MASSACHUSETTS INSTITUTE OF TECHNOLOGY

APOLLO

GUIDANCE, NAVIGATION AND CONTROL

E-2081

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

by
J. L. Nevins, E. A. Woodin &
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January 1967

MIT INSTRUMENTATION LABORATORY
CAMBRIDGE 39, MASSACHUSETTS

APOLLO

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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 simulations required, it is first necessary to describe the man-machine 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, man-machine simulations and highlights of their design.

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. Al, 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 andvelocity 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.

Navigation Sensing

Navigation angle data in cislunar space is obtained by a two-line-of-sight instrument called a space sextant. This instrument is fundamentally designed to measure the angle between a selected star and an earth or lunar landmark. This choice results in the greatest accuracy obtainable within reasonable weight, power, and development time constraints. The astronaut senses both the star and the landmarkvisually (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 andnavigation 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 is a two-line-of-sight instrument shown schematically in Fig. A7 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. Figure X8 illustrates the geometry of the navigation fix in space. Measurement of an angle, A, subtended by a star and a landmark locates the spacecraft on a locus which is a cone of semi-vertex angle, A, whose axis is in the direction of the star and whose vertex is centered on the landmark. Measurement of an angle, B, of a star above an illuminated horizon places the spacecraft on a locus which is a cone of semi-vertex angle, B, whose axis is in the direction of the star and which circumscribes the earth or moon. It is seen that three such measurements locate the spacecraft at one or the other of two points. In the **Apollo** navigation system such a "fix" is never actually made. Actually a sequence of angle measurements is made each of which updates the present best estimate of position and velocity in a statistical sense.

In local orbit, 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 is used to

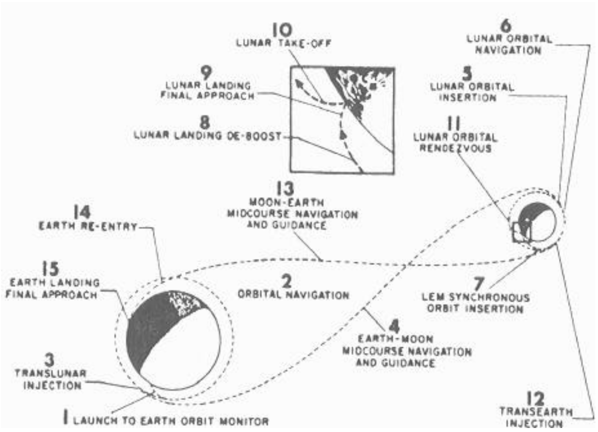


Fig. Al Mission Phase Summary

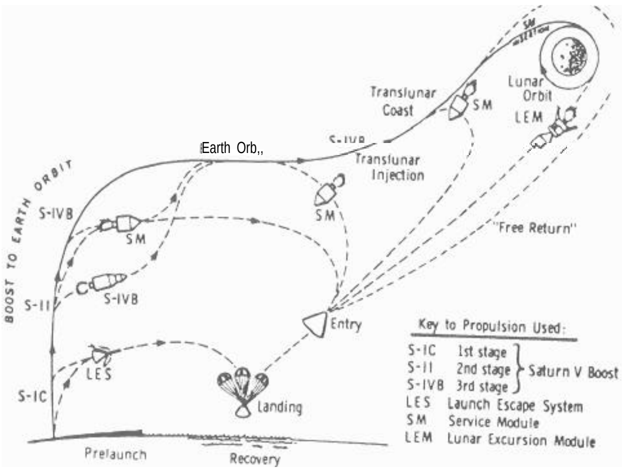


Fig. A2 Propulsion Failure Abort Paths

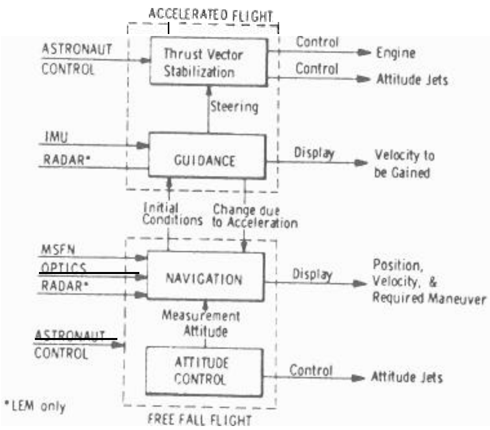


Fig. A3 G&N Function Flow

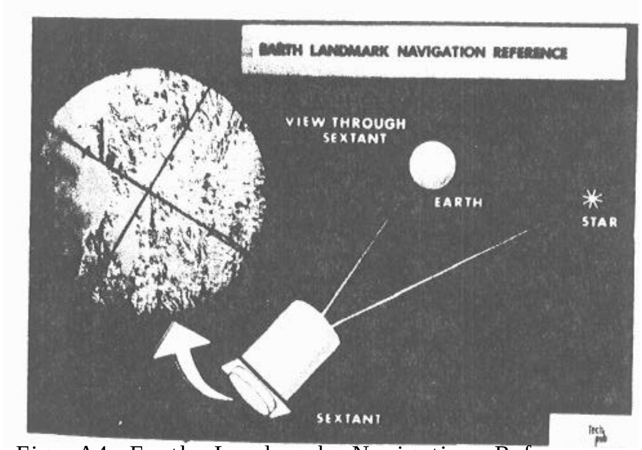


Fig. A4 Earth Landmark Navigation Reference (Sighting)

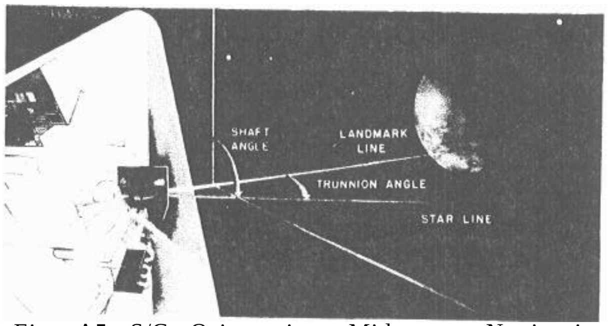


Fig. A5 S/C Orientation, Midcourse Navigation (Sighting)

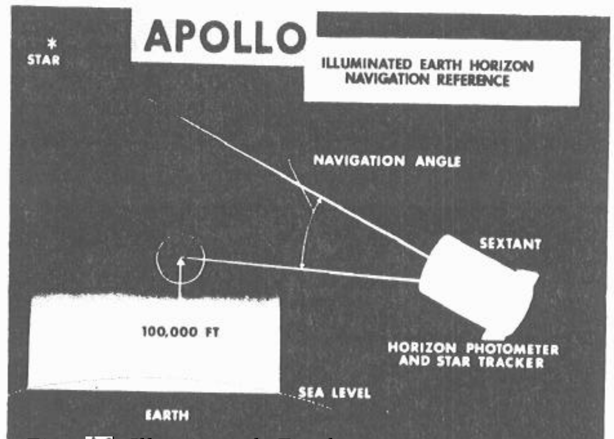


Fig. A6 Illuminated Earth Horizon Navigation Reference

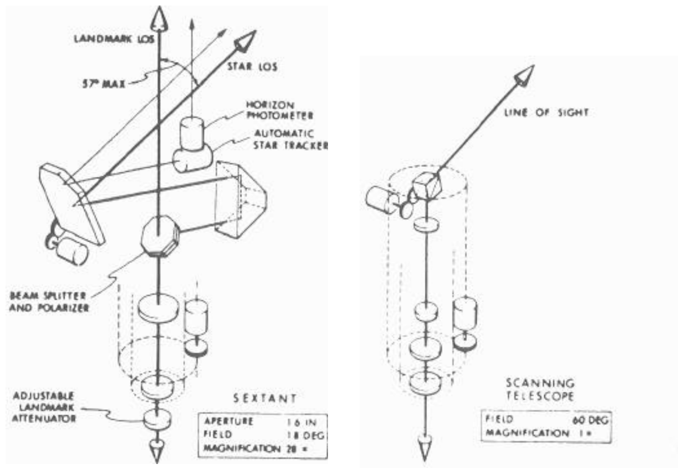


Fig. A7 Optical Schematics

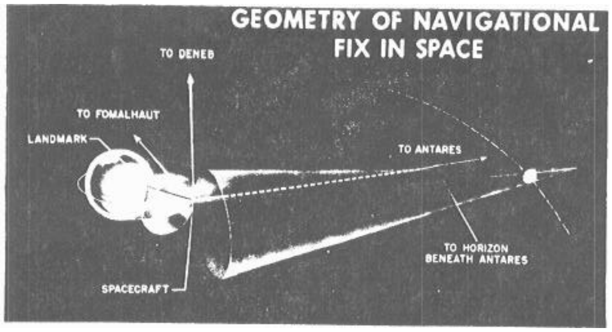


Fig. A3 Geometry of Navigational Fix in Space

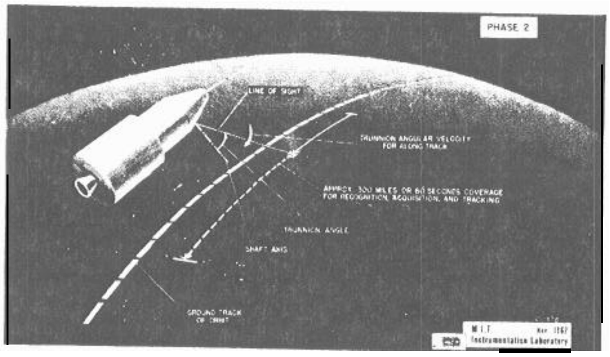


Fig. A9 S/C Orientation - Orbital Navigation
(Sighting)

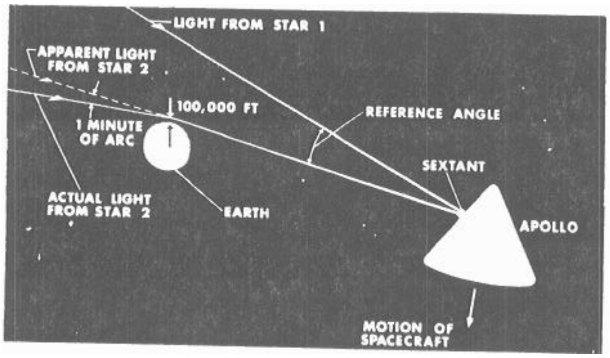


Fig. A10 Star Refraction - Earth Horizon
Navigation (Reference)

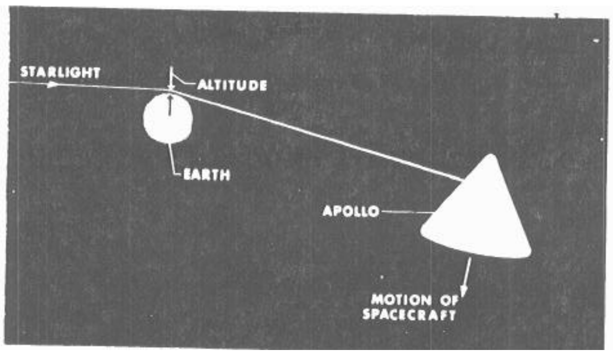


Fig. A11 Star Attenuation - Earth Horizon
Navigation Reference

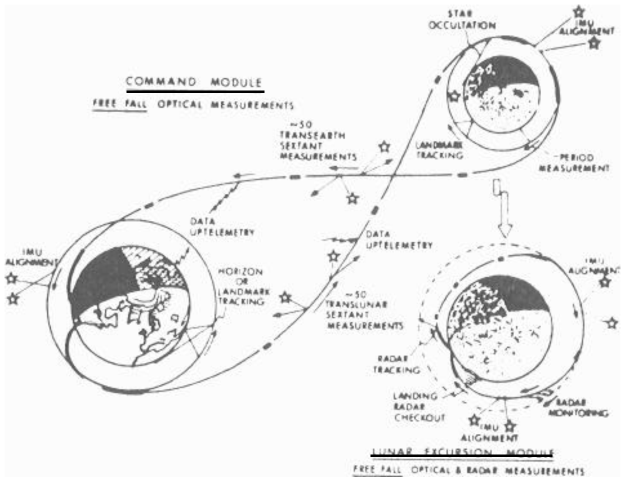


Fig. A12 Navigation Mission Phases

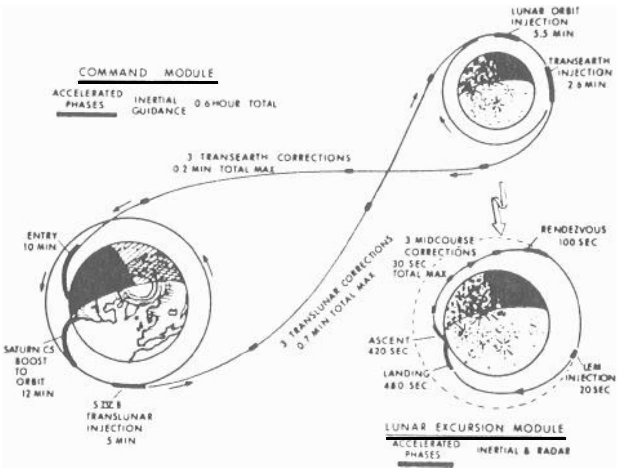


Fig. A13 Guidance Mission Phases

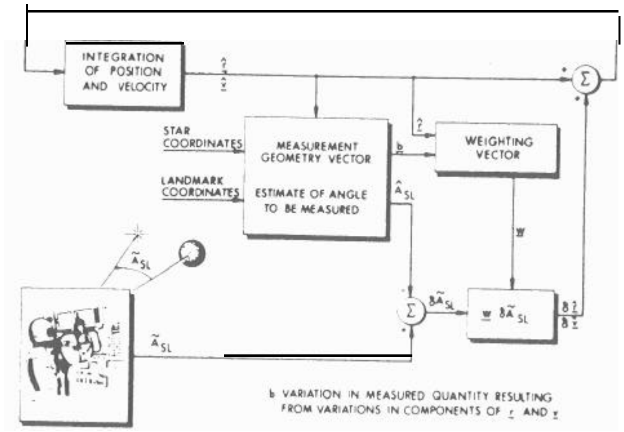


Fig. A 14 Coasting Flight Navigation Computation track landmarks (Fig. A9). The direction of the tracking line with respect to the inertial platform is read into the computer which processes this data to update the local orbit ephemeris. Such a bearing "fix" locates the spacecraft on a line in the direction of the line of sight and terminating at the landmark. The Scanning Telescope is also required as a finder for the Sextant. Inaddition, the SXT may be used in local orbits (earth or moon) to track unknown landmarks. This technique has an obvious application on the back side of the moon or when the earth is covered by clouds.

Also under investigation are the techniques of detecting the occultation and refraction of star light by the atmosphere at the earth's horizon. The amount of attenuation and refraction are related to the atmospheric density at the altitude through which the light passes. Refraction would be detected visually (Fig. A10) whereas attenuation would be detected by the photometric detector used in the automatic star tracking loop (Fig. A11). In all cases, we look into the atmosphere at a high altitude to avoid the anomalies associated with clouds.

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

Figure A12 summarizes the navigation phases in a typical mission, while Fig. A13 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 for the problem, 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. Sowhenever 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. This 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, ASL, is then compared with this estimate to establish the measurement deviation, δA_{SL}. A statistical weighting vector, W, is generated from a priori knowledge of nominal trajectory uncertainties, optical tracking performance, and a geometry vector 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 $\delta \underline{r}$, and velocity $\delta \underline{v}$, from the estimated orbit or trajectory is obtained when the weighting vector is multiplied by the measurement deviation δ ASL. The deviation of position (δr) 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. A14 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 nonfield 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	**LM Installation**
IMU Inertial Measurement Unit	**IMU Inertial Measurement Unit**
AGC Apollo Guidance Computer	**LGC L M Guidance Computer**
PSA Power Servo Assembly	**PSA Power Servo Assembly**
CDU Coupling Data Units	**CDU Coupling Data Units**
SXT Sextant	**AOT Alignment Optical Telescope**
SCT Scanning Telescope	**D&C Display and Control**
D&C Display and Control	**RR Rendezvous**
	LR Landing Radar

Apollo Guidance Computer

The AGC (References 8 and 9) 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 A15 shows the interrelationship of the AGC to thevarious 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.

IMU - Inertial Measurement Unit

The IMU is the primary inertial sensing

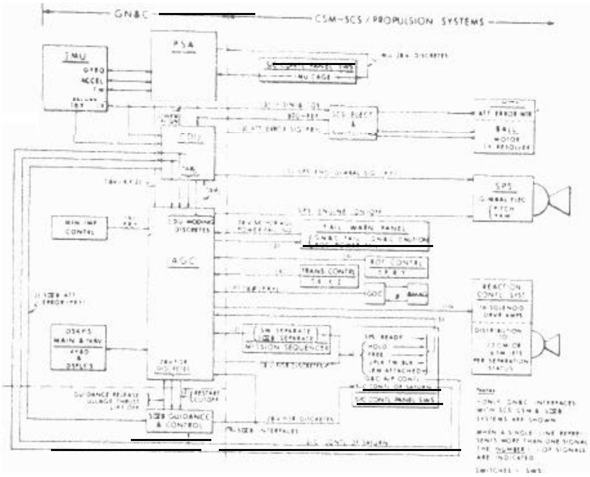


Fig. A15 GN&C Digital A/P Block Diagram

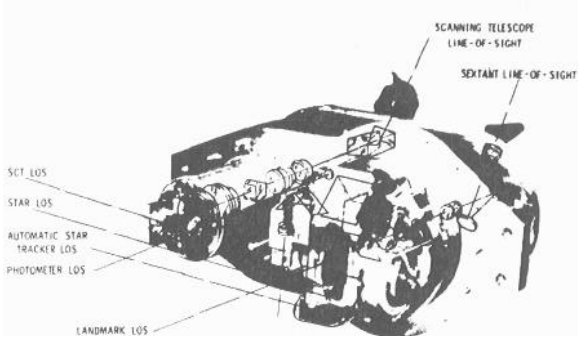


Fig. A18 Apollo Optical Unit (cut away)

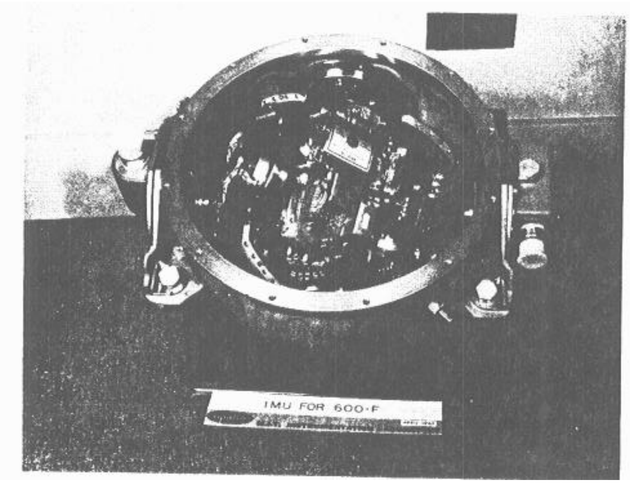


Fig. A16 IMU for 600-F

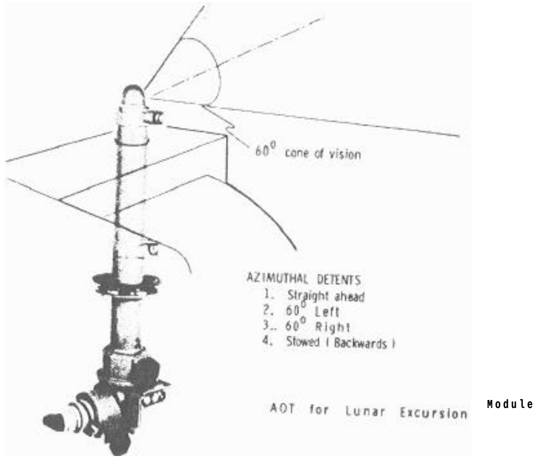


Fig. A19 LEM AOT

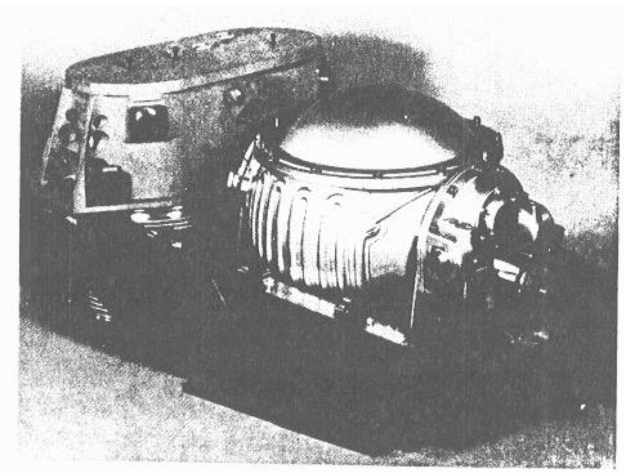


Fig. A17 IMU and Optics Mounted on NavBase

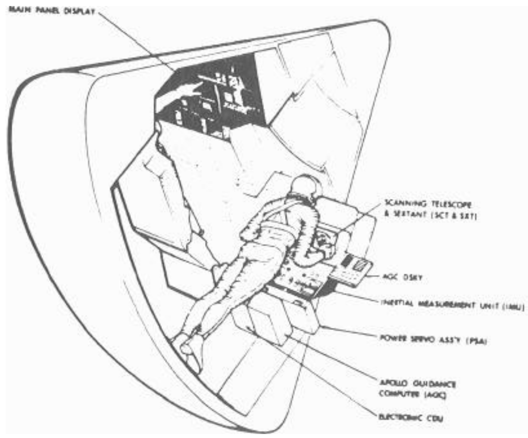


Fig. A20 AGE S/C Location - Block II

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. The information is then transmitted to the spacecraft attitude indicator and to the AGC via the CDUs. Non-field forces acting on thevehicle are sensed by the accelerometers which produce signals representing incremental change in vehicle velocity. These ΔV's are transmitted directly to the AGC.

CDU- Coupling Data Unit

The coupling data units are used to translate 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.

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- 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, 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 during non-use. 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 andvelocity 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 a 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 CM prototype system under test at the Instrumentation Laboratory at MIT.

B. Man-Machine Interfaces

1. Design Philosophy (Ref. 2 and 10)

The usual discussions concerning the man-machine interface can be broken down into two categories; unfortunately, both cases 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 would like to substitute 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 task, the following things 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 accuracyneeded, 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 horizonmeasurement 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 on the the star and that the AGC receives the automatic mark from the horizon photometer.

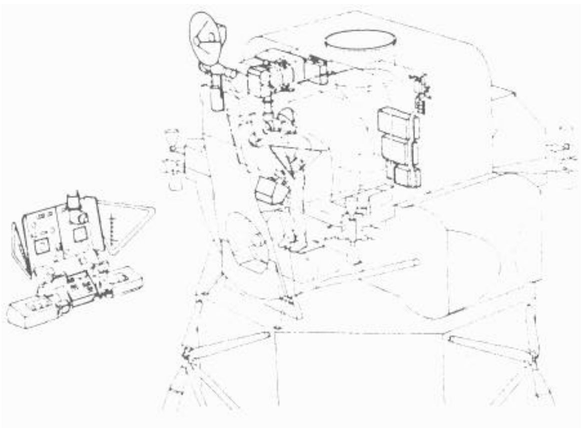


Fig. A21 LEM PGNCS Installation

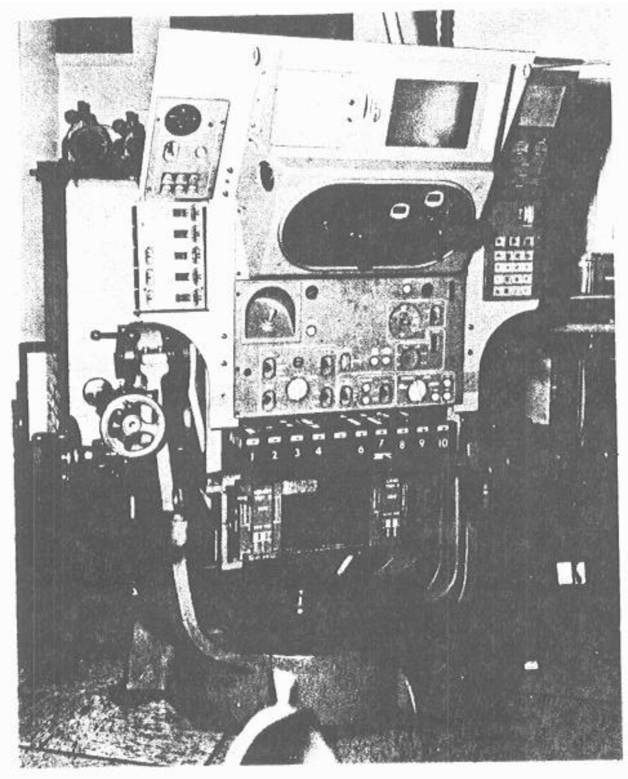


Fig. A22 1st Prototype Block I System - 4/64

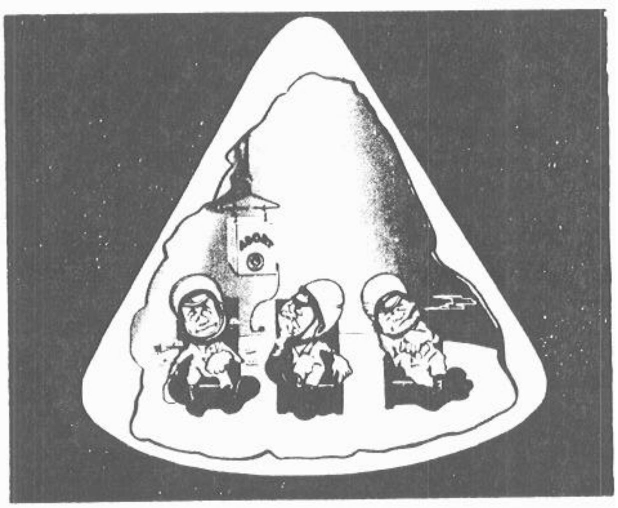
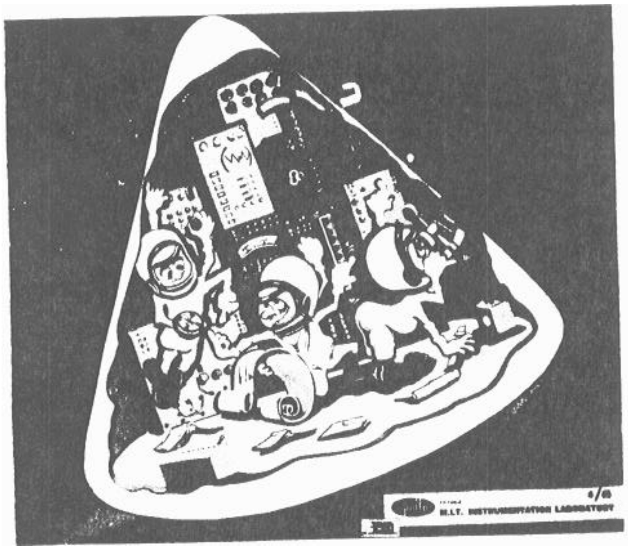


Fig. B 1 “Fully” Automatic System



Fig, B2 “Fully” Manual System

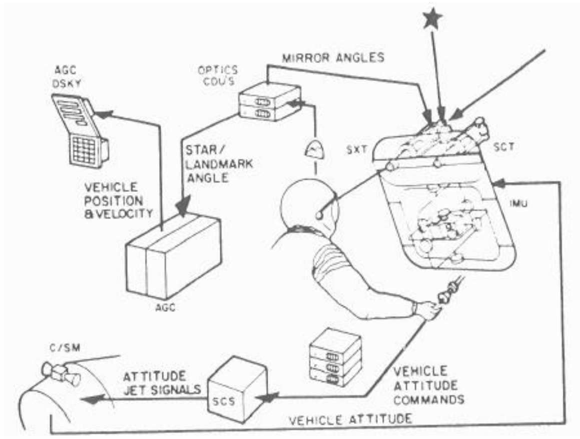


Fig. B3 Midcourse Navigation, Manual Star-Landmark Angle Measurement

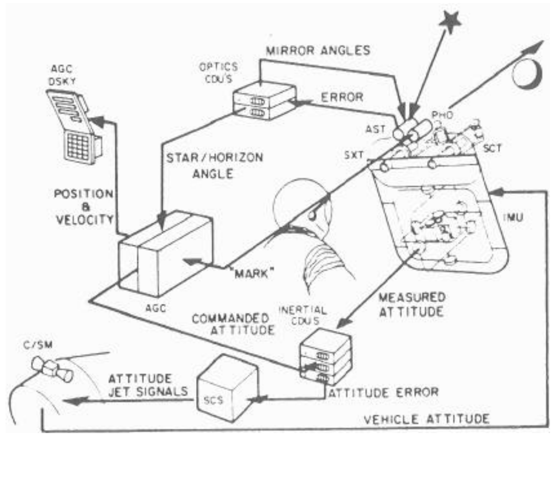


Fig. B4 Midcourse Navigation, Automatic Star-Earth Horizon Measurement

TABLE 1

Design Analysis Phase

A. Definition of man interface

- Definition of role
- Listing of tasks
- Identification of display and control functions
- Definition of critical sub -tasks 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.

Figure Cl

TABLE 2

MAJOR TASKS

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

Fig. C2 G&N Tasks - Major

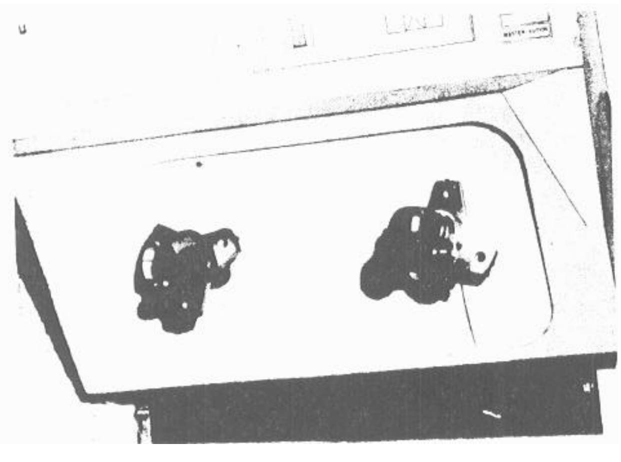


Fig. C3 Eyepieces

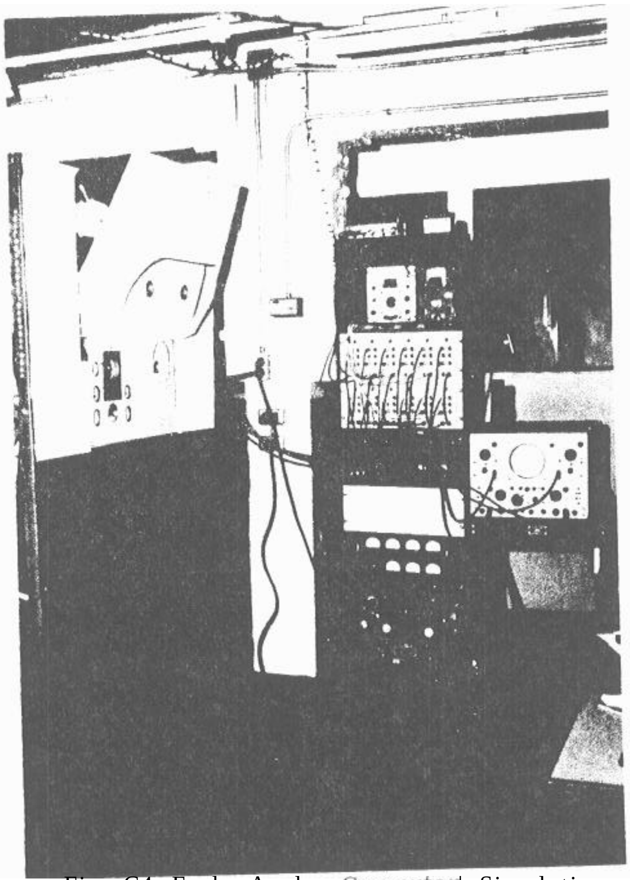


Fig. C4 Early Analog Computer Simulation of CSM Optics

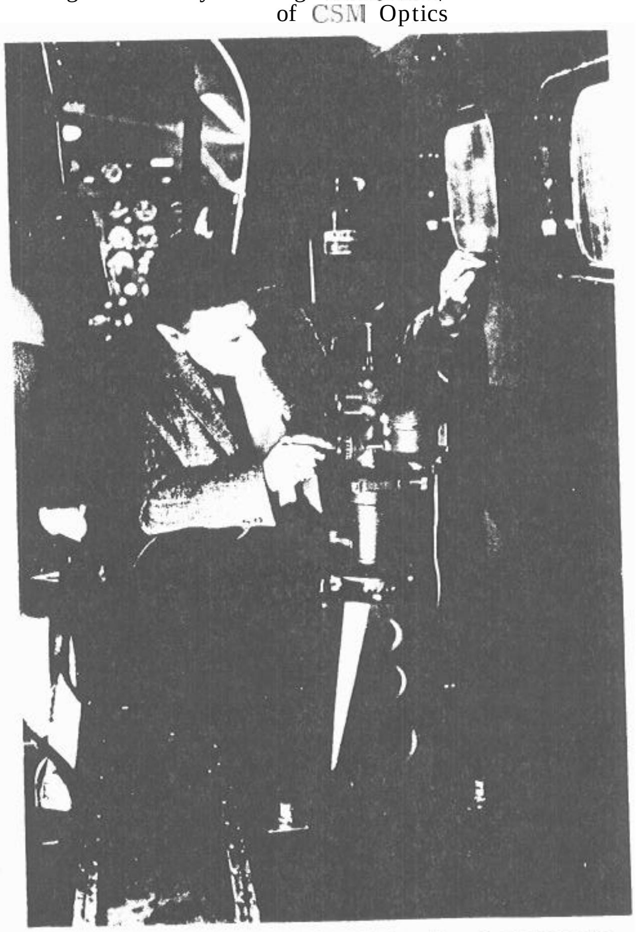


Fig. C5 Drift Sight Simulator for Landmark Tracking with SCT

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 excuting the judgement necessary to perform a successful mission in the presence of unexpected and unplanned for difficulties.

In summary then, manually aided systems make maximumuse of the unique but distinctive 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:

a. Design Analysis

b. Design Development

c. 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	Pressure Suit	Spacecraft
Height	Eye relief	Area
Visual	Dexterity	Volume
Reliability	Arm reach	Weight
Training	Volume	Power
Tethering for zero-g		

C. Man-Machine Design Evolution

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

During this initial period, man's role was defined, his specific tasks were identified (Table 2 lists his major ones, fig. C2), and thevarious 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. Figures C3 and C4 show 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 minumum 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 C5 shows a standard B-6 drift sight

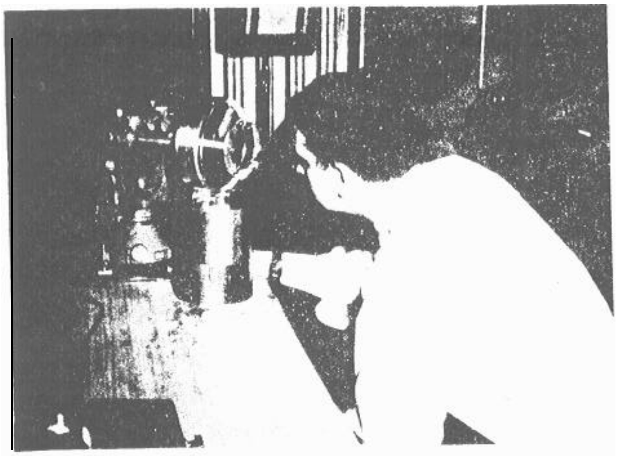


Fig. C6 Spherical Mirror LER Optics

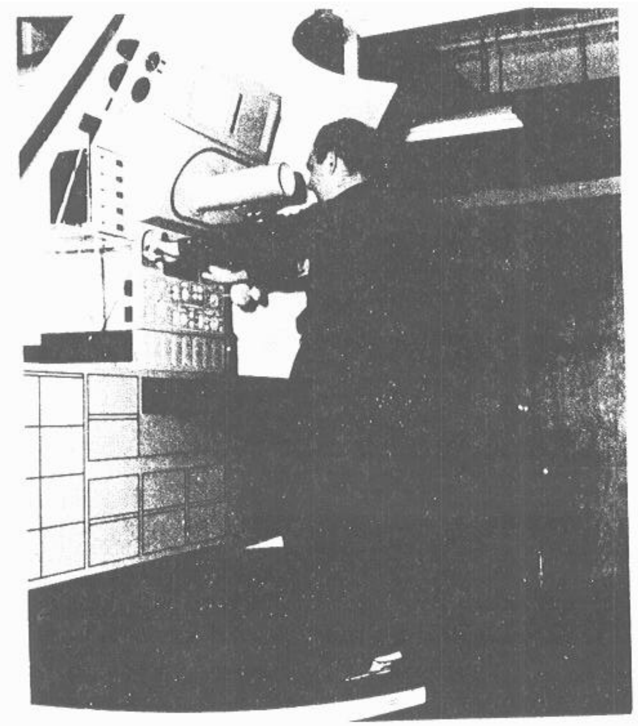


Fig. C7 Early mockup - Full FOX', Full Magnification LER Optics

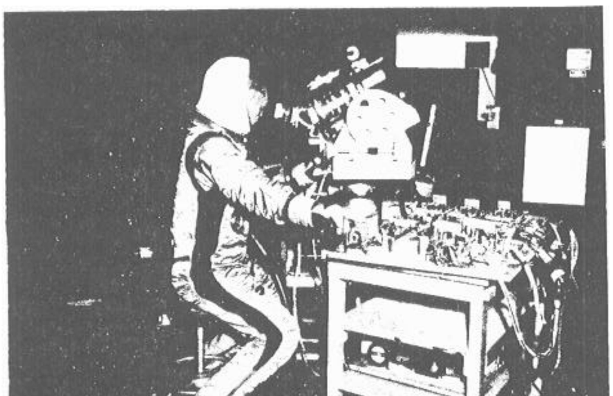


Fig. C8 Astronaut (Schweickart) evaluating LER Optics with "bubble" helment

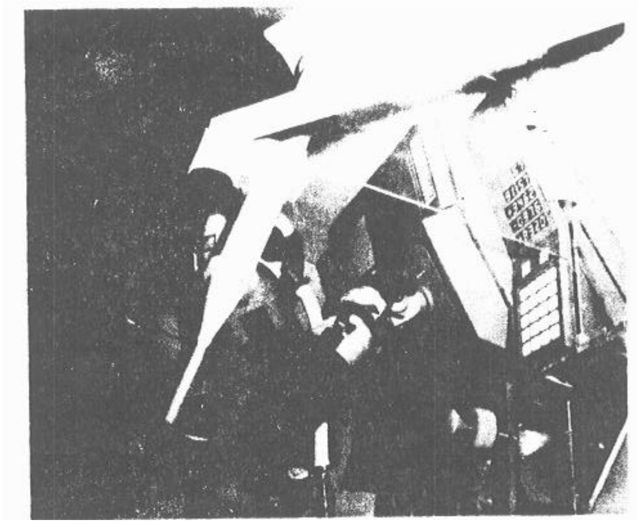


Fig. C9 Pressure Suit Evaluating - D&C Mockup

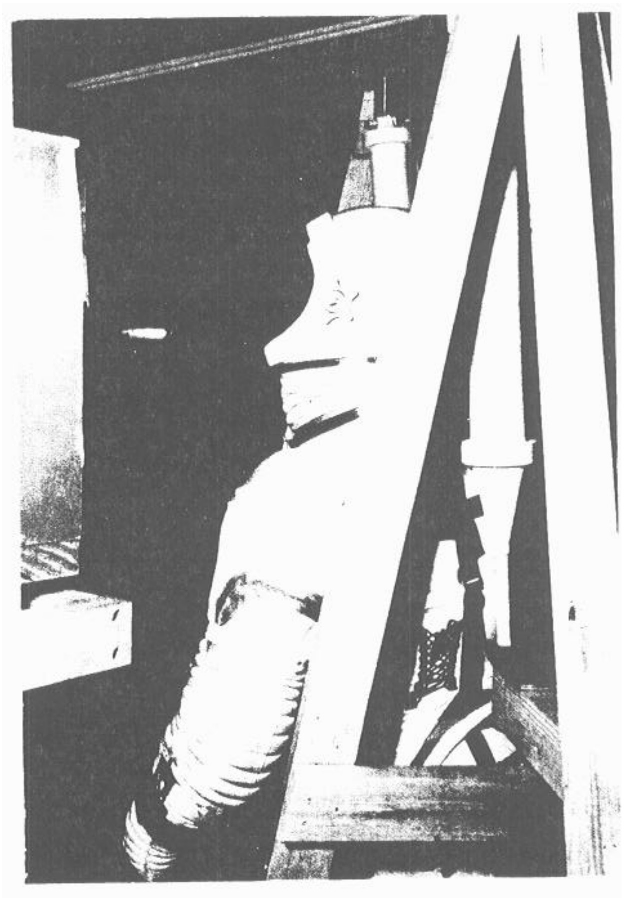


Fig. C10 Pressure Suit Evaluation - LER

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, would have the same angular rate as one would see if in orbit.

c. Evaluation of various optical techniques for coping with the large eye relief associated with the use of a full-pressure suit. Figures C6 and C7 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 C8 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 C9 and Cl0 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 (Fig. C11).

Three levels of SXT simulation were eventually used in these simulations. The first level, which was similar to the optics analog simulator described in section a, is shown in Fig. C 11. This simulation consisted of a single directlyviewed oscilloscope driven by a small analog computer, a control panel, and supporting structure. The analog computer generated two moving dots that could be manually tracked via the optics controller and the SIC minimum impulse controller. Subjective comments on the size of the dots on the CRT when compared to the optical SXT simulator (to be described later) precipitated the second level of simulation.

In the second level the CRT was no longer directly viewed. Instead, the operator viewed through a telescope a much smaller dot (star) that was now superimposed on a fixed landmark scene. This technique gave the operator a more realistic optical task to perform while evaluating the various body tethering techniques. Again a rudimentary structure was used.

In the third level, the same optics simulator was used, but this time the equipment was mounted in a complete S/C mockup. Figure 11A shows equipment mounted in the LEB. Figure 11B 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.

f. Evaluate the capability of the astronauts to read the computer electroluminescent numeric displays while undergoing stresses in excess of 10 g's. Figure C 12 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 an operational computer control panel mounted in its designed location on a partial NAA main panel installed in the gondola. A 16-button keyboard consisting of 10 digits, 2 algebraic signs, and 4 instruction buttons was provided. Two output signals were possible, one by pressing the ENTER button and the other by pressing any one of the other 15 buttons. The following displays were operated in an open loop manner by means of an externally mounted block tape reader

"AGC CAUTION", a steady luminescent (green);

"AGC WARNING", a steady luminescent;

Two-digit verb identification number used to display roll angle in tens of degrees;

Two-digit noun identification number used to display deceleration in tenths of g's;

Three registers each with algebraic sign and 5 digits to display velocity, altitude, and range.

Figures Cl3 and Cl4 summarize the various activities for pressure suit evaluation, Zero-g and high-g testing.

During this same period, many different configurations for the displays and controls were evaluated (Fig. Cl5 and C16). 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.

2. Development Phase - (Table 3, fig. C17)

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 Cl8 and C18A show an optical schematic for the SXT simulator while Fig. C 19 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. C20 was generated.

The SXT is simulated with an N2 telescope (28X, 1.8° field), two 2-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, two 2-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 2-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. C18A). A rotating eyepiece

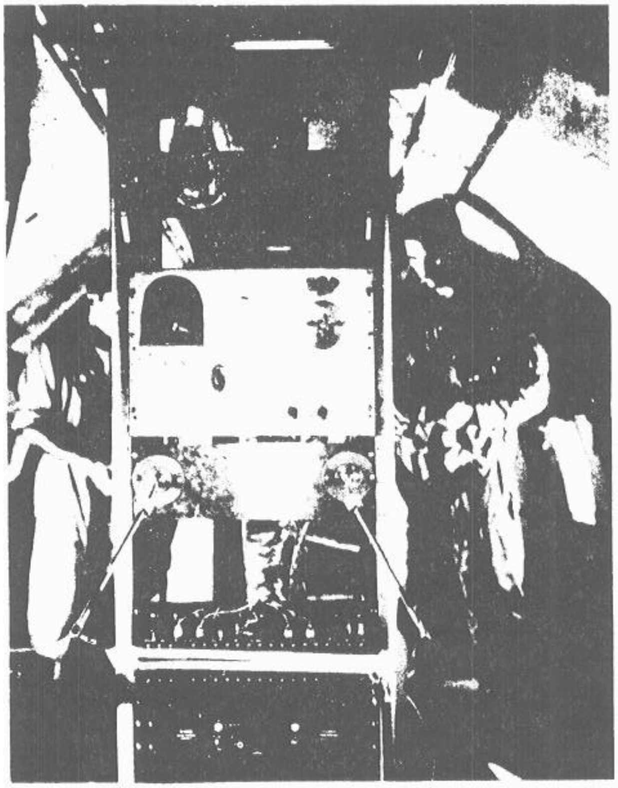


Fig. C11 CM Optics test Station -- Zero-g

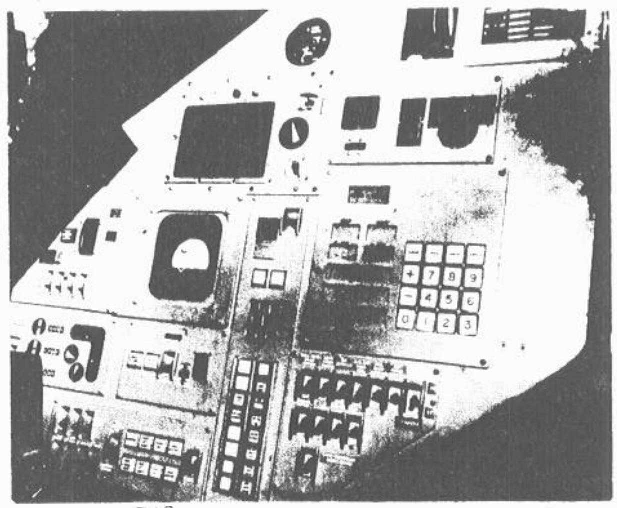


Fig. C12 G&N DSKY in NADC Gondola

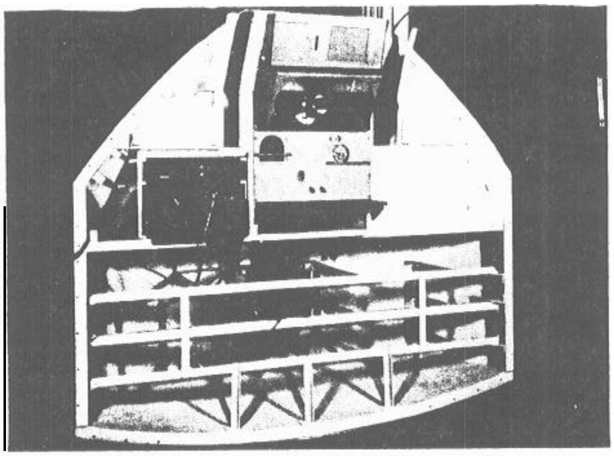


Fig. C11A Optics Test Station Mounted in Lower Equipment Bay

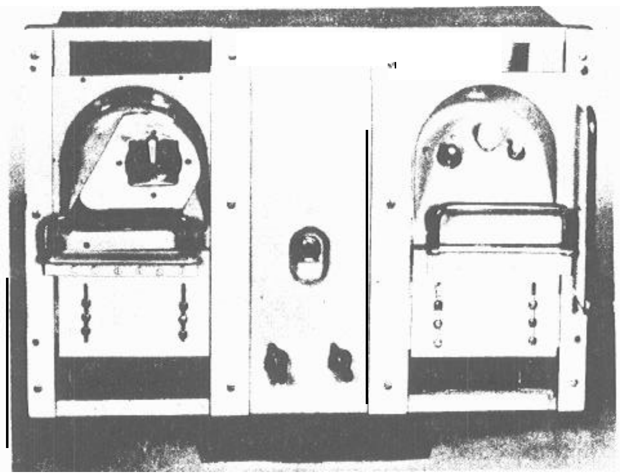


Fig. C 11B Adjustable Control Panel

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 Boost	December 3-5, 1963

Fig. Cl3 Operational Tests - Summary

	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 I
INTERIOR ILLUM	read mdc up to 20 ft-c background illum	✓	✓	IMU control panel no hindrance to viewing 3rd mag star thru sxt
VIBRATION	?	?	?	?
GAS ENVIR	✓	✓	✓	may be some loss of acuity over long haul; little qual evidence
FATIGUE				limited lab tests show no adverse effects up to 40 minutes

Fig. Cl4 Environmental Constraints - Summary

Fig. Cl5 Evaluation of Reach and Vision

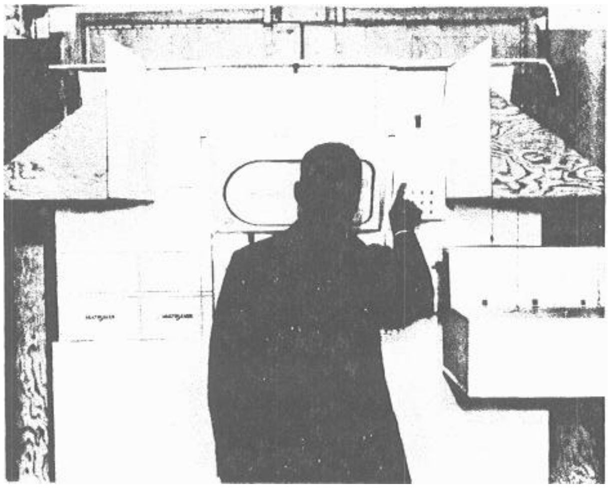


Fig. C16 Evaluation of Reach and Vision

TABLE 3

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.

Figure Cl7

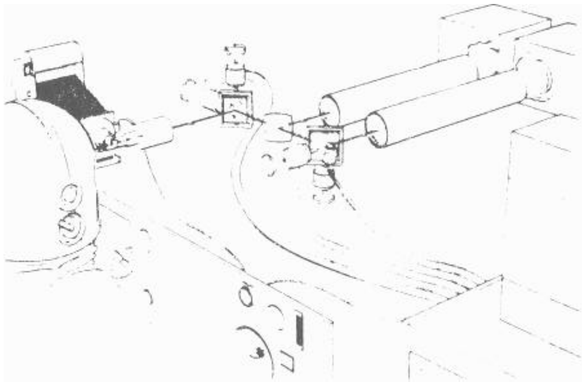


Fig. C 18 SXT Simulation - Optical Schematic

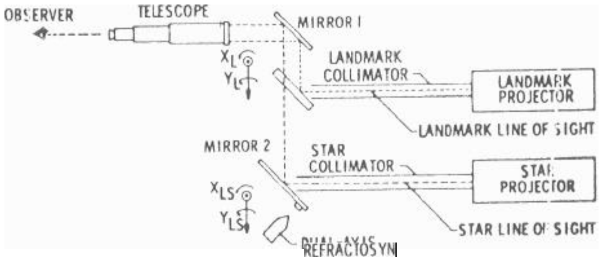


Fig. C18A Sextant Simulation - Functional Schematic

Fig. C19 SXT Sim

	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 ≈ 70% reject ≈ 1/2 of errors > 10 sec	15 - 20 seconds	zero dead band, 0.4° 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. C20 Man-Optics Performance Matrix

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
      (1) Direct or resolved optics control
      (2) Fuel slosh and CM inertia cross-coupling effects.
   B. IMU Orientation and realignment sightings
2. Earth Orbital

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

A simulator was also constructed for the scanning telescope. Figure C21 is the optical schematic for the SCT simulator.

The SCT simulator consists of a hemisphere planatarium with fourth magnitude and brighter stars of the northern hemisphere, a slide holder for earth or lunar images, and a 1X, 60° field telescope (Fig. C21A).

The telescope is actually two telescopes end-to-end with a single dove prism between then. A rotating double dove prism is mounted with the trunnion axis orthogonal to the shaft axis. Rotations of the prisms, eyepiece reticle, and telescope shaft simulate S/C motion. The same Verdan computer controls both the SCT and the SXT simulators.

The SCT simulation can be used to test:

1. Star, landmark acquisition
   a. Resolved optics controller mode
   b. Direct optics controller mode
2. Coarse IMU alignment star sighting

During this period, the whole task simulator for the CM was built. This unit (Fig. C22 and C23) is a full-size mockup with a complete set of operating controls for G&N. SCS. SPS. and RCS svstems. 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. 1) (Fig. C23A). 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 C23B shows the main display panel and Fig. C23C shows the lower equipment bay and the optics simulators.

A similar unit for the LM vehicle (Fig. C24) is now under construction. This unit will, in addition to the above mentioned items, contain a visual display for the window in order to evaluate the guidance technique for landing on the moon. The scene generation technique for thewindow uses the flying spot TV technique.

One other device constructed for navigation procedure evaluation is the Space Navigator (Fig. C25 and C25A).

The Space Navigator (SN) is an Apollo G&N systemmounted on a moving base using real stars. The moving base is a surplus Nike Ajax radar mount. The system is an updated AGE5. An NAA Verdan computer provides the resolutions needed to simulate S/C motion.

B. Operations phase (Table 4)

In this final phase, the actual detailed operationaltest objectives for a mission are defined, programs for the airborne computer are written, and crew procedures for theactual flight hardware are detailed. In order 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 "computerized", i.e., the data is stored on cards and magnetic tape (Ref. 16).

With the previously described simulators, the airborne computer program is tested, and the man-machine interface for individual tasks, as well as integrated mission sequences, are evaluated. Finally, the same devices are used to familiarize 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 C26 details the testing logic.

REFERENCES

1. D. G. Hoag, Apollo Guidance and Navigation - A Problem in Man and Machine Integration ", MIT Instrumentation Laboratory Report R-411, April 1963, given at the AIAA conference in Dallas, Texas, April 22, 1963.

2. J. M. Dahlenand J. L. Nevins, "Navigation for the Apollo Program", MIT Instrumentation Laboratory Report, R-447, May 1964, given at the National Space Meeting of the Institute for Navigation, St. Petersburg, Florida, April 30, 1964.

3. N. Sears, "Technical Development Status of Apollo Guidance and Navigation" Paper 64-17, published in Advances in the Astronautical Sciences, pp. 114-450, Vol. 18, 1964.

4. Richard H. Battin, "A Statistical Optimizing Navigation Procedure for Space Flight", MIT Instrumentation Laboratory Report R-341, May 1962, published in the American Rocket Society Journal, November 1962.

5. Richard H. Battin, "Explicit and Unified Methods of Spacecraft Guidance Applied to a "Lunar Mission", presented at the 15th International Astronautical Congress, Warsaw, 1964.

6. M. B. Trageser and D. G. Hoag, "Apollo

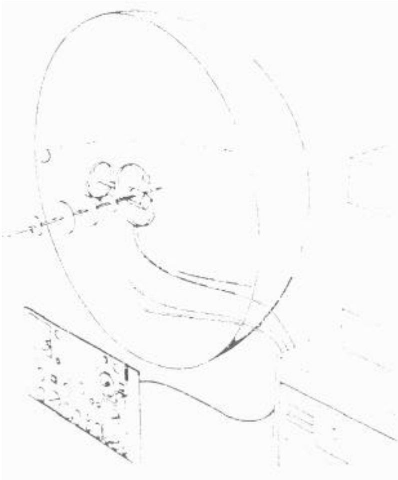


Fig. C21 SCT - Optical Schematic

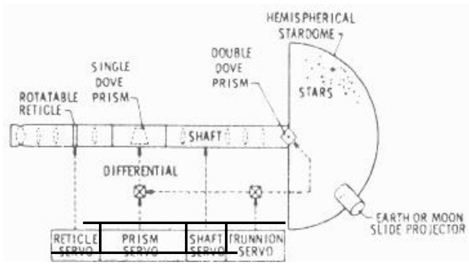


Fig. C21A SCT Simulation - Functional Schematic

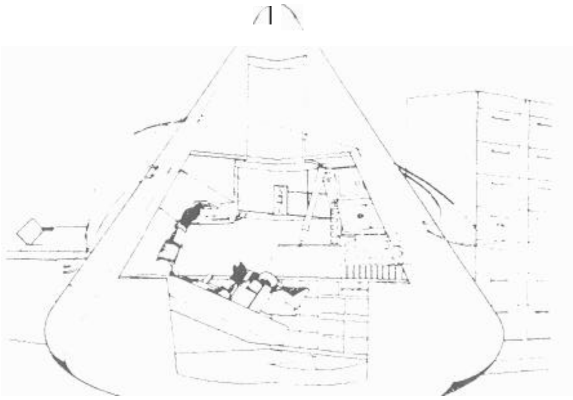


Fig. C22 CM Sim - Line Drawing

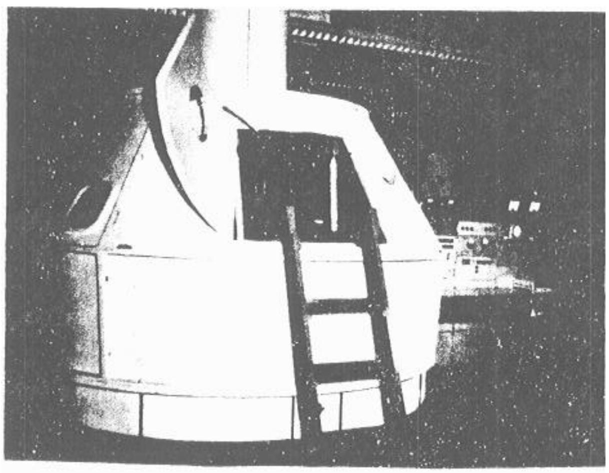


Fig. C23 CM Sim

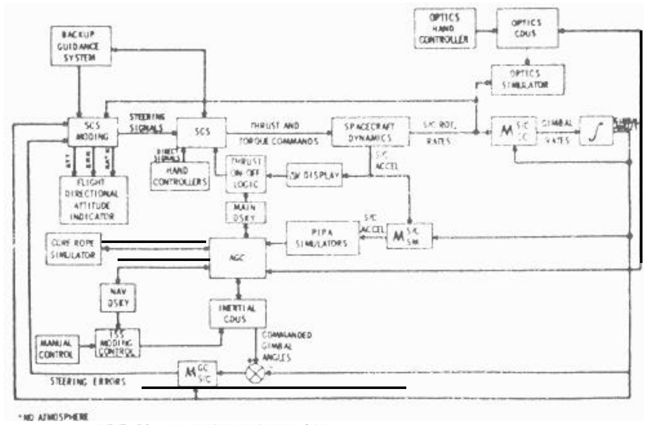


Fig. C23A Mechanization of the Manned Hybrid Simulation of Apollo G&N System

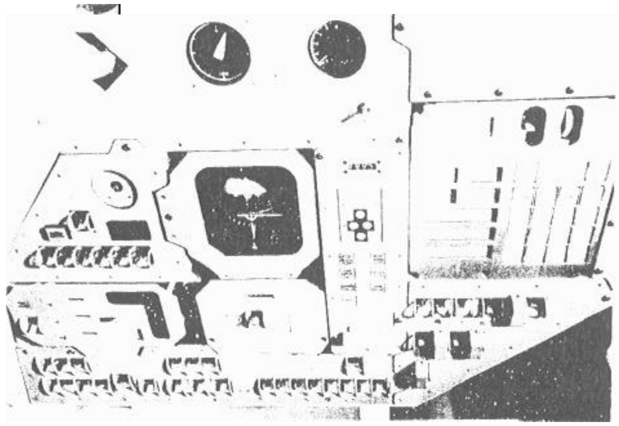


Fig. C23B CM Simulator Manual Display Panel

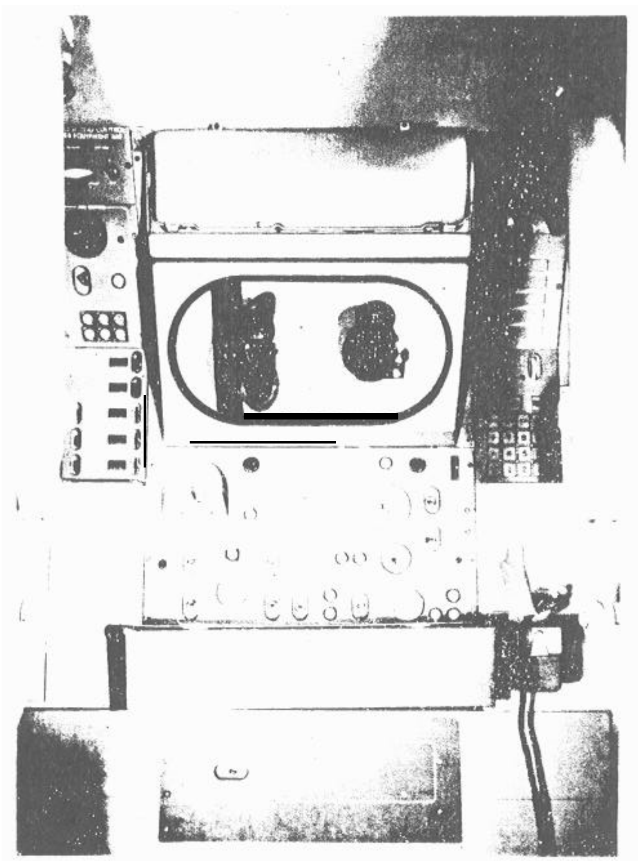


Fig. C23C CM Simulator Lower Equipment Bay

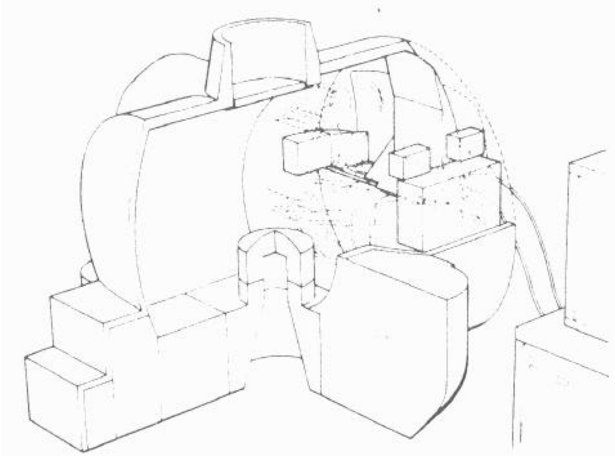


Fig. C24 LEM Sim

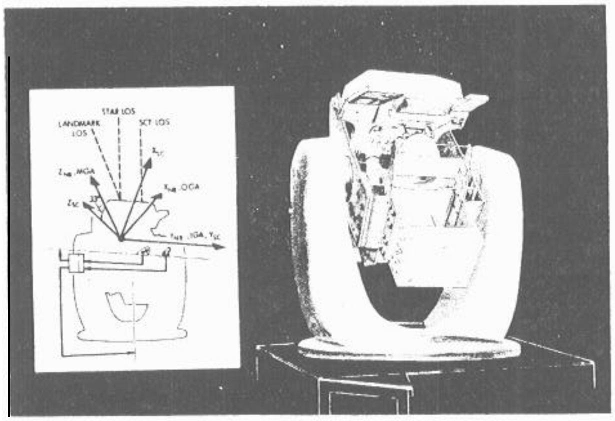


Fig. C25 Space Navigator

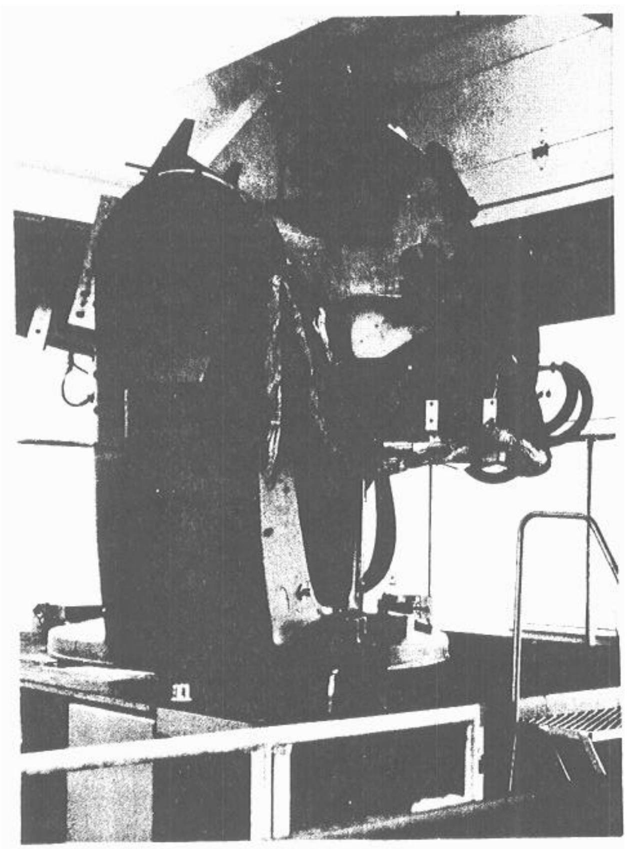


Fig. C25A Space Navigator

TABLE 4

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.

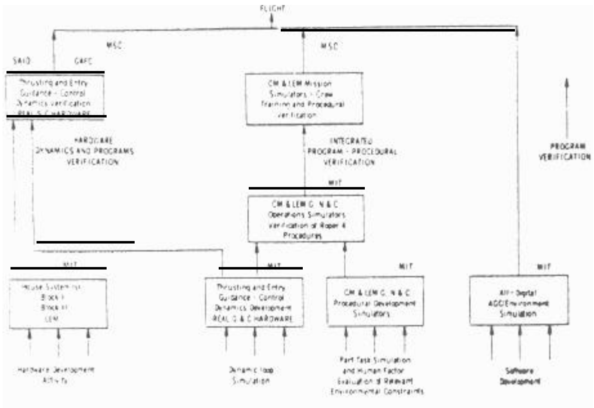


Fig. C26 Test Logic

Spacecraft Guidance System", MIT Instrumentation Laboratory Report R-495, June 1965, given at the IFAC Symposium on "Automatic Control in the Peaceful Uses of Space", Stavanger, Norway, 1965.

7. Thomas J. Lawton and Charles A. Muntz, "Organization of Computation and Control in the Apollo Guidance Computer", MIT Instrumentation Laboratory Report E- 1758, April 1965, given at the IFAC Symposium on "Automatic Control in the Peaceful Uses of Space", Stavanger, Norway, 1965.

8. R. L. Alonso, H. Blair-Smith, and A. L. Hopkins, "Some Aspects of the Logical Design of a Control Computer: A Case Study", Report EC 12, No. 5, published in the IEEE Transactions on Electronic Computers, December 1963.

9. R. L. Alonso and A. L. Hopkins, "The Apollo Guidance Computer", MIT Instrumentation Laboratory Report R-416, August 1963, reprinted as Report 6.1, PTGSET Record, published by the Professional Technical Group on Space Electronics and Telemetry of the IEEE, 1963.

10. J. L. Nevins, "Man-Machine Design for Apollo Navigation Guidance, and Control". A presentation made at the MIT Industrial Liaison Symposium on Man-Machine Systems, April 2 1 1966, Hotel Mirarma, Santa Monica, California:

11. M. Sullivan, "Hybrid Simulation of the Apollo Guidance and Navigation System", MIT Instrumentation Laboratory Report R-525, December 1965, given at the Fall Joint Computer Conference, Las Vegas, Nevada, December 3, 1965.

12. Charles M. Duke, Jr. and Michael S. Jones, "Human Performance During a Simulated Apollo Mid-course Navigation Sighting", MIT Instrumentation Laboratory Report T-385, June 1964.

13. Robert Lee Moore, Jr., "The Human As a Vernier Control In Telescope Pointing", MIT Instrumentation Laboratory Report T-422, June 1965.

14. Bruce J. McGregor, "The Effects of Handcontroller Deadband On a Terminal Tracking Task", MIT Instrumentation Laboratory Report T-406, February 1965.

15. Ivan S. C. Johnson Jr., "Human Optical Tracking of Stroboscopic Beacon for Orbital Rendezvous", MIT Instrumentation Laboratory Report T-436, September 1965.

16. J. C. Dunbar, R. A. Larson, P. T. Augart, "An Automated Technique for Integrating Apollo Crew Procedures and Computer Logic", MIT Instrumentation Laboratory Report E- 1956, May 1966 presentedat the 7th IEEE Symposium on Human Factor in Electronics, Minneapolis, Minnesota, May 5,6, 1966.

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