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APOLLO

GUIDANCE, NAVIGATION AND CONTROL

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MAN-MACHINE DESIGN FOR THE APOLLO NAVIGATION, GUIDANCE, AND CONTROL SYSTEM - REVISITED:

SUBTITLE

APOLLO, A TRANSITION IN THE ART OF PILOTING A VEHICLE

by

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Man-Machine Design for the Apollo Navigation, Guidance, and Control System-Revisited:

Sub-title
Apollo, A Transition in the Art of Piloting a Vehicle

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I INTRODUCTION

Apollo can be considered a transition in the art of piloting avehicle, where the principal dimensions are (a) Flight Operations, (b) the Flight Crew's Role, and (c) the man-machine communications, as illustrated by Fig. 1. The transitional aspects are the level and the nature of integration of the aircrews and ground controllers for flight operations. For the crews, the aspects are (1) the spectrum, or range of levels, of the general tasks and the necessity for certain tasks, (2) the nature and the requirements of the supervisory role. For the man-machine communications, the significant items are the levels and the nature of interaction of the crew with their equipment, from direct actuation of effectors to a first level of functional communications.

Consider, for example, the primary guidance, navigation, and control system designed for the Apollovehicles. The system was designed to provide the crew with a complete onboard flight-management system that would enable them to navigate and **guide** their spacecraft without ground assistance. As such, Apollo is the first manned U. S. spacecraft to contain enough sensors and data processing capability to do the job.

A. FLIGHT OPERATIONS

Apollo is the culmination of development both in ground and airborne systems. Ground systems (Fig. 1) have progressed from a few people giving minimal assistance to airplane crews (beginning in the 30's) to relatively advanced systems for military "command and control", such as the continental air defense network for North America. Systems that essentially give only directional data, however, are significantly different from the systems developed for supporting manned spacecraft: the systems supporting Apollo monitor all spacecraft systems, and, in effect, the ground controllers feel as though they are inside the vehicle" and are giving direct support to flight operations. This ground support ranges all the way from sequencing the proper charging of batteries, to trajectory control in scheduling the small thrusting effects for waste-water dumps. The flight-demonstrated capability of the ground's monitoring ability, plus the near-perfect reliability of the onboard equipment, give the aircrews the confidence to rest without keeping one man on watch.**

Spaceborne systems for manned spacecraft have progressed from the minimal onboard capability of Mercury, through Gemini with onboard navigation and guidance capability for rendezvous, to Apollo with full onboard capability for performing the full lunar-landing mission.

To achieve the desired mission reliability goals, the flight-management system, instead of being primarily an onboard operation, is actually a highly integrated system of airborne and ground-based equipment. The nature of this integrated team is a finely structured multilevel monitoring and decision process. In its simplest mode, the aircrew monitors the data for detecting errors that require immediate action, while the ground controllers are responsible for detecting the gradual-degradation-type failure of the onboard sensors. The latter failures can only be detected on the ground by monitoring and comparing the long-term trends of the data both from the airborne and ground-tracking systems.

In addition, since Apollo was man's first venture into deep space, maximum support was organized on the ground to help with any contingency. This support included not only the people manning the consoles in Houston, but hundreds of people at the various contractor facilities around the country (North American Rockwell in Downey, California; Grumman Aircraft and Engineering Corporation, on Long Island, N. Y.; the M.I.T. Instrumentation Laboratory, etc.), all tied together by voice- and data-communication links. Marshalling this kind of support in depth would be impractical if we were flying multiple missions simultaneously; e.g., a lunar-landing mission, an earth-orbit-equatorial long-duration mission, and an earth-orbit-polar mission, all manned. Therefore, ground- support systems for future manned missions can be expected either to become more automatic or else airborne systems will become more autonomous. The latter technique is necessary at distances where transmission delays are minutes long. Under these

*Modified by the fact that the data are "old," both because of transmission delay and because of system delays in the ground communication system and associated processors.

**Another example is leaving the LM vehicle unattended while both crewmen are exploring the moon. At first reading, this would to appear break one of the old explorers' prime ground rules; namely, (a) never leave a vehicle unattended, or (b) never let a man explore alone. The ground in this case really acts as a third crew member to monitor the LM while the other crew members explore the moon.

conditions, **ground systems** for space operations could only support airborne operations in the same way that the present ground systems support airplanes in flight.

B. FLIGHT CREW'S RGLE

1. General Tasks.-Man's role in spacecraft guidance and navigation ranges from supervising automatic systems to performing specific sensing and control functions. The crew functions can be categorized as follows:

a. Monitoring of, and decision making associated with, the navigation and guidance process, including the effects of navigation sensor data (target-tracking data, both visual and radar) on state-vector updates; comparing onboard data with ground-tracking data and backup charts

b. Sequencing and initialization of primary guidance, navigation, sensing systems, as well as propulsion and timing systems

c. Initializing and sequencing of backup systems

d. Performing the pattern-recognition tasks associated with (1) command-module optical tracking of the lunar module during rendezvous; (2) star acquisition, identification, and geometrical alignment to visual horizon (earth or moon) for cislunar navigation.

As technology improves in capability and reliability, many of these tasks will be replaced by automatic systems. In Apollo, however, in many respects the **most** complex vehicle every piloted, success depended upon a design that thoroughly integrated man and machine, a design concept that utilized man to achieve system flexibility and reliability not otherwise possible given present technology.

2. Supervisory tasks.—The reliability of Apollo equipment demonstrated industry's ability to produce systems that meet specified goals. Nevertheless, the limited reliability of basic components, together with the constraints on weight, volume, and power, produced system designs where single failures can cause large functional incapacitation of the affected systems. To guarantee functional capability, redundant systems are necessary. Man's most important role, therefore, especially during dynamic conditions, is to monitor both the primary system and its required backup systems. For critical functions, this requires that the crew give continual, time-shared attention to several levels of backup systems in order that their status be known should their use become necessary. Moreover, smooth and rapid transition to backup modes requires the crew functional involvement in the operation of the total system.

Awareness of, and involvement in, the operation of many levels of redundant systems, operating in parallel, places a most severe burden on the crew. With increased reliability and smaller size of basic components of the future, it will be possible to provide enough redundant sensors, electronics, processors, and highly reliable switching logic to not only detect malfunctions, but to automatically switch to redundant modes-that is, a system that degrades gracefully rather than instantly (Ref. 1). Such a system would operate most of the time in a **fully** automatic mode. For the next five to ten years, however, it is unlikely that man's present unique flexibility and decision capability can be fully replaced; during this time, systems will have to be configured to allow man's continued involvement at levels other than required strictly for supervising or monitoring. The depth of this involvement, however, should be much less than in Apollo. Consequently, the burden on the crew will continue to decrease as its role becomes more purely administrative, or supervisory.

C. MAN-MACHINE COMMUNICATION

Communication between crew and the airborne equipment comprises everything from direct task sequencing, caused by direct actuation of effectors via hand controllers, to a functional level of communications implemented by a higher -level computer language (Fig. 1 and 7). This computer language allows the crew to control groups of tasks instead of individual tasks. These **task** groups can be as small as an automatic spacecraft-attitude rotation and as large as required to integrate all the jobs necessary for performing the powered-descent portion of the lunar landing or entry into the earth's atmosphere. Although this language is a major contribution to the art of piloting a vehicle, it is crude by the standards of newer technology that allow variable format, graphical input/output display systems. In the remainder of this paper, I will first discuss the Apollo mar-machine interface from the broad perspective of the primary guidance, navigation, and control system. I will then discuss the salient features of the Apollo flight-management system, including mar-machine communications, as applied to lunar-landing powered descent; and, finally, the mar-machine control interaction for the command module rotational attitude control modes.

11 BROAD VIEW OF APOLLO MAN-MACHINE INTEGRATION

The Apollo Guidance, Navigation and Control System is described in Ref. 2 through 13. The principal aspects of the man-machine interaction are described in Ref. 14, 15, and 16. A few words are necessary, however, to provide a context for the remainder of this paper.

To control the spacecraft throughout the basic lunar-landing mission (Fig. 2) entails fifteen* distinct operational phases for the onboard Guidance, Navigation, and Control System. To accomplish these functions in the light of the pertinent ground rules (Table 1) requires a highly integrated system whose primary inputs are shown functionally by Fig. 3. Onboard navigation data come from three sensors. Two are on the command module, namely optics and a range-only capability through the VHF communications link. On the lunar module, the navigation sensor is a radar system.

"Note: Orbital navigation (earth and moon) (items 2 and 6 on Fig. 2) are not normally used, and midcourse navigation (items 4 and 13, Fig. 2) are only utilized in the "loss-of-communication" case.

Table 1 Apollo Design Ground Rules (circa 1961)

a. The system should be capable of completing the mission with no aid from the ground; i.e., self-contained.

b. The system will effectively employ human participation whenever it can simplify or improve the operation over that obtained by automatic sequences of the required functions.

c. The system shall provide adequate pilot displays and methods for pilot guidance system control.

d. The system shall be designed such that one crew member can perform all functions required to accomplish a safe return to earth from any point in the mission.

The optics system, on the command module, is designed to provide navigation data in local orbits (earth or moon) by single-line-of-sight observations (via a one-power optical instrument called the scanning telescope-SCT) from the inertial platform to known or unknown landmarks. In cislunar space navigation, data are obtained by two-line-of-sight observations (via a 28-power optical instrument called the space sextant-SXT) between stars and earth or moon horizon. During rendezvous, the optics system and the range-only capability through the VHF communications radio link provide the navigation data on the command module; on the lunar module, the navigation data come from the rendezvous radar. State vectors derived from ground tracking can be sent to either spacecraft during any coasting-flight phase, via telemetery. Guidance of the Apollo spacecraft is inertial; i.e., applied force is sensed by accelerometers mounted on a gyroscopically stabilized platform and processed by a computer that generates steering and engine-cutoff commands, as shown functionally in Fig. 3. The lunar module G&N system also uses radar and astronaut-visual inputs during the final approach to landing, and therefore the LM may be said to use radar-visual inertial guidance (Fig. 3). The components for the command module (CM) primary guidance, navigation, and control system (PGNCS) with their respective locations are illustrated by Fig. 4. In Fig. 5, the lunar module (LM) is similarly detailed. The onboard computers, which are identical, are identified as the command module computer (CMC) for the command module and the lunar module guidance computer (LGC) for the lunar module. These processors are the primary onboard sequence controllers as well as the clock or basic time and frequency reference for the spacecraft. Figure 6 shows the interrelationship of the LGC to the various sensors, the spacecraft reaction- control motors, and the spacecraft propulsion system for the LM digital autopilot functions. The computers perform the following: (1) monitor the sensor data (optics, accelerometers, IMU gimbal angles on the command module, rendezvous radar, landing radar, accelerometers, and IMU gimbal angles on the lunar module); (2) determine thrust times and vectors, vehicle-trajectory parameters, and optics or rendezvous radar-target lines of sight; (3) maintain attitude control; and (4) guide the vehicles during thrusting maneuvers.

The computer and crew primarily interface at the display/keyboard (DSKY) (Fig. 7a), which consists of electroluminescent digital displays and a numeric keyboard. Data are displayed in three five-digit registers. The displayed data can be either decimal or octal, Associated with each register is a sign bit for the display of decimal data. In addition, memory locations can be addressed directly, but this is intended primarily for ground checkout. (Although there is no* attempt to restrict crew access to the computer, the crews are trained to use primarily the technique designed for flight operations.)

For flight operations, crew-computer communications are primarily structured into two levels (Ref. 17). The first level identifies GN&C operational functions (not usually as large as a mission phase—Fig. 2), e.g., (1) targeting computations for one of the four rendezvous subphases, (2) the sequencing associated with a particular propulsion system for a. trajectory maneuver. This highest-level functional identifier is a two-digit decimal code called a program (P) identifier, where the most significant digit is related to mission phase. Figure 7b illustrates the organization. For example, zero series identify the functions associated with prelaunch checkout, the ten series identify the boost-monitoring programs, and the sixty series identify programs associated with LM lunar landing and CM entry. The unit programs define the functional programs within a particular series. Figure 8 gives the complete list of programs for a typical lunar-landing mission.

The second level of communication consists of two, two-decimal, digit identifiers called verbs and nouns. The verb identifier defines action and the action to be performed; the noun identifier defines the object of the action and identifies the data being displayed or loaded. (Figure 7b lists some typical verbs and nouns.) For example, Verb 16 instructs the computer to continuously monitor a function, display the data in decimal form, and update the display every two seconds. If we combine Verb 16 with Noun 36, we will instruct a display of the computer clock, expressed in ground elapsed time (GET), with hours in the first dataregister, minutes in the second data register, and seconds to hundredths of a second in the third data register.

Communication with a computer is always bimodal, i.e., the man talking to the computer, and the computer talking to the man. The latter mode is mechanized by allowing the computer to flash the verb-noun displays (flash rate 1/2 second on, 1/2 second off). Therefore, if the computer wants the man to review data for acceptance or rejection or to load data, it will flash the appropriate verb-noun combination.

*This philosophy gives great flexibility, but has the associate hazard of a possible wipe-out or incorrect alteration of the data in erasable memory (state vector, etc.) if the computer is not sequenced properly. For example, on the transearth leg of the Apollo 8 mission, a very tired crew member inadvertently called for a prelaunch function (Program 01-see Fig. 7) to be performed when he actually intended to load Star Number 01. To guard against these contingencies, the crew carries data and procedures to reinitialize the erasable memory.

In addition, there are activity lights for both the computer and the telemetry uplink, as well as caution and warning annunciators for both the computer and the rest of the inertial system.

Figure 9 shows the general nature of the crew-computer interface for performing operational sequences. This design permits the crew to exercise complete sequence control but also results in the crew's being an integral part of any computer sequencing. Figure 15 details the computer sequencing for the lunar-landing powered-descent phase. Additional description of the operational man-computer interface will be given in the lunar-landing section.

III LUNAR LANDING PHASE

To illustrate the salient features of the present Apollo flight-management system, I will now describe in some detail the powered-descent functions for a lunar landing. Figure 10 gives the abbreviated lunar-orbit time line for a typical lunar-landing mission. The time period covered (elapsed time of approximately 55 hours) is from the second lunar-orbit-insertion trajectory maneuver through the transearth-injection trajectory maneuver. For this discussion, the principal interest is the last 1-1/2 hours before touchdown (from separation of the two vehicles to the landing)-nominal ground elapsed time (GET) of 101:00 hours, as shown in Fig. 11 and 10. Figures 12, 13, and 14 show the principal operational phases and events associated with the lunar-module powered descent; Figure 15 is a profile view of the powered descent, including a listing of the computer-program-sequenced displays and the pertinent nonsequence displays that can be called by the crew.

The early phase of lunar-orbit tasks starts after completion of the lunar parking-orbit circularization maneuver and ends after successful completion of the descent-orbit maneuver and the associated post-burn (or maneuver) checks. During this period the lunar module is partially activated and the command-module pilot practices optical tracking of the landing site by tracking lunar landmarks. The crew then rest for nine hours or so. After the crew rest period, the two lunar-module crewmen, with detailed support from the Mission Control Center personnel, completely activate and check out all the lunar module systems. Included in these checks is a dump of the erasable memory (2,048 sixteen-bit words) in order to allow a detailed check by the ground of the initial load in the memory. During this checkout, all the backup systems are activated and checked with the primary systems and cross-checked with the ground. For GN&C, there is a complete backup system (abort guidance system- AGS) that is capable of guiding an abort from any place during the powered-descent trajectory. The AGS is also capable of guiding the rendezvous maneuvers.

After the lunar-module checkout, the command-module pilot (CMP) tracks the landing site (or a prominent landmark near the landing site) with his, optics system. These data are sent to the ground for processing by the Mission Control Center computers in order to reduce the relative uncertainty between the landing- site location and the CSM orbit. Next the vehicles undock and then separate by the command module's doing a small (≃ 2.5ft/ sec) radial maneuver to put it on an equiperiod orbit with the lunar module. This maneuver results in a maximum separation of a couple of nautical miles, which occurs one-half orbit later at descent-orbit insertion. During the next night pass, the inertial platforms of both vehicles are carefully aligned, using two stars. A check to see if the proper stars were used is made by an auto-optics routine for the command module (auto-spacecraft routine for the lunar module because its optics are fixed); this routine points the optics or vehicle to a third star. The gyro torquing-to eliminate the gyro drift since the last alignment-indicates whether the gyro-drift performance is good enough to continue the landing. Additional checks are made on the bias terms for the accelerometers and to see if the rendezvous radar on the LM and the VHF range channel on the CM are working properly. While these checks are going on, the ground continually monitors the other spacecraft systems (except for the time period when the spacecraft are behind the moon) to see if they are operating and sequencing properly.

The LM crew then select the ground-targeted pre-thrusting program (P30). After sequencing through P30, they then select the descent-propulsion-system computer program (P40); maneuver to the spacecraft attitude required for the Hohmann descent-orbit maneuver; andverify that the computer displays for velocity components, time of ignition, and spacecraft attitude all agree with the ground-computed data voiced-linked from the ground. The ignition attitude is verified by looking out the overhead window at the star selected by, and voiced from, the ground.

The descent-orbit-insertion (DOI) maneuver is performed about 194 longitude degrees before the targeted landing site. The result of this maneuver is to place the lunar module in a 60-nautical-mile by 50,000-foot Hohmann transfer orbit, with perilune occuring about 14 longitude degrees before the targeted landing site. At perilune, powered descent will be initiated.

After the maneuver is performed, the results of both the primary and the backup system and the indicated rendezvous-radar range rate between the two vehicles are evaluated to verify that the maneuver was successful. During the maneuver, if the descent engine stayed on three seconds longer than it should have, an unsafe perilune would result.

The principal decisions possible during this final phase are as follows: (a) GO/NO GO for landing; (b) if an abort is required, should the abort be made on the descent engine, or should the vehicle be staged (separate the descent stage from the ascent stage) and the abort be made on the ascent engine; and (c) whether to switch over from the primary guidance system to the backup system in case of a failure in the primary system. For an acceptable condition for landing, there must be close agreement between the onboard-computed values and the values computed on the ground and voiced up to the crew for time of engine ignition and cross-range location of the landing site to the LM orbital plane. In addition, the LM inertial-platform alignment must be checked, the LM must achieve the proper pitch attitude for the trajectory maneuver, and the airborne computer must be functioning properly.

As indicated earlier, the ground is responsible for detecting insidious slow-drift sensor malfunctions that would require switchover from the primary system to the backup system. To do this, the ground has a special powered-flight processor, which uses a Kalman filtering technique to generate a state vector, by processing the doppler-range data and the geometrical-trangulation data from several tracking stations. This statevector is then compared with the telemetered onboard-computed state vector. In addition, ground displays show the velocity residuals between onboard primary and backup guidance systems, onboard primary guidance system and ground-tracking-derived range-rate residuals, and onboard backup and ground tracking-derived range-rate residuals. For these comparisons to be made requires that there be continuous high-bit-rate data and voice communications between the ground and spacecraft.

As indicated in Fig. 12, 13, and 15, there are three main phases to powered descent.

a. Braking phase
b. Approach or visibility phase
c. Landing or vertical descent phase.

The braking phase (Computer Program P63) starts near perilune (~ 50,000 ft) of the Hohmann descent-transfer orbit, about 260 nautical miles away from the targeted landing site. The braking phase lasts approximately 8 min 30 sec and ends when the target conditions (called HI-GATE) for thevisibility phase have been met. During this braking phase, the LM is in a retrograde attitude and is using the full thrust of the descent-propulsion system to slow down the vehicle. About three-quarters (nominal time about 6:30 min — 24,000-ft altitude) of the way through the burn, the guidance law throttles the engine down to approximately 57 percent. Before throttle-down time, at an altitude of approximately 40,000 ft, the spacecraft is manually rotated to a windows-up (Fig. 12) attitude (if required) in order that the landing radar can lock on the lunar surface. At about 8.22, the vehicle begins an autopitch maneuver to enable the crew to view the landing site through the forward window during the next phase-the visibility phase.

Before this, the guidance law has been slowly pitching the vehicle to enable the engine thrust to maintain the proper altitude profile as the vehicle slows down. At approximately 8:30 min (computer program P64), the next phase begins-the final-approach, or landing- site-visibility phase. This visibility-phase program starts when the HI-GATE target conditions have been met (altitude "7,200 ft, inertial velocity ≈ 516 ft/sec, fuel remaining approximately 20-percent) and ends about 120 seconds later, when the LO-G ATE target conditions (altitude ≃ 150 ft, vertical-descent velocity 3 ft/sec, approximately lo-percent fuel remaining) have been met. During this visibility phase, the computer displays an elevation angle (via DSKY) that indicates to the crew where the computer plans to land the spacecraft.

The crewman surveys the lunar terrain and, by use of a simple reticle on the window, notes where the spacecraft is going to land, If the crewman is not satisfied with the pretargeted landing-site terrain features, he can designate another landing site, or he can fly the spacecraft to another landing site in either a semi- auto mode (computer program P66) or a fully manual mode (computer program P67). These modes will be described later. At the end of the visibility phase, if the crewman does not elect P66 or P67, the autolanding program (P65) will be automatically entered.

In P65, the vehicle is pitched to the vertical position, the translational velocities are nulled, and the vertical-descent rate is set to 3 ft/sec. Just before touchdown, a lunar contact light is activated by 5-foot-long probes attached to the landing pads. When the lunar contact light comes on, the crew manually shut down the engine and the vehicle falls the remaining distance to the lunar surface (nominal impact velocity ◁ 3ft/ sec).

To start the powered-descent sequence, the crew call up the braking-phase program (P63) about 40 minutes before the time to turn on the braking engine (Fig. 14). This is accomplished by a Verb 37 (change program request-Fig. 7b) followed by an enter (E) and a 63E as shown in Fig. 15. The first display in this program is the computation result for the ignition algorithm. The flashing Verb 06 and Noun 61 displays the following in Registers 1, 2, and 3:

R1 — Time to go (TTG), the computed time from engine on to the time the LM will reach the HI-GATE target

R2 — Time from ignition (TF1), the time to when the engine will be automatically turned on

R3 — Cross Range, the distance out of plane from the present positionto the targeted landing site.

As indicated before, the computer will flash displays requiring crew action-m this case, **the** acceptance or rejection of data. These displayed data are checked against the data computed on the ground and voiced to the crew. After checking, the crew accept the data by telling the computer to proceed to the next step in the sequence-by depressing the proceed key (PRO) on the keyboard (Fig. 7a).

The next step in the sequence requires the computer to ask the crew a question. To accomplish this the computer flashes a Verb 50 (please perform) Noun 25 (checklist item), where the particular task is identified by a number displayed in register one (R1). For this step, the R1 code is 00014, which **means,** "do you want to fine align the inertial platform?" Since he has already previously aligned the platform, the crewmember bypasses this request by depressing the enter key (E). If he had not performed the alignment, he would depress the proceed key (PRO). Depressing the PRO key starts the fine-align computer routine (R57). The enter (E) causes the computer to proceed to the next task, which is an automaneuver of the spacecraft to the attitude required for starting the braking-trajectory maneuver. This task is designateti as the automaneuver subroutine (R60). The first display in R60 is a flashing Verb 50 (please perform) Noun 18 (the inertial referenced angles that will be seen by the crew on the three-axis-ball-attitude display after the computer has rotated the spacecraft to the desired attitude-Fig. 5). Proceeding on this display activates the automaneuver and causes the display to change to a static Verb 06 Noun 18. When the computer completes the maneuver, the display will return to a flashing V50N18 display. The crew then check to see that the DSKY, the ball-attitude display, and the ground data all agree. To exit this routine, the enter key is depressed. Note that the crew could have done the maneuver manually by bypassing the routinewithanenter (E) the first time Verb 50 Noun 18 was displayed.

The next display is a static Verb 06 (displayed decimal) Noun 62:

R1 – Present LM inertial velocity (VI)

R2 – Time from DPS engine ignition (TFI)

R3 – The measured change in velocity (ΔVM), which is displayed until the engine-starting sequence begins.

At TFI equals minus 35 sec, the entire DSKY display is blanked for five seconds to indicate to the crew that the computer is starting the jobs associated with a thrusting maneuver. At TFI equals minus 30 sec, Verb 06 Noun 62 returns, and the computer starts monitoring the accelerometers, and any residual noise is indicated by small changes in the V06N62 display. A “run-away,” or failed, accelerometer would be indicated by large changes in this display. At TFI equals minus 7 sec, the computer performs ullage by turning on the +X reaction-control motors. At TFI equals minus 5 sec, the computer requests (flashing Verb 99 Noun 62) a final check from the crew before turning on the DPS engine. If the crewmember is satisfied that all spacecraft systems are GO, he depresses PRO, and the display returns to a static V06N62; at TFI equal 0 sec, the DPS engineignites. In addition, the abort programs (P70 for DPS and P71 for APS) are now available should the crew depress the abort or abort-stage buttons. If something were wrong at TFI=0, the crew would terminate the entire braking sequence by the terminate verb (Verb 34E), exit P63, and go to the idling program (P00). By not depressing the PRO key, the crew can slip starting engine ignition for approximately 5 sec beyond the nominal start time. Beyond the 5-sec slip, mission rules require delaying powered-descent insertion (PDI) for one orbit or aborting the landing, depending on the particular spacecraft problem that caused the crew to delay the engine-start sequence. Depressing the PRO key, once TFI has passed zero, will immediately start the engine.

At engine start (TFI=0), the DSKY display changes to a static Verb 06 Noun 63, where R1 is the same as Noun 62, namely inertialvelocity; R2 is the altitude rate, or verticalvelocity; and R3 is the altitude above thenominal-landing-site lunar radius. Because the engine-gimbaling drive motors are very slow moving, the descent engine comes on at lo-percent of full thrust for 26 seconds. During this time, the digital autopilot positions the engine gimbal such that the thrust axis passes through the vehicle center of gravity. At TFI = +26 sec, the computer commands loo-percent thrust from the DPS engine.

During the first four minutes” of the braking phase, the crew and the ground monitor all the spacecraft systems for proper operation, and the ground compares the various guidance system’s state vectors to ascertain if there are any drifts in the onboard sensors. Figures 16a and b show typical data formats for the ground consoles for monitoring the onboard guidance, navigation, and control systems. Figures 17a, b, and c show a simplified form of checklist that the airborne crew use to monitor their systems.

During this period, the crew can have their “front” windows facing down or up. For Apollo 11, the crew had their windows facing the moon (down) and used the reticle (called the landing-point designator— LPD) (Fig. 5 and 18) to monitor landmarks as they passed under the LM. At about two minutes into the burn (Fig. 17a), the crew also checked the altitude profile of their trajectory by observing how fast a landmark swept across the window reticle.

At about 40,000 feet (time = 3.0 min),** if the windows are facing the moon, the crew would yaw their spacecraft right 174 deg in order to orient the windows approximately up and enable landing-radar lockon. The crew would not yaw the full 180 deg, because of the following: down to 30,000 ft, the crew has control of spacecraft rotations about the thrust axis (yaw about spacecraft X-axis, called X-axis override); at 30,000 ft, however, the computer locks out this capability in order that it can accurately point the landing-radar antenna. By leaving in a small error (6 deg) for the computer to null, the crew determines that automatic X-axis control at 30,000 ft does in fact occur.

Just before four minutes, all the ground-monitor personnel check their displays and give a positive “GO” to the flight director, who in turn gives it to the Capsule Communicator (CAPCOM), who relays it to the crew (Fig. 17a). This positive “GO” is repeated once more at about 3,000-ft altitude, nine minutes into the burn (Fig. 17b).

The next event concerns the proper operation of the landing radar. In addition to the operational

“The crew can update the position of the targeted landing site with the latest data from ground tracking by use of loadable Noun (N69). He can do this anytime during the landing (down to P64) but normally does it within the first three minutes after engine ignition. A V25N69E calls Noun 69 which can then be loaded with the AX, AY, AZ components of the desired change in the landing site location.

**Note: Time is referenced to the time the braking phase started.

checks by the computer and the ground," the data must be compared with the computer inertial-altitude data before the crew will allow data to be inserted into the computer to modify the inertial-altitude data. If the difference is too large, the resulting trajectory could impact the moon (Fig. 19). To perform this check onboard, the crew call Verb 16 (monitor decimal) Noun 68, where R1 is slant range to landing site; R2 is TG, time remaining in this phase**; R3 is ΔH, the difference between altitude computed from the landing radar data and the inertial altitude. If the ΔH data are within the prescribed limits (Fig. 19) for ten seconds, the crew enables the updating of the inertial altitude with landing-radar data by performing Verb 57E. After enabling the landing-radar updating, the flight crew and the ground monitor (Fig. 16) to see that the ΔH converges as the landing- radar data force the inertial altitude to agree with the true altitude. Once satisfied, the crew can go back to the Noun 63 display, from the Noun 68 display, by depressing the KEY-RELEASE key, which allows the computer to display thenominal-sequence display, in this case Noun 63.

The next event is the throttle down time, which is predicted by ground processor and checked by the airborne crew. After that, the crew monitors the pitchup and the automatic selection of the visibility-phase program (P64) when the HI-GATE conditions have been met.

When P64 is called, the DSKY display changes from a static Noun 63 to a flashing Verb 06 Noun 64:

R1 – Time to go (or remaining) in this phase (TG) plus the landing-point-designator elevation angle (LPD)

R2 – Altitude rate

R3 – Altitude

As described earlier, during this phase the vehicle is pitched up enough that the targeted landing site can be viewed out the front windows (Fig. 18). Also, the targeted landing-site elevation, indicated by the elevation angle displayed in the right two digits of RI, can be viewed by the crew by using the window reticle (Fig. 18). If the crewmember does not like the indicated landing site, he can redesignate the landing site by the following procedure. First, he enables redesignation by depressing the PRO key, which changes the display from a flashing Verb 06 Noun 64 to a static Verb 06 Noun 64, indicating computer activation of this capability. The crewman can then use his three- axis- rotational hand controller (RHC) to redesignate by moving the controller out of detent in the desired direction and then letting it spring back to the detent. Each side redesignation moves the targeted landing site approximately 2.0 deg; each forward or backward redesignation moves the targeted landing site approximately 0.5 deg. When TG (R1 in Noun 64) goes to zero, the crew can no longer redesignate by this technique. If the crew did nothing at this point (LO-GATE), the computer would automatically select the auto-landing program (P65).* The crew normally switches out of P64, however, and into the semiauto program (P66)—at about 500 feet. Program P66 is enabled by switching the spacecraft altitude-mode switch from AUTO to ATTITUDE-HOLD. In P66, the crew controls the attitude to maneuver the spacecraft to a desired landing site, but the engine throttle is controlled by the computer to maintain a desired altitude or altitude rate. The crew controls the altitude rate by a rate-of-descent (ROD) switch, One activation of this switch changes the vertical velocity by 1 ft/sec in the direction selected (up or down). The crew can also control the engine throttle manually by enabling the fully manual program (P67). To enable this program, the crewmember switches the throttle-control switch from AUTO to MANUAL. To have manual attitude control of the spacecraft, he must select attitude hold on the at.titude-mode switch, enabling manual attitude control through the digital autopilot (DAP). Normally, P67 is not expected to be used, as P66 is a much easier mode to fly the vehicle in, and it appears to work well in flight.

From 500 feet on down, the crew selects the final landing site very carefully to make sure that it is reasonably flat and free of boulders. Once they have selected their final site, the crew nulls the translational velocities and reduces the vertical velocity to 3 ft/sec, or less, by the time the contact light comes on (altitude 5 feet). M'hen the contact light does come on, the crew manually shut down the DPS engine. During this period, all systems, particularly fuel remaining, are monitored very carefully by both crews-air and ground.

During the descent, secondary cues are also monitored; e.g., at 19,000 ft, observing the horizon in the forward window (Fig. 17a); observing the location of the earth in the front windows (Fig.18); and, as mentioned earlier, monitoring the ground track while the windows are facing down (before 40,000 ft).

Once safely on the ground, the crew calls the landing confirmation program – (P68). The object of this program is to terminate the landing guidance, set the DAP functions, and initialize the LGC for lunar surface operations. The same program displays the computed position for the landing site. Specifically, Noun 43 displays in R1 the Latitude, R2 the Longtitude and R3 the Altitude of the LM above the lunar radius of the targeted landing site.

Although I have limited my discussion to the primary system, there are comparable procedures for the backup, abort-guidance system (AGS). In

*It should also be noted that the landing radar data (altitude and altitude rate) can be monitored by the crew using a dual tape meter. Near hover, the two horizontal components of velocity from the landing radar can be displayed on a cross-pointer meter display.

**Actually, this is the time to reach the targeted conditions. The time remaining in the phase is 62 sec less than TG.

*Note: For P65, 66 and 67 the display changes to a Noun 60 (Fig. 15). Again, register one is the only new data. For Noun 60, R1 is the horizontal component of velocity.

passing, I should note that the backup system's inertial package can be aligned to the same inertial orientation as the primary system; also that (by Verb 47) the time and state vectors (CM and LM) stored in the primary system computers can be transferred to the backup-system (AGS) computer by using the LGC digital downlink.

IV MAN-MACHINE CONTROL INTERACTION FOR SPACECRAFT ATTITUDE CONTROL

The description of the powered-descent phase of the lunar landing details man's supervisory role in Apollo. The levels of control interaction available are illustrated in Fig. 20a and b, which summarize the rotational attitude-command modes for the command-module primary and backup systems.

For the primary system, there are four spacecraft control modes (Ref. 18): (1) automatic maneuver to a direction specified by either the computer or the man; (2) attitude hold about a specified attitude with selectable deadband and response rate; (3) manual maneuver with a three-axis hand controller at a fixed, but selectable, rotation rate that is also coupled to the attitude-hold mode whenever the controller is returned to its neutral position; and (4) a mode for small attitude maneuvers with timed, short, thrust impulses from the reaction-control motors, activated by a special three-axis controller. The latter mode is normally associated with cislunar-navigation observations.

For the backup system-it is really a number o:f systems or parallel paths as Fig 20a and b illustrate--the spacecraft control modes, which are all manually activated, are as follows: (1) an attitude hold with selectable deadband and response rate; (2) attitude maneuvers with (a) the same three-axis hand control-. ler as the primary system and (b) a selectable maneuver rate that is proportional to hand-, controller displacement; (3) attitude maneuvers with accelerate command; and (4) attitude maneuvers,, with the normal controller, using minimum-thrust impulses from the reaction-control motors.

Between the primary and backup systems, nine levels of control interaction give four levels of control capability: (1) automaneuver; (2) manual. maneuvers with attitude hold; (3) manual maneuvers with timed minimum-thrust impulses, and (4) manual. maneuvers with accelerate command. The interfaces to these control capabilities range from direct hand controllers to the computer DSKY. The necessity for these nine levels of interaction was to provide functional capability in the event of failures that might incapacitate large parts of systems. Again, there is great flexibility and redundancy, but heavy burden on the crew. As noted earlier, the increases in reliability offered by the newer technology will. allow system structures that should not require the crew tointeract with nine levels of control in order to change the attitude of the spacecraft.

V SUMMARY

In summary, with the expected increases in component reliability and decreases in component size, future designs will provide airborne systems with enough capability to relieve man of the necessity to play such an extensive role in either piloting or supervising his vehicle.

For the time period of its design (1962-64), the mar-machine interface for the airborne computer offers great flexibility for relatively small cost in size, weight, power, and computer memory. It should be noted that the man can be integrated to this design in a variety of ways or levels. The lunar-landing sequence described earlier illustrates near-maximum information flow and crew control of computer sequencing. The minimum level that could be implemented with this design would contain only two programs, namely, P01, "Take me to the moon," and PO2 "Take me home," The problem with the latter mode is that it would be very inflexible and difficult tomechanize on a development program as large as the first lunar-landing mission. The trouble with the present technique is that it does place a severe burden on the crew during training as well as in flight. As lunar flight experience grows, a better tradeoff between flexibility and complexity can be made, even with the present equipment. For example, in cislunar space, the spacecraft's longitudinal axis must be rotated slowly with respect to the sun in order to prevent large thermal gradients. This mode is called the passive-thermal-control (PTC) mode. During Apollo 8, this rate was maintained manually, by the crewman on watch, using SCS minimum-impulse control. During Apollo 10 and 11, revised procedures for initializing the longitudinal rate, plus a new digital-autopilot (DAP) mode, removed the necessity for a crewman to continuously monitor the PTC mode. As a result, the crew can now all sleep at once.

Again, newer technology offers control systems having variable-format, graphical input-output displays. These newer systems offer easier (less burdensome, hence less training), more-direct functional communications. In the limit (Fig. 1), the computer, like Hal in the film 2001, can read man's lips; or his mind as in The God Machine. In more practical directions, variable-format displays solve the problem of panel space devoted to systems used only for a few minutes out of the entire mission, e.g., systems for monitoring entry or boost.

Finally, these display/control systems, coupled with a more administrative role for man-less direct supervising and sequencing as compared to Apollo-create the real challenge. The direction of this challenge lies in determining the levels of interaction and the form that the interaction of man-machine communication should take. Apollo, therefore, is the transition between (a) systems that require direct constant task interaction and supervision and (b) systems in which man-machine communication is more functional, the supervisory role more administrative.

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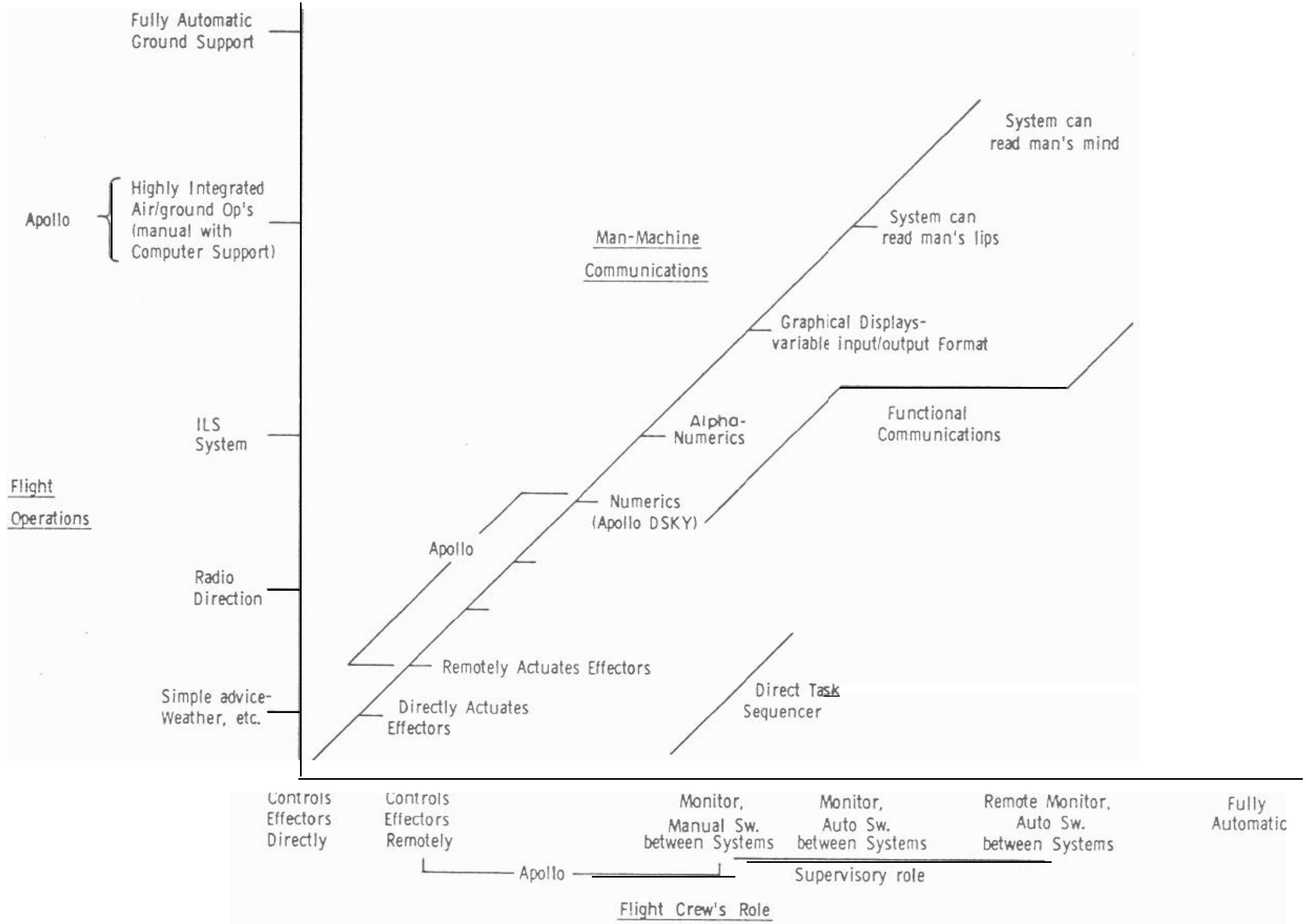


Fig. 1 Transition in Manned-Vehicle Operation

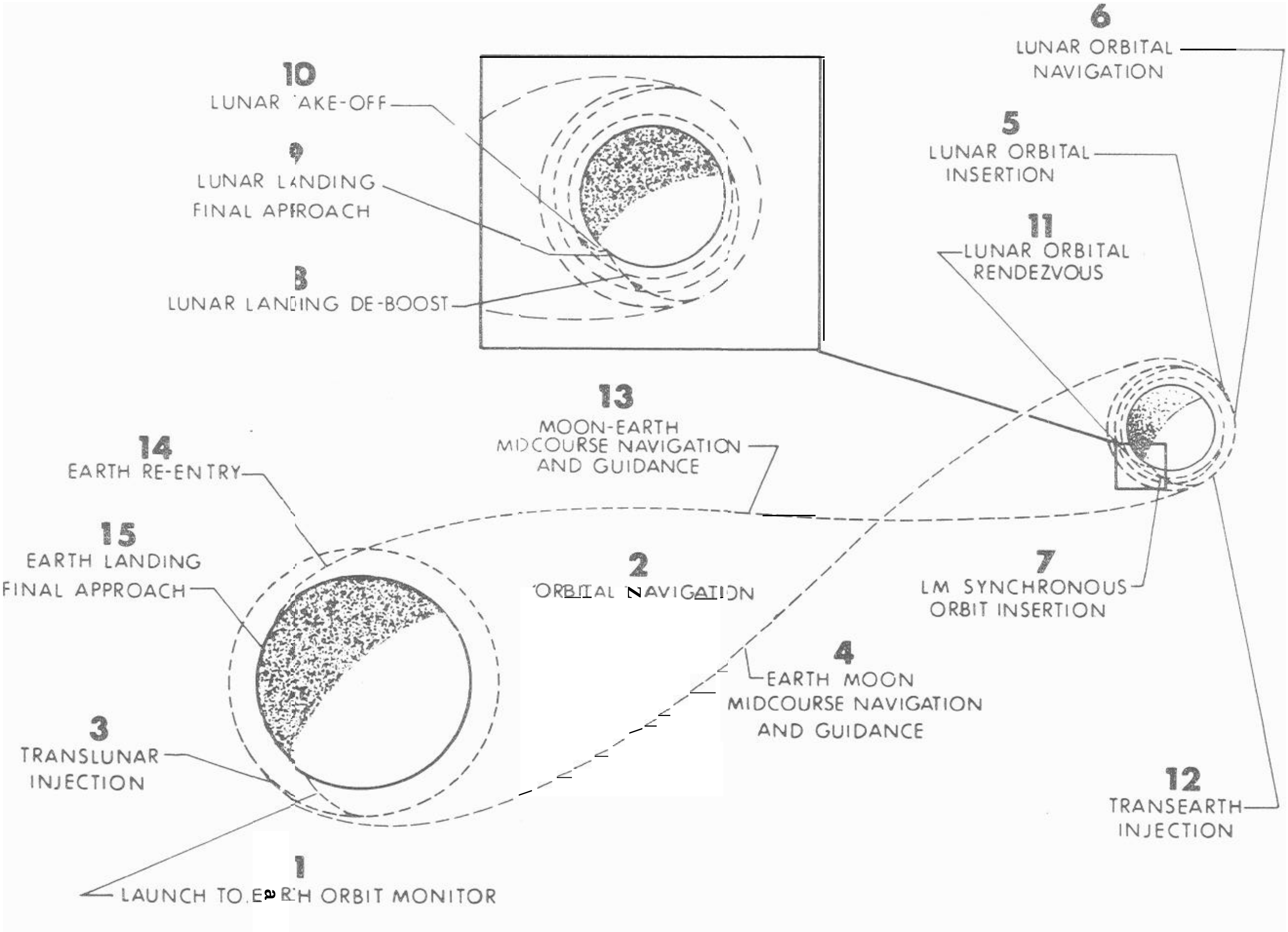


Fig. 2 G&N Mission Phase Summary

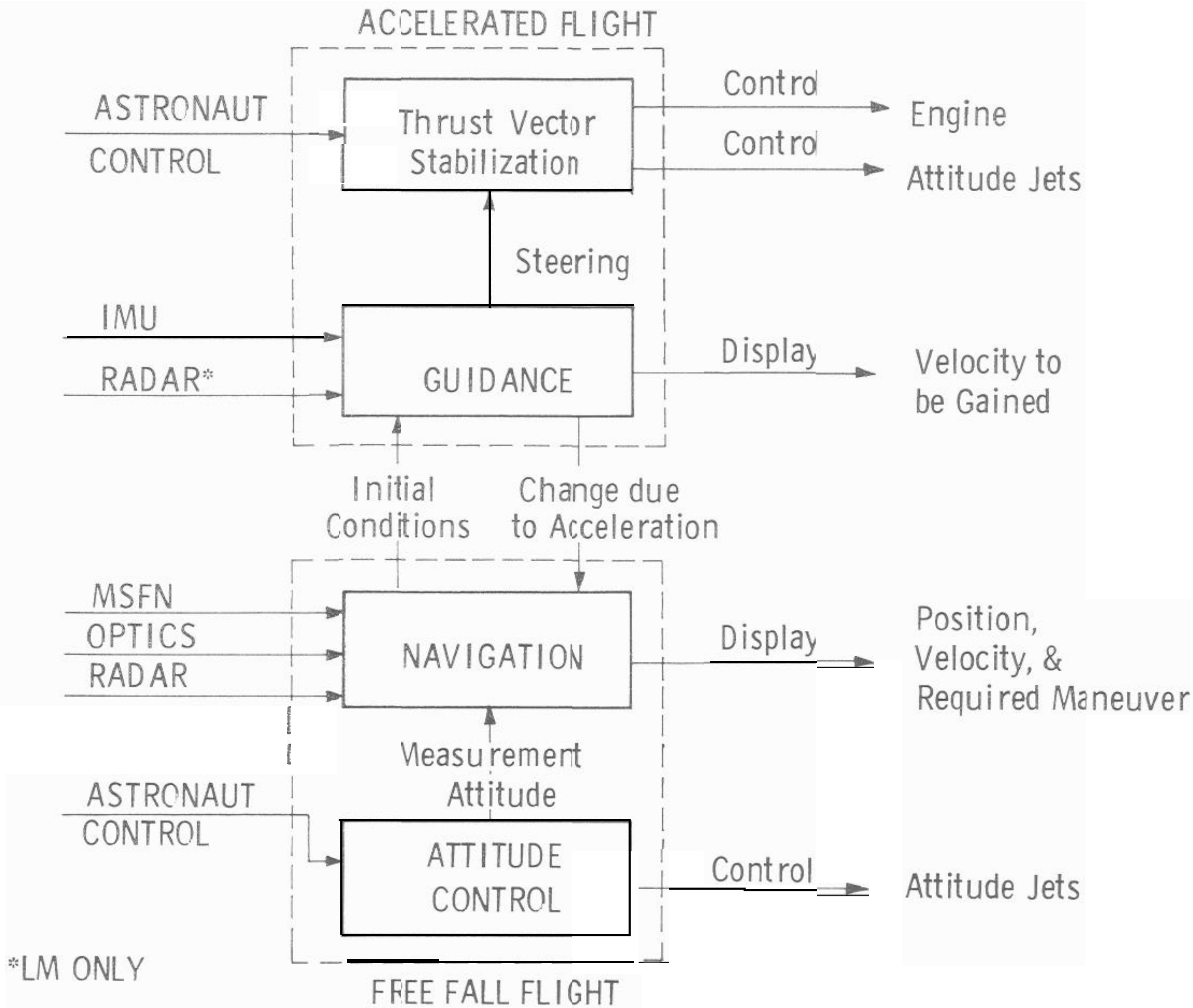


Fig. 3 Functional Drawing

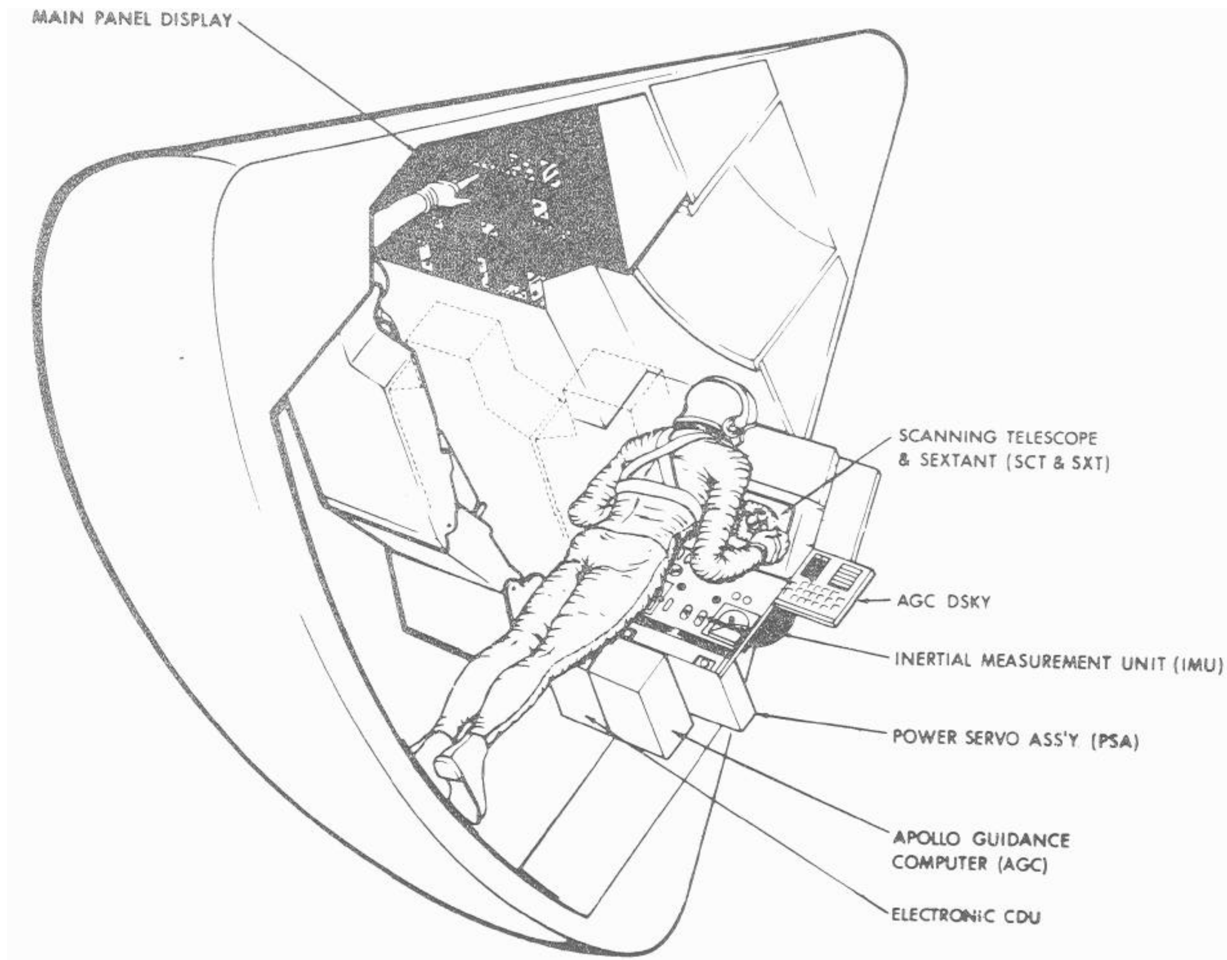


Fig. 4 CM PGNCS Installation

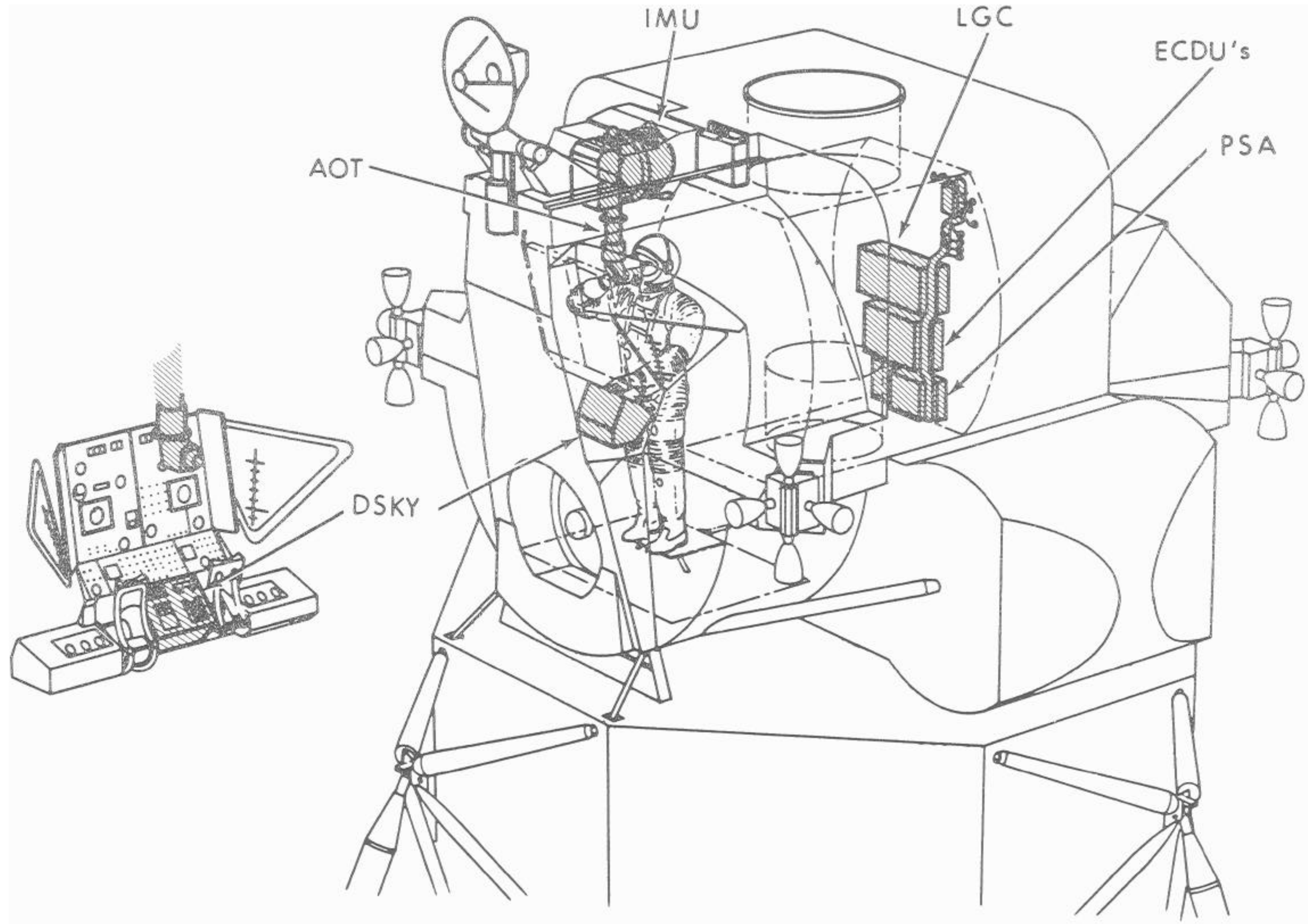


Fig. 5 LM PGNCS Installation

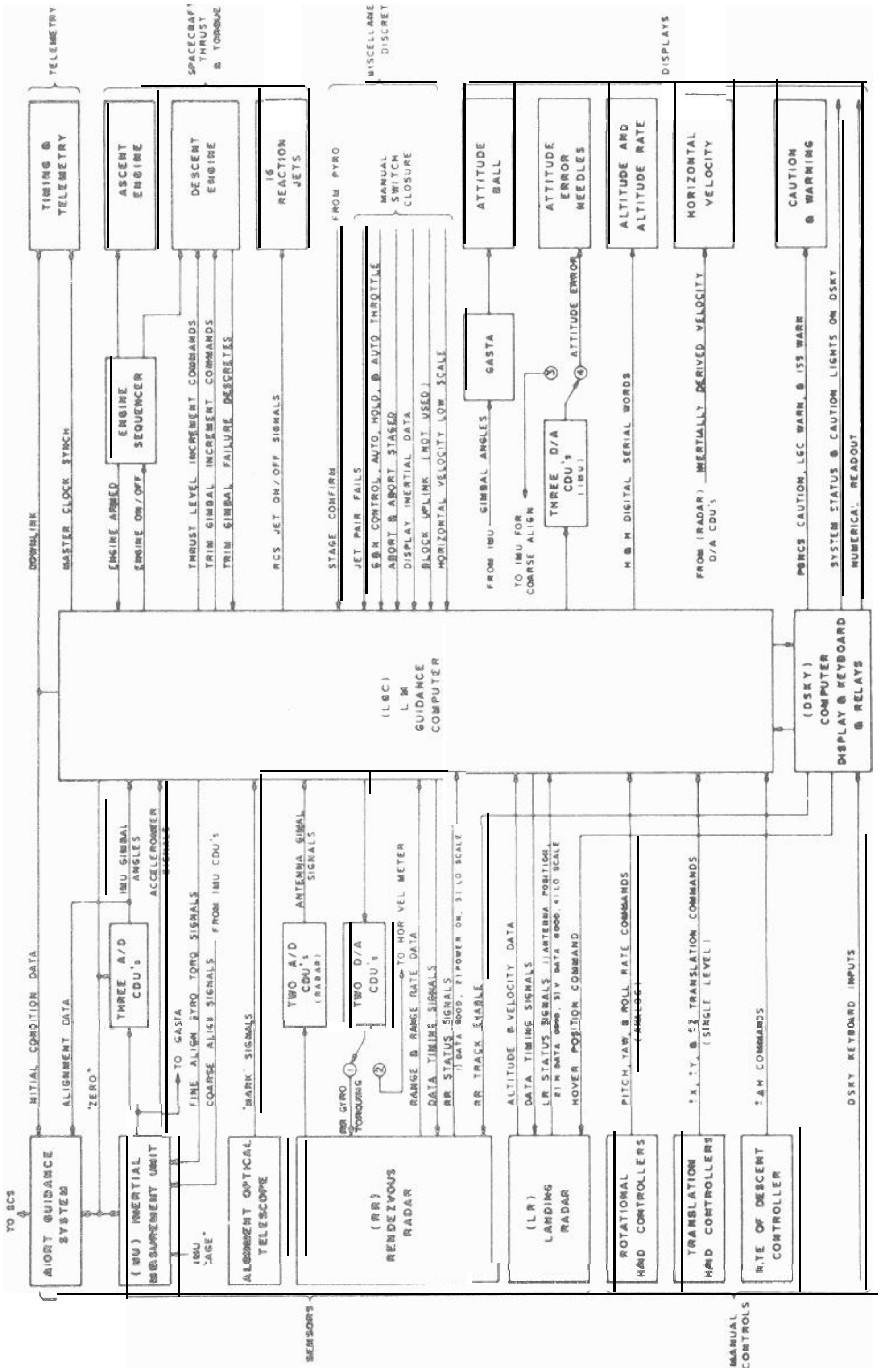


Fig. 6 LGC Block Diagram

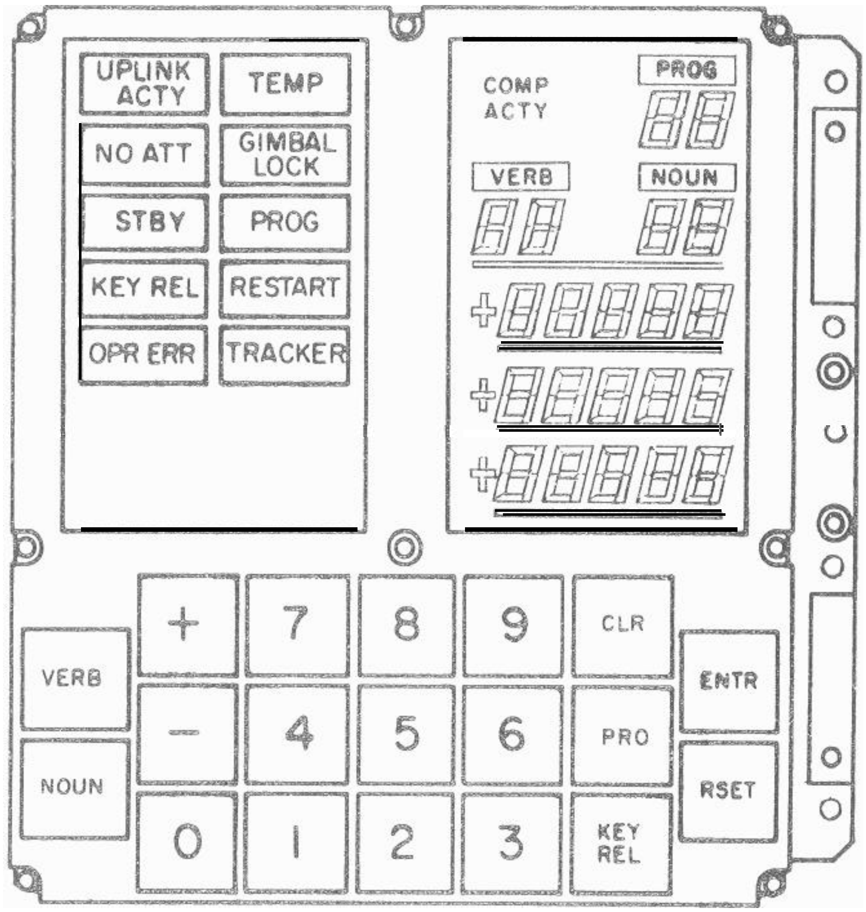
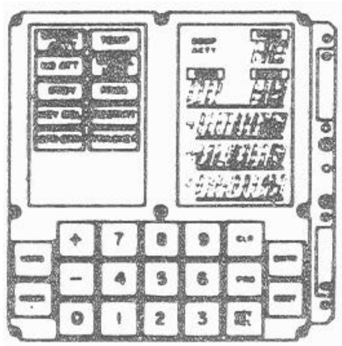

UPLINK
ACTY
TEMP
NO ATT
GIMBAL
LOCK
STBY
PROG
KEY REL
RESTART
OPR ERR
TRACKER
COMP
ACTY
PROG
VERB
NOUN
+
7
8
9
CLR
VERB
ENTR
−
4
5
6
PRO
NOUN
RSET
0
1
2
3
KEY
REL

Fig. 7(a) DSKY

CM	LM	No.
Prelaunch and	Service	(P0-
Boost	Ascent	(P1-
Navigation		(P2-)
Pre-Thrusting		(P3-)
Thrusting		(P4-)
IMU Alignment		(P5-)
Entry	Descent	(P6-)
Aborts and Backups		(P7-)



CMC Keyboard

VERBS		NOUNS	
16	Monitor decimal	20	ICDU's R, P, Y
21	Load R1	22	New ICDU, s
22	Load R2		
23	Load R3	25	Checklist (used with V50)
25	Load R_1 R_2 R_3	32	Time to Perigee hrs, min, sec.
32	Recycle		
		33	Time of Ignition
34	Terminate Function	35	Time to event
37	Change Program	39	ΔT Transfer
48	Load DAP data	43	Lat, Long, Alt.
50	Perform Option	46	Autopilot config.
51	Mark Target	47	S/C Inertias & Weight
57	Start Rend. Marks	48	Engine Trim
71	CMC Update		
86	Initialize W Matrix	49	State Vec Update
		54	R, R, Tgt Elev.

Fig. 7(b) Computer Program Summary

CMC PROGRAMS

00	CMC Idling
01	Prelaunch Initialization
02	Gyro Compassing
03	Verify Gyro Compassing
06	CMC Power Down
07	IMU Ground Test
11	Earth Orbit Insertion (EOI) Monitor
17	Transfer Phase Initiation (TPI) Search
20	Rendezvous Navigation
21	Ground Track Determination
22	Orbital Navigation
23	Cislunar Midcourse Navigation
27	CMC Update
30	External ΔV
31	Lambert Aimpoint Maneuver
32	Co-Elliptic Sequence Initiation (CSI)
33	Constant Delta Alt. (CDH)
34	Transfer Phase Initiation (TPI)
35	Transfer Phase Midcourse (TPM)
37	Return to Earth (RTE)
38	Stable Orbit Rendezvous (SOR)
39	Stable Orbit Midcourse (SOM)
40	SPS
41	RCS
47	Thrust Monitor
51	IMU Orientation Determination
52	IMU Realign
53	Backup IMU Orientation Determination
54	Backup IMU Realign
61	Maneuver To CM/SM Separation Attitude
62	CM/SM Separation & Pre-Entry Maneuver
63	Entry-Initialization
64	Entry-Post 0.05G
65	Entry-Up Control
66	Entry -Ballistic
67	Entry-Final Phase
72	LM Co-Elliptic Sequence Initiation (CSI)
73	LM Constant Delta Alt (CDH)
74	LM TPI Targeting
75	LM TPM Targeting
76	Target ΔV
77	LM TPI Search
78	LM SOR Targeting
79	LM SOM Targeting

LGC PROGRAMS

00	LGC Idling
06	PGNCS Power Down
12	Powered Ascent Guidance
20	Rendezvous Navigation
21	Ground Track Determination
22	Lunar Surface Navigation
25	Preferred Tracking Attitude
27	LGC Update
30	External ΔV
31	Lambert Aim Point Maneuver
32	Co-Elliptic Sequence Initiation (CSI)
33	Constant Delta Altitude (CDH)
34	Transfer Phase Initiation (TPI)
35	Transfer Phase Midcourse (TPM)
38	Stable Orbit Rendezvous (SOR)
39	Stable Orbit Midcourse (SOM)
40	DPS
41	RCS
42	APS
47	Thrust Monitor
51	IMU Orientation Determination
52	IMU Realign
57	Lunar Surface Align
63	Braking Phase
64	Approach Phase
65	Landing Phase (Auto)
66	Landing Phase (ROD)
67	Landing Phase (Manual)
68	Landing Confirmation
70	DPS Abort
71	APS Abort
72	CSM CSI Targeting
73	CSM CDH Targeting
74	CSM TPI Targeting
75	CSM TPM Targeting
76	Target ΔV
78	CSM SOR Targeting
79	CSM SOM Targeting

Fig. 8 Programs for Lunar Landing Mission

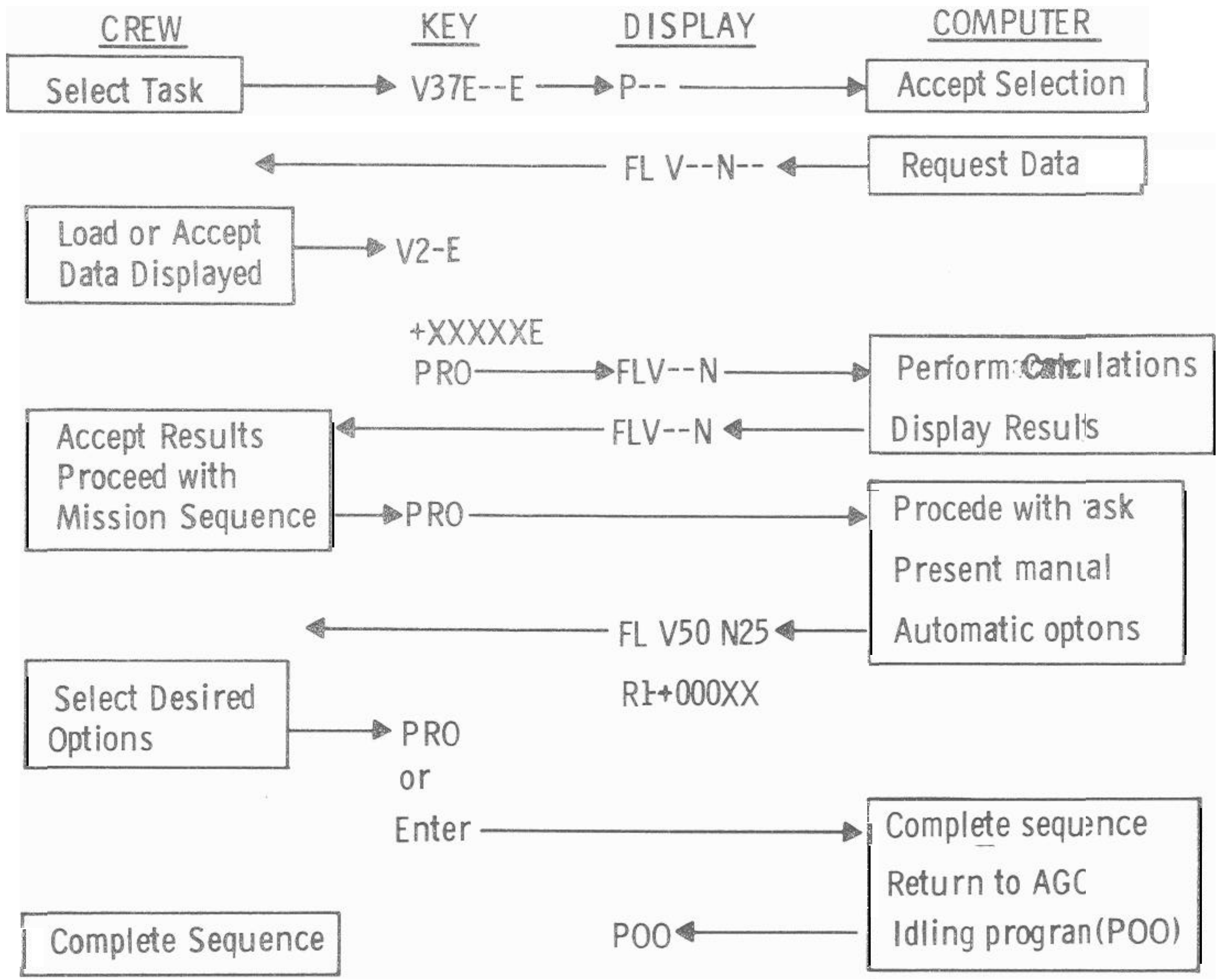
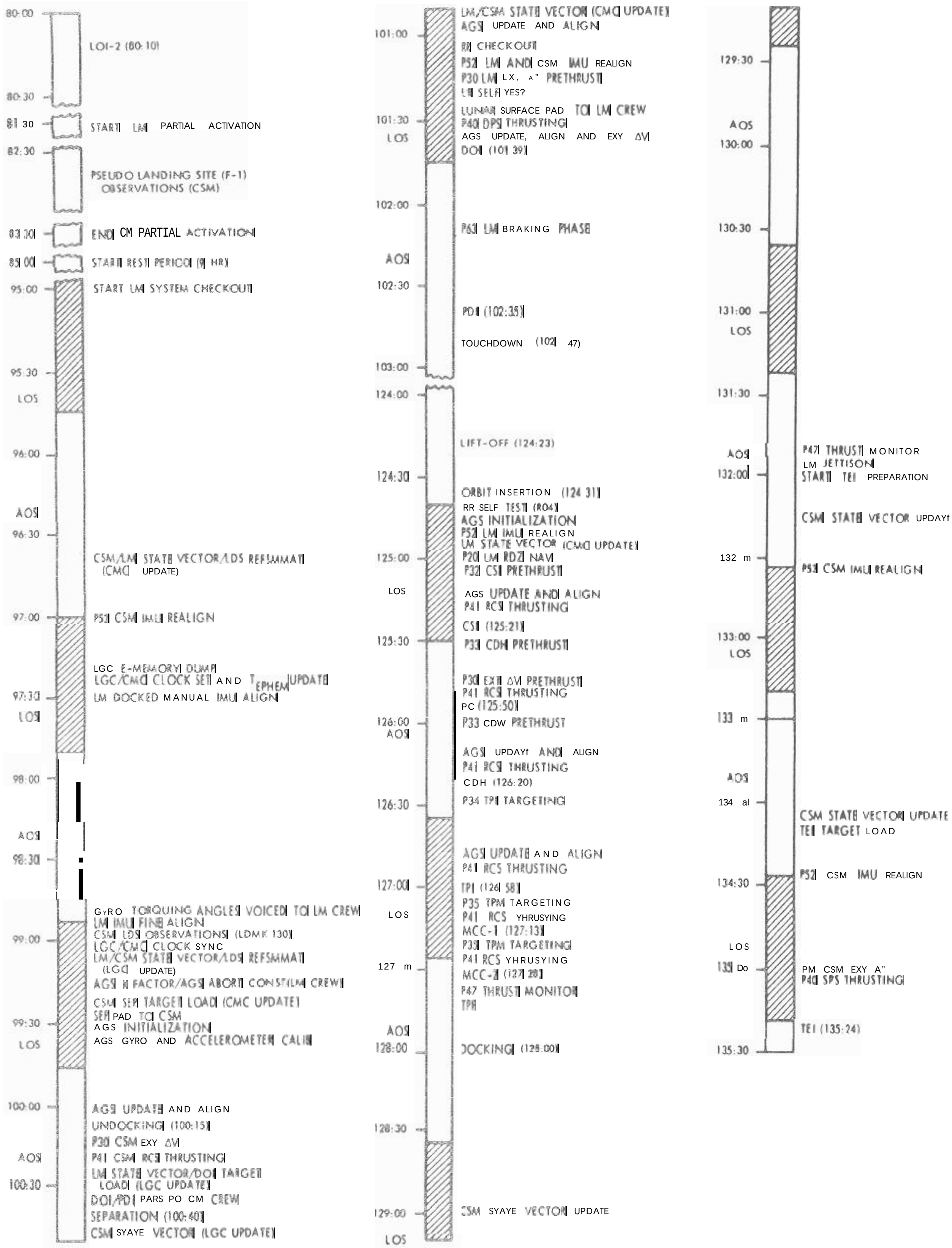
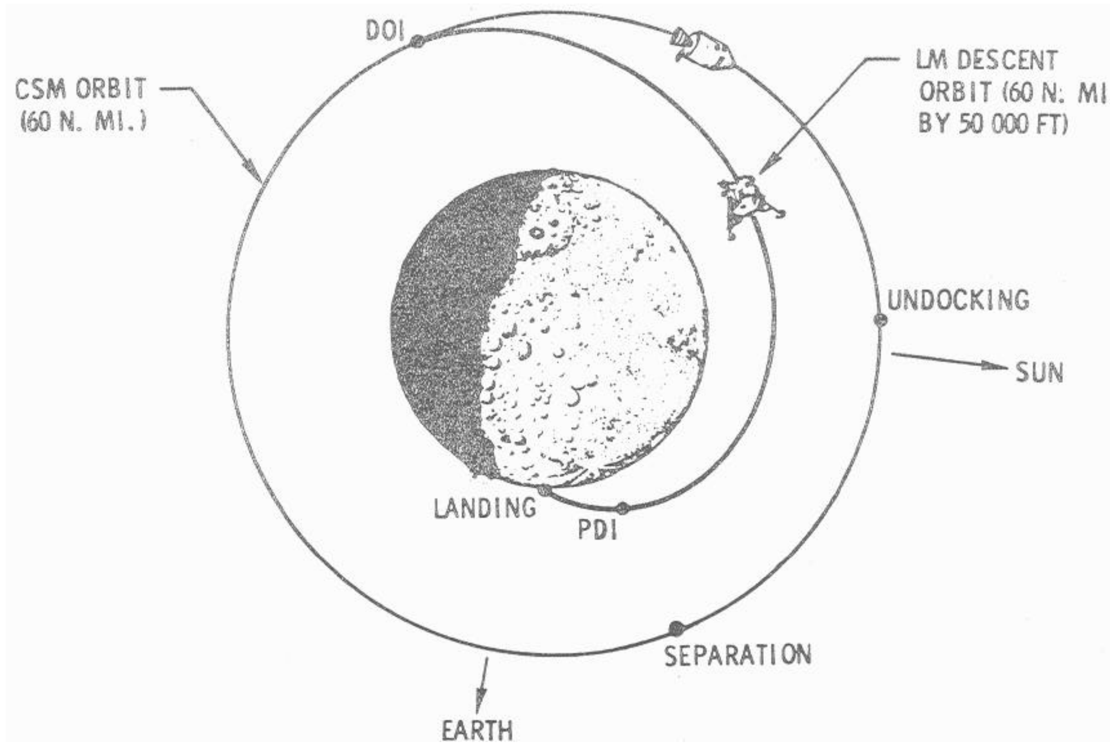


Fig. 9 General Crew/Computer Interface

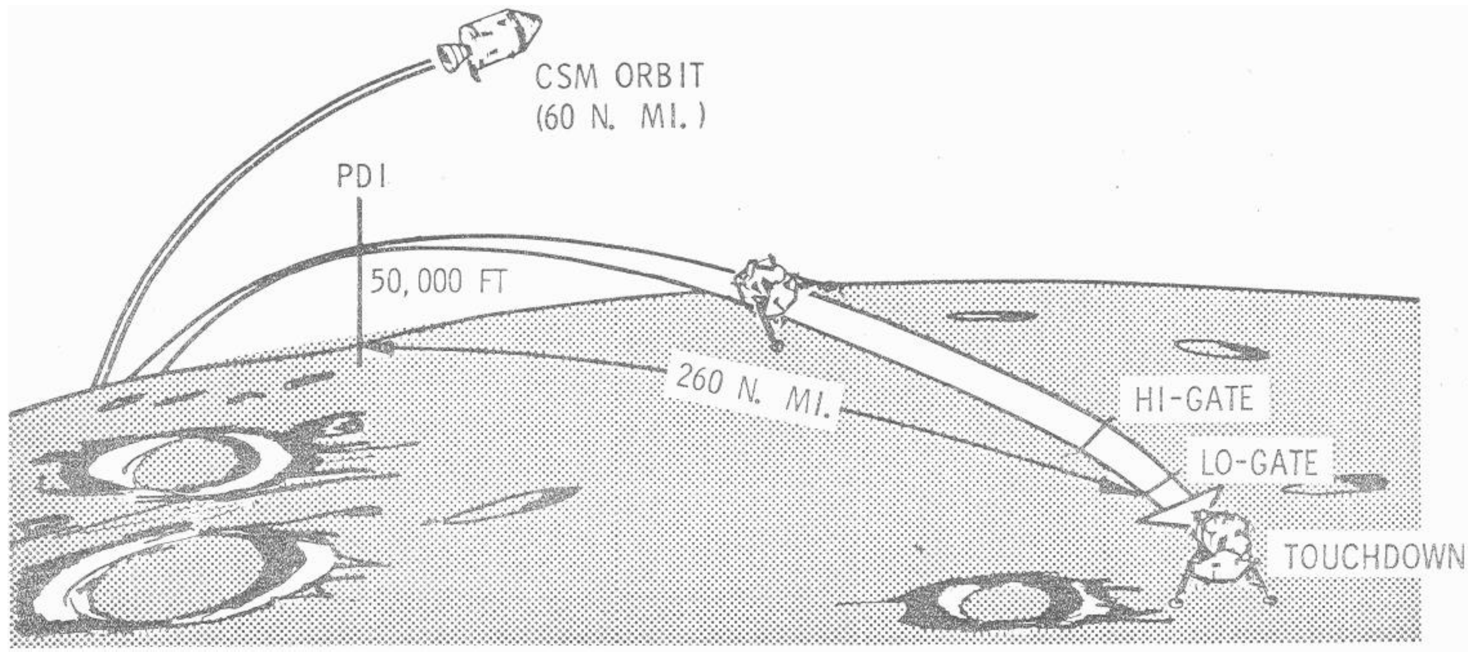


Fig, 10 Lunar Orbit Operations -Abbreviated Time Line



(a) LM descent phase geometry.

Fig. 11 LM Descent Phase



DESIGN CRITERIA

- BRAKING PHASE (PDI TO HI-GATE) - EFFICIENT REDUCTION OF ORBITAL VELOCITY
- FINAL APPROACH PHASE (HI-GATE TO LO-GATE) - CREW VISIBILITY (SAFETY OF FLIGHT AND SITE ASSESSMENT)
- LANDING PHASE (LO-GATE TO TOUCHDOWN) MANUAL CONTROL TAKEOVER

Fig. 12 Operational Phases of Powered Descent

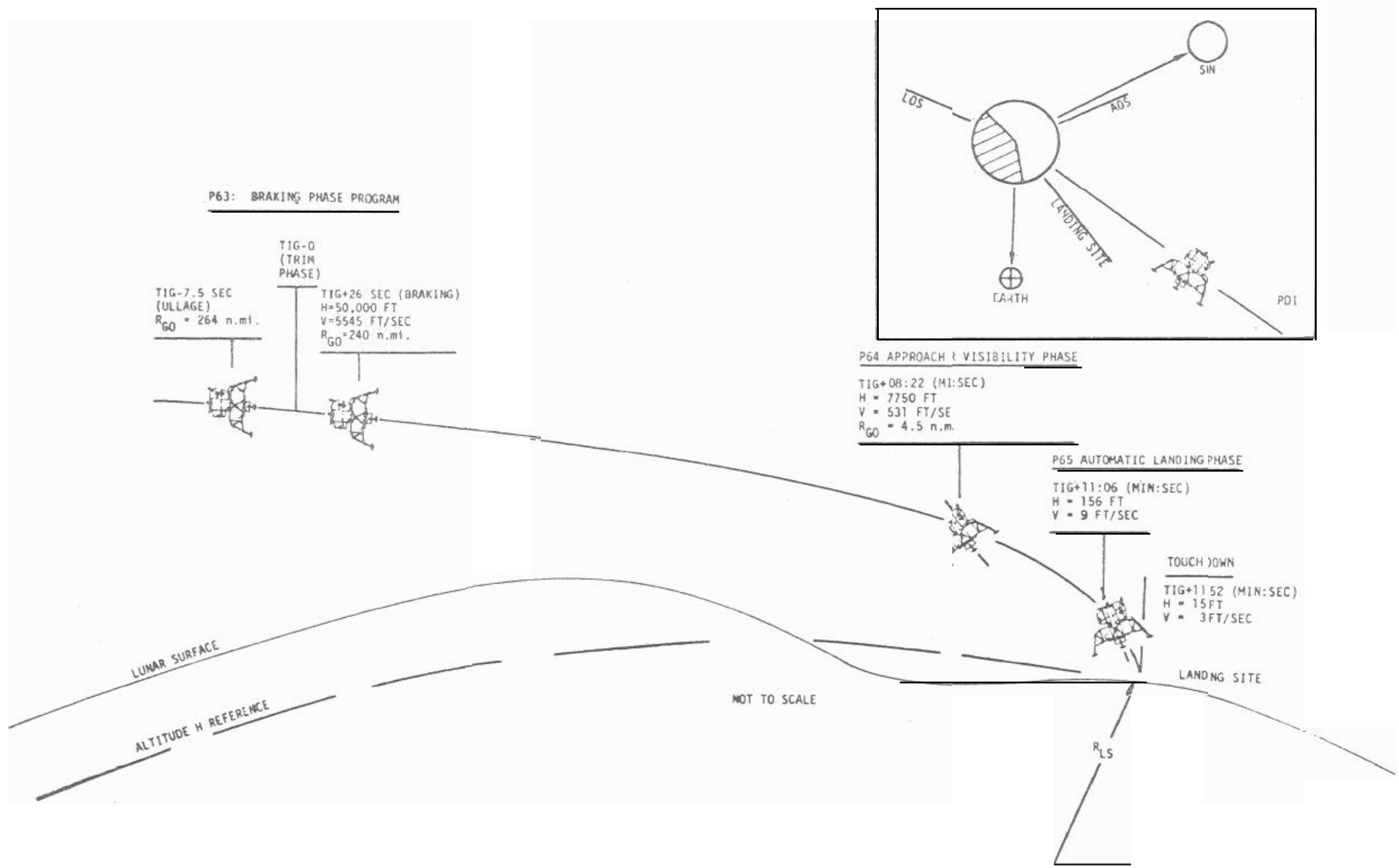


Fig. 13 Powered Descent Events

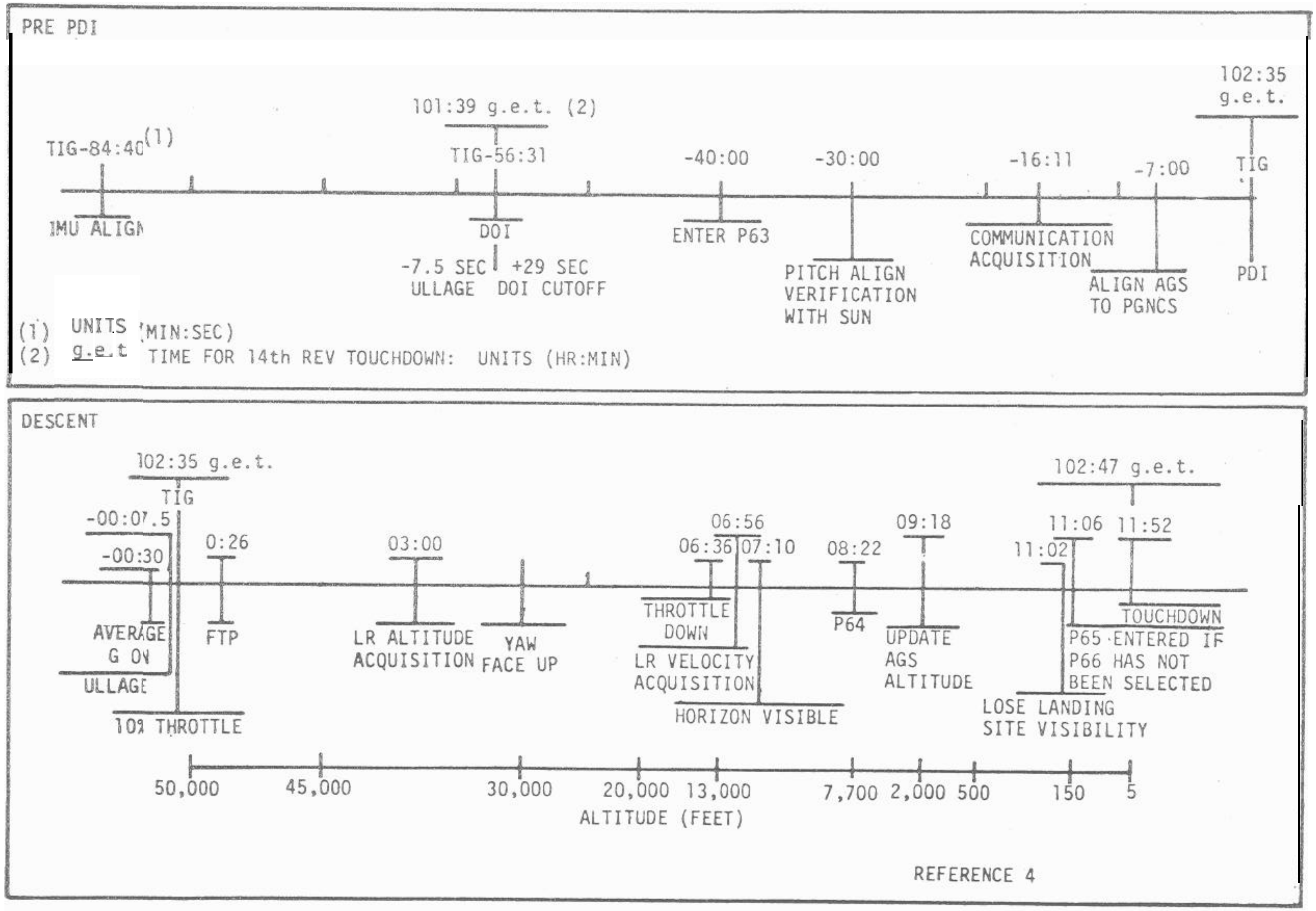


Fig. 14 Descent Timeline

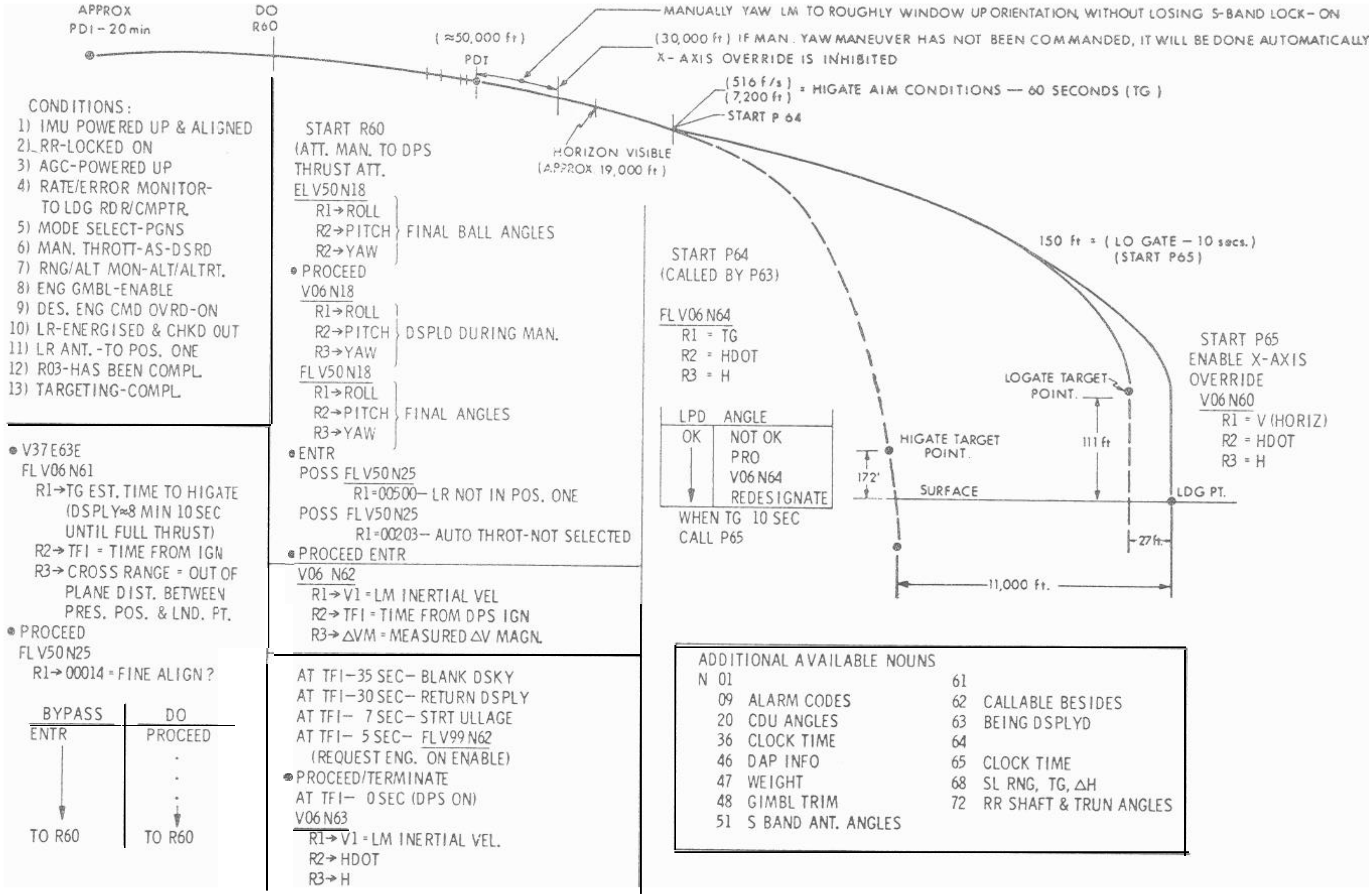


Fig. 15 G&N Displays and Descent Profile

GET ______ MET ______ 1123 (AEA | LGC | PCM |

AGS ______ LGC ______ LGC FMT ______ SITE ______

TGO ______ TTF/8 ______

PGNS RATE ______

RGA RATE ______

AGA RATE ______

______ ROLL/Z PITCH/Y YAW/X

ATF CMDS ______

LOC VER/HOR ______

RSVR GMBL ______

ICDUD ATT ______

CDUA ATT ______

IMU ATT ______

AGS ATT ______

PGNSERR ______

AGSERR ______

MMNTOFFSET ______

AGS VEL ______

LGC DELVEL ______

AGS DELVEL ______

AGS ULL ______ ACTVEL ______

AUTO — — F0 ______

R ______ A T T H — — F-1 ______

P ______ IR F2 ______

Y ______ AP — DEDA ______ DSKY ______

RR ______ VD — AD — P -

TRK ______ RD — R O - . - . - V -

R ______ R ______ CLR — N —

RDT ______ VX ______ M ______ 1 ______

SH — VY ______ ______ 2 ______

TR ______ VZ ______ R E 3 D O

Fig. 16(a) Typical Data Format for Ground Consoles

GET	GROUND ELAPSED TIME	H M S XXX:XX:XX
MET	MISSION ELAPSED TIME	H M S XXX:XX:XX
AGS	ABORT GUIDANCE SYSTEM TIME	H M S XXX:XX:XX
LGC	LM GUIDANCE COMPUTER TIME	H M S XXX:XX:XX
LGC FMT	IDENTIFICATION OF DOWNLIST BEING TRANSMITTED	
SITE	IDENTIFICATION OF SITE FROM WHICH DATA IS BEING RECEIVED	
TGO	TIME TO GO UNTIL ENGINE CUTOFF	M S XX:XX
TTF/8	TIME TO GO UNTIL END OF PHASE (DESCENT PROGRAMS)	M S XX:XX
PGNS RATE	ROLL, PITCH, YAW DAP RATES	XX.X DEG/SEC
RGA	AGS BODY MOUNTED RATE GYRO OUTPUT	XX.X DEG/SEC
ASA	AGS ABORT SENSING ASSEMBLY BODY RATES	XX.X DEG/SEC
ATT CMDS	LGC ATTITUDE COMMANDS	XX.X DEG
LOC VER/HOR	BODY ANGLES FROM THE LOCAL VERTICAL COORDINATE SYSTEM	XX.X DEG
RSVR GMBL	1X RESOLVER GIMBAL ANGLES	XXX.X DEG
ICDUD ATT	DESIRED CDU ANGLES TO THE DAP	XXX.X DEG
CDUA ATT	ACTUAL CDU ANGLES	XXX.X DEG
IMU ATT	1X RESOLVER GIMBAL ANGLES	XXX.X DEG
AGS ATT	ABORT GUIDANCE SYSTEM BODY ANGLES	XXX.X DEG
PGNS ERR	CDU-DAC OUTPUT	XX.X DEG
AGC ERR	ABORT GUIDANCE SYSTEM ATTITUDE ERRORS	XXX.X DEG
MMNT OFFSET	ANGULAR ACCELERATION ABOUT ROLL AND PITCH	XX.X DEG/SEC^2
AGS VEL	ABORT GUIDANCE SYSTEM INDICATED VELOCITY	XXXX FT/SEC
AGC DEL VEL	PIPA OUTPUT FOR A SECOND	XX.X FT/SEC

AGS DEL VEL	ABORT GUIDANCE SYSTEM MEASURED VELOCITY	XX.X FT/SEC
AGS ULL	ABORT GUIDANCE ULLAGE MEASUREMENT	XX.X FT/SEC
ACT VEL	ACCUMULATED VELOCITY ALONG THRUST	XX.X FT/SEC
AUTO	AUTO STABILIZATION MODE STATUS	XX/BLANK
R P Y	ROLL, PITCH AND YAW ACHIEVED FROM PULSES, DIRECT OR AUTO (NORM)	$\pm$XXX.X DEG
ATT H	ATTITUDE HOLD MODE STATUS	XX/BLANK
*F0 *F1 *F2 ALARM CODES	FIRST SECOND MOST RECENT	
*RR	RADAR MODE FLAGWORD (RADMODES)	$XXXXX_8$
TRK	RADAR TRACK ENABLE	CH 12 B 14
RDT	RENDEZVOUS RADAR RANGE RATE	XXXX FT/SEC
R	RENDEZVOUS RADAR RANGE	XXX.XX NM
SH	RENDEZVOUS RADAR SHAFT ANGLE	$\pm$XXX DEG
TR	RENDEZVOUS RADAR TRUNNION ANGLE	$\pm$XXX DEG
AP	LANDING ANTENNA POSITION	1 OR 2
VD	LANDING VELOCITY DATA GOOD	GOOD/BAD
RD	LANDING RANGE DATA GOOD	GOOD/BAD
R	LANDING RADAR RANGE	X NM
V_X V_Y V_Z	LANDING RADAR VELOCITIES	$\pm$XXXXX FT/SEC
DEDA	AGS DSKY	
AD	ADDRESS	
RO	READOUT	
CLR	CLEAR	
M	REGISTER 5 DIGIT CONTENTS	
REDO	NUMBER OF LGC RESTARTS	
DSKY		
*P	PROGRAM	
*V	VERB	
*N	NOUN	
1 2 3	ROW 1, 2, AND 3	

Fig. 16(b) Typical Data Format for Ground Consoles

POWERED DESCENT (PDI)

Time	CDR	VI	H DOT	H	PROP	OHW	LMP
00:00	ENG START	5560	- 4.3	48.8K	95	286	
	THRUST - 10%						
	RATES < 3°						
:05	DES ENG CMD OVRD - ON						
:26	FTP (96%)						SUPRCRIT HE < BURST (1880)
:30		5500	- 4.8	48.7K	95	285	
01:00	FDAI P - NOM	5200	-14.0	48.4K	89	279	VI, H DOT, H, PROP - NOM
	GROUND TRACK IN PLANE						V LAT AGS = 0
	OHW - 10						R DOT = 0 @ 1:10 (TM)
	R, Y - ZERO						RNG/ALT MON - ALT/ALT RT
	ERRORS < 3°						VI AGS = VI PGNS
	AGS BALL = PGNS BALL						H, H DOT AGS = H, H DOT PGNS (TM)
							LR ALT LT - ON
01:30		4900	-21.0	47.9K	84	275	
02:00	LPD ALT CHECK	4600	-30.0	47.1K	79	271	VI, H DOT, H, PROP - NOM
							DPS TEMP/PRESS - NOR
							RCS TEMP/PRESS - NOR
							RCS USAGE - NOM
							V16 N68E
							RANGE, TGO, ΔH
02:30		4300	-40.0	46.1K	74	268	
03:00	REPORT LNDMK (MASKELYNE)	4000	-53.0	44.7K	68	267	RANGE = 110 NM
	YAW RT 174°						
03:30		3600	-67.0	42.9K	63	264	
							LR ALT LT - OUT
							ΔH < 15 K @ 41K
							ΔH ACCEPTABLE FOR 10 SEC
04:00	FDAI P - NOM	3300	-80.0	40.7K	58	82	V57E
							VI, H DOT, H, PROP - NOM
							V 16 N68E
							ΔH DECREASING
							KEY RLSE
	REPORT GO/NO GO						CHECK ED BATTS

Fig. 17(a) Simplified Crew Monitoring Checklist

POWERED DESCENT (PDI) (Cont)

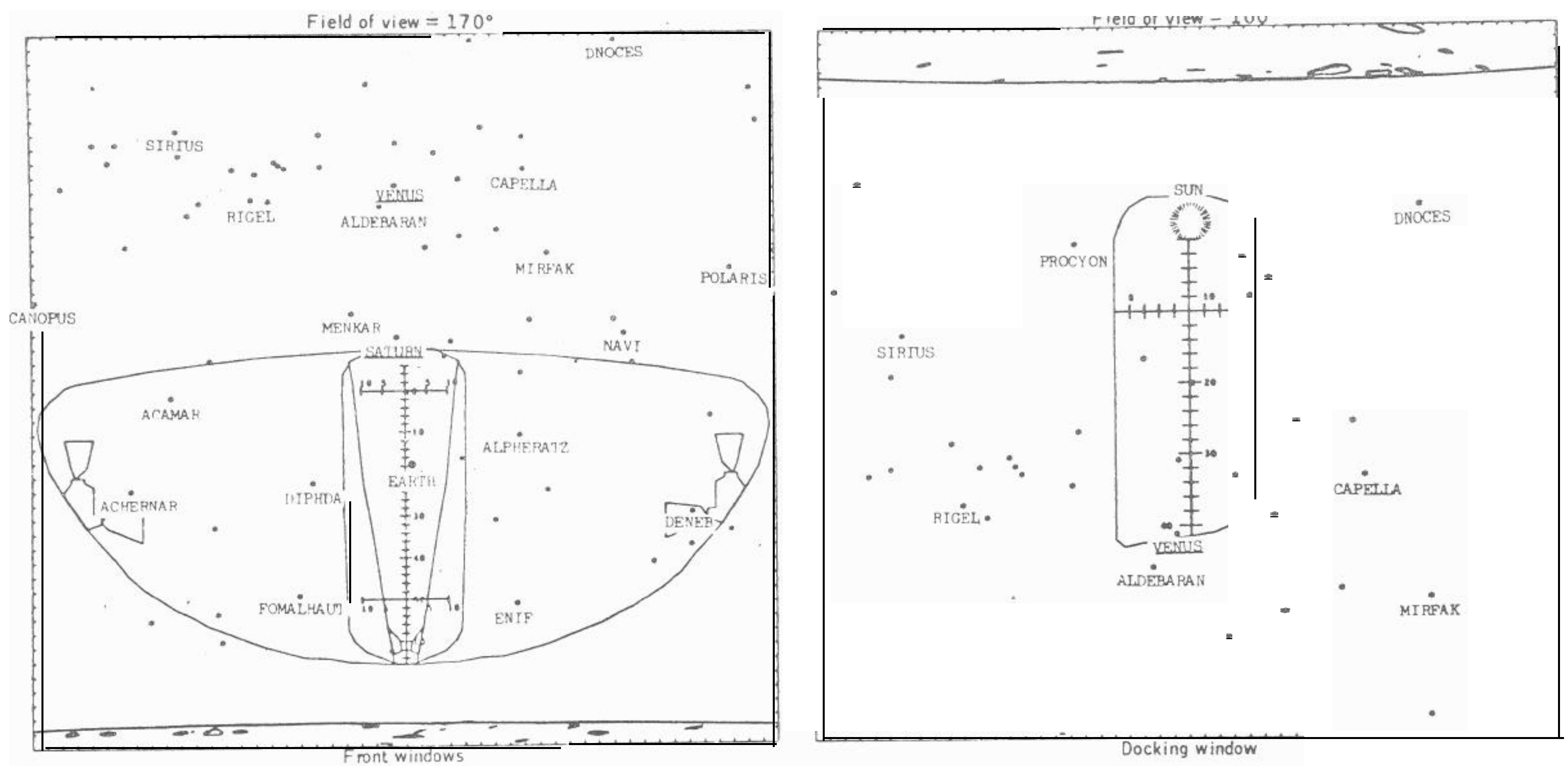
TIME	CDR	VI	H DOT	H	PROP	OHW	LMP
04:30		2900	- 95	38.0K	53	80	
05:00	FDAI P - NOM R - ZERO AUTO YAW TO ZERO 30K RECEIVE THROTTLE DOWN TIME PGNS BALL = AGS BALL	2600	-109.0	34.8K	47	78	VI, H DOT, PROP - NOM DPS TEMP/PRESS - NOR RCS TEMP/PRESS - NOR RCS USAGE - NOM V LAT AGS = 0
05:30		2200	-122.0	31.2K	42	76	
06:00	POSS PITCH TRANSIENTS (LR UPDATING) THRUST = 57% (06:36)	1800	-123.0	27.5K	37	72	H PGNS = H LR (TM) NO LR VEL LT VI = 2000
06:30		1400	-114.0	24.3K	32	68	
07:00	FDAI P - NOM HORIZON IN FWD WDW (19K) PGNS BALL = AGS BALL THRUST = 59% MODE CONTROL (PGNS) - ATT HOLD	1200	-143.0	20.2K	29	63	H DOT PGNS = H DOT LR (TM) V LAT PGNS = V LAT LR DPS TEMP/PRESS - NOR RCS TEMP/PRESS - NOR RCS USAGE - NOM V16 N 68
07:30	FLY ERROR NEEDLES	1000	-157.0	16.2K	25	60	RANGE, TGO, ΔH
08:00	FDAI P - NOM PITCH OVER AT P64 (08:22) MODE CONTROL (PGNS) - AUTO THRUST DECREASING VIEW LANDING SITE	700 LPD	-157.0 MAX	11.5K	22	57	H DOT DECREASING 2 FPS/2 SEC P64 AT TGO = 60 SEC KEY RLSE TR/LPD, H DOT, H LDG ANG - HOVER CALL OUT LPD ANGLE
08:44			-112.0 MAX	5.0K	18	43	
09:06	THRUST = 47% PRO AND REDESIGNATE IF REQ REPORT GO/NO GO FOR LDG	52°	- 76.0 MAX	3.0K	16	36	H DOT < H DOT MAX CALL OUT LPD ANGLES *AT H = 2000, ENTR MODE SEL - PGNS

Fig. 17(b) Simplified Crew Monitoring Checklist

POWERED DESCENT (PDI) (Cont)

TIME	CDR	VI/LPD	H DOT	H	PROP	OHW	LMP
09:22		47°	-55.0	2.0K	15	31	
			MAX				
10:06	THRUST = 35%	33°	-16.0	500	12	18	CALL OUT H, H DOT, PROP TILL LGD
	MODE CONTROL (PGNS) - ATT HOLD		MAX				
	NULL VH OVER LDG SITE						
10:26		31°	-7.0	300	10		
10:48	ACTIVATE ROD IF REQUIRED	43	-3.0	200	9		P65 (P66) VH, H DOT, H
11:26			-3.0	100	7		
	(LUNAR CONTACT LIGHT)						
	ENGINE STOP - PUSH						

Fig. 17(c) Simplified Crew Monitoring Checklist



(i) 5 minutes 26 seconds into descent burn.

Fig. 18 Front and Docking Window Views - Computer Generated

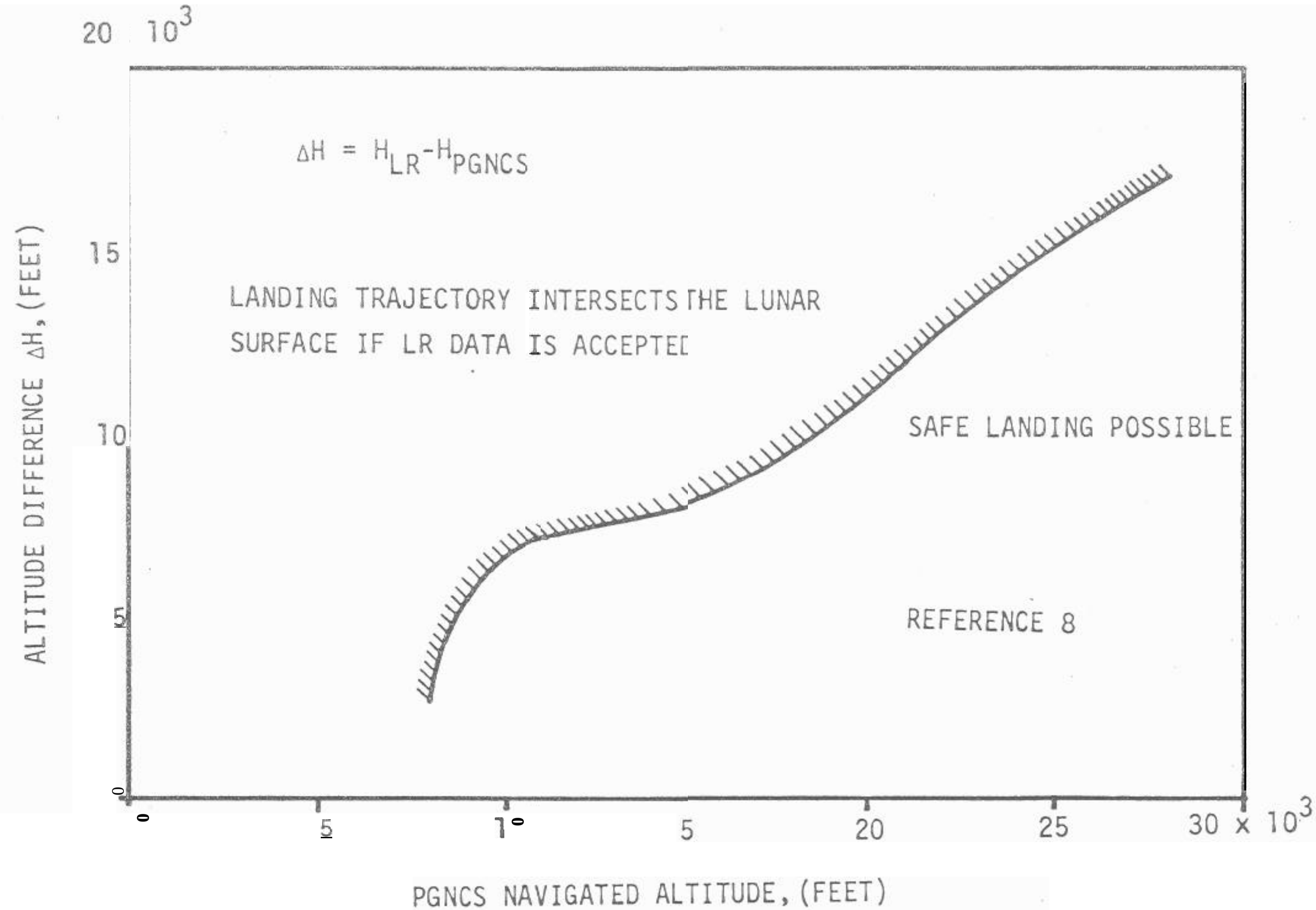


Fig. 19 Maximum Allowable PGNCS Minus Landing Radar Altitude Difference Versus Altitude

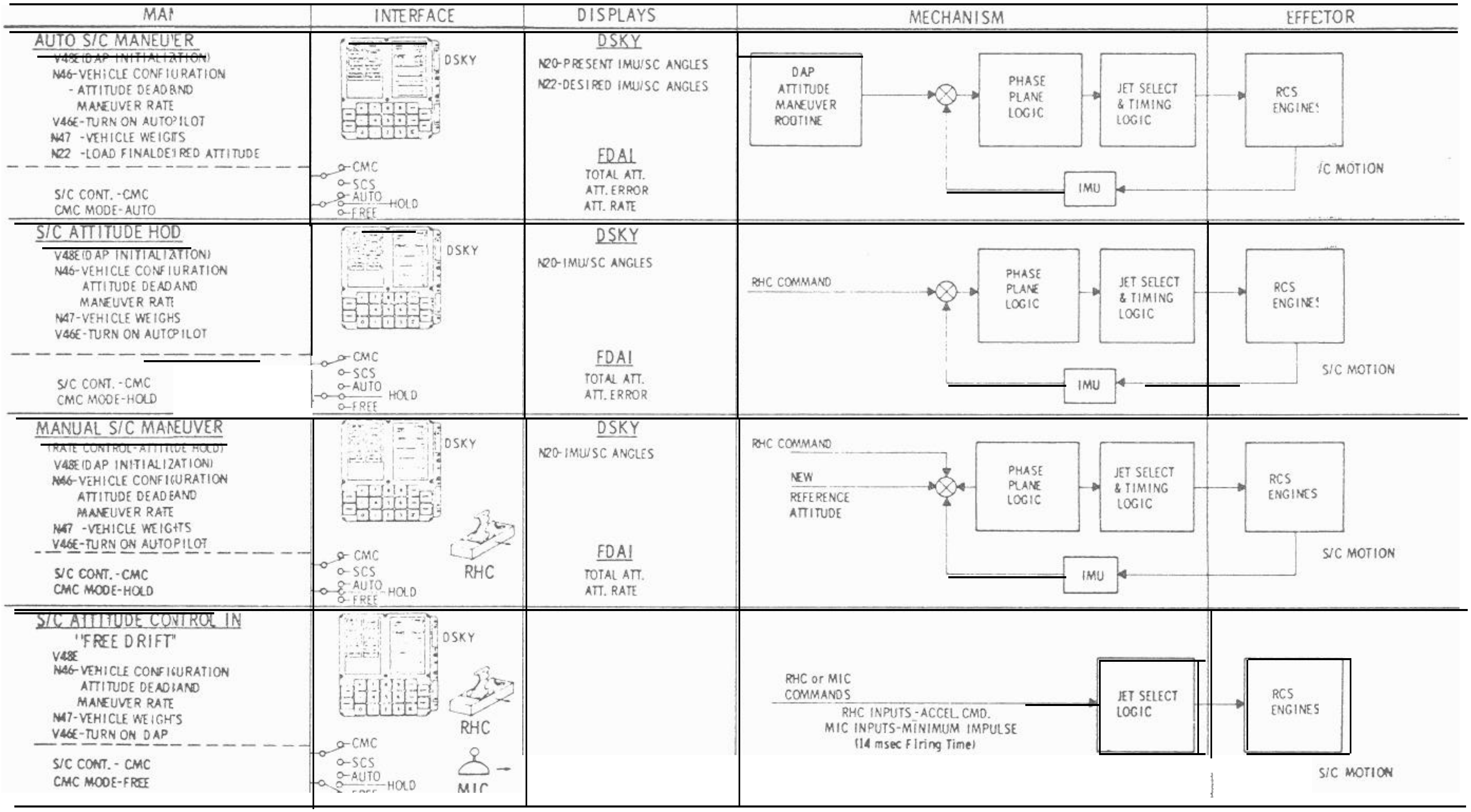


Fig. 20(a) Command Module Attitude Control Modes
Primary System

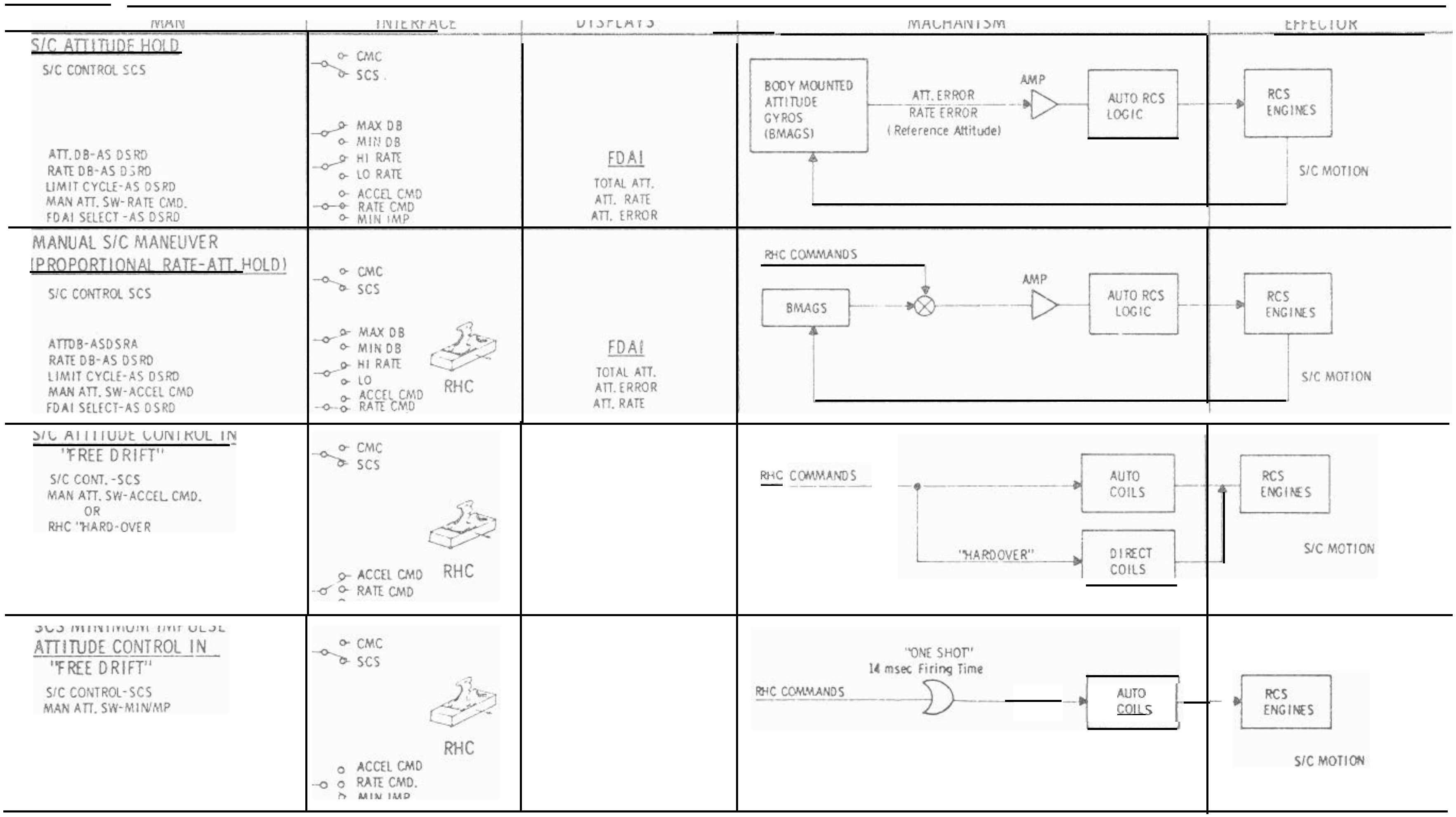


Fig. 20(5) Command Module Attitude Control Modes Back-up Systems

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