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VOYAGER BACKGROUNDER

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THE VOYAGER SPACECRAFT

The two Voyager spacecraft are designed to operate at distances from Earth and the Sun greater than required by any previous mission. Communications capability, hardware reliability, navigation and temperature control are among major challenges. The spacecraft are identical. Each can meet the objectives of either mission and their various options.

Each spacecraft at launch consisted of a mission module -- the planetary vehicle -- and a propulsion module, which provided the final energy increment to inject the mission module onto the Jupiter trajectory. The propulsion module was jettisoned after the required velocity was attained. (For the major part of the mission, "spacecraft" and "mission module" will be used interchangeably. In describing the prelaunch configuration and launch phase, "spacecraft" will refer to the combined "mission module" and "propulsion module.")

The mission module after injection weighed 825 kilograms (1,819 pounds) including a 117-kg (258-lb.) science instrument payload. The propulsion module, with its large solid-propellant rocket motor, weighed 1,207 kg (2,660 lb.). Launch weight of the spacecraft was 2,066 kg (4,555 lb.).

To assure proper operation for the four-year flight to Saturn, and perhaps well beyond, mission module subsystems were designed with high reliability and extensive redundancy.

Like the Mariners that explored the inner planets and the Viking Mars orbiters, the Voyagers are stabilized in three axes using the Sun and a star (usually Canopus) as celestial references.

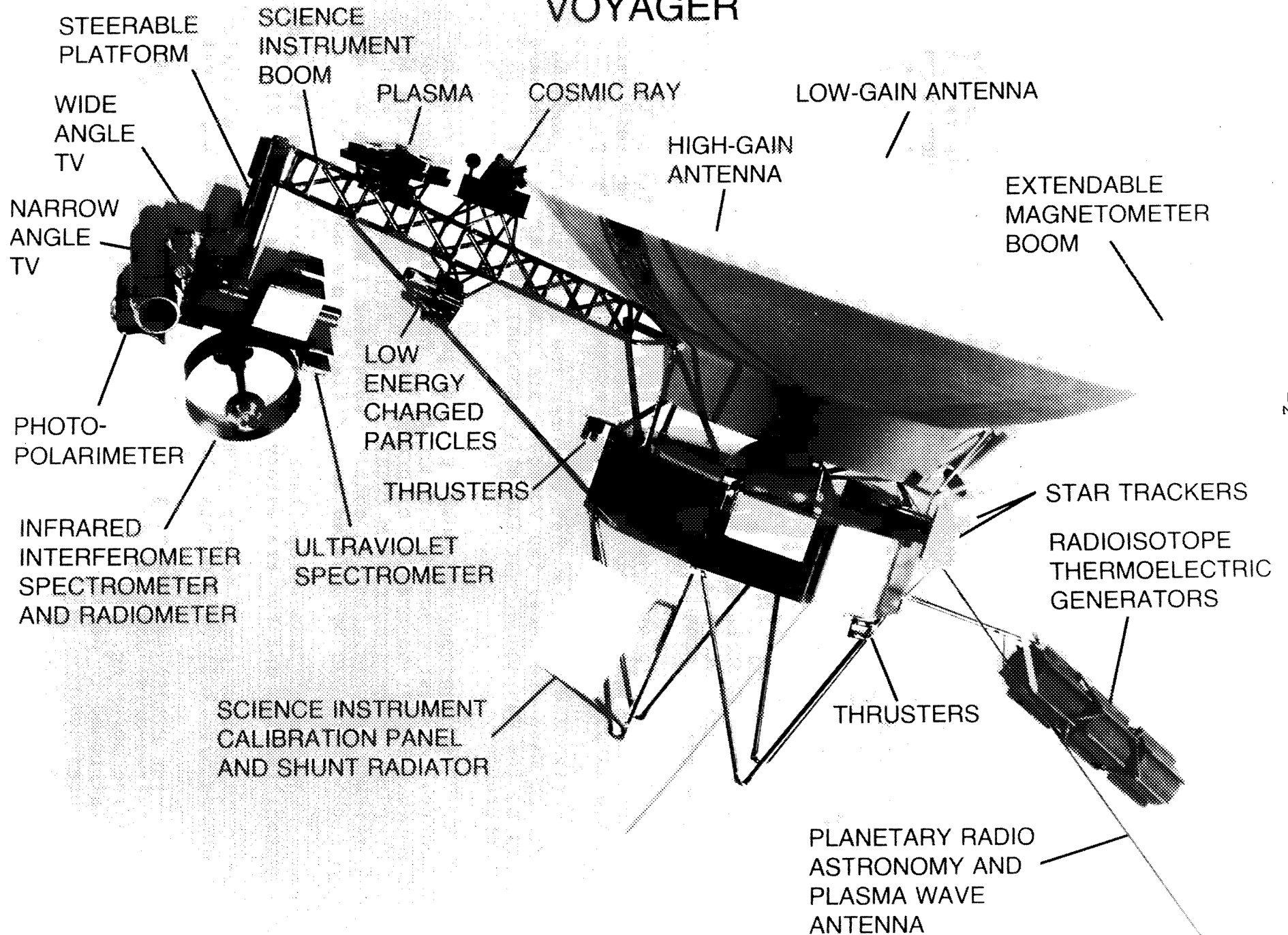
Three engineering subsystems are programmable for onboard control of most spacecraft functions. Only trajectory-correction maneuvers must be enabled by ground command. The three are the computer command subsystem (CCS), flight data subsystem (FDS) and attitude and articulation control subsystem (AACS). The memories of the units can be updated or modified by ground command.

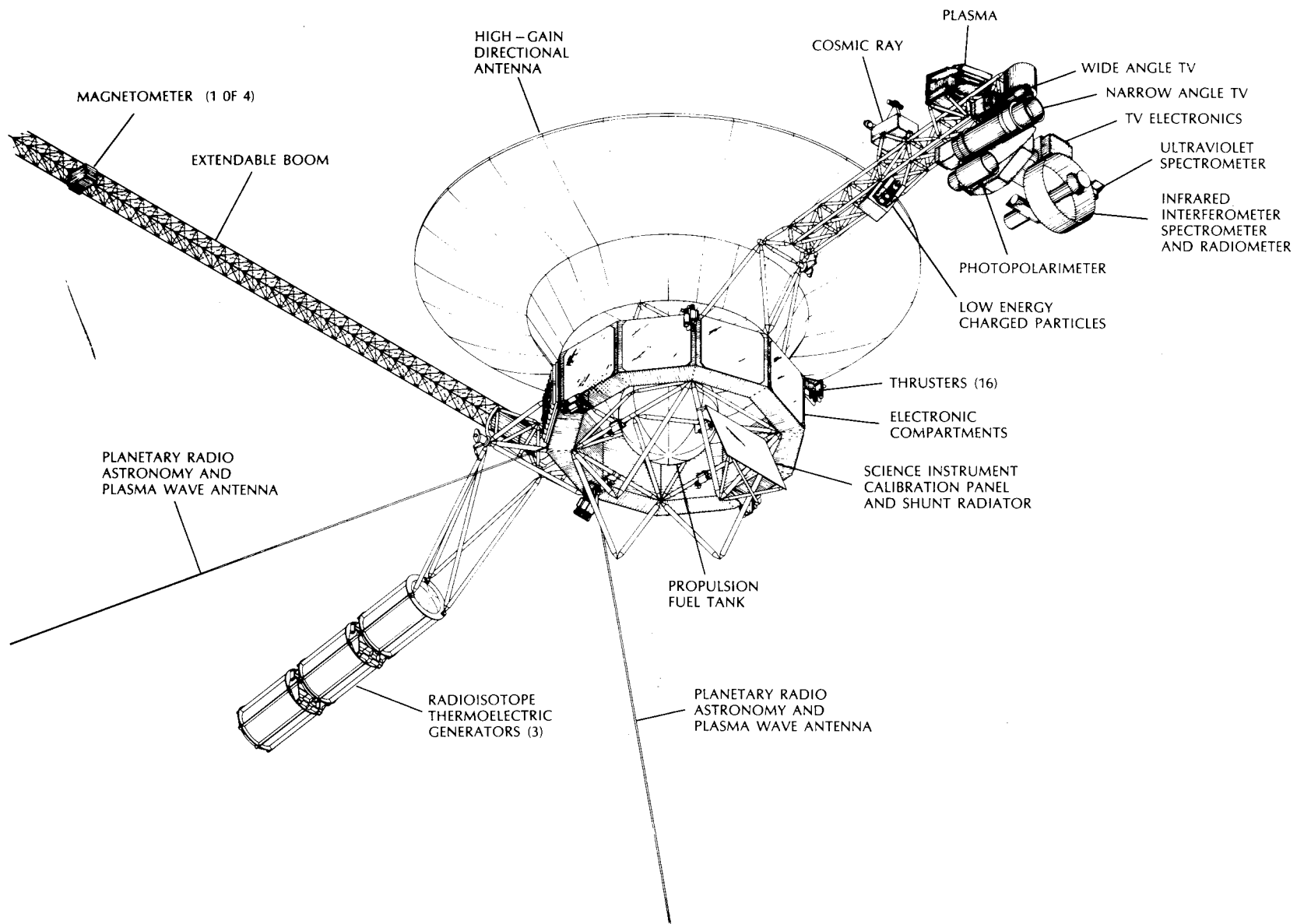
Hydrazine (mono-propellant) jets provide thrust for attitude stabilization and for trajectory correction maneuvers (TCM).

A nuclear power source -- three radioisotope thermoelectric generators (RTG) -- provides electrical power for the spacecraft.

The pointable science instruments are mounted on a commandable (two-axis) scan platform at the end of the science boom for precise pointing. Other body-fixed and boom-mounted instruments are aligned to provide for proper interpretation of their measurements.

VOYAGER





Data storage capacity on the spacecraft is about 536 million bits -- approximately the equivalent of 100 full-resolution photos.

Dual-frequency communications links -- S-band and X-band -- provide accurate navigation data and large amounts of science information during planetary encounter periods (up to 115,200 bits per second at Jupiter and 44,800 bps at Saturn).

The dominant physical feature of the spacecraft is the 3.66 meter- (12-foot-) diameter high-gain antenna that points toward Earth continually after the initial 80 days of flight.

While the high-gain antenna dish is white, most visible parts of the spacecraft are black -- blanketed or wrapped for thermal control and micrometeoroid protection. A few small areas are finished in gold foil or have polished aluminum surfaces.

Structure and Configuration

The basic mission module structure is a 24.5-kg (54-lb.) 10-sided aluminum framework with 10 electronics packaging compartments. The structure is 47 centimeters (18.5 in.) high and 178 cm (70 in.) across from flat to flat; 188 cm (74 in.) from longeron to opposite longeron. The electronics assemblies are structural elements of the 10-sided box.

The spherical propellant tank that contains fuel for hydrazine thrusters for attitude control and trajectory correction maneuvers occupies the center cavity of the decagon. Propellant lines carry hydrazine to 12 small attitude-control and four trajectory correction maneuver thrusters on the mission module and to larger thrust-vector-control engines on the propulsion module during launch.

The 3.66-m- (12-ft.-) diameter high-gain parabolic reflector is supported above the basic structure by a tubular truss work. The antenna reflector has an aluminum honeycomb core and is surfaced on both sides by graphite epoxy laminate skins. Attachment to the trusses is along a 178-cm- (70-in.-) diameter support ring. The Sun sensor protrudes through a cutout in the antenna dish. An X-band feed horn is at the center of the reflector. Two S-band feed horns are mounted back-to-back with the X-band subreflectors on a three-legged truss above the dish. One radiates through the subreflector, transparent at S-band, to the high-gain dish. The other functions as the low-gain antenna.

Louver assemblies for temperature control are fastened to the outer faces of two electronics compartments -- those housing the power conditioning assembly and the radio transmitter power amplifiers. The top and bottom of the 10-sided structure are enclosed with multi-layer thermal blankets.

Two Canopus star tracker units are mounted side-by-side and parallel atop the upper ring of the decagon.

Three radioisotope thermoelectric generators are assembled in tandem on a deployable boom hinged on an outrigger arrangement of struts attached to the basic structure. The radioisotope thermoelectric generator boom is constructed of steel and titanium. Each radioisotope thermoelectric generator unit, contained in a beryllium outer case, is 40.6 cm (16 in.) in diameter, 51 cm (20 in.) long and weighs 39 kg (86 lb.). Together, they provide over 400 watts of electrical power to the spacecraft.

The science boom, supporting the instruments most sensitive to radiation, is located 180 degrees from the radioisotope thermoelectric generator boom and is hinged to a truss extending out from the decagon behind the high-gain antenna. The boom, 2.3 m (7.5 ft.) long, is a bridgework of graphite epoxy tubing. Attached on opposite sides of the boom at its mid-point are the cosmic ray and low-energy charged particle subsystems. Farther out on the boom is the plasma science instrument.

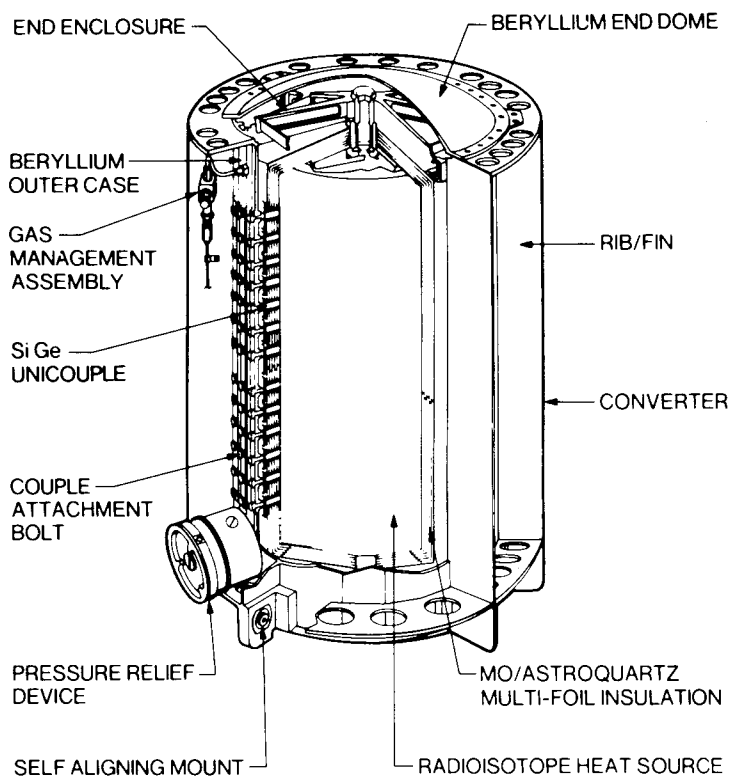
The two-axis scan platform is mounted at the end of the boom and provides precision pointing for four remote-sensing instruments -- the ultraviolet spectrometer, infrared interferometer spectrometer and radiometer, photopolarimeter (no longer operating on Voyager 1) -- and a two-camera imaging science subsystem. Total platform gimballed weight is 103 kg (227 lb.).

With both the radioisotope thermoelectric generators and science booms deployed, the nearest boom-mounted instruments to a radiation source is 4.8 m (16 ft.), with the bulk of the spacecraft between the two. The closest platform-mounted instrument is 6.4 m (21 ft.) away.

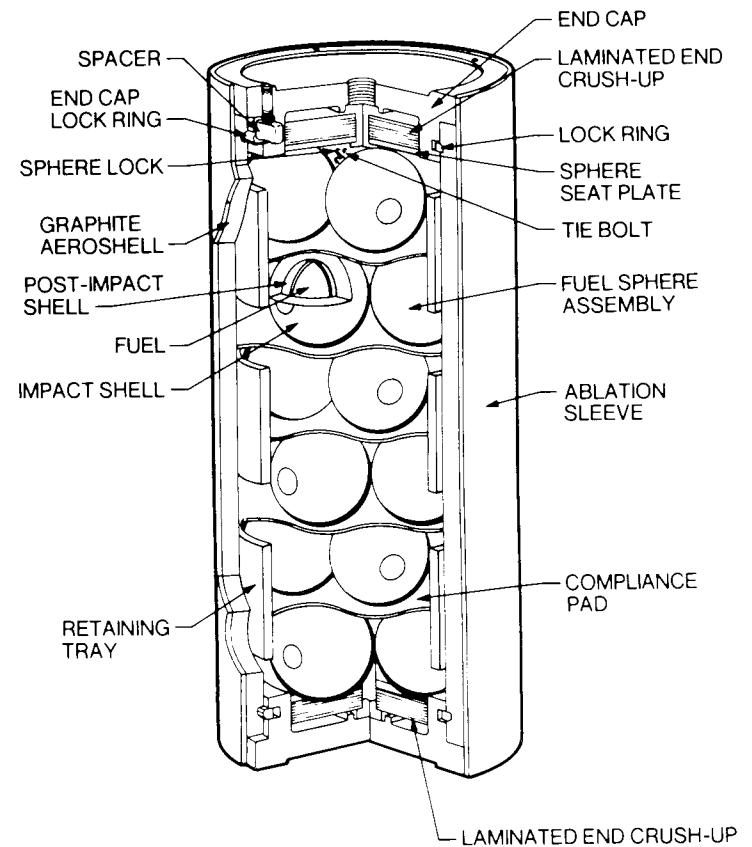
A polarimetric calibration target, called a Brewster plate, is mounted atop the mission module and aligned so that the photopolarimeter views the target during science maneuvers planned for planetary phases of the mission.

A pair of 10-m (33-ft.) antennas is deployed from a position outside the top ring of the basic structure and looking down between the radioisotope thermoelectric generator boom outrigger members. The antennas, which form a right angle, are part of the planetary radio astronomy (PRA) instrument package and are shared with the plasma wave instrument (PWS). The planetary radio astronomy and plasma wave instrument assemblies are body-mounted adjacently. The antennas, beryllium copper tubing, were rolled flat in their housing before deployment by small electric motors.

VOYAGER RADIOISOTOPE THERMOELECTRIC GENERATOR



HEAT SOURCE FOR RADIOISOTOPE THERMOELECTRIC GENERATOR



The magnetic fields experiment consists of an electronics subassembly located in one of the mission module electronics bays and four magnetometers -- two high-field sensors affixed to the spacecraft and two low-field sensors mounted on a 13-m (43-ft.) deployable boom. The boom, constructed of epoxy glass, spiralled from its stowed position in an aluminum cylinder to form a rigid triangular mast with one magnetometer attached to its end plate and another positioned 6 m (19.6 ft.) closer to the spacecraft. The mast weighs 2.26 kg (5 lb.), a few ounces less than the cabling running its length and carrying power to and data from the magnetometers. The boom housing is a 22.8-cm- (nine-in.-) diameter cylinder, 66-cm (26-in.) long, supported by the radioisotope thermoelectric generator outrigger. The mast uncoils in helix fashion along a line between the rear face of the high-gain antenna and the radioisotope thermoelectric generator boom.

The basic structure of the discarded propulsion module was a 43.54-kg (96-lb.) aluminum semi-monocoque shell. The cylinder, 99 cm (39 in.) in diameter and 89 cm (35 in.) long, was suspended below the mission module structure by an eight-member tubular truss adapter. The hollow of the structure contained the solid rocket motor that delivered the final powered stage of flight. The rocket, which weighed 1,123 kg (2,476 lb.) including 1,039 kg (2,291 lb.) of propellant, developed an average 68,054 newtons (15,300 lb.) thrust during its 43-second burn duration.

Mounted on outriggers from the structure were eight hydrazine engines that provided attitude control during the solid-motor burn. Hydrazine fuel was supplied from the mission module.

A pair of batteries and a remote driver module for powering the valve drivers to the thrust-vector-control engines were positioned on the outer face of the cylindrical propulsion module structure.

A .36-square-m (4-square-ft.) shunt radiator/science calibration target faces outward from the propulsion module truss adapter toward the scan platform. The dual-purpose structure is a flat sandwich of two aluminum radiating surfaces lining a honeycomb core. Through power collectors and emitter resistors between the plates, any amount of the electrical power from the radioisotope thermoelectric generators can be radiated to space as heat. The outer surface also serves as a photometric calibration target for the remote-sensing science instruments on the scan platform.

The shunt radiator and the propulsion-module truss adapter, remained part of the mission module when the propulsion module was jettisoned.

Steel alloy/gold foil plume deflectors extended from the propulsion module to shield the stowed radioisotope thermoelectric generators and scan platform from rocket exhaust during engine firing.

The spacecraft adapter, a truncated aluminum cone, joined the propulsion module to the Centaur stage of the launch vehicle. The adapter, 76 cm (30 in.) tall, was 160 cm (63 in.) in diameter at the base (Centaur attachment), 99 cm (39 in.) at the spacecraft separation joint and weighed 36 kg (79 lb.). The adapter remained with the Centaur rocket stage at spacecraft separation.

Launch Configuration

Some mechanical elements of the spacecraft were rigidly restrained to protect against the severe vibration during launch. After launch, appendages that had been latched securely within the Centaur stage nose fairing were deployed to their cruise positions.

The pyrotechnic subsystem provided simple and positive deployment with explosive squibs. Devices stowed securely during launch and released for deployment by the pyrotechnic subsystem were the science boom, radioisotope thermoelectric generator boom and magnetometer boom. Uncertainty concerning the full deployment and locking of the science boom on Voyager 2, first spacecraft launched, existed for several weeks.

The pyrotechnic subsystem also routed power to devices to separate spacecraft from launch vehicle, activated the propulsion module batteries, ignited the solid-propellant rocket motor, sealed off the propellant line carrying hydrazine from the mission module to the propulsion module, jettisoned the propulsion module and released the infrared interferometer spectrometer and radiometer dust cover.

Communications

Communications with the Voyagers is by radio link between Earth tracking stations and a dual-frequency radio system aboard the spacecraft.

The uplink operates at S-band only, carrying commands and ranging signals from ground stations to one of a pair of redundant receivers. The downlink is transmitted from the spacecraft at both S-band and X-band frequencies.

The on-board communications system also includes a programmable flight data subsystem, modulation/demodulation subsystem, data storage subsystem and high-gain and low-gain antennae.

The flight data subsystem, one of the three on-board computers, controls the science instruments and formats all science and engineering data for telemetry to Earth. The telemetry modulation unit of the modulation demodulation subsystem feeds data to the downlink. The flight command unit of the modulation/demodulation subsystem routes ground commands received by the spacecraft.

Only one receiver is powered at any one time, with the redundant receiver at standby. The receiver operates continuously during the mission at about 2113 megahertz. Different frequency ranges have been assigned to the radio-frequency subsystem of each spacecraft. The receiver can be used with either the high-gain (dish) or low-gain (omni) antenna. (Voyager 2's primary receiver failed on April 5, 1978, and the spacecraft is operating on its backup receiver.)

The S-band transmitter consists of two redundant exciters and two redundant RF power amplifiers, of which any combination is possible. Only one exciter-amplifier combination operates at any one time. Selection of the combination is by on-board failure-detection logic within the computer command subsystem, with ground-command backup. The same arrangement of exciter-amplifier combinations makes up the X-band transmitting unit.

One S-band and both X-band amplifiers employ traveling wave tubes. The second S-band unit is a solid state amplifier. The S-band transmitter is capable of operating at 9.4 watts or at 28.3 watts when switched to high power and can radiate from both antennas. X-band power output is 12 watts and 21.3 watts. X-band uses only the high-gain antenna. (S-band and X-band never operate at power simultaneously.)

When no uplink signal is being received, the transmitted S-band frequency of about 2295 MHz and X-band frequency of 8418 MHz originate in the S-band exciter's auxiliary oscillator or in a separate ultra-stable oscillator (one-way tracking). With the receiver phase-locked to an uplink signal, the receiver provides the frequency source for both transmitters (two-way tracking). The radio system can also operate with the receiver locked to an uplink signal while the downlink carrier frequencies are determined by the on-board oscillators (two-way noncoherent tracking).

Only the 64-m (210-ft.) antenna stations of the Deep Space Network can receive the downlink X-band signal. However, by combining signals received by the 64-m (210-ft.) and the 34-m (112-ft.) antennas ("arraying"), JPL can receive the X-band signal if required. Both the 64-m (210-ft.) and the 26-m (85-ft.) antenna stations are capable of receiving at S-band.

The X-band downlink was not normally used during the first 80 days of the mission -- until Earth was within the beam of the spacecraft's high-gain antenna. Communications during launch, near-Earth and early cruise phase operations were confined to S-band and the low-gain antenna. An exception occurred early in the flight when the spacecraft, on inertial control, pointed the high-gain antenna toward Earth to support instrument calibration and an optical navigation/high-rate telecommunications link test. During its calibration sequence on Sept. 18, 1977, Voyager 1 took pictures of the Earth-Moon system.

The high-gain antenna, with 3.66-m-diameter (12 ft.) parabolic reflector, provides a highly directional beam. The low-gain antenna provides essentially uniform coverage in the direction of Earth.

Under normal conditions, after the first 80 days of the mission, all communications -- both S-band and X-band -- have been via the high-gain antenna. X-band is turned off, however, and the S-band transmitter and receiver are switched to the low-gain antenna during periodic science maneuvers and trajectory correction maneuvers.

The S-band downlink is always on, operating at high power during maneuvers or during the cruise phase only when the 26-m-antenna Deep Space Network stations are tracking and at low power whenever X-band is on. At Saturn, both S-band and X-band transmitters will be at low power when gyros and tape recorder are on simultaneously.

Commanding the Spacecraft

Ground commands are used to put into execution selected flight sequences or to cope with unexpected events. Commands are issued in either a predetermined, timed sequence, via on-board program control or directly as received from the ground. Most commands are issued by the spacecraft's computer command subsystem in its role as "sequencer-of-events" and by the flight data subsystem as controller of the science instruments because the time delays (associated with the extreme distances) for command signals to reach the spacecraft eliminates the usual "real-time" control procedures.

All communications between spacecraft and Earth are in digital form. Command signals, transmitted at 16 bits per second to the spacecraft, are detected in the flight command unit and routed to the computer command subsystem for further routing to their proper destination. Ground commands to the spacecraft fall into two major categories: discrete commands, and coded commands.

A discrete command causes a single action on the spacecraft. For example, DC-2D switches the S-band amplifier to high power; DC-2DR, S-band amplifier low power; DC-2E, S-band radiates from high-gain antenna; DC-2ER, S-band transmits low-gain. Coded commands are the transfer of digital data from the computer command system or from the ground via the computer command subsystem to user subsystems. Subsystems receiving coded commands are flight data, attitude and articulation control, modulation/demodulation, data storage and power.

Ground commands back up all critical spacecraft functions that, in a standard mission, are initiated automatically by on-board logic. Command modulation will be off during science maneuvers and trajectory correction maneuvers unless a spacecraft emergency arises.

Downlink Telemetry

Data telemetered from the spacecraft consists of engineering and science measurements prepared for transmission by the flight data subsystems, telemetry modulation unit and data storage subsystem. The encoded information will indicate voltages, pressures, temperatures, television pictures and other values measured by the spacecraft telemetry sensors and science instruments.

Two telemetry channels -- low rate and high rate -- are provided for the transmission of spacecraft data. The low rate channel functions only at S-band at a single 40-bps data rate and contains real-time engineering data exclusively. It is on only during planetary encounters when the high-rate channel is operating at X-band.

The high-rate channel is on throughout the mission and operates at either S-band or X-band and containing the following types of data:

- Engineering only at 40 bps or 1,200 bps (the higher data rate usually occurs only during launch and trajectory correction maneuvers) transmitted at S-band only.
- Real-time cruise science and engineering at 2,560, 1,280; 640; 320; 160 and 80 bps (40, 20 and 10 bps may be used for post-Saturn operations) transmitted at S-band only.
- Real-time encounter general science and engineering at 7.2 kilobits per second (kbps) special 115.2 kbps rate was available at Jupiter for the planetary radio astronomy and plasma wave instruments) transmitted at X-band only.
- Real-time encounter general science, engineering and television at 115.2; 89.6; 67.2; 44.8; 29.86 and 19.2 kbps transmitted at X-band only.
- Real-time encounter general science and engineering, plus tape recorder playback, at 67.2 and 44.8 kbps and 29.86 kbps transmitted at X-band only.
- Recorded data playback only at 21.6 and 7.2 kbps transmitted at X-band only.

• Memory data stored in the three on-board computers -- computer command subsystem, flight data subsystem, attitude and articulation control subsystem -- readout and played back at 40 or 1,200 bps transmitted at either S-band or X-band (treated as engineering data).

The many data rates for each type of telemetered information are required by the changing length of the telecommunications link with Earth and the possible adverse effects of Earth weather upon reception of X-band radio signals. The S-band cruise science primary telemetry rate is 2,560 bps. Lesser rates result in reduced instrument sampling and will be used only when the telecommunications link cannot support the higher rate.

In order to allow real-time transmission of video information at each encounter, the flight data subsystem can handle the imaging data at six downlink rates from 115.2 to 19.2 kbps. The 115.2-kbps rate represents the standard full-frame readout (at 48 seconds per frame) of the TV vidicon. Under normal conditions, that rate was used at Jupiter. Full-frame, full-resolution TV from Saturn can be obtained by increasing the frame readout time to 144 seconds (3:1 slow scan) and transmitting the data at 44.8 kbps. A number of other slow scan and frame-edit options are available to match the capability of the telecommunications link.

The data-storage subsystem can record at two rates: TV pictures, general science and engineering at 115.2 kbps; general science and engineering at 7.2 kbps; and engineering only at 7.2 kbps (engineering is acquired at only 1,200 bps, but is formatted with filler to match the recorder input rate). The tape transport is belt-driven. Its 1/2 in. magnetic tape is 328 m (1,076 ft.) long and is divided into eight tracks that are recorded sequentially one track at a time. Total recycleable storage capacity is about 536 million bits -- the equivalent of 100 TV pictures. Playback is at four speeds -- 57.6; 33.6; 21.6 and 7.2 kbps.

Tracking the Spacecraft

Very precise navigation is required to achieve the desired maneuver and flyby accuracies for a multi-planet/satellite encounter mission.

To provide Doppler tracking data, the S-band signal transmitted from Earth is received at the spacecraft, changed in frequency by a known ratio and retransmitted to Earth. It is possible to precisely determine the transmitted downlink frequency while measuring the Doppler-shifted received signal, thereby measuring spacecraft velocity. This is called coherent two-way tracking.

One-way tracking is when no uplink signal is received and the downlink carrier frequency is provided by an on-board oscillator. Noncoherent two-way tracking occurs when uplink and downlink carriers are operating independently.

When both S-band and X-band transmitters are on, X-band frequency will always be eleven-thirds the S-band frequency regardless of the frequency source -- spacecraft receiver, ultra-stable oscillator or S-band exciter auxiliary oscillator.

Distance or range to the spacecraft is measured in the coherent two-way configuration by transmitting a digital code (ranging modulation) on the uplink, turning this code around in the spacecraft and sending it back to the ground. By measuring the total elapsed time between transmitting and receiving the code at the ground station, and knowing such factors as the speed of light, turnaround delay and relative velocities of the spacecraft and tracking station, it is possible to determine spacecraft range.

Dual-frequency ranging (both S-band and X-band ranging on) is conducted during planetary phases of the mission and during the cruise phases when the Deep Space Network's 64 m (210 ft.) antennas are tracking. Special three-way dual-frequency ranging cycles will be conducted while two or more ground stations on two continents are tracking the spacecraft.

All ranging modulation is turned off during science maneuvers, trajectory correction maneuvers and planetary occultations.

Power

The Voyager power subsystem supplies all electrical power to the spacecraft by generating, converting, conditioning and switching the power.

Power source for the mission module is an array of three radioisotope thermoelectric generators. The propulsion module, active only during the brief injection phase of the mission, used a separate battery source.

The radioisotope thermoelectric generator units, mounted in tandem on a deployable boom and connected in parallel, convert to electricity the heat released by the isotopic decay of Plutonium-238. Each isotope heat source has a capacity of 2,400 watts thermal with a resultant maximum power output of 160 watts at the beginning of the mission. There is a gradual decrease in power output. The minimum total power available from the three radioisotope thermoelectric generators on each Voyager ranges from about 450 watts within a few hours after launch to about 430 watts after the spacecraft passes Saturn.

Spacecraft power requirements from launch to post-Saturn operation are characterized by this general power timeline: launch and post-launch, 235 to 265 watts; interplanetary cruise, 320 to 365 watts; Jupiter encounter, 384 to 401 watts; Saturn encounter, 377 to 382 watts; and post-Saturn, less than 365 watts.

Telemetry measurements have been selected to provide the necessary information for power management by ground command, if needed.

Power from the radioisotope thermoelectric generators is held at a constant 30 volts DC by a shunt regulator. The 30 volts are supplied directly to some spacecraft equipment and are switched to others in the power distribution subassembly. The main power inverter also is supplied the 30 volts DC for conversion to 2.4 kHz square wave AC used by most spacecraft subsystems. Again, the AC power may be supplied directly to equipment or can be switched on or off by power relays.

Command-actuated relays control the distribution of power in the spacecraft. Some relays function as simple on-off switches and others transfer power from one module to another within a subsystem.

Among the users of DC power, in addition to the inverter, are the radio subsystem, gyros, propulsion isolation valves, some science instruments, most temperature control heaters and the motors that deployed the planetary radio astronomy antennas. Other elements of the spacecraft use the AC power.

There are two identical 2.4 kHz power inverters -- main and standby. The main inverter is on from launch and remains on throughout the mission. In case of malfunction or failure in the main inverter, the power chain, after a 1.5-second delay, is switched automatically to the standby inverter. Once the switch-over is made, it is irreversible.

A 4.8 kHz sync and timing signal from the flight data subsystem is used as a frequency reference in the inverter. The frequency is divided by two and the output is 2.4 kHz. The AC regulation is accurate to .004 percent. The 4.8 kHz timing signal is sent, in turn, to the computer command subsystem, which contains the spacecraft's master clock.

Because of the long mission lifetime, charge capacitor energy-storage banks are used instead of batteries to supply the short-term extra power demanded by instantaneous overloads that would cause the main DC power voltage to dip below acceptable limits. A typical heavy transient overload occurs at turn-on of a radio power amplifier.

Full output of the radioisotope thermoelectric generators, a constant power source, must be used or dissipated in some way to prevent overheating of the generator units and DC voltage rising above allowed maximum. That is controlled by a shunt regulator that consumes excess radioisotope thermoelectric generator output power above that required to operate the spacecraft. The excess power is dissipated as heat in resistors in the shunt radiator mounted outside the spacecraft and radiated into space.

Two batteries independently supplied unregulated DC power to a remote driver module (RDM) for powering valve drivers to the thrust-vector-control engines on the propulsion module during the injection phase of the mission. The batteries and the remote driver module were located in the propulsion module that was jettisoned a few minutes after the mission module was placed on the Jupiter trajectory. Each battery was composed of 22 silver oxide-zinc cells with a capacity of 1,200 ampere seconds at 28 to 40 volts, depending upon the load.

Basic requirement on the batteries was high power for a short period -- 12 minutes. With a lifetime of only 66 minutes, the batteries were kept inert until just four seconds before Centaur separation and 20 seconds before solid rocket ignition. After activation, at which an electrolyte was injected into the cells, the batteries were at full voltage in one-half second and ready for use in two seconds.

Computer Command Subsystem

The heart of the on-board control system is the computer command subsystem, which provides a semi-automatic capability to the spacecraft.

The computer command subsystem includes two independent memories, each with a capacity of 4,096 data words. Half of each memory stores reusable fixed routines that do not change during the mission. The second half is programmable by updates from the ground.

Most commands to other spacecraft subsystems are issued from the computer command subsystem memory, which, at any given time, is loaded with the sequences appropriate to the mission phase. The computer command subsystem also can decode commands from the ground and pass them along to other spacecraft subsystems.

Under control of an accurate on-board clock, the computer command subsystem counts hours, minutes or seconds until some preprogrammed interval has elapsed and then branches into sub-routines stored in memory that result in commands to other subsystems. A sequencing event can be a single command or a routine that includes many commands (e.g., manipulating the tape recorder during a playback sequence).

The computer command subsystem can issue commands from one of its two processors or from both in parallel or tandem. An example of computer command subsystem dual control is the execution of trajectory correction maneuvers.

Trajectory correction maneuver thrusters are started with a tandem command (both processors must send consistent commands to a single output unit) and stopped with a parallel command (either processor working through different output units can stop the burn).

The computer command subsystem can survive any single internal fault; each functional unit has a duplicate elsewhere in the subsystem.

Attitude Control and Propulsion

Stabilization and orientation of the spacecraft from launch vehicle separation until end of the mission is provided by two major engineering subsystems -- attitude and articulation control (AACS) and propulsion.

Propulsion Subsystem

The propulsion subsystem consists of a large solid-propellant rocket motor for final Jupiter trajectory velocity and a hydrazine blowdown system that fuels 16 thrusters on the mission module and eight reaction engines on the propulsion module.

The single hydrazine (N_2H_4) supply is contained within a 71-cm (28-in.) diameter spherical titanium tank, separated from the helium pressurization gas by a Teflon-filled rubber bladder. The tank, located in the central cavity of the mission module's 10-sided basic structure, contained 104 kg (230 lb.) of hydrazine at launch and was pressurized at 2,895,480 newtons per square meter (n/m^2) (420) psi. As the propellant is consumed, the helium pressure will decrease to a minimum of about 130 psi.

All 24 hydrazine thrusters use a catalyst that spontaneously initiates and sustains rapid decomposition of the hydrazine.

The 16 thrusters on the mission module each deliver .889 N (0.2 lb.) thrust. Four are used to execute trajectory correction maneuvers; the others, in two redundant six-thruster branches are used to stabilize the spacecraft on its three axes. Only one branch of attitude control thrusters is needed at any time.

Mounted on outriggers from the propulsion module are (444.8-N (100 lb.) thrust engines that, during solid-motor burn, provided thrust-vector control on the pitch and yaw axes. Four 22.2 N (5 lb.) thrust engines provided roll control.

The solid rocket, which weighed 1,123 kg (2,476 lb.) including 1,039 kg (2,291 lb.) of propellant, developed an average 6,805,440 N (15,300 lb.) thrust during its 43-second burn duration.

Attitude and Articulation Control Subsystem

The attitude articulation control subsystem includes an on-board computer called HYPACE (hybrid programmable attitude control electronics), redundant sun sensors, redundant Canopus star trackers, three two-axis gyros and scan actuators for positioning the science platform.

The HYPACE contains two redundant 4,096-word plated-wire memories -- part of which are fixed and part programmable -- redundant processors and input/output driver circuits. For a nominal mission, the memories will be changed only to modify predetermined control instructions.

Injection Propulsion Control

Because of the energy required to achieve a Jupiter ballistic trajectory with an 825 kg (1,819 lb.) payload, the spacecraft launched by the Titan III E/Centaur included a final propulsive stage that added a velocity increment of about 2 km/s (4,475 mph).

The solid-rocket motor in the propulsion module was ignited 15 seconds after the spacecraft separated from the Centaur and burned for about 43 seconds. Firing circuits to the motor were armed during launch vehicle countdown.

The four 444.8 N (100-lb.)-thrust engines provided pitch and yaw attitude control and the four 22.2 N- (5 lb.-) thrust engines provided roll control until burnout of the solid rocket motor. The hydrazine engines responded to pulses from the attitude and articulation control subsystem computer. Only two pitch/yaw and two roll engines at most were thrusting at any given time.

Before solid rocket ignition and after burnout, only the smaller roll engines were required until the propulsion module separated from the mission module. They were oriented on the propulsion module so that, by proper engine selection by the attitude and articulation control subsystems, attitude control was maintained on all three axes.

Approximately 11 minutes after solid-rocket burnout, the propulsion module was jettisoned. Several seconds earlier, the propellant line carrying hydrazine from the mission module to the propulsion module was sealed and separated.

Celestial Reference Control

The sun sensors, which look through a slot in the high-gain antenna dish, are electro-optical devices that send attitude position error signals to HYPACE, which in turn, signals the appropriate attitude control thrusters to fire and turn the spacecraft in the proper direction. Sun lock stabilizes the spacecraft on two axes (pitch and yaw).

The star Canopus, one of the brightest in the galaxy, is usually the second celestial reference for three-axis stabilization. Two Canopus trackers are mounted so that their lines of sight are parallel. Only one is in use at any one time.

The star tracker, through HYPACE logic, causes the thruster to roll the spacecraft about the already-fixed Earth or Sun-pointed roll axis until the tracker is locked on Canopus. Brightness of the tracker's target star is telemetered to the ground to verify the correct star has been acquired.

One of the Canopus star trackers on Voyager 1 exhibited degraded performance beginning April, 1980. Extensive ground and flight testing has led to both a high-confidence failure model as well as complete characterization of the Canopus star trackers degraded performance. Accordingly, at this time, it is planned to continue using this unit through the Saturn encounter period rather than switch to the backup unit which has been operated only briefly since launched. All preparations have been made to switch to the backup unit should any further degradation of the Canopus star tracker occur (none has occurred for the last six months). No science impact is anticipated.

To enhance downlink communication capability, the Sun sensor is electrically biased (offset) by commands from the computer command subsystem to point the roll axis at or as near the Earth as possible. The sun sensor can be biased plus and minus 20 degrees in both pitch and yaw axes.

Three-axis stabilization with celestial reference is the normal attitude-control mode for cruise phases between planets.

Inertial Reference Control

The spacecraft can be stabilized on one axis (roll) or all three axes with the attitude and articulation control subsystems inertial reference unit consisting of three gyros.

Appropriate inertial reference modes are used whenever the spacecraft is not on Sun/star celestial lock. Such situations include maintaining inertial reference from Centaur separation until initial celestial acquisition is achieved; purposely turning the spacecraft off Sun/star lock to do required trajectory corrections or science instruments mappings or calibrations; providing a reference when the Sun is occulted; and providing a reference when concern exists that the Canopus or Sun sensor will detect stray intensity from unwanted sources -- planets, rings, satellites.

Each gyro has associated electronics to provide position information about two orthogonal axes (Gyro A: pitch and yaw, Gyro B: roll and pitch; Gyro C: yaw and roll). Normally, two gyros are on for any inertial mode. The gyros have two selectable rates, one -- high rate -- for propulsion-module injection phase; the other for mission-module cruise and trajectory-correction and science maneuvers.

Trajectory Correction Manuevers

The Voyager trajectories are planned around nine trajectory correction manuevers with each spacecraft between launch and Saturn encounter. Mission requirements call for extremely accurate manuevers to reach the desired zones at Jupiter, Saturn and the target satellites. Total velocity increment capability for each spacecraft is about 190 mps (425 mph).

Trajectory correction manuever sequencing is under control of the computer command subsystem, which sends the required turn angles to the attitude and articulation control subsystem for positioning the spacecraft at the correct orientation in space and, at the proper time, send commands to the attitude and articulation control subsystem to start and stop the trajectory correction manuever burn. Attitude control is maintained by pulse-off sequencing of the trajectory correction manuever engines and pulse-on sequencing of two attitude-control roll thrusters. Position and rate signals are obtained from the gyros. After the burn, reacquisition of the cruise celestial references is accomplished by unwinding the commanded turns -- repeating the turn sequence in reverse order. All trajectory correction manuevers are enabled by ground command.

Science Platform (Articulation Control)

Voyager's two television cameras, ultraviolet spectrometer, photopolarimeter, infrared spectrometer and radiometer are mounted on the scan platform that can be rotated about two axes for precise pointing at Jupiter, Saturn and their moons during the planetary phases of the flight. The platform is located at the end of the science boom. Total gimballed weight is 102.5 kg (226 lb.).

Controlled by the attitude and articulation control subsystem, the platform allows multiple pointing directions of the instruments. Driver circuits for scan actuators -- one for each axis -- are located in the attitude and articulation control subsystem computer. The platform's two axes of rotation are described as the azimuth angle motion about an axis displaced 7 degrees from the spacecraft roll axis (perpendicular to the boom centerline) and elevation angle motion about an axis perpendicular to the azimuth axis and rotating with the azimuth axis. Angular range is 360 degrees in azimuth and 210 degrees in elevation.

The platform is slewed one axis at a time with selectable slew rates in response to computer command subsystem commands to the attitude and articulation control subsystem. Slew rates are: .083 degrees per second; and a special ultraviolet spectrometer low rate: .0052 degrees per second. Camera line-of-sight is controlled to within 2.5 milliradians.

Temperature Control

The two Voyager spacecraft are designed to operate farther from Earth than any previous manmade object. Survival depends greatly upon keeping temperatures within operating limits while the solar spacecraft traverses an environmental range of one solar constant at the Earth distance to 4 percent of that solar intensity at Jupiter and less than 1 percent at Saturn.

Unprotected surfaces at the Saturn range, nearly 1.6 billion km (1 billion mi.) from the Sun, can reach 160 C (320 degrees F) below zero -- the temperature of liquid nitrogen.

Both top and bottom of the mission module's basic decagon structure are enclosed with multi-layer thermal blankets to prevent the rapid loss of heat to space. The blankets are sandwiches of aluminized Mylar, sheets of Teflar for micrometeoroid protection and outer black kapton covers that are electrically conductive to prevent the accumulation of electrostatic charges.

Also extensively blanketed are the instruments on the scan platform. Smaller blankets and thermal wrap cover eight electronics bays, boom and body-mounted instruments, cabling, propellant lines and structural struts. Only a few exterior elements of the spacecraft are not clad in the black film -- the high-gain antenna reflector, plasma sensors, sun sensors and antenna feed cones.

Temperature control of four of the 10 electronics compartments is provided by thermostatically controlled louver assemblies that provide an internal operating range near room temperature. The louvers are rotated open by bimetallic springs when large amounts of heat are dissipated. These bays contain the power-conditioning equipment and the radio power amplifiers. Mini-louvers are located on the scan platform, cosmic ray instrument and the Sun sensors.

Radioisotope heating units, small non-power-using heat elements that generate one watt of thermal energy, are located on the magnetometer sensors and the Sun sensors. No radioisotope heating units are used near instruments that detect charged particles. Electric heaters are located throughout the spacecraft to provide additional heat during portions of the mission. Many of the heaters are turned off when their respective valves, instruments or subassemblies are on and dissipating power.

COSMIC-RAY EXPERIMENT

The cosmic-ray experiment has four principal scientific objectives:

1. To measure the energy spectrum of electrons and cosmic-ray nuclei;
2. To determine the elemental and isotopic composition of cosmic-ray nuclei;
3. To make elemental and isotopic studies of Jupiter's radiation belts and to explore Saturn's environment;
4. To determine intensity and directional characteristics of energetic particles as a function of radial distance from the Sun, and determine location of the modulation boundary.

The cosmic-ray experiment uses multiple solid-state detector telescopes to provide large solid-angle viewing; the low-energy-telescope system covers the range from 0.5 to 9 million electron volts (MeV) per nucleon; the high-energy telescope system covers the range from 4 to 500 MeV. The electron telescope system covers the range from 7 million to 100 MeV.

The cosmic-ray experiment weighs 7.52kg (16.57 lb.) and uses 5.2 watts of power.

Dr Rochus E. Vogt of the California Institute of Technology is principal investigator.

LOW-ENERGY CHARGED-PARTICLE EXPERIMENT

Scientific objectives of the Low-Energy Charged-Particle Experiment include studies of the charged-particle composition, energy-distribution and angular distribution with respect to:

1. Saturn's magnetosphere (exploratory) and Jupiter's magnetosphere (detailed studies);
2. Interactions of charged particles with the satellites of Jupiter and Saturn and possibly with the rings of Saturn;
3. Measurements of quasi-steady interplanetary flux and high-energy components of the solar wind;
4. Determination of the origin and interstellar propagation of galactic cosmic rays (those that come from outside the solar system);
5. Measurements of the propagation of solar particles in the outer solar system.

The experiment uses two solid-state detector systems on a rotating platform mounted on the scan platform boom. One system is a low-energy magnetospheric particle analyzer with large dynamic range to measure electrons with energy ranging from 15,000 electron volts (15 keV) to greater than 1 million electron volts (1 MeV); and ions in the energy range from 15,000 electron volts per nucleon to 160 million electron volts per nucleon.

The second detector system is a low-energy particle telescope that covers the range from 0.15 million electron volts per nucleon to greater than about 10 million electron volts per nucleon.

The Low-Energy Charged-Particle Experiment weighs 7.47 kg (16.47 lb.) and draws 3.9 watts during cruise and 4.2 watts during planetary encounter.

Dr. S. M. (Tom) Krimigis of the Applied Physics Laboratory, Johns Hopkins University, is principal investigator.

MAGNETIC FIELDS EXPERIMENT

The magnetic field of a planet is an externally measurable manifestation of conditions deep in its interior.

The magnetic-fields instruments on Voyager 1 and 2 determine the magnetic field and magnetospheric structure at Jupiter and Saturn; they study the interaction of the magnetic field and the satellites that orbit the planet inside that field and study the interplanetary-interstellar magnetic field.

Four magnetometers are carried aboard Voyager. Two are low-field, three-axis instruments located on a boom to place them as far from the spacecraft body as possible. That allows separation of the spacecraft's magnetic field from the external field that is to be measured. The other two magnetometers are high-field, three-axis instruments mounted on the spacecraft body.

The boom-mounted, low-field instruments measure the magnetic fields in the range from 0.002 gamma to 50,000 gamma. (Fifty-thousand gamma equals one-half gauss, about the average magnetic field strength at the surface of Earth.) The high-field instruments cover the range from 12 gamma to 20 gauss.

Total weight of the magnetic-fields experiment is 5.5 kg (12 lb.). The experiment uses 3.2 watts of power.

Dr. Norman Ness of NASA's Goddard Space Flight Center is principal investigator.

INFRARED INTERFEROMETER SPECTROMETER AND RADIOMETER

The Infrared Interferometer Spectrometer and Radiometer is designed to perform spectral and radiometric measurements of the planetary systems, and targets of opportunity during the cruise phases.

Scientific objectives are:

1. Measurement of the energy balance of the planets;
2. Studies of the atmospheric compositions of the planets, Titan and other satellites;
3. Temperature, structure and dynamics of the atmosphere;
4. Measurements of composition and characteristics of the surfaces of clouds and aerosols;
5. Studies of the composition and characteristics of ring particles and the surfaces of those satellites the instrument will observe.

The instrument provides broad spectral coverage, high spectral resolution and low noise-equivalence-radiance through use of dual interferometers. That and the variable resolution of the instrument, as well as the precision of the radiometer, will allow scientists to acquire information about a wide variety of scientific questions concerning the atmospheres of the planets and satellites, local and global energy balance, and the nature of satellite surfaces and the rings.

The instrument has two fields of view from its position on the scan platform. The first is centered on the boresight of the 51 cm (20 in.) Cassegrain telescope. The second field of view -- for solar calibration -- is pointed 20 degrees off the telescope boresight. It approximately overlaps the ultraviolet spectrometer's occultation field of view. Infrared interferometer spectrometer and radiometer pointing is controlled by the scan platform.

Dr. Rudolf A. Hanel of Goddard Space Flight Center is principal investigator.

PHOTOPOLARIMETER

(The photopolarimeter aboard Voyager 1 is not operating. The instrument aboard Voyager 2 will be used at the Saturn encounter in summer 1981.)

A great deal of information about the composition of an object can be learned from the way that object reflects light. The Voyager spacecraft's photopolarimeter is polarized by the chemicals and aerosols in the atmospheres and on the surfaces.

The photopolarimeter measures methane, molecular hydrogen and ammonia above the cloud tops; it studies aerosol particles in the atmospheres of the planets and satellites; the textures and compositions of the surfaces of satellites; size, albedo, spatial distribution, shape and orientation of particles in Saturn's rings; measures optical and geometric thickness of the rings; and observes the sky background to search for interplanetary and interstellar particles.

The instrument is made up of a 15 cm (6 in.) Cassegrain telescope, aperture sector, polarization analyzer wheel, filter wheel and photomultiplier-tube detector.

The filter wheel carries eight filters ranging from 2,350-Angstrom to 7,500-Angstrom wavelength; three linear polarizers (0 degrees, 60 degrees and 120 degrees) plus "open" or blank. The instrument's field of view can be set at 3.5 degrees, 1 degree, one-quarter degree and one sixteenth degree.

The photopolarimeter weighs 4.4 kg (9.7 lb.) and uses 2.4 watts average power.

Dr. Arthur L. Lane of the Jet Propulsion Laboratory is principal investigator.

PLANETARY RADIO ASTRONOMY

The Planetary Radio Astronomy experiment consists of a stepped frequency radio receiver that covers the range from 20 kHz to 40.5 MHz, and two monopole antennas 10 m (33 ft.) long, to detect and study a variety of radio signals emitted by the planets.

Scientific objectives of the experiment include detection and study of radio emissions from Jupiter and Saturn and their sources and relationship to the satellites, the planets' magnetic fields, atmospheric lightning and plasma resonance. The instrument also measures planetary and solar radio bursts from new directions in space and relates them to measurements made from Earth.

The receiver is designed to provide coverage in two frequency bands -- one covering the range from 20.4 kHz to 1,345 kHz, the second from 1,228.8 kHz to 40.5 MHz. The receiver bandwidth is 1 kHz in the low-frequency range and 200 kHz in the high-frequency band. There are three signal input attenuators to provide switchable total attenuation from 0 to 90 decibels.

The instrument weighs 7.6 kg (16.8 lb.) and draws 6.8 watts of power.

Principal investigator is Dr. James W. Warwick of Radio-physics, Inc., Boulder, Colo.

PLASMA EXPERIMENT

Plasma, clouds of ionized gases, move through the interplanetary region and come from the Sun and from stars. The plasma experiment uses two Faraday cup plasma detectors, one pointed along the Earth-spacecraft line, the other at right angles to that line.

Scientific objectives of the plasma experiment are:

1. Determine properties of the solar wind, including changes in the properties with increasing distance from the Sun;
2. Study of the magnetospheres that are intrinsic to the planets themselves and that corotate with the planets independent of solar wind activity;
3. Study of the satellites;
4. Detection and measurement of interstellar ions.

The Earth-pointing detector uses a novel geometrical arrangement that makes it equivalent to three Faraday cups and determines microscopic properties of the plasma ions. With this detector, accurate values of the velocity, density and pressure can be determined for plasma from the Earth (1 A.U.) to beyond Saturn (10 A.U.). Two sequential energy scans are employed to allow the instrument to cover a broad range of energies -- from 10 electron volts (eV) to 6,000 electron volts (6 KeV). Significant measurements can be made between subsonic and supersonic speeds in cold solar wind or hot planetary magnetosheath.

The variable energy resolution allows scientists to detect and sort out ions that flow with the solar wind at the same time they are measuring the solar wind's properties.

The instrument has a large (180-degree) field of view at planetary encounters and a 90-degree field of view in the solar wind; no electrical or mechanical scanning is necessary.

The other Faraday cup, an side-looking or lateral detector, measures electrons in the range of 10 electron volts to 6 KeV and should improve spatial coverage for any drifting or corotating positive ions during planetary encounters.

The instrument was designed primarily for exploring planets' magnetospheres. It is capable of detecting hot subsonic plasma such as has been observed in the Earth's magnetosphere and is expected from ions originating in the McDonough-Brice ring of Io. The instrument's large angular acceptance allows detection of plasma flows well away from the direction of the Sun, such as plasma flows that corotate with the planet.

The plasma experiment weighs 9.9 kg (21.8 lb.) and draws 8.3 watts of power.

Dr. Herbert Bridge of the Massachusetts Institute of Technology is principal investigator.

PLASMA WAVE

Scientific objectives of the plasma wave experiment are measurements of thermal plasma density profiles at Jupiter and Saturn; studies of wave-particle interaction and study of the interaction of the Jovian and Saturnian satellites with their planet's magnetospheres.

The plasma-wave instrument measures electric-field components of local plasma waves over the frequency range from 10 Hertz to 56 kHz.

The experiment shares the two extendable 10 m (33 ft.) electric antennas provided by the planetary radio astronomy experiment team. The two groups use the antennas in different ways. The plasma-wave-experiment uses the antenna's V-type balanced electric dipole (while the radio astronomy experiment uses them as a pair of orthogonal monopoles).

In the normal format, the plasma-wave signals are processed with a simple 16-channel spectrum analyzer. At planetary encounters the system provides a spectral scan every four seconds.

The plasma-wave system has a broadband amplifier that uses the Voyager video telemetry link to give electric field waveforms with a frequency range from 50 Hertz to 10 kilohertz at selected times during planet encounters.

The experiment is designed to provide key information on the wave-particle interaction phenomena that control important aspects of the dynamics of the magnetospheres of the outer planets. Wave-particle interactions play extremely important roles at Earth, and scientists understand that at least the inner magnetosphere of Jupiter is conceptually similar to that of Earth despite the vast differences in size and in the energy of trapped particles.

In addition, the satellites of Jupiter and Saturn appear to provide important localized sources of plasma and field-aligned currents, and they should significantly affect the trapped-particle populations.

The instrument weighs 1.37 kg (3.02 lbs.) and draws 1.4 watts of power in the step frequency mode and 18 watts in the step frequency plus waveform analyzer mode.

Dr. Frederick L. Scarf of TRW Defense and Space Systems Group is principal investigator.

RADIO SCIENCE

The spacecraft's communications system is used to conduct several experiments by observing how the radio signals are changed on their way to Earth.

By measuring the way signals die out and return when the spacecraft disappears behind a planet or satellite and then reappears, the radio science team can determine the properties of planetary and satellite atmospheres and ionospheres.

The radio signals also allow scientists to make precise measurements of the spacecraft's trajectory as it passes near a planet or satellite. Post-flight analyses allow determination of the mass of a body and its density and shape.

The rings of Saturn will also be explored by the radio science team by measuring the scattering of the radio signals as they travel through the rings. This will provide measurements of ring mass, particle size distribution and ring structure.

The experiment uses the microwave receivers and transmitters on the spacecraft as well as special equipment at the Deep Space Network tracking stations. The spacecraft transmitters are capable of sending 10 or 25 watts at S-band; and 12 or 20 watts at X-band. The spacecraft antenna is a 3.66 m (12 ft.) parabola and is aimed by special maneuvers performed during planet occultations.

Dr. G. Len Tyler of the Center for Radar Astronomy, Stanford University, is principal investigator.

TELEVISION

The Voyager imaging system is based on those flown aboard Mariner spacecraft, with advancements and changes dictated by the specific requirements of flybys of Jupiter, Saturn and their satellites.

Science objectives for the television experiments include reconnaissance of the Jupiter and Saturn systems, including high-resolution photography of atmospheric motions, colors and unusual features (such as the Great Red Spot and similar smaller spots); vertical structure of the atmospheres of the planets; comparative and detailed geology of satellites; satellite size and rotation, and detailed studies of the rings of Saturn.

Two television-type cameras are mounted on the spacecraft's scan platform: a 200 mm focal-length, wide-angle camera with 4,000-Angstrom to 6,200-Angstrom sensitivity; and a 1,500 mm focal-length, narrow-angle camera with a 3,200-Angstrom to 6,200-Angstrom range.

The disks of Jupiter and Saturn exceed the field of view of the narrow-angle camera about 20 days before closest approach. At that time, resolution is about 400 km (250 mi.).

For several days before and after closest approach, scientists will have several simultaneous imaging opportunities:

1. Photography at high resolution of planets whose angular diameters are many times larger than the field of view;
2. Close encounters (some comparable with Mariner 10's Mercury flybys) with the major satellites;
3. More distant photography of several additional satellites;
4. High-resolution photography of Saturn's rings.

To exploit such a variety of opportunities, it is necessary for the spacecraft to return large quantities of imaging data. The camera-spacecraft system has been designed to return imaging data over a wide range of telemetry rates in real time. Data can also be recorded onboard the spacecraft for later playback to Earth -- during occultation by Jupiter, for instance.

Each camera is equipped with a filter wheel whose individual filters have a variety of uses:

The wide-angle camera's filter wheel contains one clear filter, one each in blue, green and orange wavelengths, a 7-Angstrom sodium-D filter for special observations near satellites, and two 100-Angstrom filters at the wavelength of methane absorption, for study of the distribution of methane in the atmospheres of Jupiter, Saturn, Titan and Uranus.

The narrow angle camera's filter wheel carries two clear filters, two green, and one each of violet, blue, orange, and ultraviolet.

Voyager will be the first imaging system with narrow-band capability to directly observe distribution of atomic and molecular species. The 7-Angstrom sodium-D filter is the narrowest bandwidth filter ever flown with this kind of camera.

Because the Voyager spacecraft will pass the planets and satellites at high velocities and must take pictures in dimmer light than Mariner missions to the inner planets, image-smear conditions are more severe than on previous flights. To overcome these problems, the camera's pre-amplifiers have been designed to lower system noise and to incorporate a high-gain state; both changes are meant to provide high-quality images with minimum smear.

During the several months before closest approach, the narrow-angle cameras photograph Jupiter and Saturn regularly and often to provide information on cloud motions.

Those pictures are taken on a schedule that permits scientists to make motion pictures in which the planet's rotation has been "frozen" so that only the cloud motions are apparent. Resolution during the period ranges from about 1,600 km (1,000 mi.) to about 400 km (250 mi.) Once the planet grows larger than the narrow-angle camera's field of view, the wide-angle camera begins its work. The narrow-angle camera then repeatedly photographs portions of the planets that warrant special scientific interest. The cameras can be shuttered simultaneously during these periods so scientists can relate small-scale motions to larger patterns.

Because of the nature of the planetary flybys, the cameras are not able to concentrate on a single target for hours at a time. As each satellite moves, it presents an ever-changing appearance to the cameras; the planets' clouds are also in constant motion. Therefore, observational sequences are structured to provide repeated images at differing intervals for each target. Additionally, large amounts of multicolor imaging data are being obtained for the planets and satellites.

The camera system weighs 38.17 kg (84.15 lbs.), and uses 41.9 watts of power.

Dr. Bradford A. Smith of the University of Arizona is principal investigator.

ULTRAVIOLET SPECTROMETER

The ultraviolet spectrometer looks at the planets' atmospheres and at interplanetary space.

Scientific objectives of the experiment are:

1. To determine distributions of the major constituents of the upper atmospheres of the planets and Titan as a function of altitude;
2. To measure absorption of the Sun's ultraviolet radiation by the upper atmospheres as the Sun is occulted by the planets and satellites;
3. To measure ultraviolet airglow emissions of the atmospheres from the bright disks of the three bodies, their bright limbs, terminators and dark sides;
4. Determine distribution and ratio of hydrogen and helium in interplanetary and interstellar space.

The instrument measures ultraviolet radiation in 1,200-Angstrom bandwidth in the range from 400 to 1,800 Angstroms. It uses a grating spectrometer with a microchannel plate electron multiplier and a 128-channel anode array. A fixed-position mirror reflects sunlight into the instrument during occultation.

The instrument has a 0.86-degree by 0.6-degree field of view during occultation and a 0.86 by 2 degree field of view for air-glow measurements.

The ultraviolet spectrometer weighs 4.49 kg (9.89 lbs.) and uses 2.5 watts of power.

Dr. A. Lyle Broadfoot of the University of Southern California is principal investigator.

TRACKING AND DATA ACQUISITION

Tracking, commanding and obtaining data from the spacecraft are part of the mission assigned to the Jet Propulsion Laboratory. These tasks cover all phases of the flight, including telemetry from launch vehicle and spacecraft, metric data on both launch vehicle and Voyager, command signals to the spacecraft and delivery of data to the Mission Control and Computing Center at JPL.

The Tracking and Data System provides elements of the worldwide NASA/JPL Deep Space Network, Air Force Eastern Test Range, the NASA Spaceflight Tracking and Data Network and the NASA Communications System.

During the launch phase of the mission, data acquisition was accomplished through use of the near-Earth facilities -- the Air Force stations, downrange elements of the spaceflight network, instrumented jet aircraft and a communications ship. Radar-metric data obtained immediately after liftoff and through the near-Earth phase was delivered to and computed at the Air Force Real-Time Computer system facility in Florida so that accurate predictions could be transmitted to Deep Space Network stations giving the locations of the spacecraft in the sky when they appeared on the horizon.

Tracking and communication with the Voyagers since injection into Jupiter trajectory and until the end of the mission are being carried out by the Deep Space Network.

The Deep Space Network consists of nine deep space communications stations on three continents, a spacecraft monitoring station in Florida, the Network Operations Control Center at JPL and ground communications linking all locations.

Deep Space Network stations are located around the Earth -- at Goldstone, Calif.; Madrid, Spain; and at Canberra, Australia. Each location is equipped with a 64-m (210-ft.) diameter antenna station and two 26-m (85-ft.) antenna stations.

The three multi-station complexes are spaced at widely separated longitudes so that spacecraft beyond Earth orbit -- and, for the Voyager mission, the planets Jupiter and Saturn -- are never out of view.

The spacecraft monitoring equipment in the Spacecraft Tracking and Data Network station at Meritt Island, Fla., covered the prelaunch and launch phases of the mission. A simulated Deep Space Network station at JPL, called CTA-21, provided prelaunch compatibility support.

In addition to the giant antennas, each of the stations is equipped with transmitting, receiving, data handling and inter-station communication equipment. The downlink includes super-cooled low-noise amplifiers.

The 64-m (210-ft.) antenna stations in Spain and Australia have 100-kilowatt transmitters. At Goldstone, the uplink signal can be radiated at up to 400 kilowatts. Transmitter power at all six 26-m (85-ft.) stations is 20 kilowatts.

The downlink is transmitted from the spacecraft at S-band (2,295 MHz) and X-band (8,400 MHz) frequencies. The uplink operates at S-band (2,113 MHz) only, carrying commands and ranging signals from ground stations to the spacecraft.

Only the 64-m (210-ft.) antenna stations can receive the X-band signal and can receive at both frequencies simultaneously. The 64-m (210-ft.) stations provide continuous coverage during planetary operations and periodically during the cruise phase for maneuvers, spacecraft recorder playbacks and dual-frequency navigation sequences. A 26-m (85-ft.) antenna subnet provides continuous coverage -- shared by the two spacecraft -- throughout the mission.

Various data rates for each type of telemetered information are required by the changing length of the telecommunications link and the possible adverse weather effects at ground stations on reception of X-band radio signals.

The nerve center of the Deep Space Network is the Network Operations Control Center at JPL that provides for control and monitoring of Deep Space Network performance. All incoming data are validated at that point while being simultaneously transferred to the computing facilities of the Mission Control and Computing Center for real-time use by engineers and science investigators.

Ground communications facilities used by the Deep Space Network to link the global stations with the control center are part of a larger network, NASCOM, that connects all of NASA's stations around the world. Data from the spacecraft are transmitted over high-speed circuits. Telemetry at rates up to 15.2 kbps are carried in real-time on wideband lines from Goldstone and Madrid. The Canberra stations will send encounter data in real time at rates up to and including 44.8 kbps. Higher downlink rates are recorded at the Australian station and played back to Mission Control and Computing Center at 44.8 kbps.

Simultaneously with the routing to the Mission Control and Computing Center of the spacecraft telemetry, range and range-rate information is generated by the Deep Space Network and transmitted to the control center for spacecraft navigation. To achieve the desired maneuver and encounter accuracies, very precise navigation data are required. Navigation information include S/Z ranging, DRVID (differenced range versus integrated Doppler) and multi-station tracking cycles.

Commands are sent from the Mission Control and Computing Center to one of the Deep Space Network stations where they are loaded into a command processing computer, automatically verified for accuracy and transmitted to the proper spacecraft at 16 bps. Commands may be aborted, if necessary. Manual control and entry of command data at the station are possible in the event of a failure in the high-speed data line from the control center.

For all of NASA's unmanned missions in deep space, the Deep Space Network provides the tracking information on course and direction of the flight, velocity and range from Earth. It receives engineering and science telemetry and sends commands for spacecraft operations on a multi-mission basis.

Concurrent with the four-year or longer Voyager mission, the network is supporting survey mission activities of the Viking Project with one lander on Mars; and complementing West Germany's space communications facilities on two Helios Sun-orbiting missions. The Deep Space Network also is supporting a Venus exploration mission by two Pioneer spacecraft -- a planetary orbiter and atmospheric probe -- launched in May and August, 1978, and planetary science activities that began in December, 1978.

All of NASA's networks are under the direction of the Office of Tracking and Data Systems. JPL manages the Deep Space Network. The NASA Spaceflight Tracking and Data Network facilities and NASCOM are managed by NASA's Goddard Space Flight Center, Greenbelt, Md.

The Goldstone Deep Space Network stations are operated and maintained by JPL with the assistance of the Bendix Field Engineering Corp.

The Canberra stations are operated by the Australian Department of Supply. The stations near Madrid are operated by the Spanish government's Instituto Nacional de Tecnica Aeroespacial.

MISSION CONTROL AND COMPUTING CENTER

The Mission Control and Computing Center (MCCC) at JPL is the focus of all Voyager Project flight operations. It is through the center's computer systems that data from the Voyagers pass, are processed and presented to engineers and scientists for analysis.

Through the extensive and varied displays of the computers in the Mission Control and Computing Center, the flight analysts observe and control the many ground processing function and the spacecraft.

The Mission and Control Computing Center is housed in two JPL buildings containing its computer systems, communications and display equipment, photo processing lab, and mission support areas. The various areas are outfitted to satisfy the diverse needs of the Voyager mission operations team -- the requirements of the mission controllers, spacecraft performance analysts and science investigators.

The Mission Control and Computing Center contains several computer systems designed to receive the incoming Voyager data, process it in real time, display it and organize it for further processing and analysis. After the data have been received as radio signals by the Deep Space Network stations located around the world, they are transmitted to Pasadena and into the Mission Control and Computing Center computer where the processing begins. Software developed by the Mission control and Computing Center, operating in those computers, performs the receiving, displaying and organizing function. Computer programs generated by other elements of the Voyager Project further process the data.

Commands causing the spacecraft to maneuver, gather science data and perform other complex mission activities are introduced into the Mission Control and Computing Center computers and communicated to a station of the Deep Space Network for transmission to the appropriate spacecraft.

The Mission Control and Computing Center is composed of three major elements, each with its own computer system. They are the Mission Control and Computing Facility, the Large Scale Information Processing System and the Mission and Test Computing Facility.

The Mission Control and Computing Facility consists of three IBM 360-75 processors and supports the Voyager command, data records and tracking systems. The 360-75s provide the means through which commands are sent to the spacecraft.

They also are used to process and display tracking data and provide the data management capability to produce plots and printouts for the day-to-day determination of spacecraft operating condition. The 360-75s also produce the final records of data for detailed analysis by the science community.

The Large Scale Information Processing System, with two UNIVAC 1100/81 computers, supports the Voyager Project's navigation and mission sequence systems. The 1100/81s also are used to develop prediction programs and detailed spacecraft engineering performance analysis. Computer terminals located in the mission support area allow project analysts to execute their programs and obtain results displayed on TV monitors, or on various printers and plotters.

The Mission and Test Computing Facility provides telemetry data processing for the science and engineering information transmitted from the Voyagers. Within this facility are the telemetry system, imaging system and photo system. The telemetry system uses two strings of UNIVAC and Modcomp computers to receive, record, process and display the data as requested by analysts in the mission support areas. The imaging and photo systems produce the photographic products from data generated by Voyager's TV cameras. Pictures of Jupiter, Saturn and their moons are analyzed by scientists housed in the mission support areas.

Scientists are provided both electronic and photographic displays.

Mission Control and Computing Center, like the Deep Space Network, also supports the other flight missions, Viking, Pioneers 10 and 11, Helios and Pioneer/Venus.

VOYAGER SUBCONTRACTORS

This is a list of some key subcontractors who provided instruments, hardware and services for the Voyager Project:

Algorex Data Corp.
Syosset, N.Y.

Boeing Co.
Seattle, Wash.

Fairchild Space and
Electronics Co.
Germantown, Md.

Automated Design Support
for Flight Data Subsystem

Radiation Characterization
of Parts and Materials

Temperature Control
Louvers

Ford Aerospace and
Communications Corp.
Palo Alto, Calif.

S/X Band Antenna
Subsystem;
Solid State Amplifiers

Frequency Electronics, Inc.
New Hyde Park, N.Y.

Ultra Stable Oscillators

General Electric Co.
Space Division
Philadelphia, Pa.

Radioisotope
Thermoelectric Generators

General Electric Co.
Utica, N.Y.
Processors

Computer Command
Subsystem; Flight Control

General Electric Co.
Space Systems Organization
Valley Forge, Pa.

Attitude Control and
Articulation Subsystem

Hi-Shear Corp.
Ordnance Division
Torrance, Calif.

Pyrotechnic Squibs

Honeywell, Inc.
Lexington, Mass.

Canopus Star Trackers

Hughes Aircraft Co.
Aerospace Group
Culver City, Calif.

Radiation Characterization
of Parts and Materials

Lockheed Electronics Co.
Industrial Technology Div.
Plainfield, N.J.

Data Storage Tape
Transport

Martin Marietta Aerospace
Denver, Colo.

Attitude Control
Electronics;
Propulsion Subsystem

Motorola, Inc.
Government Electronics Div.
Scottsdale, Ariz.

Modulation/Demodulation
Subsystem;
Radio Frequency Subsystem

Rocket Research Corp.
Redmond, Wash.

Rocket Engine and Thruster
Valve Assemblies

SCI Systems, Inc.
Huntsville, Ala.

Computer Command Subsystem
Memories

Teledyne Microelectronics
Los Angeles, Calif.

Hybrid Memories for Flight
Data Subsystem

Texas Instruments
Dallas, Texas

Data Storage Electronics

The Singer Co.
Little Falls, N.J.

Dry Inertial Reference
Units (Gyroscopes)

Thiokol Chemical Corp.
Elkton Div.
Elkton, Md.

Solid Rocket Motor

Watkins-Johnson Co.
Palo Alto, Calif.

S/X Band Traveling Wave
Tube Amplifiers

Xerox Corp.
Electro-Optical System
Pasadena, Calif.

Power Subsystem

Yardney Electronics Corp.
Denver, Colo.

Flight and Test Battery
Assemblies

Science Instruments

Massachusetts Institute of
Technology
Cambridge, Mass.

Plasma Subsystem

University of Colorado
Boulder, Colo.

Photopolarimeter Subsystem

University of Iowa
Iowa City, Iowa

Plasma Wave Subsystem

Xerox Corp.
Electro-Optical Systems
Pasadena, Calif.

Imaging Science (TV)
Electronics

Kitt Peak National Observatory
Tucson, Ariz.

Ultraviolet Spectrometer

Johns Hopkins University
Applied Physics Laboratory
Baltimore, Md.

Low-Energy Charged-
Particle Subsystem

Goddard Space Flight Center
Greenbelt, Md.

Magnetometer; Cosmic-Ray
Subsystem

Texas Instruments
Dallas, Texas

Modified Infrared
Interferometer,
Spectrometer and
Radiometer

Martin Marietta Aerospace
Denver, Colo.

Planetary Radio
Astronomy Subsystem

Astro Research Corp.
Santa Barbara, Calif.

Magnetometer Boom;
Planetary
Radio Astronomy Antennas

TRW Defense and Space Systems
Redondo Beach, Calif.

Matrix Corp.
Acton, Mass.

General Electrodynamics Corp.
Dallas, Texas

Ultraviolet Spectrometer
Electronics

Plasma Subsystem
Electronics

TV Vidicons

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