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Ground-Control System for Satcom Satellites

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A ground-control system is described that utilizes inexpensive ground stations to 1) maintain the two present Satcom satellites in geostationary orbit and on station in both latitude and longitude to within ±0.1°, 2) to provide the same capabilities for one additional satellite, and 3) to assure uninterrupted 24-hour domestic communications capability. Reliability of the system through highly automated dual, but autonomous, control is discussed, as are the tracking, telemetry, and command (TT&C) stations and spacecraft operations control centers (SOCC's) located at two earth stations in New Jersey and California. In addition, details are presented as to system computers and associated software, antenna functions, and the accomplishment of the command, telemetry, and ranging functions.

Nomenclature

A/D	= analog-to-digital (conversion)
EIRP	= effective isotropic radiated power
FSK	= frequency shift keying: frequency modulation where modulating wave shifts output frequency between preset values
G/T	= gain vs noise temperature (figure of merit)
Hamming	= number of digit positions in which corresponding digits of two same-length binary words are different
LNR	= low noise receiver
PAM	= pulse amplitude modulation: amplitude modulation of a pulse carrier
PCM	= pulse code modulation: modulation which uses coding to transform analog waveforms to digital
PM	= phase modulation: modulation that changes the phase angle of a carrier in proportion to the instantaneous value of the modulating signal
S/C	= spacecraft
SOCC	= spacecraft operations control center
TT&C	= tracking, telemetry, & command
WWV	= frequency standard radio station

Introduction

TWO Satcom satellites, presently in U.S. domestic communications service, are supported by a highly reliable ground-control system to insure uninterrupted communications coverage. Accordingly, the Satcom ground system embodies a high degree of automation, redundancy, and autonomy of operation.

The key mission requirements of the Satcom ground segment are to control three satellites in geostationary orbit, provide continuous monitoring of health and status and command and control, and keep the satellites on station within ±0.1° in longitude and latitude. The ground segment must also support transfer-orbit operations for each spacecraft, with an expected peak loading of two spacecraft in geostationary orbits and one in a transfer orbit. Figure 1 represents the ground complex, set up for transfer-orbit operations.

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The basic design considerations for the ground segment were operational reliability and economy of operation, which dictated a solution relying on a high degree of autonomy and automation. However, human decision is called for in the system at critical junctures, e.g., authorization of commands.

High-Reliability System

The emphasis on high reliability, which included the consideration of catastrophic ground-station failures, led to the concept of two redundant control stations. Each station is capable of performing the required tracking, telemetry, and command functions (TT&C) in the orbital arc designated for domestic communcations (99° to 132.5° W. long.).

Locating these TT&C stations at Vernon Valley, N.J. and Moorepark, Calif., provides even wider coverage of the orbital path for the support of transfer-orbit operations. The addition of leased Intelsat facilities at Carnarvon, Australia, and Fucino, Italy produced global coverage (see Fig. 2). The Intelsat stations were instrumented for compatibility with the Satcom spacecraft.

Operating economics require the satellite operations control center (SOCC) and the TT&C to be located together. The combined TT&C/SOCC is then collocated with a major satellite-communications earth station. This setup means that a single operator can use a central control console to monitor the performance, ascertain the orbital position, and command each of the three spacecraft.

Dual but Autonomous Control

Normally, the Vernon Valley TT&C/SOCC is the primary Satcom systems controller for all spacecraft, with Moorepark operating in a "hot standby" mode. At a moment's notice, however, the Moorepark site can assume the role of systems controller should the need arise, as in the case of equipment malfunction, for example. This concept yields additional operating flexibility by permitting sharing of control, where one site controls one spacecraft, and the other site controls the remaining spacecraft. This kind of load sharing was practiced during the launch of Satcom F-2. In that case, Moorepark acted as controller for Satcom F-1, in geostationary orbit, while Vernon Valley acted as mission controller for F-2, in transfer orbit. After the successful injection of F-2 into its geosynchronous (drift) orbit, control of F-1 reverted back to Vernon Valley.

The requirement of making each TT&C station autonomous has been achieved, except for orbit-related computations. The high precision and speed required there, particularly during transfer-orbit operations, requires the use of large-scale computers. Their relatively low utilization, coupled with the high cost of purchase, led to the leasing of

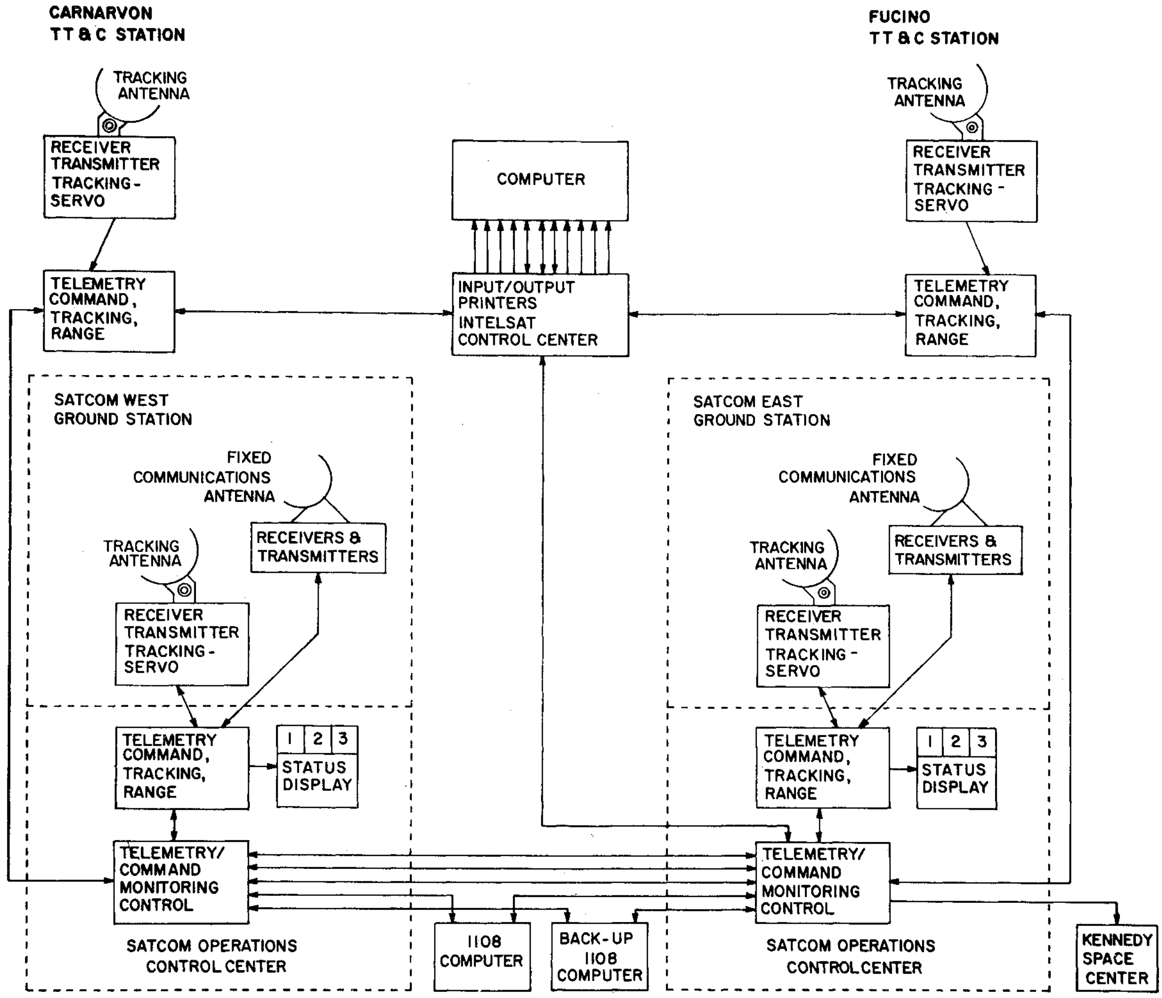

Fig. 1 Ground-station setup for a transfer-orbit operation. The two Intelsat stations are leased for such operations only; the two U.S. stations alone are sufficient for covering the arc needed for domestic communications.

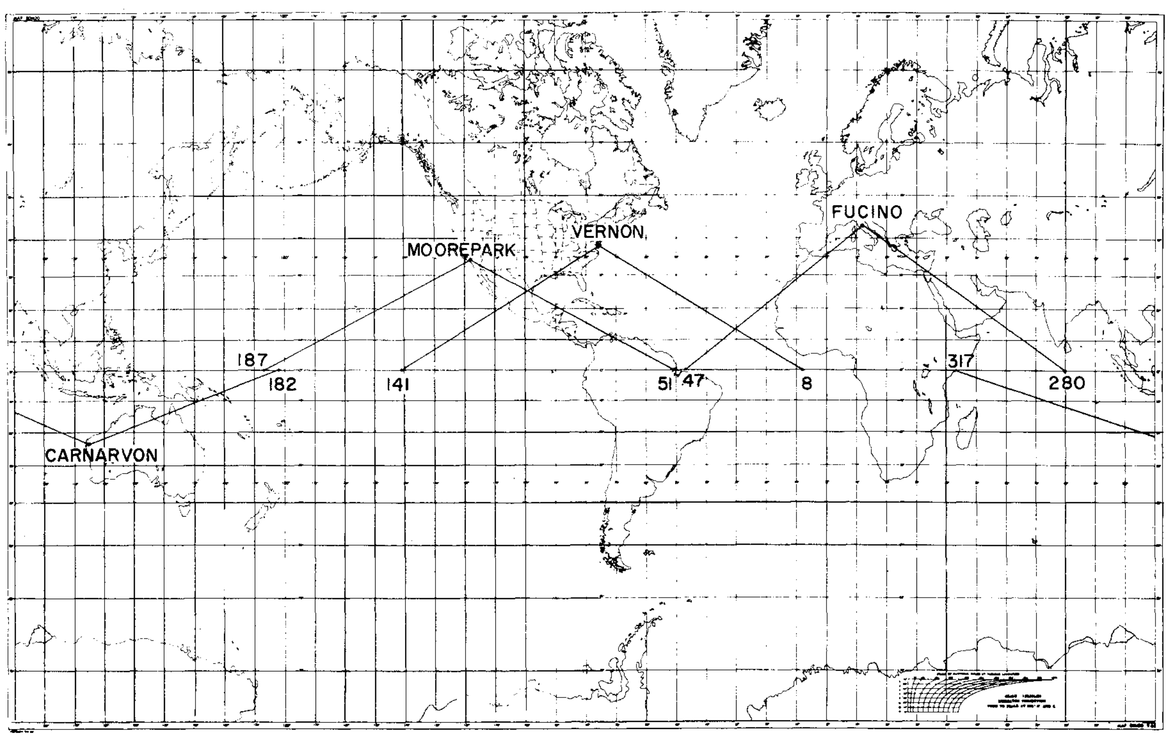

Fig. 2 Four stations provide worldwide coverage for transfer-orbit operations when their antennas are at 10-deg elevation and the satellites are at synchronous altitude. Numbers on chart are W. longitude expressed on a 360-deg basis.

Univac 1108 computers from computer utilities. Again, reliability requirements, including the possibility of catastrophic failures, dictated the use of two physically separated computers, one prime and one backup. During transfer-orbit operations the backup computer was used as a "hot" standby; i.e., it was continually updated to keep abreast of the mission, as well as periodically exercised to cross-check with the primary computer.

State-of-the-art permitting, (i.e., the availability of low-cost, high-precision, high-speed minicomputer) a self-contained orbit-computing capability, the Perkin Elmer 8/32, is being installed for the TT&C/SOCC.

Computer Complex

Two Hewlett-Packard 2100 minicomputers, designated "data" and "control," are at the core of each TT&C/SOCC. These minicomputers and the two leased Univac 1108 computers, which are both accessible from each U.S. ground station, produce a system, and individual TT&C/SOCC's, with a high degree of automation. An HP 2100 is also in use at each of the two transfer-orbit stations at Carnarvon and Fucino.

The eight-computer complex is interconnected via a communications network that enables computer-to-computer transfer of data and commands (Fig. 3).

Two dedicated, full-duplex, 4800-baud lines interconnect the Moorepark and Vernon Valley TT&C/SOCC's: one line interconnects the data computers, transferring spacecraft telemetry received by one computer to the other; the second interconnects the two control computers. Command-list transfer and station coordination are done using this link. Finally, a 300-baud line is provided for data transfer to and from Univac 1108 computers.

TT&C/SOCC Ground Station

The TT&C/SOCC has three basic functional areas: the rf receiving and transmitting equipment, the signal-processing equipment, and the spacecraft operations control center.

Both TT&C/SOCC ground stations are identical in capability and hardware. Within each station a high degree of redundancy and "cross-strapping" is provided, minimizing the effects of single-point failures. For example, should the computer-controlled automated commanding fail, either one of two redundant command and range tone generators provides manual command generation (see Fig. 4).

Each ground station can command or range with each of the three spacecraft, one at a time; telemetry can be received and processed simultaneously from all three spacecraft.

Antennas

A ground antenna is dedicated to each satellite in orbit. Each antenna performs two functions during commercial operations: communications, and command and control.

All antennas have 13-m dishes and a G/T of 32.4 dB/K.

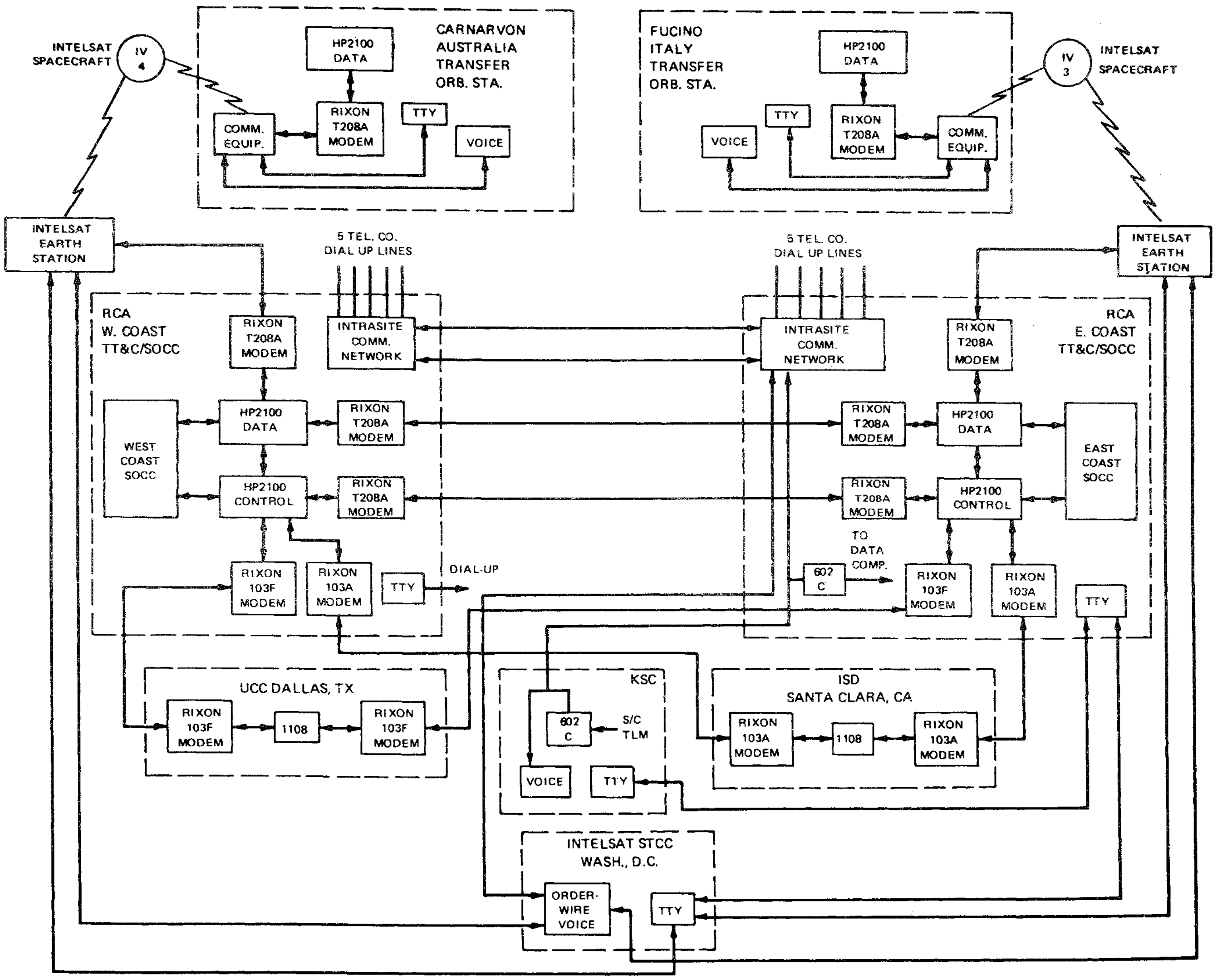

Fig. 3 Data and commands are transferred back and forth between eight computers in the sytem. Data computers deal with telemetry, ranging, and attitude data; control computers deal with command sequences.

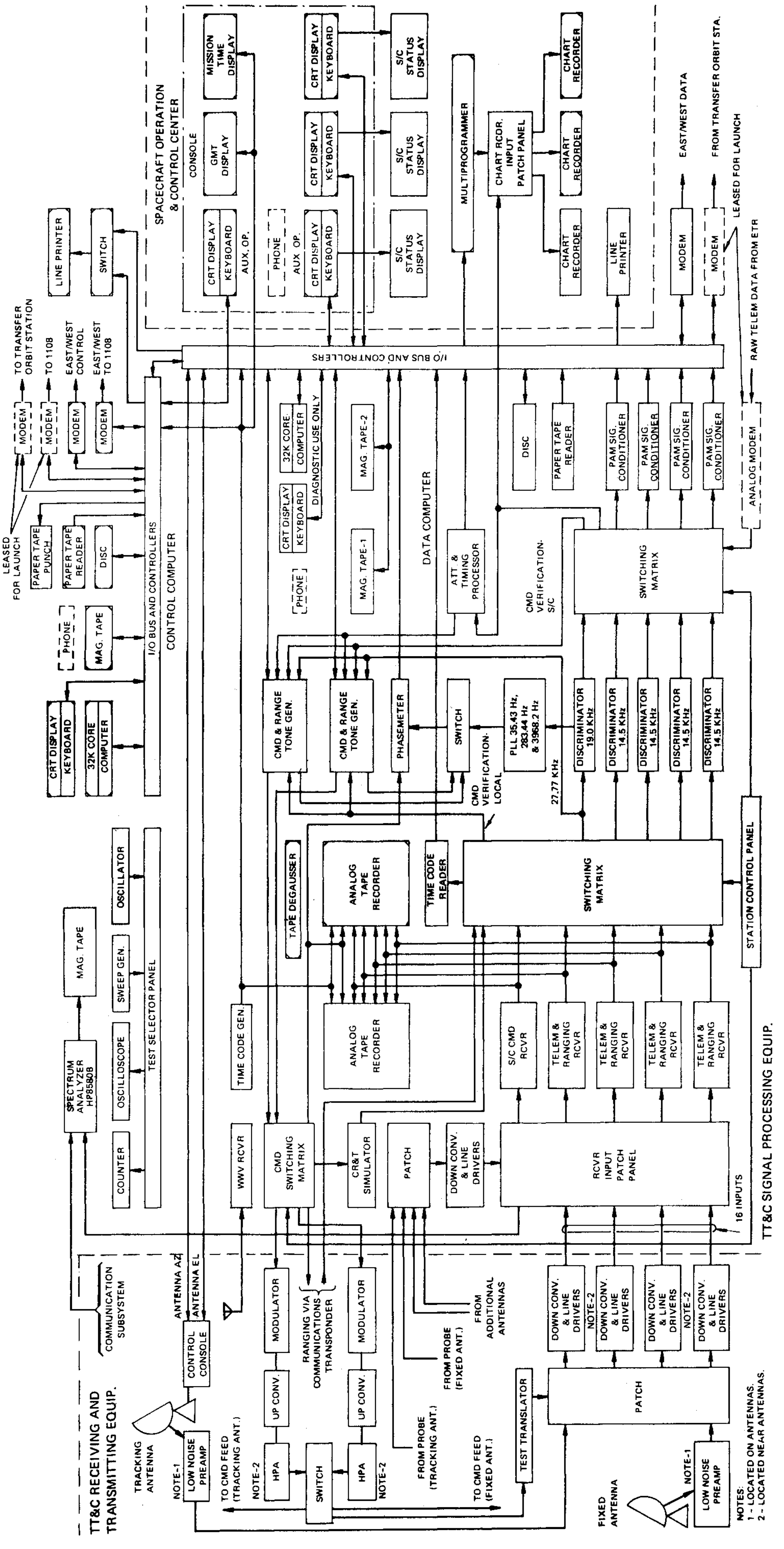

Fig. 4 Combined TT&C/SOCC ground station. Each of the two such Satcom stations is totally autonomous.

The rf feeds are of dual orthogonal polarization, capable of receiving and transmitting simultaneously in both polarizations. The feeds are designed for 500 MHz of bandwidth, with 6 GHz uplink and 4 GHz downlink. The gain at 6 and 4 GHz is 56 dB and 53 dB, respectively. When driven by a 3-kW transmitter, the antenna system is capable of producing an effective isotropic radiated power (EIRP) of 89 dBW, which is ample for ranging and commanding during both transfer-orbit and on-station commercial operations.

Tracking System

To facilitate transfer-orbit operations, one antenna at each TT&C/SOCC is equipped with auto-track capability. This antenna has an extended range (± 270 deg in azimuth and 90 deg in elevation) and higher angular velocity (3 deg/s) when compared with the standard communications antenna. Four tracking elements comprise the monopulse feed system.

The pointing accuracy of the antenna is 0.025 deg rms and the tracking errors in the auto-track mode are less than 0.008 deg rms. The shaft position readout for azimuth and elevation has a resolution of 0.01 deg; it is transmitted to the data computer for further processing, in conjunction with spacecraft ranging.

In addition to its auto-track mode, the antenna can also be controlled via computer-driven "programmed-track" and manual-track modes. Both tracking modes were successfully used at each TT&C/SOCC site during the transfer orbit of Satcom F-1 and F-2 when attempting an initial acquisition (the first time the spacecraft appears over the horizon). Predictions for azimuth and elevation generated by the Univac 1108's off-line software are used to position the antenna.

When on station, the auto-track antenna can track either of the two orthogonally polarized spacecraft beacon frequencies: 3700.5 MHz, horizontally polarized (east-west); and 4199.5 MHz, vertically polarized (north-south), originating at the spacecraft communications antenna. The commanding frequency is 6423.5 MHz and is horizontally polarized.

When in transfer orbit, the spacecraft's omni-antenna is used, with both beacons copolarized. The command signal is orthogonal to that of the beacons. The beacon polarization is linear and parallel to the spacecraft's spin axis, which changes in the course of the transfer mission as the spacecraft spin axis precesses. Consequently, manual polarization adjustments have to be made during this phase of tracking. The tracking antenna has a polarization adjustment over ± 45 deg for both orthogonally positioned rf feeds. Additionally, the polarization of the uplink feeds can be adjusted relative to the downlink feeds by ± 10 deg in order to optimize polarization alignment.

Redundant low-noise receivers (LNR's), provided for each polarization, enhance the reliability of the telemetry downlink. The primary pair is thermoelectrically cooled, and has a maximum noise temperature of 55 K. The standby LNR's are uncooled, with a noise temperature of 62 K. Figure 4 is a block diagram of the TT&C receiving and transmitting system.

Commanding System

The command system is designed to minimize errors on several levels: coding, transmission, and command generation.

Under routine operating conditions, commanding is performed using "canned" command lists designed to execute the desired functions. Generating and executing each list entails authorization. The control computer provides command-list generation, storage, and initiation. Commands are time-tagged and, once authorized, will be executed in accordance with the predetermined time sequence.

Spacecraft commanding entails the concept of load, then verify, then execute. The received command is retransmitted via the spacecraft beacon to the TT&C/SOCC, where it is compared to the original command. Upon verification, an "execute" command is sent to the spacecraft. In addition to the space-to-ground link, verification is also provided via a ground-antenna feedback loop, facilitating rapid fault-isolation to the ground segment.

Finally, protection is provided in the command format and code. A Hamming distance of two exists between the spacecraft address and operation codes (opcodes), so a single-bit error at the spacecraft will not result in acceptance of the command.

Beyond the preceding, commands which could adversely affect revenue-producing capability or spacecraft life are classified as "hazardous" commands. These cannot be transmitted without activating the "hazardous command key," located on the operations control console.

The format allows for 256 command opcodes, of which 210 have been implemented in the spacecraft. Command transmission is at 100 bits/s. The modulation is PCM/FSK/FM, with ternary FSK; the "execute" tone is a different frequency from either the "mark" or "space," giving added protection against false command execution.

Given the the above-described system, the probability for false command reception by the spacecraft is less than 10^{-22}.

Telemetry

The state of the spacecrfaft is sampled every two seconds, and transmitted to earth via the onboard telemetry system. One hundred and ten channels require processing by the data computer in real time. A total of 145 points of information (155 with both beacons) are relayed from the spacecraft either as status or analog data.

Each Satcom spacecraft can transmit two telemetry signals simultaneously, one on each beacon. PAM/FM/PM is used for "housekeeping" telemetry; analog/FM/PM is used with both attitude telemetry during transfer orbit, and "dwell" telemetry where a given channel is examined for closer evaluation of a given parameter. A 14.5-kHz subcarrier is FM-modulated by either PAM or analog data. The modulated subcarrier in turn phase-modulates the beacon rf carrier.

After down-conversion (see Fig. 4), telemetry is patched to one of the four telemetry and ranging receivers, where it is demodulated and switched to one of the four 14.5-kHz discriminators. After recovery of the baseband signal, PAM telemetry is switched to any one of four PAM signal conditioners, where analog-to-digital (A/D) conversion is made. The digitized data are received by the data computer for processing, logging on disc and digital tape, and display on CRT's, stripcharts, or line-printer hard copy.

After they are received, attitude data are routed to the attitude and timing processor, where they are quantized and transmitted to the data computer for display on stripcharts or for preprocessing into an "attitude data file," which is transmitted to the off-line 1108 for subsequent determination of the spacecraft's spin-axis orientation. Dwell data are routed directly for display on one of the 18 available stripchart recorder channels.

Telemetry is backed up on several levels, providing for greater system operating reliability and flexibility. Two seven-track analog tape recorders can continually store received telemetry (including ranging and command verification data). Should the data computer be unable to process in real time because of a failure or scheduled maintenance, the stored analog tape may be played back to recover telemetry data. Analog tapes may be maintained for a period of several days as a backup to the processed data logged on the digital tape. The digital tapes are stored for several months for use in intermediate term trend analysis. Subsequently, "data compression" is performed on these tapes. Compressed tapes are then stored for long-term trend analyses and posterity.

Table 1 Real-time software resident in data and control computers

Key modules of the real-time software system
Data computer
Telemetry calibration processing
Telemetry logging
Telemetry data intersite telecommunications
Video display
Chart recorder display
Attitude data processing
Antenna (Az&El) data collection
TT&C antenna control
Ranging data processor
Control computer
Command-list generation
S/C command-list execution
Station command-list execution
East coast/west coast system coordination
Intrasite communications
1108 file processing
1108 execution control
1108 file transmission

Ranging

Slant range to the spacecraft is measured by using the spacecraft command receiver and beacon transmitter in transponder fashion. Four coherently generated sinewave tones are transmitted one at a time via the command uplink, then received via the beacon downlink. The range is determined by measuring the shift in phase angle between each transmitted and received tone.

The four tones, generated by the command and range-tone generator under data-computer control, are 35.4 Hz, 283.4 Hz, 3968.1 Hz, and 27.777 kHz. One cycle of the low tone measures to within 4241 km, the next two higher tones resolve ambiguities to within 530 and 37 km, and the high-frequency tone resolves the range to within 5.409 km.

Using all four tones together, the resultant range measurement is typically accurate to within 25 m (1σ), when using one-station ranging, and 12 m (1σ) when using two-station ranging.

The ranging system employs FM/FM modulation on the uplink, and FM/PM on the downlink.

Typically, ranging to each spacecraft is performed subsequent to a maneuver. Data are collected hourly, alternating between Vernon Valley and Moorepark, to achieve greater accuracy. Ranging tones are applied for a period of approximately 15 min each time. Accumulated tracking-data files are transmitted to the off-line 1108, via the control computer, for orbit-determination processing.

Spacecraft Operations Control Center (SOCC)

A six-cabinet wraparound console is the focal point for Satcom spacecraft system operations. Four CRT/keyboards are the prime monitoring and controlling devices. Three of these keyboard terminals and their associated character-mode CRT screens interface with the data computer and also request and display telemetry data. All three CRT's can display telemetry from one spacecraft or each CRT can display telemetry from a different spacecraft.

Three additional 23-in. black-and-white TV monitors suspended from the ceiling act as repeaters, enabling operations analysts to monitor spacecraft health and status without crowding the console area.

A fourth character-mode CRT/keyboard interfaces with the control computer and acts as the executive-command input to the system. Command generation, authorization, and spacecraft control are done here.

An operator control panel allows the console operator to monitor and control the TT&C equipment remotely: e.g., computer status monitoring, stripchart recording, and analog tape-recorder control. The panel also contains the hazardous-command lock and alarms.

Intersite voice and data communications control is performed at the control console, where the operator can control data transmission to the off-line 1108 or to the other TT&C/SOCC, for example. A mission-time clock and a GMT clock round out the console equipment. Both clocks are driven from a time-code generator that is synchronized with a WWV receiver.

In addition to the console and its equipment, a line printer, three six-channel stripchart recorders connected to the data computer, and a second printer, switchable to either the data or control computer, give the control center area the required hard-copy capability.

Computer Software

Development of new computer software was a major undertaking needed to accommodate a new spacecraft.

The software system consists of two major parts: real-time software, needed to accept and operate on telemetry and provide spacecraft command and control; and off-line software, associated with orbital computations, establishing orbital positions, planning maneuvers to effect the desired transfer-orbit, and on-orbit stationkeeping.

All the software except the orbit determination and prediction software are new; the latter was based on the "Space 360" program used by the U.S. Government.

The off-line software performs the key function of orbit determination and prediction, spin-axis attitude determinations, spin-axis precession planning, apogee kick motor firing planning, maintaining and updating the thruster performance parameters used in maneuver planning, hydrazine fuel status, station acquisition planning, stationkeeping planning, and data-base management.

Table 1 lists the key software modules comprising the "real-time" software system resident in the data and control computers.

Concluding Remarks

The common thread throughout the Satcom ground system development was the newness of its constituent parts. This meant that meeting the launch date with the desired degree of confidence became a challenging exercise in testing and rehearsals.

To expedite testing, the orbit-determination and prediction software, for example, were tested against spacecraft data supplied by NASA and Telesat, Canada.

The ultimate way of testing a satellite tracking system, however, is with a satellite in orbit. This enables testing of not only software, but the antennas, the uplink, the downlink, and data and control computers, as well as the personnel.

In order to have this testing done prior to the launch of the Satcom spacecraft, it was arranged to have the ATS-1, ATS-5, and Telesat's ANIK II exercise the ranging subsystem and the orbit-determination and prediction software. This accelerated system debugging immeasurably. Also, incorporating live ranging into the mission rehearsals lent a high degree of reality to the exercises, and led to the ultimate achievement of two successful missions.

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