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APOLLO GUIDANCE AND NAVIGATION - A PROBLEM IN MAN AND MACHINE INTEGRATION

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Abstract

The decision to send man to the moon created the need for development of accurate measurement and data processing equipment integrated into a man controlled operation. This report shows the design of the Apollo guidance and navigation equipment and the displays, controls, and operations utilized by the astronauts in performing a difficult and necessarily accurate task. The compromise between a completely automatic system and one configured for extreme dependence on the man is met with one solution having good features of both approaches. The system is described in which the navigator has complete choice and control of the system operation using his senses and judgement where they are superior, and depending upon mechanisms where man is unable or too stressed to be utilized. The details of the design of the sensors, the computer, and the displays and controls are described in enough detail to illustrate the astronaut operation of the Apollo Guidance and Navigation System.

Section 1. Introduction

When this nation's greatest identified space mission, Apollo, gets underway later this decade after years of planning, design, and experimentation, three men will be responsible to carry through an almost fantastic operation: the landing of man on the moon and his safe return.

This voyage will depend upon near perfect operation of a series of events and equipment. A failure of any of these will be a serious obstacle to mission achievement if not peril to the crew. The boost vehicle, the spacecraft, its propulsion system, ground operations, the crew life support, communications, and so on, are links in this chain. This paper is concerned, in particular, with the equipment and its operation which navigates the space vehicle and steers it through required maneuvers. This is the Guidance and Navigation system of Apollo, herein called G&N.

As part of a manned operation, it became necessary for the NASA and its contractors to determine the degree of involvement that the astronauts would have in the use of their craft. Groundrules had to be formulated as some compromise best understood by describing the extremes....

Completely Automatic. Certainly the manned lunar landing objectives requested by President Kennedy in May 1961 would be met by automatic equipment delivery of an astronaut, wrapped and bundled as it were, in a life maintaining cocoon to the lunar surface; and then, abruptly carrying him back home like any inert payload. But certainly the astronauts, once aboard the vehicle, can contribute mightily to attainment of objectives. The lessons of the Mercury manned space flight program emphasize this.

Completely Manual. At the other extreme could be a design wherein the men are given a rocket, a control stick, a big window, and appropriate charts and tables. This point of view was suitable for Lindberg's adventure where the most energy-efficient path from New York to Paris was only slightly better than that followed by the "Spirit of St. Louis". However, the possibility of a trip to the moon's surface and back is extremely sensitive to the velocity change attainable by rocket propulsion technology now available to push the required payload. The day of "seat of the pants" flying in outer space may not have to wait until Buck Rogers' twenty-fifth century, but today project Apollo must depend upon efficient paths determined by accurate and complex guidance and navigation equipment.

This report will describe the status of the Apollo Command Module G&N system, its relation to the astronaut, and the particular engineering compromises selected for this complex man and machine operation.

First the Apollo mission will be described briefly using Figure 1 to provide foundation for the description of the G&N equipment and operation.

In current plans, an Advanced Saturn Booster will launch the complete Apollo spacecraft and the upper stage boost rocket into a low altitude parking orbit. In this circular satellite it is envisioned that equipment will receive a final period of checkout before committing the spacecraft to escape velocity. With one or more orbits of the earth, the on-board navigation can determine accurately the actual ephemeris required for precise initial conditions for the next phase.

A second thrusting period of the booster, using the last Saturn stage, will inject the spacecraft to the necessary translunar velocity for the mission. After cutoff and staging, the Apollo is made up of the Command Module (CM), Service Module (SM), and Lunar Excursion Module (LEM). These components must first be arranged from their boost configuration to the cislunar operational configuration shown in Figure 2.

As soon as possible after translunar injection, a continuing set of navigation measurements must be made to determine the actual trajectory parameters and velocity corrections necessary. The first correction will be made a few hours after injection using the rocket in the service module. This will be followed by further navigation measurements and with one or two more velocity corrections.

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The approach to the moon would now require a final correction about an hour before the larger thrust period to inject into lunar orbit.

The spacecraft assembly would orbit once or twice around the moon taking navigation measurements for an accurate ephemeris, inspecting the proposed landing area, and performing the countdown of the LEM.

The letdown of two of the men in the LEM to the lunar surface, the takeoff from the moon, and the LEM rendezvous with the parent craft left in orbit will not be described in this paper. While on the moon for several hours or up to several days the two men will perform the limited exploration and scientific examination which constitutes the goal of project Apollo.

Finally, back in lunar orbit, the three men set up and inject into a transearth trajectory using the service module propulsion and leaving the LEM in orbit. The trip back to earth will be similar to the outgoing leg. Guidance and navigation will control to the desired reentry corridor by application of several velocity corrections.

Just prior to reentry, the service module is staged and the guidance system is prepared to control the reentry path. This control is performed by steering the direction of the lift, available from the aerodynamic characteristics of the command module, such as to achieve a safe reentry to a prepared landing site.

In this mission we see two distinct modes of spacecraft operation and a corresponding configuration and requirement on the guidance and navigation equipment. First, during boost, translunar insertion, midcourse corrections, lunar orbit insertion, etc. the vehicle assembly is operating under thrusting conditions with requirements on the G&N to provide steering signals for guidance to the required velocity change. Second, during the majority of the time Apollo is in free fall motion following paths determined by the gravity pull of earth and moon. During this time, the G&N must navigate to determine position, velocity, and any velocity corrections required to accomplish the next target.

These operations of guidance and navigation are illustrated in Figure 3. The steering function of guidance operates on angular velocity and acceleration sensed by inertial instruments. The navigation uses optical line of sight angle measurements on which to base the determination of position and velocity. The two functions are interrelated as shown. Part of the navigation function is to provide information on initial conditions and desired velocity changes for guidance purposes during vehicle steering control phases. The guidance, on the other hand, measures changes in velocity actually accomplished during thrusting in order to update the navigation process. (In the above discussion the lift and drag forces during earth atmospheric entry are considered in the same class as the rocket thrusting phases, i. e. non-gravitational forces.)

We now identify four major subsystems of the Apollo Guidance and Navigation equipment:

1. Inertial Measurement Unit: The primary sensor for guidance phases providing measurements of angular velocity and acceleration from inertial instruments.

2. Optics: The primary sensors for the navigation phases providing angle measurements between lines of sight to stars and near planets.

3. Computer: The primary data processor for both guidance and navigation computations.

4. Displays and Controls: The communication interface between the navigator and the rest of the equipment.

Section 2. G&N Phenomena

The use of the equipment identified in the previous section depends upon application of physical phenomena, some of which are well known and understood and others which are unique to the Apollo G&N.

For steering control, the use of gyroscopes, accelerometers, and clocks as measurement devices in inertial guidance is well documented in applications to ballistic missiles control. Nothing will be said here about principles or theory, other than a description of actual hardware in a later section.

Use of optical instruments for space navigation, on the other hand, is not so familiar and indeed some of the phenomena utilized in Apollo are quite new. The basic principle of position determination from observations of heavenly body directions by an earthbound observer is not new. A mariner (or winged aircraft navigator) measures the angle of the sun or star above his local horizon with his sextant. An astronaut away from the earth also may use the horizon usefully or its near equivalent the local earth vertical or direction from him to the earth. Also he may use any identifiable landmark on the earth. Any of these would serve.

The earthbound mariner, from his star elevation data, the time of observation and the navigation tables, determines a line of position on the earth. Anywhere on this line an observer would measure the same star elevation. A second star sighting leads to a second line which intersects the first at his indicated position.

The astronaut would interpret an angle between the earth's direction and a known star as defining a conical surface of position. Anywhere on this cone he would expect to obtain the same angle measurement.

Figure 4 shows a hypothetical situation for this method of space navigation. From his spacecraft the navigator measures the angles from a particular earth landmark to the star Fomalhaut. This places him somewhere on the small cone shown which has its axis in the direction of Fomalhaut and whose half angle is equal to his measurement. A second sighting to the same landmark and to the star Deneb defines the second cone - very flat in this case because the measurement angle was near 90°. These two cones inter-

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sect in a line containing the landmark and somewhere on which he is assured to lie. (The earth-bound mariner could stop here because his third coordinate was known explicitly by the fact that he was bound to the surface of the earth.)

The astronaut could complete his fix by utilizing a second earth landmark separated from the first and any star. This would work well in the vicinity of the earth but accuracy degrades as the apparent size of the earth gets small. So the third sighting shown in Figure 4 is with respect to the moon. In this case the moon's horizon or limb is used rather than a lunar landmark. The third cone, defined by this sighting of the elevation angle of the star Antares above the moon's horizon, intersects the previously determined line of position at the indicated location of the spacecraft. Actually the three cones have four mutual intersection points. The wrong three could be discarded easily in a practical situation.

By a technique such as this it is theoretically possible for the space navigator to determine a fix of his position with respect to the earth-moon system. Similar measurements repeated at some later time in his trajectory would provide data to determine velocity and the free fall path describing the spacecraft trajectory. The method described implies that the three angle measurements could be made simultaneously. Practically this would put too much of a burden on the navigator and/or equipment design to be considered for Apollo.

The navigation measurements for Apollo are the angles between the planets and stars, as described above, and the time the measurements are made. These measurements are taken in time sequence separated from 15 minutes to several hours apart according to an optimum plan. The details of the Apollo navigation scheme are described elsewhere.[1] Some of the important features follow.

The navigation measurements are used to determine position and velocity on any free fall trajectory - such as earth or moon satellite orbits or the transearth or translunar phases.

A measurement schedule is determined prior to the trip for approximate time of sighting, identity of planet, and identity of star such that the greatest enhancement of navigation accuracy occurs for the astronaut's effort under assumed accuracy of measurements and other existing limitations on the navigator, his equipment, and available celestial objects. For a normal flight, about 40 sightings in midcourse, each way to and from the moon, are anticipated.

Each sighting is used by the on-board computer to improve all six components of position and velocity in an optimum manner. The computation scheme also keeps an estimate of the uncertainties in its determination of position and velocity.

The system will accept navigation measurements of any form, such as ground track data or time of star-moon occultation as well as the planet-star angle measurements described above.

Velocity corrections to improve target conditions are made only when the knowledge of the required correction is sufficiently accurate and large enough to make the rocket start and expenditure of maneuver fuel worthwhile. Approximately three corrections are anticipated for each midcourse leg of the trip. The level of fuel expenditure for either the outgoing or incoming leg is equivalent, roughly, to 100 feet per second rms velocity change.

Planet to star angles during earth-moon or moon-earth midcourse phases will be measured in Apollo with a visual sextant instrument capable of an rms accuracy of 10 arc seconds (about 0.05 milliradians).

Angle sightings, with respect to the moon, can be taken either to lunar landmarks or the horizon. An examination of good lunar photographs show an ample supply of distinctive landmarks on the near side and it may be safely assumed that, in the coming years, satisfactory marks may be mapped for the far side. The illuminated lunar horizon or limb is quite distinctive against the dark sky. Consideration of the shape and motions of the moon, altitude of the landmarks, and mountains on the limb must be included if the best accuracy is to be obtained. However, the problem is only one of obtaining the data, maps, and charts. A particular sighting is limited only by the systematic illumination of the moon by the sun.

The situation with earth referenced sightings is not so clear cut because of the effects due to the atmosphere. Cloud cover might obscure a particularly desirable landmark and the horizon seen from space shows no distinctive edge against the sky.

One attack on this problem has investigated earth-direction determination using longer wavelength radiation. The use of visual techniques, however, have so many advantages for manned Apollo that the problems associated with earth atmospheric effects at optical frequencies has received considerable attention.

Weather generated cloud cover over landmarks occur with a frequency which varies over the earth. Some areas are usually free, others may be usually covered. The problem of how many of the good distinctive landmarks are available at any time is clearly amenable to statistical analysis using local weather history for data. Work in progress[2] shows no reason why landmarks cannot be used as an excellent reference for earth-direction measurements most of the time. If good landmarks all become obscured, recourse to the horizon is possible.

The use of landmarks in sextant operation is illustrated in Figure 5. The figure is made from an accurate photo mosaic simulation* of the San Francisco Bay Area and hypothetical clouds as seen from 2500 miles with a 1.8° field telescope. This 28 power optical instrument will also have a second, displaced line of sight to pick up a known star and superimpose it onto the scene. The Apollo sextant instrument and its use will be described in more detail in later sections. By controlling the aim of the instrument and the offset angle of the optical axis for seeing the star the astronaut can superimpose the star, shown as a

*The reproduction process for this document severely limits the resolution available on the original simulation.

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white dot, onto a particular landmark for which he has the geographical coordinates. The navigation measurement consists of the measured angle between the lines of sight and the time at the instant of superposition.

Use of the illuminated earth's horizon is illustrated in Figure 6. The observer out in space above the atmosphere sees, on the sunlit side, the earth-color blend into a brilliant white which turns toward sky blue and then gradually to the black sky as he scans to higher altitudes. The bright light is sunlight scattered in passing through the atmosphere. Light from an object on the horizon at sea level must pass through 23 atmospheres to reach an observer in space, whereas the light from an object straight below him passes through only one atmosphere. The object at the sea level horizon has its light scattered and attenuated such that it is invisible relative to the intense scattered sunlight.

In looking from space through the earth's edge at about 100,000 feet altitude above the sea level horizon, the observer sees the sky through one atmosphere. He should observe the same intense blue as is seen when looking straight up through the same amount of sunlit atmosphere from the ground. If the brightness of a little patch of sky at 100,000 feet is measured from space,one would expect to obtain a value very close to some standard value. This value could be computed on the basis of the sunlight aspect angle and would be only slightly affected by local sea level atmospheric pressure. At this altitude the brightness of the scattered sunlight decreases, due to a corresponding density variation, by a factor of two for each 17,000 foot increase in the altitude. Thus a measurement of absolute brightness to 10% should determine the altitude of the line of sight with an accuracy of approximately 2500 feet. An obvious advantage of working with line of sight measurements at this 100,000 altitude is that it is well above all common cloud types which would interfere with the measurement.

The instrument for this measurement includes an automatic star tracker and horizon photometer attachment in place of the sextant visual eyepiece. The navigator uses the second optical instrument - a low power telescope - to sense visually and then control the spacecraft attitude as required for making the above measurement.

On the dark side of the earth, the 100,000 foot atmosphere could be sensed by the refraction effect on the background stars, Figure 7. If two stars are observed - one setting near the horizon - until the apparent angular distance between them decreases by one arc minute vertical component, then the line of sight to the lower star is at some determinable point near 100,000 feet altitude where the density gradient is well known. The navigation measurement, in this case, consists of the time at which the one minute of arc change is complete. The earth's limb is now determined with respect to the background star - the setting star.

This measurement is similar to the occultation time of stars by the distinct moon's limb, a phenomena available to Apollo navigation. A closer analogy to occultation phenomena uses the photometer described earlier to sense the intensity change, Figure 8, as the starlight sinks into the earth's atmosphere. The photometer would be set for the reference intensity of the particular star well before it is occulted. Once the attenuation reaches the preselected level, the time is recorded. This intensity change is predictable and is due primarily to two phenomena: The scattering of the light out of its path by the air and the light dispersion due to refraction in passing through the atmospheric density change.

These occultation measurements depend upon the existence of stars setting behind the planet's limb. This occurs very often while in earth or moon low satellite orbit and frequently enough in the cislunar trajectory to provide a useful source of navigation data.

The sextant operations of landmark-to-star or horizon-to-star angle measurements are excellent and natural operations on the part of the astronaut navigator with reasonable adroitness as long as the rates of change of the angles and directions are not excessive. This is the case during midcourse translunar and transearth operations for Apollo. Landmark sightings when in satellite orbit around either planet, however, must use instruments that can cope with the high rates involved and the short time that any particular landmark is in view. Fortunately, at these altitudes, the angular accuracy required for the landmark direction is considerably relaxed. In 100 mile altitude orbit, accuracies of the order of a milliradian or so (corresponding to 0.1 mile error) are sufficient. Thus, for orbital navigation, the high magnification available from the sextant is not used. It is replaced by a single line of sight, low power, wide field telescope whose optical direction with respect to the spacecraft, when on target, is compared with the orientation of the inertial guidance stabilized member. Of course, the stabilized member had been previously aligned to the stars with the same instrument. These data allow the computation of landmark direction with respect to the stars as limited by the inertial guidance stable member alignment and drift and the accuracy of the angle transducers reading the telescope directions and the stable member orientation. The use of this wide field telescope for orbital navigation is described in more detail in a later section.

The choice of navigation measurement techniques for use by Apollo has been primarily predicated on the requirement for completely on-board capability. This is necessary, certainly, on the far side of the moon out of reach of earth tracking or communications. However, earth tracking information, when available to the astronaut navigator and when of accuracy which is judged capable of improving the on-board navigation, would certainly be used. The on-board computer will be able to accept ground based data as well as the astronaut's sightings and make a proper weighting of their estimated accuracies in influencing the computed trajectory. The use of earth based tracking becomes primary in the event of failure of the on-board optical equipment.

In this same vein, cooperative land targets could be considered. Many points on the earth are cloud free practically all the time but unfortunately have no distinctive features. The African desert, for instance, might be a logical place to

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install a flashing high intensity light during the mission to provide an almost certain landmark during the local night.

Section 3. Equipment Description

This section will give a physical description of the G&N equipment. Later sections will describe the modes of use and astronaut operation.

Figure 9 shows a cutaway view of the Apollo command module with the major elements of the guidance and navigation equipment shown in their approximate location.

During stress periods the three astronauts will be protected by their couches (the third couch shown dotted) in front of the main display panel where necessary operation of guidance and navigation can be performed. These periods, when all the crew is confined to the couches, are limited; immediately before and during earth launch, possibly during translunar injection, and during earth re-entry. The thrust levels during the rest of the mission are small and acceleration that is felt is of the order of 1g or less. The figure shows the center couch - for the navigator - with the couch knees folded so that he may make sightings at the navigation station while in earth orbit prior to translunar injection. Before starting translunar injection, he may go back to his couch for protection during the rocket burning phase. After this the couch is removed, folded up, and stored under the pilot's couch on the left. This provides considerable floor area for other crew tasks and allows operation at the navigation station in a standing position. This configuration is maintained until just before earth atmospheric re-entry when the center couch must be again installed for the coming stress.

The navigation station, which contains most of the guidance and navigation equipment, is located in the area called the lower equipment bay. Starting from the top in Figure 9, the first item identified is guidance and navigation display and controls, D&C. The sextant, SXT, is the two line of sight instrument for midcourse navigation angle sightings. The scanning telescope, SCT, with its two eyepieces is the single line of sight low power unit for earth and moon orbital sightings and provides general viewing. The IMU is the Inertial Measurement Unit used for inertially measured attitude signals and velocity changes. The Apollo Guidance Computer, AGC, is the central data processing, general-purpose, digital computer. Special power supplies, servo amplifiers, and miscellaneous electronics are contained in the Power Servo Assembly, PSA. The junction box and cabling complete the guidance and navigation hardware in the lower equipment bay.

Figure 10 is a photograph of a full-scale installation mockup of the Optics and IMU in the lower bay with the display panels removed. The optics, without the eyepieces installed, appears above the spherical IMU. Both are mounted on a rigid framework, called the Navigation Base, used so that angle measurements can be referenced between the two instruments. Space for the miscellaneous electronics of the PSA is shown below the IMU. The computer is installed in the space just underneath the mockup.

The display and control panels are shown installed in the mockup of Figure 11. Details and operation will be described in the following sections.

Figure 12 shows a cutaway diagram of the wide field, low power, single line of sight scanning telescope, SCT. Figure 13 is a cutaway of the other optical instrument: the narrow field, high power, two line-of-sight sextant, SXT. The significant details and use of these instruments will be described in Section 7.

The inertial measurement unit is shown schematically in Figure 14. Three gyros and three accelerometers are carried conventionally in a three degree of freedom gimbal structure. The outer axis of gimbal freedom, OGA, is mounted parallel to the re-entry control wind axis so that the high angular rates, during reentry roll control of lift, are "unwound" by the outer gimbal. This places the outer gimbal axis 33 degrees from the spacecraft symmetry axis. The inner gimbal, or stable member, carrying the inertial components, is aligned prior to each use of the IMU such that the inner gimbal axis, IGA, is normal to the plane of any planned trajectory or attitude turning maneuvers. Thus in orbit, for instance, the inner axis would be placed normal to the orbital plane so that the relative spacecraft rotation caused by keeping a fixed attitude with respect to the local vertical will not cause gimbal lock since it is "unwound" by the inner gimbal. By aligning the stable member in this fashion before each mission phase the three degree of freedom gimbal structure avoids danger of gimbal lock without the weight, size, and operation penalty of a fourth degree of freedom. However, unusual maneuvers of the spacecraft could bring the outer axis around into parallelism with the inner axis where the inertially fixed orientation of the stable member would be lost and re-alignment would have to be performed again.

Operations with the IMU are described in more detail in Section 5.

Figure 15 is a photograph of the stable member of a display model of the IMU. The three 2 1/2" diameter gyros, 25 IRIG, and two of the three 1.6" diameter accelerometers, 16 PIPA, are shown. The inter-gimbal assemblies on each end contain slip rings, bearings, servo torque motors, and electromagnetic resolvers. Figure 16 shows a higher stage of assembly of this model. The gimbals are not conventional rings but are pairs of hemispheres of thin section aluminum. The device at the bottom on which the model rests is one of a pair of blowers which is used to circulate air for heat transfer. Figure 17 shows the complete assembly.

Figure 18 shows the package of miscellaneous support electronics called the Power Servo Assembly or PSA. Figure 19 shows a photo of the computer mockup. Both are constructed with removable trays on which are plugged modules. The modules are replaceable for inflight repair. One tray of the PSA and one tray of the computer carry spare modules. The design incorporates multiple use of common modules to gain maximum use of carried spares. Characteristics and operation of the computer are described in a later section.

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Section 4. Operation Modes

The purpose of this section is to give a brief description for each of the various modes of operation of the utilization of the hardware previously described. This will provide an over-all picture before more detailed descriptions of operations are given in the following sections.

Major Subsystems

Figure 20 identifies the major subsystems of the guidance and navigation system. The left-hand column of boxes in the figure depicts the input sensing devices of the system. Similarly, the center column depicts the control and data-processing devices. The right-hand column lists the other spacecraft functions of direct concern to the guidance and navigation functions.

The data sensors of the G&N system are the radar, scanning telescope, sextant, and inertial measurement unit. The latter three are mounted on the "navigation base" in the command module of the spacecraft so that angle measurements can be related to a command rigid structure representing the spacecraft.

(The radar, the first sensor represented in Figure 20, is utilized in lunar landing operations not covered in detail in this paper.)

The G&N system performs its control and data processing by the astronaut using: display and controls, the computer, the coupling display units, and the power servo assembly shown in the second column of Figure 20.

The Apollo guidance computer (AGC) is the data-processing center of the guidance and navigation system. It is a general-purpose digital computer having a large quantity of wired-in memory and programs and sufficient erasable memory to meet all requirements. (See Section 6.)

The coupling and display units (CDU) are used to transfer angular information among the IMU, the computer, and the spacecraft autopilot, as well as to display various angle parameters to the astronaut.

The power servo assembly (PSA) is a support item. It provides various types of d-c and a-c power to the rest of the G&N system and also serves as the location of various other support electronics - in particular, the servo control amplifiers for the IMU and optics drives.

Three spacecraft functions outside the G&N system and part of the spacecraft stabilization and control system are of direct concern to the G&N system and are shown on the right of Figure 20. The attitude control system, the first, determines spacecraft orientation during non-accelerated phases and affects the ability to make optical sightings for navigation and IMU alignment purposes. The second is the equipment for control of propulsion-rocket thrust magnitude - starting and stopping these engines and modulating their thrust level when appropriate. The guidance system sends signals to initiate these functions. Finally, the autopilot function of the stabilization and control system receives the guidance steering error signals during the accelerated phases to direct and control the rocket directions (or lift forces during reentry) so as to achieve the desired trajectory.

The use of these subsystems in carrying out the guidance and navigation functions during the important phases of the Apollo mission will be explained using block diagrams in the same format as Figure 20.

Guidance and Thrust Control, Figure 21

The G&N system here controls rocket thrust during the powered or accelerated phases of a mission and controls reentry lift during the reentry phase. The IMU is the only sensor used in this phase. It produces two outputs: velocity increments, which go to the computer (AGC), and spacecraft attitude, which goes to the coupling display units (CDU). The velocity increments are measured by the accelerometers in the IMU stabilized framework within which the computer determines the steering signals that it sends to the CDU. These increments are then compared within the CDU with the spacecraft attitude measured by the IMU gimbal angles, in order to generate attitude errors. The autopilot acts on these attitude errors and controls the rocket-motor thrust direction (or re-entry lift direction), causing changes to the spacecraft attitude so as to bring these errors to zero. Meanwhile, on the basis of these velocity measurements on which the steering signals are based, the computer also determines the rocket-engine cutoff and, when appropriate, modulation of the thrust. The display and controls (D&C) provide monitor functions to the astronaut. He can take control, of course, in various secondary modes to enhance mission success.

In order to carry out properly this guidance phase, the stabilized member of the IMU must be prealigned with the appropriate fixed coordinate frame. There are two phases of this alignment: coarse and fine.

IMU Coarse Alignment, Figure 22

Neither the sextant, the scanning telescope, nor the radar are involved in the coarse alignment of the IMU. From the action of the stabilization and control system, the spacecraft has an expected or estimated attitude. This would be determined by the free-fall attitude control constraints for the vehicle. Based upon this orientation, the astronaut can use the computer to determine the desired IMU gimbal angles that would place the IMU stabilized member in the desired orientation for its next control use. These angles can be fed automatically to the CDU, which compares them with actual gimbal angles and generates error signals giving the difference between actual gimbal angles and desired gimbal angles. These error signals go to the IMU gimbal servos and rapidly move the stable member around to the orientation required. This coarse alignment results in an alignment accuracy on the order of one degree except as limited of course by the knowledge of spacecraft attitude as determined by the spacecraft stabilization and control system.

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IMU Fine Alignment, Figure 23

The IMU fine alignment, as contrasted with the IMU coarse alignment, depends upon optical measurements. The sextant is the primary sensor and is used for tracking with its articulating line of sight the direction to a star that is to be used as the orientation reference. The scanning telescope, with its wide field of view, is used for acquisition and to check that the correct star is being sighted. The astronaut, through the display and controls, puts the sextant cross hairs on the star, thereby generating the star direction angles with respect to the navigation base. The IMU gimbal angles with respect to the navigation base are then measured,using the CDU to feed these angles to the computer. There a comparison between the actual and required gimbal angles is made. If the gimbal angles are not appropriate, gyro torquing signals are sent to the gyroscopes on the stabilized member of the IMU to drive the gimbals to the orientations that match up with the requirements for the IMU fine alignment. The accuracy of this fine alignment is of the order of a minute of arc. Since a single star direction can give only two degrees of freedom of orientation reference, a second star sighting is then necessary to complete the three-degree-of-freedom fine alignment of the IMU stabilized member.

Midcourse Navigation, Figure 24

The principal sensor used in midcourse navigation is the sextant with its two lines of sight. In its field of view, the star and the landmark are superimposed by the astronaut through the use of the sextant controllers. The navigator astronaut can also look through the scanning telescope for acquisition and identification as required, using its wide field of view. When the two targets are superimposed, the sextant feeds to the computer the angle between them. The computer uses this information to update its knowledge of free-fall trajectory, so that it can provide, at any time, information on position, motion, and trajectory.

The sextant has only two degrees of articulation with respect to spacecraft. Since there are two lines-of-sight, however, each requiring two degrees of freedom, additional freedom is required. This is obtained by control of the spacecraft attitude pitch and roll on signals from the navigator.

Orbital Navigation, Figure 25

During navigation phases in which the spacecraft is in orbit close to the moon or the earth, angular measurements do not have to be quite as accurate, but angular velocities are rather extreme. In this case, the scanning telescope is used as a single-line-of-sight instrument to track a landmark. With the IMU prealigned to a star framework, it is simultaneously giving spacecraft and navigation base attitude with respect to that framework while the scanning telescope gives landmark angles with respect to the navigation base. From these two subsystems, accordingly, the landmark direction with respect to the aligned space direction of the IMU is obtained. The computer receives this information to update the trajectory parameters of the orbit, and can supply to the navigator - by means of the display and controls - position, motion, and trajectory information. Again, attitude control is necessary here, mainly to provide suitable conditions for tracking with the scanning telescope.

Rendezvous and Lunar Landing, Figure 26

Figure 26 can be interpreted as representing equipment in the Lunar Excursion Module for rendezvous and lunar landing. The sextant will not exist in the LEM, and the SCT will be a modified version of that in the command module. The radar and optical tracking devices provide the computer, AGC, with landing point or mother craft coordinates relative to the LEM. The IMU input to the computer provides a measurement of velocity. These data are processed to modulate and steer the rocket thrust appropriately.

Section 5. IMU Operation

The primary use of the IMU is in the measurement and control of the specific forces from the rocket thrust or atmospheric drag and lift. Figure 27 is a simplified block diagram showing the control loops used during the thrusting phases of vehicle operation. The spacecraft orientation, position, and motion are a result of the rocket thrust and rocket angles commanded to the engine gimbal servos. The spacecraft autopilot section has rate gyro feedback to the autopilot servo for rate stabilization. Spacecraft orientation and acceleration is measured by the guidance and navigation equipment using the IMU mounted on the navigation base attached to spacecraft structure. Based upon these acceleration or velocity changes measured with the pulsed integrating pendulum accelerometers, PIPAs, the Apollo guidance computer, AGC, generates steering attitude commands as angular rate signals which are integrated and summed with present attitude in the Coupling Display Units, CDUs. The outputs of the CDUs are steering attitude errors which are sent to the spacecraft stabilization and control system for response by the autopilot.

Based upon the measured acceleration history the computer generates an engine cutoff signal when the desired velocity change is achieved.

Before the IMU can be used for such control purposes the stabilized member carrying the accelerometers and stabilizing gyros must first be aligned to a particular inertial orientation relative to the desired trajectory. This introduces a number of different modes of IMU operation. Figure 28 shows a detail photo of the IMU control panel and the CDU panel. The meter provides the astronaut with indication of existing attitude error in three coordinates. He may choose to have the computer and its program operate the various IMU modes or do this himself depending upon which position he sets the transfer switch. If the navigator operates the IMU he uses the six button matrix shown. The first button "zero encode" drives the CDUs to null so that the computer can empty its CDU angle registers and start from zero. This is the first action after applying power to the IMU.

The second button "Coarse Align" sets the IMU gimbal angles to those matching angles set into the CDUs by the computer.

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The "Fine Align" button is used in conjunction with star sightings made with the sextant to orient the IMU, via computer gyro torquing, to the angles desired by the computer.

The "Manual CDU" button provides for manual CDU operation with the hand slew switch and vernier thumbwheel on the front of the CDUs in case the computer is failed. The manual align button in this mode drives the IMU to the set CDU angles.

"Attitude Control" is the normal mode for providing steering and attitude errors to the spacecraft. During atmospheric entry, the button "entry" increases the slew capabilities in roll to provide the fast attitude changes about the wind axis to modulate the lift.

The bottom three CDU are associated with corresponding axes of the IMU. The top two CDUs are used with the two degrees of freedom of optics articulation as will be described in a later section.

Figure 29 shows the interconnections among the IMU, CDU, AGC, and spacecraft to accomplish the modes described.

Section 6. Computer Operation

Only general features of the Apollo Guidance Computer (AGC) will be given here since details of the logical organization are covered elsewhere.[3] This section will stress more the operations of information transfer with the other spacecraft equipment and the astronauts.

The Apollo computer is a general purpose, versatile, digital computer in the usual understanding of the term, but is very specifically organized for the requirements of Apollo space-flight data handling and computation. Basic word length in the parallel operations is 15 bits with an added bit for parity check with routines for double and triple precision operations as required. Single precision additions have a 20 μsec instruction time while double precision multiply subroutine is 800 μsec.

Programs and fixed data are stored in a 12,000 word core rope memory. Variables are stored in a 1000 word coincident current Ferrite matrix erasable memory. Memory capacity can easily be almost doubled by eliminating the feature of the computer providing storage of its own spare replaceable modules within its basic case.

Use of the computer, for the purposes of this report, are best described by the interfaces with other hardware. The following is not a complete listing of these input and output data transfer features but will serve to help understand computer capability.

Discrete inputs are of several kinds. A simple contact closure, for instance, telling the computer that the astronaut has turned on power to the optics subsystem or that the CDUs are operating with the IMU in a particular mode, are simple input bits appearing on separate lines which the computer can examine under program. More imperative data, like the detection of an emergency failure of the IMU, or the pushing of the computer keyboard buttons by the astronaut, cause interrupts to the existing computer operations so that early action, as required, is accomplished. The computer handles a number of programs at once with instructions being carried out in each in order of programmed priority, with less urgent programs getting their instructions handled after the more urgent are attended.

Discrete outputs are also of several kinds. Computer determination to turn on main rocket engines is signaled by the existence of a train of high frequency pulses on the particular lines to the engine control. The computer can change mode of operation of the various G&N subsystems by closing relays, under permission of the astronaut given either by the operations of the G&N controls or the computer keyboard.

Output variables are governed by the controlled number of pulses - or average pulse rate - sent on appropriate lines. Each of the five CDUs associated with the IMU and optics subsystems can have their shafts controlled by the computer in this fashion. Engine thrust level is similarly controlled when operating with a throttleable engine.

Input variables arrive as a sequence of single pulses representing increments (or decrements) in the variable and go to counters in the computer. Incremental encoders on each CDU shaft provide shaft angle data of this nature. Velocity increments from the Pulsed Integrating Pendulous Accelerometers mounted on the IMU stable member provide the sensed motion input from the IMU as a train of pulses.

Contents of particular registers in the erasable memory are arranged into words with appropriate identifying code for serial delivery to the telemetry system. After completion of the transmission of each word to the ground, a new word is assembled with new data under program or keyboard control.

For ground checkout on the launch pad, the checkout gear can transmit serial words to the computer through the umbilical which are decoded into the same format and treated exactly, by the computer, as are computer keyboard data to be described.

The communication between the computer and the astronaut is accomplished by the computer 21 digit character display and 12 button keyboard control as shown in Figure 30.

The three, two-digit displayed numbers labeled "program", "verb", and "noun" utilized a code which is listed for the astronaut prominently on the front of the G&N/D&C panel (see Figure 36). "Program" refers to the major operation mode of the computer such as "translunar injection", "midcourse navigation", or "entry". The "verb" and "noun" are taken together to give numerous possibilities of meaningful imperative sentences requiring only a limited vocabulary of verbs and nouns. Examples of verbs and nouns are listed below in acceptable pairs:

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Verb	Noun
Display Value	Position
Display Uncertainty	Velocity
Compute	Abort Velocity
Read In	Star-Planet Angle
Change Program	Lunar Orbit Insertion

Paired verbs and nouns which are meaningless or not in the computer program repertoire will not be accepted by the computer through the keyboard and the astronaut is so informed by the "illegal order" error light at the top of the panel of Figure 30.

A verb is inserted by the astronaut by first pushing the verb key and then the two digit verb code. The display then lights up with the verb accepted by the computer. Then the noun is pushed in, similarly. If data also must be inserted, this is punched in with the numbers appearing as they are accepted. The computer takes no action on the verb, noun, and data until the astronaut is satisfied with the received sentence and pushes the enter button. If he sees a mistake, he pushes "Clear" and starts over.

When the computer wishes to communicate to the astronaut a request for data or signify an alarm, the verb and noun numbers flash at 1.5 cps until the astronaut takes action.

Detected failures within the computer are displayed on the lights at the top of the panel. If the error reset button does not correct the problem, various levels of diagnostic procedures have been worked out to identify what replaceable module is at fault. This capability for in-flight repair increases mission and safety probabilities by a tremendous factor.

The computer display and control panel of Figure 30 is located at the command module lower equipment bay next to the rest of the G&N equipment. A slightly abridged version operating in parallel with this panel is mounted on the main display area between the center and left astronauts.

Section 7. Optics Operation

The sextant, telescope, and associated support hardware of the optics subsystem are used for a number of measurements:

1. Star - earth landmark midcourse angle measurement
2. Star - moon landmark midcourse angle measurement
3. Star - earth illuminated horizon angle measurement
4. Star - moon illuminated horizon angle measurement
5. Star - earth dark horizon refraction time measurement
6. Star - earth dark horizon attenuation time measurement
7. Star - moon occultation time measurement
8. Earth landmark direction measurement
9. Moon landmark direction measurement
10. Star direction IMU alignment measurement

Only measurements 1, 3, and 8 will be described in this report to show the general methods available in the Apollo optics subsystem configuration.

Figure 31 shows optical schematics of the two instruments shown in more detail back in Figures 12 and 13. The sextant landmark sight line is fixed to the spacecraft along the shaft axis; the sextant star sight line has shaft axis and trunnion axis articulation as does the scanning telescope line of sight. These motions alone are not enough to provide the necessary operations of the instruments. First of all, the limited unobstructed field of view requires at least some spacecraft orientation control just so that the objects can be acquired. The sextant use is more constraining since the landmark line is rigidly fixed to the spacecraft along the shaft axis requiring that the shaft axis be aimed at the landmark, within the field of view, by orientation of the spacecraft.

Figure 32 shows the relationships along spacecraft roll, pitch, and yaw axes, the attitude control jets, and the optics instruments shaft axes. From this figure the motions of images in the optics fields resulting from spacecraft roll, pitch, and yaw motions can be inferred.

Figure 33 shows these motions within the field of unobstructed view of the instruments. Three sets of contour lines show directions of local image motions in a field identified in polar coordinates corresponding to the shaft and trunnion angles. The three sets of contours correspond to roll, pitch, and yaw spacecraft motions.

The sextant landmark-line, along the shaft axis, is in the center of the figure with the 1.8 degree field shown. Spacecraft pitch motion causes images to move vertically (in the normal sense of the observer astronaut) while roll motion causes "across" image motion. Note that yaw could also be used for "across" control but is less satisfactory as far as curvature of local field motion is concerned, and also requires more attitude fuel burning due to the larger yaw axis inertia. Thus the landmark line can be aimed by logical and easily interpreted controlled motions of spacecraft roll and pitch.

The star-line of the sextant is displaced from the landmark-line by the trunnion angle in a direction determined by the shaft angle. Trunnion angles are limited to within 50 degrees or so because of line-of-sight interference with local spacecraft structure. The star image would normally be moved in the 1.8 degree field by controlled motions of the shaft and trunnion. Controlled spacecraft motions, in order to keep the landmark in the field, cause roughly parallel motions of the starline - the variations increasing for the larger trunnion angles. The operation of the sextant, then, during the final measurement is roll and pitch, controlled periodically to keep the landmark in the field, and shaft and trunnion control to achieve the required superposition of the star on the landmark.

The scanning telescope can be made to look along the shaft or to follow the same shaft and trunnion angles as the sextant. With its much

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wider field of view - 60 degrees at unity power - it, then, is used as a recognition and acquisition aid for the sextant.

The control of spacecraft orientation and optics articulation is diagrammed in Figure 34. Three control sticks for the navigator's use are shown on the left.

The top stick controls single impulse bursts from the appropriate attitude jets. An up motion of the stick causes one small torque impulse burst from the positive pitch jet causing a positive pitch angular velocity change of 1 minute per second for the light vehicle to something much smaller than this for the fuel- and LEM-heavy configuration. A resulting motion of the landmark in the down direction follows. Letting the stick return to center and pushing up again causes a second downward velocity increment of images in the field of view. Pushing the stick to the left and right cause corresponding increments in "across" velocity of the images by use of small roll impulses. This stick is used for vernier control of spacecraft motion and as a corresponding fine control to hold the landmark in the 1.8 degree field of view of the sextant.

The bottom stick in Figure 34 is used for coarse control and slew. This stick is normally mounted on one of the couch arm controls but is moved below to the navigation station during navigation operations. A flexible cord from the stick allows use at either station. This stick commands roll, pitch, and yaw spacecraft angular velocity. With this portable hand controller, the navigator will bring the spacecraft to the sighting orientation. After this he will use the single impulse stick to stop residual motion and perform fine control. While under single impulse control the normal spacecraft attitude control system is disabled and only the single impulses may occur in response to navigator commands.

The center stick in Figure 34 is used for control of shaft and trunnion of the optics. A resolver is shown which may be selected to give up-down and left-right control instead of the shaft centered, polar motion resulting from by-passing the resolver. The cosecant attenuation on the shaft drive signal changes the shaft control gain as a function of trunnion angle so that shaft motion gain from the stick in the field of view is independent of the size of the trunnion angle. The stick sends angular velocity command signals to two small CDU velocity servos (physically identical to the IMU CDUs of Section 5), where the corresponding shaft and trunnion commands are integrated and displayed on dials. The commanded angles are here encoded on an incremental encoder for summation in the digital computer. The provision for zeroing of this encoding system is not shown.

The sextant shaft and star-line trunnion follow precisely the commanded angles. Necessary accuracy is obtained on the sextant trunnion transmission by use of a multipole, ultra precise, resolver-transmitter which provides a 64 speed electrical signal while its rotor operates at one speed on the sextant trunnion. The corresponding receiver system in the command servo has a normal precision one-speed resolver-receiver geared to 64 speed and located close in the gear train to the readout dials and the encoder.

The scanning telescope follows the command shaft angle all the time. The telescope trunnion drive may be set (1) to follow the sextant trunnion command, or (2) may be set to zero to look along the shaft, or (3) may be set to 25 degrees offset. This third position is advantageous for sextant target acquisition, as will be shown.

Figure 35 shows the area of interest of the displays and controls mockup used in operation of the optics. The initial acquisition with spacecraft orientation is done by the navigator with the right hand while he is looking through the scanning telescope. After this his left hand is used with the optics control stick while his right hand can provide, periodically, the necessary small impulses from the impulse control stick. When a satisfactory alignment is controlled with the left hand and observed through the sextant, the right hand is available to punch the "mark" button which causes the computer to record the time and appropriate angles.

Star-Earth Landmark Midcourse Angle Measurement

The general situation for a midcourse navigation sighting is illustrated in Figure 36. This shows the acquisition orientation of the spacecraft with the optics shaft axis and sextant landmark-line pointed to the desired feature on the planet. This operation may be accomplished by the use of the wide field of the telescope with its trunnion set on zero. Just prior to this time, the expected star-landmark angle may be set into the sextant trunnion as shown.

After initial rough orientation of the spacecraft with the telescope trunnion on zero, the 25 degree offset can be set which would cause a view through the telescope, for example, as shown in Figure 37, where the earth is seen from 50,000 miles. The small circle 25 degrees from the center then is along the shaft axis and represents what would be seen in the 1.8^{o} landmark field in the sextant. The navigator can periodically control small impulses to keep the landmark in the small circle while he slews the shaft to acquire the star. The star should come up on the scale, shown in the reticle, at the expected trunnion angle. The wide field of view provides ample neighboring stars to assure recognition of the navigation star being used. After the shaft is controlled to put the star nearly on the index line, with the trunnion of the sextant preset to the expected value, and with the landmark inside the small circle, the navigator is assured that both the landmark and the proper star images will appear within the superimposed fields through the sextant.

What he sees now, when he changes over to look through the sextant, will be as shown in Figure 38. The landmark, in this case, might be a distinct pointed peninsula on the Isle of Pines off Cuba. With the small impulse control stick he will keep spacecraft motion such that this target drifts slowly across the field. If necessary, near the edge he can reverse its motion to drift back. Meanwhile, with his optics control, he attempts to achieve superposition of the star on this landmark - or, lacking this, to set up so that the two objects are equidistant from any one of the array of parallel "M" (for measurement) lines shown.

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The exact control at this point is worth more careful study. The spacecraft, if it has any angular velocity about a random axis, can move the landmark and star in the field in any combination of three modes. (1) It could make the star and landmark move together in the field along M lines; (2) It could make them move together across M lines; or (3) it could make them separate or come together in a direction along M lines. A fourth possibility, having them separate or come together across M lines, cannot happen due to spacecraft angular velocity because of the purposeful feature of this sextant - or any sextant - which prevents an acceptable measurement situation from being affected by rotations of the instrument as a whole. This counter motion across M lines can be controlled only by trunnion angle changes and will change independently only as the direction to the landmark changes with respect to the stars. The landmark angular velocity will be the result of the spacecraft linear velocity component across the line of sight. Values of the order of 1 milliradian per second or less are typical of the midcourse situation.

The most precise operation, then, appears to consist of setting up a situation with the trunnion command held stationary such that the images are coming together as the star-landmark angle is changing. The shaft control alone can be used to keep the two images close together along the M line direction. As the two images pass over each other the navigator pushes the "mark" button which records the existing precision measurement angle and records the time of the event. Experience may show that tracking "on the fly" may be entirely satisfactory, however. Accuracy of 10 arc seconds is typical. This corresponds to almost 5 arc minutes in the 28 power field of view.

Star-Earth Illuminated Horizon Angle Measurement

This measurement utilizes the atmospheric scattering of sunlight phenomena described in Section 2, Figure 6. Because the eye is so poorly adapted to making absolute brightness estimates, an automatic eyepiece is substituted on the sextant for the visual eyepiece. This eyepiece has a rotating wedge star tracker which sends tracking error signals to the optics CDU drives positioning the articulating line of sight of the sextant to the chosen star. The landmark-line is pointed by spacecraft attitude control commands toward the horizon. The intensity of the horizon is sensed in the automatic eyepiece. The specific controls for this mode of operation are shown on Figure 35 labeled NVE for non-visual eyepiece. The intensity level is preset according to the sun aspect angle. The NVE level meter indicates unity when the detector sends a "mark" to the computer. Special procedure is necessary to assure that the horizon is directly below the star being tracked.

Earth Landmark Direction Measurement

The navigation situation for orbital operations is illustrated in Figure 39. The technique is equally applicable in lunar or earth satellite orbit. The spacecraft orientation is shown with the roll axis forward and horizontal. Other orientations are possible but this attitude has what is judged to be the best features.

The landmark is chosen to be reasonably close to the orbit ground track so that it will pass close to underneath the craft. The target is tracked with the scanning telescope to achieve a measurement.

The view in the telescope during this orbital navigation is shown in Figure 40. Acquisition consists of first picking up the target as it comes into view from the horizon by gross roll motion and forward trunnion setting. A period for recognition and acquisition of about 30 seconds or so is expected. Finally the trunnion shaft is used to track along its path by controlling the image to stay at the center of the reticule. During acceptable tracking, the navigator pushes the "mark" button which records time, the telescope trunnion angle, and IMU gimbal angles. The IMU was previously aligned, of course, with star sightings. The computer uses these data to improve its orbital navigation knowledge.

Section 8. Astronaut Operations

In the previous sections a number of operations associated with G&N hardware were described in which the astronaut was involved and had direct control and choice. This section will complete the description of design features concerning the operation by the navigator.

Information on standard and emergency procedures, diagnosis and repair, star charts, earth and lunar maps, etc. are displayed on the map and data viewer, Figure 41. This projection system takes film cartridges and displays data with high resolution on a 42 square inch screen. It is estimated that five of these cartridges would be carried on a lunar landing mission. This would correspond to about 9000 frames with high information density. Each cartridge can be removed and inserted with any frame in projection position. Motor slew of the film drive is provided.

To the right of the viewer in Figure 41 are condition lights informing the navigator of detected subsystem errors. Error detection at critical points throughout the equipment monitor error signals which are combined by logical "or" into groups of master error detection signals: "IMU fail", "accelerometer fail", etc. The ones which would sense emergency conditions are sent as discrete bits to the computer which, at astronaut option, can be instructed to take the appropriate emergency action. In any event, the computer displays the condition on the subject lights (and a corresponding set at the main panel). If the computer is not operating, the top light in the series "error detect" will be lit if any error is detected anywhere by the error monitors. The multitude of monitor points which make up the failure detections can be sampled individually by the spacecraft in-flight test system in order to localize the failure. Repair consists of replacing the failed module with a spare. A minimum of spares can back the many modules due to the purposeful design constraint of minimizing the number of different modules.

If failure occurs, each of the major subsystems can be individually turned off. The design is such that the remaining operating equipment can be usefully utilized in back-up modes of

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operation. The spacecraft stabilization and control system can be used by the crew utilizing ground track information via voice radio to provide backup for complete G&N failure. The chances of these failures is small due to the extensive reliability provisions now being used for qualification of manned and unmanned space flight hardware.

It is this ability for making in-flight repairs and operating in alternate and backup modes by which the astronauts enhance the operations of the mission.

Other capabilities of man not easily instrumented are utilized in Apollo. Specifically, the remarkable ability to recognize star and landmark patterns from charts and maps is a unique asset possessed by the astronauts. Another is man's judgement in determining proper operation of his equipment and optimum course of action.

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In summary, we have described a flexible system for manned operations. Almost every function can be accomplished automatically to relieve strain and tedium on the navigator, but he is given information in displays and command in controls to take over usefully at his discretion to enhance the probabilities of mission success and crew safety. We see a balance between complex and high speed measurement and data processing of the automatic equipment operating with the wonderfully adaptable sensors and judgement of man in a difficult task: the guidance and navigation for a moon trip.

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2. W. E. Toth, "Visual Observation of Landmarks," MIT Instrumentation Laboratory Report E-1067, (Monthly Technical Progress Report Project Apollo Guidance and Navigation Program, Period August 11, 1961 to September 13, 1961).

3. A. L. Hopkins, Jr., R. L. Alonso, and H. Blair-Smith, "Logical Description for the Apollo Guidance Computer," MIT Instrumentation Laboratory Report R-393, March 1963.

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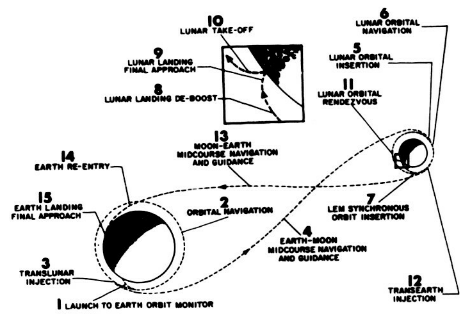

Fig. 1 Mission phase summary

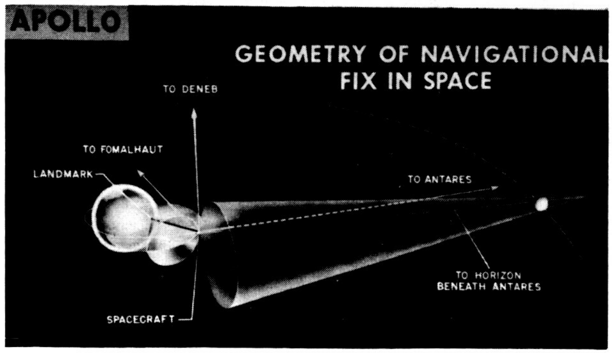

Fig. 4 Geometry of navigational fix in space

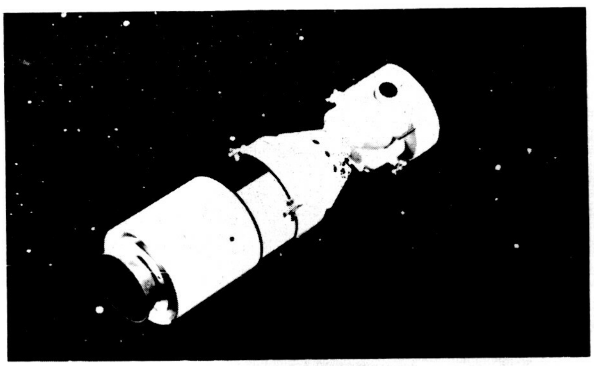

Fig. 2 CM, SM and LEM with translunar configuration

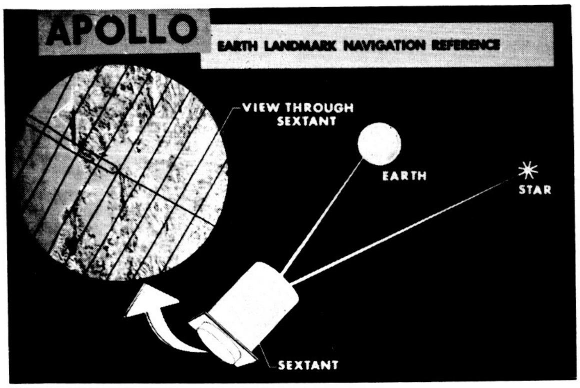

Fig. 5 Earth landmark navigation reference

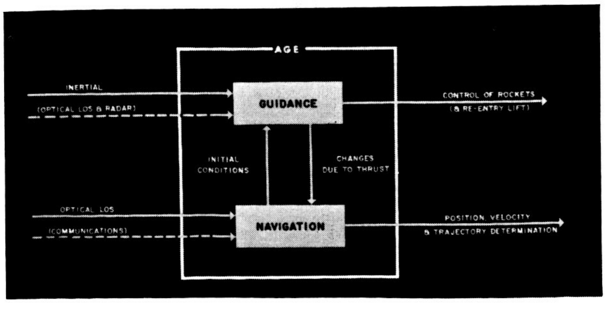

Fig. 3 G and N diagram

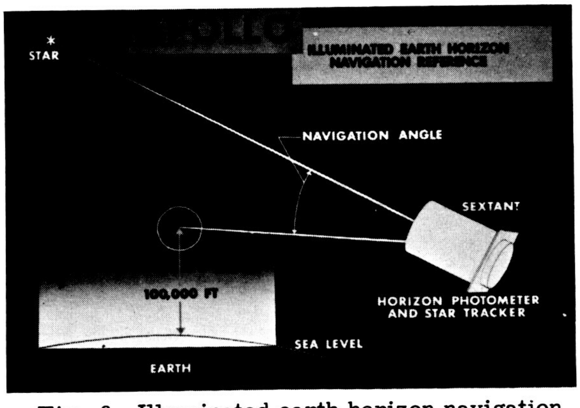

Fig. 6 Illuminated earth horizon navigation reference

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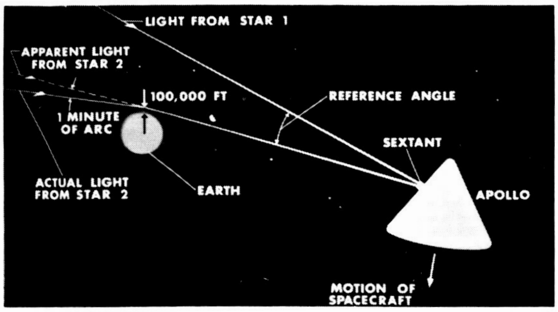

Fig. 7 Star refraction--earth horizon navigation reference

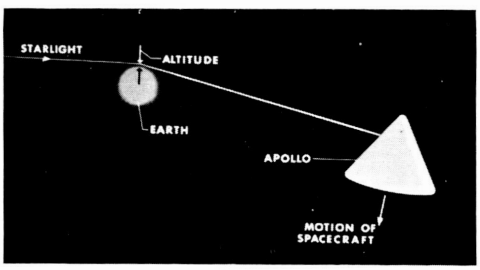

Fig. 8 Star attenuation--earth horizon navigation reference

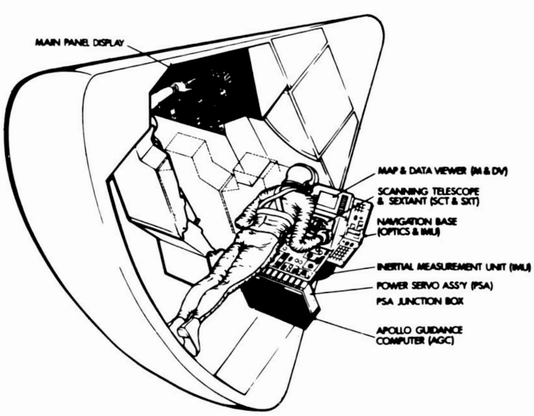

Fig. 9 Command module cutaway

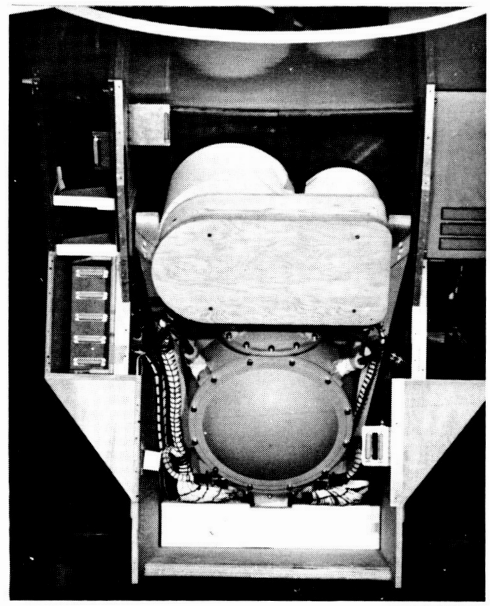

Fig. 10 Installation mockup

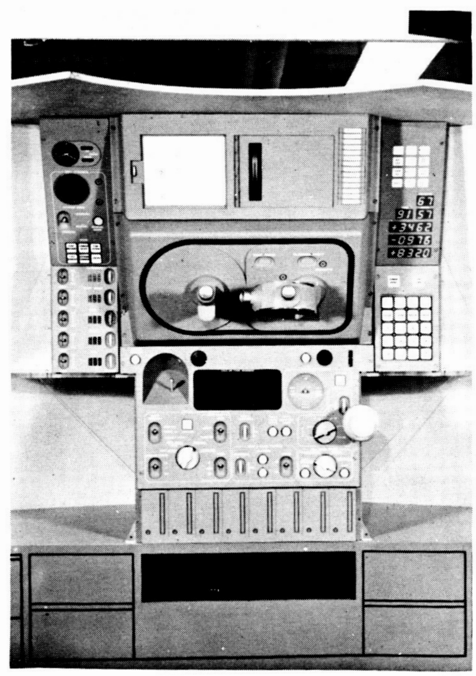

Fig. 11 Display and control mockup

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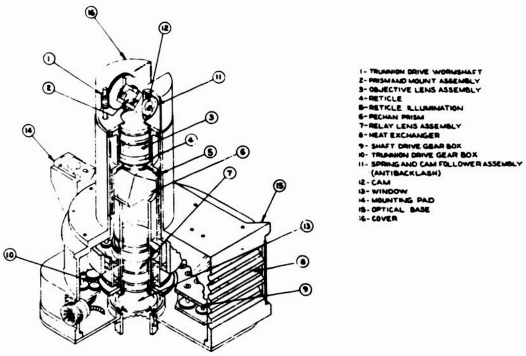

Fig. 12 Scanning telescope cutaway

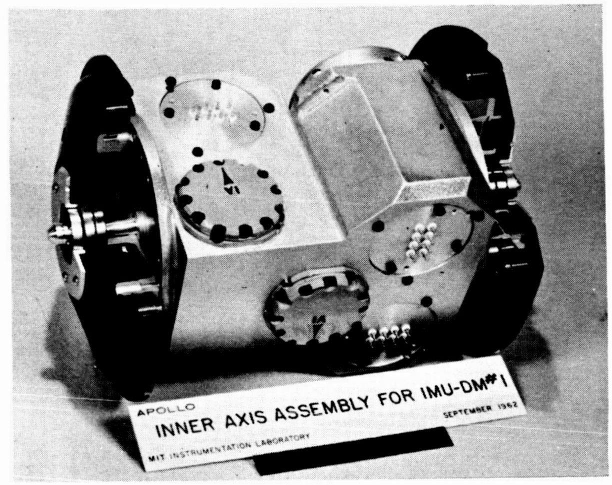

Fig. 15 Inner axis assembly for IMU-DM #1

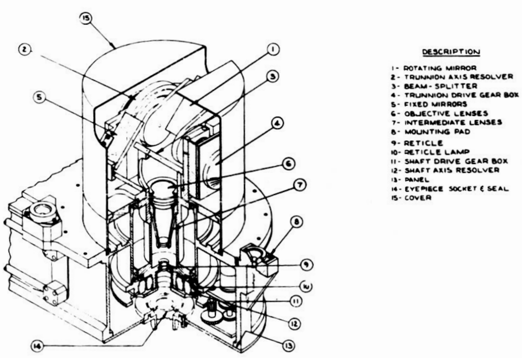

Fig. 13 Sextant cutaway

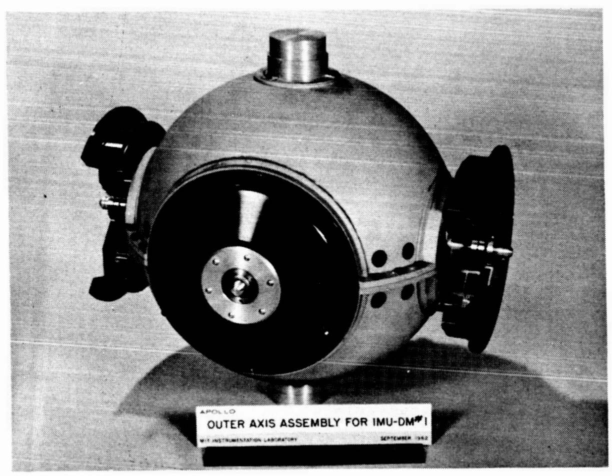

Fig. 16 Outer axis assembly for IMU-DM #1

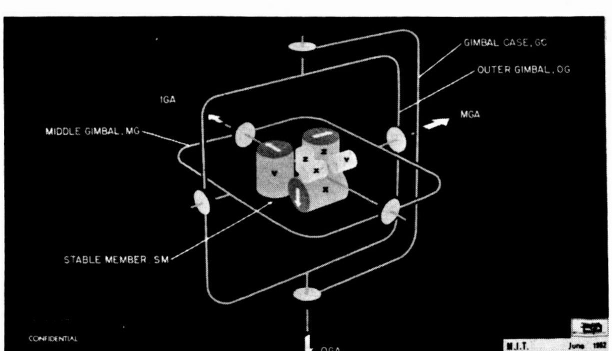

Fig. 14 IMU schematic

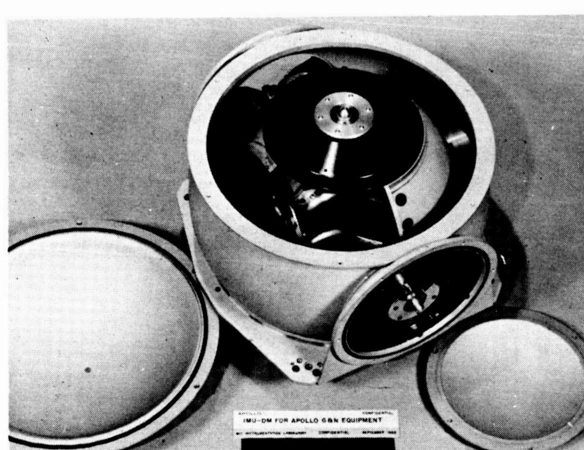

Fig. 17 IMU-DM for Apollo G and N equipment

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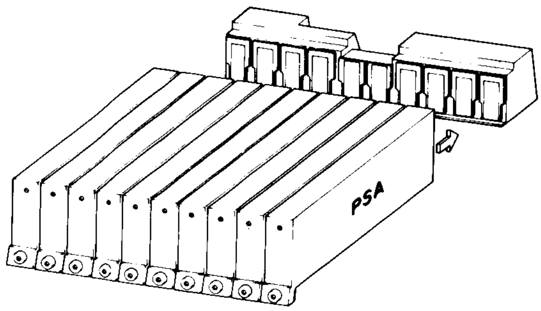

Fig. 18 Sketch of PSA

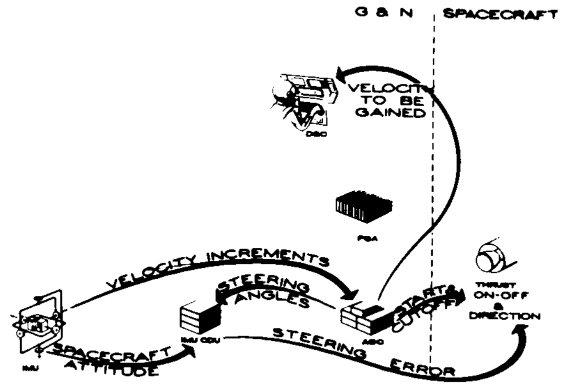

Fig. 21 Guidance and thrust control

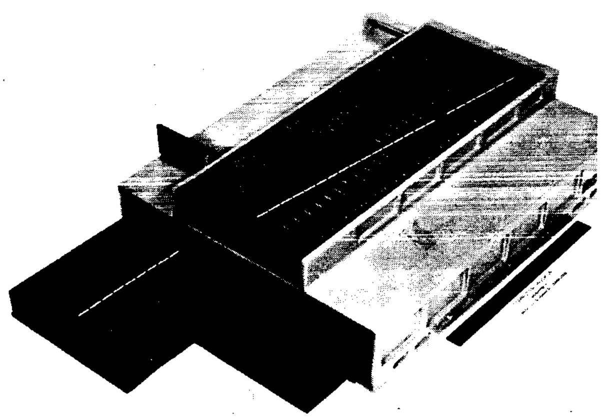

Fig. 19 Computer mockup

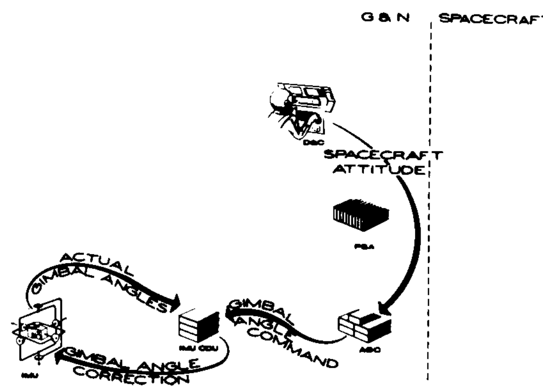

Fig. 22 IMU coarse alignment

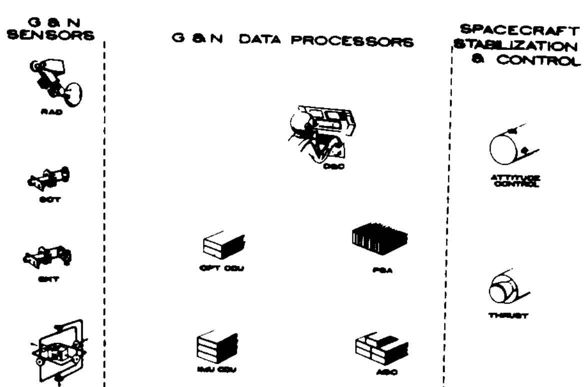

Fig. 20 Major subsystems

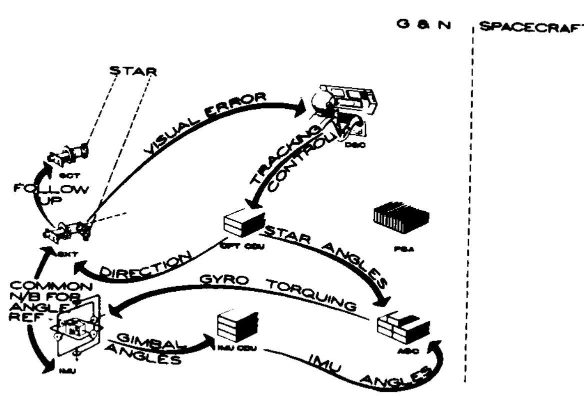

Fig. 23 IMU fine alignment

[redacted]

[redacted]

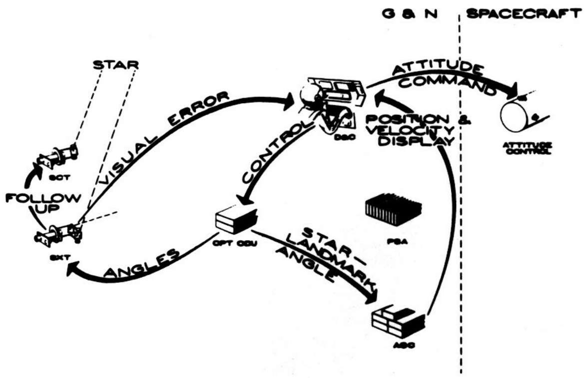

Fig. 24 Midcourse navigation

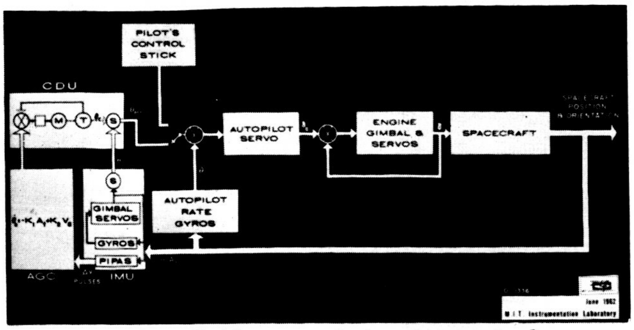

Fig. 27 Guidance and steering control

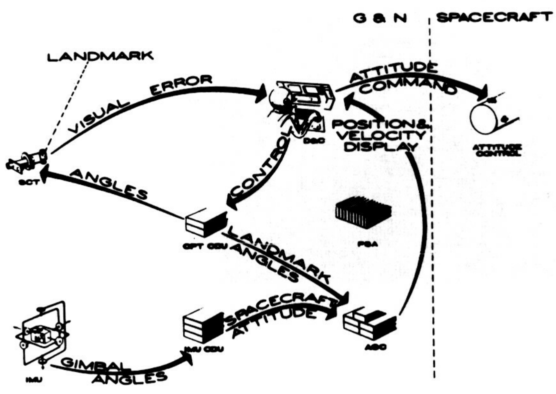

Fig. 25 Low orbit navigation

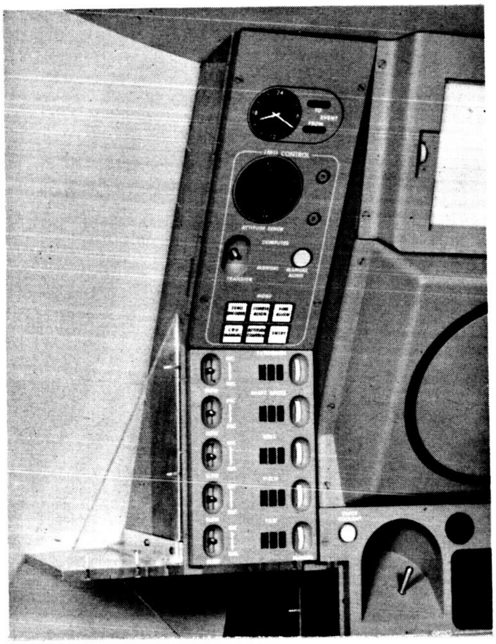

Fig. 28 IMU control panel and CDU panel

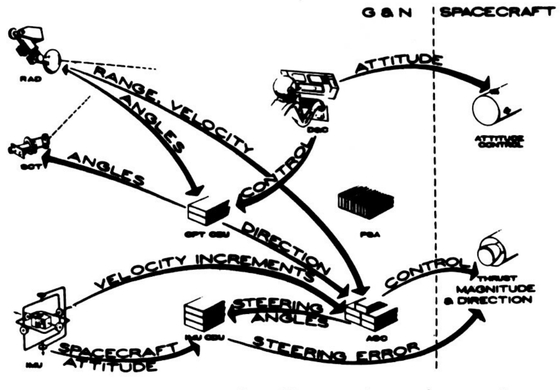

Fig. 26 Lunar landing and rendezvous

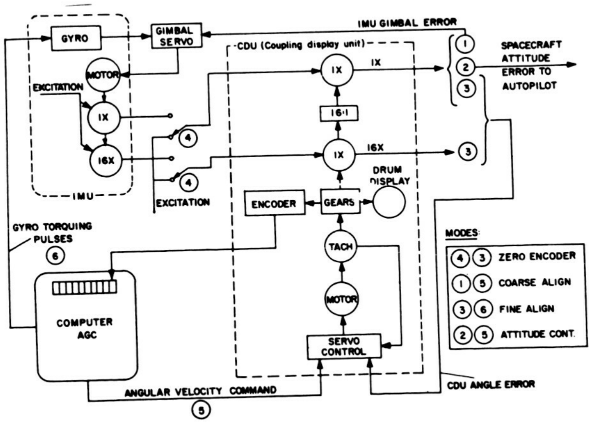

Fig. 29 Single axis schematic--IMU, CDU and AGC operation

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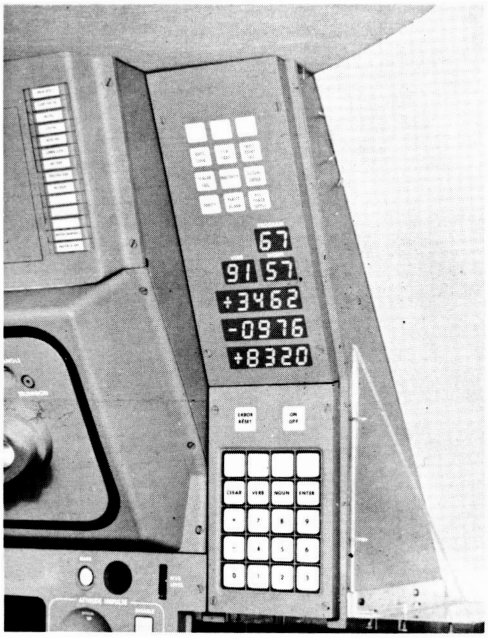


Fig. 30 Computer display and control panel

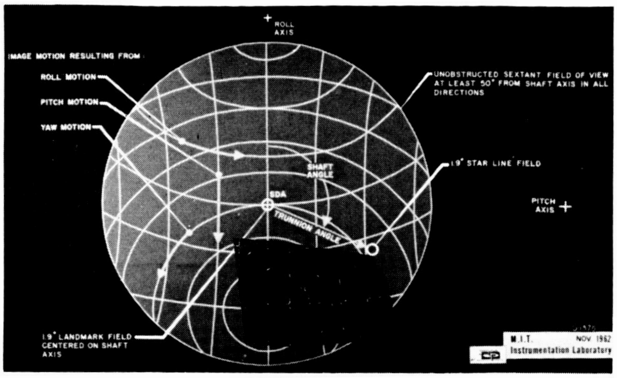


Fig. 33 Sextant field notions

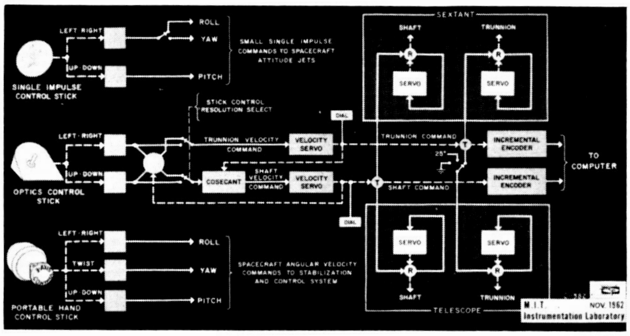


Fig. 34 Optics control instrumentation block diagram

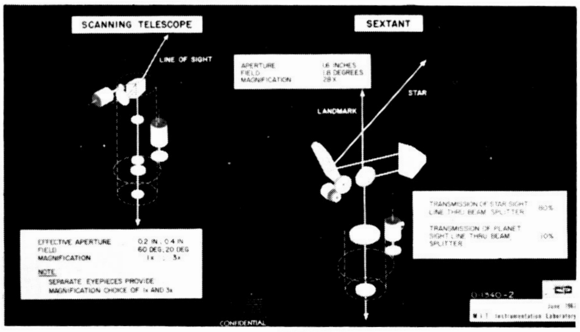
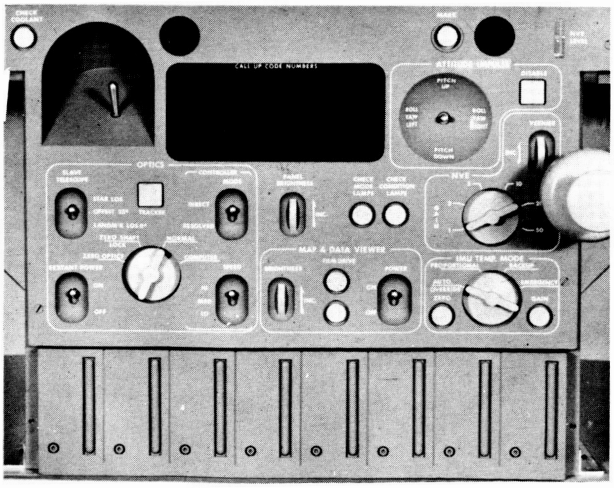


Fig. 31 Optical schematics



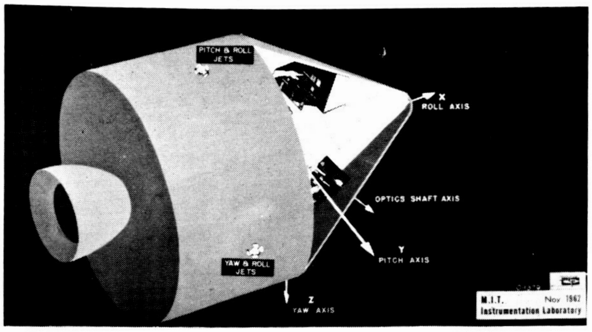


Fig. 32 Spacecraft and optics axes

Fig. 35 Optics control panel

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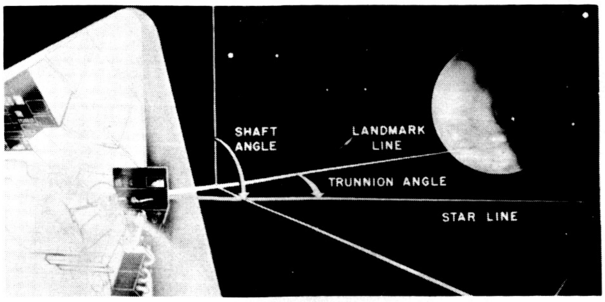

Fig 36 Spacecraft orientation midcourse navigation sighting

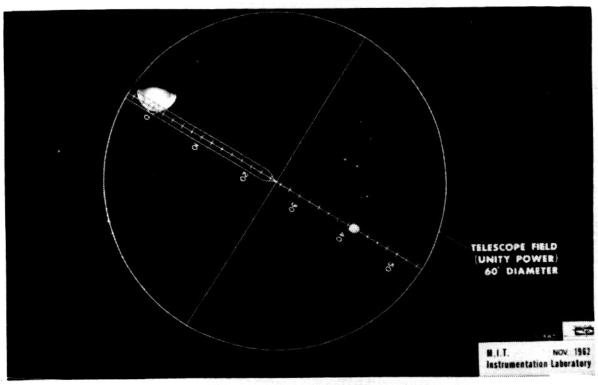

Fig. 37 Telescope view--midcourse navigation

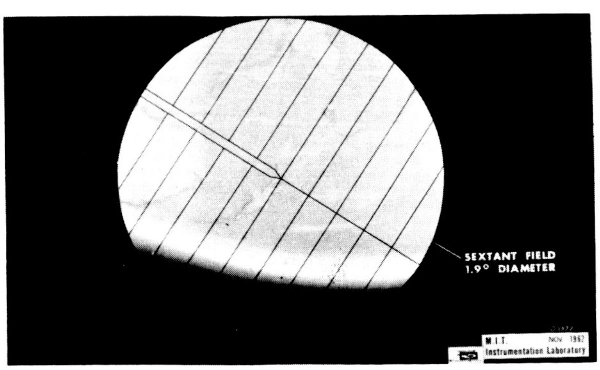

Fig. 38 Sextant view--midcourse navigation

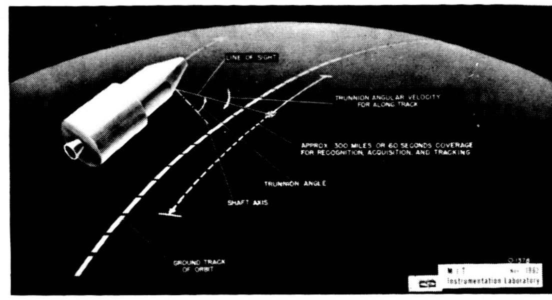

Fig. 39 Spacecraft orientation--orbital navigation sighting

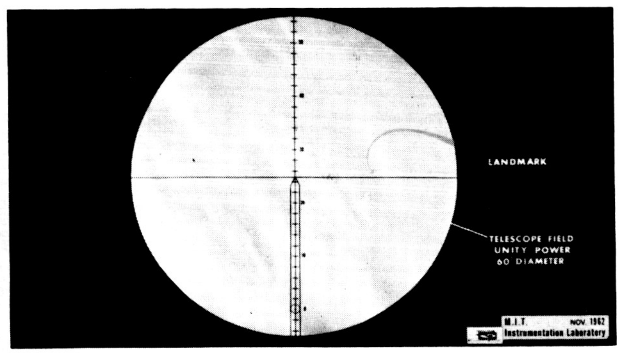

Fig. 40 Telescope view--orbital navigation

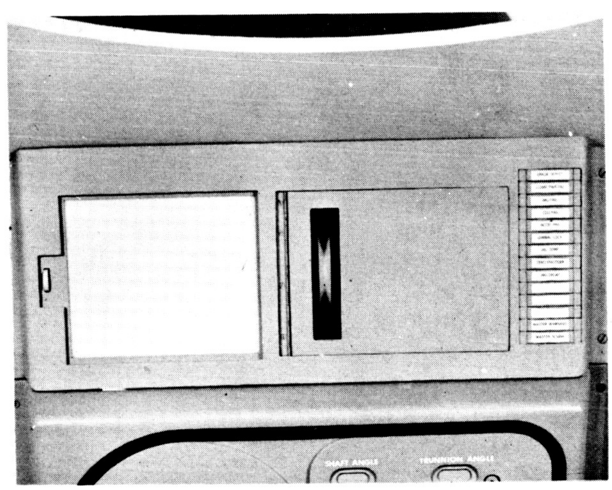

Fig. 41 Map and data viewer mockup