GUIDANCE AND NAVIGATION

NAVIGATION BASE AND INERTIAL MEASUREMENT UNIT (BEHIND)

ACCELEROMETER ELECTRONICS

EYEPIECE STORAGE

SIGNAL CONDITIONER

KEYBOARD

CONTROL PANEL

ROTATION HAND CONTROL MOUNT

SEXTANT TELESCOPE

COMPUTER

COUPLING DATA UNIT

POWER SERVO ASSEMBLY

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Location of guidance and navigation equipment in lower equipment bay

The guidance and navigation subsystem gives astronauts the ability to navigate the spacecraft on a required course through space. It can be operated either semi-automatically or manually and performs the basic functions of guidance and navigation -- similar to the navigation of an airplane or of a ship at sea. It can also be updated by the ground via telemetry.

While an airplane or ship at sea is concerned with two-dimensional navigation (it is always on or near the surface of the earth), Apollo is faced with exacting three-dimensional navigation as it speeds through deep space. Sightings from the spacecraft of stars and pre-determined landmarks on the earth and moon are used to establish the location and path of the spacecraft in space. The guidance and

navigation system is used in conjunction with the stabilization and control, service propulsion, reaction control, electrical power, environmental control, and telecommunications subsystems.

Massachusetts Institute of Technology, an associate contractor to NASA's Manned Spacecraft Center, is responsible for development and design of the subsystem. AC Electronics Division of General Motors is responsible for its production, operation, and integration. The guidance computer is manufactured by the Raytheon Co. and the optics are produced by Kollsman Instrument Co.

There are three main elements in the guidance and navigation subsystem. The inertial guidance subsystem measures changes in the spacecraft position and

velocity and assists in generating steering commands. The optical subsystem is used to take precision navigational sightings and provide the computer with measured angles between the stars and landmarks. The computer subsystem consists of a digital computer which takes data from the inertial guidance and optical subsystems and calculates spacecraft position, velocity, and steering commands.

The components of the guidance and navigation subsystem, including the primary controls and displays, are located in the lower equipment bay of the command module. The main display console contains the switches and displays necessary for the astronauts to control the spacecraft while in their couches.
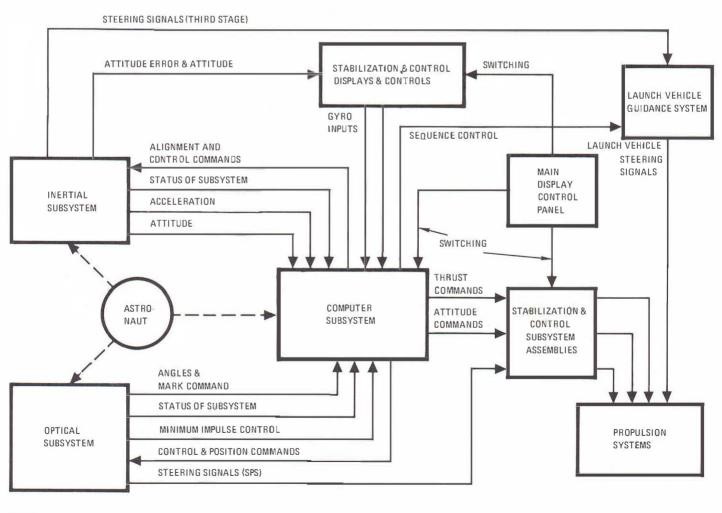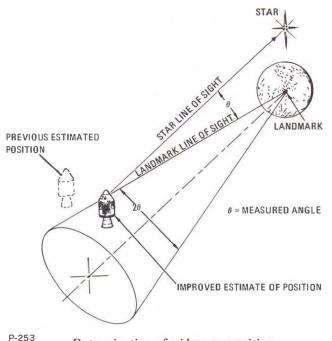
INERTIAL GUIDANCE SUBSYSTEM

This subsystem measures changes in the spacecraft position, assists in generating steering commands, and measures spacecraft velocity changes. Its instruments sense changes in velocity and attitude in a manner similar to the balance system in the human ear.

The main part of this subsystem is an inertial measurement unit mounted on a navigation base. The key part of this mechanism is a device called a stable platform, suspended on gimbals which allow it to incline freely regardless of spacecraft position. It is aligned to star direction references and retains this alignment regardless of the rotational movement of the spacecraft and thus provides a reference against which the movements of the spacecraft can be measured.

Mounted on this stable platform are the actual sensors: three accelerometers and three gyroscopes. The gyros are used to keep the stable platform fixed with respect to some point in space. The accelerometers sense any change in the speed of the vehicle -- forward, backward, up, down, sideways.

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Data flow in guidance and navigation subsystem

Determination of midcourse position

Any change from the pre-determined flight path or attitude generates electronic signals which result in firing of the reaction control subsystem engines (for attitude change only) or positioning of the service propulsion engine for flight path changes. The service propulsion engine is fired on signal from the computer or astronauts.

Devices known as resolvers, mounted on the gimbal axes, measure how far the spacecraft has rotated with respect to the stable platform. These measurements are transmitted to the guidance computer. While the gyros are used to maintain the spacecraft in a required attitude, the resolvers are used primarily to orient the spacecraft when firing the service propulsion engine.

The inertial guidance subsystem is controlled automatically by the guidance computer through crew selection of a computer program.

OPTICAL SUBSYSTEMS

This subsystem is used by the astronauts to take navigational sightings of the stars and earth or moon landmarks. It consists of a navigation base, a telescope, a sextant, and equipment to permit operation with the computer and inertial guidance subsystems.
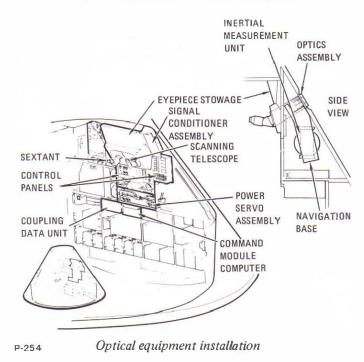
The telescope and sextant can be operated independently but generally are used together to obtain precision navigational sightings. The telescope has a 60-degree field of view with no magnification and is used to obtain coarse sightings of the stars or landmarks. Because of the telescope's limited field of view, controls are provided so the astronaut can maneuver the entire spacecraft to point the instrument in the general desired direction. The sextant is used to take the precision sightings and has a much smaller field of view (1.8 degrees) but has a magnification of 28.
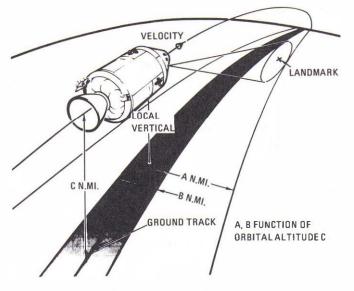
These two instruments are used to measure the angle between two targets such as stars and earth or moon landmarks. The telescope and then the sextant are manipulated by the astronaut to line up a sighting and enter the reading into the computer.

COMPUTER SUBSYSTEM

This subsystem consists of a digital computer which stores and uses signals from the inertial guidance subsystem and sightings by the optical subsystem with other data. This highly sophisticated computer uses this data to calculate necessary corrections to maintain course. The computer memory contains 38,912 words, or pieces of guidance data, and is divided into non-erasable and erasable sections. The non-erasable memory contains all the basic data necessary to achieve the round trip to the moon. The erasable memory is used by the astronauts when performing the various guidance and navigation computations.

The major functions of the computer are to

Optical equipment installation

P-255   *Orbital tracking of landmark*

calculate spacecraft position, velocity, and steering data; to calculate the signals for the main engine and attitude control jets necessary to keep the spacecraft on the required flight path and attitude; to position the stable platform in the inertial measurement unit as defined by precise optical measurements; to position the optical unit to celestial objects; to monitor the guidance and navigation subsystems for failure indications; and to supply information to the display and control panel.
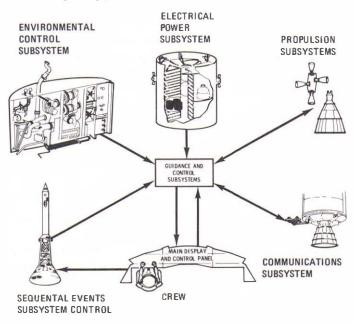
The display of information, the results of computations, and the control of the computer by the astronauts is accomplished with two display and keyboard panels. One is located in the lower equipment bay and the other (a duplicate) is on the main display console. Lights on the panels also indicate the detection of malfunctions in guidance and navigation systems.
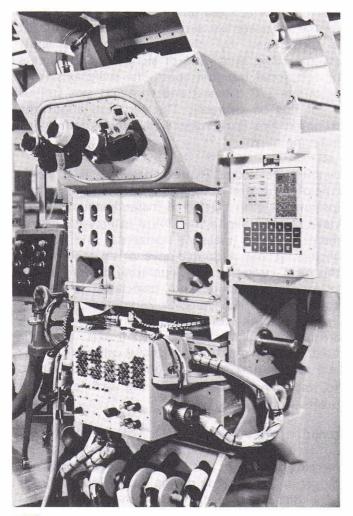
SEQUENCE OF OPERATIONS

Operation of the guidance and navigation subsystem in specific flight phases, control modes, and critical maneuvers during a typical lunar mission is described here briefly.

To conserve electrical power and fuel, the subsystem is activated only about 20 percent of the time, for specific sightings, alignments, and engine-firing maneuvers. Each time the guidance and navigation subsystem is activated the stable platform must be aligned with respect to a predetermined reference. Before launch the platform is aligned with respect

to the earth and during flight it is aligned to the stars.

Launch and Translunar Injection — Guidance of the launch vehicle is monitored during the ascent from earth and firing of the third stage which sends the spacecraft on a trajectory to the moon. At launch, the inertial measurement unit is switched from an earth reference to a space reference frame. The crew then uses the guidance and navigation subsystem to monitor the spacecraft flight profile.

Earth and Lunar Orbit — During these phases, the crew checks the spacecraft position and orbital path with optical sightings. The crew takes these sightings by identifying and tracking landmarks with the optical instruments. The computer records optical sighting data, spacecraft attitude, and the time of the optical sighting.

Midcourse Navigation — This may be performed several times during the translunar and transearth mission phases. Starlandmark sightings are taken and the computer records the angles and time of sighting and determines spacecraft position and velocity.

Course Correction — The spacecraft's course must be corrected during both the translunar and transearth journeys. The computer, after calculating spacecraft position and velocity from navigation sightings, determines the need for a course

Guidance and control relationship to other subsystems

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P-257 *Guidance and navigation equipment in test fixture simulating spacecraft installation*
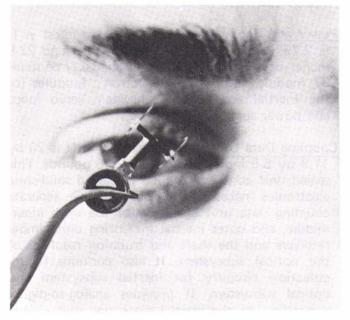
EQUIPMENT

The guidance and navigation system occupies a space 4 feet high, 2 feet deep, and about 3 feet across the top and 2-1/2 feet across the bottom. It is in the command module lower equipment bay.

Inertial Measuring Unit (AC Electronics Division of General Motors) — This ball-shaped unit has a diameter of 12.6 inches and weighs 42.5 pounds.

It consists of three gimbals of which the inner gimbal is the stable member, with three gyroscopes and three accelerometers, all can-shaped and mounted onto the stabilized inner member structure, or platform. The gimbals are connected to each other by drive motors and angle resolvers. The unit is pressurized in dry air for good heat transfer. When in operation, the unit requires 217 watts at 28 volts dc. It maintains an inertially referenced coordinate system for spacecraft attitude control and measurement and maintains three accelerometers in this coordinate system for accurate measurement of spacecraft velocity changes.

Navigation Base (AC Electronics) — This 27-by-22-by-4.5-inch unit weighs 17.4 pounds and is made of riveted and bonded anodized preformed sheet aluminum alloys. It is filled with polyurethane foam. It is a rigid supporting structure for the inertial measuring unit and optical equipment.

Power and Servo Assembly (AC Electronics) — It is 2.75 inches high, 23.1 inches wide, and 22.6 inches deep and weighs 49.4 pounds. It contains 37 modules, most of the electronic modules for the inertial and optical subsystem servo loops and power supplies.

Coupling Data Unit (AC Electronics) — It is 20 by 11.3 by 5.5 inches and weighs 36.5 pounds. This sealed unit contains modular packaged solid-state electronics necessary to provide five separate coupling data unit channels for use with inner, middle, and outer inertial measuring unit gimbal resolvers and the shaft and trunnion resolvers of the optical subsystem. It also contains failure detection circuitry for inertial subsystem and optical subsystem. It provides analog-to-digital conversion of the inertial measuring unit gimbal angles and optical subsystem trunnion and shaft angles, and digital-to-analog conversion of

correction by comparing the actual to the required trajectory. If a course correction is necessary, the computer calculates the time of firing and velocity change needed, repositions the spacecraft, and controls the initiation and duration of thrusting of the service propulsion engine.

Lunar Injection and Return to Earth — The guidance and navigation subsystem places the spacecraft into the attitude required for firing the service propulsion engine and controls the time of thrusting required.

Entry — The guidance and navigation subsystem controls the flight path of the command module during entry. The computer determines the proper trajectory and steers the command module by rolling it. This changes the lifting force acting on the command module and thereby varies its trajectory.

computer-derived data to control inertial subsystem and optical subsystem modes of operation using discretes issued by the computer. It also controls service propulsion system engine gimbaling, attitude error display, and, as a backup mode, it controls the attitude of the launch's third stage.
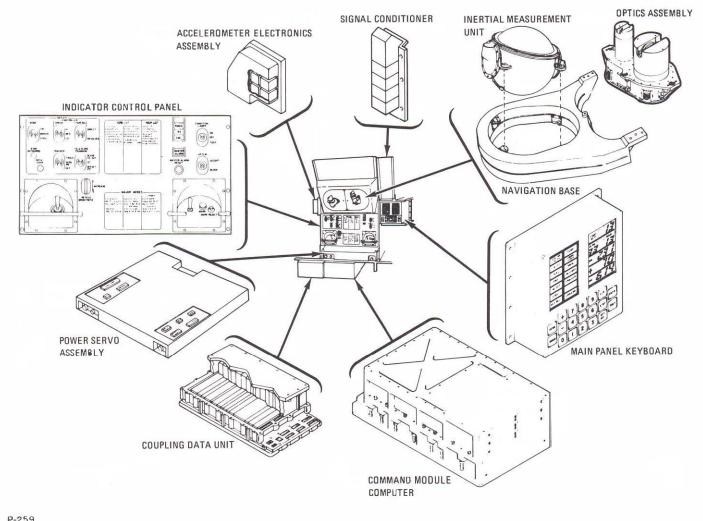
Inertial Reference Integrating Gyros (AC Electronics) — Three gyros are mounted mutually perpendicular to each other on the stable platform of the inertial measuring unit. Each is 2-1/2 inches in diameter. They sense displacement of the inertial measuring unit's stable platform and generate error signals. They are pressurized in an atmosphere of helium to provide good heat transfer.

Accelerometers (AC Electronics) — There are three pulse-integrating pendulous accelerometers mounted perpendicular to each other on the stable member of the inertial measuring unit. Each is can-shaped with a 1.6-inch diameter. They measure velocity changes along all axes of the three-axis inertial measuring unit.

Sextant (Kollsman Instrument Co., Syosset, N.Y.) — This is a highly accurate dual line-of-sight electro-optical instrument with 28X magnification and 1.8 degrees field of view. It can sight two celestial targets simultaneously and measure the angle between them with 10 arc seconds accuracy to determine the position of the spacecraft. It is mounted on the navigation base. One

This tiny pendulum is heart of an accelerometer, a key component in guidance and navigation subsystem.

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line of sight is fixed along the shaft axis normal to the local conical surface of the spacecraft. It is positioned by changes in the spacecraft attitude. The other line of sight has two degrees of rotational freedom about the shaft axis (plus or minus 270 degrees) and trunnion axis (minus 5 to plus 50 degrees). The variation about the trunnion axis is represented by movement of an indexing mirror.

Scanning Telescope (Kollsman) — It is a single line-of-sight, refracting-type, IX magnification instrument with 60-degree instantaneous field of view. It is similar to theodolite (surveyor's instrument used to measure horizontal and vertical angles). It has a double-dove prism mounted in the head assembly. The operating power for the telescope, sextant, and associated electronic equipment is 94.5 watts at 28 volts dc. The telescope has two axes of rotational freedom, which are normally slaved to the sextant axis. The wide field of view is used for general celestial viewing and recognition of target bodies. It is also used to track landmark points during earth and lunar orbits.

Computer (Raytheon Co.) — This is 24 by 12.5 by 6 inches and weighs 70.1 pounds with six memory modules. It consumes 70 watts of power at 28 volts dc during normal operation. It is a digital computer with fixed and erasable memory. The erasable memory has a capacity of 2048 words; fixed memory has a capacity of 36,864 words. The fixed memory contains programs, routines, constants, star and landmark coordinates, and other pertinent data. The computer solves guidance and navigation problems, provides control information to optical and inertial subsystems as well as other spacecraft systems, provides pertinent information to astronauts and the ground on request, provides means by which astronauts or ground control can directly communicate with the primary guidance navigation control system, provides direct on-off control for reaction control jets and service propulsion engines, and monitors its own operation and other primary guidance navigation control system operations.

Display Keyboard (Raytheon Co.) — This 8-by-8-by-7-inch panel weighs 17.5 pounds. It is made up of a keyboard, power supply, a decoder relay matrix, status and caution circuits, and displays. It is a 21-digit character display and a 16-button keyboard through which crewmen can

Major guidance and navigation subsystem equipment

communicate in a coded numerical language. Crewman inserts data and commands the computer by punching numbers on the keyboard. They are then displayed to him in electroluminescent counter-type readout windows. The computer communicates with the crewman by displaying numbers in the same windows. When the computer requests the crewman to take some action, numbers flash to attract attention.

Signal Conditioner Assembly — This 3-by 5.7-by-14.3-inch unit weighs 5.8 pounds. It contains encapsulated electronic circuitry to condition primary guidance navigation control system signals so that they are acceptable to the spacecraft telemetry system.

DETAILED DESCRIPTION

INERTIAL SUBSYSTEM

The inertial subsystem provides a space stabilized inertial reference from which velocity and attitude changes can be sensed. It is composed of the inertial measurement unit, the navigation base, parts of the power and servo assembly, parts of the control and display panels, and parts of the coupling data unit.
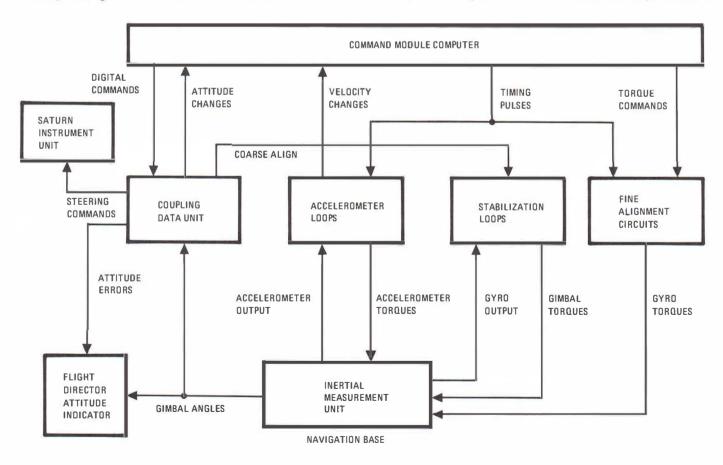
The navigation base is the rigid supporting structure on which the inertial measurement unit and optical instruments are mounted. It is manufactured and installed to close tolerances to provide accurate alignment of the equipment mounted on it. It also

provides shock mounting for the inertial measurement unit and optics.

The inertial measurement unit is the main unit of the inertial subsystem. It is a three-degree-of-freedom stabilized platform assembly, containing three inertial reference integrating gyros, and three pulsed-integrating pendulous accelerometers. The stable member is machined from a solid block of beryllium with holes bored for mounting the accelerometers and gyros.
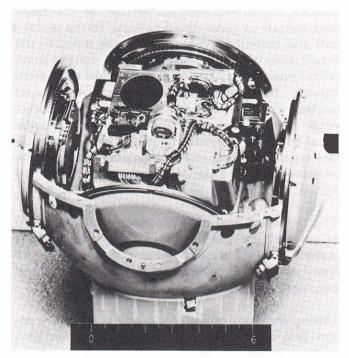
The stable platform attitude is maintained by the gyros, stabilization loop electronics, and gimbal torque motors. Any angular displacement of the stable platform is sensed by the gyros which generate error signals. These signals are resolved and amplified at the inertial measurement unit and applied to stabilization loop electronics. The resultant signal is conditioned and applied to the gimbal torque motors, which restores the desired attitude.

The stable platform provides a space-referenced mount for the three accelerometers, which sense velocity changes. The accelerometers are mounted

orthogonally (each at right angles to the other two) to sense the velocity changes along all three axes. Any translational force experienced by the spacecraft causes an acceleration or deceleration which is sensed by one or more accelerometers. Each generates an output signal proportional to the magnitude and direction of velocity change. This signal, in the form of a pulse train, is sent to the computer which uses it to update the velocity information.

Temperature is controlled by a thermostatic system that maintains the gyro and accelerometer temperatures within their required limits during inertial measurement unit standby and operating modes. Heat is applied by end-mount heaters on the inertial components, stable member heaters, and a temperature control anticipatory heater. Heat is removed by convection, conduction, and radiation. The natural convection used during inertial measurement unit standby modes is changed to blower-controlled, forced convection during operating modes. Inertial measurement unit internal pressure is normally between 3.5 and 15 psia, enabling the required forced convection. To aid in removing heat, a water-glycol solution passes through coolant

Block diagram of inertial subsystem

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Cutaway of inertial measurement unit

passages in the outer case of the inertial measurement unit. Therefore, heat flow is from the stable member to the case and coolant. The temperature control system consists of the temperature control circuit, the blower control circuit, and the temperature alarm circuit.

The coupling data unit is an all-electronic device used to convert and transfer signals among the inertial, computer, and optical subsystems and between the computer and various controls and displays. Each of the five channels has two sections: one acting as an analog-to-digital converter and the other as a digital-to-analog converter. These five channels are: one each for the inner, middle, and outer inertial measurement unit gimbals, and one each for the shaft and trunnion optical axes. Each channel converts inertial or optical gimbal angles from a resolver analog form to a digital form, supplies the computer with this information, and converts digital signals from the computer to either 800-cycle per second or direct current analog signals. The coupling data unit also controls the modes of the inertial and optical subsystems through logical manipulations with the computer.

The power and servo assembly provides a central collection point for most of the guidance and navigation subsystem power supplies, amplifiers, and other electronic components. It is located in the lower equipment bay directly beneath the inertial measurement unit. It consists of 42 modules mounted to a header assembly. Connectors and harnessing are integral to the construction of the header assembly, and guidance and navigation harness branches are brought out from the power servo assembly header. A thin cover plate is mounted on the assembly to provide a hermetic seal for the interior. During flight this permits pressurization of the assembly to remain at 15 psi. Connectors are available for measuring signals at various system test points.

OPTICAL SUBSYSTEMS

The optical subsystem is used to take precise optical sightings of celestial bodies and landmarks. These sightings are used to align the inertial measurement unit and to determine the position of the spacecraft. The system includes the navigational base, two of the five coupling and data units, parts of the power and servo assembly, controls and displays, and the optics, which include the scanning telescope and the sextant.

The optics consist of the telescope and the sextant mounted in two protruding tubular sections of the optical base assembly. The scanning telescope and sextant line of sight may be offset depending on the mode of operation.

The sextant is a highly accurate optical instrument capable of measuring the included angle between two targets and the direction of any single target with respect to the navigation base. Angular sighting between two targets is made through a fixed beam splitter and a movable mirror located in the sextant head. The sextant lens provides 1.8-degree true field-of-view with 28X magnification. The movable mirror is capable of sighting a target to 57 degrees line of sight from the shaft axis. This is reduced to approximately 45 degrees when installed in the spacecraft, however, because of interference from structure. The mechanical accuracy of the trunnion axis is twice that of the line-of-sight requirement due to mirror reflection which doubles any angular displacement in trunnion axis.
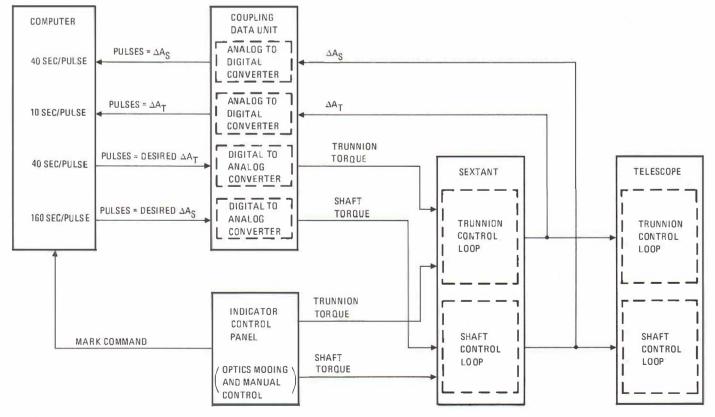
The scanning telescope is similar to a theodolite in its ability to measure elevation and azimuth angles of a single target accurately using an established reference. The lenses provide 60-degree true

field of view at 1X magnification. This is reduced to about 40 degrees when installed because of obstruction by vehicle structure.
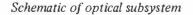
The coupling data unit used in the inertial subsystem is also used as a part of the optical subsystem. Two channels of the unit are used, one for the sextant shaft axis and one for the sextant trunnion axis. These channels repeat the sextant shaft and trunnion angles and transmit angular change information to the computer in digital form.

The angular data transmission in the trunnion channel is mechanized to generate 1 pulse to the computer for 5 arc-seconds of movement of the sextant trunnion which is equivalent to 10 arc-seconds of star line-of-sight movement. The shaft channel issues 1 pulse for each 40 arc-seconds of shaft movement. The location of the sextant shaft and trunnion axes are transmitted to the coupling data units through 16X and 64X resolvers, located on the sextant shaft and trunnion axes. This angular information is transmitted to the units in the form of electrical signals proportional to the sine and cosine of 16X shaft angle and 64X trunnion angle. During the computer mode of operation, the unit

provides digital-to-analog conversion of the computer output to generate an ac input to the sextant shaft and trunnion servos. This analog input to the sextant axes will drive the star line of sight to some desired position. In addition, the optical subsystem channels of the coupling data unit perform a second function on a time-sharing basis. During a thrust vector control function these channels provide digital-to-analog conversion of the service propulsion engine gimbal angle command between the computer and the service propulsion subsystem gimbals.

The modes of operation for the optical subsystem are selected by the astronaut using the controls located on the indicator control panel. There are three major modes: zero optics, manual control, and computer control.

During the zero optics mode, the shaft and trunnion axis of the sextant are driven to their zero positions by taking the output of the transmitting resolvers (1X and 64X in trunnion, and 1/2X and 16X in shaft) and feeding them through the two-speed switches to the motor drive amplifier. This in turn drives loops to null positions as indicated

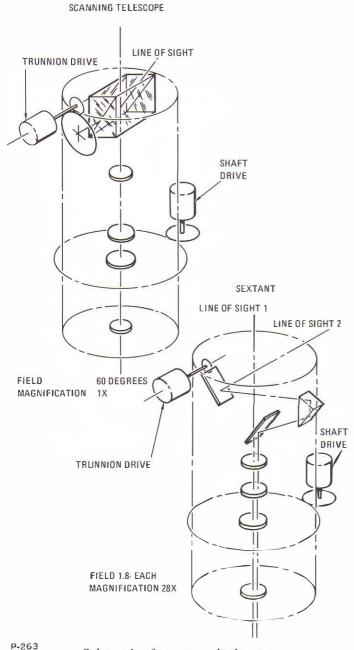P-262

Schematic of optical subsystem

by zero output from the resolvers. The telescope and trunnion axes follow to a zero position. The zero optics mode can be selected either manually by the flight crew or by the computer after the computer control mode of operation has been manually selected.

The manual mode can be selected to operate under either direct hand control or resolved hand control. Independent control of the telescope trunnion is possible in both of these variations.

In direct hand control the hand controller outputs are applied directly to the sextant shaft and trunnion

SCANNING TELESCOPE

LINE OF SIGHT

TRUNNION DRIVE

SHAFT DRIVE

SEXTANT

LINE OF SIGHT 1

LINE OF SIGHT 2

FIELD 60 DEGREES
MAGNIFICATION 1X

SHAFT DRIVE

TRUNNION DRIVE

FIELD 1.8- EACH
MAGNIFICATION 28X

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Schematic of sextant and telescope

motor drive amplifiers. Forward and back motion of the hand controller commands increasing and decreasing trunnion angles, and right and left motion of the hand controller commands increasing and decreasing shaft angles. The apparent speed of the image motion can be regulated by the flight crew by selecting either low, medium, or high controller speed on the indicator control panel. This regulates the voltage applied to the motor drive amplifier and therefore the shaft and trunnion drive rates.

The slave telescope modes provide for alternate operation of the telescope trunnion while the sextant is being operated manually. Three alternate modes can be selected by a telescope trunnion switch: the telescope trunnion axis slaved to the sextant trunnion (the normal operating position), the telescope trunnion locked in a zero position (by applying fixed voltage to the telescope trunnion 1X receiving resolver, causing this position loop to null in a zero orientation. Therefore, this means the centerline of the telescope 60-degree field-of-view is held parallel to the landmark line of sight of the sextant), and the telescope trunnion axis is offset 25 degrees (the centerline of the 60-degree field of view is offset 25 degrees from the landmark line of sight of the sextant). This last position of the telescope trunnion will allow the landmark to remain in the 60-degree field of view while still providing a total possible field of view of 110 degrees if the telescope shaft is swept through 360 degrees.

In manual resolved operation, the hand controller outputs are put through a matrix transformation before being directed to the shaft and trunnion motor drive amplifiers. The matrix transformation makes the image correspond directly to the hand controller motion. That is, up, down, right, and left motions of the hand controller commands the target image to move up, down, right, and left, respectively, in the field of view.

Buttons on the indicator control panel are used to instruct the computer that a navigation fix has been made and that sextant shaft and trunnion position and time should either be recorded or rejected. The "mark" command is generated manually by the flight crew which energizes the mark relay. The mark relay transmits a mark command to the computer. If an erroneous mark is made, the "mark reject" button is depressed.
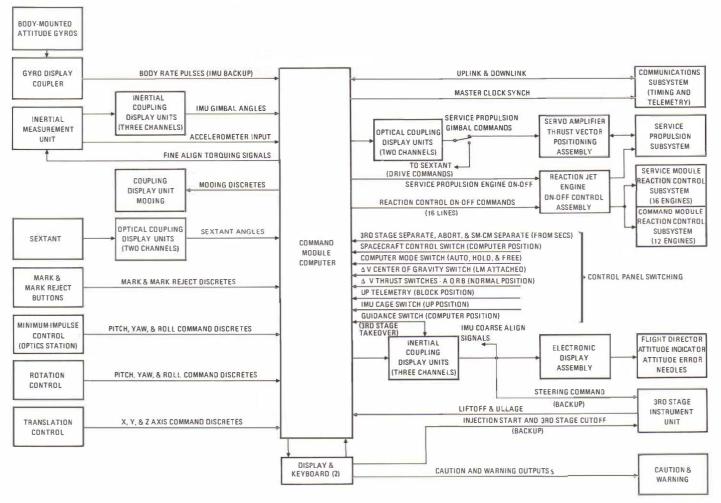
The computer-controlled operation is selected by placing the moding switch in computer position. The mechanization of this loop is chosen by the

computer program that has been selected by the flight crew. The computer controls the sextant by completing the circuit from the coupling data unit digital-to-analog converters to the shaft and trunnion motor drive amplifier. The computer can then provide inputs to these amplifiers via a digital input to the coupling data unit which converts it to an 800-cycle signal that can be used by the motor drive amplifier. This mode is used when it is desired to look at a specific star for which the computer has the corresponding star coordinates. The computer will know the attitude of the spacecraft from the position of the inertial measurement unit gimbals and will, therefore, be able to calculate the position of the sextant axes required to acquire the star.

COMPUTER SUBSYSTEM

The computer subsystem consists of the command module computer and two display and keyboard panels. The computer and one keyboard are located in the lower equipment bay. The other keyboard is located on the main display console. All computer controls and displays are located on the keyboards.

The computer is a core memory digital computer with both fixed and erasable memory. The fixed memory permanently stores navigation tables, trajectory parameters, programs, and constants. The erasable memory stores intermediate information.

The computer processes data and issues discrete control signals, both for guidance and control and for other spacecraft subsystems. It is a control computer with many of the features of a general-purpose computer. As a control computer, it aligns the stable platform of the inertial measurement unit in the inertial subsystem, positions the optical unit in the optical subsystem, and issues control commands to the spacecraft thrusters. As a general-purpose computer, it solves guidance problems required for the spacecraft mission. In addition, it monitors the operation

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Block diagram of computer relationships

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of the guidance and control and other spacecraft subsystems.

The computer computes information about the flight profile that the spacecraft must assume in order to complete its mission. This position, velocity, and trajectory information is used by the computer to solve the various flight equations. The results of various equations can be used to determine the required magnitude and direction of thrust required. Corrections to be made are established by the computer. The spacecraft engines are turned on at the correct time, and steering and engine control signals are generated by the computer to re-orient the spacecraft to a new trajectory if required. The inertial subsystem senses acceleration and supplies velocity changes to the computer for calculating the total velocity. Drive signals are supplied from the computer to coupling data unit and stabilization gyros in the inertial subsystem to align the gimbal angles in the inertial measurement unit. Error signals are also supplied to the coupling data unit to provide attitude error display signals for the flight director attitude indicator. Coupling data unit position signals are fed to the computer to indicate commanded changes in engine gimbal angles. The computer receives mode indications and angular information from the optical subsystem during optical sightings and uses it to calculate present position and orientation and to refine trajectory information. Optical subsystem components can also be positioned by drive signals supplied from the computer.

The computer is functionally divided into seven blocks: timer, sequence generator, central processor, memory, priority control, input-output, and power.

The timer generates the synchronization pulses to assure a logical data flow from one area to another within the computer. It also generates timing waveforms which are used by the computer in alarm circuitry and other areas of the spacecraft for control and synchronization purposes.
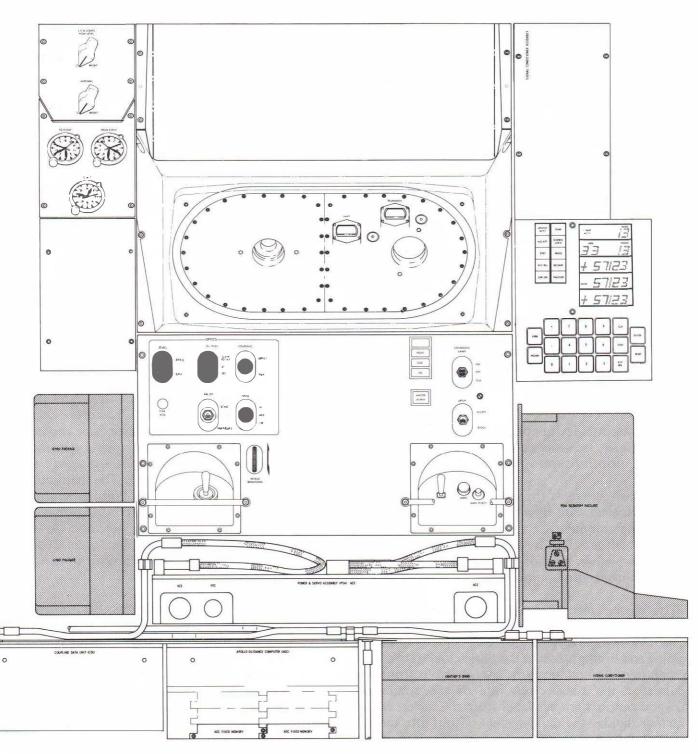
The master clock frequency is generated by an oscillator and is applied to the clock divider logic. The divider logic divides the master clock input into gating and timing pulses at the basic clock rate of the computer. Several outputs are available from the pulses at the basic clock rate of the computer. Several outputs are available from the scaler, which further divides the divider logic output into output pulses and signals which are used for gating, to generate rate signal outputs, and for the accumulation of time. Outputs from the divider logic also drive the time pulse generator which produces a recurring set of time pulses. This set of time pulses defines a specific interval (memory cycle time) in which access to memory and word flow takes place within the computer. The start-stop logic senses the status of the power supplies and specific alarm conditions in the computer and generates a stop signal which is applied to the time pulse generator to inhibit word flow. Simultaneously, a fresh-start signal is generated which is applied to all functional areas in the computer.

The sequence generator directs the execution of machine instructions. It does this by generating control pulses which sequence data throughout the computer. The control pulses are formed by combining the order code of an instruction word with synchronization pulses from the timer. The sequence generator contains the order code processor, command generator, and control pulse generator. The sequence generator executes the instructions stored in memory by producing control pulses which regulate the data flow of the computer. The manner in which the data flow is regulated among the various functional areas of the computer and between the elements of the central processor causes the data to be processed according to the specifications of each machine instruction.

The order code processor receives signals from the central processor, priority control, and peripheral equipment (test equipment). The order code signals are stored in the order code processor and converted to coded signals for the command generator. The command generator decodes these signals and produces instruction commands. The instruction commands are sent to the control pulse generator to produce a particular sequence of control pulses, depending on the instruction being executed. At the completion of each instruction, new order code signals are sent to the order code processor to continue the execution of the program.

The central processor performs all arithmetic operations required of the computer, buffers all information coming from and going to memory, checks for correct parity on all words coming from memory, and generates a parity bit for all words written into memory. It consists of flip-flop registers, the write, clear, and read control logic, write amplifiers, memory buffer register, memory address register and decoder, and the parity logic.

Primarily, the central processor performs operations indicated by the basic instructions of the program stored in memory. Communication within the central processor is accomplished through the write amplifiers. Data flows from memory to the flip-flop registers or vice versa, between individual flip-flop registers, or into the central processor from external sources. In all instances, data is placed on the write lines and routed to a specific register, or to another functional area under control of the write, clear, and read logic. The logic section accepts control pulses from the sequence generator and generates signals to read the content of a register onto the write lines, and write this content into another

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register of the central processor or to another functional area of the computer. The particular memory location is specified by the content of the memory address register. The address is fed from the write lines into this register, the output of which is decoded by the address decoder logic. Data is subsequently transferred from memory to the memory buffer register. The decoded address outputs are also used as gating functions within the computer.

The memory buffer register buffers all information read out or written into memory. During readout, parity is checked by the parity logic and an alarm is generated in case of incorrect parity. During write-in, the parity logic generates a parity bit for information being written into memory. The flip-flop registers are used to accomplish the data manipulations and arithmetic operations. Each register is 16 bits or one computer word in length. Data flows into and out of each register as dictated by control pulses associated with each register. The control pulses are generated by the write, clear, and read control logic.
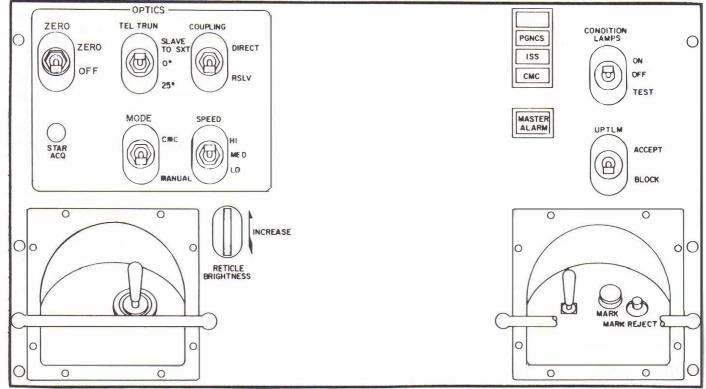
External inputs through the write amplifiers included the content of both the erasable and fixed memory bank registers, all interrupt addresses from priority control, control pulses which are associated with specific arithmetic operations, and the start address for an initial start condition. Information from the input and output channels is placed on the write lines, and routed to specific destinations either within or external to the central processor.

Memory provides the storage for the computer and is divided into two sections: erasable memory and fixed memory. Erasable memory can be written into or read from; it is destroyed when it is read out (displayed); therefore, information required for later use must be restored. Fixed memory cannot be written into and its readout is nondestructive. Erasable memory stores intermediate results of computations, auxiliary program information, and variable data supplied by the guidance and control and other subsystems of the spacecraft. Fixed memory stores programs, constants, and tables. There is a total of 38,912 sixteen-bit word storage locations in fixed and erasable memories. It should be noted that the majority of the memory capacity is in fixed memory (36,864 word locations). The erasable memory uses planes or ferrite (iron) cores as storage devices. A core is a magnetic storage device having two stable states. It can be magnetized in one or two directions by passing a sufficient current through a wire which pierces the core. The direction of current determines the direction of magnetization. The core will retain its magnetization indefinitely until an opposing current switches the core in the opposite direction. Wires carrying current through the same core are algebraically additive. Sense wires which pierce a switched core will carry an induced pulse. The fixed memory is high-density core rope— tiny nickel-iron cores woven together with thousands of copper wires and encapsulated in plastic. Each core functions as a transformer and storage does not depend on magnetization. The advantages of encapsulated core rope for fixed memory are indestructibility, permanence of data, and storage of a vast amount in a small volume. The technique requires, however, that programs for classes of missions be developed and verified before the rope is woven, because the program determines the wiring sequence.

Priority control establishes a processing priority of operations that must be performed by the computer. These operations are a result of conditions which occur both internally and externally. Priority control consists of counter priority control and interrupt priority control. Counter priority control initiates actions which update counters in erasable memory. Interrupt priority control transfers control of the computer to one of several interrupt subroutines stored in fixed memory.

The start instruction control restarts the computer after a hardware or program failure. The counter instruction control updates the various counters in erasable memory upon reception of certain incremental pulses. The interrupt instruction control forces the execution of the interrupt instruction to interrupt the current operation of the computer in favor of a programmed operation of a higher priority.

The input-output section routes and conditions signals between the computer and other areas of the spacecraft. In addition to the counter interrupt and the program interrupts previously described, the computer has a number of other inputs derived from its interfacing hardware. These inputs are a result of the functioning of the hardware, or an action by the operator of the spacecraft. The counter interrupts, in most cases, enable the computer to process inputs representing such things as changes in velocity. The program interrupt inputs are used to initiate processing that must be done a relatively short time after a particular function is present. The other inputs to the computer, in general,

Optics control panel

enable it to be aware of conditions which exist in its environment. These inputs are routed to computer and are available to its programs through the input channels.

The outputs of the computer fall in one of the following categories: data, control, or condition indications. Some of these outputs are controllable through the computer program while others are present as a function of computer circuitry. All of the outputs which are controlled by the computer programs are developed through the computer output channels.

The power section provides voltage levels necessary for the proper operation of the computer. Power is furnished by two switching-regulator power supplies: a +4-volt and a +14-volt power supply which are energized by fuel cell powerplants in the electrical power subsystem.

The power supply outputs are monitored by a failure detector consisting of four differential amplifiers. There are two amplifiers for each power supply, one for overvoltage and one for undervoltage detection. If an overvoltage or undervoltage condition exists, a relay closure signal indicating a power fail is supplied to the spacecraft.

The display and keyboard panels provide communication between the flight crew and the computer. They operate in parallel, with the main display console keyboard providing computer display and control while crewmen are in their couches.

The exchange of data between the flight crew and the computer is usually initiated by crew action; however, it can also be initiated by internal computer programs. The exchanged information is processed by the keyboard program. This program allows the following four different modes of operation:

1. Display of internal data—both a one-shot display and a periodically updating display (called monitor) are provided.

2. Loading external data—as each numerical character is entered, it is displayed in the appropriate display panel location.

3. Program calling and control—the keyboard is used to initiate a class of routines which are concerned with neither loading nor display; certain routines require instructions from the operator to determine whether to stop or continue at a given point.
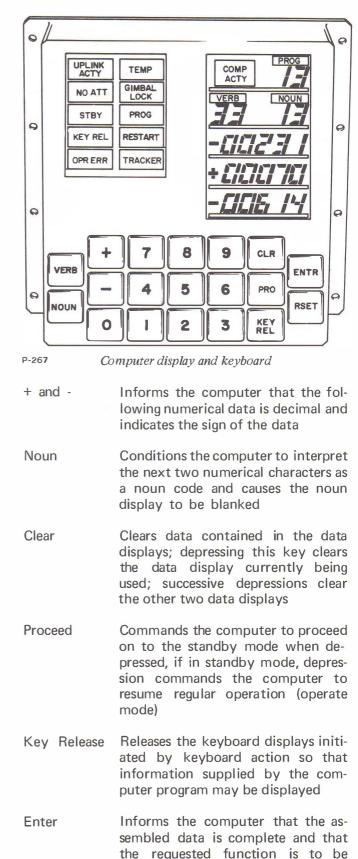
4. Changing major mode—the initiation of large-scale mission phases can be commanded by the operator.

The data involved in both loading and display can be presented in either octal or decimal form as the operator indicates. If decimal form is chosen, the appropriate scale factors are supplied by the program. Decimal entries are indicated by entering a plus or minus sign.

The basic language of communication between the operator and the computer is a pair of words known as verb and noun. Each of these is represented by a two-character decimal number. The verb code indicates what action is to be taken (operation); the noun code indicates to what the action is applied (operand). Typical verbs are those for displaying and loading. Nouns usually refer to a group of erasable registers within the computer memory. The program, verb, and noun displays provide two-digit numbers which are coded numbers describing the action being performed. The register 1, 2, and 3 displays show the contents of registers or memory locations. These displays are numbers which are read as decimal numbers if a plus or minus sign is present and octal numbers if no sign is used. The register displays operate under program control unless the contents of a specific register or memory location is desired. The crew may request display of the contents of a specific register or memory location by commanding the display from the keyboard. The only other displays are the "activity" lights which indicate whether the computer is computing or accepting telemetry from the ground and status lights.

The keyboard consist of ten numerical keys (pushbuttons) labeled 0 through 9, two sign keys (+ or -) and seven instruction keys: Verb, Noun, Clr (clear), Pro (proceed), Key Rel (key release), Entr (enter) and Rset (reset). Whenever a key is depressed, 14 volts are applied to a diode encoder which generates a unique five-bit code associated with that key. There is, however, no five-bit code associated with the proceed key. The function of the keys is as follows:

Pushbutton	Function
0 through 9	Enters numerical data, noun codes, and verb codes into the computer

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+ and -	Informs the computer that the following numerical data is decimal and indicates the sign of the data
Noun	Conditions the computer to interpret the next two numerical characters as a noun code and causes the noun display to be blanked
Clear	Clears data contained in the data displays; depressing this key clears the data display currently being used; successive depressions clear the other two data displays
Proceed	Commands the computer to proceed on to the standby mode when depressed, if in standby mode, depression commands the computer to resume regular operation (operate mode)
Key Release	Releases the keyboard displays initiated by keyboard action so that information supplied by the computer program may be displayed
Enter	Informs the computer that the assembled data is complete and that the requested function is to be executed

Reset	Extinguishes the lamps that are controlled by the computer
Verb	Conditions the computer to interpret the next two numerical characters as a verb code and causes the verb display to be blanked

The standard procedure for the execution of keyboard operations consists of a sequence of seven key depressions:

Verb V_2 V_1 Noun N_2 N_1 Enter

Pressing the Verb key blanks the two verb lights on the keyboard and clears the verb code register in the computer. The next two numerical inputs are interpreted as the verb code. Each of these characters is displayed by the verb lights as it is inserted. The Noun key operates similarly with the keyboard noun lights and computer noun code register. Pressing the Enter key initiates the program indicated by the verb-noun combination. Thus, it is not necessary to follow a standard procedure in keying verb-noun codes; it can be done in reverse order or a previously inserted verb or noun can be used without re-keying it. No action is taken by the computer in initiating the verb-noun-defined program until the Enter key is actuated. If an error is noticed in either the verb or noun code before actuation of the Enter key, it can be corrected simply by pressing the corresponding Verb or Noun key and inserting the proper code.

If the selected verb-noun combination requires data from the operator, the Verb and Noun lights flash on and off about once per second after the Enter key is pressed. Data is loaded in five-character words and is displayed character-by-character in one of the five-position data display registers. The Enter key must be pressed after each data word. This tells the program that the numerical word being keyed in is complete.

The keyboard also can be used by internal computer programs for subroutines. However, any operator keyboard action (except error reset) inhibits keyboard use by internal routines. The operator retains control of the keyboard until he wishes to release it. This assures that the data he wishes to observe will not be replaced by internally initiated data displays.

A noun code may refer to a device, a group of computer registers, or a group of counter registers, or it may simply serve to convey information without referring to any particular computer register. The noun is made up of 1, 2, or 3 components, each entered separately as requested by the verb code. As each component is keyed, it is displayed on the display panel: component 1 in Register 1, component 2 in Register 2, and component 3 in Register 3. There are two classes of nouns: normal and mixed. Normal nouns (codes 01 through 39) are those whose component members refer to computer registers which have consecutive addresses and use the same scale factor when converted to decimal. Mixed nouns (codes 40 through 99) are those whose component members refer to nonconsecutive addresses or whose component members require different scale factors when converted to decimal, or both.

A verb code indicates what action is to be taken. It also determines which component member of the noun group is to be acted upon. For example, there are five different load verbs. Verb 21 is required for loading the first component of the selected noun; verb 22 loads the second component; verb 23 loads the third component; verb 24 loads the first and second component; and verb 25 loads all three components. A similar component format is used in the display and monitor verbs. There are two general classes of verbs: standard and extended. The standard verbs (codes 01 through 39) deal mainly with loading, displaying, and monitoring data. The extended verbs (codes 40 through 99) are principally concerned with calling up internal programs whose function is system testing and operation.