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

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Introduction

Apollo is the first manned U.S. spacecraft that contains enough sensors and data processing capability to allow the crew to navigate and guide their spacecraft from the "on board" equipment only.

Navigation and guidance for Apollo can be described as a problem in fuel management of very high accuracy. To obtain the data, optical, force, and attitude measurements of high precision are required. This data must then be processed and the results communicated in some convenient form to both the crew and the ground. In addition, the design must be very efficient because the spacecraft is as limited in electrical power, weight, and volume as it is in fuel.

In order to describe the man-machine design for this problem, it will first be necessary to briefly define the problem. This paper is, therefore, organized along the following lines:

First, general description of the Apollo guidance and navigation system
Second, definition of the man-machine interfaces and philosophy of design
Third, highlights of the design evolution

A. Navigation, Guidance, and Control for the Apollo Program

Descriptions of the primary guidance and navigation (G&N) system for the Command and Service Modules (CSM), and the Lunar Module (LM) have previously been given in References 1, 2, 3, and 6. Therefore, this section will only briefly summarize this system.

The G&N system has the capability to control the spacecraft path throughout its mission which, for the basic lunar landing mission illustrated in Fig. A1, contains fifteen distinct guidance and navigation phases. Also required, Fig. A2, is the capability to guide aborts from all phases prior to trans-earth injection. In order to perform these functions, three distinct tasks must be accomplished:

1. Determine position and velocity on present spacecraft orbit.
2. Compute future spacecraft orbit or landing point and the initial conditions for the required maneuver.
3. Control application of thrust or lift so as to achieve the desired new orbit or landing point.

Task 1 and 2 are performed periodically during free fall phases - an activity we refer to as navigation. Task 3 is performed continuously during powered maneuvers - an activity we refer to as guidance. 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 which generates steering and engine cutoff commands (Fig. A3). The Lunar Module G&N system also utilizes 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. A3)

Navigation Sensing

Navigation angle data in cislunar space is obtained by a two-line-of-sight instrument called a space sextant (SXT). This instrument is designed to measure the angle between a selected star and an earth or lunar landmark. The astronaut senses both the star and the landmark visually (refer to Fig. A4 and A5) and controls the instrument to track both with the aid of servo drives and spacecraft attitude control.

Additionally, the sextant may contain photometric sensors for automatic star tracking and detection of light in the visual band radiated from the atmosphere at the earth's bright horizon. These features illustrated in Fig. A6 permit acquisition of navigation data when earth landmarks are obscured by cloud cover or when a fully automatic guidance and navigation capability is desired. Single-line-of-sight operation to track stars provides the orientation data required for alignment of the inertial platform.

The space sextant, shown schematically in Fig. A7, is a two-line-of-sight instrument designed and used very much like the conventional mariner's sextant. It is operated to superimpose a star on a landmark at which time the angle is read out electronically into the computer. The navigation process uses a sequence of these angle measurements to update the present best estimate of position and velocity in a statistical sense. (Ref. 4 and 5)

In local orbit, (earth or moon), the star-landmark angle rate of change is too great for measurement by the sextant. In this case, a single-line-of-sight, wide-field instrument called the Scanning Telescope (SCT) is used to track landmarks (Fig. A8). The direction of the tracking line with respect to the inertial platform is read into the computer which processes this data to update the local orbit ephemeris. Such a bearing "fix" locates the spacecraft on a line in the direction of the line-of-sight and terminating at the landmark. The Scanning Telescope is also required as a finder for the Sextant. In addition, the SXT may be used in local orbits to track unknown landmarks. This technique has an obvious application when on the back side of the moon or when the earth is covered by clouds.

For rendezvous, navigation sensing is accomplished with a radar on the Lunar Module tracking a transponder on the Apollo S/C. A backup and monitor capability will be provided by the SXT on the mother ship tracking a light on the LM.

Figure A9 summarizes the navigation phases in a typical mission, while Fig. A10 summarizes the guidance phases in a typical mission.

Navigation and Guidance Techniques

For a detail description of these techniques, see Ref. 4 and 5. In order to gain an appreciation of how the system is to be used, a description of the computation for position and velocity will be given here.

Of all the main programs in the computer, the position and velocity is the most important, and it is the only one that functions throughout the entire mission. Although it has to be done quite accurately, most of the time the computation is done on an open loop basis. The loop is closed whenever measurements are made, but this is a rather infrequent event. So whenever it is desired, the computer can provide knowledge of position and velocity simply by extrapolating information and integrating the equations of motion.

To preserve accuracy, the open loop integration uses the Enke technique which integrates the deviation between a simple conic trajectory and the perturbation caused by the sun, the moon, and higher order terms of the earth's gravity field.

Closing the loop once a measurement has been made requires a comparison between the external measurement and an on-board prediction of this measurement. The estimate of the angle to be measured, $\hat{A}_{SL}$, is computed on the basis of current estimated vehicle position and stored landmark coordinates. The actual angle measured, A_{SL}, is then compared with this estimate to establish the measurement deviation, δA_{SL}. A statistical weighting vector, $\underline{W}$, is generated from a priori knowledge of nominal trajectory uncertainties, optical tracking performance, and a geometry vector $\underline{b}$ based on the type of measurement being made. This weighting vector is defined such that a statistically optimum linear estimate of the deviation of the vehicle position δr, and velocity δv, from the estimated orbit or trajectory is obtained when the weighting vector is multiplied by the measurement deviation δA_{SL}. The deviation of position ($\delta \underline{r}$), and velocity ($\delta \underline{v}$), are then added to the vehicle position and velocity estimates respectively to form a new orbit estimate. This procedure is repeated for each navigation measurement until orbital uncertainties are reduced to an acceptable level.

The general procedure shown in Fig. A11 is used in all unpowered portions of the CSM and LM mission phases. Any type of valid tracking data or measurement can be used, such as range, range rate, optical or radar tracking angles.

The salient points of this technique are three:

a. This scheme is applicable to all phases of the mission for which there are only field forces. (approximately 99% of the time).
b. No dependence on a reference trajectory.
c. Measurement data can be accepted from a variety of sources including ground-based and vehicle-based radar.

Equipment Description

To sum up, navigation in deep space requires three things.

a. Optics to make sightings
b. A data processor
c. Guidance which requires:
   1. Gyros for attitude reference
   2. Specific force instruments for measuring non-field forces.
   3. Optics for aligning the gyros

Of course, we require engines for making velocity changes and a vehicle stabilization system to neutralize vehicle dynamics. For rendezvous maneuvers, we also need radar in order to get range, range rate, and line-of-sight information.

The primary G&N system consists of the following basic units in CSM and LM installations:

CSM Installation

IMU	Inertial Measurement Unit
AGC	Apollo Guidance Computer
PSA	Power Servo Assembly
CDU	Coupling Data Units
SXT	Sextant
SCT	Scanning Telescope
D&C	Display and Controls

LM Installation

IMU	Inertial Measurement Unit
LGC	LM Guidance Computer
PSA	Power Servo Assembly
CDU	Coupling Data Units
AOT	Alignment Optical Telescope
D&C	Display and Controls
RR	Rendezvous Radar
LR	Landing Radar

Apollo Guidance Computer

The AGC (References 8, 9, and 10) is the central processor for the guidance and navigation system. It is also the clock or basic time and frequency reference for the spacecraft. Figure A12 shows the interrelationship of the AGC to the various sensors and to the spacecraft control and propulsion system for the CSM digital autopilot function.

The AGC can also communicate with the sextant and scanning telescope via the Coupling Data Units (CDU's). It can also communicate with the displays, and it can receive inputs from the astronauts via the keyboard. In addition, the AGC can count pulses from the accelerometers, read gimbal angles, and read and control radar angles. The AGC can send information to earth via telemetry and receive telemetry information on an uplink. During guidance modes of operation, the AGC can control and stabilize the spacecraft and start and stop the engines.

Two computers have been designed-a Block I and a Block II. The Block II is a more powerful version of the first design. Figure A13 shows the Block I computer and its associated Display-Keyboard (DSKY's), and Figure A14 shows the Block II Computer and associated DSKY's. Figure A15 lists the characteristics of both computers.

IMU - Inertial Measurement Unit

The IMU is the primary inertial sensing element. It consists of three gyros and three accelerometers mounted on the innermost member of a three-degree-of-freedom gimbal structure (Fig. A16). Angular orientation of this inner platform is obtained from resolvers mounted on the gimbals. This angular information is then transmitted to the spacecraft attitude indicator and to the AGC via the CDUs. Non-field forces acting on the vehicle are sensed by the accelerometers which produce signals representing incremental change in vehicle velocity. These V's are transmitted directly to the AGC.

CDU- Coupling Data Unit

The coupling data units are used to transfer angular information between the guidance computer, the IMU, the optics, the rendezvous radar, and the vehicle stabilization and control system. The CDU is essentially an analog-digital conversion device. There are three CDUs for the IMU and two CDUs for the optics and radar. (Fig. A22 and A23)

Optics

There are two optical units in the CM, the scanning telescope (SCT), and the sextant (SXT). These two units are rigidly mounted and aligned to the same mounting structure as the IMU. This mounting structure is called the navigation base (Fig. A17).

The SCT is a single-line-of-sight, wide-angle, unity-power instrument used for acquisition and general viewing of stars and earth-based or moon-based landmarks (Fig. A18).

The SXT is a two-line-of-sight, narrow-field-of-view, high-power instrument used for making precise midcourse sightings and for aligning the IMU during the mission (Fig. A18).

The optical subsystem used in the LM vehicle is different from that in the CSM in that a single-line-of-sight non articulating telescope is used for IMU alignment. This is a unity-power instrument with wide-field-of-view that can be positioned in three distinct viewing positions or a fourth position for storage. The AOT has a manually rotated reticle with visual read-out (Fig. A19).

RR - Rendezvous Radar

The rendezvous radar is a tracking radar which normally operates against a transponder unit on the other vehicle. Basic inputs to LGC from the RR will be tracking angles, range and range rate signals.

LR - Landing Radar

The landing radar will be installed on the LM and will provide the LGC altitude and velocity signals during the powered landing maneuver. The landing radar uses a four-beam antenna array. Three beams are used for CW velocity sensing, and the fourth beam provides altitude in an FM-CW mode.

PSA - Power and Servo Assembly

The PSA is a support item and is used in all operations involving the system. It provides various levels and kinds of power to the rest of the system. In addition, it serves as a location for the support electronics for the system, such as the servo control amplifiers for the IMU and optics drives.

The equipment is mounted in the CSM, as shown in Fig. A20. The location of the equipment for the LM is shown in Fig. A21. Figure A22 shows a Block I system under test at the Instrumentation laboratory at MIT, while Figure A23 is a Block II system undergoing tests.

B. Man-Machine Interfaces

1. Design Philosophy

The usual discussions concerning the man-machine interface can be broken down into two categories; unfortunately, both categories usually represent extreme points of view. One point of view, illustrated by Fig. B1, is the "fully automatic" system where the astronaut, wrapped in a life-maintaining cocoon, is delivered to the lunar surface. The only real problem here is keeping him entertained during the mission. The other point of view, illustrated by Fig. B2, is the "fully manual" system where the astronauts are given a rocket, a big window, a control stick, and appropriate charts and tables. This technique is certainly feasible in infinite-energy vehicles (an airplane with inflight fueling certainly falls within this classification) but becomes questionable for finite-energy vehicles, such as Apollo, where highly accurate and complex navigation systems are needed to determine the most efficient path, or orbit, to the moon and back.

Instead of the two extremes quoted above, we have substituted a third category. This third category could be called "manually aided" systems and would combine the best features of both the man and the machine.

In order to illustrate this point of view, Fig. B3 shows the functional relationship of the man to the spacecraft for a typical midcourse star-landmark angle measurement. For this, the following sequence of tasks are expected of the man.

a. Acquisition and identification of a particular star and landmark. To do this, he must be able to maneuver the spacecraft via the control system. Also he must perform the pattern recognition problem of associating the desired star and landmark patterns from maps and charts to the real world beyond his optics.

b. He must be able to operate the displays and controls associated with the optics to position the desired landmark into the sextant field of view.

c. He performs the superposition of the star on top of the landmark, to the accuracy needed, and "marks" this event to the computer which notes the time of the mark and the angle.

d. Monitor and communicate with the on-board data processor as it processes his and other data and solves the complex functions necessary in order to navigate and guide the spacecraft to the moon.

Thus, we have employed man in three major levels of activity. In the first level, he performs his major role of monitoring the on-board processor. In the second level, he solves a complex pattern recognition problem which would be costly in weight and system complexity to instrument. In the third level, he performs the fairly routine mechanical job of accurately pointing the optics. Again, instrumenting this problem would add weight and system complexity.

Figure B4 illustrates an automatic star/earth horizon measurement as an example of a technique that allows man to make a measurement automatically which, if he were to do so manually, would require additional equipment. For this job, the man is expected to perform the following tasks:

a. Acquisition and identification of the star and proper horizon.

b. Establish the proper geometrical relationship of the star to the horizon.

c. Observe that the automatic star tracker locks onto the star and that the AGC receives the automatic mark from the horizon photometer.

This technique reduces the number of purely mechanical tasks, lets man perform those tasks for which he is uniquely fitted, and allows the equipment to perform a measurement which, if he were to make, would require additional electronics and indicators. The additional equipment would then allow man to perform the simple task of noting when the brightness displayed by an indicator passed through a certain level.

Another facet of this discussion is the question of control or sequence of operations. Here again, man possesses unique abilities in assessing the proper operation of his equipment and the optimum course of action. Again, the equipment can aid the man by doing a lot of routine sequencing associated with the many spacecraft tasks. At least it could check the sequencing to make sure that it had been performed and that it was done according to the checklist.

On this level, the man and machine think exactly alike. They each need a predetermined checklist, or logical path, and then a display, or signal, in order to confirm the event. If both perform the total sequence, the overall mission reliability goes up. At a minimum it allows man to sit back and modify the sequence, as necessary, to meet the myriad of possible contingencies. Only man is capable of executing the judgement necessary to perform a successful mission in the presence of unexpected and unplanned for difficulties.

In summary then, manually aided systems make maximum use of the unique abilities of man and equipment. This combination, we feel, minimizes the weight and complexity of the equipment and maximizes the reliability.

2. Design Problems

Before the specific design problems are defined, it seems appropriate to review the pertinent Apollo design ground rules, as follows:

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.

These ground rules, combined with a knowledge of the possible instrumentation techniques for midcourse navigation and guidance, describe the design problem.

The actual design period can be viewed as three overlapping periods of activity, namely:

1. Design Analysis
2. Design Development
3. Operational

which will be detailed in the next section. Within these periods were areas of human factors activity that could also be defined, namely:

a. Anthropometry and gross configuration associated with
   - Display and control arrangement
   - Zero g tethering
   - General lighting and caution annunciators

b. Visual and visual-motor subtasks for the
   - Optics - Space sextant, scanning telescope and alignment optical telescope
   - Computer - display keyboard
   - Data and data handling

c. Evaluation of relevant environmental constraints associated with
   - Pressure suit
   - Zero g
   - * High g
   - Interior illumination
   - * Vibration, acoustic noise
   - * Gaseous environment
   - Physiologic stress, fatigue

The items marked with asterisks are generally the responsibility of the contracting agency. The last one is merely listed, in frustration, because we have found no suitable way of accomplishing this evaluation.

One additional way of defining the problem is to list the interfaces for the display and control equipment, namely:

Man

Height
Visual Acquity
Reliability
Training
Tethering for zero-g

Pressure Suit

Eye relief
Dexterity
Arm reach
Volume

Spacecraft

Area
Volume
Weight
Power

C. Man-Machine Design Evolution

1. Design Analysis Phase - (Table 1, fig. C1)

During this initial period, man's role was defined, his specific tasks were identified (Table 2 lists his major ones, fig. C2), and the various display and control functions were identified and defined. Critical subtasks requiring simulation were identified and simulations started.

The principle subtasks requiring simulation were as follows:

a. Moding for the optics and the associated interface with the spacecraft control system. Figure C3 shows an early analog simulation of the CSM optics that was used in this evaluation. Behind the cardboard panels (Fig. C3) were mounted two oscilloscopes, one for the SXT and one for the SCT. With the aid of high-speed switches, a scene was generated consisting of dots for the star and/or landmark with superimposed reticle patterns. Specific problems resolved with this simulation were as follows:

   1. Definition of the operational interface between the crew, two movable optical systems, and a non-stationary spacecraft for acquiring, tracking, and superimposing targets and "marking" the event to the AGC.

   2. Definition of the need for a minimum impulse controller for reducing S/C rates to about 1 arc min/sec.

   3. Development of the optics controller characteristics; type of controller, restoring forces, deflection angle, speed ranges, and so forth.

b. Use of the scanning telescope to track landmarks on the earth's surface from orbit. Figure C4 shows a standard B-6 drift sight mounted in a small airplane that was used to evaluate the acquisition and tracking of landmarks on the earth's surface at orbital rates. When this airplane was flown at the proper combination of altitude and speed, landmarks on the earth, when viewed through the vertically mounted drift sight, had the same angular rate as one would see if in orbit. From this simulation and the test results from Gemini flights, it appears that acquiring and tracking landmarks from orbit is quite feasible if the crew is given fairly good pointing data to acquire the desired target.

c. Evaluation of various optical techniques for coping with the large eye relief associated with the use of a full-pressure suit. Figures C5 and C6 show some of the techniques and mockups used to evaluate this complex problem. The problem is complex because large-eye-relief optics unfortunately cost very dearly in weight. Figure C7 shows an astronaut in a recent evaluation using real optics and sighting actual stars from a rooftop-mounted simulator.

d. Investigation of the constraints on the display and control (D&C) layout and design imposed by the crew wearing full pressure suits.

These evaluations are continually necessary because there is much activity in the field of pressure-suit design. Figures C8 and C9 show some of these evaluations.

e. Investigation of body tethering and the constraints imposed on the D&C layout and design by a zero-g environment. A number of flights were made in a specially modified Air Force KC-135 airplane, in order to test the various designs. Figure C10 shows an early part-task optical simulator while Fig. C11 is a more refined version mounted in the LEB Section of the CM that was flown aboard the KC-135. Figure C11A shows the adjustable control panel used to evaluate hand-hold configurations and to determine the proper elevation of the controllers above the S/C floor.

   Two techniques evolved for tethering the crewman during sightings. The first one has the man standing at the LEB with his feet secured by "Velchro" with the rest of his body supported from the hand-holds shown in Figure C11A. For the second technique, the man sits on the lowered foot pan of the center couch, restrained by a lap belt.

f. Evaluate the capability of the astronauts to read the computer electroluminescent numeric displays while undergoing stresses in excess of 10 g's. (See Fig. C14)

Figure C12 shows the computer display-keyboard mounted in the gondola of the man centrifuge at the Naval Air Development Center, Johnsville, Penna.

This test simulation consisted of a partially operational keyboard with computer displays operational in an open loop manner by means of an externally mounted block tape reader. The computer control panel was mounted on a partial NAA main display panel installed in the gondola.

Figures C13 and C14 summarize the various activities for pressure suit evaluation, Zero-g and high-g testing.

During this initial period, many different configurations for the displays and controls were evaluated. Figures C15 and C16 show two configurations for the computer display-keyboard. As expected, these design changes were caused by "hardening" of both the G&N system design and spacecraft design.

These same kind of mockups were also used for "acting out" or "dry running" of the various operating procedures prior to assembly of more realistic simulators.

In this phase, the basic man-computer interface was defined. The interface device is shown in Figures A13 and A22 and is called a computer display-keyboard or DSKY. The differences in the design of the Block I and Block II DSKY's can be seen in Figures A13 and A14. From an operational viewpoint, both units are similar. The Block I DSKY has a larger group of computer internal alarms displayed on the LEB DSKY, while the Block II DSKY's have a group of functional signals displayed on the DSKY. The same Block II computer and DSKY are used in both vehicles. Each DSKY consists of a keyboard, relay matrix with associated decoding circuits, displays, alarm circuits, and power supply. The keyboard, which contains numerics, signs, and other control keys, allows the astronaut to exercise control of the AGC. The inputs from the keyboard are entered into an input register and are not processed by the AGC until the enter key is actuated.

The displays, which are electroluminescent, perform the following functions: (1) display data, (2) identify the data, and (3) monitor certain functional discretes. Data is displayed in three five decimal, or octal, digit registers. Associated with each register is a sign bit for the display of decimal data. In addition, memory locations may be addressed directly, but this is intended primarily for ground checkout. We might point out that there is no attempt to restrict the access of the crew to the computer. However, we primarily train them to use the technique designed for flight operations. For flight operations, data is displayed in two levels (Reference 11). The highest level is a two-digit decimal code called a program identifier.

Programs are major functional operations where the most significant digit is strongly related to mission phase. (Figure C17 is a set of programs for typical earth orbit type mission without rendezvous.) For example, the zero series are the pre-launch programs; The ten series are the boost monitoring programs; the twenty series are the navigation programs; the thirty series are the targeting programs for changing orbits, rendezvous, etc.; the forty series are concerned with the guidance for thrusting and the starting and stopping of the engines; the fifties are concerned with inflight alignments of the inertial sensors; the sixties with entry; and the seventies with aborts.

The unit programs define the functional programs within a particular series.

The second level of addressing consists of two 2-decimal digit identifiers called appropriately Verb and Noun. The intent of the Verb identifier is to define action. The Noun identifier modifies the action of the verb and identifies the data being displayed or loaded. (Figures C18 and C19 list some examples of verbs and nouns.) For example, Verb 16 means the computer will continuously monitor a function, display the data in decimal form, and update the display every half-second. If we associate that with Noun 16, then we will have displayed the AGC clock expressed in ground-elapsed-time (GET), with hours in the first data register, minutes in the second data register, and seconds to hundredths of a second in the third data register. Another example is Noun 51, which is the noun used just prior to and during an actual thrusting maneuver. In the first data register, the time-to-ignition is displayed in minutes and seconds. Displayed in the second data register is the magnitude of the velocity-to-be-gained. The third register displays the magnitude of the velocity measured by the inertial components during the thrusting maneuver.

Communication with a computer always is 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. For example, to load registers of data, the man would select a V25 N--E. As soon as he keyed the enter, the verb register displays a flashing V21 and the first data register is blanked, permitting the man to read the data as he enters it. Note again that this data is not recognized by the computer until the "enter" has been keyed. As soon as the enter is keyed on the first register of data, the flashing verb will now change to 22, and the second data register will be blanked. This process is then repeated for the third register. Another example is the "please perform checklist" combination of verb (V50) and Noun (N25). Here the computer has gone through an internal sequence check and discovered that the external switches have not been thrown correctly, or else it needs certain switches to be operated which it cannot operate or monitor. (For example, circuit breakers for the various units.) The identifying checklist code is displayed in the first data register. Figure C20 lists some typical checklist codes.

In addition, there are "activity" lights for both the computer and the telemetry uplink; there are also alarm lights for both computer and the rest of the inertial system. There are three basic groups of alarm lights, namely: equipment failure alarms, and two levels of program alarms. The program alarms are called main and side alarms. Main alarms in general indicate that the computer program in process has reached the limit of its capability to solve the problem. Main alarms cause the AGC Fail and Program Alarm lights to illuminate and the computer to stop processing the troubled program. In addition a V05 N31 will be displayed accompanied by an error code identifier in the first data register. Figure C21 is a list of some typical main and side alarm error codes. Side alarms indicate problems at the computer interface. For example, computer unable to achieve desired mode; too much data; etc. In this case the computer merely displays the program alarm light, and the program in process continues. When the crewman desires to know what caused the alarm, he would key in V05 N31 E. Again the error code would be displayed in the first data register. When he has noted the error code, depressing the Key Release key will normally return him to the same point in the program from which he exited to look at the error code.

The use of this man-computer interface in the context of airborne missions will be discussed under the Operations phase, the third period of design activity.

2. Development Phase - (Table 3, Fig. C22)

In this period, the various display and control designs were finalized and released to manufacturing. The writing and testing of detailed operating procedures was also pursued. Detailed optical simulations were constructed in order to determine man's performance under more realistic conditions. The simulations created are accurate photometrically, in optical image resolution and size of images, in eye relief, and in image motion as a function of spacecraft dynamics. Figures C23 and C23A show the optical and functional schematics for the SXT simulator, while Fig. C24 shows the actual unit before it was coupled to the CM whole task simulator. With this simulator, the man-optics performance matrix shown in Fig. C25 was generated.

The SXT is simulated with an N2 telescope (28X, 1.8° field), 2 two-degree-of-freedom mirrors, a beam splitter, a two-axis refractosyn, and two collimators. Associated CDU displays and electronics are included in the LEB.

Photometrically correct star and landmark images are produced and directed through the collimators, 2 two-axis drive mirrors and beam splitter to the telescope objective.

Each SXT line-of-sight (LOS) is simulated by an image generator and associated collimator. A two-axis refractosyn, accurate to 1 sec of arc, continuously measures the angular position of the star mirror from an initial null-output reference where the star and landmark images have been superimposed in the SXT field of view.

The mirrors are driven by output voltages from an Autonetics "Verdan" computer. Outputs from the optics controller and mode switches, attitude impulse, and S/C rotational controller (in the LEB) are combined in the verdan to obtain the correct drive signals for the mirrors to properly simulate S/C and optics motion. CM motion is simulated by motion of mirror number 1 and optics motion by mirror number 2 (Fig. C23A). A rotating eyepiece reticle is also used to simulate SXT shaft rotation. The rotating reticle feature also allows the SXT simulator to be used as a SCT simulator for tracking landmarks in low orbits.

The SXT simulation has been used to investigate the following:

1. Midcourse Navigation
    A. Star-Landmark (earth or lunar) sightings (Ref. 12 and 13)
        (1) Direct or resolved optics control
        (2) Fuel slosh and CM inertia cross-coupling effects.
    B. IMU Orientation and realignment sightings (Ref. 14 and 15)
    C. Acquisition and tracking of the LM rendezvous beacon against star and earth-illuminated moon backgrounds (Ref.16)
2. Local Orbit

Simulate SCT tracking of known or unknown landmarks. This simulation has a limited realism due to a lack of terrain foreshortening.

Simulators for the scanning telescope (SCT) have also been constructed. Figure C26 is the optical schematic for the first generation of SCT simulator.

This version of the SCT simulator consists of a hemisphere planetarium with fourth magnitude and brighter stars of the northern hemisphere, a slide holder for earth or lunar images, and a 1X, 60^o field-of-view telescope.

A second version, consisting of a four-gimbal ball projector, is presently under construction. This device will remove the inherent restrictions of the first design for testing the various inertial sensor alignment programs.

During this period, the whole task simulator for the CM was built. This unit (Fig. C27 and C27A) is a full-size mockup with a complete set of operating controls for G&N, the stabilization and control system (SCS), the service module propulsion system (SPS), and the reaction motor control system (RCS). The previously described optical simulations are also a part of this simulator. Displays and controls of the CM simulator are activated by a hybrid computer facility that accurately represents spacecraft dynamics, including the effects of cross coupling, c.g. offset, body bending, and fuel sloshing (Ref. 17 and 18) (Fig. C27B). Driving the hybrid facility is an airborne computer complete with its interface equipment. In addition, an electromechanical IMU simulator with accurate gimbal angle dynamic response is used.

The airborne computer is operated in a configuration which allows program changes to be readily loaded into the AGC memory. With this facility, actual flight programs may be evaluated as they are written.

Figure C27C shows the main display panel and Fig. C27D shows the lower equipment bay and the optics simulators.

A similar unit for the LM vehicle (Fig. C28) has been constructed. This unit has, in addition to the above mentioned items, a visual display for the window in order to evaluate the guidance technique for landing on the moon (Ref. 19). The scene generation technique for the window uses the flying-spot TV technique.

One other device constructed for navigation procedure evaluation is the Space Navigator (Fig. C29 and C29A).

The Space Navigator (SN) is an Apollo G&N system mounted on a moving base using real stars. The moving base is a surplus Nike Ajax radar mount. Either a Block I or a Block II system may be used in the SN. A surplus NAA Verdan computer provides the resolutions needed to simulate S/C motion.

3. Operations Phase (Table 4) (Fig. C30)

In this final phase, the actual detailed operational test objectives for a mission are defined, programs for the airborne computer are written, and crew procedures for the flight hardware and airborne computer are detailed.

We will now proceed to describe the man-computer interface in the context of airborne missions.

The airborne computer programs are designed to require continuous or discrete monitoring by the crew. In addition, sequencing of the associated S/C system functions, such as engine thrusting, may be performed by the crew with monitoring by the AGC. The crew must also review the initial computational parameters for all G&N system maneuvers, including spacecraft attitude, thrusting, and entry.

To illustrate these processes, we will examine in some detail the following Programs (Fig. C17):

A. Portions of Program P24 - Ground Track Determination
B. Program P52 - Inertial component alignment, including automatic optics point routine.
C. Portions of Programs P31 and P41 - P31 is the pre-thrusting program for an orbit change, and P41 is the thrusting program.

Figure C31 outlines program P24. Of interest are the routines initiated by verbs V64 and V66. When the crew keys V64, the program number changes to 24, and the computer integrates the S/C state vector stored in the computer with its associated time tag to the present time. The computer activity light will come on, and the computer will sit and think for awhile. When a solution is reached, the AGC displays a flashing V16 N43 and displays the apogee and perigee altitude of the present orbit in nautical miles and the time-to-go to the point where the spacecraft orbit would intersect 300,000 feet if the perigee were low enough (so-called time-to-free-fall). The display is 59 minutes - 59 seconds for a stable orbit.

At this point, the computer holds the flash until the crewman indicates that he is through reviewing the data by keying a proceed (V33E). The computer then displays the time to the next perigee (N45). Again the crewman reviews the data and gives a proceed when he is through. At this point, the routine is finished, and the DSKY is cleared except to display the idling program (P00). During program P00, the computer performs a continuous automatic self-check.

Crew keying of V66 selects another routine in P24. The first call in this routine is a flashing V21 N34, which requests the crew to load the ground elapsed time for which he desires the S/C Latitude, Longitude, and Altitude. That is, the program will calculate and display a point on his ground track. Note: He may load any time (present, past, or future). Once the time is loaded, the computer updates the state vector to the specified time. After it is through thinking, it flashes V06 N44, displays the Latitude, Longitude, and Altitude of the orbit at the desired time. When the crewman is through reviewing the data, he keys a proceed. A proceed in this routine causes the state vector to be re-computed and displayed for a time ten minutes beyond the initial time. Additional proceeds update the ground track in ten minute increments. This routine is terminated by keying the terminate code (V34E).

To summarize, we have shown how programs are called, the formats for displaying data, and some of the ways the crew can step through the programs. Table 5 (Fig. C31A) lists the possible crew keyboard codes.

The next program (P52) illustrates additional facets of the interface.

Program 52 is selected by using the program selection verb (V37). This verb is the primary way of selecting or re-designating new programs (except for P24, which is really a collection of routines that can be called by individual verbs). Thus, P52 is selected by a V37E 52E.

The outline of P52 is shown in Fig. C32. In these outlines, we are trying to show the program sequence with the various options for the crew's re-loading new data, re-cycling to an earlier point within the program, and/or terminating that program and selecting other programs.

The purpose of P52 is to check or re-establish the orientation of the inertial components in space. In this program, the pointing angles of the optics at specified stars are noted by the computer to establish the desired reference coordinates. As soon as P52 is selected, the computer selects two stars from a stored list of 37 coded navigation stars. The routine selects the stars on the basis of their being simultaneously visible in the SCT cone of view and having a maximum angular separation, in order to optimize the sighting mark information. In addition, the routine checks to see that they are not occulted by sun, moon, or earth. The stars may be acquired manually or by computer control of the optics. When the star is centered on the optics reticle, the navigator sends a mark signal to the computer. One such mark on each of two stars provides enough information to establish the inertial sensor orientation. After the two sighting marks, the computer calculates the actual angle between the stars (from the star positions stored in memory) and the angle between the stars from the sighting mark data and displays the difference between these two values. This data provides two checks. One, that the crewman sighted the correct stars, and two, that his pointing was sufficiently accurate. If this angle error is satisfactory, the AGC automatically drives the inertial sensors to the desired orientation.

To select the program, the navigator keys in V37E 52E, the first step in the outline for P52 shown in Fig. C32. In the next step, the AGC then displays the first of two selected stars. The navigator accepts the star with a proceed (V33E) or loads his own star with a (V21). The computer requests the navigator to select computer control of optics positioning for star acquistion. The navigator accepts by placing the primary optics mode switch to the computer mode and keys ENTER to start the automatic optics positioning. As the AGC drives the optics, it simultaneously flashes V51, requesting a sighting mark. The navigator verifies that the proper star has been acquired, takes over manual optics control, centers the star image on the SXT reticle and marks.

The AGC next requests termination of the sighting mark sequence, but the navigator may reject a poor mark by depressing the "mark reject" button or by keying V52E. The AGC will then go back and request a mark. After a good mark, the navigator keys ENTER to terminate the mark sequence. The navigator then loads the code of the star marked, and the entire sequence is repeated for the second star. After receiving the second star code subsequent to a good mark, the AGC displays the marking accuracy data. If this value is greated than 0.05°, the navigator would have to decide to proceed with this data; if less than 0.05°, the data is automatically accepted by the AGC, which then automatically torques the inertial sensors to the desired orientation and displays the angles through which the sensors are driven. The AGC then requests an alignment check, consisting of a repeat of the entire sequence, which the navigator may reject.

To summarize, P52 illustrates navigator optical measurements upon request of the computer with the "please mark" verb (V51); that the computer checks the data and can be forced by the navigator to accept larger than nominal errors (step 15); that the AGC checks that the crew have set the control switches for proper program execution (step 5); and that the AGC notifies the crew of improper mode selection or sequencing.

We will now turn to our final examples - the pre-thrusting program P31 and the thrusting program P41. The outlines for these programs are shown in Figures C33A and C34.

The objective of Program 31 is to calculate and display the apogee and perigee of a new orbit, the amount of fuel required and s/c attitude required to achieve that new orbit based on the following crew inputs: (1) ignition time, (2) aim point coordinates, (3) period of new orbit, and (4) thrust engine gimbal angles to compensate for c.g. shifts and thrusting engine tail-off characteristics. (This last factor is required because, for program simplicity, the computer assumes a step function burn cut-off, which does not actually occur.)

Having decided the nature of the orbit change, the crew may determine the above values by means of the orbital parameter determination program (P24) and charts provided in the onboard data package. The aim point coordinates may be determined, for example, by keying V66E, and loading a time about 1/4 period beyond ignition time. The computer calculates the S/C coordinates for this time. The aim point is selected about 1/4 period after ignition time to minimize dispersions in computer calculations of the new orbit. (Fig. C33)

The crew selects the pre-thrusting orbit change program P31 by keying V37E 31E (first step Fig. C33A). The AGC first displays a time of ignition, which the operator may change by keying V25E and loading the appropriate data. When the operator is satisfied with the data loaded, he may proceed to the next data display, aim point coordinates. The estimate of the period of the new orbit is loaded next, followed by loading of thrust engine gimbal angles and cut-off bias.

The AGC computes and displays the resultant apogee and perigee and fuel (in feet per second) to achieve that orbit. If these values are not satisfactory, the program may be reselected and the data adjusted. Subsequent displays for time to ignition and inertial gimbal angles at thrust are provided when the operator keys proceed (V33E). If these are satisfactory, the S/C is positioned either manually or by the AGC to the desired thrusting orientation. The thrusting program P41 is then entered. In this program, the engine ignition and shutdown are controlled by the crew through the computer, and the resulting orbital parameters are displayed after the burn.

The programs described in detail were from a typical earth orbit program for a mission without rendezvous. For a lunar mission, where both CM and LM vehicles are used, the computer programs for both vehicles are shown in Fig. C35. In addition to the programs shown in Fig. C17, we have the programs for rendezvous in the computer for both vehicles and the lunar landing programs in the LM computer. In addition, the lunar mission programs contain digital control systems or autopilots (DAP). In these programs, the crewman, using verb-noun combinations, identifies to the computer the inertia configuration (vehicles docked or undocked), the desired vehicle maneuver rate, the size of the control system dead-band, etc.

We have shown previously (Fig. A20 and A21) that the computer and DSKY's on both vehicles are exactly the same. It should also be noted that over 60 % of the respective computer memories are devoted to the same routines and service programs.

In summary we have described a man-computer interface design for a family of space-oriented tasks which can be generalized, as shown in Fig. C36. The interface described costs approximately 8% of the computer memory to mechanize and represents about 20 % of the total gross weight of the computer.

To record all this detail, we have resorted to a single document called the Computer Logic - Checklist Interface Document. Needless to say, for flexibility and speed, it is assembled by the use of data stored on cards and magnetic tape. (Ref. 20)

In this document, all the individual computer programs are listed for a given spacecraft mission, including the purpose of each, the associated assumptions needed to make the particular program function, and all the initial switch positions in the spacecraft. The data in each program are in four columns. The four columns are titled airborne computer, ground, crew, and checklists. Each column shows the logical sequence and intercommunication required in order to complete a particular function. This document serves four main purposes: a) It is an instrument to record the data needed to write computer programs prior to actually coding the flight computer; b) It is detailed enough for computer programmers to use while writing their programs; c) For flight personnel, it lists both the total checklist, as well as the suggested abbreviated checklist for airborne operations; d) It is the tool used to test the computer programs and the crew interface in the previously described whole task simulators and the moving base simulator.

Figure C37 shows a portion of the Ground Track Determination Program (P24) that has been described earlier and is outlined in Fig. C31.

Evaluation of these programs is carried out in the previously described cockpit simulators using actual computer flight programs. Finally, these simulators are used to train flight crews.

Beside the procedural testing done in the whole task simulator at MIT/IL, it is expected that similar testing and evaluation of a more complex nature using three crew members and all the spacecraft systems will be done in the Apollo Mission Simulator at the NASA Manned Spacecraft Center. Figure C38 details the testing logic.

ACKNOWLEDGEMENT

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LIST OF FIGURE TITLES*

LIST OF FIGURE TITLES (cont'd)

LIST OF FIGURE TITLES (cont'd)

MISSION PHASE SUMMARY

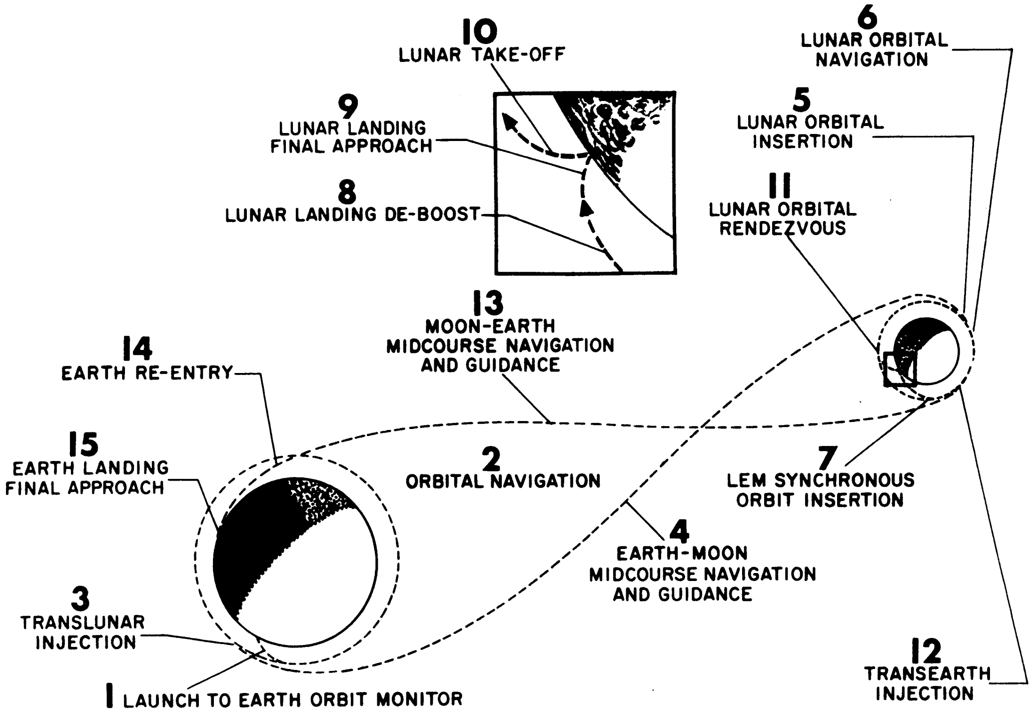


Fig. A1

PROPULSION FAILURE ABORT PATHS

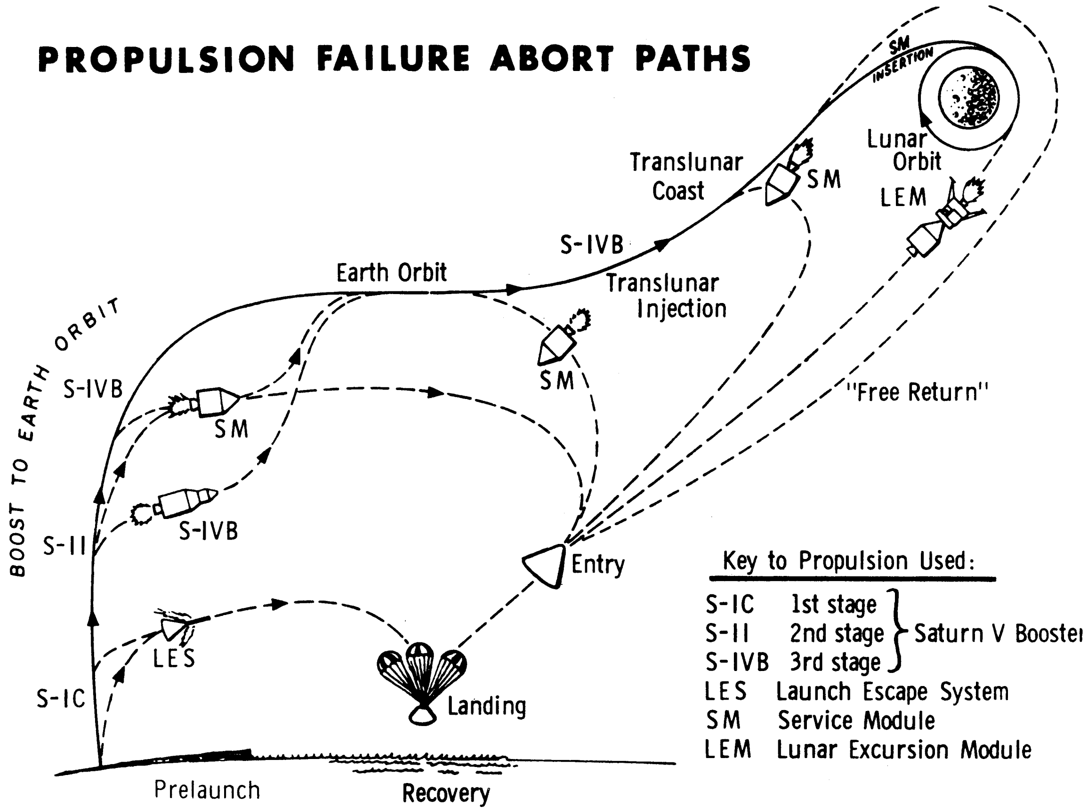


Fig. A2

APOLLO GUIDANCE AND NAVIGATION - FUNCTION FLOW

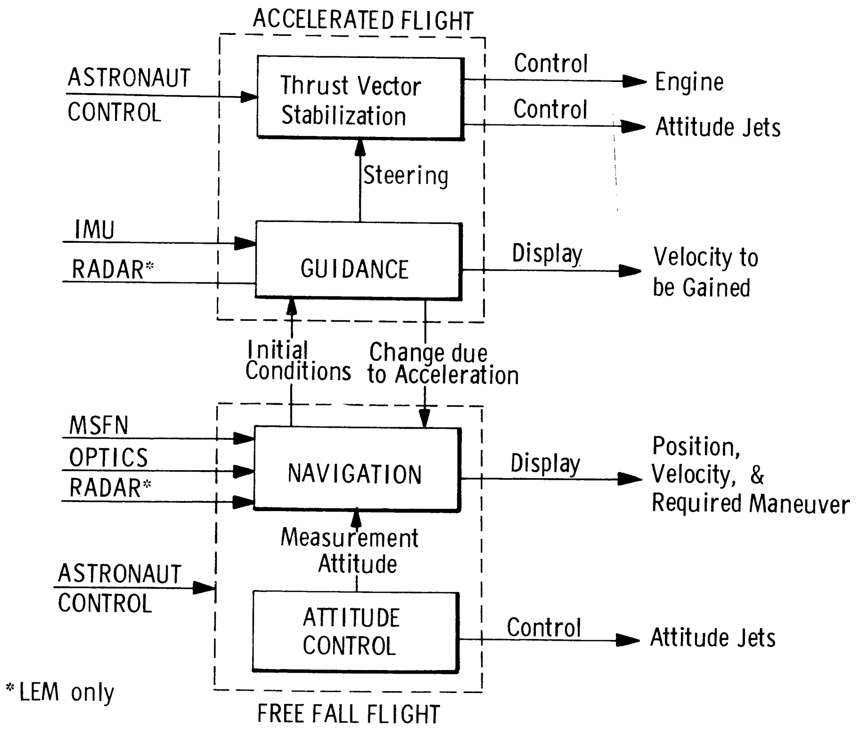


Fig. A3

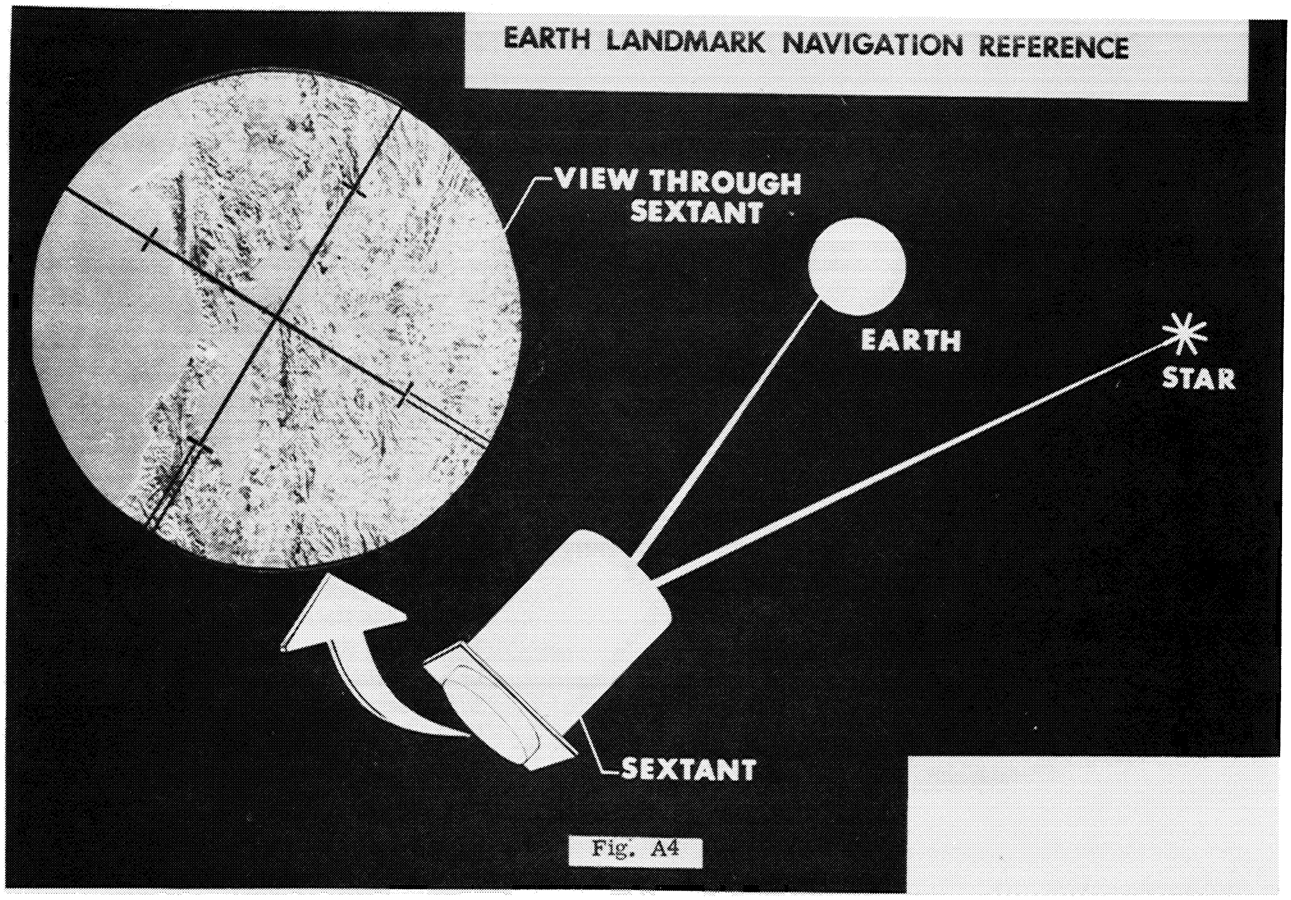


Fig. A4

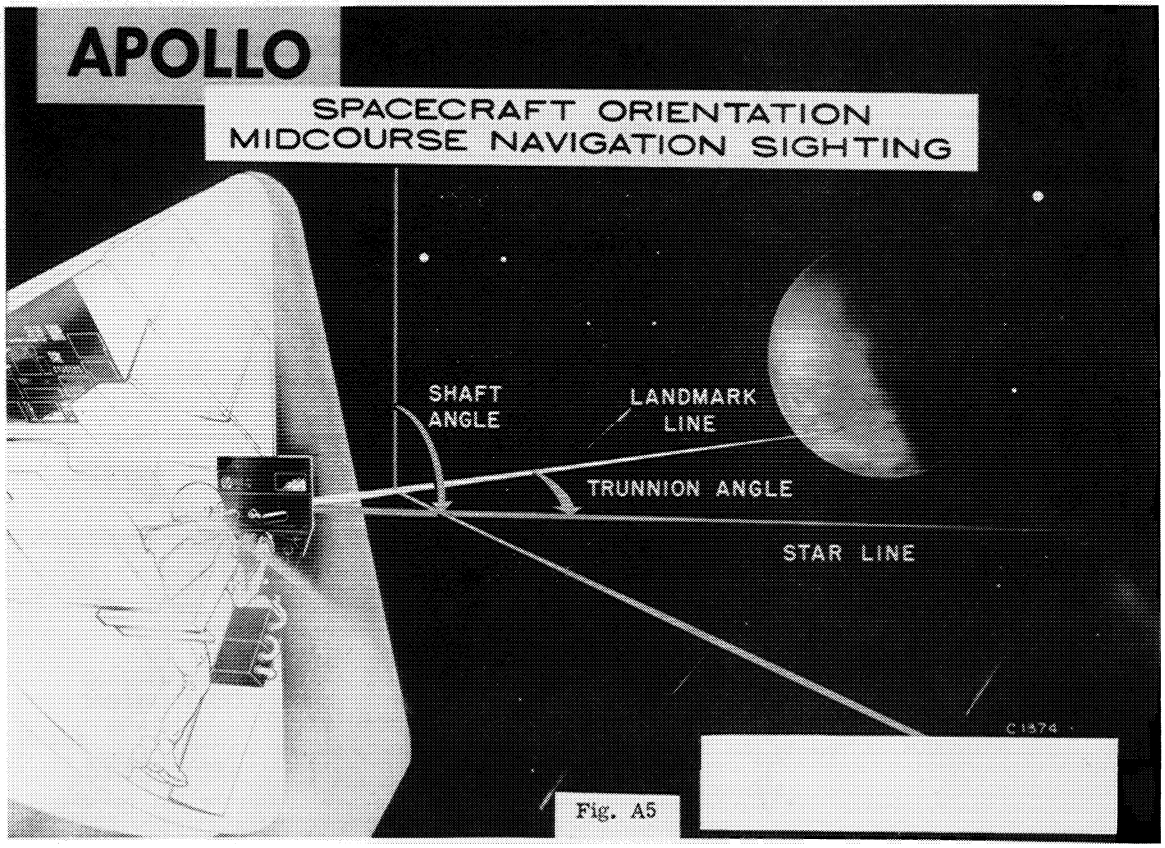

APOLLO
SPACECRAFT ORIENTATION
MIDCOURSE NAVIGATION SIGHTING
SHAFT ANGLE
LANDMARK LINE
TRUNNION ANGLE
STAR LINE
C1874

Fig. A5

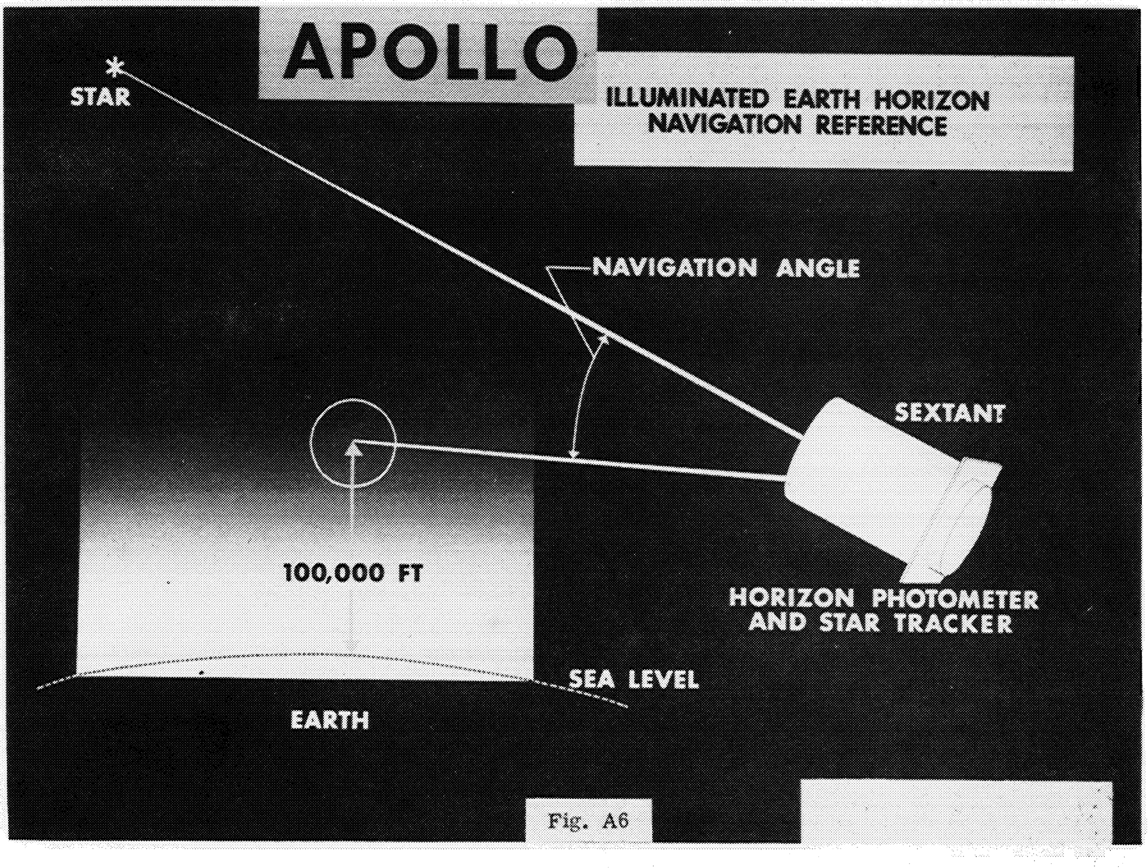

APOLLO
ILLUMINATED EARTH HORIZON
NAVIGATION REFERENCE
STAR
NAVIGATION ANGLE
SEXTANT
100,000 FT
HORIZON PHOTOMETER
AND STAR TRACKER
SEA LEVEL
EARTH

Fig. A6

OPTICAL SCHEMATICS

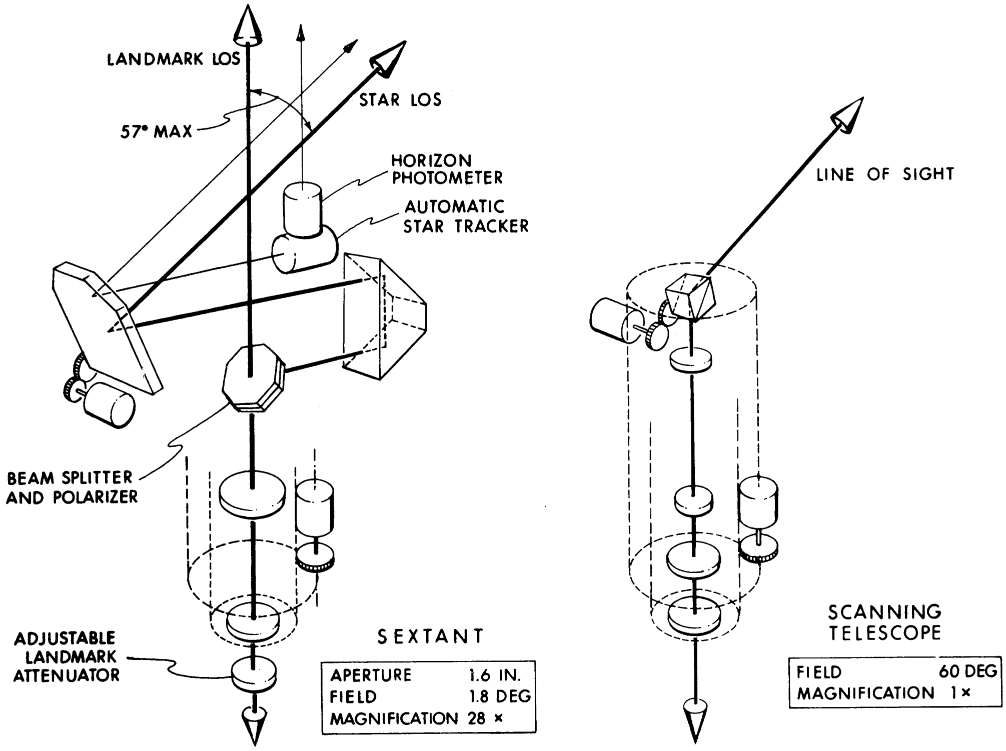


Fig. A7

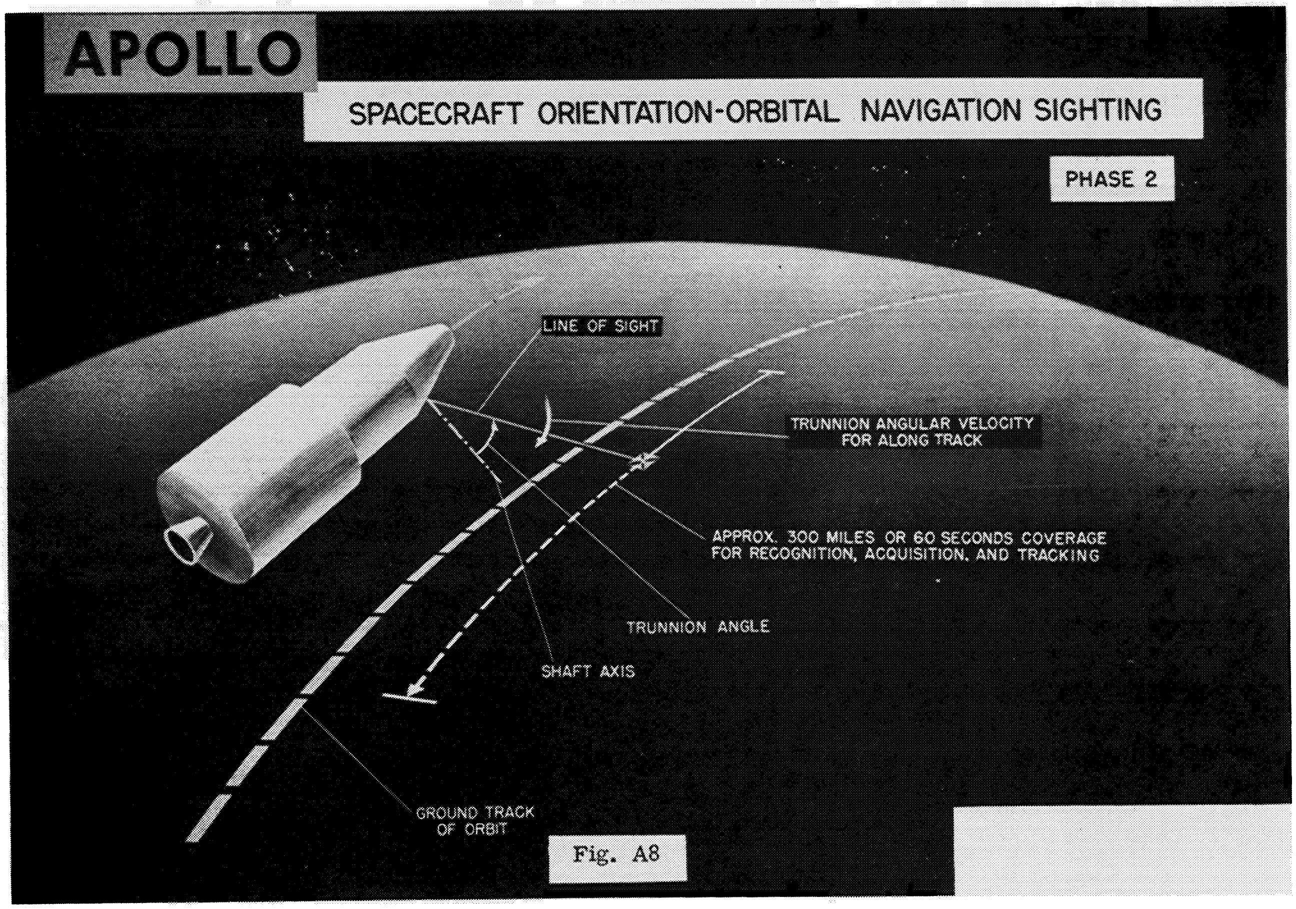


Fig. A8

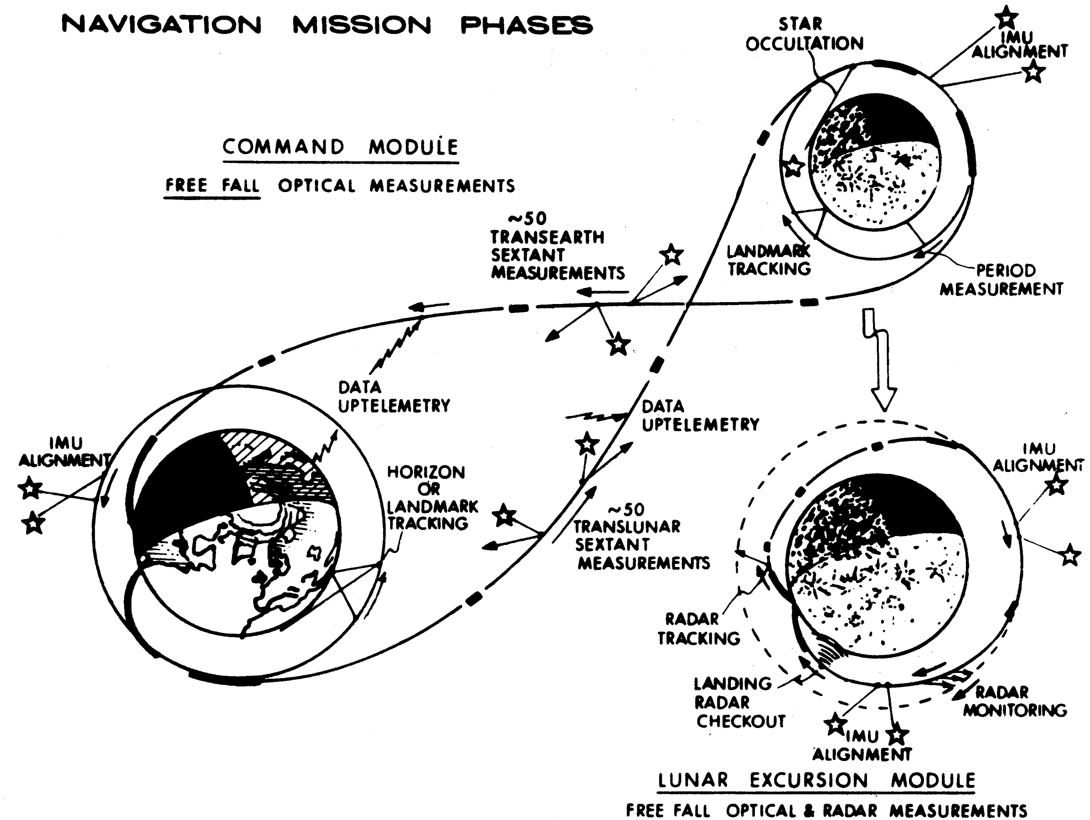


Fig. A9

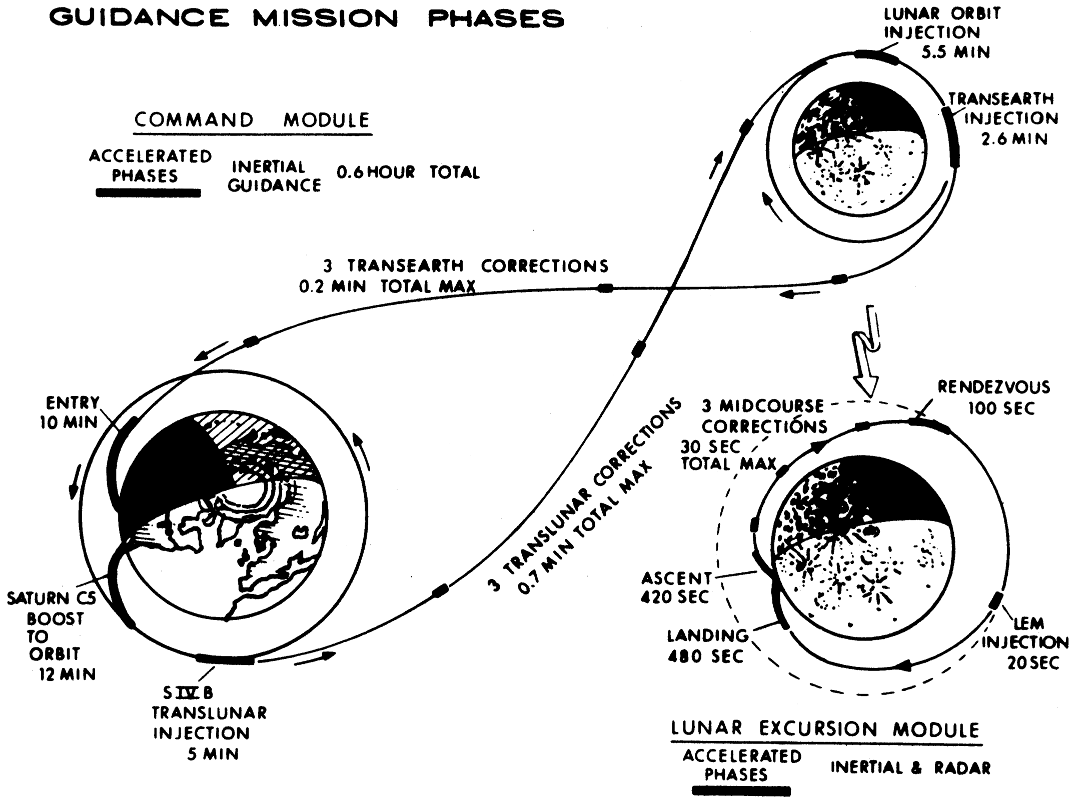
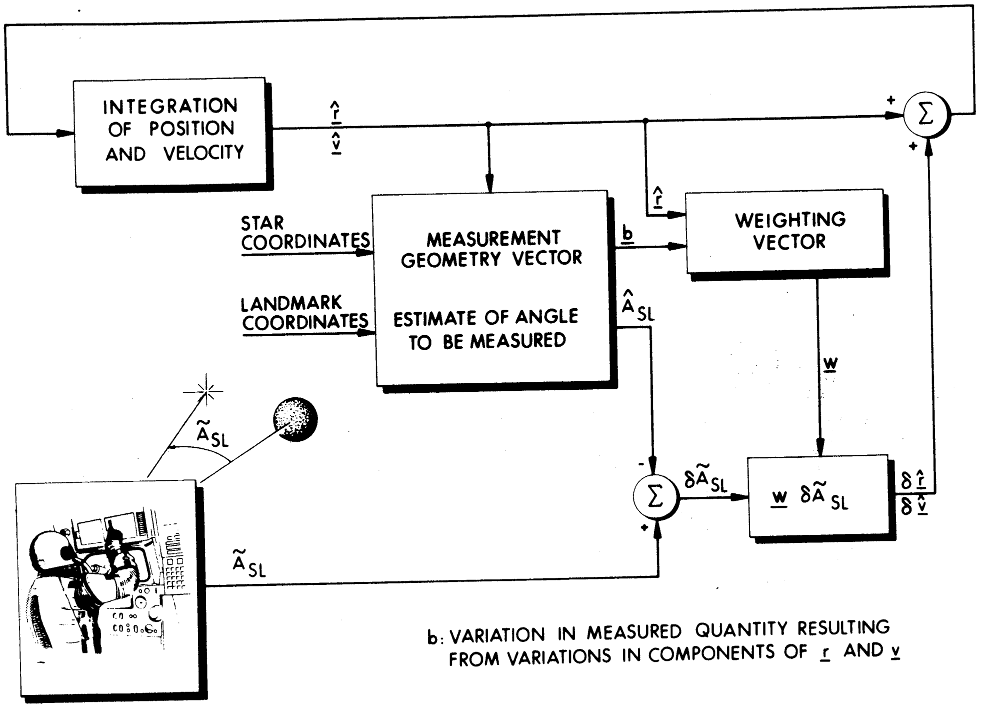


Fig. A10

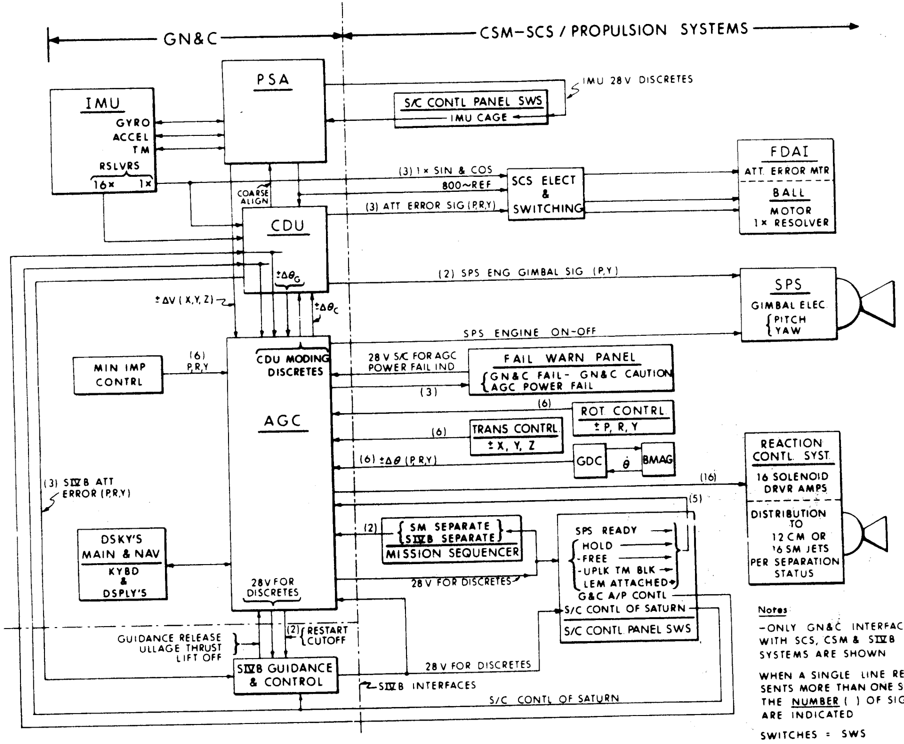
COASTING FLIGHT NAVIGATION COMPUTATION



b: VARIATION IN MEASURED QUANTITY RESULTING FROM VARIATIONS IN COMPONENTS OF $\underline{r}$ AND $\underline{v}$

Fig. A11

GN&C DIGITAL A/P BLOCK DIAGRAM



Notes

-ONLY GN&C INTERFACES WITH SCS, CSM & SIVB SYSTEMS ARE SHOWN

WHEN A SINGLE LINE REPRESENTS MORE THAN ONE SIGNAL THE NUMBER ( ) OF SIGNALS ARE INDICATED

SWITCHES = SWS

Fig. A12

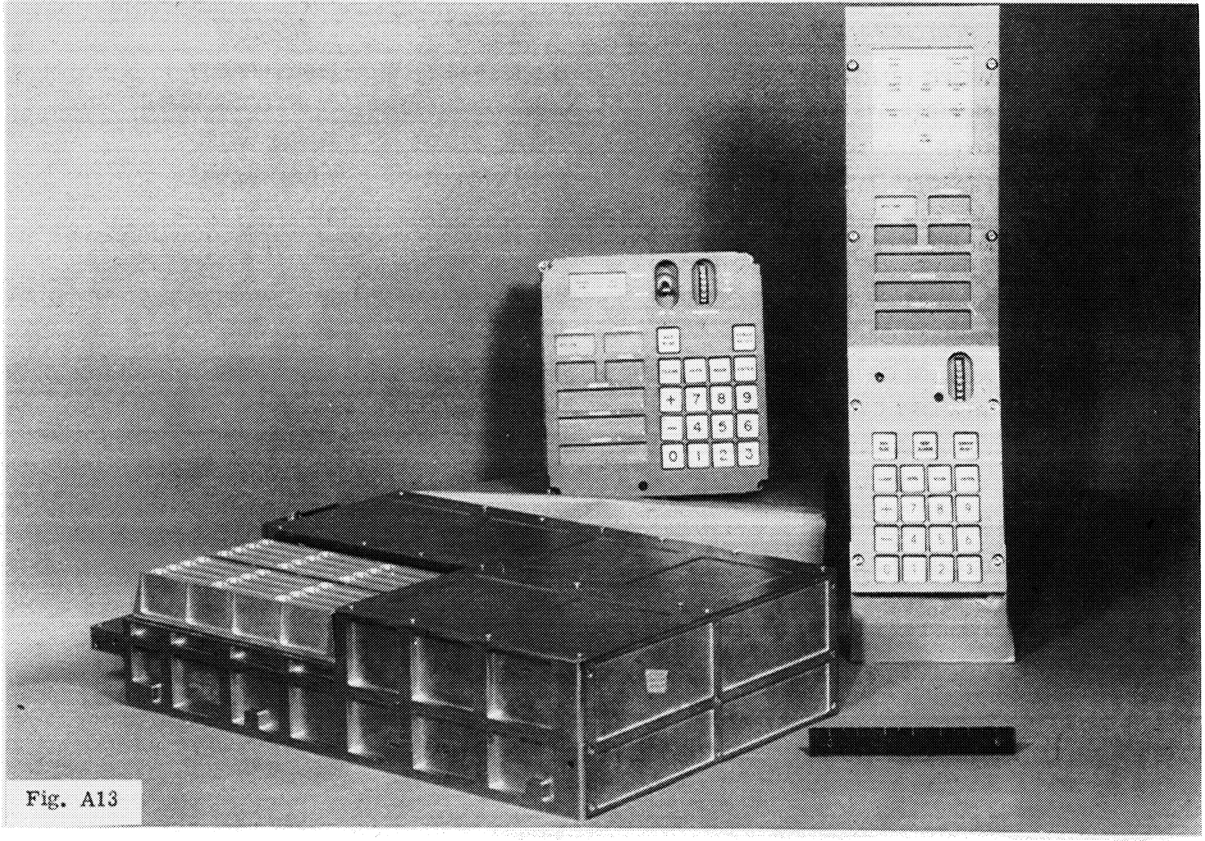


Fig. A13

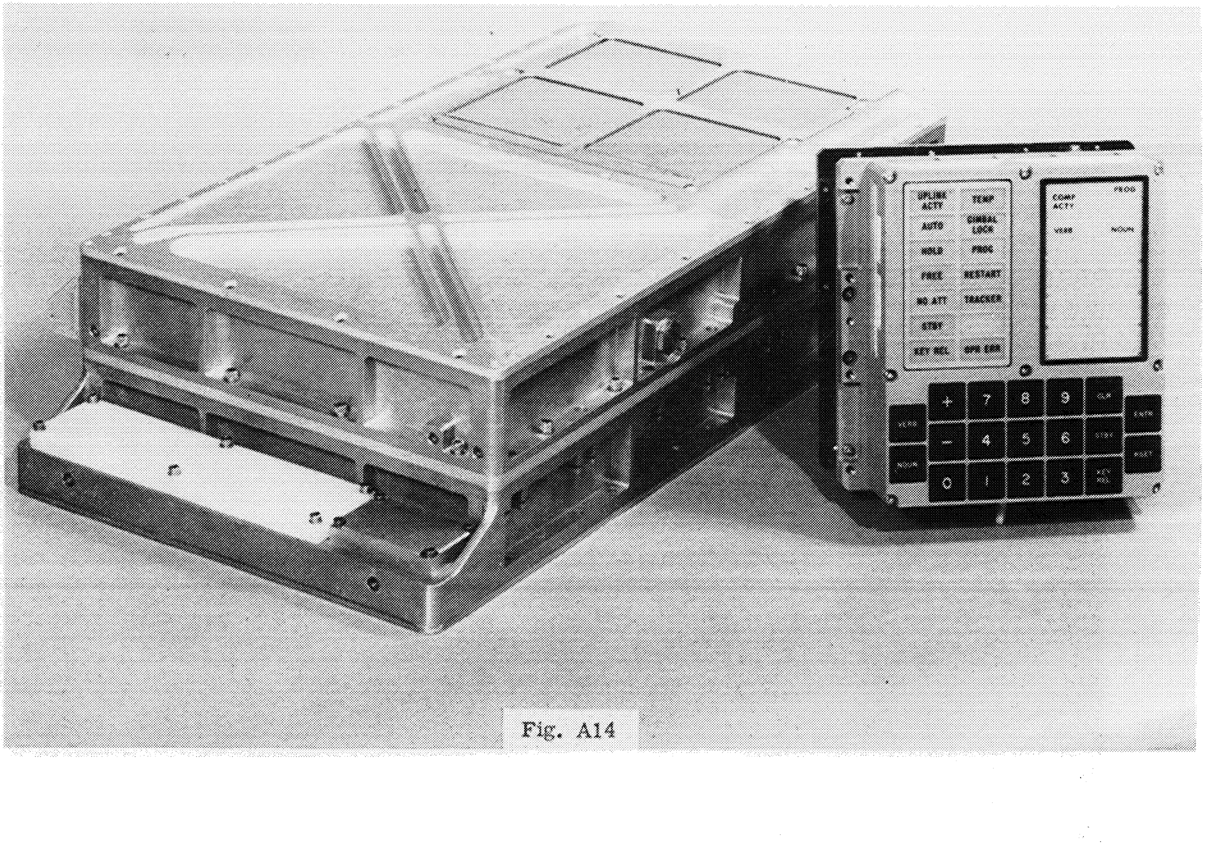


Fig. A14

PERFORMANCE CHARACTERISTICS	*BLOCK I*	*BLOCK II*
WORD LENGTH	15 BITS + PARITY	15 BITS + PARITY
NUMBER SYSTEM	ONE'S COMPLEMENT	ONE'S COMPLEMENT
FIXED MEMORY REGISTERS	24,576 WORDS	36,864 WORDS
ERASABLE MEMORY REGISTERS	1,024 WORDS	2,048 WORDS
NUMBER OF NORMAL INSTRUCTIONS	11	34
NUMBER OF INVOLUNTARY INSTRUCTIONS (INTERRUPT, INCREMENT, ETC.)	8	10
NUMBER OF INTERRUPT OPTIONS	5	10
NUMBER OF COUNTERS	20	29
NUMBER OF INTERFACE CIRCUITS	143	227
MEMORY CYCLE TIME	11.7 μSEC	11.7 μSEC
COUNTER INCREMENT TIME	11.7 μSEC	11.7 μSEC
ADDITION TIME	23.4 μSEC	23.4 μSEC
MULTIPLICATION TIME	117 μSEC	46.8 μSEC
DOUBLE PRECISION ADDITION TIME	SUBROUTINE (1.65 MILLISEC)	35.1 μSEC
NUMBER OF LOGIC GATES (MICROCIRCUITS)	4,100	5,600 (2,800 PACKAGES)
VOLUME	1.21 CUBIC FT (34,300 CC)	0.97 CUBIC FT (27,400 CC)
WEIGHT	87 LBS (39.4 KG)	71 LBS (32.2 KG)
POWER CONSUMPTION	100 WATTS	70 WATTS

Fig. A15

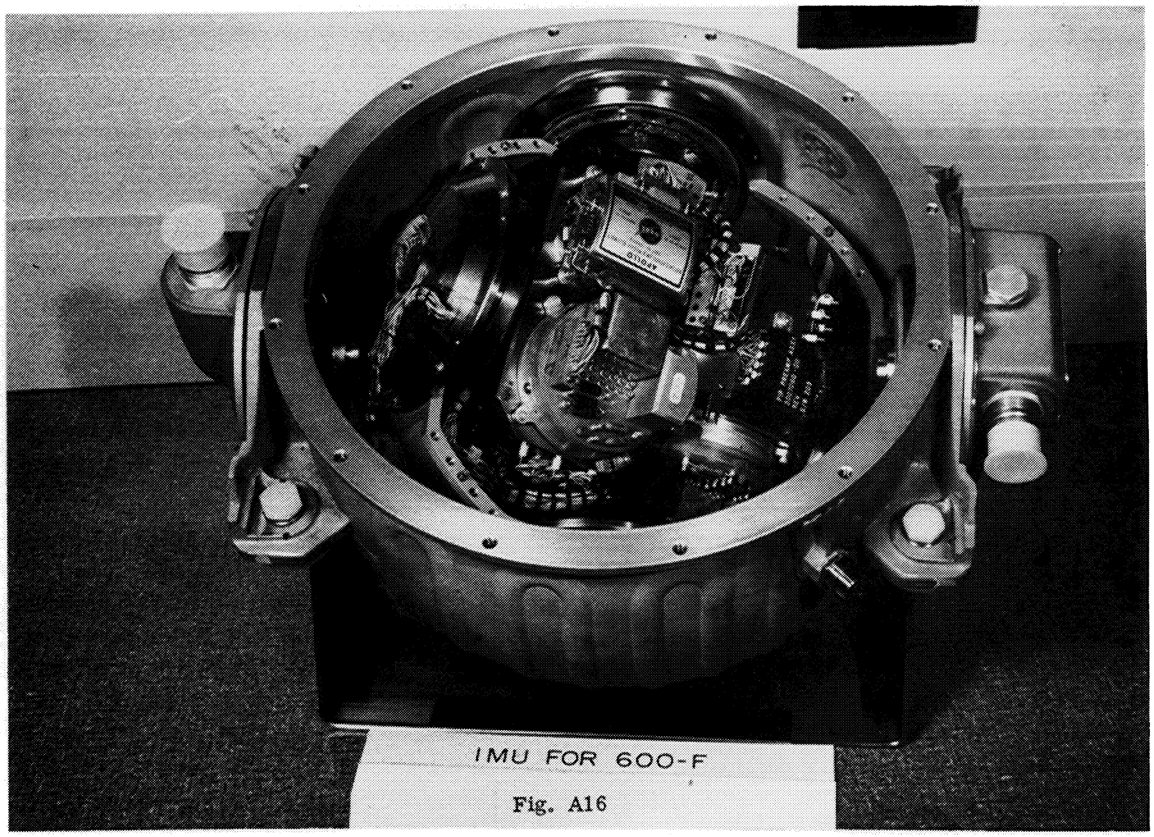


Fig. A16

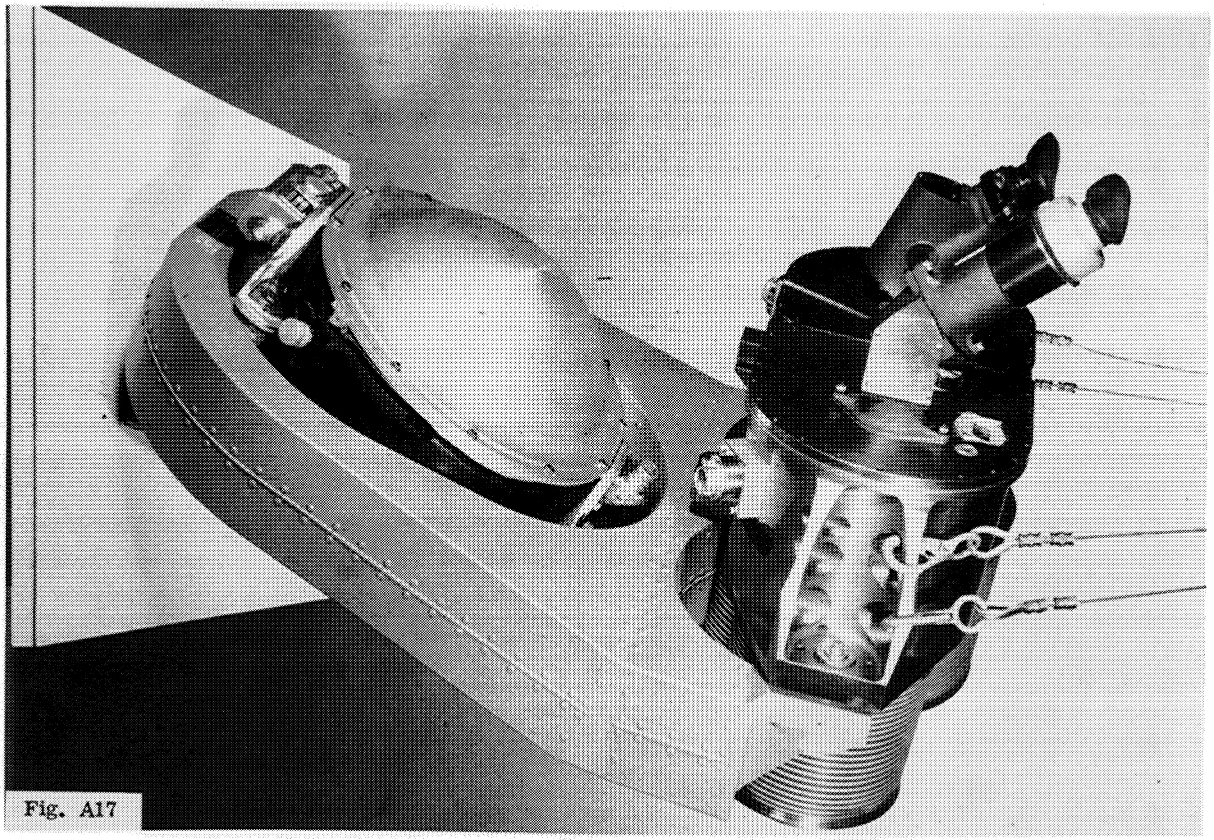


Fig. A17

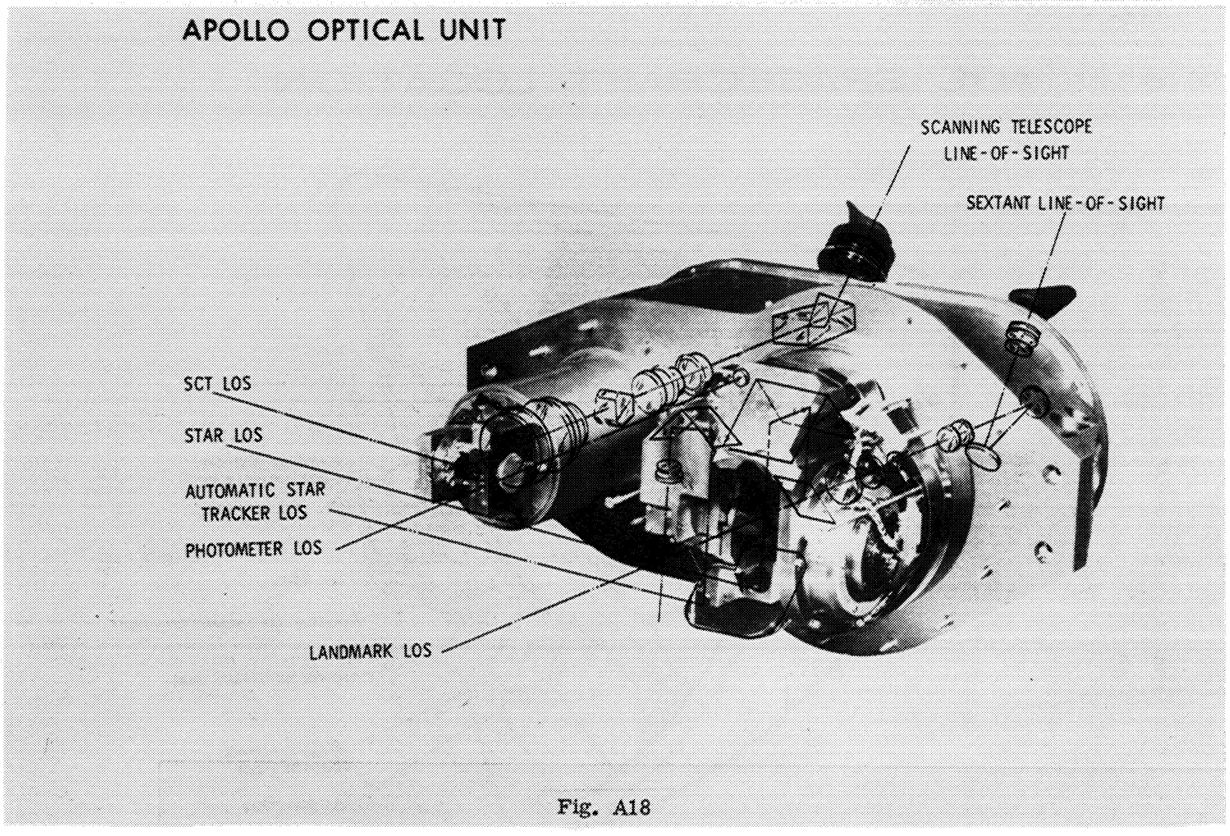
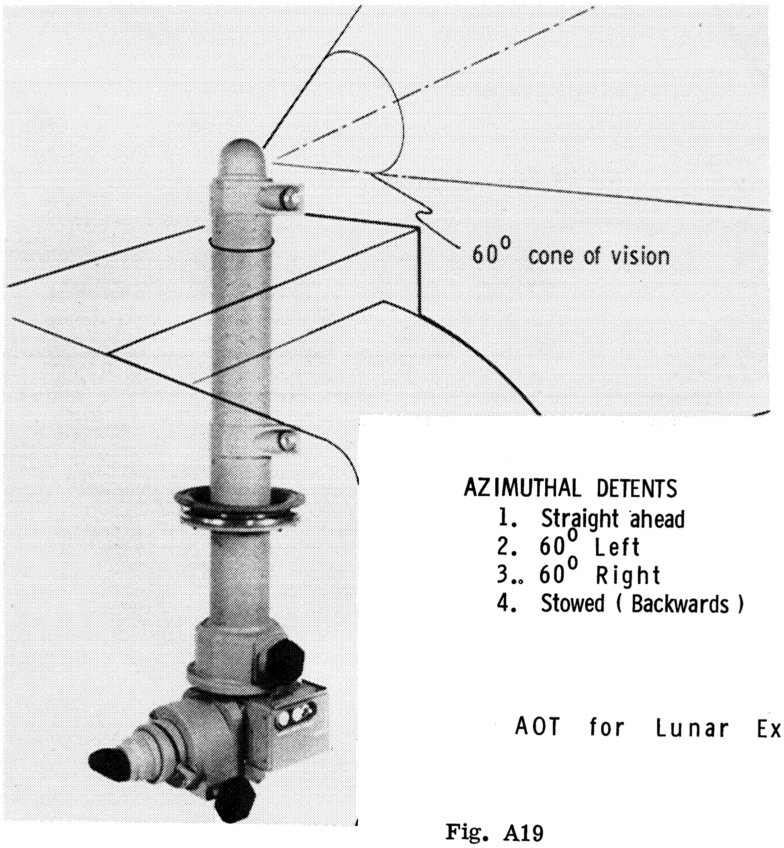


Fig. A18



AZIMUTHAL DETENTS
1. Straight ahead
2. 60° Left
3. 60° Right
4. Stowed (Backwards)

AOT for Lunar Excursion Module

Fig. A19

4/65

AGE SPACECRAFT LOCATION

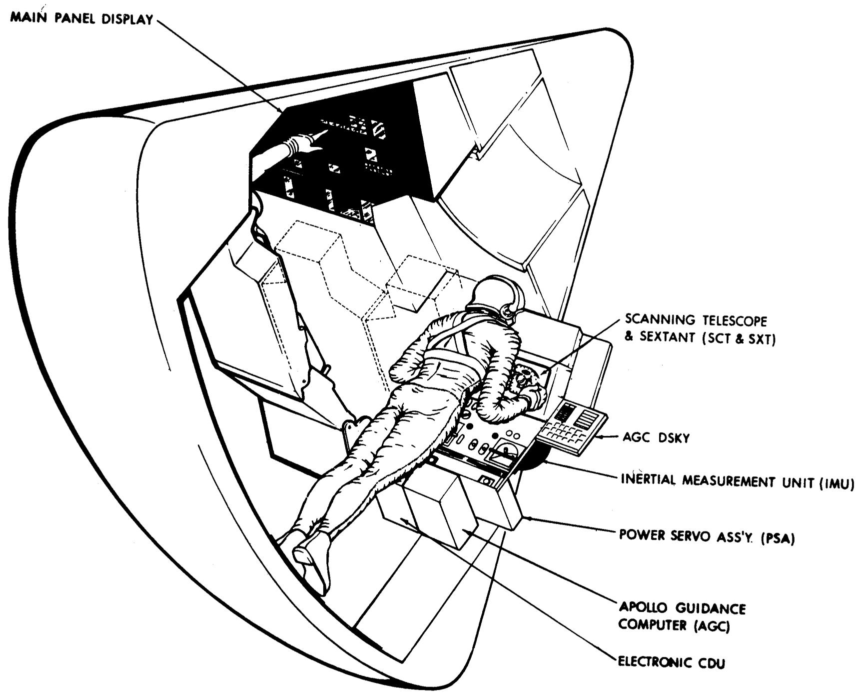


Fig. A20

LEM PGNCS INSTALLATION

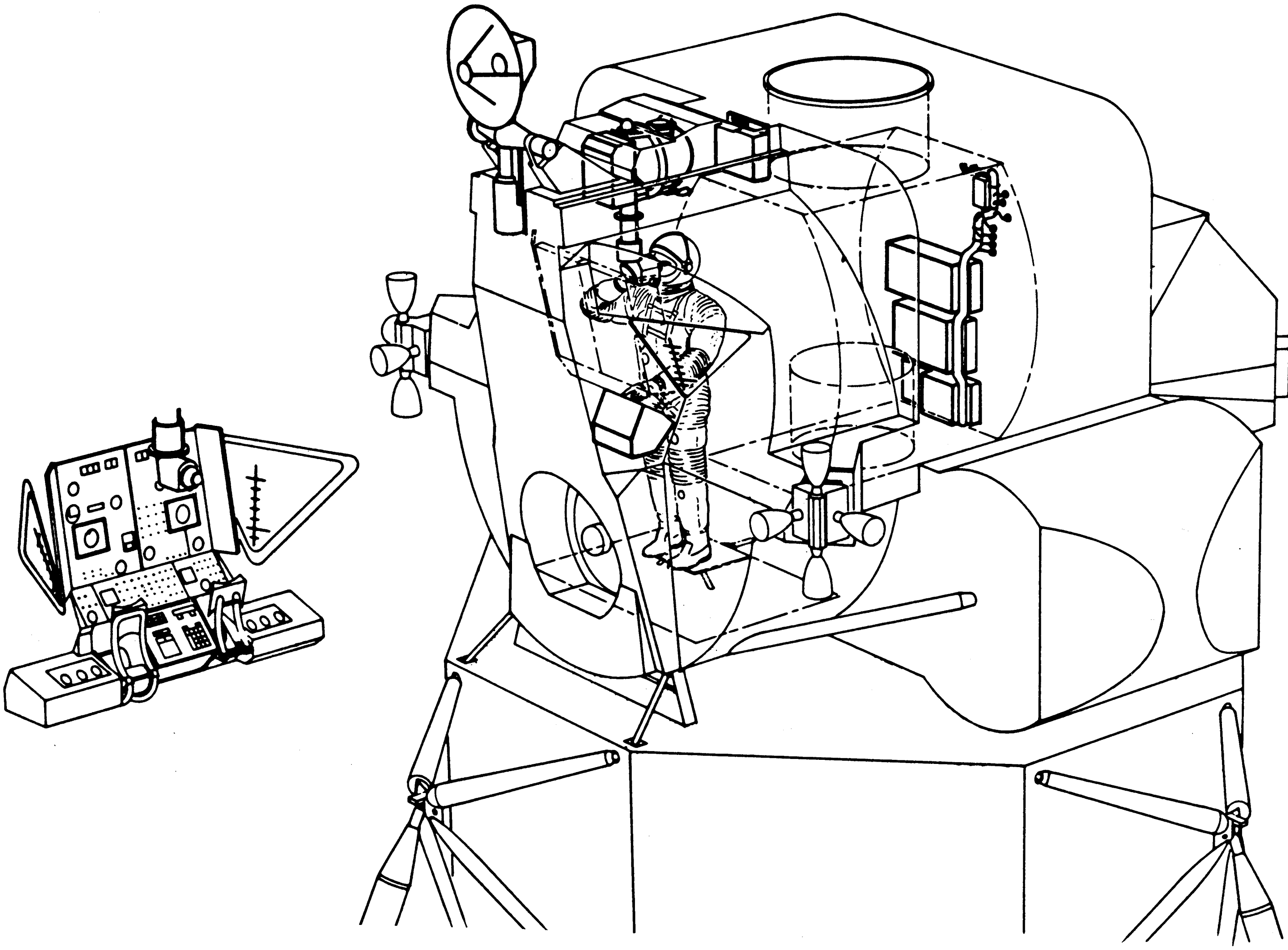


Fig. A21

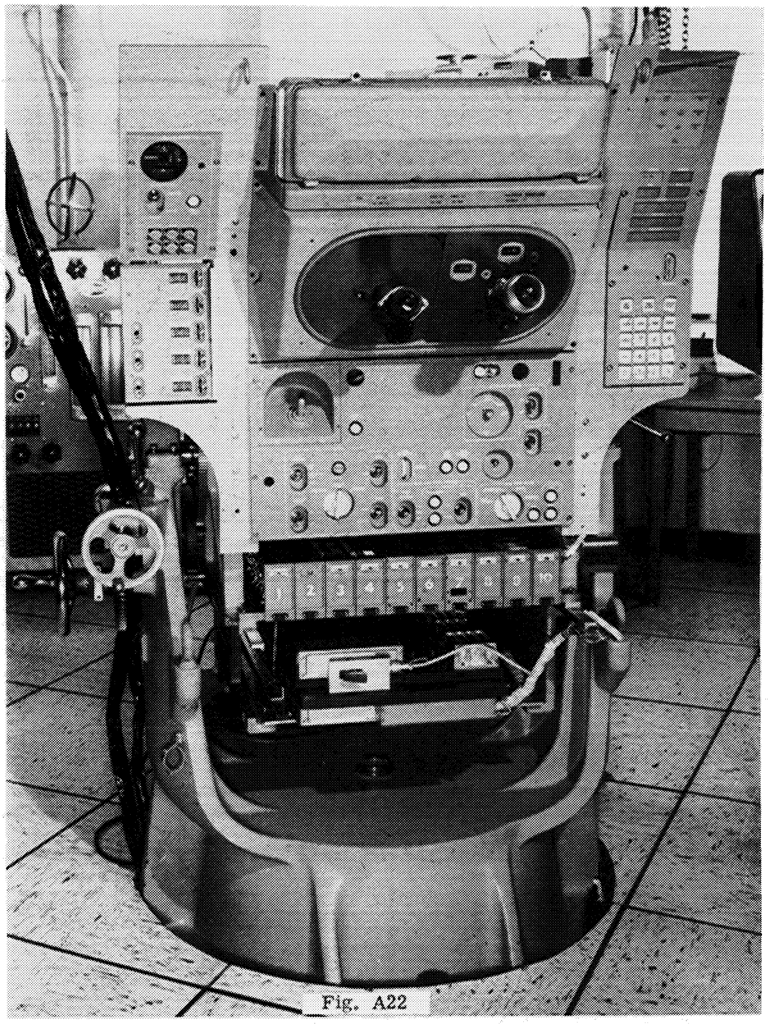


Fig. A22

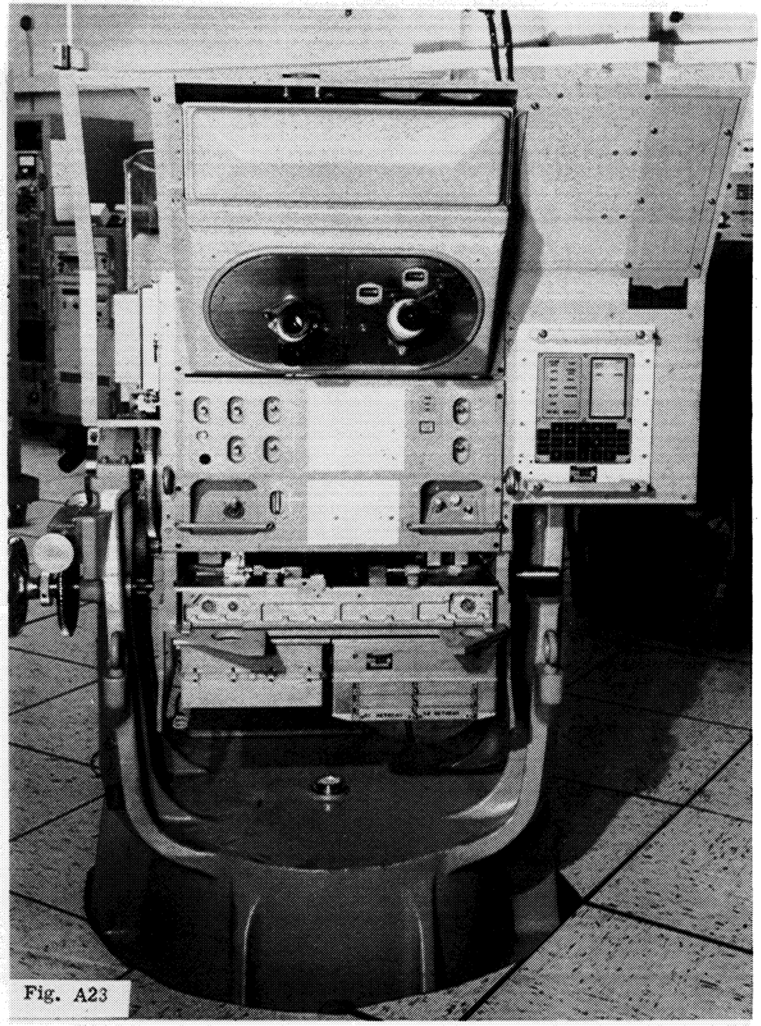


Fig. A23

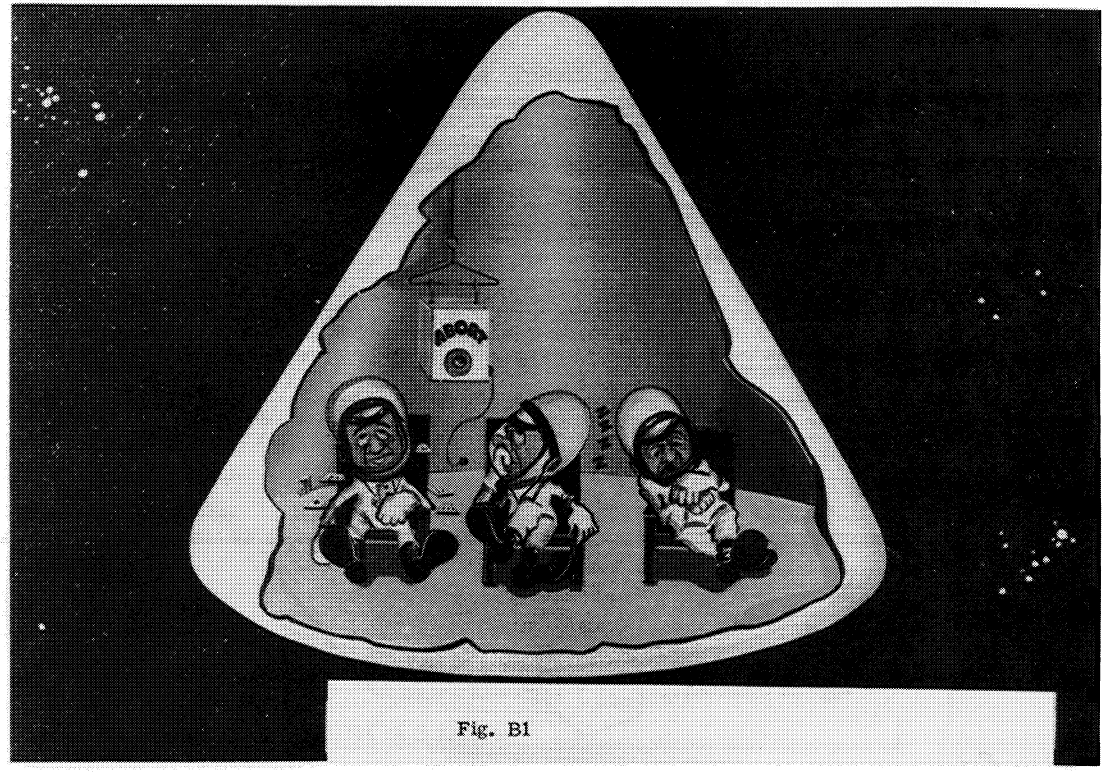


Fig. B1

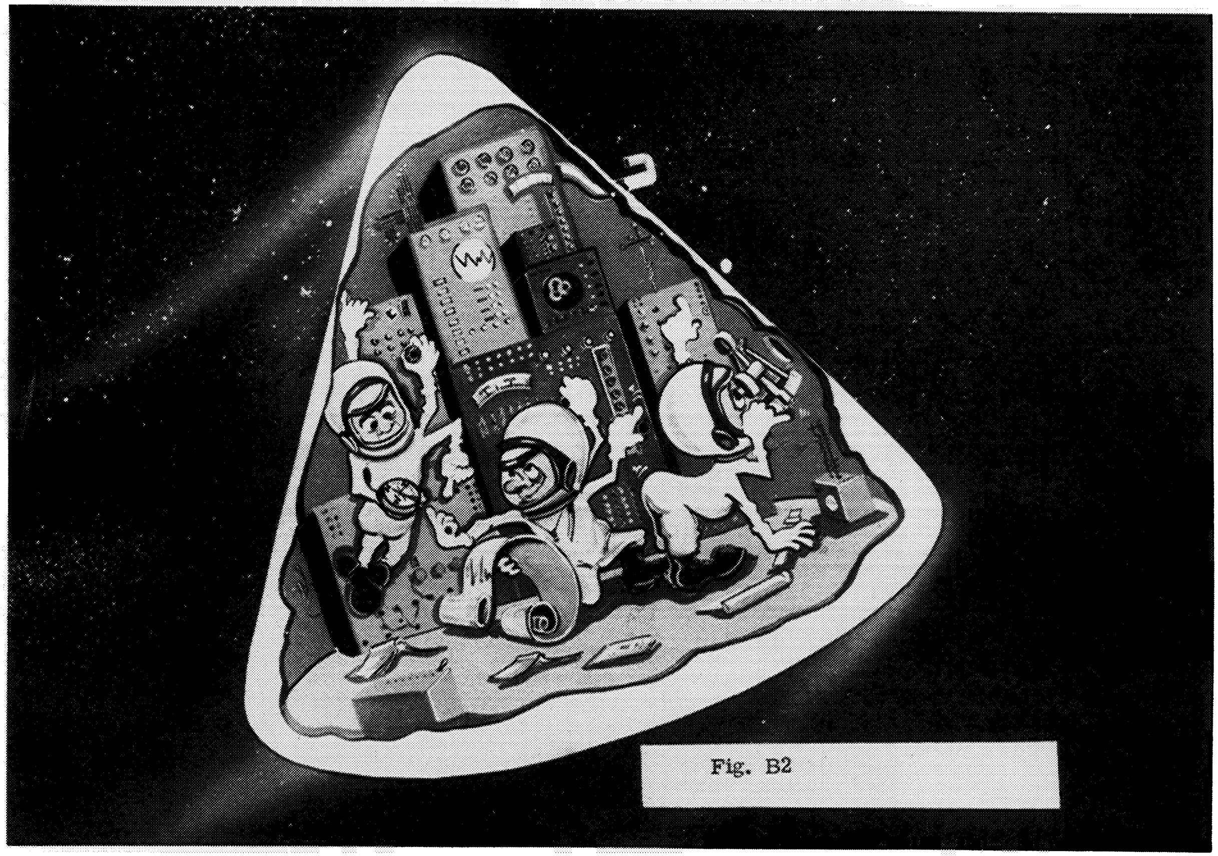


Fig. B2

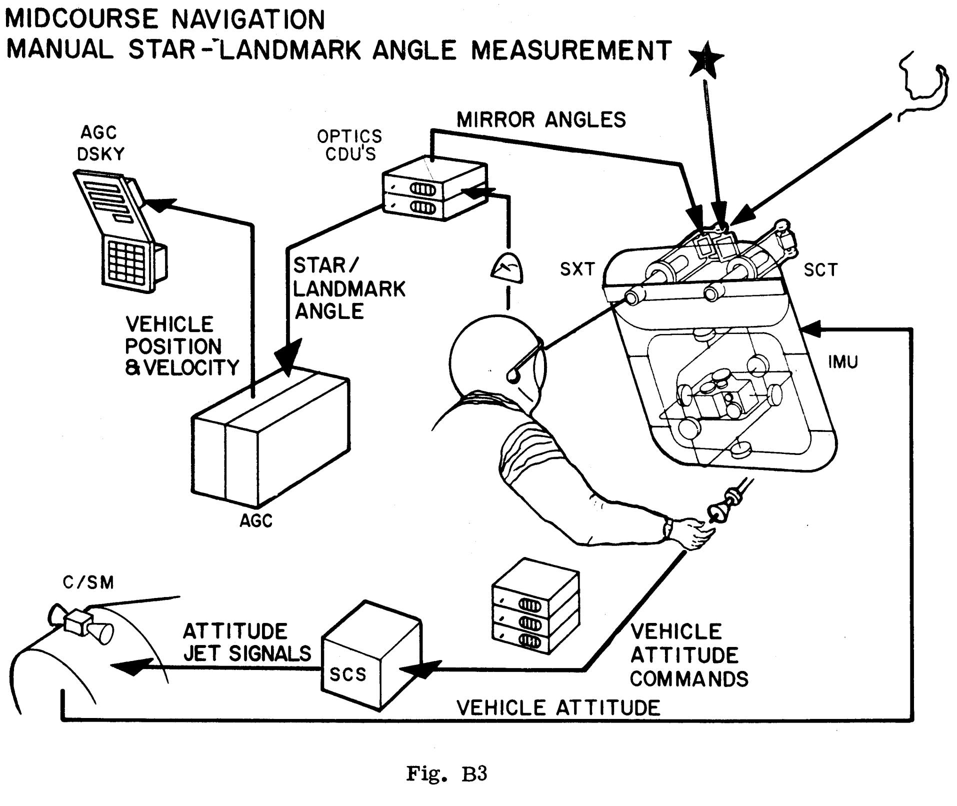

MIDCOURSE NAVIGATION
MANUAL STAR-LANDMARK ANGLE MEASUREMENT
MIRROR ANGLES
AGC
DSKY
OPTICS
CDU'S
STAR/
LANDMARK
ANGLE
SXT
SCT
VEHICLE
POSITION
& VELOCITY
IMU
AGC
C/SM
ATTITUDE
JET SIGNALS
SCS
VEHICLE
ATTITUDE
COMMANDS
VEHICLE ATTITUDE

Fig. B3

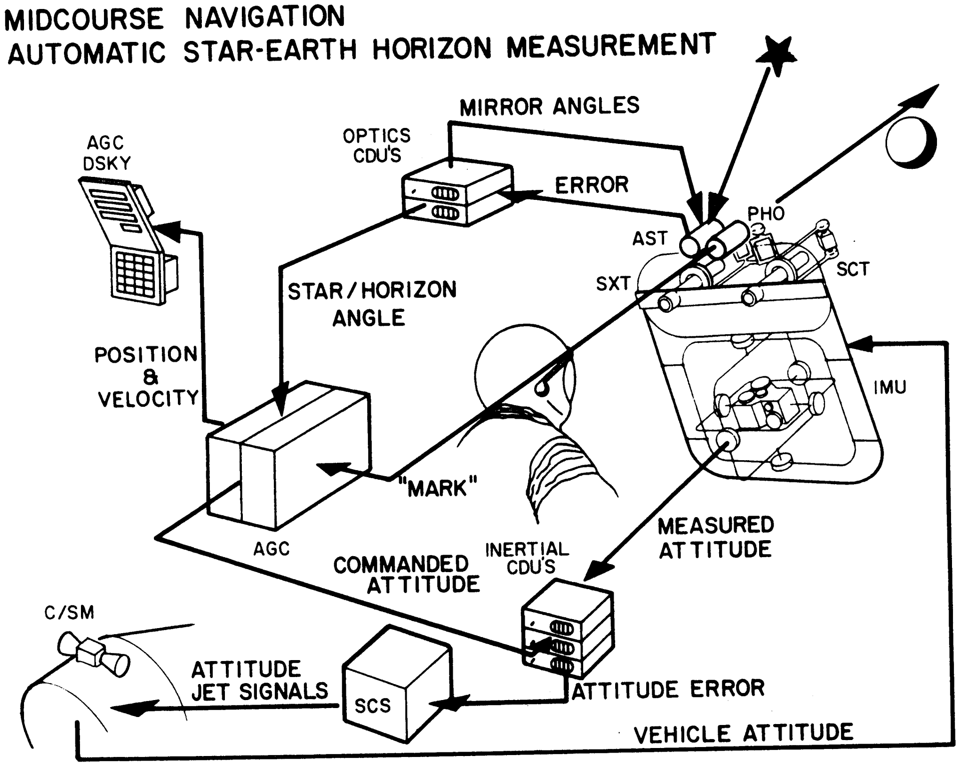


Fig. B4

DESIGN ANALYSIS PHASE

A. DEFINITION OF MAN INTERFACE

Definition of role

Listing of tasks

Identification of display and control functions

Definition of critical subtasks requiring simulation

Definition of computer display-keyboard

General task description and time line defined

Training requirements were defined

B. DISPLAY AND CONTROL DESIGN

At least eight major design steps were caused by "hardening" of both the G&N system design and spacecraft design.

C. SIMULATIONS OF CRITICAL SUBTASKS

Fig. C1

MAJOR TASKS

Fig. C2

1. PRELAUNCH G&N SYSTEM CHECKOUT
2. LAUNCH BOOST MONITORING
3. IMU ALIGNMENT
4. EARTH AND LUNAR ORBIT NAVIGATIONAL MEASUREMENT
5. △V MANEUVER
6. MIDCOURSE NAVIGATION MEASUREMENT
7. LUNAR DESCENT AND LANDING (LM AND CM)
8. LUNAR LAUNCH AND ASCENT (LM AND CM)
9. RENDEZVOUS MANEUVER
10. ENTRY MONITORING
11. ABORTS

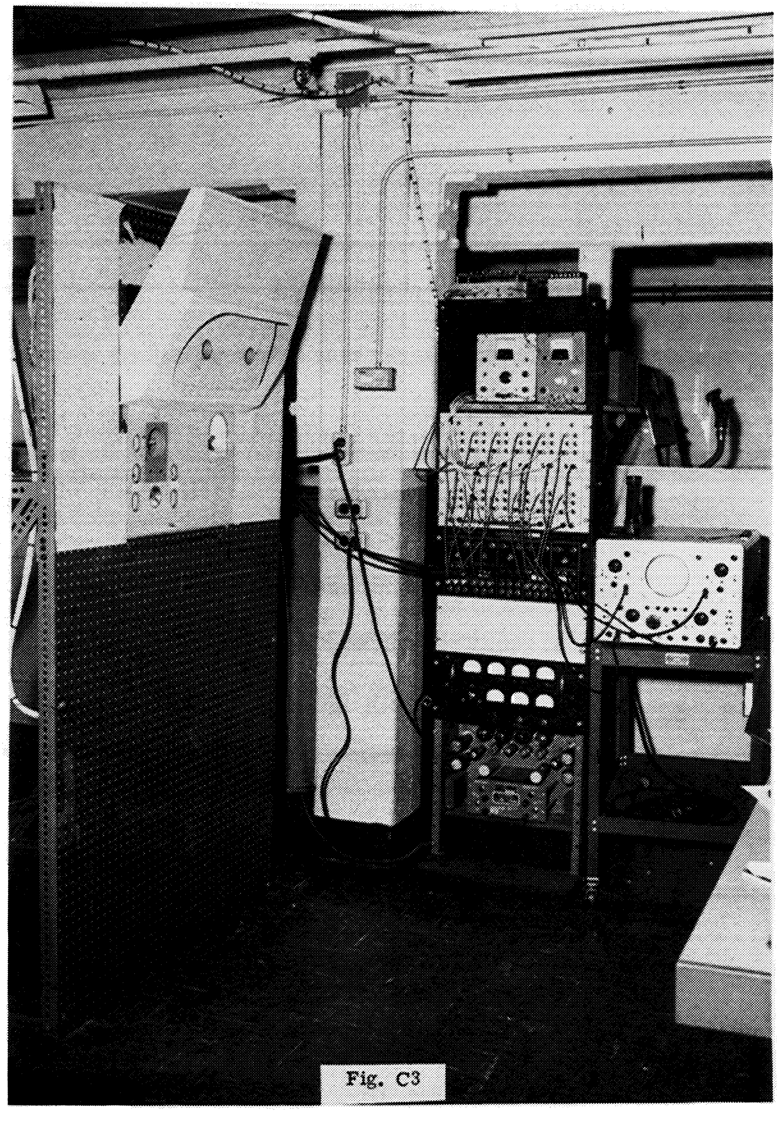


Fig. C3

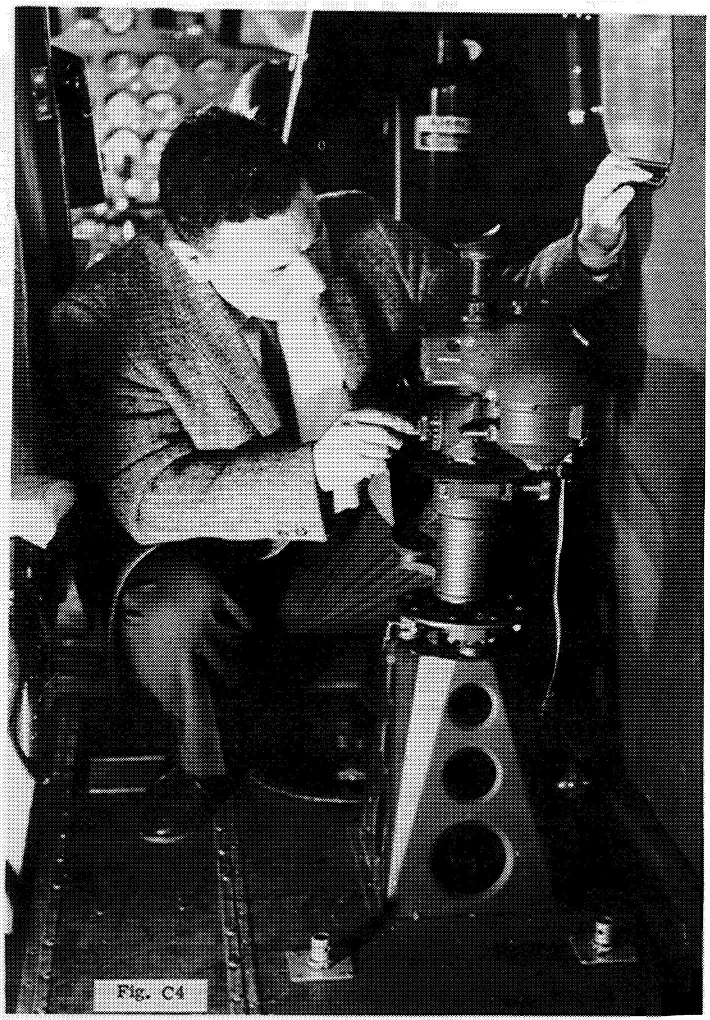


Fig. C4

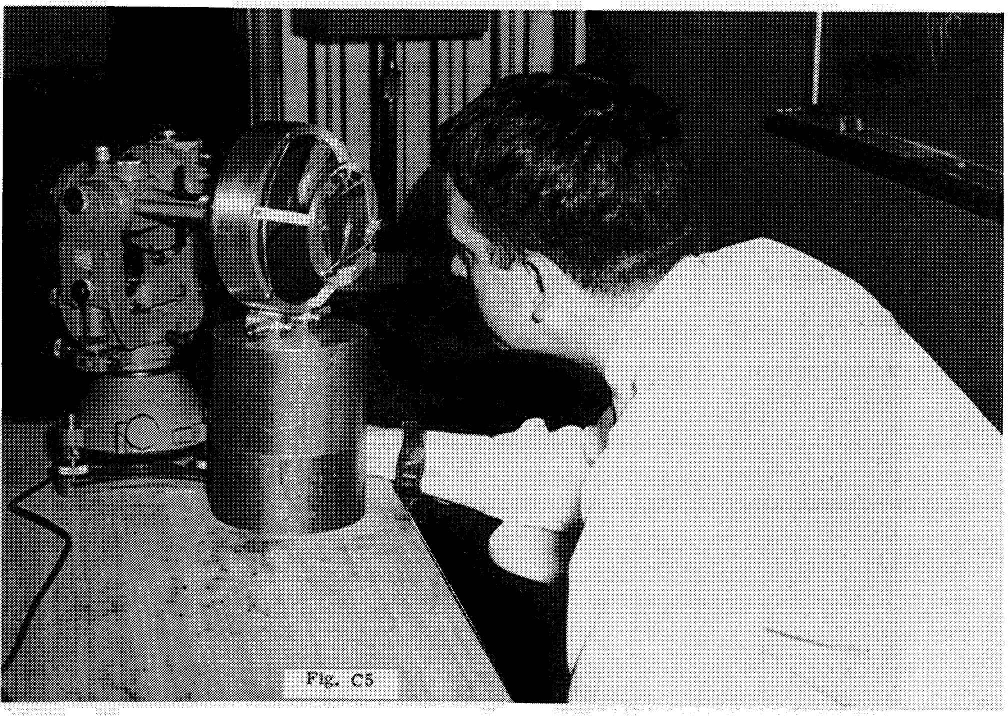


Fig. C5

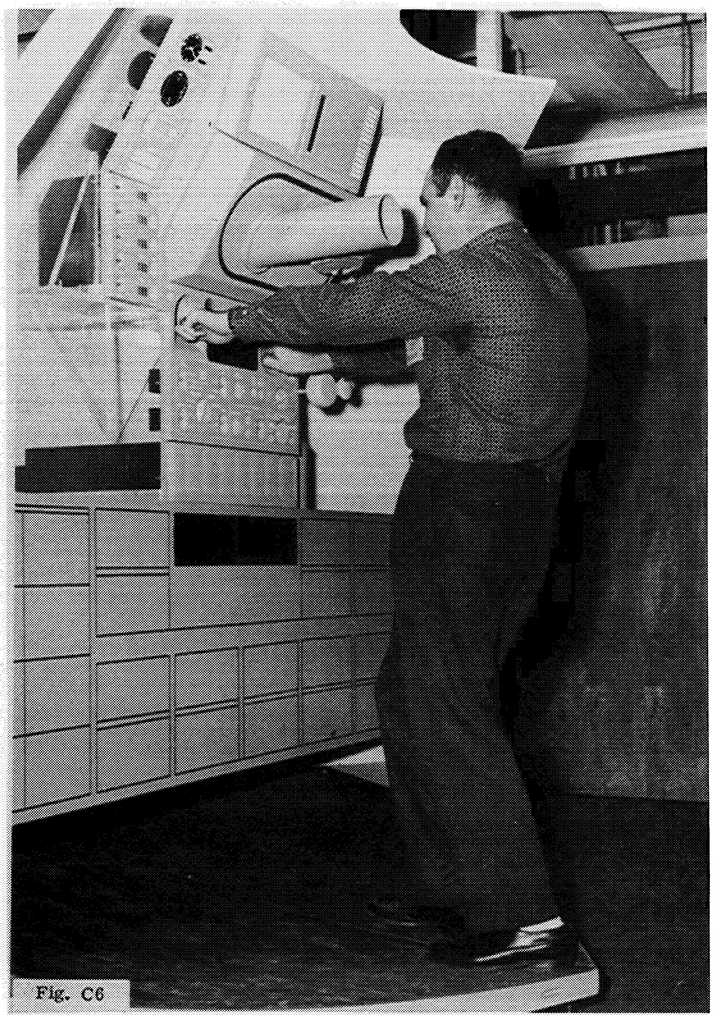


Fig. C6

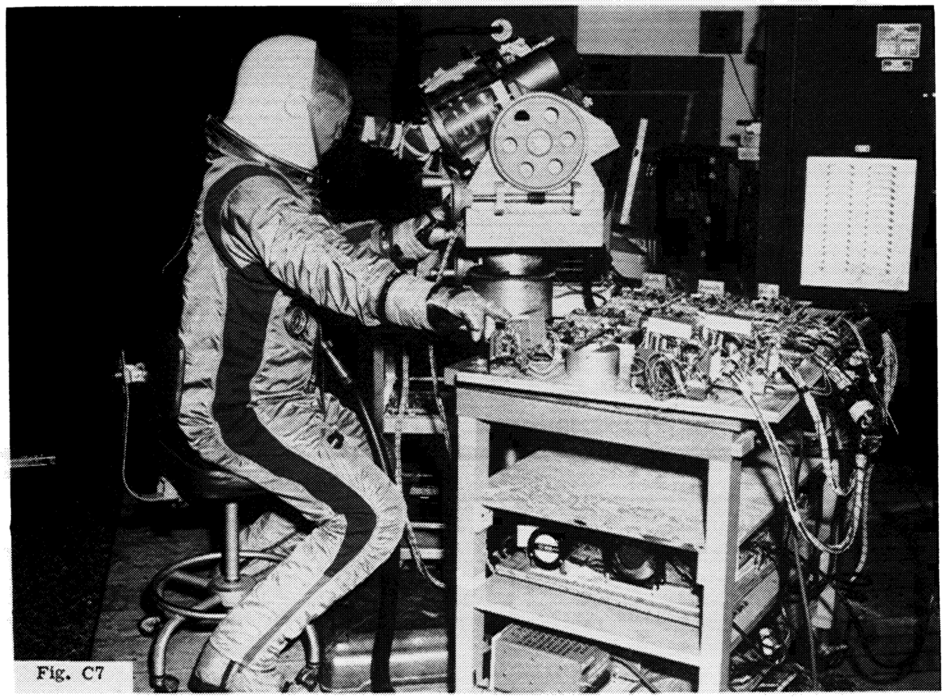


Fig. C7

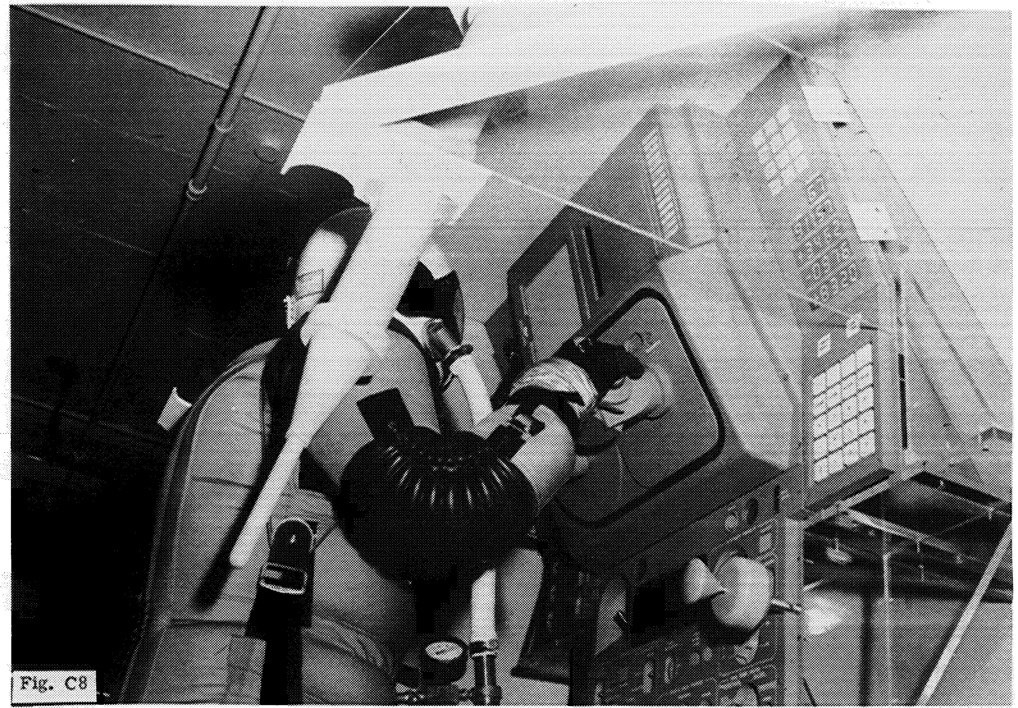


Fig. C8

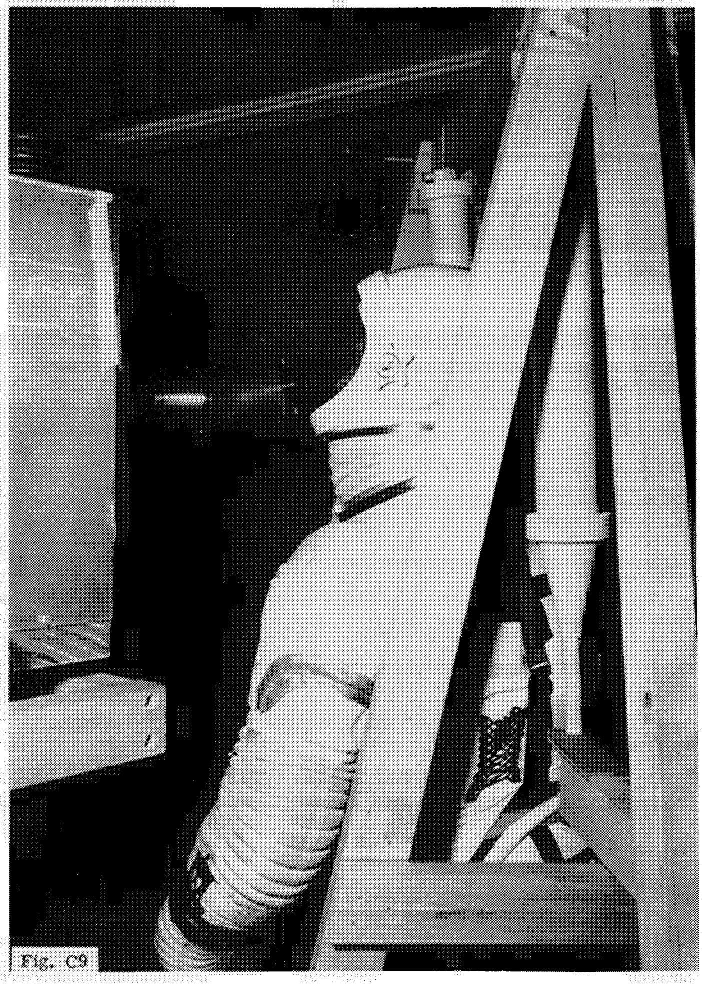


Fig. C9

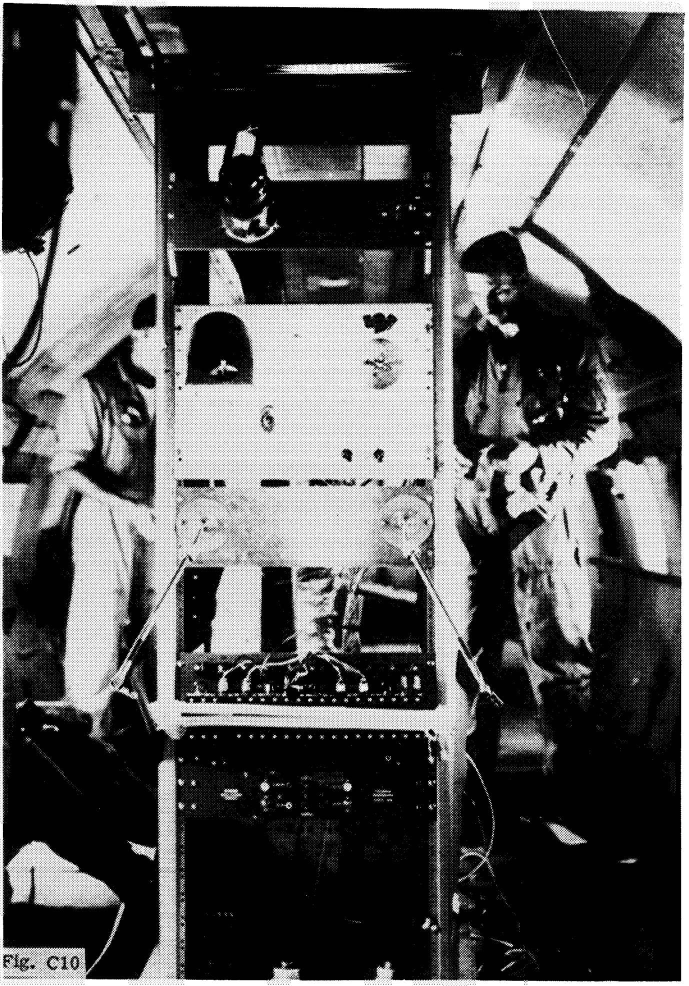


Fig. C10

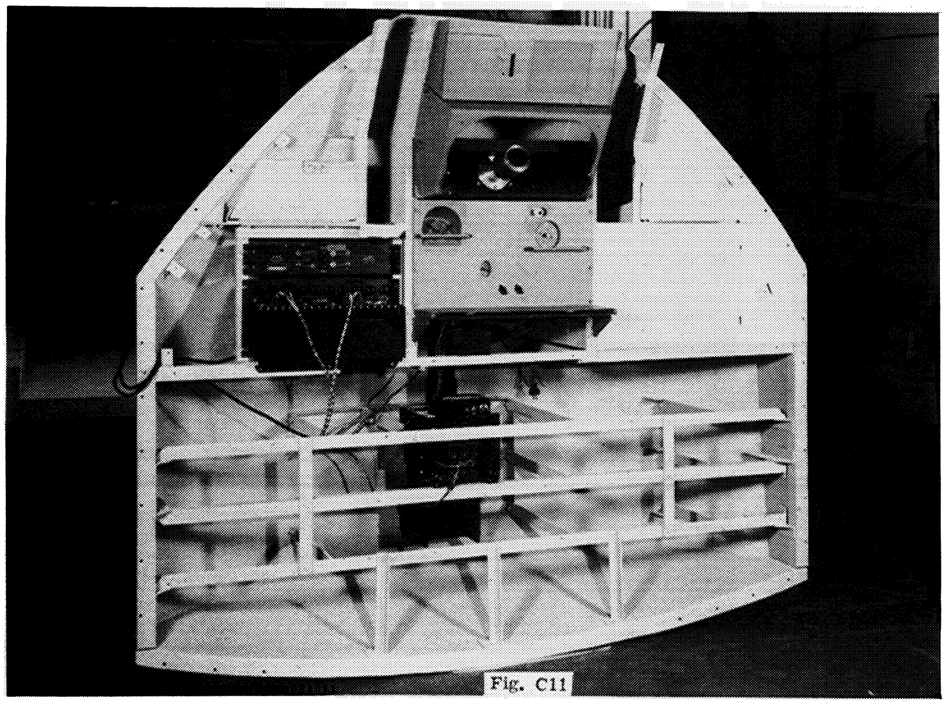


Fig. C11

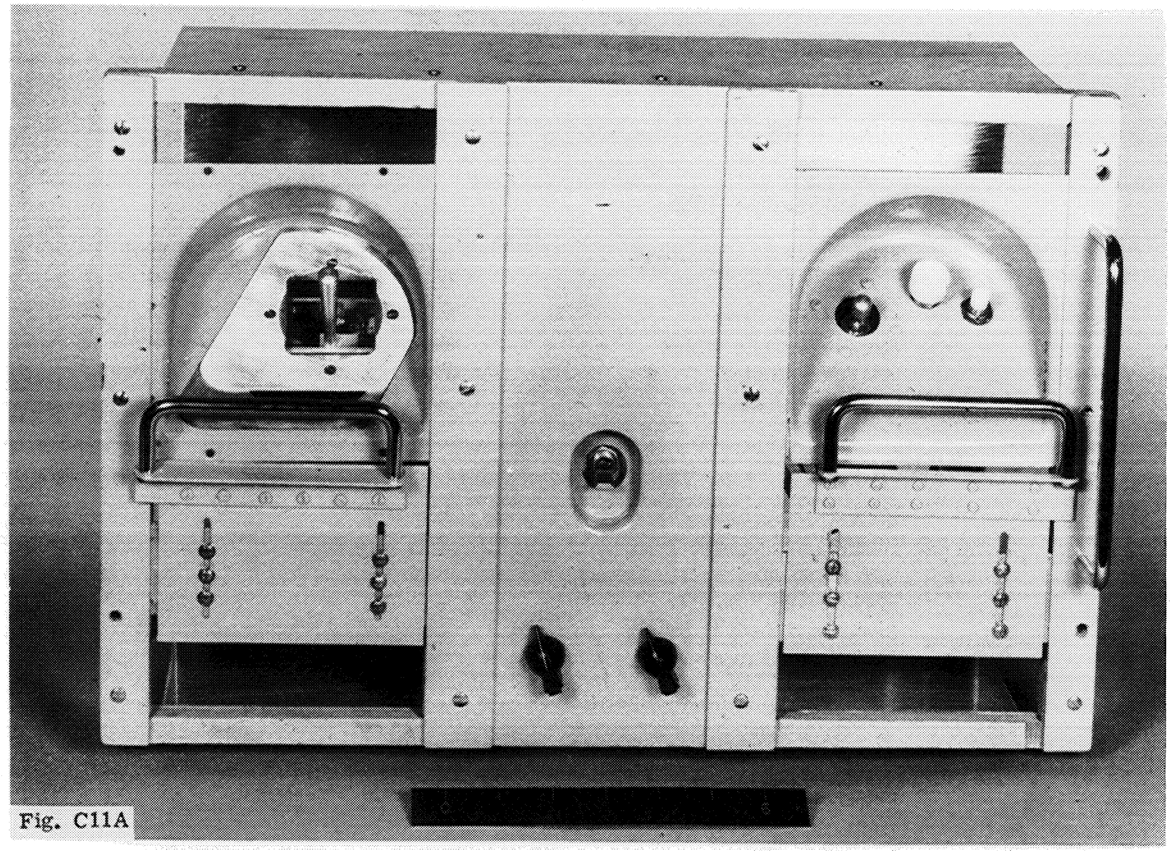


Fig. C11A

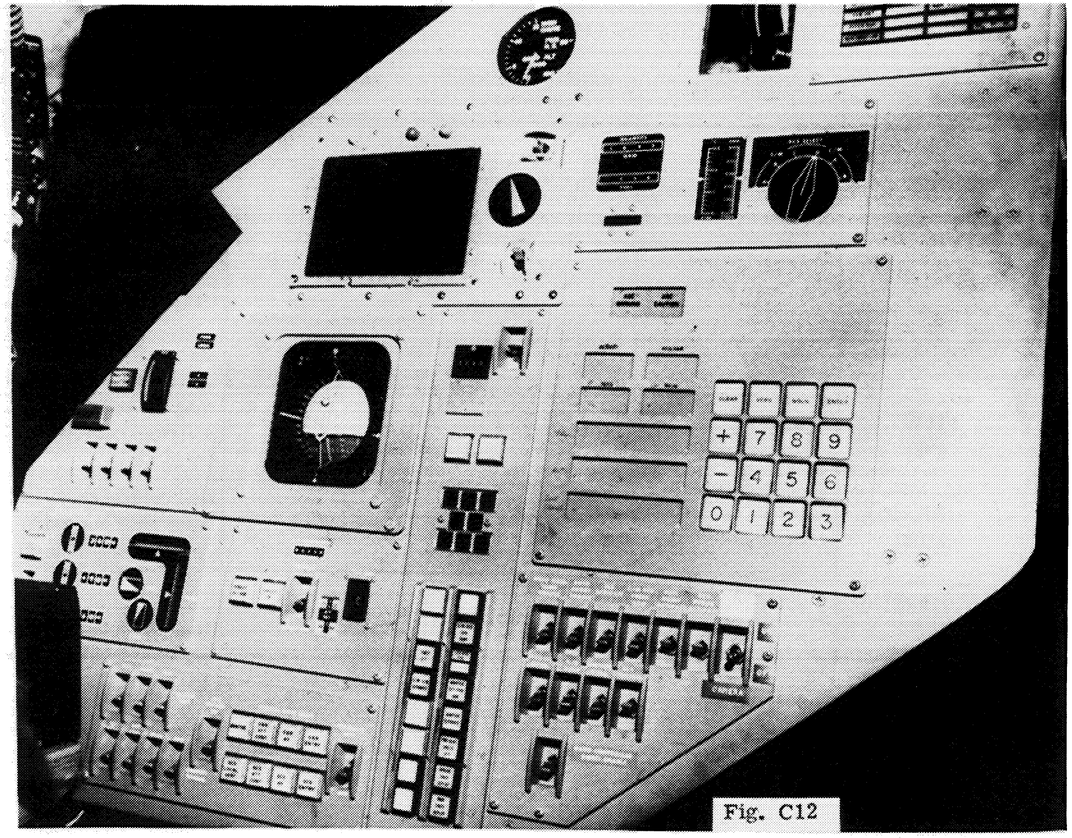


Fig. C12

OPERATIONAL TESTS

PRESSURE SUIT EVALUATIONS

Block I D&C and G&N Tasks	March 8 and April 17 and 18, 1963
Long Eye Relief Eyepiece	March 23, 1964
Block II I&C Panel	March 23, 1964
Block II Hand Controller	March 23, 1964
LEM Optics Control	March 23, 1964
Eyepiece Evaluation	June, 1965

ZERO G - WPAFB

Block I	July 1963
Long Eye Relief Eyepiece	July 1963
NAA Tethering	July 1963
Presure Suit - (suit leaked)	July 1963
Block I and Block II D&C	September, 1964
Block I and Block II D&C	November, 1965

(Re-evaluation with book and M&DV)

HIGH G

Entry	December 3-5, 1963
Boost	

Fig. C13

ENVIRONMENTAL CONSTRAINTS

	READ DISPLAYS	HANDLE CONTROLS SWITCHES	MOBILITY	PERFORM NAV SIGHTINGS
ZERO G	✓	✓	better than 1g in many instances of close quarters	✓
HIGH G	✓ some peripheral blurring > 8g	✓	×	×
PRESSURIZED GARMENT	✓	✓	some probs in close quarters; flexibility of suit a hindrance	✓
HELMET	✓	✓	✓	long eye relief optics a virtual necessity for block 1
INTERIOR ILLUM	read mdc up to 20 ft-c background illum	✓	✓	IMU control panel no hindrance to viewing 3rd mag star thru sxt
VIBRATION	?	?	?	?
FATIGUE				limited lab tests show no adverse effects up to 40 minutes

Fig. C14

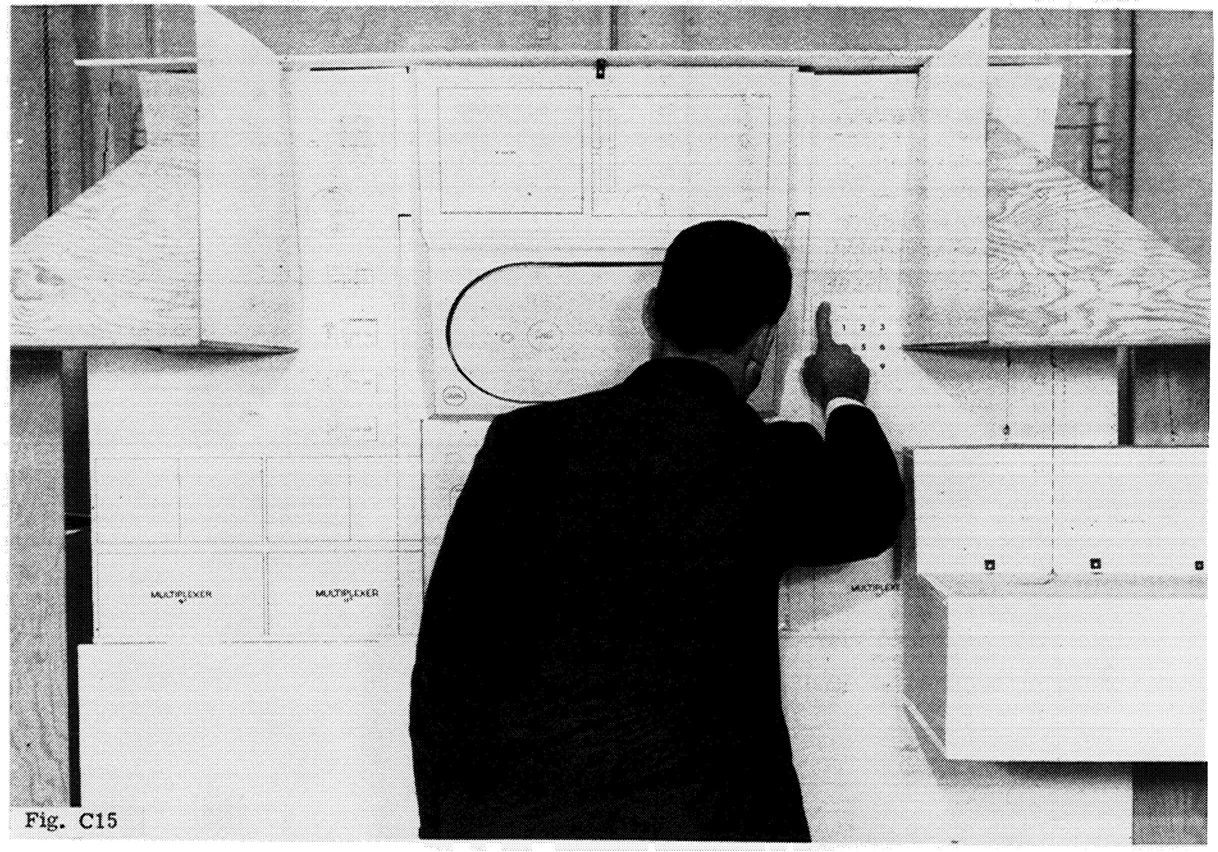


Fig. C15

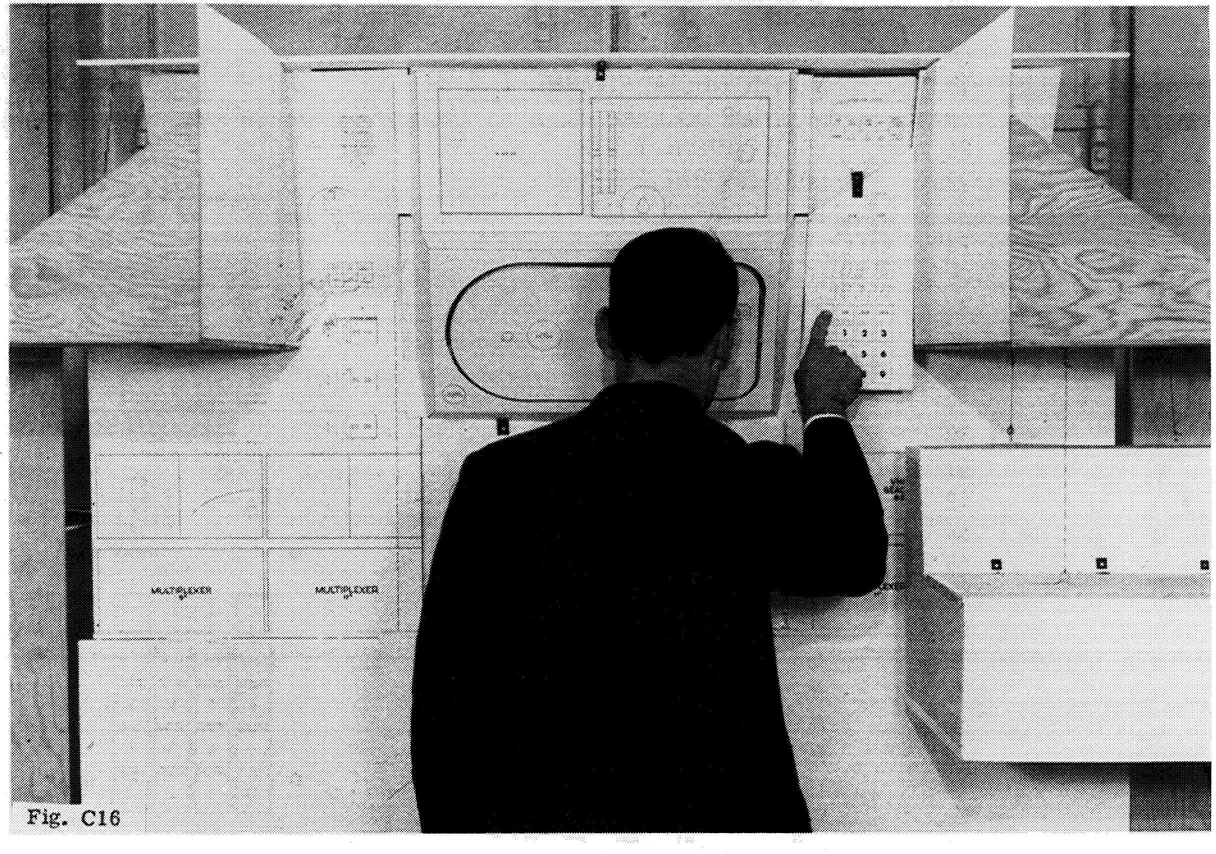


Fig. C16

MISSION PHASE	PROG. NO.	CM
SERVICE	00	AGC Idling
	01	Prelaunch Initialization
	02	Gyrocompassing
	03	Optical Verification of Azimuth
	04	Inertial Reference
	05	G&N Startup
	06	G&N Power Down
	07	System Test (non-flight)
BOOST	10	----------
	11	Pre-LET Jettison
	12	Post-LET Jettison
	13	----------
	14	----------
	15	----------
	16	----------
	17	LET Abort
COAST	20	----------
	21	----------
	22	Landmark Tracking Nav. Measurment
	23	Star/Landmark on Horizon Nav. Measurement
	24	Ground Track Determination
	25	----------
	26	----------
	27	AGC Update
PRE-THRUSTING	30	----------
	31	Orbit Change
	32	Return to Earth
	33	SPS Minimum Impulse
	34	----------
	35	----------
	36	----------
	37	----------
THRUSTING	40	----------
	41	Orbit Change
	42	Return to Earth
	43	Minimum Impulse
	44	----------
	45	----------
	46	----------
	47	----------
ALIGNMENT	50	----------
	51	IMU Orientation Determination
	52	SIVB/IMU Align
	53	CSM/IMU Align
	54	IMU Realign
	55	----------
	56	----------
	57	----------
ENTRY/DESCENT	60	----------
	61	Maneuver to CM/SM Sep. Attitude
	62	CM/SM Sep. & Pre-entry Maneuver
	63	Entry Initialization
	64	Post 0.05 G
	65	----------
	66	----------
	67	Final Phase
ABORTS	70	----------
	71	1st Abort Burn Monitor
	72	----------
	73	----------
	74	----------
	75	----------
	76	----------
	77	----------

Fig. C17

VERB LIST

01	DISP OCT COMPNT 1 (R1)
05	DISP OCT COMPNT 1, 2, 3
06	DISP DECIMAL
15	MONITOR OCTAL COMPNT. 1, 2, 3
16	MONITOR DECIMAL
21	LOAD COMPNT 1 (R1)
22	LOAD COMPNT 2 (R2)
23	LOAD COMPNT 3 (R3)
24	LOAD COMPNT 1, 2
25	LOAD COMPNT 1, 2, 3
33	PRO W/O DATA
34	TERMINATE PROG
36	FRESH START
37	CHANGE PROG
50	PLEASE PERFORM
51	PLEASE MARK
52	REJECT MARK
64	CALC ORBL PARMTS
65	CALC T OF ARR AT LONG
66	CALC LAT LONG AT SPEC T
67	CALC MAX DEC, T OF ARR
70	MAN ATT MANEUVER
71	MTVC TAKEOVER
72	MIN IMP AIM PT UPDATE
73	RET-EARTH AIM PT UPDATE
74	ORB CHGE AIM PT UPDATE
76	R, V, T UPDATE (STATE VEC)
77	LIFTOFF TIME UPDATE

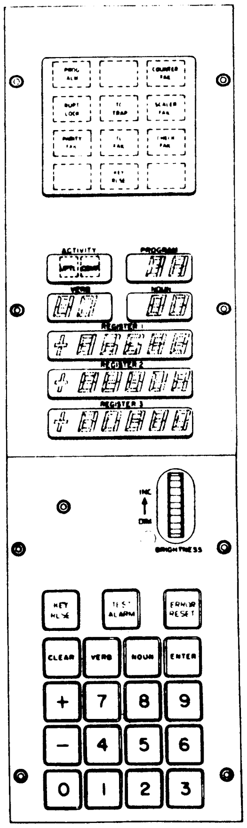


Fig. C18

NOUN LIST (Partial)

01	Specify machine address (fract)		.XXXXX	
02	Specify machine address (whole)		XXXXX	
05	Angular error		XXX.XX	DEG
07	Change of program (perform)		OCTAL	
11	Thrust on enable (perform)			
14	ΔV SCS counter set		XXXXX.	FT/SEC
15	Increment machine addresss		OCTAL	
16	AGC clock time		00XXX.	HRS.
			000XX.	MIN
			0XX.XX	SEC
17	Final ICDU angles R, P, Y		XXX.XX	DEG
25	Checklist (please perform)		000XX.	
30	Star number		+000XX.	
31	Failure info	Fail reg	OCTAL	
		Sfail	OCTAL	
		Ercount	OCTAL	
33	Time of ignition (GETI) HRS, MIN, SEC			
34	Event time HRS, MIN, SEC			
35	Δ event time HRS, MIN, SEC			
43	Apogee altitude (HA),		XXXX.X	NAUT MI
	Perigee altitude (HP),		XXXX.X	NAUT MI
	Free-fall time (TFF)		XXBXX	MIN/SEC
44	Latitude		XXX.XX	DEG
	Longitude,		XXX.XX	DEG
	Altitude		XXXX.X	NAUT MI
45	Apogee altitude (HA),		XXXX.X	NAUT MI
	Perigee altitude (HP),		XXXX.X	NAUT MI
	ΔV required		XXXXX.	FT/SEC
51	Time to event (IG or ECO),		XXBXX	MIN/SEC
	Velocity to be gained (VG),		XXXXX.	FT/SEC
	Measured velocity change		XXXXX.	FT/SEC
62	Impact latitude,		XXX.XX	DEG
	Impact longitude,		XXX.XX	DEG
	Heads up/down		+00001/-00001	
70	Pitch trim,		XXX.XX	DEG
	Yaw trim,		XXX.XX	DEG
	Δ time tail-off		XXX.XX	DEG
71	Command roll angle (beta),		XXX.XX	DEG
	Present acceleration (G),		XXX.XX	G
	Predicted range-range to targ		XXXX.X	NAUT MI

Fig. C19

CHECKLIST CODES

00001	SCS - G&N ATTITUDE
00002	SCS - G&N DELTA V
00003	SCS - G&N ENTRY
00004	SCS - SCS ATTITUDE
00007	ATT TRIM MANEUV ENABLE
00011	AUTO OPTICS POS
00013	OPTICS MODE - COMPUTER
00014	FINE ALIGN CHECK
00015	PERFORM STAR ACQ
00016	TERMINATE MARK SEQUENCE
00041	CM/SM SEP
00051	FINAL IMU/FINAL VEHCILE
00052	INTERIM IMU/FINAL VEHICLE
00053	FINAL IMU/INTERIM VEHICLE
00054	INTERIM IMU/INTERIM VEHICLE
00060	IMU TURN ON
00061	IMU POWER DOWN
00062	AGC POWER DOWN

V50 N25

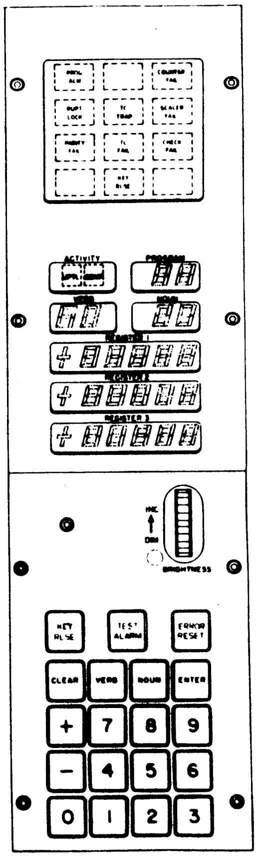


Fig. C20

AGC ERROR CODES

ERROR CODE	ERROR
00101	Optics Mode switch removed from Zero Optics position before end of 60 sec wait.
00106	Too many marks.
00112	Optics mark with none requested.
**00122	Only one mark made for unknown landmark.
00201	IMU Mode changed from Zero Encode before end of 35 sec delay.
00202	Computer unable to achieve desired mode.
**00412	Time and longitude too far apart.
**01410	Entry conditions not computable.
**01427	IMU orientation reversed for entry (Computer waits 5 sec and proceeds.)

** Main alarms.

V05 N31

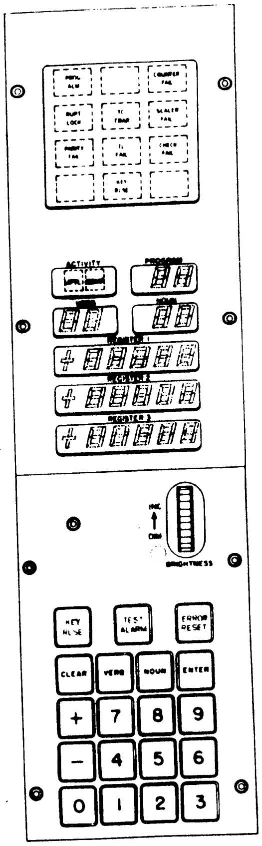


Fig. C21

DEVELOPMENT PHASE

A. DISPLAY AND CONTROL DESIGNS DEVELOPED AND RELEASED TO MANUFACTURING.

B. DETAILED OPERATING PROCEDURES DEVELOPED FOR TASKS.

C. DETAILED SIMULATIONS BUILT FOR PART TASK AND WHOLE TASK EVALUATION.

D. PERFORMANCE MODELS FOR MAN DETERMINED.

Fig. C22

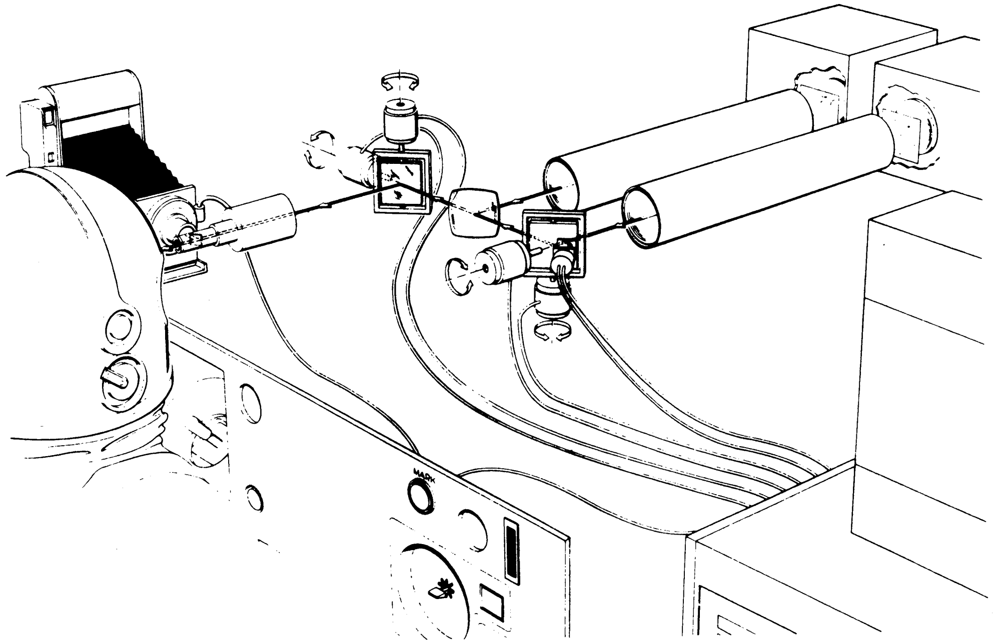


Fig. C23

SEXTANT SIMULATION - FUNCTIONAL SCHEMATIC

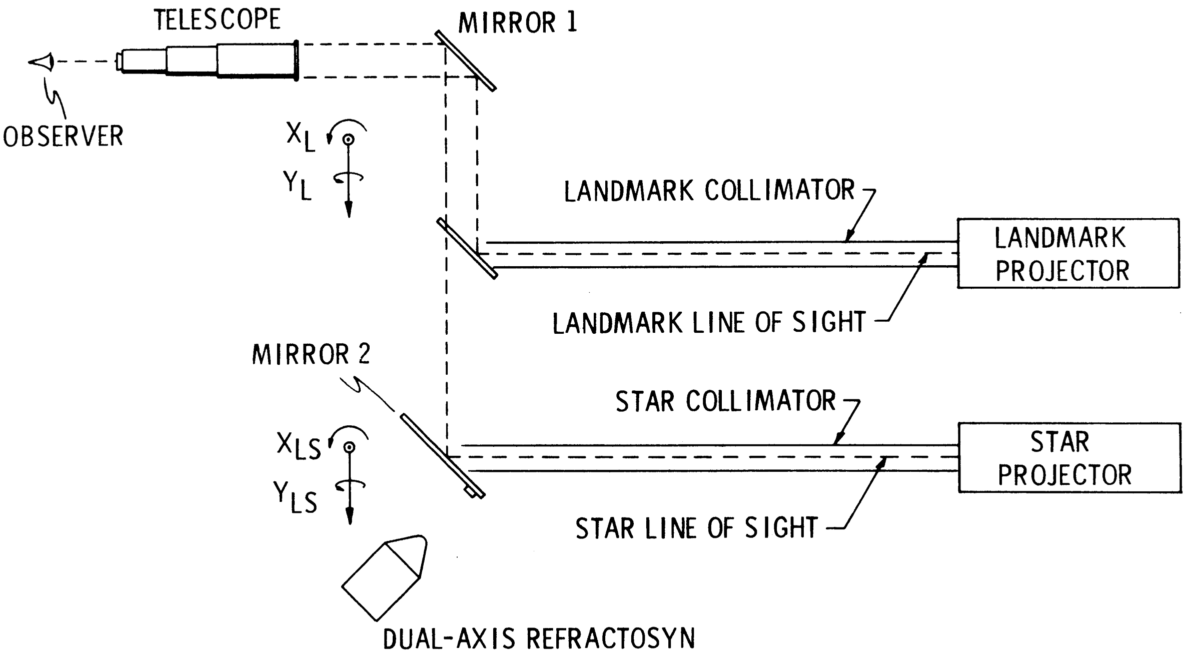


Fig. C23A

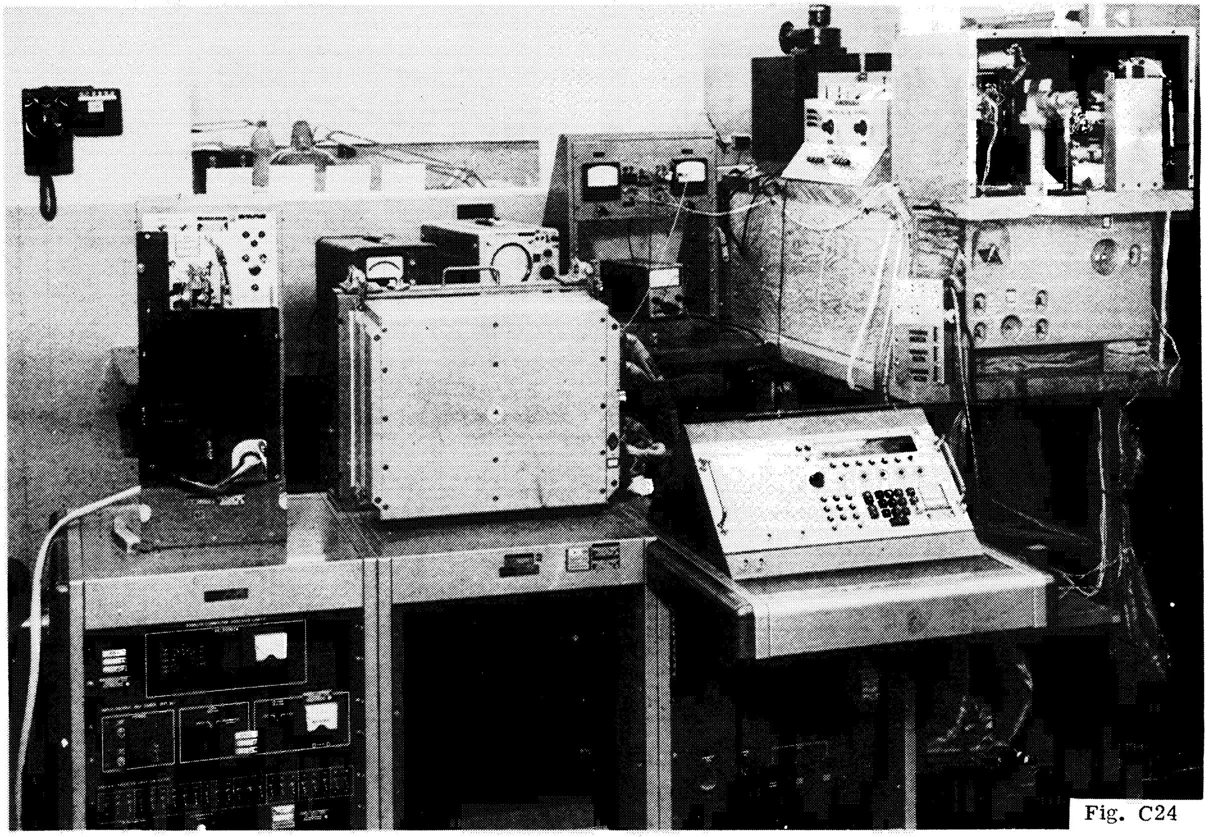


Fig. C24

MAN OPTICS PERFORMANCE MATRIX

	MARK ACCURACY	ERROR ESTIMATION REJECT	TIME TO MARK	OPTICS HAND CONTROLLER
SEXTANT STAR-LINK	3.7 - 5 arc sec, linearly with s/c axial drift 0 - 440 arc sec/sec 99% errors < 13 arc sec	underestimate errors by ≈ 20% reject ≈ 1/2 of errors > 10 sec	15 - 20 seconds	zero dead band, 0.1°/sec maximum displacement most satisfactory; 35 arc sec/sec dead band increases star-link super position error up to 25% 75 arc sec/sec dead band increases error up to 60%
IMU ALIGNMENT	3 - 5 arc sec, 0 - 400 arc sec/sec s/c drift; error relatively insensitive to drift > 100 arc sec/sec		15 - 20 seconds	
LEM RENDEZVOUS	3.5 - 7 arc sec as flash period increases from 0.5 - 3 seconds		time to mark (in minutes) ≈ flash period (in secs)	
SCANNING TELESCOPE MOL	human responds to angular displacement 4.4 arc minutes		reduces s/c drift to 1/2 arc min/sec within 20 secs	performance best when controller acceleration twice maximum input acceleration
AOT - ORBITAL IMU ALIGNMENT	mark star crossing time, 1 axis only < 6 arc min for s/c rates < 3°/sec 9 arc min error for 4°/sec drift			

Fig. C25

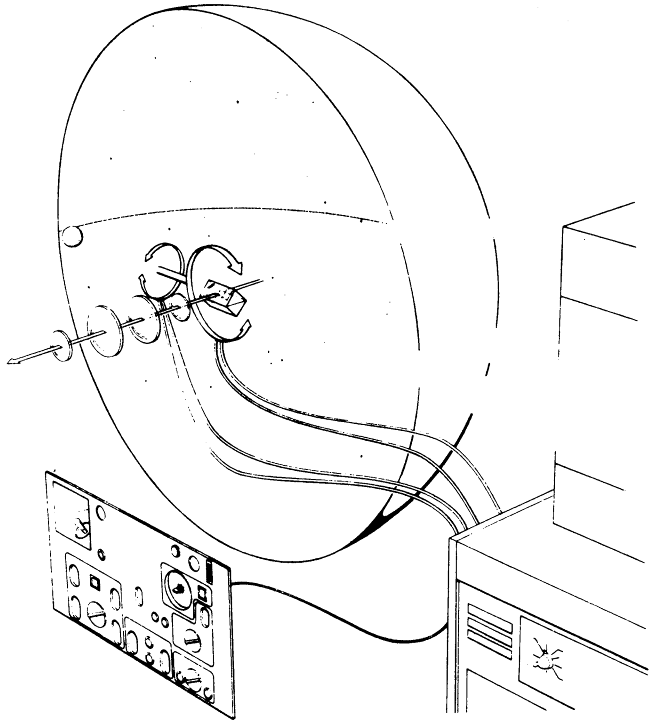


Fig. C26

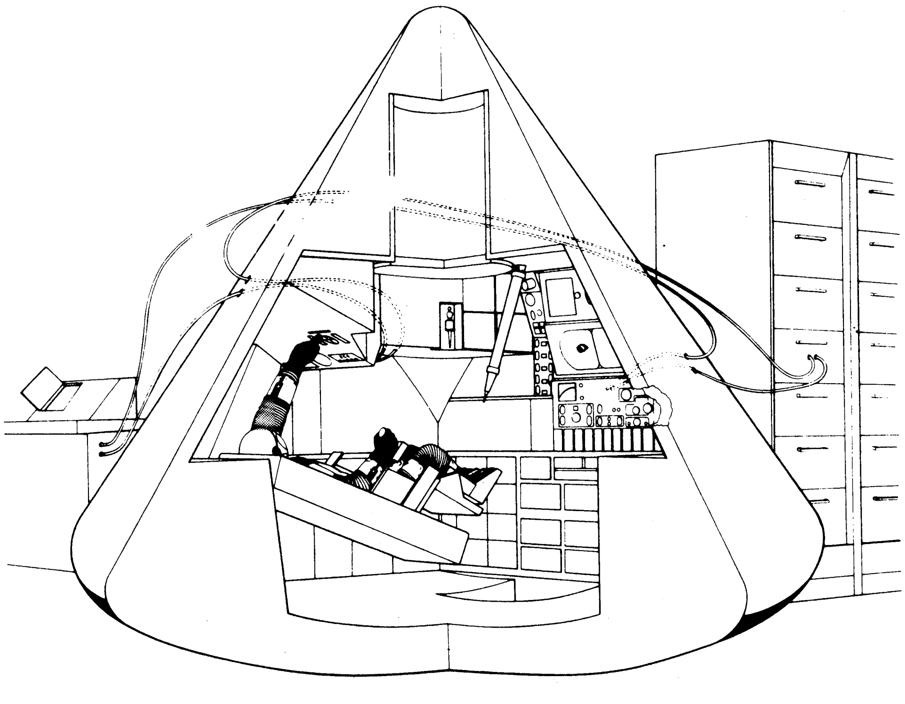


Fig. C27

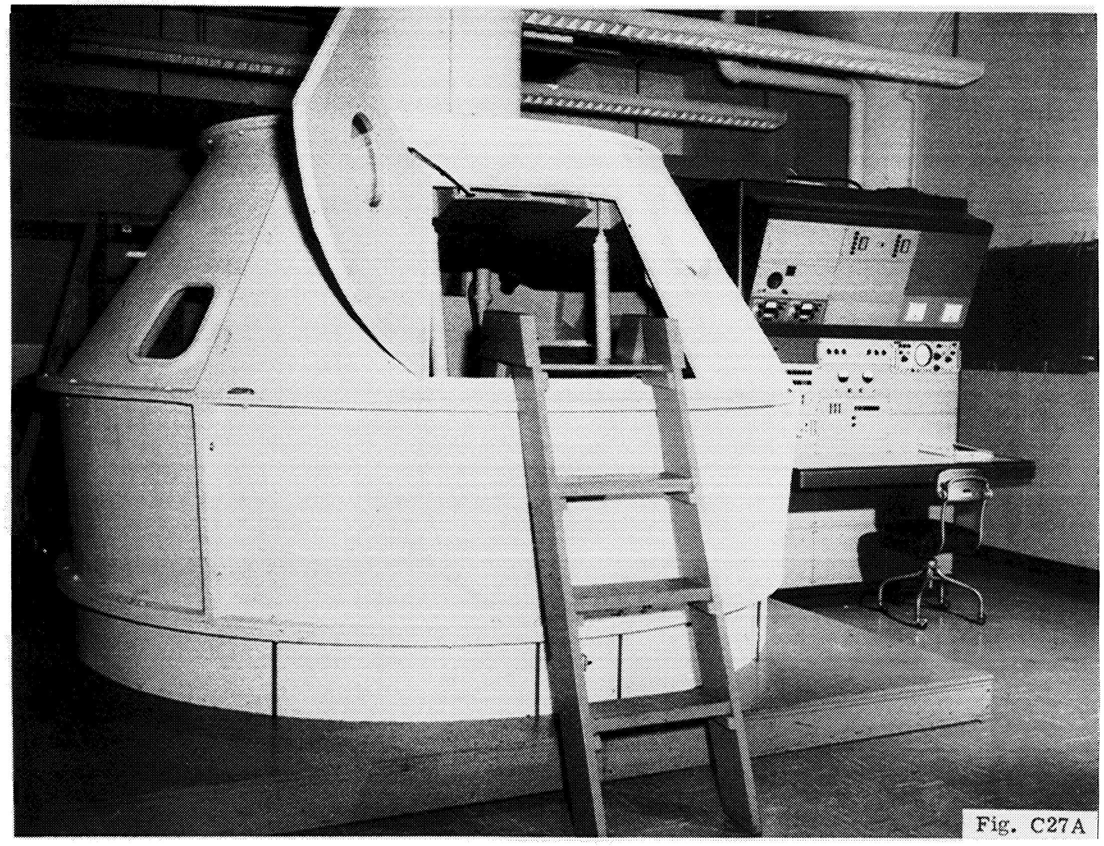


Fig. C27A

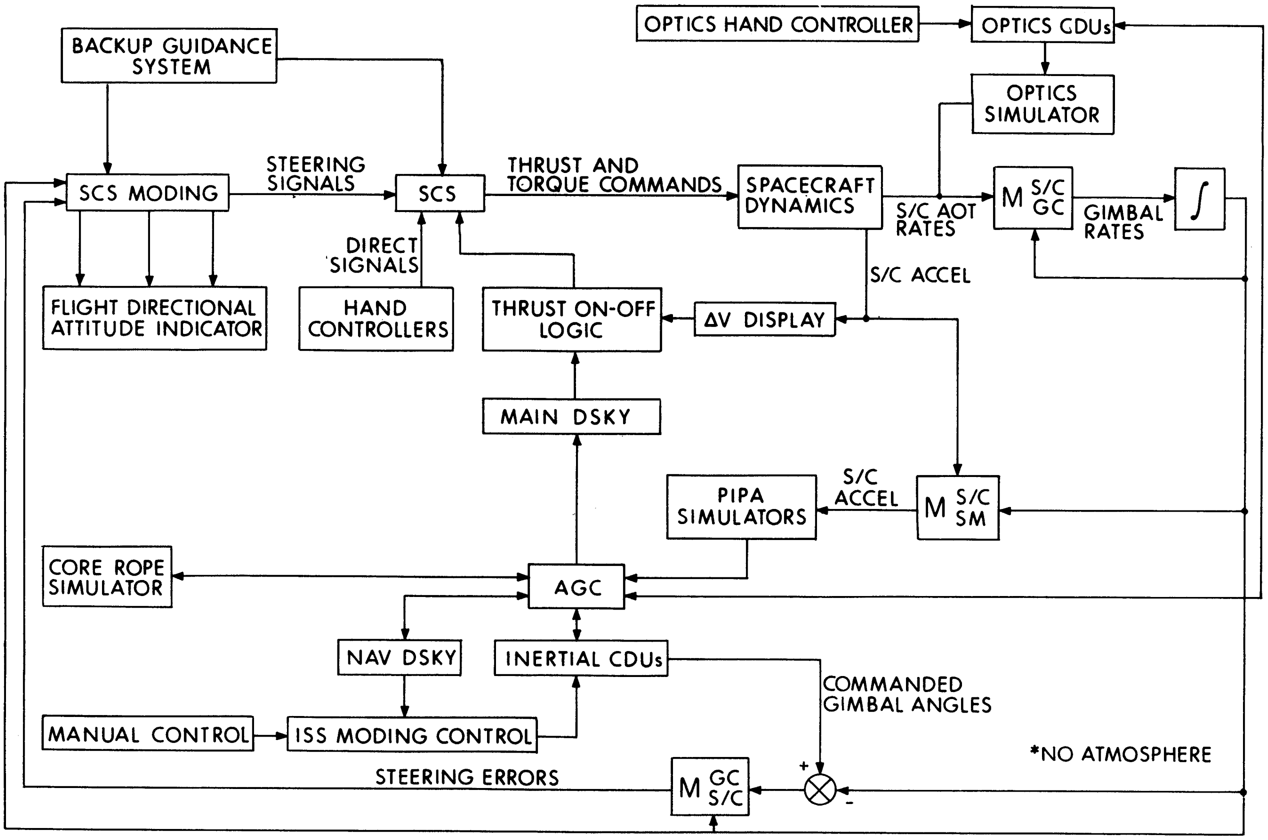


Fig. C27B

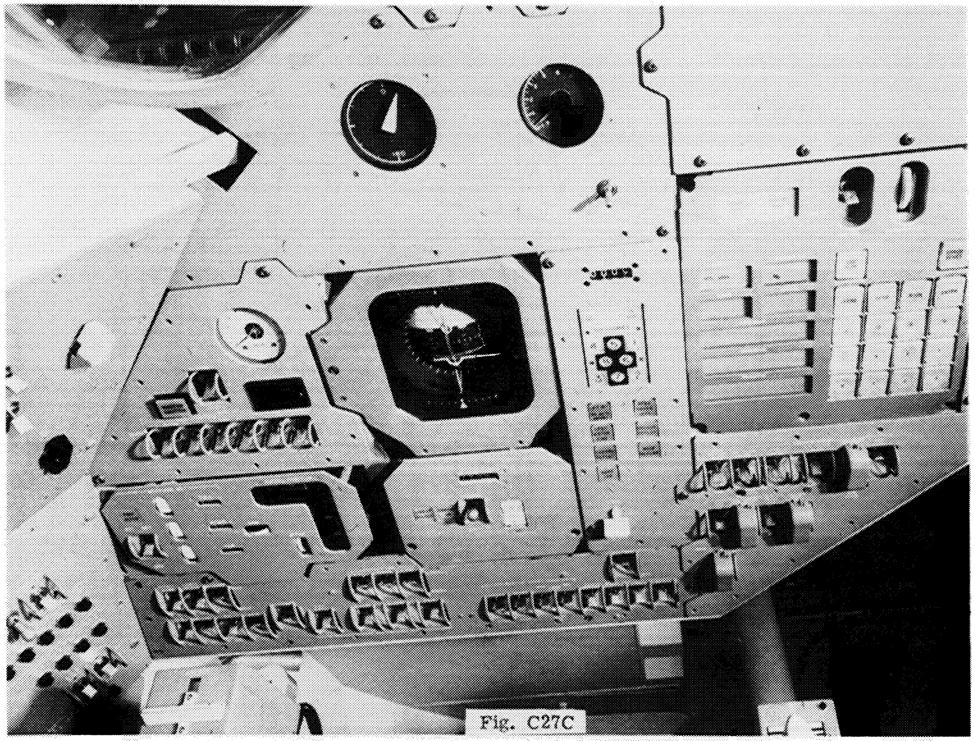


Fig. C27C

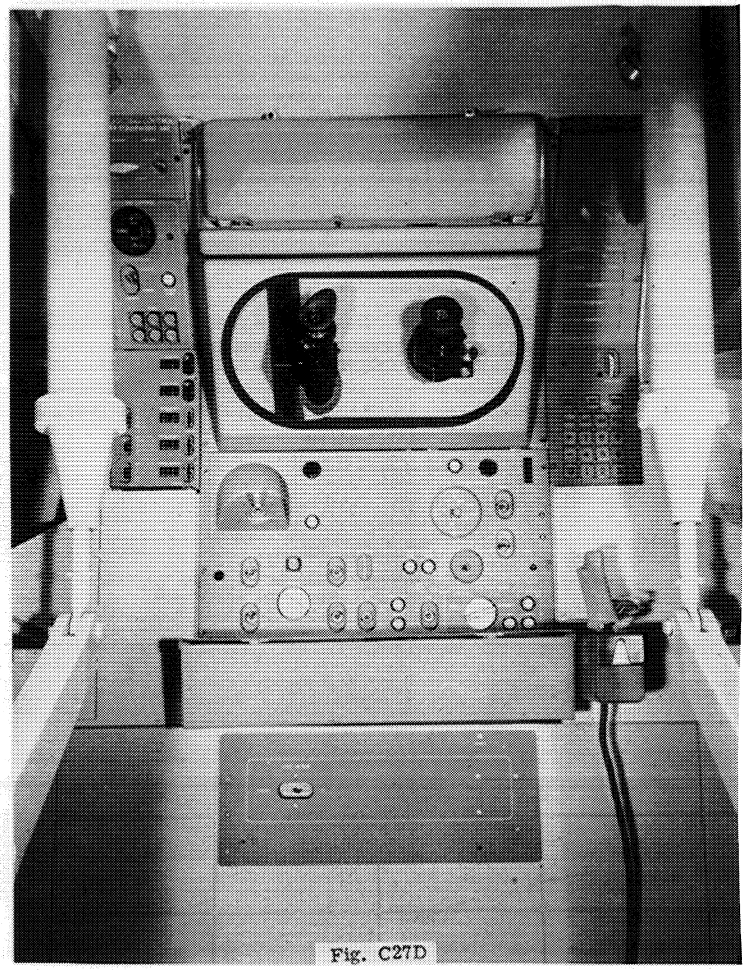


Fig. C27D

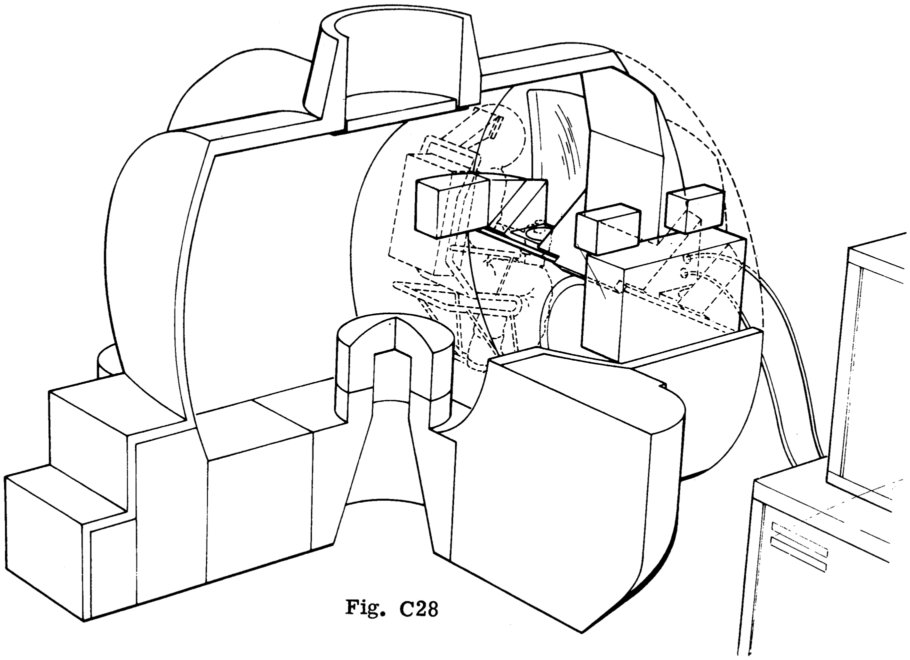


Fig. C28

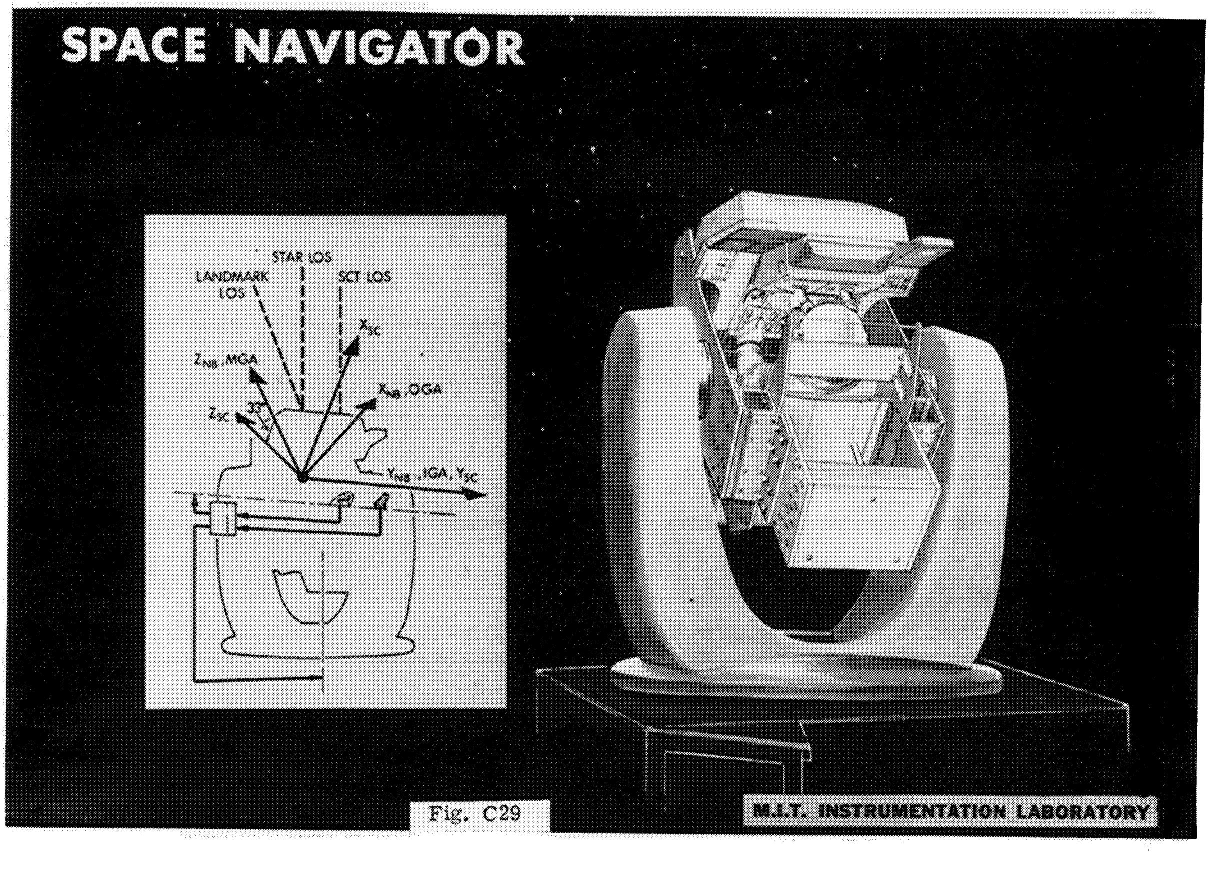


Fig. C29

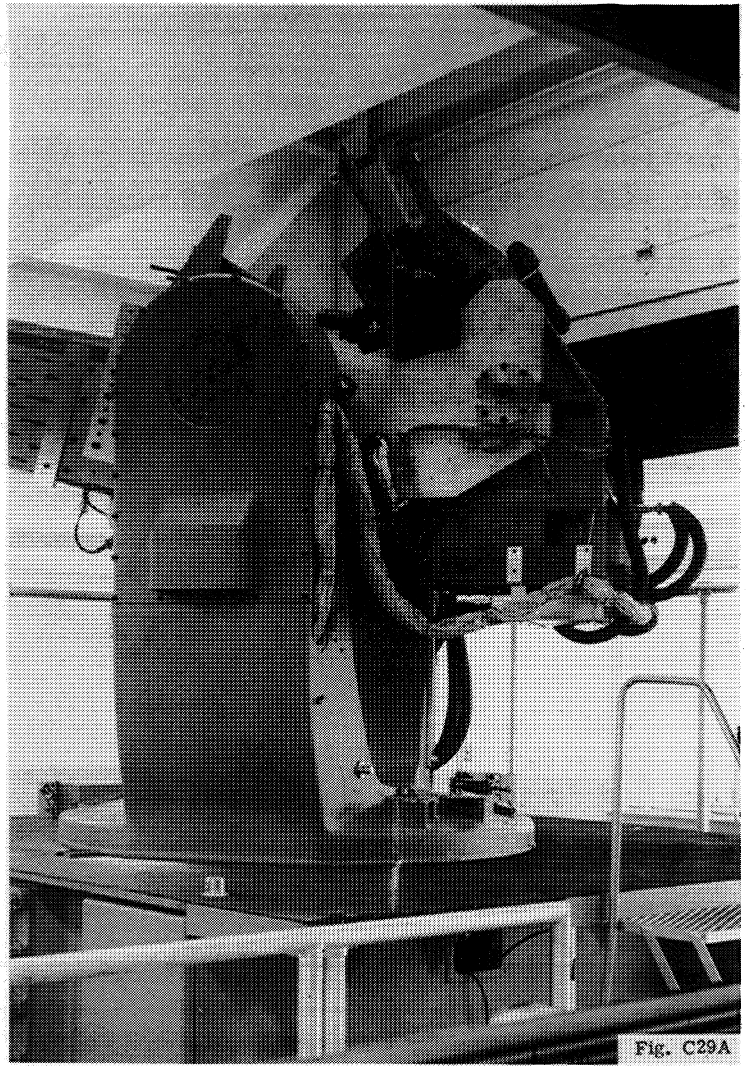


Fig. C29A

OPERATIONS PHASE

A. DETAILED MAN-COMPUTER INTERFACES DEFINED BASED ON FINAL SPACECRAFT CONFIGURATIONS FOR THE GUIDANCE AND NAVIGATION SYSTEM (G&N), THE SERVICE MODULE PROPULSION SYSTEM (SPS), THE VEHICLE STABILIZATION AND CONTROL SYSTEM (SCS), AND THE VEHICLE REACTION CONTROL SYSTEM (RCS).

B. WHOLE TASK EVALUATION IN COCKPIT SIMULATOR WITH ACTUAL COMPUTER FLIGHT PROGRAMS AND SPACECRAFT DYNAMICS.

C. TRAINING SUPPORT OF ACTUAL FLIGHT CREWS.

Fig. C30

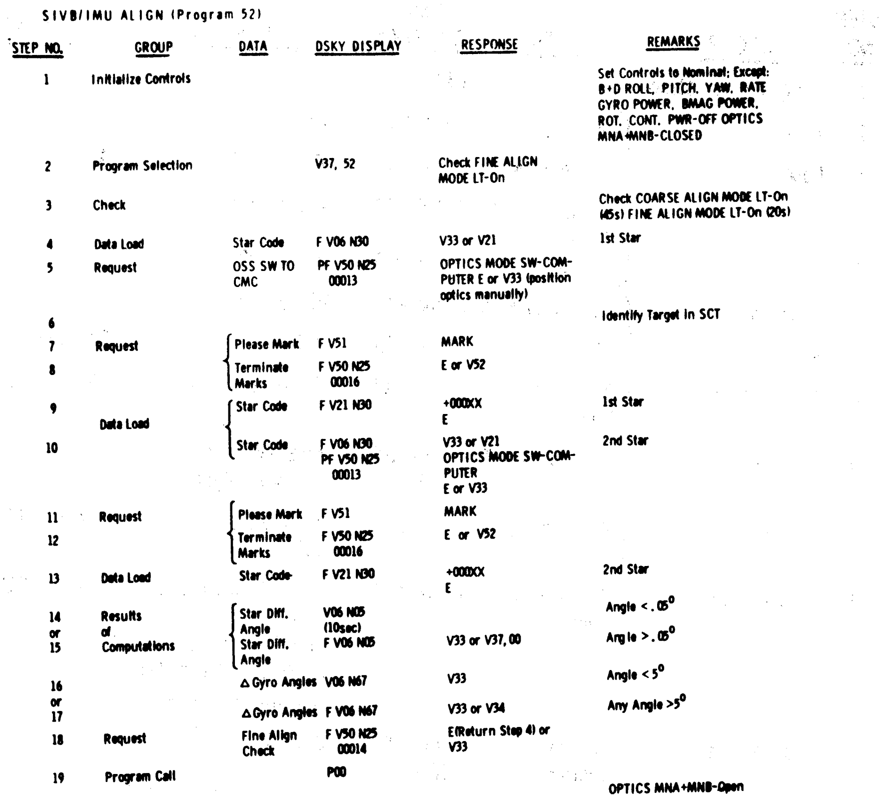
GROUND TRACK DETERMINATION (Program 24)

STEP NO.	GROUP	DATA	DSKY DISPLAY	RESPONSE	REMARKS
			V64		
1	Results of Computation	HA, HP, TFF	F V16 N43	V33	
2		T to Perigee	F V16 N35	V33	
3	Program Call		P00		
or					
			V65		
1	Request	Load-T Permissible	F V21 N34		
2		Load-Longitude	F V22 N44		
3	Results of Computation	T-Long	F V06 N34	V33	
4		Lat, Long, Alt	F V06 N44	V33	
5	Program Call		P00		
or			V66		
1	Request	Load-T	F V21 N34		
2	Results of Computation	Lat, Long, Alt	F V06 N44	V33 or V34	
3	Program Call		P00		
or					
1	Request	Load-T Permissible	F V21 N34		
2	Results of Computation	T Max Dec	F V06 N34		
3		Lat, Long, Alt	F V06 N44		
4	Program Call		P00		

Fig. C31

CREW KEYBOARD CONTROL OF COMPUTER AND MISSION SEQUENCES	OPERATION
(1.) V37E$\overset{XX}{\text{--}}$E	Select program specified by code XX.
(2.) V--N--	Perform function defined by Verb code with and/or upon values defined by Noun code.
a.) V16N$\overset{YY}{\text{--}}$	Monitor continuously updated data display defined by Noun Code, YY.
b.) V2-N--	Enable load data into computer.
(3.) V33E	Proceed to next step in program.
(4.) V32E	Recycle to head of program or subroutine.
(5.) V34E	Terminate sequence.
(6.) ENTER	Complete data load, program selection, or crew option specified by computer display.
(7.) CLEAR	Erase improperly keyed data.
(8.) RESET	Reset the flip-flop circuits that activate the DSKY error lights.
(9.) KEY RELEASE	Permit computer to regain requested control of keyboard.

Fig. C31A



SIVB/IMU ALIGN (Program 52)

STEP NO.	GROUP	DATA	DSKY DISPLAY	RESPONSE	REMARKS
1	Initialize Controls				Set Controls to Nominal; Except: B+D ROLL, PITCH, YAW, RATE GYRO POWER, BMAG POWER, ROT. CONT. PWR-OFF OPTICS MNA+MNB-CLOSED
2	Program Selection		V37, 52	Check FINE ALIGN MODE LT-On	
3	Check				Check COARSE ALIGN MODE LT-On (45s) FINE ALIGN MODE LT-On (20s)
4	Data Load	Star Code	F V06 N30	V33 or V21	1st Star
5	Request	OSS SW TO CMC	PF V50 N25 00013	OPTICS MODE SW-COMPUTER E or V33 (position optics manually)	
6					Identify Target in SCT
7	Request	Please Mark	F V51	MARK	
8		Terminate Marks	F V50 N25 00016	E or V52	
9	Data Load	Star Code	F V21 N30	+000XX E	1st Star
10		Star Code	F V06 N30 PF V50 N25 00013	V33 or V21 OPTICS MODE SW-COMPUTER E or V33	2nd Star
11	Request	Please Mark	F V51	MARK	
12		Terminate Marks	F V50 N25 00016	E or V52	
13	Data Load	Star Code	F V21 N30	+000XX E	2nd Star
14 or	Results of Computations	Star Diff. Angle	V06 N05 (10sec)		Angle $< .05^0$
15		Star Diff. Angle	F V06 N05	V33 or V37, 00	Angle $> .05^0$
16 or		Δ Gyro Angles	V06 N67	V33	Angle $< 5^0$
17		Δ Gyro Angles	F V06 N67	V33 or V34	Any Angle $> 5^0$
18	Request	Fine Align Check	F V50 N25 00014	E(Return Step 4) or V33	
19	Program Call		P00		
20					OPTICS MNA+MNB-Open

Fig. C32

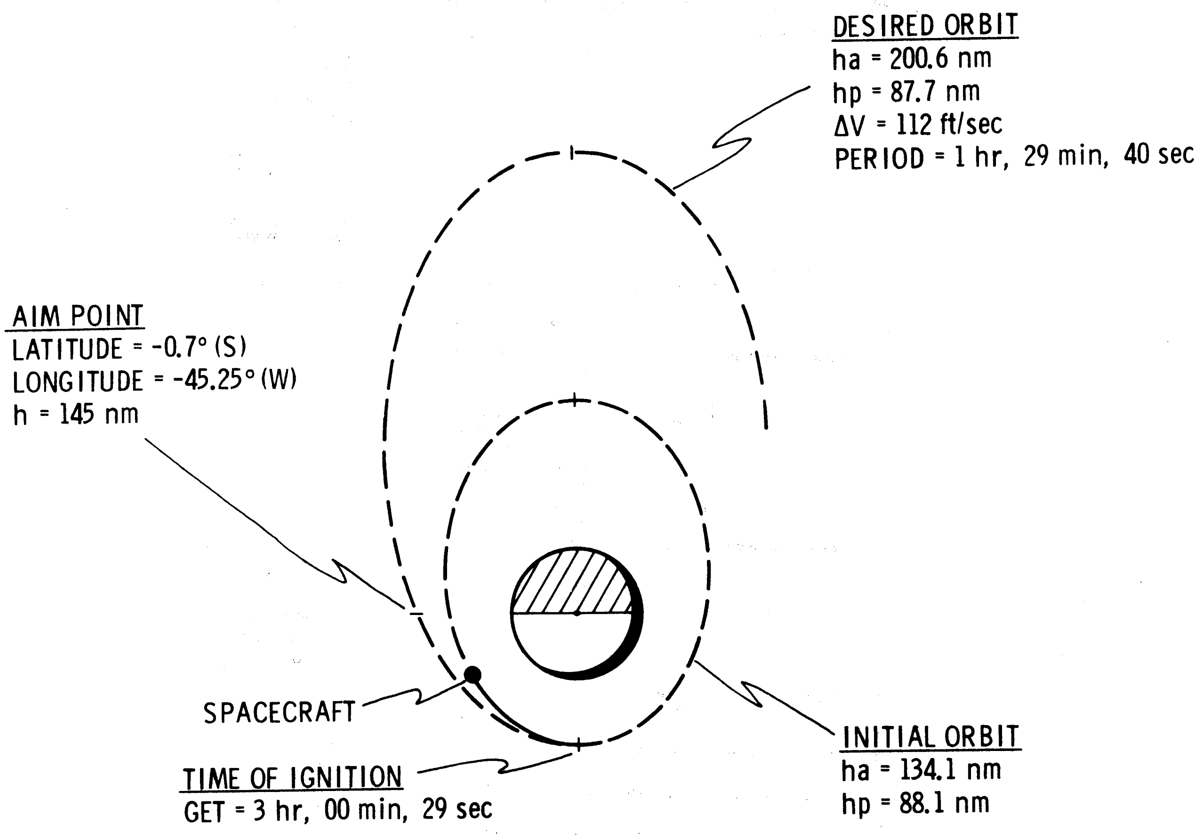


Fig. C33

PRE-THRUSTING ORBIT CHANGE (Program 31)

STEP NO.	GROUP	DATA	DSKY DISPLAY	RESPONSE	REMARKS
1	Program Selection		V37, 31		
2	Data	GET I	F V06 N33	V33 or V25	
3	Load	Lat, Long, Alt	F V06 N44	V33 or V25	Aim Point Data.
4		Period P Trim, Y Trim	F V06 N34	V33 or V25	
5		ΔT Tailoff	F V06 N70	V33 or V25	
6	Results	H_A, H_P ΔV Req.	F V06 N45	V33 or V37, 00	
7	of	TTI	F V16 N35	V33	Set Clocks.
8	Computation	Roll, Pitch, Yaw	F V06 N17	V33 or V37, 53	IMU Agles at Thrust
9	Request	SCS-G&N ATT.	F V50 N25 00001	AME SW-ATT. E or V33 (Bypass)	
10	Results	Roll, Pitch, Yaw	F V16 N20	Align AGCU V33	Present ICDU Angles.
11	of Computation	Roll, Pitch, Yaw	F V06 N17	Set ATT SET dials. V33 or V70 (Manual Manu) or THC-CW and V33 (Manual Maneuver)	Final ICDU Angles.
12	Program Call	Program Request	F V50 N07 00041	V37, 41	

Fig. C33A

THRUSTING ORBIT CHANGE (Program 41)

STEP NO.	GROUP	DATA	DSKY DISPLAY	RESPONSE	REMARKS
1	Initialized Controls				Controls to Nominal. Except: DIRECT RCS-OFF LIMIT CYCLE-ON A/M/E-ATTITUDE Set for 2 Jet Ullage TO USE OPEN QUAD B+D YAW JETS- Y AXIS PITCH MNA YAW MNA QUAD A+C PITCH JETS- Z AXIS PITCH MNB YAW MNB
2	Program Selection		V37, 41		
3		Roll, Pitch, Yaw	F V16 N20	Set ATT SET dials V33	R 180^0, P 327^0, Y 0^0
4	Results of Computation	VG	F V06 N14	TVC 1 Power-AC1 TVC 2 Power-AC2 Set ΔV Counter V33	
5		TTI, VG, ΔVM	V06 N51	Update DET Check sight on boresight star	
6		P Trim, Y Trim	V06, 70 (Optional)	Key Release	
7	Request	G+N ΔV	F V50 N25 00002	Set Controls E	
8	Results of Computation	TTI, VG, VM	V06 N51		
9					Report TTI -2 MIN THRUST SW-MORMAL INJECT PREVALVES A+B-ON PRIM. THC-ARMED.
10					Check ΔVM for PIPA bias.
11					Start Ullage- TTI-20sec (2- Jet)
12	Request	Thrust On Enable	F V50 N11		TTI - 5 sec
13				E	
14	Results of Computation During Burn	TG, VG, ΔVM	V06 N51		Confirm Engine Ignition
15					Monitor Engine Cutoff
16	Results of Computation	TG, VG, ΔVM	F V16 N51	V33	
17					Set Controls after Tailoff
18	Results of Computation	H_A, H_P, TFF	F V16 N43	V33	
19		T to Perigee	F V16 N35	V33	
20	Program Call		F V50 N25 00000	V37, 00	

Fig. C34

MISSION PHASE	PROG NO.	CSM	LM
SERVICE	00	CMC Idling	LGC Idling
	01	Prelaunch Initialization	-----
	02	Gyrocompassing	-----
	03	Optical Verification of Azimuth	-----
	04	-----	Lunar Surface Checkout
	05	GNCS Startup	PGNCS Startup
	06	GNCS Power Down	PGNCS Power Down
	07	System Test	System Test
BOOST	10	-----	Predicted Launch Time (CFP)
	11	EOI Monitor	Predicted Launch Time (TPI)
	12		Powered Ascent
	13		-----
	14	Trans Lunar Injection Monitor	-----
	15	-----	-----
	16	-----	-----
	17	TPI Search	TPI Search
COAST	20	Rendezvous Navigation	Rendezvous Navigation
	21	Ground Track Determination	Ground Track Determination
	22	Orbital Navigation Measurement	RR Lunar Surface Navigation
	23	Cislunar Midcourse Nav. Meas.	-----
	24	-----	-----
	25	Predicted Lunar Landing	Preferred Tracking Attitude
	26	LGC Initialization	-----
	27	CMC Update	LGC Update
PRETHRUSTING	30	External ΔV	External ΔV
	31	General Lambert	-----
	32	Lunar Orbit Insertion (LOI)	Co-Elliptic Sequence Initiation (CSI)
	33	Lunar Orbit Plane Change	Constant Altitude
	34	Transfer Phase Initialization (TPI)	Transfer Phase Initiation (TPI)
	35	Transfer Phase (Midcourse)	Transfer Phase (Midcourse)
	36	-----	-----
	37	Return to Earth	-----
THRUSTING	40	SPS	DPS
	41	RCS	RCS
	42	-----	-----
	43	-----	-----
	44	-----	-----
	45	-----	-----
	46	-----	-----
	47	Thrust Monitor	Thrust Monitor
ALIGNMENT	50	-----	Docked IMU Align
	51	IMU Orientation Determination	IMU Orientation Determination
	52	IMU Realign	IMU Realign
	53	IMU Realign (Backup)	IMU Realign (Backup)
	54	-----	Lunar Surface Align (Post-Land)
	55	-----	Lunar Surface Align (Normal)
	56	-----	Lunar Surface Align (Backup)
	57	-----	Any Time Launch Align
ENTRY/DESCENT	60	-----	Predicted Lunar Landing
	61	Maneuver to CM/SM Sep. Attitude	Descent Orbit Injection (DOI)
	62	CM/SM Sep. & Pre-entry Maneuver	-----
	63	Entry Initialization	Braking Phase
	64	Post 0.05 G	Approach Phase
	65	Up Control	Landing Phase (Auto)
	66	Ballistic	Landing Phase (ROD)
	67	Final Phase	Landing Phase (Manual)
ABORTS	70	Safe Perilune	DPS Abort
	71	-----	APS Abort
	72	-----	CSM-CSI Targeting
	73	-----	CSM-CDH Targeting
	74	LM-TPI Targeting	CSM-TPI Targeting
	75	LM-Midcourse Targeting	CSM-Midcourse Targeting
	76	-----	Trans Earth Injection (Backup)
	77	LM-TPI Search	-----

Fig. C35

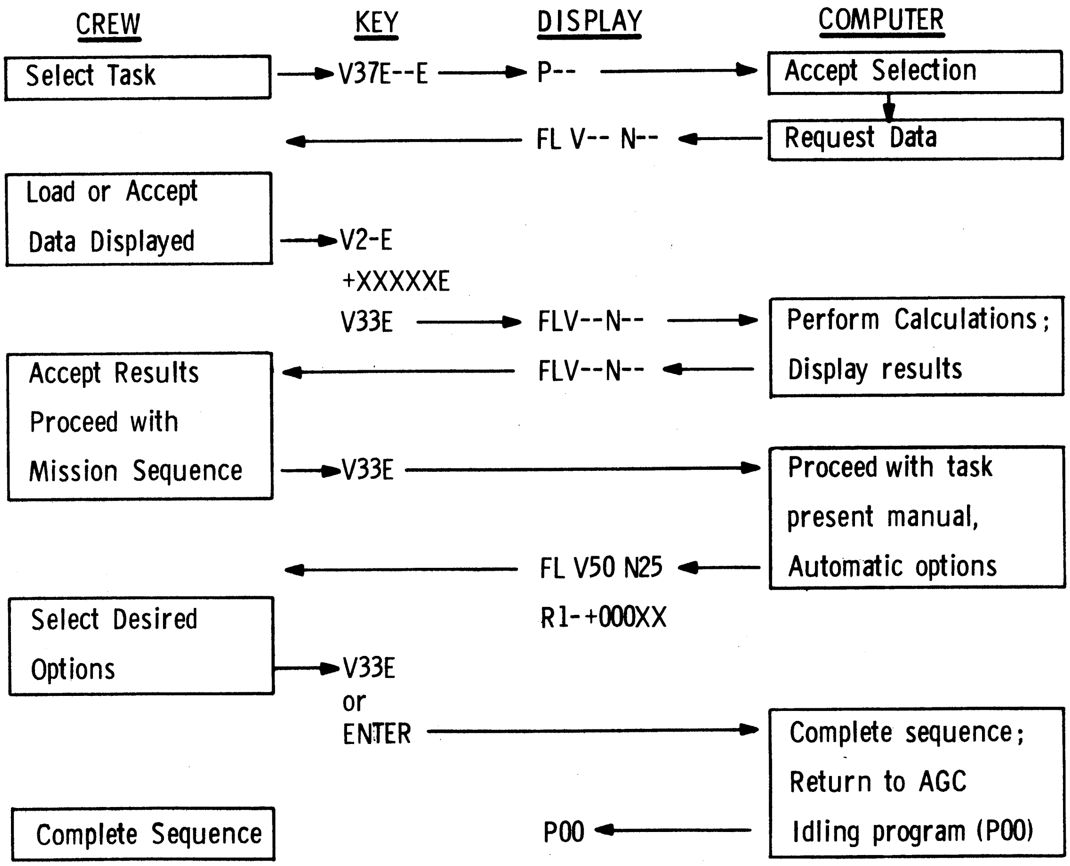


Fig. C36

APOLLO COMPUTER LOGIC CHECKLIST INTERFACE

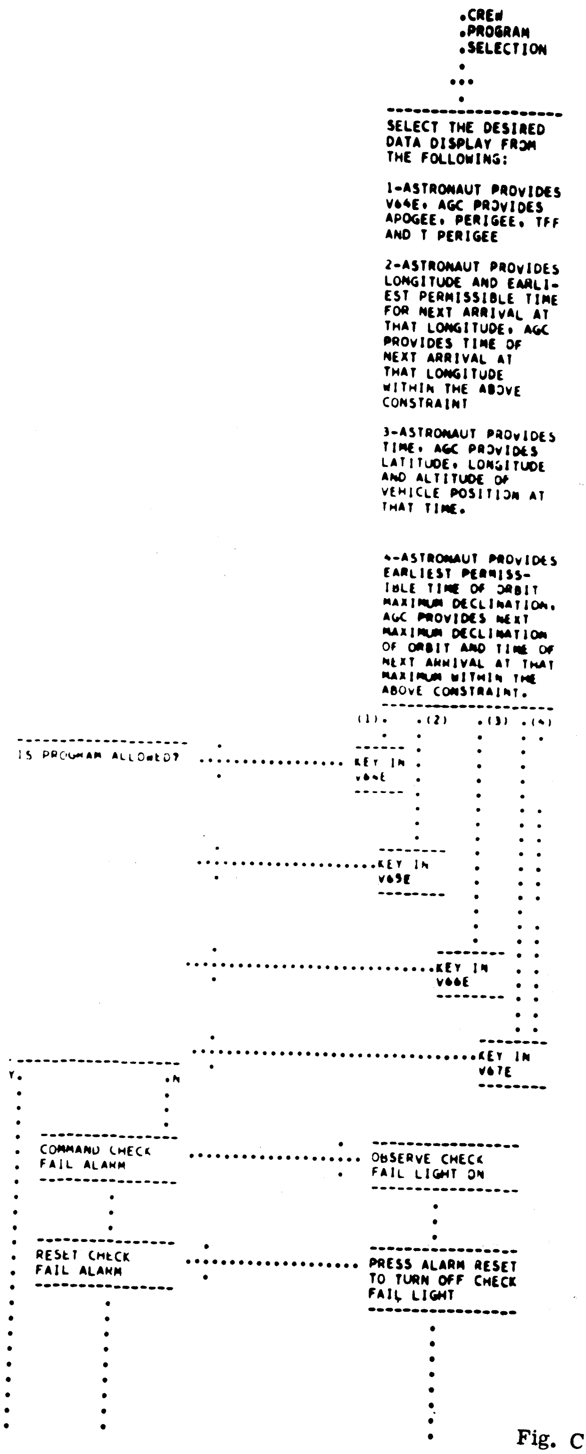
COAST - GROUND TRACK DETERMINATION PROGRAM (P 24) REV 6 9/26/66

PURPOSE: (1) TO PROVIDE THE ASTRONAUT DETAILS OF HIS GROUND TRACK WITHOUT THE NEED FOR GROUND COMMUNICATION.

ASSUMPTIONS: (1) THE PROGRAM IS SELECTED BY THE ASTRONAUT BY DSKY ENTRY.

(2) THIS PROGRAM CAN ONLY BE ENTERED FROM PROGRAM 00

PROG CONT AGC GROUND CREW CHECKLIST TIME TOTAL TIME



010

020

030

040

050

1. SELECT DESIRED DATA DISPLAY:

A. APOGEE, PERIGEE, TFF AND T TO PERIGEE.

OR B. TIME OF ARRIVAL AT A SPECIFIED LONG

OR C. LAT-LONG AND ALTITUDE OF SC AT A SPECIFIED TIME

060

OR D. MAX DEC OF ORBIT AND TIME OF NEXT MAX DEC OF ORBIT

070

NOTE: 080

POSSIBLE CHECK FAIL. IF PRESENT PROGRAM DOES NOT ALLOW SELECTION OF P24 (ENTRY OF V65, V66 OR V67) THE CHECK FAIL LIGHT WILL ILLUMINATE AND THE OLD PROGRAM DISPLAY WILL REMAIN

OBSERVE: 090

CHECK FAIL LIGHT (LEB)
PGNS LIGHT (LEB)
COMP FAIL LIGHT (MDC)

Fig. C37

```
    .          .                                   .
    .          .                                   .                                                              P24/CSM 1
    .          .                                   .
    .          .                                   .
    .  ---------------                             .
    .  HOLD FOR NEW                                .                        SELECT A PROGRAM WHICH IS ALLOWED
    .  PROGRAM SELECTION                           .
    .  ---------------                             .                  *    A.  TO DETERMINE APOGEE, PERIGEE,
    .          .                                   .                           TFF AND TIME TO PERIGEE                #100
    .          .                                   .
    .          .                                   .                  *      (1)  KEY IN V64E
    .  ---------------    .                   ----------------
    .  GO TO PROGRAM      .....................KEY IN PROGRAM         *      (2)  PERFORM ORBIT PARAMETER
    .  SELECTED           .                   SELECTION AS                           DISPLAY ROUTINE (R34)
    .  ---------------                        DESIRED
    .          .                                V37E --E              *      (3)  CHECK AGC DISPLAYS PROGRAM 00
    .          .                              ----------------
    .         ...                                  .
    .          .                                   .                                                                  #110
    .      EXIT P--                               ...                 *    B.  TO DETERMINE TIME OF ARRIVAL AT
    .                                              .                           A SPECIFIED LONGITUDE
    .                                          EXIT P--
    .                                                                 *      (1)  KEY IN V65E
    .
------------------                            -------------------     *      (2)  CHECK AGC DISPLAYS PROGRAM 24
START GROUND TRACK                       .    MONITOR DSKY:                        AFTER STATE VECTOR IS UPDATED
DETERMINATION         ....................... OBSERVE DISPLAY OF
PROGRAM (P24)                            .    PROGRAM 24
DELAY AND UPDATE                              -------------------                                                     #120
STATE VECTOR TO
PRESENT TIME

DISPLAY PROGRAM 24
------------------
V67E.   .V66E  .V65E  .V64E
    .    .      .      .
    .    .      .      .
    .    .      . ------                      -------------------                                                     #130
    .    .      . DO OR-                 .    DO ORBIT PARAMETER
    .    .      . BIT     ................... DISPLAY ROUTINE
    .    .      . PARAME-                .    (R34)
    .    .      . TER                         -------------------
    .    .      . DISPLAY
    .    .      . ROUTINE
    .    .      . (R34)
    .    .      . ------
    .    .      .    .
    .    .      .    .                                                                                                #140
    .    .      .    .
    .    .      . ------                      -------------------
    .    .      . GO TO                  .    MONITOR DSKY:
    .    .      . AGC     ................... OBSERVE DISPLAY OF
    .    .      . IDLING                 .    P00
    .    .      . PROGRAM                     -------------------
    .    .      . (P00)                          .
    .    .      . ------                         .
    .    .      .    .                           .
    .    .      .    .                           .
    .    .      .    .                           .
    .    .      .    .                           .
    .    .      .    .                           .                                                                P24/CSM 1
    .    .      .    .                           .
```

Fig. C37 (Cont)

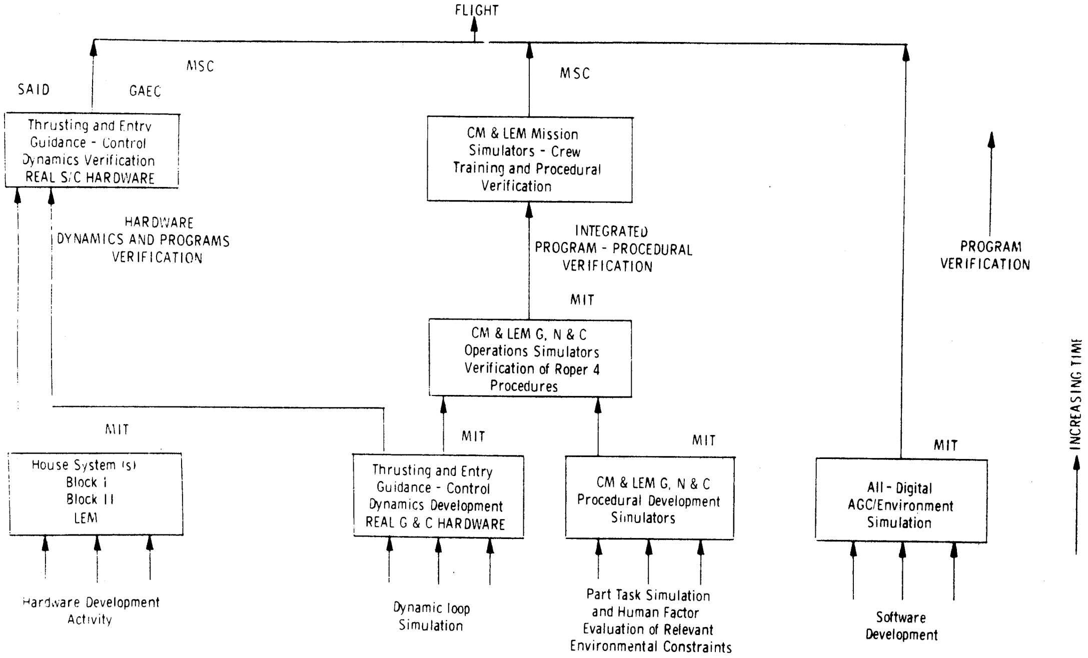


Fig. C38