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THE DESIGN AND OPERATION OF GEOSAT

The GEOSAT spacecraft was launched in March 1985 from Vandenberg Air Force Base, Calif. The 1400-pound spacecraft was placed in an 800-kilometer circular orbit with an inclination of 108 degrees. In March 1985, attitude capture and system checkout were complete and the mission was declared operational. Through the completion of the 18-month geodesy mission in September 1986, the spacecraft provided uninterrupted support for precision radar altimetry and tracking. The velocity control subsystem was then used to achieve a 17-day exact repeat orbit in November 1986. The orbit has since been maintained within 1 kilometer of Exact Repeat Mission ground tracks, and data collection continues.

SPACECRAFT DESIGN AND OPERATION

GEOSAT was designed specifically to support the precision radar altimeter in addition to associated satellite tracking beacons and a C-band transponder system. The spacecraft (Fig. 1) provides the structure, power, thermal, attitude and velocity control, telemetry, command, and tape data-storage instruments as well as tracking-beacon functions to support them. The altimeter includes redundant telemetry and command interfaces. The redundancy is continued through the spacecraft subsystems, as shown in the functional system block diagram (Fig. 2). The subsystem design and in-orbit performance of the GEOSAT spacecraft are summarized below.

Structure Subsystem

The basic structural configuration of GEOSAT is similar to that of the core structure of the flight-proven GEOS-C design. A conical structure below the core provides for the structural attachment of the launch vehicle as well as the mounting for the fuel tanks, shut-off valves, regulators, and thrusters of the velocity control system. A honeycomb shield and a cylindrical support structure are added to the core structure to support the radar altimeter and tape recorders.

The structure provides the interface to the Atlas-E launch vehicle and a mission-unique orbital insertion stage with a Star 27 motor (Fig. 3).

Attitude Control Subsystem

The GEOSAT attitude control subsystem (a gravity-gradient system) was designed to point the radar altimeter to within 1 degree of nadir 98 percent of the time. Its principal components are a 20-foot scissors boom with 100-pound end mass, redundant momentum wheels for roll and yaw stiffness, and pitch and roll attitude control thrusters (used only for initial attitude capture). Attitude sensing is accomplished through the use of three digital sun-attitude detectors and a three-axis vector magnetometer.

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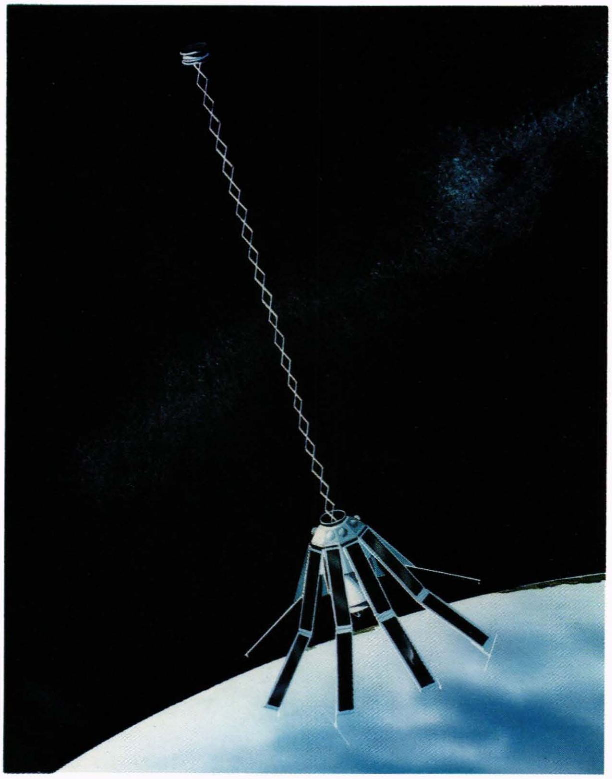

Figure 1—GEOSAT radar altimeter spacecraft.

Attitude capture and stabilization involved a sequence of operations and maneuvers, the first of which was to despin the spacecraft from the 90 revolutions per minute that resulted from spin stabilization of the launch-vehicle orbit-insertion stage. Despin was achieved using a double yo-yo system, where two pairs of yo-yo despin cables were used for both system despin and solar panel restraint during launch. Secondary despin systems were not used because of the precision of the primary yo-yo system in achieving the targeted residual spin rate of less than 0.5 revolution per minute. Figure 4 shows the spacecraft deployment.

Subsequent three-axis local-vertical stabilization was achieved via the following attitude capture scenario:

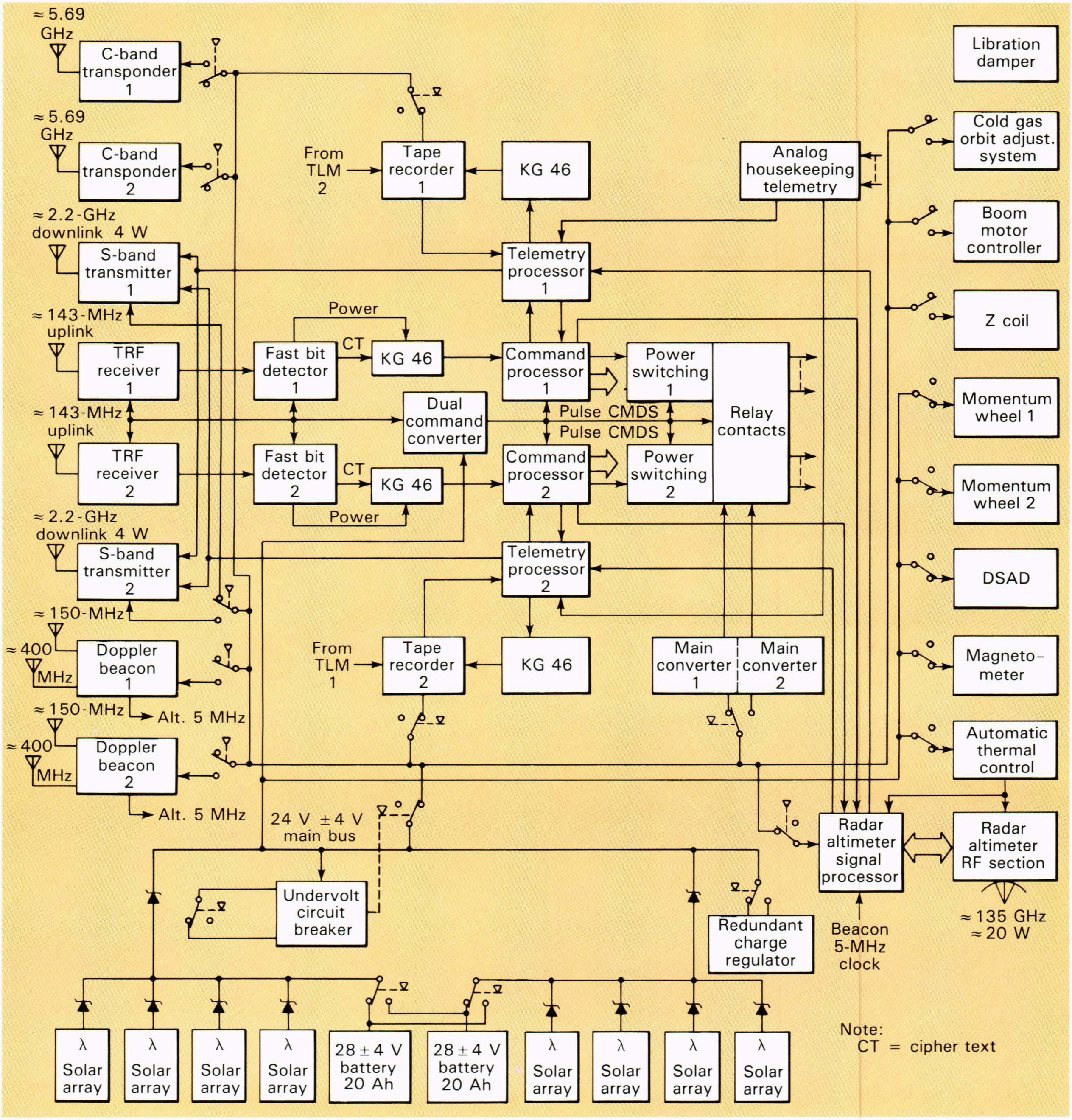

Figure 2—GEOSAT system block diagram.

1. Extend the scissors boom 1 meter to enable the magnetically anchored eddy current damper to remove residual spacecraft motion (this was performed 20 hours after launch).
2. Release both momentum wheels and energize one wheel to full speed.
3. Maneuver the momentum vector (the spacecraft pitch axis) to the orbit normal by using the roll attitude-control thrusters.
4. Extend the scissors boom to full length in order to achieve gravity-gradient capture.
5. Damp residual motions using the attitude thrusters and passive damper to achieve less than 1 degree of nadir pointing.

Full-boom deployment was performed on the second day of the mission (day 074). Rough attitude stabilization, spacecraft system checkout, and initial radar altimeter turn on were achieved in less than one week (by day 078). By day 090, 1 degree of nadir pointing was achieved and GEOSAT was declared operational.

Velocity Control Subsystem

The primary function of the velocity control subsystem (Fig. 5) is to control the satellite orbit. A secondary func-

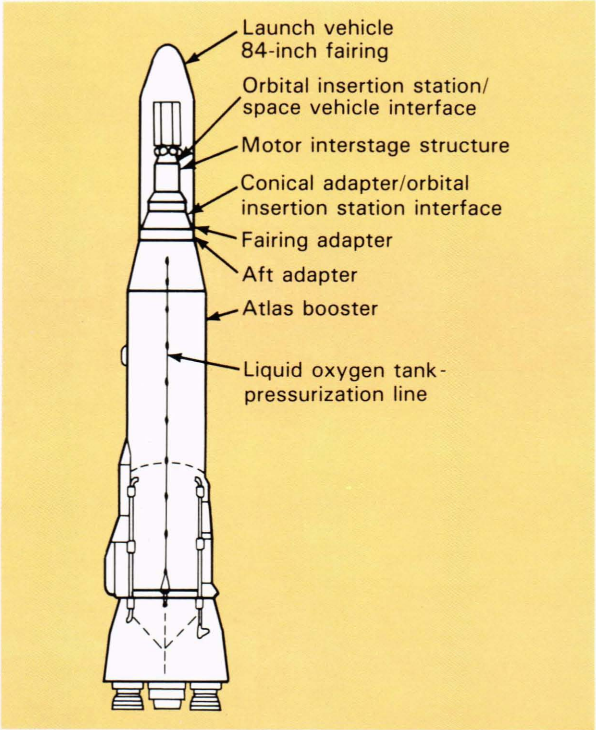

Figure 3—Launch vehicle configuration.

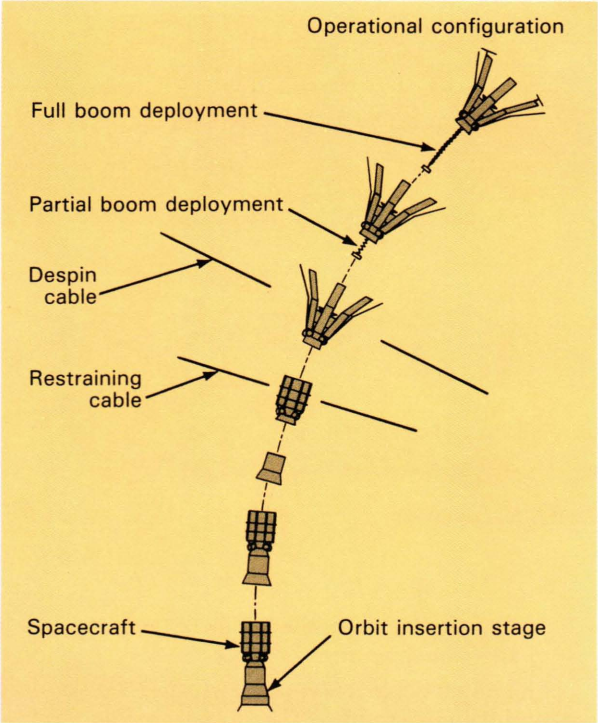

Figure 4—Orbit insertion phase.

tion is to stabilize the attitude or enhance the libration damping of the spacecraft. This cold gas subsystem uses 84 pounds of Freon 14® as a propellant (stored in six tanks) with a specific impulse of approximately 40 seconds. Each tank was initially pressurized to 2700 pounds per square inch; this was reduced by pressure regulators to 15 pounds per square inch absolute at the 0.01-pound force thrusters. One thruster pointing forward and one pointing aft constitute the velocity control thrusters. Four additional thrusters produce pitch and roll torques in both positive and negative senses. The system can provide a velocity change of 77 feet per second.

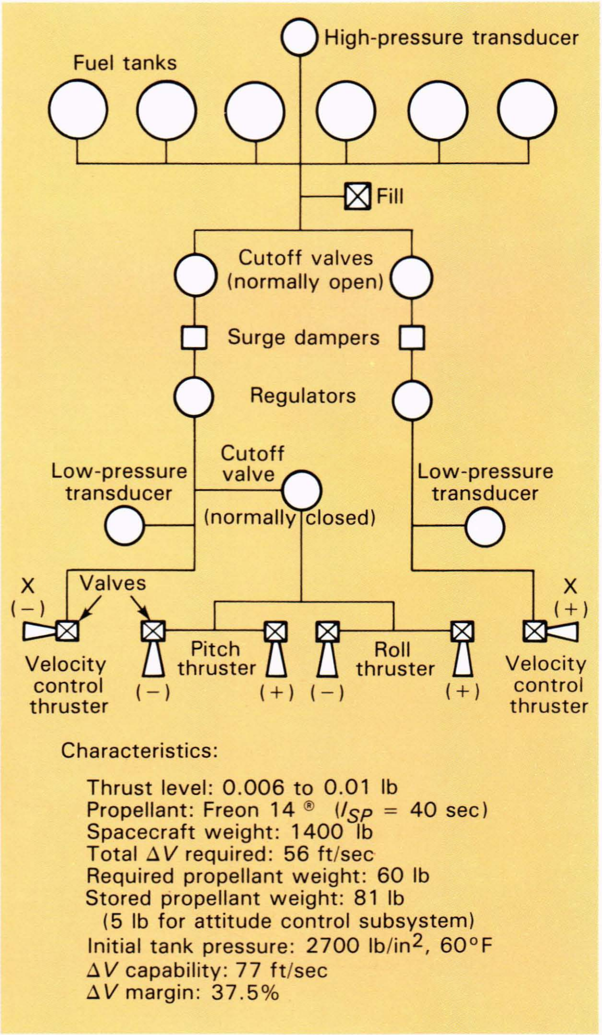

Figure 5—Schematic diagram of the velocity control system.

During initial spacecraft attitude acquisition and altimeter checkout, precision tracking of the spacecraft established that the ground track satisfied mission objectives on coverage and timeliness to the extent that orbit adjustment by the on-board velocity control subsystem was not required.

The attitude thrusters were used during the geodesy mission to execute a series of attitude maneuvers to reduce libration oscillations that resulted during capture. The translational thrusters were operated 239 times to adjust the orbit as required for the Exact Repeat Mission.

Propellant mass has been monitored since launch to verify that no substantial amount of fuel has escaped.

Command Subsystem

Spacecraft command is accomplished via a VHF uplink from the APL ground station. The microprocessor-based command subsystem receives, authenticates, and executes commands for spacecraft configuration control on a real-time or delayed basis. The subsystem, which is redundant, consists of two linearly polarized antennas mounted on the solar arrays, tuned radio receivers, bit detectors, decryptors, command processors, and one set of power switching relays with redundant coils and contacts. Command capabilities consist of relay contact closure for power switching (relay commands), pulses to drive relays contained within user packages (pulse commands), and generation of parallel and serial data words to control subsystem internal configurations (data commands). The subsystem supplies 68 relay commands, 28 pulse commands, and 21 data commands.

From launch through completion of the geodesy mission, the command subsystem has executed 25,294 commands successfully, either on a real-time basis (immediate execution command) or on a delayed basis (stored for processing at a later time as determined by a relative offset from an epoch). The microprocessor is able to detect bit errors in an uplinked command block such that if a bit error is found, the entire command block is rejected and no command is executed. This error checking minimizes the possibility of executing an incorrect command.

S-band transmitter and tape recorder operations are managed through commands stored for delayed execution. As many as 145 delayed commands may be stored in each command processor. They are transmitted to the satellite in 29 command-long sequences loaded in one command block during a pass. After each block transmission, the command subsystem dumps the memory area containing the loaded sequence into the downlinked telemetry stream where it is compared to a ground image of the intended command sequence. During the geodesy mission, more than 539 sequence loads into command subsystem 1 and 34 loads into subsystem 2 (functioning as the backup subsystem) have been accomplished. No errors were detected by the verification process or spacecraft operations for any of these loads.

Telemetry Subsystem

The GEOSAT telemetry subsystem provides the mechanisms to transfer consolidated radar altimeter information and spacecraft subsystem performance data to the ground station. In addition, it provides a means of verifying the contents of command system memories by transmitting delayed command load data in three special minor frames of the telemetry.

The telemetry subsystem consists of a redundant telemetry processor, two S-band transmitters, two tape recorders, and two encryption units. The telemetry processor is comprised of two electrically identical redundant halves sharing a nonredundant housekeeping commutator. The digital circuitry employs complementary metal oxide semiconductor chips and provides transistor transfer logic where required by higher speeds or interface requirements.

The subsystem receives the digital science-data stream from the radar altimeter at 8.5 kilobits per second and combines it with housekeeping data at 1.5 kilobits per second that are collected from the spacecraft subsystems. The data are formatted into a single time-annotated frame and transmitted to the ground station via the S-band link either in real time or as the tape-recorder playback (dump) of 12 hours of stored encrypted data. The downlink signal of the transmitter is based on a carrier frequency of 2207.5 megahertz and a subcarrier frequency of 1.5 megahertz that may be added to the carrier for transmission of real-time telemetry. Since launch, dump data have been transmitted on the carrier and real-time data have been transmitted on the subcarrier. S-band 1 has been used as the primary transmitter since launch with no anomalies, while S-band 2 is being reserved as a backup. The first transmitter is typically turned on by delayed command, with an average transmission lasting 14 hours per week. Since January 9, 1986, the Western Space Missile Center and Vandenberg Air Force Base have requested use of the S-band transmitter along with positioning and ephemeris data to perform calibrations on their radars. This additional and important use of the S-band transmitters has averaged less than one hour per week.

Tape Recorders

GEOSAT is equipped with two Odetics (5×10^8) dual-track high-density tape recorders that can independently record the 10.205-kilobit-per-second telemetry stream and play it back at 833.4 kilobits per second for transmission to the ground.

Operationally, the recorders are cycled between record, standby, and playback modes with a 10-minute overlap between each recorder in the record mode. Nominal record spans for each recorder are 11 to 13 hours. During normal operations, tape recorder management is accomplished via spacecraft-delayed commands. The playback command is sent by control center personnel during real time.

From the time the altimeter was declared operational through the completion of the geodesy mission, GEOSAT recorders supported 1193 data dumps (582 on tape recorder 1; 611 on tape recorder 2). All tape recorder parameters have remained within design limits.

From day 86:038 to 86:054 (331 to 347 days into the mission), a slight increase in the dump data errors of recorder 2 was noted; however that increase was well within performance specifications and occurred when the temperature of the recorder passed through a seasonal peak in its outer case temperature (30.5°C). Figure 6 displays the external temperatures of tape recorders 1 and 2 where periods of peak temperature represent full-sun orbits. As the external temperature dropped below 30°C, dump data errors essentially disappeared. The reasons for the temperature disparities between recorders can be attributed to the location of each recorder: recorder 1 on the $-x$ side of the spacecraft and recorder 2 on the $+y$ side. There is a period of approximately 12 months between similar spacecraft thermal conditions.

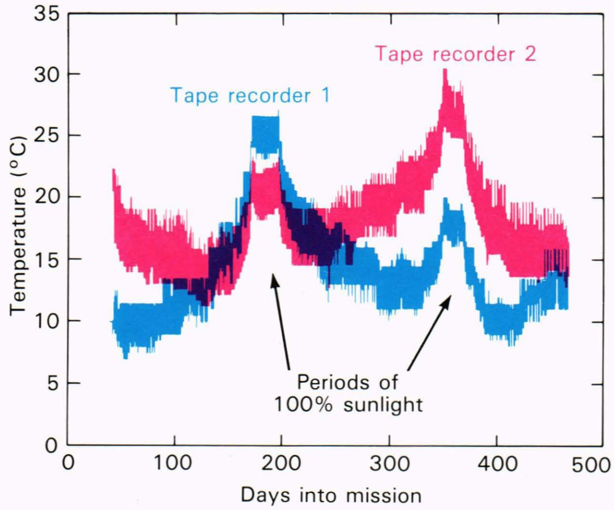

Figure 6—External temperatures of the tape recorders.

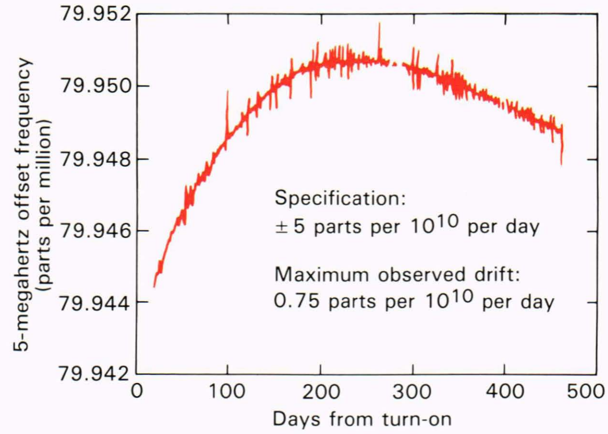

Figure 7—The drift of the 5-megahertz oscillator frequency of the Doppler beacon.

GEOSAT Doppler Beacon Subsystem

GEOSAT includes redundant Doppler beacons that provide two major functions. First, each beacon generates two ultrastable and coherent frequencies (150 and 400 megahertz) that are continuously broadcast for spacecraft Doppler tracking by a network of ground stations within the Defense Mapping Agency complex. The received Doppler data, along with time data from a precise ground clock, are recorded on magnetic tape and are routinely forwarded to the Naval Surface Weapons Center for post-facto satellite precision position determination. Second, the ultrastable 5-megahertz frequency source, included as part of the beacon, gives a source of accurate timing to both the radar altimeter and the telemetry subsystems. Therefore, one of the beacons must be operating at all times to receive telemetry and maintain the timing reference.

To prevent disruption to that reference, only one beacon has been used since launch and it has performed exceptionally well. A critical measure of beacon performance is its output frequency, specified to drift less than 5 parts per 10^{10} per day. Figure 7 plots the beacon frequency offset from 5 megahertz verses time since beacon turn-on. This history indicates that the largest drift rate was about $+0.75$ parts per 10^{10} per day during the first 50 days of operation, which is well within the specified drift range.

C-Band Transponder

The C-band transponder, the secondary payload package on GEOSAT, is an Air Force instrument used as an in-orbit calibration aid for precision tracking radars. The subsystem is side-redundant with one side enabled at a time. Transponders are switched monthly to extend magnetron life. Scheduling for C-band interrogation (turn-on) is done by Vandenberg Air Force Base independently of mission scheduling performed at APL.

The transponders have performed flawlessly to date. On the average, a transponder is interrogated six times per week for about 15 minutes. All subsystem parameters have remained within nominal operating guidelines. Fluctuations in subsystem temperatures are the result of the sun's orientation and the C-band power cycle. Current draw, which has remained within limits, is a function of the main bus voltage at the time of interrogation.

Electrical Power Subsystem

The electrical power subsystem has generated and distributed all electrical power required to operate the spacecraft since launch. Power is generated by an array of 16 (18- × 60-inch) solar cell panels. Two panels are joined end-to-end on each of the eight faces of the spacecraft body, resulting in an array that is approximately conical. The panels contain 12,032 solar cells wired into 32 individually controlled circuits. These solar arrays generate all the power required to operate the main bus and to charge the two 20-ampere-hour nickel-cadmium batteries. Redundant battery charge regulators sense battery voltage, current, and temperature and regulate the solar-array output to limit battery overcharge. The battery-charge regulators are microprocessor-based units that can operate in several different modes, depending on the orbital situation and the thermal limitations placed on battery charging. Solar-array control is implemented by shorting the surplus solar-array current directly to ground by very compact hybrid field-effect transistor circuits. Heat generation is thus virtually eliminated. One regulator currently controls the charging of each solar array/battery pair.

GEOSAT charge-control methods include selectable temperature-dependent voltage limits, current limits, and a coulometer that measures battery discharges and activates a selectable trickle charge when an adequate recharge has occurred. When a need to reduce the array current is indicated, a solar-array circuit is shorted by a transistor contained within the regulator. Circuits are shorted sequentially at one circuit per second until the desired battery condition is achieved. As a result of this "digital" approach to charge control, a given voltage or current limit is maintained by using two or more step changes in the battery current. This approach is unique in that an average battery voltage or current is maintained, rather than a more typical slow-changing direct current value.

The solar arrays have a combined orbital average power output ranging between 275 and 350 watts, depending on the angle between the sun and satellite orbit plane. The angle from the orbit normal to the sun line progresses from about 23 to 157 degrees and back, over a period of 343 days. This progression results in two distinct "seasons" for power generation. The main bus consumes an average of 205 watts of this power either directly from the solar array or indirectly through the batteries. Additional power is consumed due to other losses in the system (batteries are not 100-percent-efficient storage devices). The remaining power is shunted by the battery-charge regulators to prevent overcharging. The shunted power has been a good measure of the difference between how much power the electrical power system has at its disposal and how much is actually required to power the spacecraft. At least 30 watts of extra electrical power have been available to the electrical power system during the mission to date, implying that no measurable solar-array degradation has occurred.

Orbital average loads on the main bus have remained around 205 watts with only slight variations due to S-band, C-band, and tape recorder activities. Main bus voltages have varied between 25.9 and 31.5 volts since launch, with lower measurements of 25.9 volts occurring during periods of maximum earth shadowing of the orbit.

The two nickel-cadmium batteries provide all the power required to operate GEOSAT during periods when the solar arrays are not generating adequate power. Because of the constant rotation of the GEOSAT orbital plane about the earth, eclipse durations have varied between 0 and 35 minutes per orbit. Battery charge levels have not dropped below 85 percent of full charge at any time during the mission.

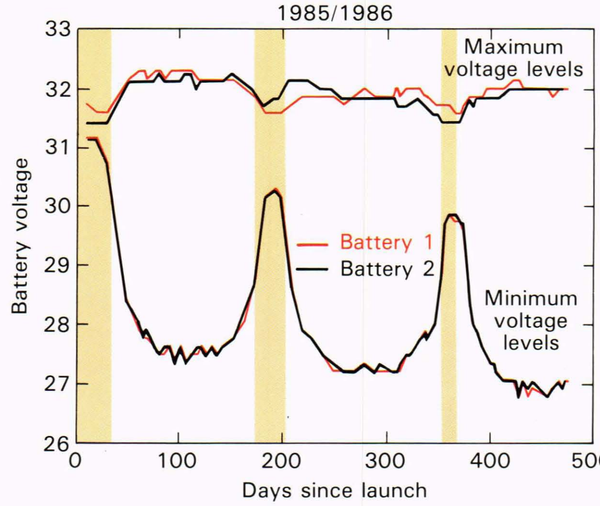

Figure 8—Battery voltage performance. The shaded area shows the sunlit orbit, and the unshaded area shows the partially eclipsed orbit.

Battery voltage levels for the geodesy mission are shown in Fig. 8. Levels have stayed within a 5.5-volt range, with the greatest variance occurring during periods of maximum solar eclipse. Minimum battery voltages have been decreasing with each successive eclipse period. This first sign of battery aging is an expected characteristic. Even if battery voltages continue to drop at present rates, it will probably be another 2½ years before battery reconditioning is necessary. Special on-board circuitry for battery reconditioning has been incorporated into the design and is available for use if the need arises.

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