crew hazard exists.

Network Management

During the mission, the MCC provides positive direction to the MSFN. The management consists of scheduling periods of support, designating handover times, configuring the remote site to process and relay specific data, and exercising command coordination.

Recovery Planning

The recovery of the spacecraft and crew is the responsibility of the Department of Defense (DOD), and the planning for this activity is accomplished jointly by NASA and the DOD. Nominal and contingency recovery plans are developed prior to each mission. Although recovery forces are concentrated in the planned landing area, the capability exists to retrieve the crew and the spacecraft from almost anywhere in the world. One of the important functions performed in the MCC is the real-time recovery planning to provide for contingencies such as emergency returns to earth or unacceptable weather conditions in the prime recovery area.

MCC SUPPORT DURING LM DESCENT AND LANDING PHASE

This section contains a description of the MCC trajectory control and navigation support provided to the spacecraft during the preparation for and the execution of the lunar landing in Apollo 11. Other specific activities such as systems analysis and management, flight planning, and so forth, are not discussed in this paper.

Phase Description

At the beginning of the lunar-landing day, both spacecraft modules were docked, circling the moon in a 60-nautical-mile-altitude orbit. For each 2-hour orbit period, the spacecraft was occulted by the moon for approximately 46 minutes.

The LM was undocked from the CSM (fig. 7) (prior to acquisition) on revolution 12, approximately 4 hours after initiation of systems activation. After 25 minutes of visual inspection and formation flying, the CSM performed an RCS translation maneuver of 2.5 fps radially downward to provide additional separation between the two spacecraft. This maneuver, which occurred in view of the earth, placed the CSM in an "equiperiod" orbit with the LM and allowed the rendezvous ranging devices to be checked before the LM was committed to an orbit from which a rendezvous would be required. The LM began the descent to landing with the DOI maneuver approximately 1 hour after the CSM performed separation. This maneuver, using the descent engine, occurred behind the moon while out of contact with the MCC. The DOI maneuver decreased the LM velocity by 72 fps and placed the LM in an elliptic orbit with a perilune altitude of 8.3 nautical miles. The maneuver was targeted so that the powered descent (PD) to landing could be initiated at perilune, approximately 260 nautical miles uprange of the landing site. The powered descent required a continuous thrusting of the descent engine for 12 minutes 36 seconds. During this maneuver, the thrust direction and magnitude were modulated as necessary to bring the LM to a hovering condition about 4 miles west of the center of the planned landing area. The pitch attitude profile allowed the crew to avoid obstacles by visually inspecting the lunar surface during the terminal phase.

Powered descent consisted of three phases as shown in figure 8. The first phase, called braking, lasted 8-1/2 minutes, during which the LM guidance computer (LGC) automatically controlled the spacecraft attitude and descent engine thrust magnitude in order to arrive at the specified state-vector target conditions at "high gate." During the braking phase, the LM landing radar was activated, and it provided altitude updates to the inertial navigation system. The spacecraft attitude did not allow the crew to see the moon until about the last minute during this phase.

The second phase, called approach, was entered at high gate, where the LM was pitched up to about a 45° attitude which allowed the crew to see the landing area for the first time. The approach phase lasted approximately 1-1/2 minutes, and it gave the crew an opportunity to select a specific landing point within the maneuver capability of the spacecraft. This phase is normally under automatic control of the LGC, but manual redesignation of the desired landing point was accomplished during Apollo 11. The approach phase began at approximately 5 nautical miles from the landing point and ended at "low gate," approximately 1500 feet uprange of the landing point. At low gate, approximately 500 feet above the surface of the moon, the commander assumed control of the LM; and the third phase, called landing, was completed manually.

MCC Activities

The period prior to, and during the lunar descent and landing, is one of very high activity in the MCC, as well as in the spacecraft. In this time period, the LM is powered up and activated, all systems are checked out, and the landing maneuvers are targeted and executed. A time-line summary of the MCC activities during this period is presented in figure 9.

Guidance and navigation system activation and checkout. - The MCC plays a direct part in the guidance and navigation system activation. The LGC clock synchronization, which is manually performed by the crew, is checked by the MCC to a greater accuracy by reading the telemetry data from both spacecraft. If the LGC clock requires updating, it is accomplished by the updata link by the MCC.

After initial start of the LGC, it is desirable to check the quantities that were stored in the erasable memory prior to launch to ensure that the extended period of shutdown and the power up have not altered the values. A dump of the LGC erasable memory registers is recorded by the MSFN and printed out in the MCC. The values contained in each register are checked by computer specialists in the MCC and verified to be correct. If any values have changed, they are corrected by the MCC by way of the uplink.

Because the LM alinement optical telescope is useless in the docked configuration, the MCC participates in the docked alinement of the LM inertial platform. A coordinated procedure involving the crews of both spacecraft was developed which results in coarse alinement of the LM platform, based on the CSM platform alinement and the relative angles between the two spacecraft axes. The platform gimbal angles of both spacecraft, when read simultaneously, are used by the MCC to compute the differences in alinement between the two spacecraft platforms. The MCC then computes the torquing angles which will accurately aline the LM platform to the desired orientation.

The direction cosines defining the desired orientation of the inertial platform relative to the reference coordinate system, called REFSMMAT, are loaded into the computers of both spacecraft. These values are computed by the MCC so that the gimbal angles between the platform and the spacecraft will be all zeros for the LM as it touches down on the lunar surface.

The accelerometers in the inertial measurement units (IMU) of both spacecraft modules are periodically checked by the MCC. A null bias compensation is loaded into the spacecraft computers for each accelerometer. If the bias changes, the compensation can be changed accordingly. The MCC monitors the output of each accelerometer during nonthrusting periods and is prepared to update the bias compensation if necessary.

The LM has two onboard guidance systems. The primary system employs an inertial platform with accelerometers mounted to it and a large-capacity digital computer. The backup guidance system, called the abort guidance system (AGS), uses strapdown gyros and a relatively small-capacity digital computer. The AGS provides a second source of navigation on board the LM and can compute targeting for the rendezvous maneuvers; however, the AGS computer is not programed to accomplish the landing maneuver. After checkout, the AGS is initialized and alined to the primary system by the LM crew, and this procedure is repeated periodically during the LM activities. The contents of the AGS computer registers are monitored by the MCC to verify that the AGS is configured properly and that the correct values were read from the primary system into the abort system. The MCC also monitors the insertion of digital autopilot data into the LGC and verifies that the correct numbers appear in the computer registers.

Navigation and orbit prediction. - The orbit navigation is performed by the earth-based tracking radar of the MSFN. The typical time line of activity (summarized in fig. 10) consists of tracking the spacecraft for an entire front-side pass (approximately one-half of a full orbit), processing the data to compute a state-vector update while the spacecraft is behind the moon, and updating the spacecraft state vector during the next front-side pass. This update requires that the spacecraft state vector be propagated approximately two orbits in advance of the landing. Thus, extremely accurate orbit prediction, based on accurate tracking data, is essential to achieve small landing errors.

The MSFN radars and the orbit determination and propagation data computed in the MCC can precisely determine the inertial parameters of the lunar-orbit trajectories. However, the uncertainties in the selenographic parameters of latitude, longitude, and altitude can be determined only to the degree of accuracy with which the lunar surface is mapped. To reduce the inaccuracy in the location of the orbit relative to the desired landing site, optical tracking is performed by the command-module pilot prior to LM descent. A well-defined, easily identifiable feature near the landing site is tracked, using the 28-power sextant. The data are processed by the MCC and are used to locate the spacecraft orbit relative to the desired landing site.

The final navigation updates prior to the landing are relayed to both spacecraft during the front-side pass preceding DOI. Earth-based radar data obtained after acquisition and prior to the powered descent are used to evaluate the execution of the DOI maneuver. In addition, the navigation data from the spacecraft computer are read from telemetry and compared with the MCC-computed values to evaluate the onboard navigation accuracy during the time interval immediately preceding the powered descent initiation.

Targeting. - The MCC also provides the spacecraft with target quantities to be used by the onboard guidance systems for the maneuvers required in order to achieve the landing. The DOI is a simple velocity-change maneuver, and the target parameters are the three components of the change in the velocity vector and the time to ignite the engine. These quantities are inserted into the onboard computer, and, if enabled by the crew, the maneuver is performed automatically.

Powered descent targeting by the MCC consists only of defining the desired landing site position relative to the LM orbit. Two intermediate target vectors and the time to ignite the engine are computed on board the spacecraft, based on the ground-supplied position data. In addition to the descent and landing targeting, the MCC also computes rendezvous target data to be used if an abort is required during landing.

The target quantities are uplinked directly into the spacecraft computer and are voiced to the crew in "PAD" messages (fig. 11) which also contain additional information the crew uses to monitor the performance of the spacecraft during the maneuver.

Descent monitoring. - Descent monitoring by the MCC begins as soon as data are available after the DOI. At acquisition, the LM is approximately 20 minutes away from powered descent initiation. The onboard computations of ignition time and navigation data are read from telemetry and compared with the MCC-computed values. Any significant differences must be resolved prior to commencing the powered descent.

The objectives of the guidance and navigation monitoring by the MCC during powered descent are to detect any slow degradation of the guidance and navigation system and to maintain a safe trajectory prior to crew takeover. The onboard monitoring is directed toward detecting discrete rapidly diverging failures and is exclusively responsible for maintaining a safe trajectory after crew takeover.

The ground monitoring to detect guidance and navigation system problems includes direct comparison of telemetered data from the two guidance systems on board the LM with data derived from earth-based radar tracking. The parameters that are monitored to detect guidance and navigation system failures are the velocity components, altitude, and commanded thrust. The earth-based radar data are used only in the velocity comparisons. The differences in velocity measured by the three sources are plotted on chart recorders and displayed to the flight controllers. Any divergence is readily detected, and the errant system can be isolated by reference to the three sources. The crew, with access to only two data sources, can detect differences but have difficulty determining which system is in error. If either onboard system degrades beyond established limits, the landing must be aborted. The limits are defined so that a safe abort trajectory can be achieved.

Altitude differences between the inertial system and the landing radar are also displayed to the flight controllers. Altitude data derived from earth-based radar were not used on Apollo 11 because of an uncertainty on the part of trajectory analysts as to how accurate the data would be. A sophisticated new process of simultaneously tracking data from three stations was used to obtain altitude and out-of-plane information during the powered descent. The first time that the processor could be used with real data was during the actual landing, and there was a reluctance to use the results in any trajectory evaluation decisions. Subsequent analysis, however, indicates that the technique worked very well, and altitude was accurately computed from the earth-based radar data. The landing-radar data, if "reasonable," are incorporated by the onboard computer to modify the altitude data in the inertial navigation system. The radar data, which are considered essential for landing, are combined in a weighted manner such that the altitude difference between the two systems should gradually be reduced to zero. The difference in altitude was plotted on a chart recorder and monitored by the Guidance Officer in the MCC. Had this difference exceeded a predetermined magnitude or failed to converge, the landing would have been aborted.

The performance of the total guidance and navigation system was evaluated by monitoring the commanded thrust magnitude. During the braking phase, the descent engine is normally at maximum throttle for approximately 6 minutes. The characteristics of the guidance equations are such that the initial thrust command should be 160 percent, with a gradual reduction to less than 100 percent after approximately 6 minutes. The display in the spacecraft does not indicate values above 100 percent; therefore, the crew cannot tell what thrust magnitude is being commanded, except that it is 100 percent or greater. The actual value commanded by the guidance equations was telemetered to the MCC and displayed in the MOCR as a function of velocity, as shown in figure 12. If this quantity is not 160 ± 10 percent at ignition or if it ever shows an increasing trend, an abort will be considered. Confirmation by a trajectory deviation or a low-thrusting descent engine are grounds for aborting the landing. The MCC also informed the crew at what time to expect throttle-down.

A "safe" trajectory is defined as one from which the LM could be successfully aborted with either the ascent or descent propulsion system and with either the primary or abort guidance system. The principal considerations are the accuracy with which the abort maneuver can be executed and the reaction time required to arrest the descent. The guidance system monitoring prevents the landing from being continued with a slowly degrading guidance system to the point where a safe abort could not be accomplished with that system. The velocity differences, previously described, are the basis for this evaluation.

It is possible for the guidance systems to perform within operating limits and still place the LM on an unsafe trajectory. This could be caused by large dispersions at the initiation of powered descent or by an off-nominal thrust level from the descent engine. The approach to an unsafe condition must be recognized soon enough to take action to avoid it. The situation which must be avoided is one of having too high a descent rate to be arrested by the abort maneuver. The time delay between the abort decision and execution must be considered.

The reaction time limitations are protected by altitude versus altitude rate boundaries, with a boundary for each engine. A plot of altitude versus altitude rate (fig. 13) from all three data sources was monitored by the Flight Dynamics Officer, who can call for an abort if a boundary is crossed prior to the crew taking manual control of the landing.

The guidance and navigation support is only a part of the MCC activities during the lunar landing. The MCC is also actively monitoring and apprising the crew of the status of all systems in the spacecraft. The period of LM activation and checkout is an especially busy period, requiring much coordination between the flight controllers and the crew. This systems monitoring activity is essentially independent of mission phase, but becomes more significant during high activity periods such as the lunar landing. With the crew's attention devoted to the demanding guidance and control tasks, the MCC assumes the prime responsibility for monitoring the environmental and electrical systems.

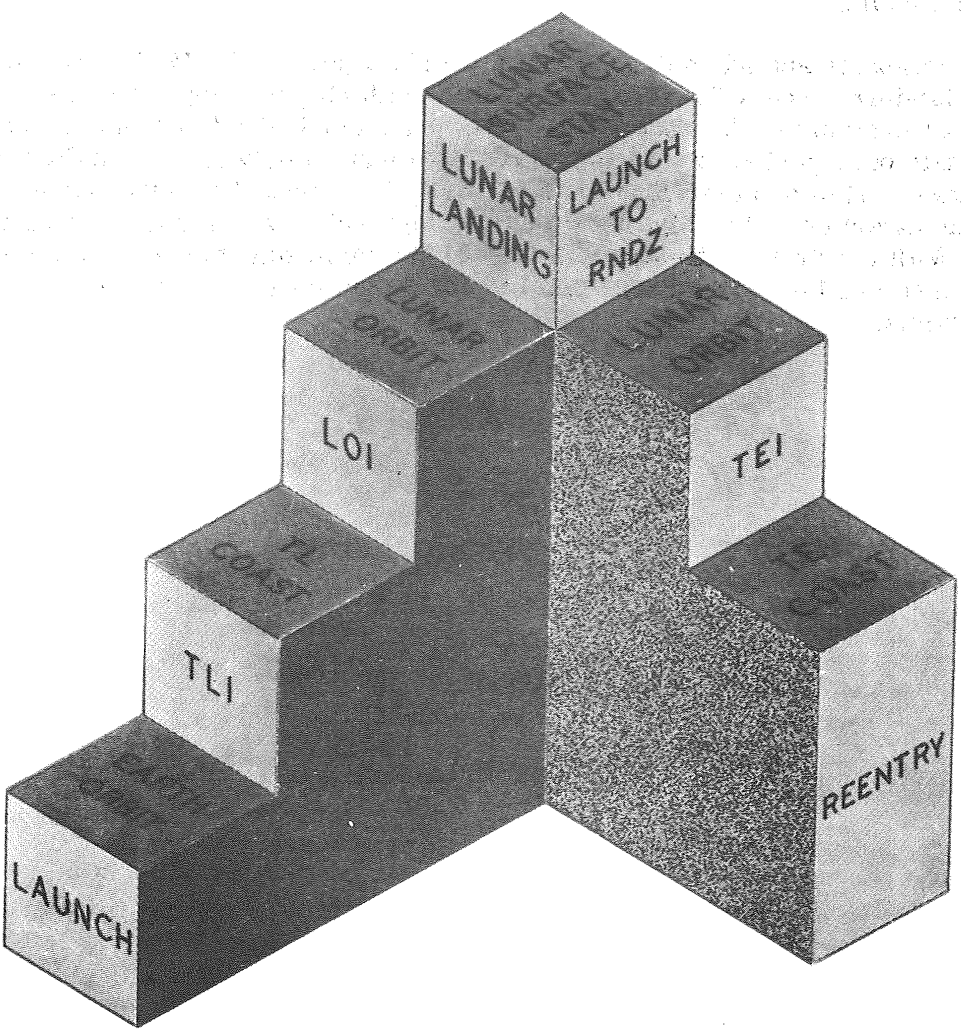


Figure 1. - Lunar-landing mission plateaus.

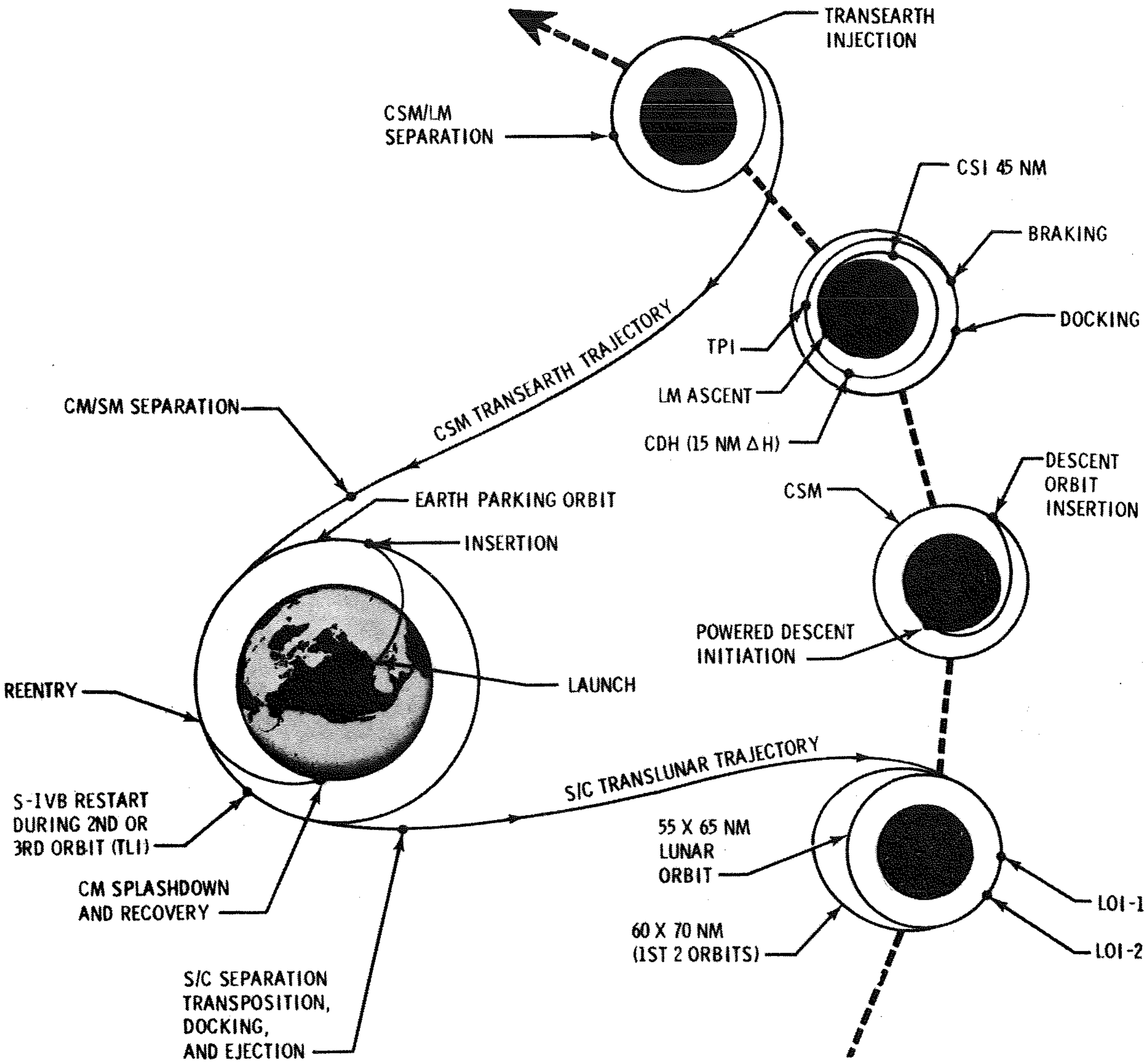


Figure 2. - Apollo 11 mission profile.

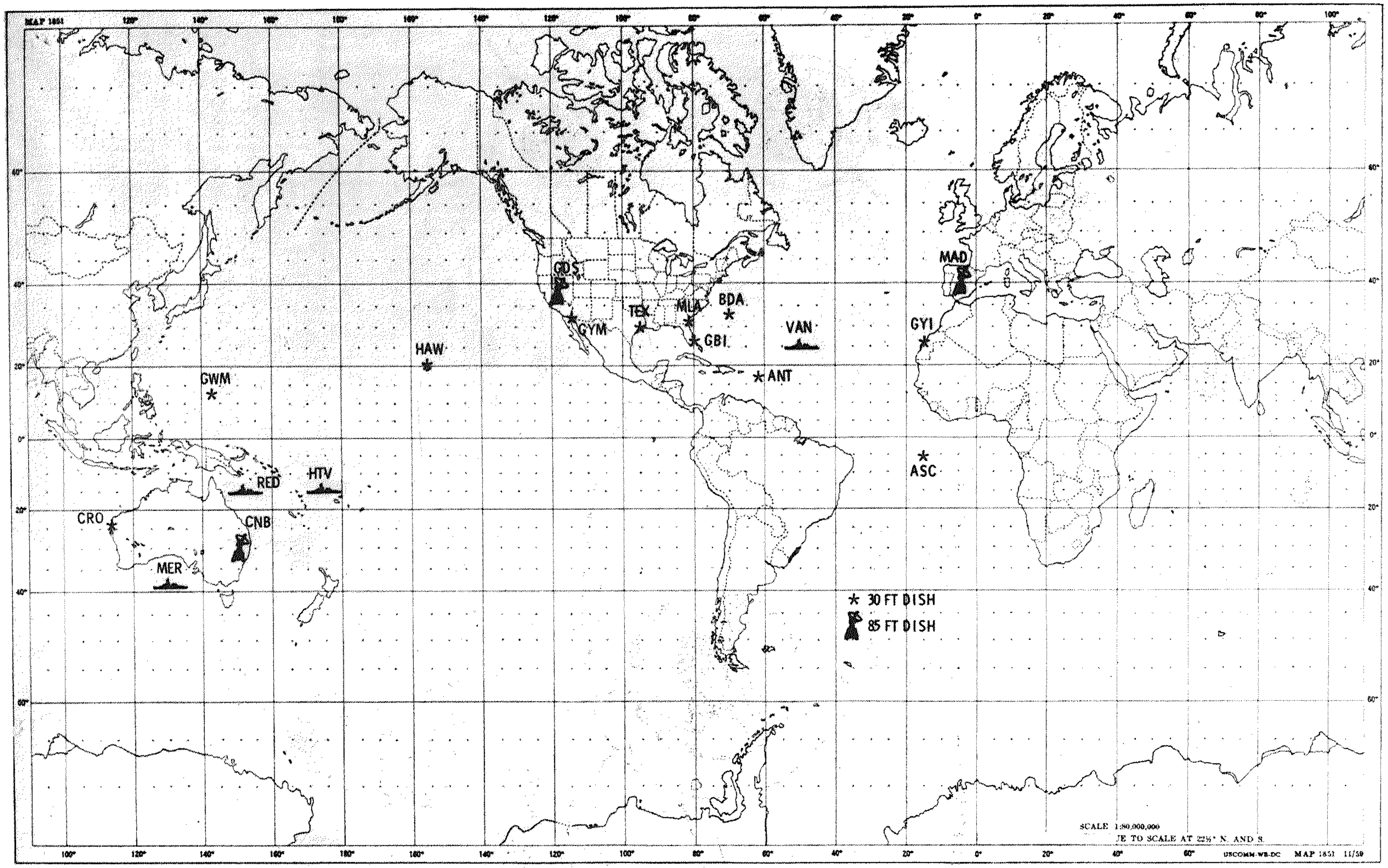


Figure 3. - Apollo Manned Space Flight Network.

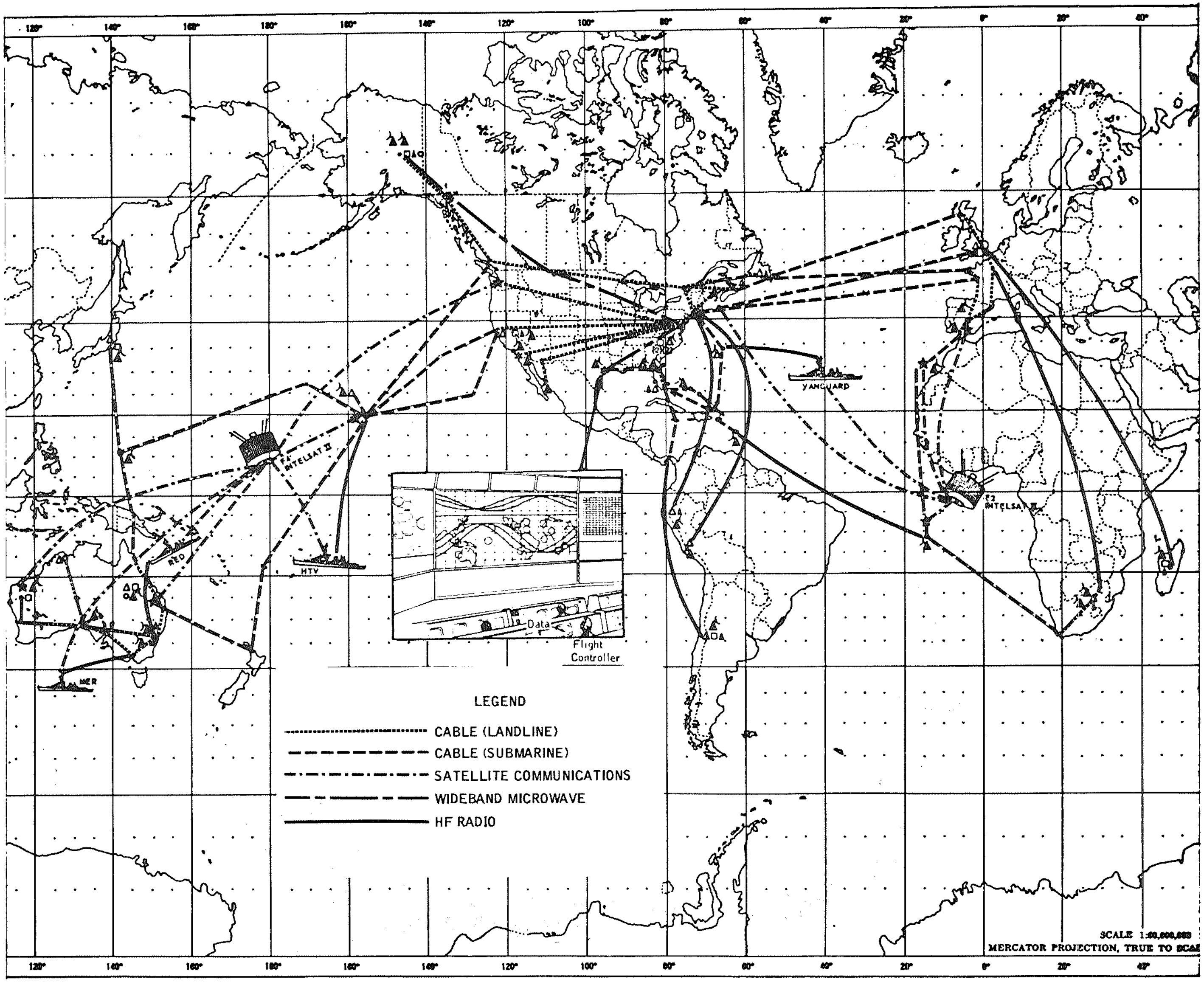


Figure 4. - Apollo launch orbital NASCOM network.

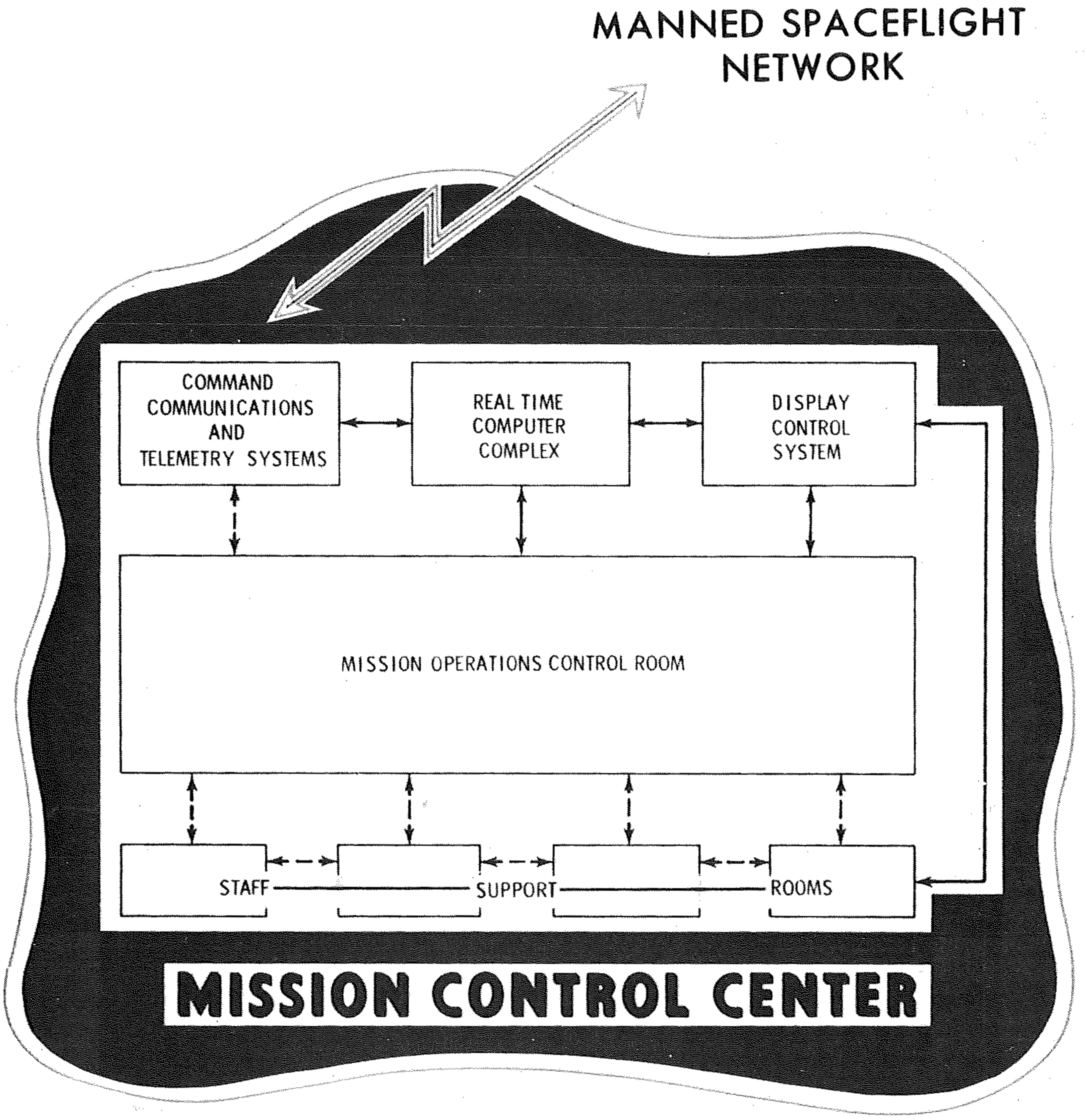


Figure 5. - Mission Control Center.

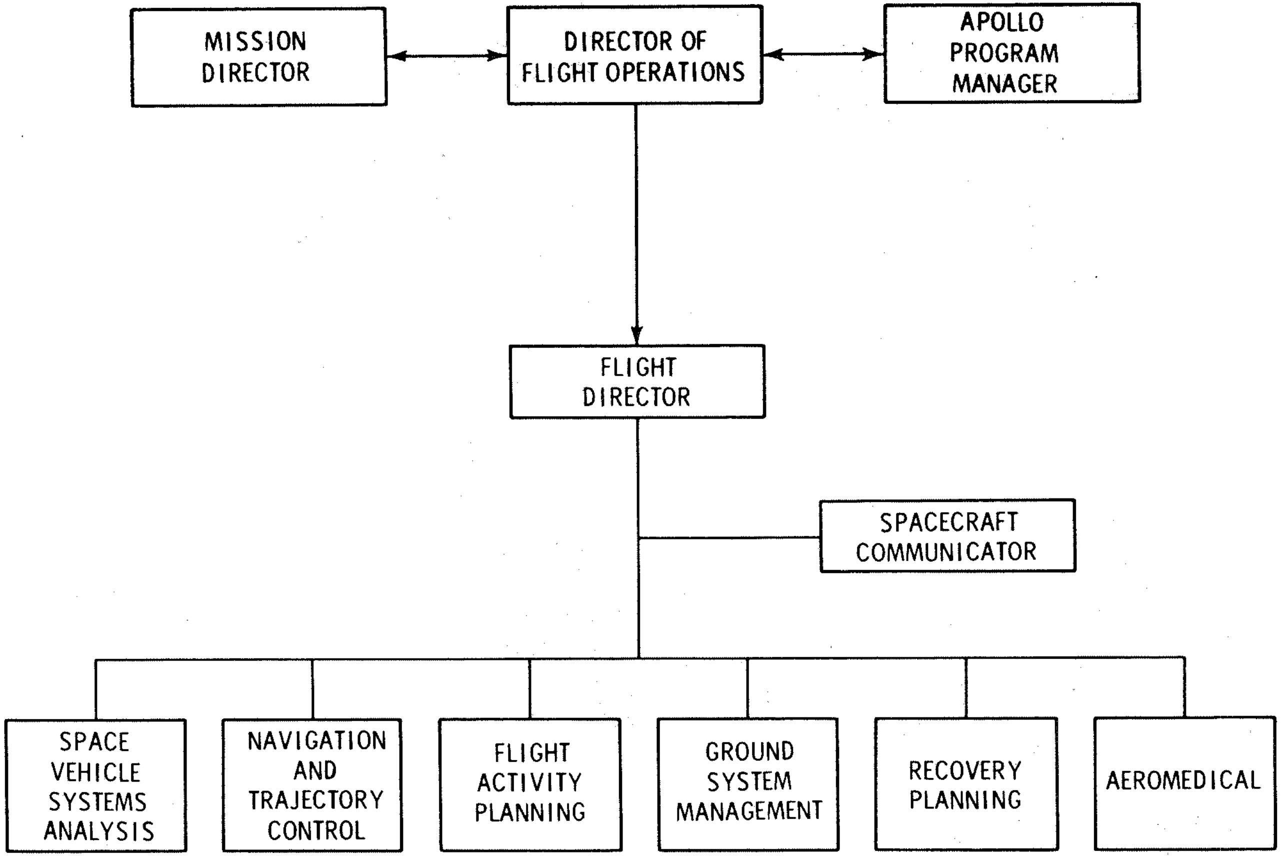


Figure 6. - Mission Operations Control Room organization.

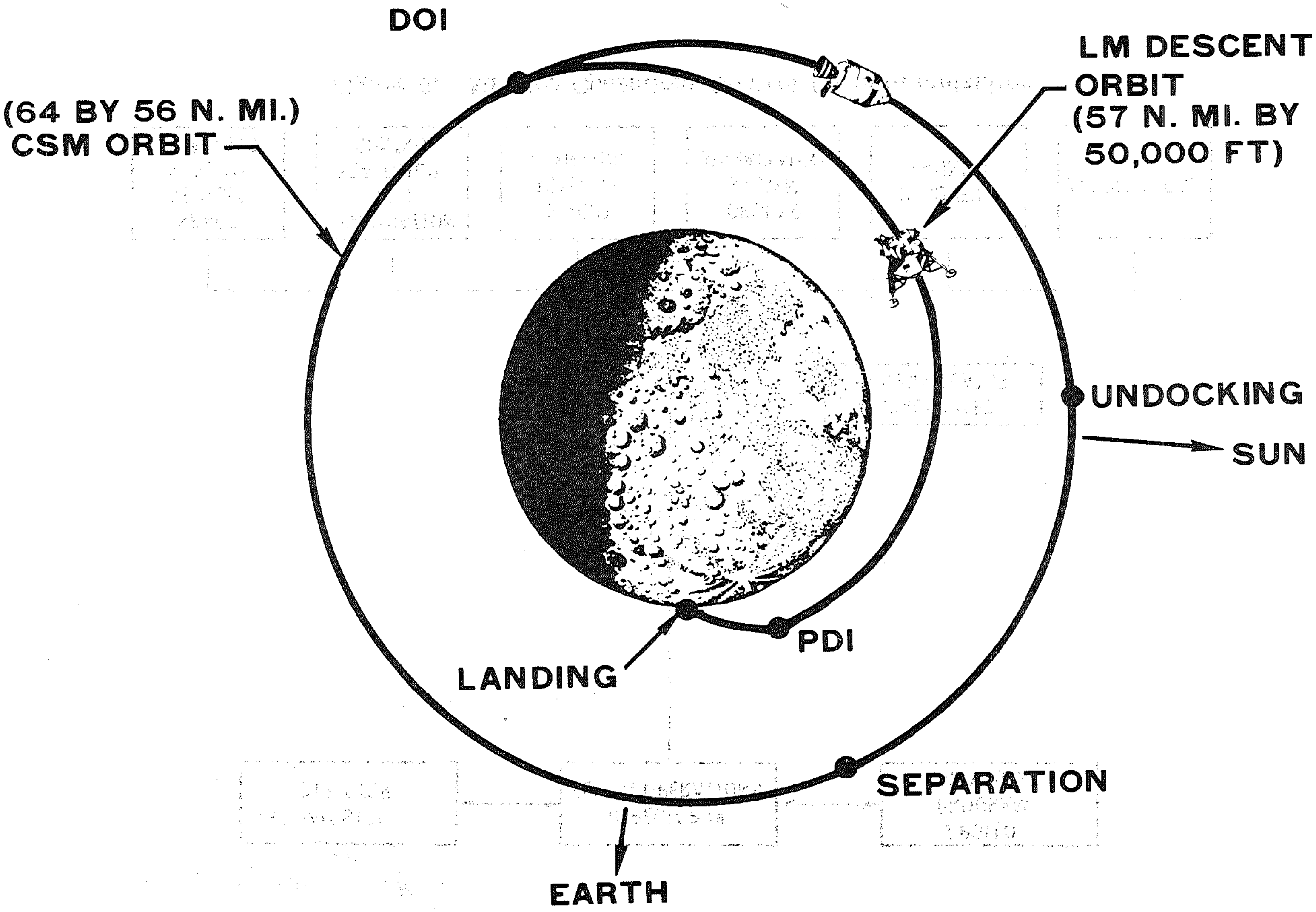
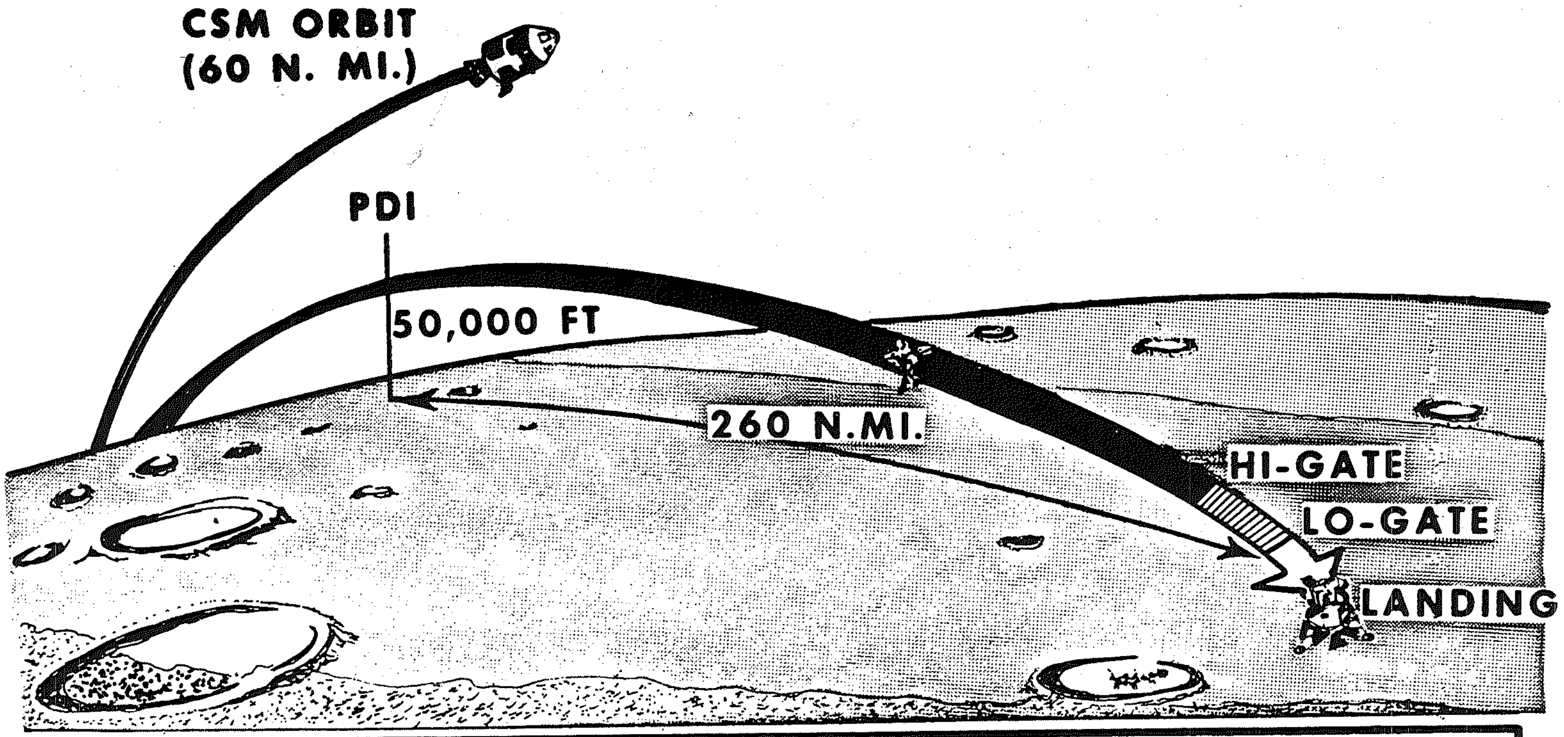


Figure 7. - Lunar module descent.



PHASE	INITIAL EVENT	DESIGN CRITERIA
BRAKING	PDI	MINIMIZE PROPELLANT USAGE
APPROACH	HIGH GATE	CREW VISIBILITY
LANDING	LOW GATE	MANUAL CONTROL

Figure 8. - Operational phases of powered descent.

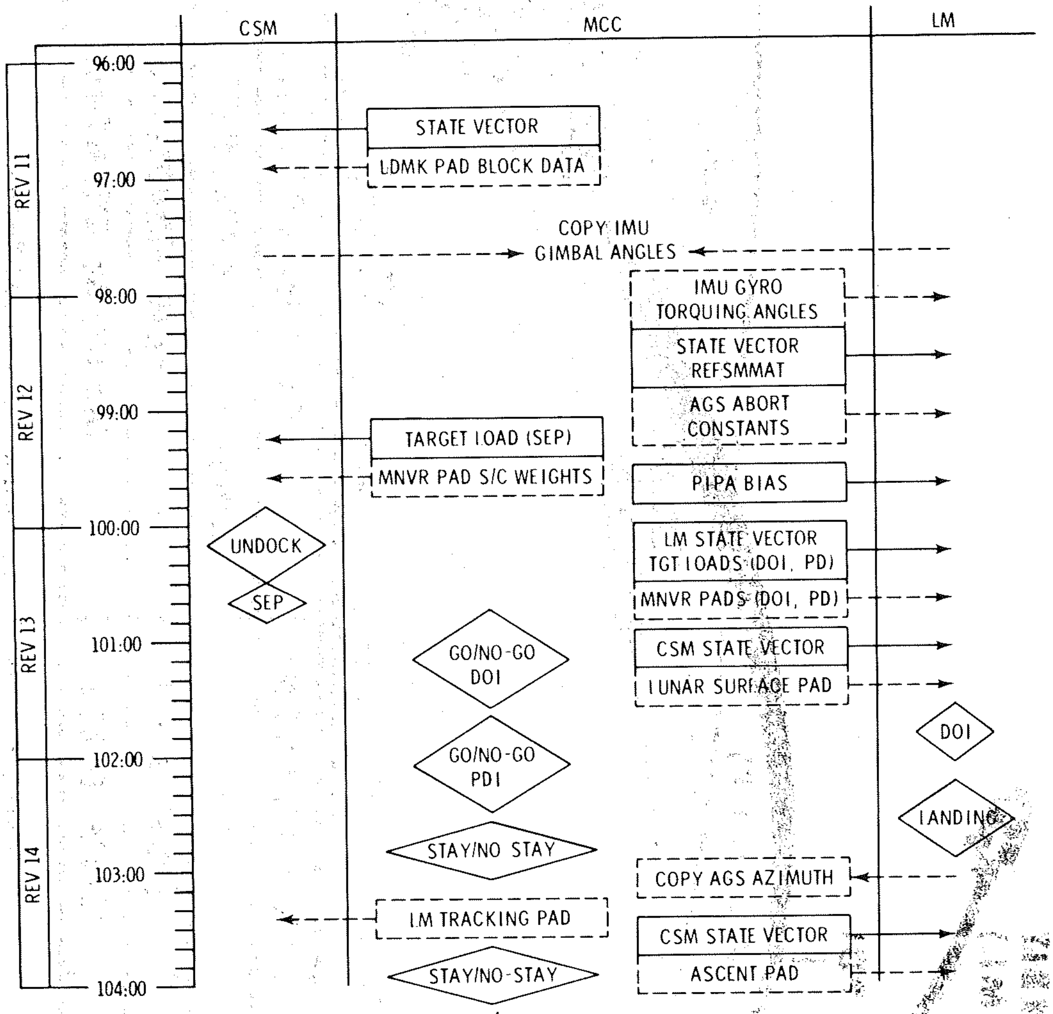


Figure 9. - Guidance and navigation activities time line for lunar landing.

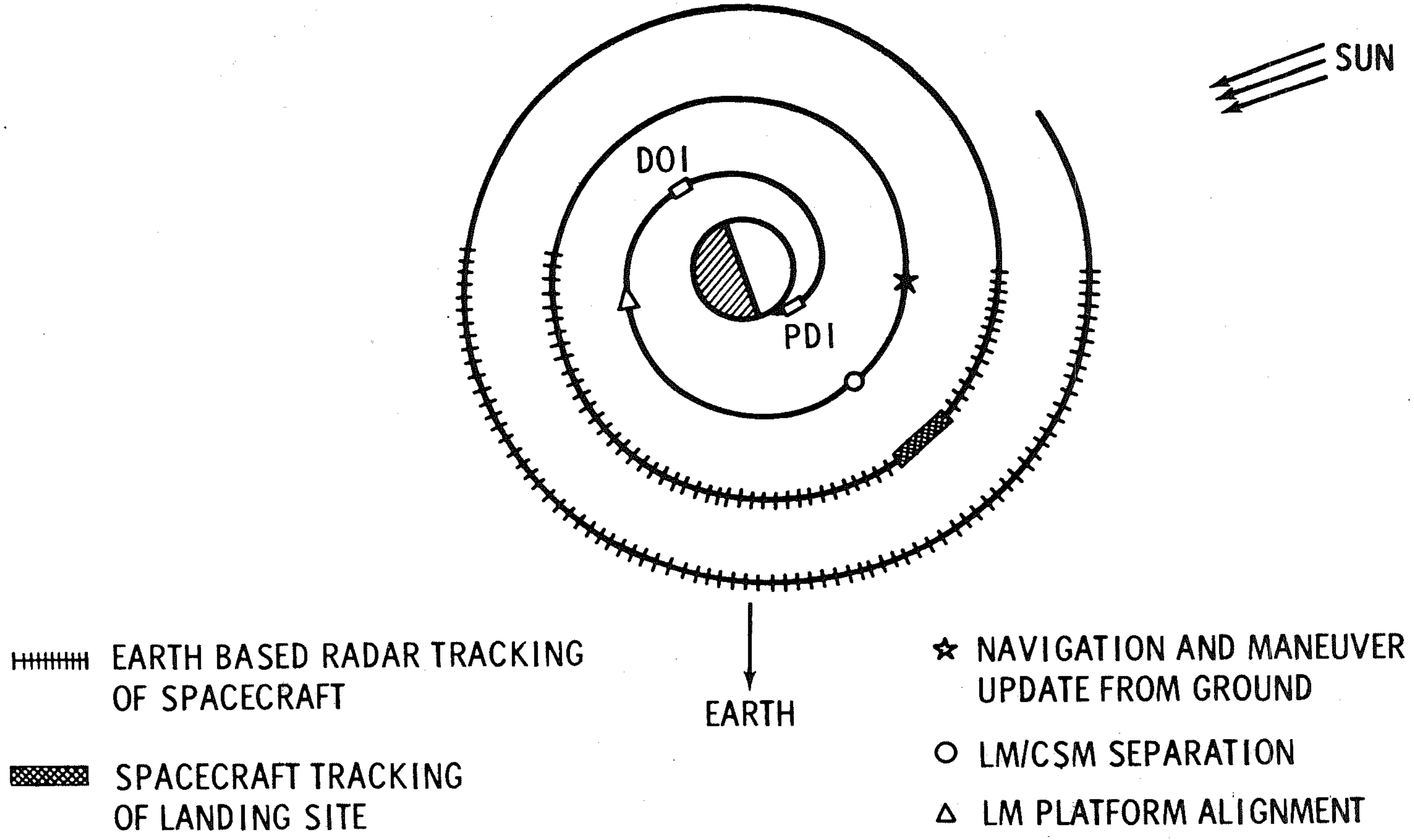


Figure 10. - Lunar-landing navigation time line.

DATA CARD CARRIED ONBOARD

P30													
HR	N33	+	0	0				+	0	0			
MIN	TIG	+	0	0	0			+	0	0	0		
SEC		+	0					+	0				
ΔVX	N81												
ΔVY	LOCAL												
ΔVZ	VERT												
H_A	N42	+											
H_P													
ΔVR		+						+					
BT		X	X	X				X	X	X			
R	FDAI	X	X	X				X	X	X			
P	INER	X	X	X				X	X	X			
ΔVX AGS N86													
ΔVY AGS													
ΔVZ AGS													
COAS		X	X	X	X			X	X	X	X		
AZ		X	X					X	X				
EL		X	X					X	X				

DEFINITION OF PARAMETERS

N33 DOI TIG	XXX:XX:XX.XX (HR:MIN:SEC)	IGNITION TIME OF LM MANEUVER
N81 LOCAL VERTICAL ΔV		LOCAL VERTICAL ΔV COMPONENTS OF THE MANEUVER
ΔVX	±XXXX.X (FPS)	
ΔVY	±XXXX.X (FPS)	
ΔVZ	±XXXX.X (FPS)	
N42 ORBITAL PARAMETERS		
HA	+XXXX.X (NM)	PREDICTED APOGEE RESULTING FROM MANEUVER
HP	±XXXX.X (NM)	PREDICTED PERIGEE RESULTING FROM MANEUVER
ΔVR	+XXXX.X (FPS)	TOTAL ΔV REQUIRED FOR THE MANEUVER
BT	X:XX (MIN:SEC)	DURATION OF THE MANUEVER
FDAI		
R	XXX (DEG)	INERTIAL FDAI ANGLES AT THE BURN ATTITUDE
P	XXX (DEG)	
N86 AGS ΔV		
ΔVX AGS	±XXXX.X (FPS)	LOCAL VERTICAL ΔV COMPONENTS OF THE MANEUVER TO TARGET THE AGS
ΔVY AGS	±XXXX.X (FPS)	
ΔVZ AGS	±XXXX.X (FPS)	
COAS	XX (OCTAL)	COAS STAR FOR MANEUVER ATTITUDE CHECK
AZ	±XX.X (DEG)	COAS AZIMUTH AND ELEVATION ANGLES FOR COAS STAR FOR MANEUVER ATTITUDE CHECK
EL	±XX.X (DEG)	

Figure 11. - Descent orbit insertion data card.

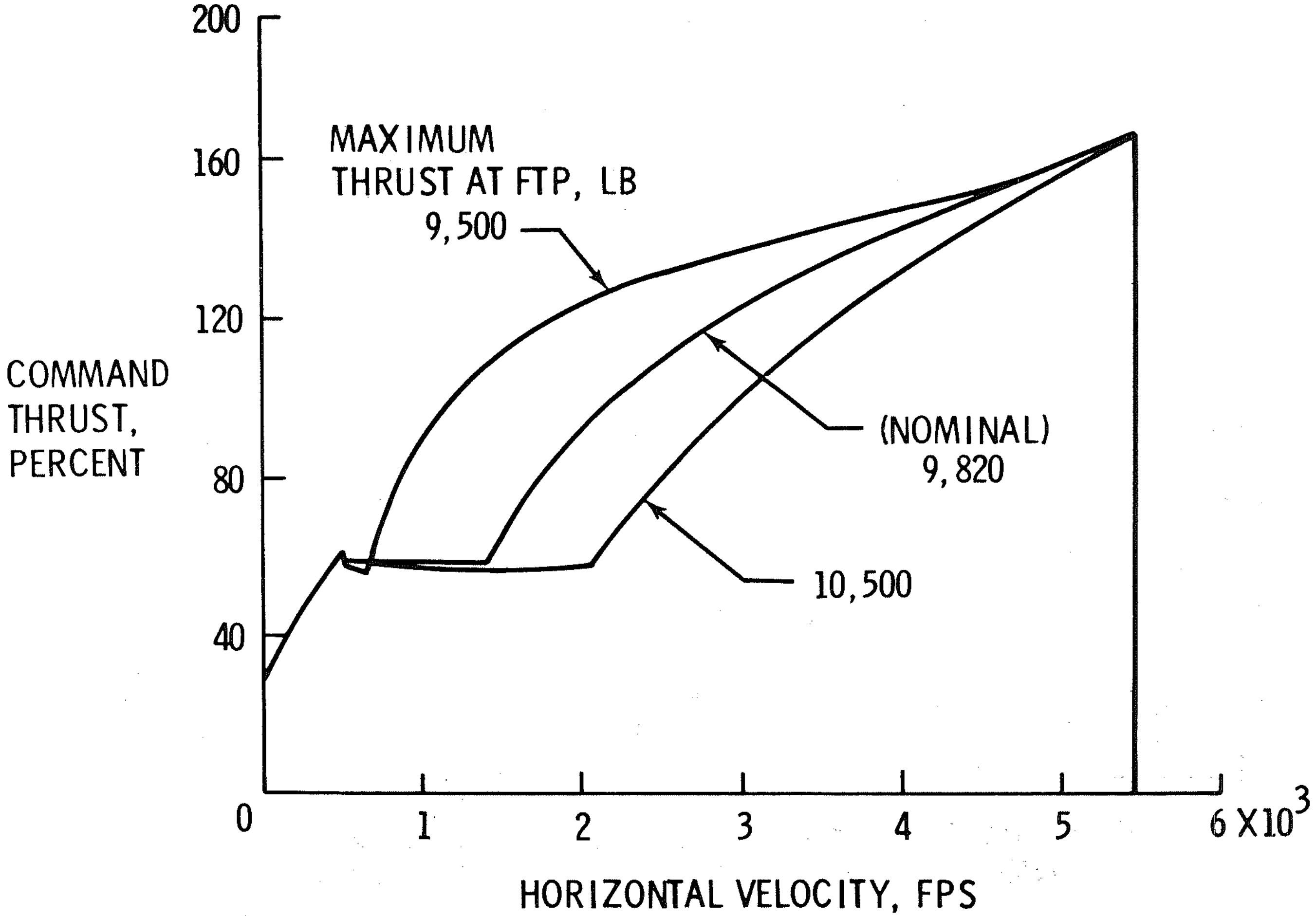


Figure 12. - Command thrust versus horizontal velocity.

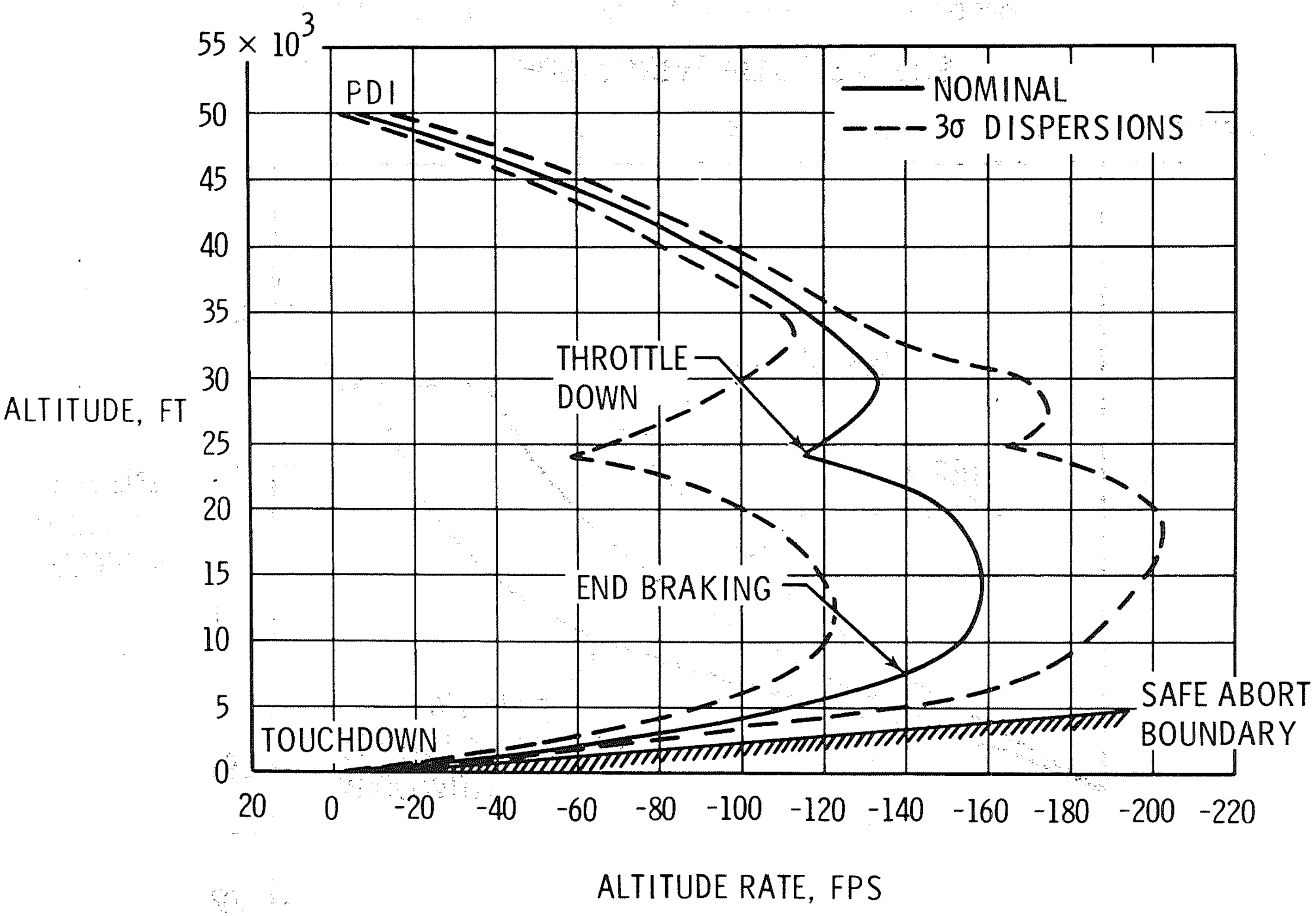


Figure 13. - Altitude versus altitude rate.