THE TRIAD SPACECRAFT

J. Dassoulas

The Transit Improvement Program is sponsored by the Strategic Systems Project Office of the United States Navy. It is intended to provide for flight testing potential improvements in the Navy Navigation Satellite System that could be introduced into the operational system at some future time. TRIAD was the first spacecraft in this program. The Applied Physics Laboratory was responsible for the overall mission, from concept through data acquisition and analysis. Stanford University provided the Disturbance Compensation System in a joint collaborative effort with APL. The nuclear power source was provided by the Atomic Energy Commission. TRIAD was launched from the Western Test Range on September 2, 1972, and its success is reported in this and a subsequent issue of the APL Technical Digest.

Introduction

THE TRIAD SPACECRAFT IS THE FIRST OF A series of three experimental/operational spacecraft designed to flight test improvements to the Navy Navigation Satellite System. TRIAD contained several devices new to APL spacecraft. Among these were the Disturbance Compensation System (DISCOS), a Psuedo Random Noise Experiment (PRN), an Incremental Phase Shifter (IPS), and a Programmable Computer.

DISCOS is a device that compensates for the effects of aerodynamic drag forces and solar radiation pressure which act on the satellite in orbit, thus permitting the satellite to follow an orbit influenced solely by the gravitational field of the earth. The dramatic success of this experiment has provided a new scientific instrument for research in the fields of geodesy and relativity. By virtue of the long-term predictable orbits made possible by DISCOS, user navigation equipment may be simplified and manufactured at lower cost, thus providing excellent navigation capabilities to a wider variety of users. The design of the DISCOS system is reported in this issue in the paper by D. B. DeBra.

PRN is a coded modulation format exercised by ground command that is used to phase modulate both the 150 MHz and 400 MHz transmitters. The experiment has four objectives, which are: (a) to evaluate the feasibility to reduce data collecting time required for a navigation fix by making simultaneous measurements of range and range rate; (b) to evaluate the feasibility of world-wide time dissemination by use of PRN signals; (c) to demonstrate interference and multipath rejection properties of PRN coded satellite signals, and (d) to confirm the PRN techniques presently being considered for advanced navigation systems. The PRN design and performance details will be reported in a later issue in an article by E. F. Prozeller and V. Schwab.

IPS provides, on ground command, the capability to compensate for long term drifts of the 5 MHz satellite reference oscillator that has been experienced on previous navigation satellites. Although this is not a problem with the present system, future navigation requirements demanding greater precision will necessitate some form of drift compensation. Accumulated histories of this drift rate have indicated that the drift rate can be predicted with very good precision. Knowing this aging characteristic, IPS can be updated automatically by the spacecraft computer memory, and any corrections to the predicted rate may be made by satellite injection commands from the ground. Details of IPS design and its performance in orbit will be reported in a later issue in an article by T. L. McGovern and L. J. Rueger.

The integrated experiment demonstrates that significant advances have been made in the art of navigation. The article by R. E. Jenkins in this issue reports on the performance in orbit of the DISCOS system.

System Constraints

There were several constraints that had to be satisfied in the design of the satellite: (a) to minimize cost it was desirable to use the Scout booster and to use the satellite station at APL as the telemetry and command site; (b) to demonstrate the success of the mission, the spacecraft was to have the capability of operating either in the experimental mode without interference to current navigational users or as an operational satellite; (c) for flexibility, the power systems were to be designed so that either a nuclear or a solar power generating system could be flown interchangeably without disrupting the spacecraft's mechanical, thermal or electrical integrity; and (d) perhaps the most significant constraint, in that it defined the mechanical configuration, was the fact that the Disturbance Compensation System had to be the center body of the deployed configuration. The reason for this was two-fold. First, the primary sensing unit called the proof mass is optimally located if it lies at the center of mass of the deployed configuration. The thrusters which respond to error signals generated by the proof mass position react through the center of mass to control the satellite's accelerations. Thus, no disturbing torques are applied to the gravity gradient stabilized spacecraft by the thrusters. A second, and more subtle reason for this choice location, was the mass attraction problem, that is, the mutual gravitational attraction of the satellite's components to the proof mass. This required the design of a mass to compensate for the unsymmetrical distribution of spacecraft component masses about the proof mass. In order to determine the geometry of the compensating mass, an elaborate program of weighing and locating each individual component that comprised electronic and mechanical systems in the DISCOS was accomplished. The majority of the spacecraft systems were deployed at the end of "scissors type" extendible booms to minimize their influence.

The mechanical/thermal requirements on the extendible booms were considerable. The boom straightness under varying conditions of solar illumination was such that a displacement of only one millimeter at the ends from a line of symmetry through the three masses was permitted. This was achieved and demonstrated by tests in the APL thermal vaccuum chamber and corroborated by the DISCOS performance in orbit. Absolute boom length was measured, via telemetry, by means of a wire attached to the structure at one end and connected to a multiturn potentiometer at the other. This device could not be fooled by "bunching" of various boom links during deployment.

The three-bodied configuration is gravity gradient stabilized in pitch and roll by virtue of its elongated configuration. A momentum wheel located in the main electronics unit provided yaw stabilization, i.e., about the local vertical, principally to align a pair of thrusters with the orbit velocity vector, and also some additional stiffness in roll. Librations of the spacecraft have been well within three degrees in all axes.

The reference coordinate system is shown in Fig. 1. The orbit vector is normal to the plane of the paper in Fig. 1.

The deployed configuration measures approximately 24½ ft in overall length. This was required to collapse to a height of approximately 5½ ft from the separation interface to the top of the Radioisotope Thermoelectric Generator (RTG) power source. This is known as the launch configuration and can be seen in Fig. 2 inside of the Scout nose fairing.

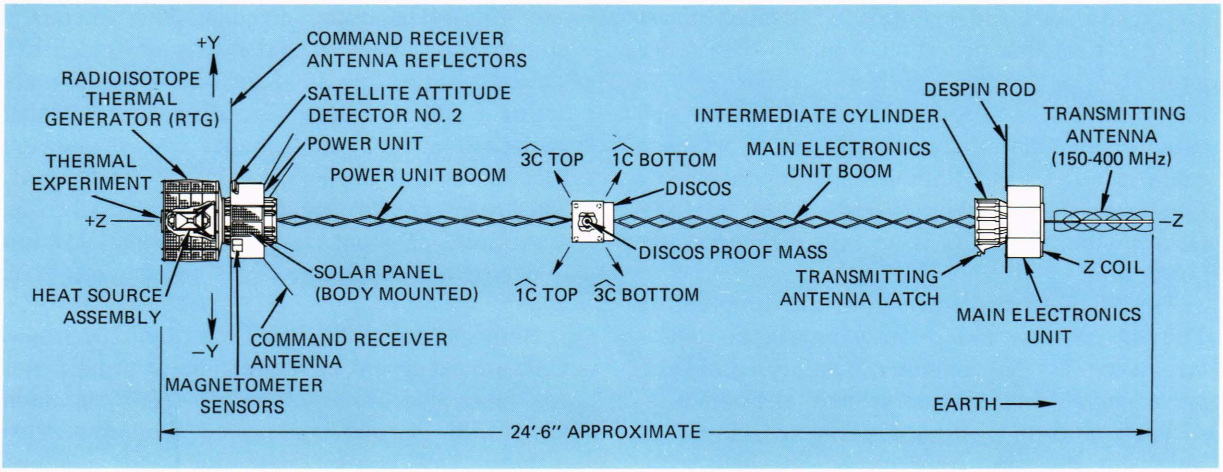


Fig. 1—Orbital configuration of TRIAD.

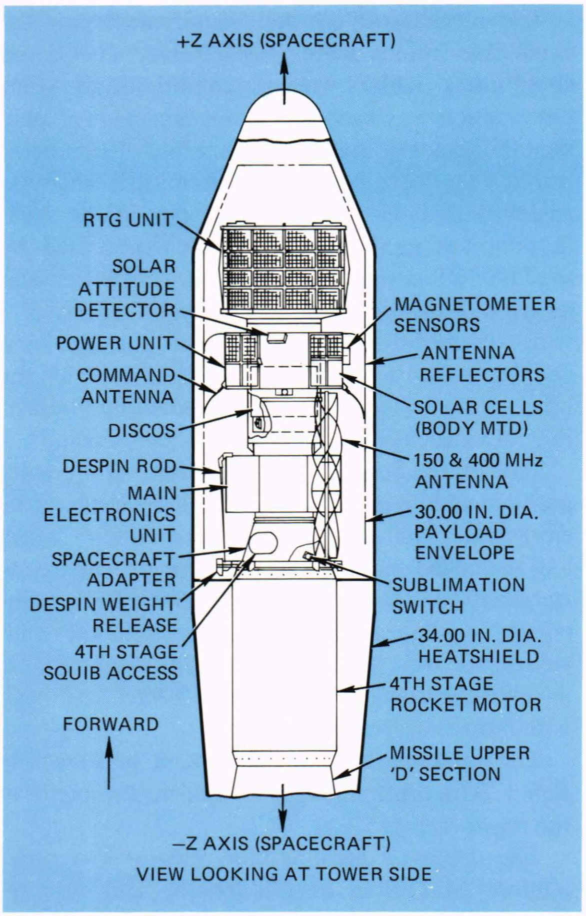


Fig. 2—Launch configuration of TRIAD.

Mechanical Configuration

The TRIAD body is comprised of three main units: Power, Main Electronics, and DISCOS. The Power Unit contains the components necessary to produce and maintain a balanced power source for satellite operation. Figure 3 depicts the internal arrangements of electronic packages in the power unit. The top surface of the power unit structure includes a mating surface to which a clamp strap retains a Radioisotope Thermoelectric Generator, the primary power source for TRIAD. Once mated, the RTG is an integral part of the power unit.

The Main Electronics Unit at the other end of TRIAD contains the primary navigation equipment such as the computer/memory, oscillator, power amplifiers, telemetry, and electronics associated with navigation experiments. Figure 4 shows the internal arrangement. Attached to the underside of this unit is the composite 150 MHz and 400 MHz volute antenna. The antenna is mounted on hinges so that it may be folded in a stowed position in the launch configuration and automatically unlatched for orbital deployment. Mounted on the forward, or topside, of the Main Electronics Unit are two magnetic hysteresis rods. The rods, folded aft for compactness during launch, unfold about the hinged joints after despin to deploy one rod in the *X* axis and one rod in the *Y* axis.

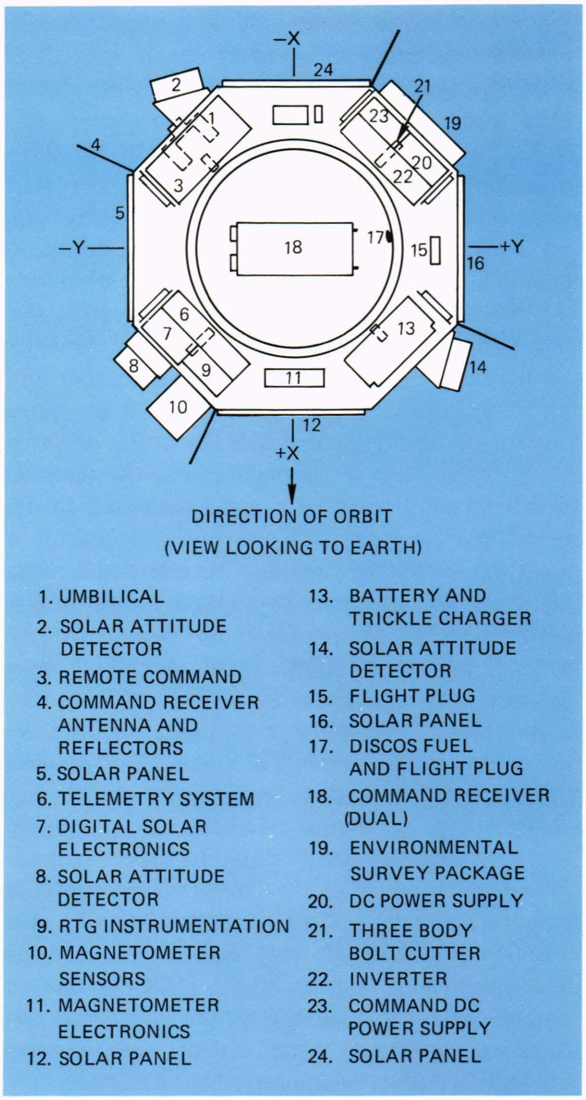
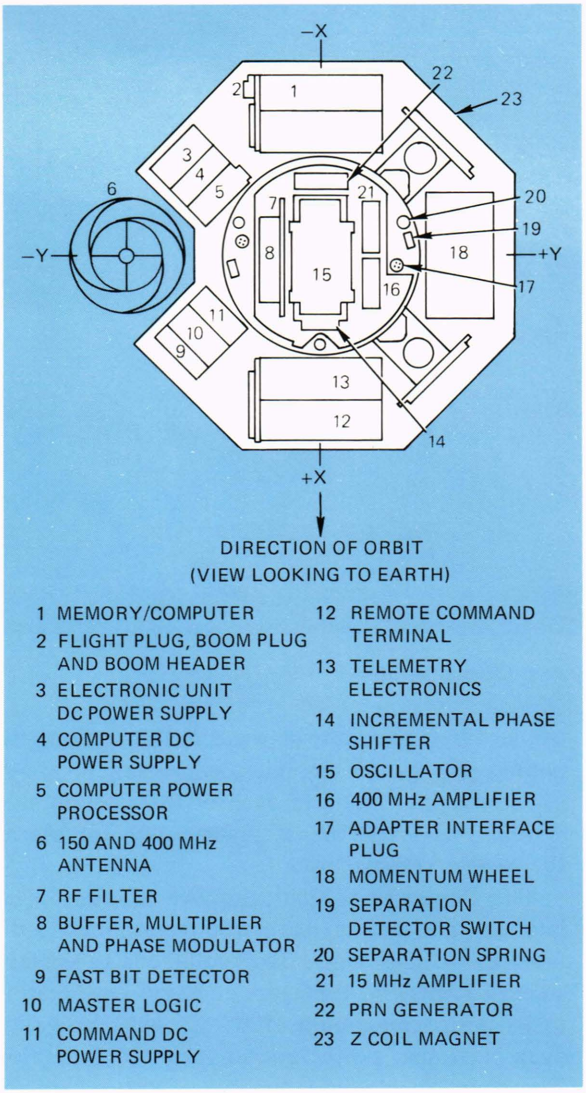


Fig. 3—TRIAD power unit.

Both the Power Unit and the Main Electronics Unit are octagonal in shape. The external panels are fabricated from 0.016-inch-thick aluminum alloy with thermal coating on the Main Electronics. The Power Unit sides are aluminum honeycomb panels, $^3/_{16}$ inch thick. Four of the panels have solar cells, the fifth panel has an Environmental Survey Package, the sixth and seventh panels each have SAD (Solar Attitude Detector), and the eighth panel has a third SAD and magnetometer sensors.

The centrally mounted DISCOS Unit is a cylindrical body that houses the Disturbance Compensation System in its entirety. It includes the proof mass sensing and propulsion systems, and command and telemetry electronics. This unit is approximately 12 inches high by 12½ inches in diameter except for the attach flange, mating connectors, and external boom-to-boom wiring. The DISCOS Unit is provided with a structural load-carrying cover which separates when the booms are extended. The surface of the exposed cylinder provides thermal control for DISCOS after deployment.



1 MEMORY/COMPUTER
2 FLIGHT PLUG, BOOM PLUG AND BOOM HEADER
3 ELECTRONIC UNIT DC POWER SUPPLY
4 COMPUTER DC POWER SUPPLY
5 COMPUTER POWER PROCESSOR
6 150 AND 400 MHz ANTENNA
7 RF FILTER
8 BUFFER, MULTIPLIER AND PHASE MODULATOR
9 FAST BIT DETECTOR
10 MASTER LOGIC
11 COMMAND DC POWER SUPPLY
12 REMOTE COMMAND TERMINAL
13 TELEMETRY ELECTRONICS
14 INCREMENTAL PHASE SHIFTER
15 OSCILLATOR
16 400 MHz AMPLIFIER
17 ADAPTER INTERFACE PLUG
18 MOMENTUM WHEEL
19 SEPARATION DETECTOR SWITCH
20 SEPARATION SPRING
21 15 MHz AMPLIFIER
22 PRN GENERATOR
23 Z COIL MAGNET

Fig. 4—TRIAD electronics unit.

The three units are held together by two ten-foot-long extendible booms. The booms are contracted while in the launch or handling configuration, and extended on command after the satellite has been injected into orbit, thereby separating the three units to achieve gravity gradient stabilization. Each boom is a fixed-pivot scissors type, consisting of structural links that also serve as conduits for the power and signal cables that interconnect the three TRIAD units. The booms are extended by a DC gear motor drive which permits a controlled rate extension of the boom and also allows the center of mass of the satellite to be adjusted to coincide with the center of mass of the DISCOS proof mass cavity. Differential gears control the orientation of the three units as the booms deploy, in order to prevent possible collisions.

Of no small consequence was the design of several additional systems required to make the mission possible, notably, the power, doppler, antenna, computer/memory, attitude control and detection, command telemetry, and thermal systems. All presented major design challenges because of the weight restrictions imposed by the Scout booster. Available packaging volume and system weights were critical parameters from the outset.

Systems Design

TRIAD employs eight major satellite subsystems in order to accomplish its mission. These subsystems are discussed in this section. A system block diagram can be seen in Fig. 5.

Power—Primary electric power is supplied by a Radioisotope Thermoelectric Generator (RTG) which was developed by the Atomic Energy Commission for the Transit Program. The RTG derives its power from the heat of decay of a radioisotope and subsequently converts this power to electricity by solid-state thermoelectric elements. Twelve thermoelectric panels comprise the converter, which receives radiant energy from the heat source and converts this to electricity at about a 4½% efficiency. Excess heat is rejected into space by radiators which accept heat from the cold junction of the thermoelectric elements.

Since the multilayer foil insulation in the thermoelectric panels is fully functional only in a

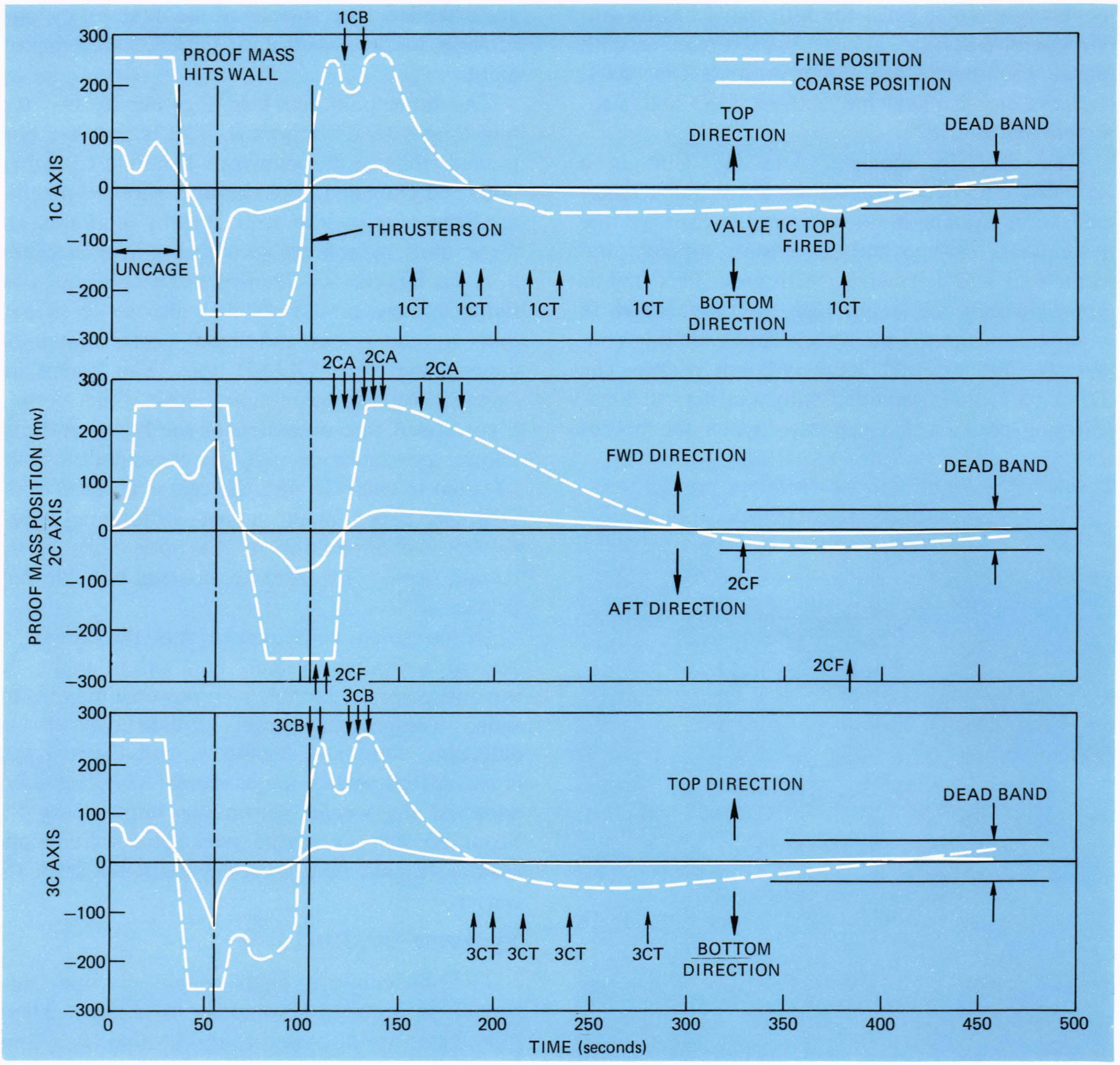


Fig. 5—TRIAD satellite system block diagram.

vacuum environment, the temperature difference between hot and cold junctions is rather minimal in air and relatively little electrical power may be obtained from the converter in this environment. Open circuit voltage at room ambient conditions is approximately 1.5 volts. The RTG cannot produce any useful power for the TRIAD spacecraft in air and external power supplies were used for system tests in air.

DC power from the thermoelectric generator is converted to AC power in a regulated DC/AC inverter for distribution by the Power Subsystem. It is also distributed to the DISCOS and Main Electronics Unit by means of wires installed along the booms. DC power supplies, consisting of transformer-rectifier-filters in each of the satellite subsystems, reconvert the AC power to DC for use by the various subsystems.

The Power Subsystem employs a shunt regulator to limit the maximum voltage at input to the inverter to 5.47 volts. This voltage was selected since it limits the RTG hot junction temperature to its design maximum, 400° C, while providing near maximum power output from the generator. The shunt regulator is capable of dissipating the entire RTG power output, if called upon to do so, in elements mounted on the exterior of the spacecraft Power Unit. At its output voltage of 5.47 volts, the RTG provides a current of 6.81 amperes, or 37.2 watts of power.

A nickel-cadmium battery satisfied the need for energy storage during peak load demands, and provided a method of powering the spacecraft during the launch ascent phase. The TRIAD battery consists of 4 series, 6 ampere-hour cells operating at a nominal voltage of 5.3 volts. The battery is deemed noncritical to the operation of the Power Subsystem and is connected to the main bus through OR-ing diodes. An experimental auxiliary solar array provides a trickle charge to the battery during normal spacecraft operation. The RTG may charge the battery via a trickle charge limiter. The maximum output current from this limiter is approximately 300 mA.

The experimental auxiliary solar array comprised of four identical solar panels is mounted on the exterior of the Power Unit. Each panel employs two circuits each containing two parallel strings of 20 series solar cells. The array produces an orbital average power of approximately 3 watts. The output from the array, normally used to maintain a trickle charge to the battery, may be switched to test loads for the purpose of evaluating solar panel electrical characteristics in orbit.

The Power System employs low voltage sensing elements that will automatically remove all noncritical spacecraft loads should low voltage be sensed. This capability is separately incorporated in the Power, DISCOS, and Main Electronics Unit. The Power Unit low voltage switch will trip a number of relays in an attempt to rectify any apparent overload or power deficiency while maintaining power to the Command System. Should low voltage occur in the Power Unit, the low voltage switch will remove noncritical loads and "OR" the RTG and battery in order to power the Command System. The battery will automatically be charged by the RTG via the trickle charge limiter at a maximum current value of approximately 300 mA. Similar low voltage sensing elements in the DISCOS and Main Electronics Unit are designed to sequentially remove loads should abnormally low voltages occur. All low voltage sensing elements sense the 20-volt output from the Command System DC supply. Each sensor has a backup voltage trip point of approximately 15 volts enabled by ground command.

Doppler—The Doppler System is located in the Main Electronics Unit of the satellite. Basically, the Doppler System of TRIAD is quite similar to that of the current navigation satellites. Significant differences operationally are: the commandable high or low RF output modes of the power amplifiers and the highly improved antenna performance. Additionally, the 5-MHz oscillator crystals have dual offsets of 80 ppm and 140 ppm. While in the operational mode, the 80 ppm offset is used. When commanded to the experimental mode, the 140-ppm offset crystal is used. This arrangement eliminates possible interference with the operational navigation system while the experiments are being performed and telemetry data are being collected. Mechanically, the doppler electronics have been redesigned to provide ease of fabrication and some subminiaturization.

Either of the dual 5-MHz proportional oven controlled oscillators may be selected through the spacecraft command system to drive the doppler transmissions on 150 MHz and 400 MHz. The oscillator provides timing for other spacecraft subsystems. Either of the dual-proportional oven control circuitry may be selected by command so that any one of four possible combinations may be chosen in the event of a failure of oven or oscillator circuitry.

The 150-MHz and 400-MHz power amplifiers provide the power source for the spacecraft doppler transmitters. In addition, these RF carriers are phase modulated with the necessary orbit ephemeris information to allow the user to compute a navigation fix. Other phase modulations include telemetry and experimental PRN ranging code. Functionally, the power amplifiers multiply the 50-MHz signal from the frequency multiplier/phase modulator to 150 MHz and 400 MHz, and amplify these signals to the specified level. These signals are then radiated by the antenna as the doppler RF carriers. The satellite AC voltage is tailored specifically to the transmitter requirements; consequently only a rectifier-filter is needed in the power converter for this system.

Antenna—An improved transmitting antenna was developed for the TRIAD satellite to achieve good left-hand circular polarization, wide beamwidth, coincident phase centers at 150 and 400 MHz, and mechanical compatibility with the satellite configuration. The array consists of separate 400-MHz and 150-MHz short backfire quadrifilar helix (volute) antennas mounted on a common balun mast hinged to allow the array to deploy from a compact launch configuration to a fixed operational position in orbit. Deployment, which is initiated by electronic timer and squib-operated latch, occurs after the payload and fourth rocket separate.

Computer/Memory System—The spacecraft computer is loaded from a ground transmitter with a navigation message that is transmitted from the spacecraft to the navigator as phase modulation on the 150-MHz and 400-MHz signals. The computer program stored in the memory may be changed by ground command. The memory also stores telemetry data from DISCOS and other spacecraft systems to allow a continuing record of their performance to be obtained. Delayed commands may also be implemented by the Computer System.

The computer functions as a real-time controller. It receives and stores orbit parameters for navigation and transmits these data to users with a real-time accuracy of one hundred nanoseconds. The computer monitors the satellite telemetering commutator and, under program control, inputs, formats, and stores selected telemetry data for retransmission to receiving stations. The computer, via its interrupt system, monitors, formats, and stores the valve action of six thrusters which are a part of the DISCOS propulsion system. The computer, acting through error-detection circuits, also outputs delayed commands into the satellite Command System.

The computer processor combines low, medium, and high power transistor-transistor logic (TTL) to optimize computation-to-energy ratio. Most of the processor control is fabricated from medium power TTL. The process control logic is pulse powered and automatically shuts down when not in use. The arithmetic registers are low power and may stay on during energy recharge periods when background computing is in process. The various energy metering modes capable under program control allow fast reaction to interrupts combined with low speed, low power background when computing is in process.

The core memory system uses sixty-four hybrid circuits. These circuits consist of sixteen complementary current switches, sixteen complementary voltage switches, sixteen dual digit regulated voltage switches, and sixteen sense amplifier dual comparator threshold networks. The memory core stack is three-dimensional, 3-wire, using 20-mil lithium-doped ferrite wide-temperature cores. The sense amplifier, digit loop, and address select logic are medium power integrated circuits. A memory alert signal from the processor controls the standby power in the memory. Complete power shutdown occurs in the memory if the memory alert signal is not present.

The read-only memory contains the single program that must be preserved: the Bootstrap loader program. The read-only memory operates at one-half to one-fourth the power that is required for operation with the core memory.

Attitude Control and Detection—The TRIAD satellite is stabilized in three axes because orientation of the DISCOS thrusters fore and aft along the flight path provides maximum efficiency in the use of thruster propellant, and accurate drag and solar pressure data may be more intelligently interpreted. Overall satellite system benefits to be derived from three-axis stabilization are refinement in transmitting antenna pattern and better predictability of satellite thermal conditions.

Attitude Control of the TRIAD satellite is accomplished by the "dumbbell" configuration which provides the gravity gradient stabilizing torque necessary to align the Z axis (the long axis) with the vertical. Figure 1 shows the satellite orbit coordinates and relates the attitude detectors to the referenced control axes. Control of the X and Y axes is obtained principally by use of a momentum wheel whose spin axis is perpendicular to the Z axis of the satellite. Satellite oscillations are damped with magnetic hysteresis rods that interact with the earth's magnetic field.

To establish in-orbit capture a yo-yo despin system is used to decelerate the spin rate to a few rpm. Magnetic hysteresis rods remove residual spin and later provide librational motion damping. Current is passed through a Z axis magnet coil to achieve magnetic stabilization, a necessary prerequisite to right-side-up gravity gradient stabilization. The Z axis coil is made of aluminum wire and can produce a magnetic dipole of 2×10^4 pole-cm on ground command.

The sequence of events, required to establish the deployed configuration in orbit, is as follows:

1. After the satellite and fourth stage rocket combination is injected into polar orbit, redundant sublimation switch action initiates the yo-yo despin mechanism which reduces the spin rate to a few rpm.

2. Further action by the sublimation switches applies power to the clamp strap bolt cutters to allow satellite fourth-stage rocket separation.

3. An electronic time delay circuit, initiated also by the sublimation switches, unlatches the 150/400-MHz antenna.

4. The hysteresis rods, folded aft for compactness during launch, unfold about the hinge joints after despin to deploy one rod in the *X* axis and one rod in the *Y* axis.

5. The hysteresis rods dissipate the residual satellite spin. Then the *Z* axis magnetic dipole coil is turned on to achieve magnetic stabilization. Also, the momentum wheel is turned on at low speed to achieve yaw stabilization.

6. After acceptable magnetic stabilization has been achieved, attitude stabilization is analyzed in real time to discover an opportunity to achieve gravity capture. This is done by deploying the booms upon ground command, and turning off the *Z* magnetic coil.

7. Also by ground command, the momentum wheel is operated in one of several possible modes to aid in maintaining three-axis stabilization.

The momentum wheel is used in the TRIAD satellite during the magnetic and gravity-gradient stabilizing maneuvers, and after gravity-gradient capture. The wheel may be operated in any of the following modes:

1. The angular momentum vector may be directed along either the plus or minus pitch axis, i.e., the wheel spin direction may be either forward or reverse as determined by ground command.

2. The magnitude of the angular momentum vector is commandable from 0 to 4 slug-ft^2 rpm in ¼ slug-ft^2 rpm steps with the motor running nonsynchronously (wheel speed variations ±5%).

3. The wheel speed is commandable to produce either 4 slug-ft^2 rpm or 8 slug-ft^2 rpm while running synchronously (wheel speed variations 0.03%).

The attitude detection portion of this system is comprised of a three-axis vector magnetometer and solar attitude detectors that produce both analog and digital data outputs. Outputs of these devices are telemetered and used in the analysis of the performance of the Attitude Control System. DISCOS data analysis will also benefit from data derived from the Attitude Detection System.

The three vector components of the magnetic field are measured at the satellite in the satellite body coordinate system by duty cycling power to the magnetometer coil. This determines the strength and direction of the magnetic field relative to the satellite. Knowing where the satellite has been at each instant of time, and knowing the direction and strength of the earth's magnetic field, it can be determined how the satellite axes are oriented, except for the undetermined degree of freedom of rotation of the satellite about the field line as an axis. Elimination of this ambiguity is achieved by reference to the sun line angles by use of solar attitude detectors.

A Digital Solar Attitude Detector (DSAD) system has the capability of determining the sun line vector in satellite body coordinates with an accuracy of ±1°. The DSAD system consists of three sense heads and associated electronics.

Each sense head contains two binary coded reticles mounted orthogonally to provide two-axis digital encoding. Each sense head has a conical field of view of 128 degrees. The output of each sensor consists of 14 binary bits giving attitude information along the two orthogonal axes and an output of an analog sensor. Sensor locations can be seen in Figs. 1 and 3. Each sense head weighs 2.5 oz. Three sense heads are mounted so that the normal vectors to each sensor reticle have equal angular separation and are each 64° from the satellite +*Z* axis. In this manner, the entire celestial sphere will be covered with the exception of that portion occulted by the earth and three small triangular areas equally spaced around the earth's horizon.

DSAD electronics compares the analog output of the three sense heads and selects the one with the greatest output. The digitized outputs of the selected sensor are then detected by comparing each to the sensor's analog output. The fourteen detected bits, and two bits that determine which sense head was selected by the analog comparator, are stored in a shift register and serially read out by telemetry. A pulse on the Sync-Pulse-Out line is generated at the start of each 16-bit sun-line readout. This Sync-Pulse also serves to turn on power to the DSAD detection circuitry, thereby minimizing power consumption.

The three DSAD sensors are mounted externally on the Power Unit. The electronics are packaged in a single book in the Power Unit.

Command System—The TRIAD Command System contains 140 discrete functions, 48 of which are allocated to the Power Unit, 20 to

DISCOS, and 72 to the Main Electronics Unit. There are also six data commands and a single computer command (to dump stored telemetry).

The Command System is fully redundant with the exception of the computer/memory load data link. The redundant system starts with two dipole antennas for the two tuned radio frequency (TRF) receivers. The outputs of the receivers are direct and cross-coupled to the two slow-bit detectors. Each slow-bit detector feeds its respective master logic. The outputs of the master logics are enabled via the computer/memory to the data combiners whose outputs drive all the remote command terminals. The remote command terminals start with OR-ing of the command information from the data combiner transmitters in the Electronics Unit. The output of each "data OR-ing box" drives respective remote logics which provide outputs to their respective relay matrices, or provide data outputs to the user's data combining circuits. The redundancy ends at the electromechanical interface in the relays or at the user's data combining circuits.

The command power system contains two transformer rectifier filters, each with its respective current detector for each unit of the TRIAD spacecraft. Each power supply is driven from the primary AC power bus and supplies the necessary voltages for one channel of the redundant command subsystem. The possibility of a short circuit in any of the remote terminals reflecting back to the primary AC power bus is prevented by current detectors which will sense the short and remove power from the shorted terminal.

Telemetry System—The Telemetry System in the TRIAD satellite has been designed to be highly flexible to meet the requirements that are unique to the TRIAD configuration and performance capabilities. The Telemetry System provides real-time digital data for pre-launch operations and post-launch operational monitoring of in-orbit status, and stores selected telemetry information in the computer/memory for delayed readout. This storing feature allows the collection for delayed readout of DISCOS and attitude data during intervals when the satellite is out of contact with ground telemetry receiving stations.

Packaged in each of the three TRIAD units are telemetry components necessary to sample desired data points and condition the selected information to useful voltages in analog form, which can then be commutated and delivered to the main telemetry electronics for further conditioning. The main telemetry electronics, located in the Main Electronics Unit, converts the commutated analog data to digital format to be transmitted in real-time to the ground receiving stations, stored in the computer/memory for later readout, or both.

Transmission of TRIAD telemetry data must be specifically commanded from the ground. Command options allow for either real-time data transmission, or stored data readout from the computer/memory. Also commandable is the RF carrier, since the data may be transmitted via either the 150-MHz or 400-MHz transmitter, or both. This design provides for telemetry data, real-time or stored, to be always available for sampling at will without disrupting the navigation message.

The Telemetry System of TRIAD utilizes three subcommutators and one main commutator. The subcommutator packaged in the DISCOS Unit has 60 analog samples, or channels, and in addition can accept 24 bilevel signals (telltales). The Power Unit subcommutator has 68 analog channels and 40 bilevel signals. The Main Electronics Unit has 54 analog channels and 56 bilevel signals. Three of the analog channels on each are calibrate voltage samples. The main commutator is a 3-channel commutator that samples the subcommutator outputs in series. The subcommutators may be stopped independently. When one is stopped, the format of the other two remains unchanged. Each analog or bilevel input is sampled once every 5.16 seconds during normal operations. During commutator stop, any one function may be sampled 13.563 times per second.

Signal attenuators are packaged in each TRIAD unit to provide a nominal ±0.250 volt with 3.64K ohms resistance for each analog function input to the subcommutators. Telltales are bilevel functions that indicate a change of state such as separated/attached, on/off, solar blades folded/solar blades deployed, etc. Absolute magnitudes of greater than 0.175 volt are considered a digital "1" and absolute magnitudes of less than 0.075 volt are considered a digital "0." The digits are sometimes referred to as "Hi" or "Lo" which are synonymous with the change of state.

A thermal reference regulator is packaged in each of the three TRIAD units. The regulators bias the temperature and pressure transducers with a nominal output of 4 milliamps at ±0.5 volt.

A special instrumentation package reads out voltages and temperatures from sensors located in the RTG power supply. These data are sub-subcommutated in the Power Unit and one complete readout is obtained every 82.56 seconds.

The main commutator sends the information received from the three subcommutators to two analog-to-digital converters. One performs an eight-bit conversion of analog data, and the other performs a one-bit conversion of the bilevel data. A Sync generator injects a once-a-frame, 24-bit sync pattern into the data stream. The data stream, in the format of 8-bit parallel words, may then be encoded for modulation via phase shift keying over either or both of the satellite transmitters by command. During the epoch when the computer/memory has been programmed to store telemetry data, the 8-bit parallel word data stream may be simultaneously delivered to the memory/computer for storage.

Thermal Control—The TRIAD spacecraft employs passive thermal control to maintain a nominal operational temperature of the spacecraft systems during orbit.

Passive thermal control of the TRIAD spacecraft is accomplished primarily by external coatings and internal insulation. The Power Unit and Main Electronics Unit are coated externally with aluminized Teflon and aluminized Mylar that produce an average absorptivity to emissivity ratio of approximately 0.5. Thermal radiation and conduction coupling between the electronic components and the satellite structure is controlled by low emissivity surfaces and conduction resistors. Radiated heat transfer created by the open DISCOS cylinder (the cavity in the Power and Main Electronics Units that DISCOS occupies during launch) is controlled by a thin layer of insulation around the inside of the cylinder. Multi-layer insulation was held to a minimum to help maintain the low weight budget that was afforded the Thermal Control Subsystem. Electronic book temperatures will remain within a temperature range of 30° F to 100° F with this design.

Control of temperature gradients across the DISCOS propellant tanks is a principal thermal objective for the DISCOS unit. This is implemented by external coatings of aluminized Teflon and Mylar to provide a solar absorptance of about 0.13. Internal radiation coupling between the propellant tanks and the outer structure are minimized by the low emissivity of gold plated surfaces. Also, high emissivity surfaces of Tiodize increase radiation coupling across the propellant tanks and black anodize increases the radiation coupling across the inside of the cylindrical shell.

Launch

TRIAD was successfully launched from the Western Test Range, Vandenberg Air Force Base on September 2, (day 246) 1972. Lift-off was at 1750 UT (1:50 PM EDT). At launch, oscillator No. 1 in the satellite was on (140 ppm offset), the 150-MHz transmitter was on (high power), the telemetry system was on with telemetry modulation on the 150-MHz transmissions, and the computer was on and programmed to store telemetry data on power system performance.

During the powered flight the tracking station at the launch site monitored the satellite transmissions. The signals radiated by the satellite's volute antenna were excellent, allowing tracking through fourth stage vehicle burn, monitoring of power turn-on in the satellite solar panels as heat shield ejection exposed the panels to sunlight, and power rise in the RTG to its normal value as the air in the RTG evacuated in the space environment.

The vehicle placed the satellite in orbit spinning at a nominal value and with inclination and eccentricity values close to nominal. The average altitude however was approximately 50 nm below nominal.

During its initial revolution, the satellite was observed by TRANET tracking stations at Pretoria, South Africa; Brussels, Belgium; and Anchorage, Alaska. The satellite signals were strong, and satisfactory doppler data were obtained. The AGC nulls in the signals indicated that the yo-yo despin system on the satellite had deployed and that the satellite spin rate had decreased from the rate at orbit injection. The launch site tracking station then observed the satellite signals and obtained telemetry data. The data showed that all the telemetry telltales were normal and indicated satellite-vehicle adapter separation, despin, and antenna deployment.

The first pass of the satellite at Station 502, APL, Howard County, Maryland, occurred about 8 hours after lift-off. The initial memory readout and injection operation was made to obtain the stored telemetry data and begin the post-launch check-out of the satellite.

Post-Launch Operations

Magnetic Stabilization—During the initial APL pass, TRIAD was tumbling about its vertical axis at about one rpm. Approximately 12 hours later the tumble rate had decreased to about 0.2 rpm, and during the 0252 UT pass on September 4, the momentum wheel was commanded on to assist in satellite stabilization. On September 5 the electromagnet was commanded on and by September 7 the satellite was stabilized magnetically and ready for the boom operations to achieve gravity gradient stabilization.

Gravity Gradient Stabilization—The command to fire the three-body separation squib was transmitted from Station 502 to the satellite during the 1332 UT pass on September 7, separating the TRIAD power unit (PU) from the electronic unit (EU). During the next pass at 1513 UT the PU and EU booms were extended on command, successfully orienting the satellite along the local vertical in the configuration illustrated in Fig. 1. The sequence of operations was preprogrammed for the Sigma 3 computer in Station 502 and executed under control of that computer. The objective of the programmed sequence was to cause both booms to be driven out 30 seconds apart for a drive time of six minutes each and then to turn off the electromagnet. The boom lengths desired to place the satellite center of mass at the center of the DISCOS proof mass housing cavity were as follows:

PU Boom Length	96.0 inches
EU Boom Length	119.5 inches.

The TRIAD telemetry data indicated that the boom lengths achieved were as follows:

PU Boom Length	74.37 inches
EU Boom Length	75.29 inches.

Stiffness in the cables that run along the boom contributed to the shorter lengths achieved.

During September 8 to 12, boom trimming operations were conducted to place the satellite center of mass within the desired ±0.3937 inch tolerance band about the center of the DISCOS proof mass cavity. In addition to boom extension by actual commands it was noted that the strain on the boom cables was relaxing because of the cold flow property of the cable insulation, and this relaxation was resulting in a slight additional elongation of both booms. By September 12 the drift rate of the satellite center of mass caused by cable strain relief was observed to be decaying exponentially such that by the APL pass at 1218 UT on September 13 the satellite mass center was essentially stabilized within the ±0.4 inch tolerance band about the center of the proof mass cavity thus allowing DISCOS operations to be started.

The telemetry data indicated that the boom lengths were as follows:

PU Boom Length	90.485 inches
EU Boom Length	113.044 inches.

The satellite mass center lay within the proof mass cavity, 0.189 inch toward the electronic unit.

DISCOS—The commands to uncage the DISCOS proof mass and to activate the DISCOS thruster jets were sent to the satellite during the 1355 UT pass on September 13. The telemetered data on the proof mass position, resolved into axial components showed that it took five minutes from the time the uncaging command was given until the proof mass became located within a ±1 mm dead band position at the center of the proof housing cavity.

DISCOS thruster valves are located along axes identified in Fig. 1 as 1C, 2C, and 3C, with two oppositely firing valves along each axis. The 2C forward axis is in the direction of satellite motion and is maintained in this direction by the momentum wheel. The 1C top and 3C top axes are oriented to the upper left and upper right of the 2C forward axis, respectively. When caged, the proof mass is at the top of the proof mass cavity, centered along the 2C axis.

Both fine and coarse measurements of proof mass position are telemetered. Plots of proof mass position are shown in Fig. 6. All three components of the ball position are shown as a function of time. The coarse position data showed that the proof mass struck the caging rod, before the rod was fully retracted. It then returned part way toward the top of the cavity, reversed direction, struck the bottom of the cavity, and rebounded toward the center. At thruster activation (105 seconds after the start of the uncaging) thrusters 1CB and 3CB fired immediately to begin moving the satellite to center itself on the proof mass. Subsequent firings of the other thrusters occurred resulting in the proof mass becoming positioned within the dead band. The results showed that the closed-loop control system on proof mass position was operating as designed.

Initiation of the DISCOS experiment completes

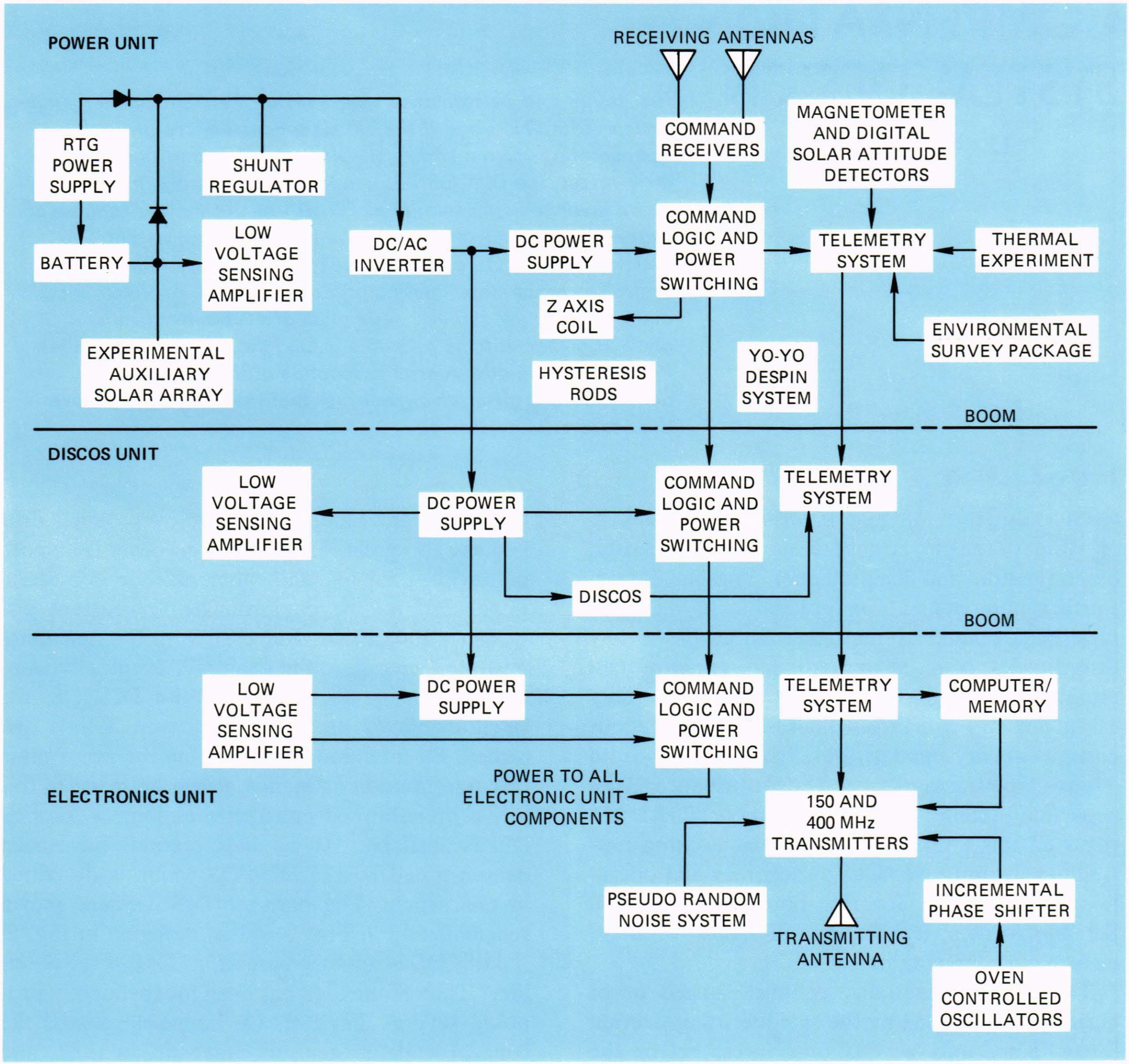


Fig. 6—DISCOS proof mass uncaging.

the immediate post-launch orbital operations and establishes the configuration for future experimentation. During the first two months of post-launch operations, all systems and experiments were exercised and predicted performance either achieved or surpassed. Unfortunately, anomalies in the analog telemetry and computer inject loader limited the utility of the spacecraft by restricting its use to the experimental mode and forfeiting long term data on proof mass position and integrated thruster-on time. Though this data most certainly would have contributed much information on system performance and to aeronomy studies, the most meaningful evaluation of performance lies in the tracking data. In this regard the long-term performance of TRIAD/DISCOS experiment has been superb. Significant contributions to the art of navigation have been demonstrated and much new technology developed for use in future Navigation Satellites. After one year of continuous drag-free tracking, DISCOS was commanded "OFF" to permit tracking of the spacecraft while influenced by drag and radiation pressure forces.