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Command and Telemetry Systems

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The command and telemetry portions of the Telstar system provide necessary support functions for the basic communications experiment and the radiation experiment. By means of the command system, the states of 9 magnetic latching relays in the satellite are controlled from the ground. Commands are sent to the satellite by coded signals modulated on a carrier in the VHF band. The telemetry system also uses a VHF carrier to transmit encoded information from the satellite. Data on 112 items are provided once each minute. This paper discusses the over-all command and telemetry systems and considers the general objectives, system aspects and detailed implementation.

AUTHOR

I. INTRODUCTION

The Telstar satellite includes circuits designed to perform two basic experiments: (*i*) a communications experiment using a wideband, active repeater and (*ii*) a radiation experiment designed to provide information on the environment in outer space and the effects of this environment on devices used in communication circuits. The command and telemetry portions of the Telstar system provide a very necessary support function for these experiments. This paper discusses the over-all command and telemetry systems; it considers first the need and general objectives and then the systems aspects of the design. Finally it gives a detailed discussion of the implementation of each system.

The need for a command system for the Telstar project arises primarily because of power considerations associated with the satellite repeater: the communications circuits consume more power than the solar plant is capable of supplying.[1] To be able to operate under full load, batteries are provided which supply the additional power needed during operation of the communications circuits. During those intervals when the communications circuits are not on, the batteries are recharged by the solar plant. Hence a command system is necessary to turn the high-power communications circuits on and off. Having provided a

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command system, it is then convenient to turn other circuits on and off and provide some other functions which can only be available with a command system. These functions include changing telemetry encoders, testing the two command receivers, and activating a torquing coil for attitude control, as well as turning on and off the traveling-wave tube, the IF amplifiers, the microwave carrier supply, telemetry and the radiation experiments. The command receiver circuits must always be energized so that commands may be acted upon to turn on other circuits. The VHF beacon, used for wide-angle acquisition and tracking, is also left on; however, it can be turned off under special conditions.

The telemetry carried aboard the Telstar satellite provides information on 112 different quantities at a rate of one full frame per minute. These quantities fall in four major categories. One type of data relayed from the satellite consists of status information: for example, the state of control relays, some critical temperatures, the solar plant output, and the battery voltage. These data must be decoded and displayed in real time so that the satellite can be operated with the least chance of damage. The second class of data includes those items which pertain to the general condition of the satellite. Such items include internal and external temperatures, pressure, and solar aspect angle. These data are normally monitored and recorded to be analyzed at a later time. They provide a continuous record of the condition of the satellite and some of the effects of its environment. The third main category of telemetry data is that which monitors parameters pertinent to the communications repeater. These data are monitored and recorded to provide correlation data for the communications experiments. Such items as satellite receiver AGC voltage, transmitted power levels, and certain temperatures are necessary for correlating test data. The fourth category of telemetry information is that which provides data from the radiation damage experiments and those channels which contain the radiation counter information. About one fourth of all the telemetry channels are used in the radiation experiment, one third are used to measure various temperatures, and the remaining channels are used to measure a variety of relay states, currents, voltages, biases and calibrations.

II. SYSTEMS DESCRIPTION

The command and telemetry systems are each one-link transmission systems. The command system has its transmitting terminal on the ground and the receiver in the satellite. The telemetry system, on the other hand, transmits from the satellite and the signals are received on the ground. Fig. 1 shows a block diagram of each system and those por-

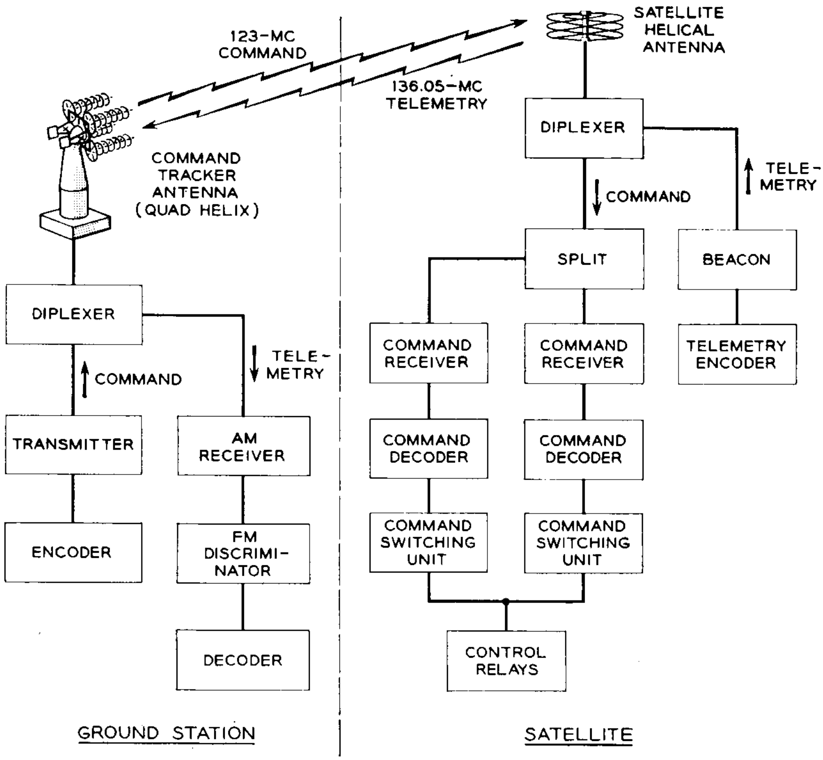

Fig. 1 — Block diagram of command and telemetry systems.

tions of the equipment which are common to the two systems, such as the diplexers and the antennas.

The command system transmits signals to the satellite at approximately 123 mc. The transmitting terminal consists of a command encoder which generates the specified code and a VHF command transmitter which is amplitude modulated by the command signal. The output of the command transmitter goes through the ground diplexer to the command tracker antenna and is radiated to the satellite. The signal picked up by the satellite helical antenna goes through the satellite diplexer and a splitting arrangement into two command receivers. The baseband pulses out of each receiver drive a decoder which activates the proper relay through the action of the switching unit.

The telemetry system transmits information from the satellite back to ground. The transmitting equipment in the satellite consists of a telemetry encoder whose output modulates the 136-mc beacon. The signal then goes through the satellite diplexer to the helical antenna where it is radiated. The telemetry signal is picked up on the ground by the command tracker antenna and then goes through the ground diplexer to the telemetry receiver. The output of the telemetry receiver drives the decommutator, which presents the information in printouts and displays.

The details of each of these systems will be discussed separately in later portions of this paper. The nature of the signals and the over-all system design considerations will be covered in the following sections.

III. GENERAL DESCRIPTION OF TRANSMISSION SIGNALS

3.1 *Command Signals*

The commands are transmitted to the satellite in the VHF band. The 123-mc carrier is amplitude modulated with a keyed subcarrier. The subcarrier, a 5.451-kc signal, is keyed on and off to generate a code made up of bursts of subcarrier of different widths. A command word is composed of a guard space, a start pulse and six code bits, each occupying a time slot equal in length to 72 cycles of subcarrier. A guard space is no pulse (a blank time slot), and a start pulse is a burst of subcarrier for three fourths of the time slot. The six code bits are made up of three ones (50 per cent duty cycle, burst of subcarrier for half a time slot) and three zeros (25 per cent duty cycle, burst for one fourth of the time slot). This three-out-of-six code permits 20 unique commands, of which 15 are used in the Telstar system. The transmission of a command consists of sending the desired code word five times in succession. This repetition is strictly redundant since each word is decoded and acted upon independently in the satellite. Fig. 2 shows the baseband waveform of a typical word (110100), the keyed subcarrier, and the carrier modulated by this subcarrier. This particular code structure, the carrier, and the subcarrier frequencies were chosen to be compatible with existing command facilities at the NASA Minitrack stations. The command and telemetry signals were thus chosen to provide the greatest flexibility and compatibility with these existing facilities.

The code signal, as described above, is generated in the command encoder. This signal 100 per cent amplitude modulates the command transmitter. The command signal is transmitted from the command tracker antenna and is received at the satellite by the helical VHF antenna situated at one of the poles of the satellite. The command receiver in the satellite shifts the carrier to a 5-mc IF, amplifies it, and detects the code to produce a baseband pulse train which is decoded and which

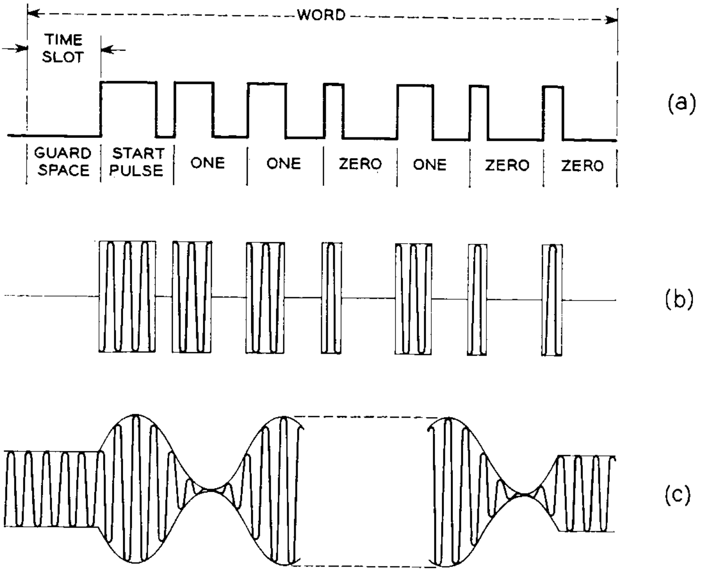

Fig. 2 — Command signal waveforms: (a) baseband code, (b) gated subcarrier (c) modulated carrier (expanded time scale).

causes the proper relay switching to accomplish the function designated by the command being sent.

3.2 *Telemetry Signal*

The telemetry signal is transmitted from the satellite to the ground telemetry receiver, also in the VHF band. The same antennas are used: the satellite helix transmits the 136-mc beacon signal and the command tracker antenna receives it. The telemetry encoder within the satellite generates a PCM signal made up of 120 eight-bit words. Each eight-bit word is made up of a seven-bit binary code with an eighth bit used for word synchronization. Of the 120 words there are 118 data words, and two words (119 and 120) are used for frame synchronization. The baseband PCM signal frequency modulates a 3-kc subcarrier with a deviation of ±7.5 per cent (±225 cps). The modulating signal is two-level, so the output of the FM modulator is a signal alternating between two frequencies, 2775 and 3225 cps. This signal in turn 50 per cent amplitude modulates the beacon. Fig. 3 shows a typical telemetry word (level 90, on a 7-bit binary scale from 0 to 127), the corresponding plot of frequency versus time of the subcarrier, and the modulated

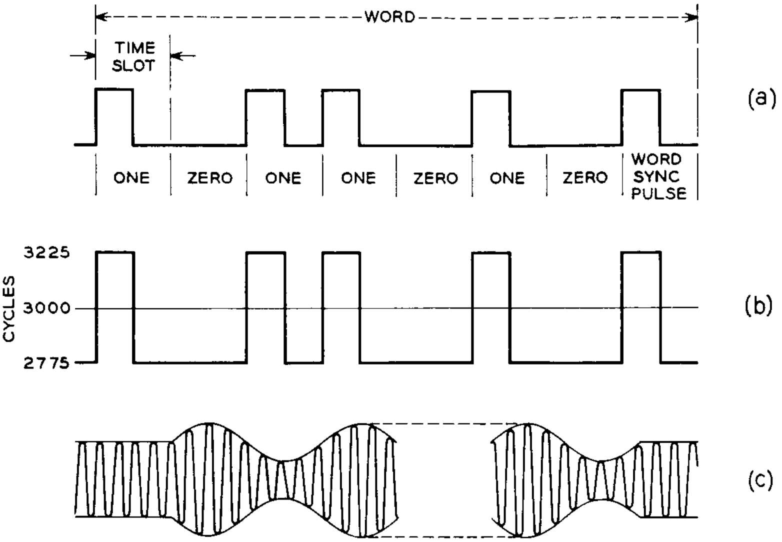

Fig. 3 — Telemetry signal waveforms: (a) baseband code (bit level 90); (b) subcarrier frequency deviation; (c) modulated carrier (expanded time scale).

carrier. This PCM/FM/AM signal is transmitted from the satellite helical antenna and is received by the command tracker antenna. After amplification, the carrier is shifted to a 10-mc IF, and an amplitude detector retrieves the frequency modulated 3-kc subcarrier. A frequency discriminator extracts the baseband PCM signal, which is then decoded to provide the corresponding output for each of the telemetry channels.

3.3 *Command and Telemetry Interaction*

The command and telemetry systems are essentially independent systems. Certain commands are interlocked in such a way that their use depends on what commands have been sent and upon the status indicated by the received telemetry. The telemetry circuits in the satellite can be turned on and off, and some of the telemetry channels monitor parameters in the command circuits. To this extent the two systems interact. Since the two directions of transmission use the same antennas, diplexers are used at each terminal, and there will be some leakage of each transmitter into the other receiver. The frequency separation is large enough so that the leakage problem is not severe. The details of this effect will be discussed under System Performance, Section V.

IV. SIGNAL LEVELS

4.1 *Command*

The command transmitter has an output capability of 200 watts of average unmodulated carrier power. At the Andover, Maine, ground station the cabling distance from the command transmitter to the command tracker antenna is about 150 feet. The signal then goes through the diplexer before being radiated from the antenna. Cabling and diplexer losses are 2.5 db, and the antenna provides a gain of 17.5 db at 123 mc, for a net gain of 15 db.

Loss from transmitting antenna on the ground to the receiving antenna on the satellite may be calculated from the theoretical free-space path loss. Since the range (distance from transmitting to receiving antenna) is constantly changing in a satellite system, the path loss is a variable. For the Telstar satellite launched July 10, 1962, the range may vary from as much as 6500 miles (looking at apogee on the horizon) to as little as 500 miles (perigee directly overhead). These variations in range will result in a path loss variation of 22 db (from 155 to 133 db).

The radiation pattern of the satellite helical antenna is described in detail elsewhere in this issue.[2] Ideally, the antenna would be isotropic. The antenna pattern is essentially a surface of revolution; that is, the gain at any angle does not change as the satellite spins on its axis. However, the gain is not constant as a function of the angle between the satellite spin axis and the direction from which the satellite is viewed. This angle, when measured from the end of the spin axis away from the helical antenna, is called the spin angle. Fig. 4(a) shows the antenna gain (including cabling and matching network losses) as a function of the spin angle. Near the poles the antenna has considerable loss and is difficult to measure; however, if we consider only those angles between 5 and 165 degrees, we see a range in antenna gain of 16 db. Combining this variation with the variation due to range as given by Fig. 4(b), the signal level at the command receiver may vary as much as 38 db over all combinations of range and spin angle. It is possible on a given pass to see a wide range of spin angles; however, to see the full variations in range requires that the apsides advance through half a cycle, which in this case takes about 3 months. The command receiver in the satellite is designed to handle a signal level range of 30 db. This AGC range, while not adequate to cover all cases, is adequate to cover the range of signal levels that result during any pass or group of passes.

In addition to the path loss and the loss in the satellite helical antenna.

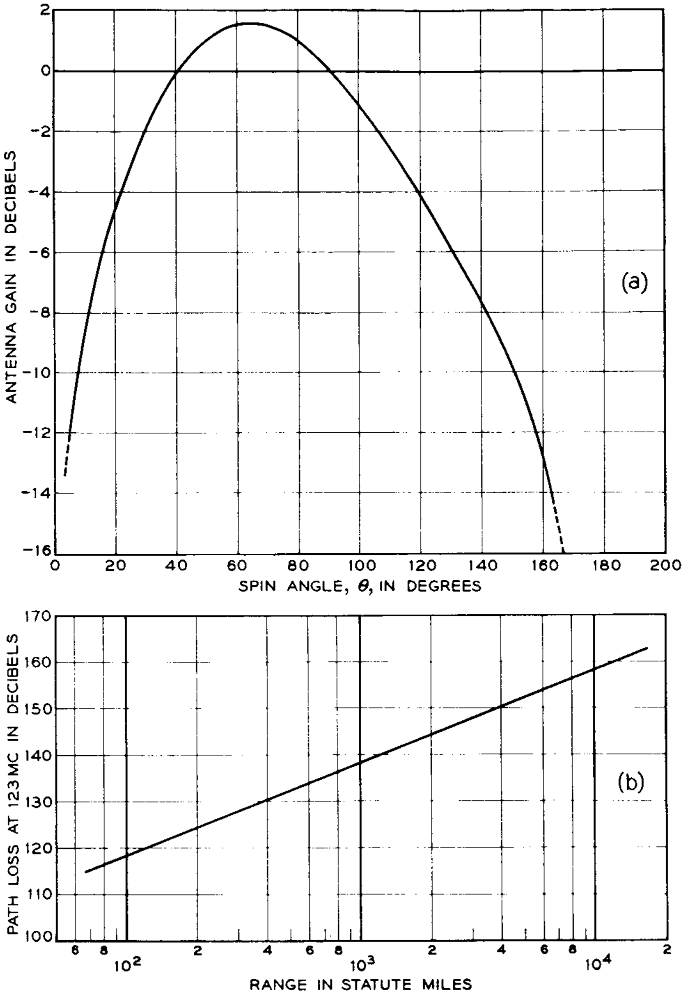

Fig. 4 — (a) Satellite antenna gain as a function of spin angle, (b) free-space path loss at 123 mc as a function of range.

there is a 3-db polarization loss. The helical antenna on the satellite has an essentially linear polarization, and the command tracker antenna quad-helix has a right-hand circular polarization. To get from the antenna to the command receiver, the signal loses 2.5 db in the diplexer and another 3 db in a splitting pad (two receivers operating in parallel for redundancy). The AGC range of each command receiver is such that it can handle signals at its input of −100 to −70 dbm.

4.2 *Telemetry*

The down link of the command and telemetry system consists primarily of the satellite beacon transmitter, the transmission medium, and the RF and telemetry receivers. The beacon puts out 200 milliwatts (+23 dbm) of average unmodulated carrier power. The satellite antenna pattern at 136 mc has approximately the same shape as at 123 mc, but the gain is down about 1 db due to cabling and matching network losses. Free-space path loss at 136 mc is about 0.8 db greater than at 123 mc, and the net gain associated with the command tracker antenna is about 18 db rather than the 15 db at 123 mc. The command tracker antenna is 3 db better at the telemetry frequency than at the command frequency for two reasons. First, the beam is narrower at 136 mc, giving a gain increase of about 1.5 db, and secondly, the 1.5 db of cabling loss is avoided by placing the RF preamplifier in the antenna pedestal instead of in the control room 150 feet away.

There is again a loss of 3 db due to polarization, and the range of received signal levels as before is 38 db. The limitation on the signal level received at the ground is that it be strong enough to produce a detectable signal. The next section will show that a detectable signal will be received if the command link is workable.

V. SYSTEM PERFORMANCE

5.1 *The Command System*

The performance of the command and telemetry systems can best be described by first considering the parameters of the command system. From noise considerations, the minimum allowable received signal level can be determined. Then, knowing the properties of the ground transmitter and of the satellite receiver, the worst combinations of spin angle and range can be determined. The performance of the telemetry system will then be determined, based on the poorest combination of range and spin angle allowed by the command system.

Contributors to the noise performance of the command receiver are (*i*) thermal noise, (*ii*) galactic or cosmic noise, and (*iii*) leakage of the beacon signal into the command system. The effective bandwidth of the command receiver is less than 60 kc. The thermal noise power available in a 60-kc band referred to the input of a 5-db noise figure amplifier is −122.8 dbm. Cosmic noise available in a 60-kc band at 123 mc is taken to be −121 dbm (1000°K)[3]. The leakage of the 136-mc beacon into the command receiver results in an interfering signal at the output of the receiver. The off-frequency rejection in the receiver referred to −100 dbm at the input is 64 db; the diplexer has 80 db rejection against the +24-dbm, 136-mc signal getting into the command system; and taking the 3-db splitting pad loss, the leakage signal referred to the input of the command receiver is −123 dbm. Adding these three interferences on a power basis results in an interference level at the input to the command receiver of −117.5 dbm. With a −100-dbm input signal, the resulting signal-to-noise ratio of 17.5 db will provide essentially error-free performance in the command decoder.

The minimum signal level within the AGC range of the receiver, as stated earlier, is −100 dbm. Since this also results in a signal-to-noise ratio corresponding to error-free operation, it will be taken as the threshold of commandability. In practice it has been found that a received signal level of −100 dbm is 3 to 5 db above the point where commands will be recognized but with an occasional error.

The received power equation for the command system is

$$P_R = P_T + G_1 - PL + G_2 - 8.5 \text{ db} \tag{1}$$

where P_R = received signal level at the input to each command receiver in dbm
P_T = ground transmitter output power (+53 dbm)
G_1 = command tracker antenna gain at command frequency minus cable and diplexer loss (+15 dbm)
PL = path loss at command frequency (db)
G_2 = satellite helical antenna gain at command frequency (db).

The 8.5 db is made up of 3 db polarization loss, 2.5 db satellite diplexer loss, and 3 db splitting pad loss for driving the two command receivers in parallel. To keep the minimum signal at the command receiver input at −100 dbm requires that the path loss minus the satellite antenna gain shall not exceed 159 db. The path loss at the command frequency is given by

$$PL = 78.4 + 20 \log R \text{ (db)} \tag{2}$$

where R is the range from transmitter to satellite in statute miles. Fig. 4 shows path loss as a function of range and the satellite antenna gain as a function of spin angle. Fig. 5 shows the relationship between range and spin angle such that the minimum workable signal is assured. The contour plotted is for $P_R = -100$ dbm. The received signal level anywhere to the left of the curve will exceed −100 dbm; to the right of the curve the level will be less than −100 dbm and commanding should not be attempted. For an isotropic antenna (the actual antenna has unity

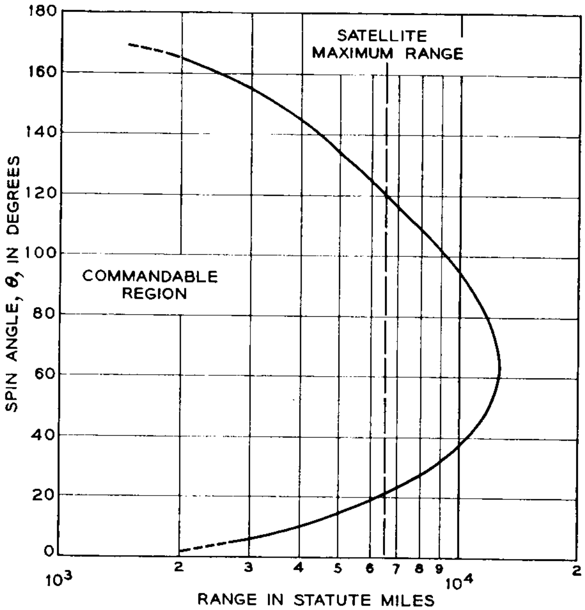

Fig. 5 — Commandability contour for received signal level of −100 dbm.

gain at 90 and 40 degrees) the maximum workable range is 10,700 miles. For the actual antenna, the maximum range which will be safe for any spin angle between 5 and 165 degrees is 2000 miles, and the maximum range for the best spin angle (65 degrees) is 12,900 miles. For the Telstar satellite orbit with its maximum slant range of 6500 miles, the command system will be workable as long as the spin angle stays within 20 to 120 degrees.

5.2 *The Telemetry System*

If the command system is within range, then the path loss minus satellite antenna gain is less than 159 db at the command frequency. Under the same conditions, the path loss minus satellite antenna gain at the telemetry frequency will be less than 161 db (the difference in path loss and antenna gains were pointed out previously) and the received signal level at the input to the telemetry receiver will be at least −120 dbm: satellite transmitted beacon power of +23 dbm, minus 161 db for path loss and antenna gain, plus 18 db for the ground antenna, results in a received signal level of −120 dbm. The noise level referred to the input of a 3.5-db noise figure receiver with a 20-kc band is −130 dbm. The minimum carrier-to-noise ratio (C/N) for the AM detection is then 10 db. With a C/N ratio of 10 db, the AM detector will not enhance the noise appreciably and the signal-to-noise ratio (S/N) for the FM detector may be calculated directly. The signal power in each sideband for a 50 per cent amplitude modulated carrier is 12 db below the carrier level. With double-sideband detection and a 600-cps bandwidth, the S/N at the input to the FM detector is 16 db: power in each sideband is −132 dbm; noise in a 600-cps band is −145 dbm. Single-sideband detection would give S/N = 13 db, and double-sideband detection results in S/N = 16 db. This signal-to-noise ratio at the input to the FM detector will result in output performance which is essentially error free. To keep a S/N ratio of at least 10 db at the FM detector, the signal level might be allowed to drop another 4 db to −124 dbm. At this point the C/N ratio at the AM detector would be 6 db and the full 3-db advantage of double-sideband detection could not be realized. Hence, the S/N ratio at the input to the FM detector would be about 10 db, and this should be near the breaking point of the system. This has been borne out in practice since the telemetry system has been found to break at input levels of −122 to −124 dbm.

As seen from the above discussion, the command and telemetry systems are both workable under just about the same conditions. In the Telstar satellite orbit (maximum range 6500 miles) both systems are operable with 2- to 4-db margin for spin angles between 20 and 120 degrees. To date the spin angle from the Andover station has not been less than 20 degrees, but it has been as high as 165 degrees. At the command and telemetry station at Cape Canaveral the spin angle has been much greater; in fact spin angles very near 180 degrees have been encountered. Under these conditions both the command and telemetry systems were unworkable as expected. The times of these "spin outages" are predictable and can be avoided by appropriate scheduling.

VI. COMMAND SYSTEM

Previous sections stated the purpose of the command system, gave a brief over-all system description, and discussed signal levels and noise performance. We now proceed to a more detailed description of the command system. First the entire system will be given a general description to functionally relate the major portions. This will be followed by still more detailed descriptions of the major blocks.

6.1 *General Description*

The command system employs fifteen different commands as given in Table I. These are listed here as a matter of general interest and for convenience in understanding subsequent sections.

A functional block diagram of the command system is shown in Fig. 6. A command can be originated in the ground station at the telemetry and operating panel or remotely at the ground station control console. The command encoder translates the specific command to a preselected code and sends this code via the ground station command transmitter to the satellite.

Upon initiation of a command, a control signal is sent over one out of 20 lines to the encoding circuit. This signal is translated to an individual 6-bit parallel code consisting of three ones and three zeros.

A decoding circuit converts the code back to a signal suitable for lighting indicators to show that the proper command has been encoded. Thus, when the command button is pressed it lights up, and another group of six indicator lights shows the actual binary code.

The encoder output is also applied to the word assembly and to "parity and lockout" circuits. The word assembly unit transforms the 6-bit parallel word to an 8-bit serial word consisting of a start bit, the 6-bit code, and a guard space. The 8-bit word is applied to the "parity and lockout" circuit where the code is checked for an odd parity of three

TABLE I — COMMANDS

Command	Function
A	turns on TWT filament voltage
B	turns on TWT helix and collector voltages, energizes circuits associated with the communications experiment
C	turns on TWT anode voltage
CC	turns off TWT anode voltage
AA	turns off TWT helix, collector, and filament voltages; de-energizes circuits used in the communications experiment
D	turns on telemetry and radiation experiment circuits
DD	turns off telemetry and radiation experiment circuits
E	turns on current orientation loop
EE	turns off current orientation loop
F	connects telemetry encoder No. 1
FF	connects telemetry encoder No. 2; F and FF also control direction of current through the orientation loop
SS	initiates CC, AA, DD, and EE and disconnects battery and VHF beacon
S	connects battery back into circuit and turns on VHF beacon
T-1	turns off command decoder No. 2 for 15 seconds
T-2	turns off command decoder No. 1 for 15 seconds

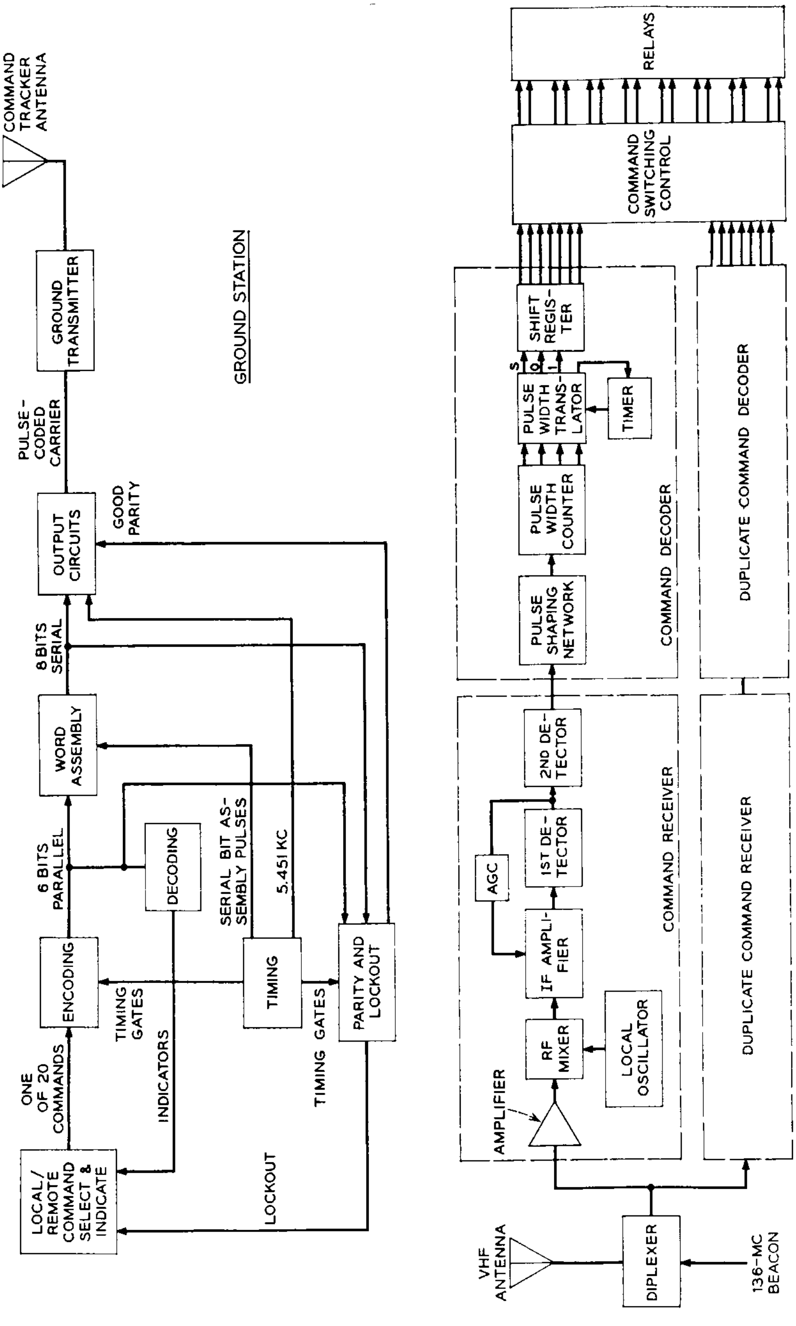

Fig. 6 — Command system block diagram.

ones. If an improper code is detected, a parity relay operates which in turn actuates the lockout circuit. The lockout circuit prevents transmission of the invalid code and selection of a new command until a reset button is depressed.

The word assembly output, if found to be proper, is applied to the output circuit five times in succession. In the output circuit the 8-bit word 100 per cent modulates a 5.451-kc carrier. This amplitude-modulated subcarrier signal is sent to the command transmitter where it 100 per cent amplitude modulates the 123-mc carrier and is then transmitted to the satellite via the quad-helix command tracker antenna.

For reliability, the command portion of the satellite (except for relays) is duplicated and is powered continuously. The two halves of the command system are nearly independent except for some interconnections made to insure proper operations under unusual circumstances. The signal from the diplexer is transformer-coupled to the two command receivers.

The command receiver is of the superheterodyne type and consists of an RF mixer, local oscillator, IF amplifier, AGC, and a two-stage detector. The receiver AGC obviates the need for a variable threshold in the command decoder.

The command receiver output is detected in the shaping network, which has a threshold level fixed at half the average signal amplitude.

The command decoder translates the baseband train of pulses which the receiver has recovered into a pulse on the appropriate one-out-of-fourteen output leads. The decoder consists of a pulse shaping network, pulse width counter, pulse width translator, timer, and shift register.

The one-out-of-fourteen outputs of the decoder are amplified and stretched in the switching units, and the resultant outputs trigger magnetic latching relays. Sensitive magnetic latching relays are employed to conserve power.

To prevent damage to the TWT and the battery of the satellite, a number of safety interlock features are incorporated in the command encoder on the ground and in the switching unit in the satellite.

The TWT anode turn-on (C command) cannot be sent unless three minutes have elapsed since the TWT filament was turned on (A command) and unless telemetry indicates that the filaments are actually on, except when an override push-button is depressed. The override feature is used to permit rapid turn-on of the tube when the 3-minute warm-up time is unnecessary (i.e., if the tube had just been turned off).

Whenever the A relay in the satellite transfers (TWT heater on or TWT off), the B relay (TWT helix and collector) is reset. This obviates the need for a BB command and prevents turning on the TWT helix and collector voltages prior to the TWT heater. The A and C relays are interlocked to assure that the TWT anode voltage (C relay) will be turned off before the heater, helix and collector voltages are removed. These features prevent damage to the TWT.

A low-voltage trigger circuit removes all loads (except for the command system) and disconnects the battery by resetting the S relay. With the S relay reset, the 136-mc beacon is inoperative and no telemetry is available. The S relay reset state also inhibits the commands A, B, and C, thus preventing turn-on of the TWT with low battery voltage. If the S relay is reset by the low-voltage trigger, it cannot be set by a ground command (S) until the low-voltage condition subsides. This safety feature prevents damage to the battery and to the TWT due to a low-voltage condition which, for example, might be caused by leaving the TWT on for an excessive period.

6.2 *Ground Command System*

6.2.1 *Command Encoder*

A detailed diagram of the encoder is shown in Fig. 7. Operation of a command switch momentarily energizes a command select relay. The matrix input register stores this information temporarily until it is transferred (in the form of a parallel 6-bit code) to the matrix output registers. The use of two stores permits a new command to be selected without interfering with the transmission of the previous command.

The heart of the encoder is the crystal oscillator which furnishes the basic 5.451-kc subcarrier frequency to be used for code transmission. All of the encoder timing is generated from this frequency with countdown circuits. To insure proper timing accuracy in the frequency divider circuits, the oscillator output is applied to a Schmitt Trigger circuit

The N/3 countdown circuit of the cycle counter is of the relaxation divider type, whereas the N/2 countdown circuits consist of binary counter stages. The primary and secondary outputs from the final two binary counters, representing the zero and the one respectively of the ternary code, are applied to the logic I unit to obtain the start pulse and the bit duration. The one and zero are also applied to the parity counter gate. A parity count can be taken in AND gates since, as shown in Fig. 8, the coincidence of the eight code (excluding start) with ones and zeros can have three outputs if and only if the code contains only three ones and three zeros. (The parity enable eliminates the start pulse.) The start, zero, and one outputs control the duration of the outputs of the word timing gate.

A three-stage binary bit counter counts out the 8-bit code word, and feeds the logic II gate whose outputs are used for timing and for the

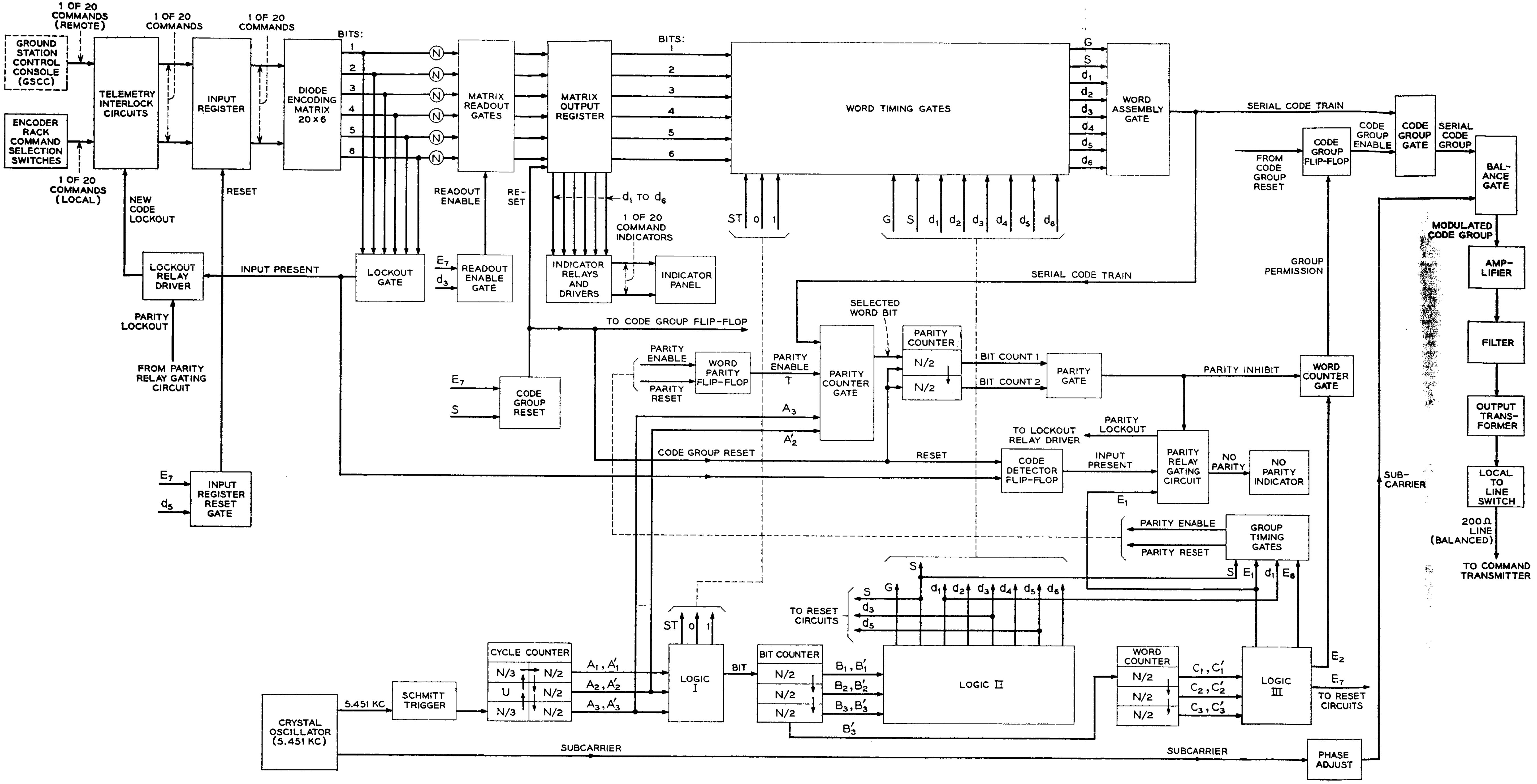

Fig. 7 — Command encoder.

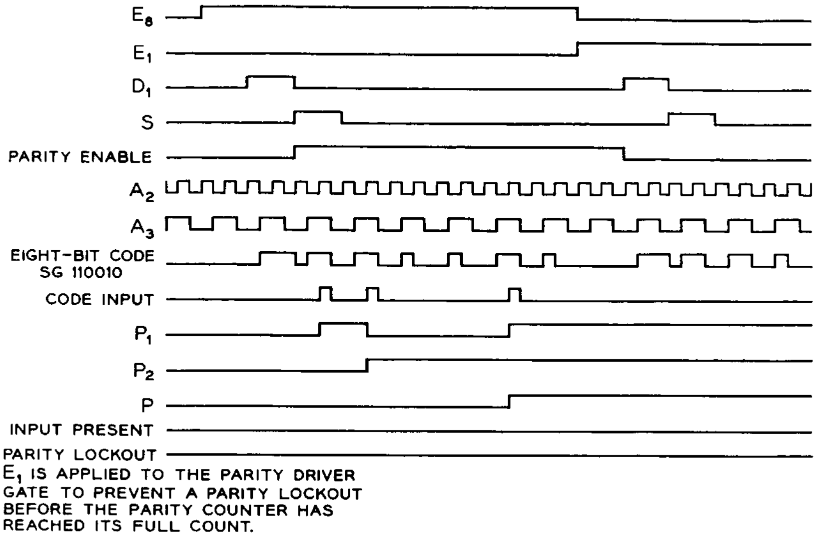

Fig. 8 — Parity count timing sequence.

parallel code to serial code conversion. The output of the third stage of the bit counter feeds the word counter, which in conjunction with logic III permits the code to be generated five times in succession. By the nature of the circuits, a gap of three word intervals follows the generation of the five code groups. Since the timing block of the encoder operates continuously, there can be a delay of about $\frac{1}{2}$ second in transmission of a command if a command is selected just after a word counter cycle has started. Partial code transmission is prevented by the parity and lockout, which can only operate once during a code group (five codes) and is initiated with the third code (dead interval).

6.2.2 *Command Transmitter*

The command transmitter consists of an RF exciter, intermediate power amplifier, modulator, RF power amplifier and an output section. The exciter generates the 123-mc crystal-controlled carrier which drives the intermediate power amplifier. The RF power amplifier then provides the power gain necessary to radiate 200 watts. The output stage is push-pull and is plate-modulated by the signal out of the modulator. The modulator is flat to ±1 db from 200 cps to 10 kc and is capable of providing 100 per cent modulation of the 200-watt output. The output section provides coupling into the load, and matching trimmers and filters. The equipment is housed in two bays and was designed and man-

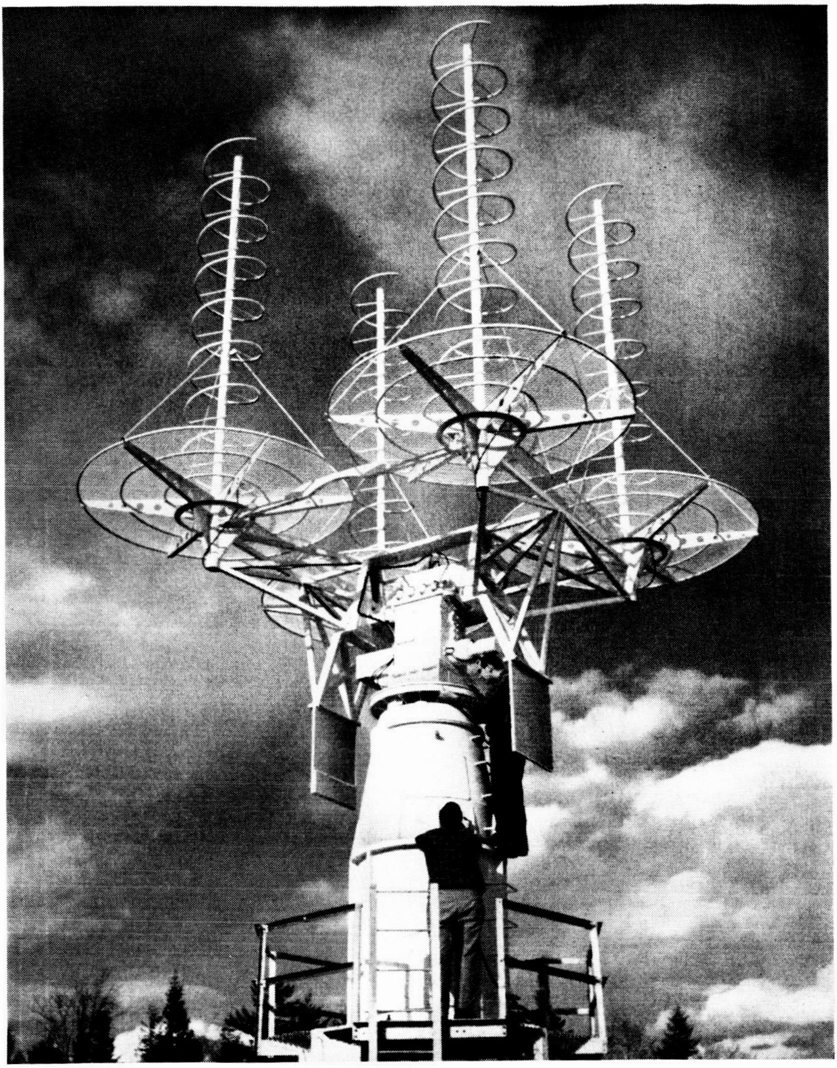

Fig. 9 — Command tracker antenna.

ufactured to Bell Telephone Laboratories specifications by Lockheed Electronics Company, a division of Lockheed Aircraft Corporation.

6.2.3 *Command Tracker Antenna*

The command tracker antenna shown in Fig. 9 is a quad-helix VHF antenna used to transmit the command signals, receive the telemetry signals, and track the VHF beacon. The antenna has full autotrack capabilities, so the command and telemetry operation can be completely independent of other satellite operations. It can, however, serve as an acquisition aid by providing pointing information to other antennas, such as the precision tracker.[4] It uses phase-sensitive monopulse tracking employing a 4-element helix array and giving over-all pointing accuracy of approximately ±1 degree.

As a transmitting antenna (123 mc) it has a gain of 17.5 db with right-hand circular polarization, and its side lobe levels do not exceed -11 db. For receiving at 136 mc, the gain is 19 db and the polarization and side lobe performance are the same as at 123 mc. The command tracker antenna was designed and built to Bell Telephone Laboratories specifications by Radiation, Incorporated, of Melbourne, Florida.

6.3 *Satellite Command System*

6.3.1 *Command Receiver*

Each of the two command receivers consists of an RF section, mixer, local oscillator, amplifier and detector. The two command receivers (See Fig. 10) are transformer coupled to the diplexer. The manner of making the connection places the loads in series, permits the use of ground for all returns, and provides the proper generator impedance for optimum noise figure.

The RF section provides 18 to 20 db of gain at 123 mc and has an over-all bandwidth of 3 mc (3 db points). This section consists of two stages separated by a low-Q parallel tuned circuit while the second stage has connected to its emitter a high-Q tuned series circuit. This combination provides a low over-all noise figure with at least 10 db image frequency rejection. The mixer is a single-stage amplifier employing emitter injection of the local oscillator while the RF signal is applied to the base. The conversion gain of the stage is approximately 4 db and the IF signal is at 5 mc. A temperature-stabilized crystal oscillator followed by two diode doubler circuits provides the local oscillator signal of 128 mc for the mixer.

A 4-stage IF amplifier provides 50-80 db of gain, depending upon the AGC control. AGC control is maintained on the first three IF stages and provides a constant detected output level over a 30 db range of receiver input signals. Primary-tuned interstage coupling transformers provide an IF bandwidth of approximately 50 kc (3 db points), which allows for Doppler shifts and transmitter and receiver frequency drifts.

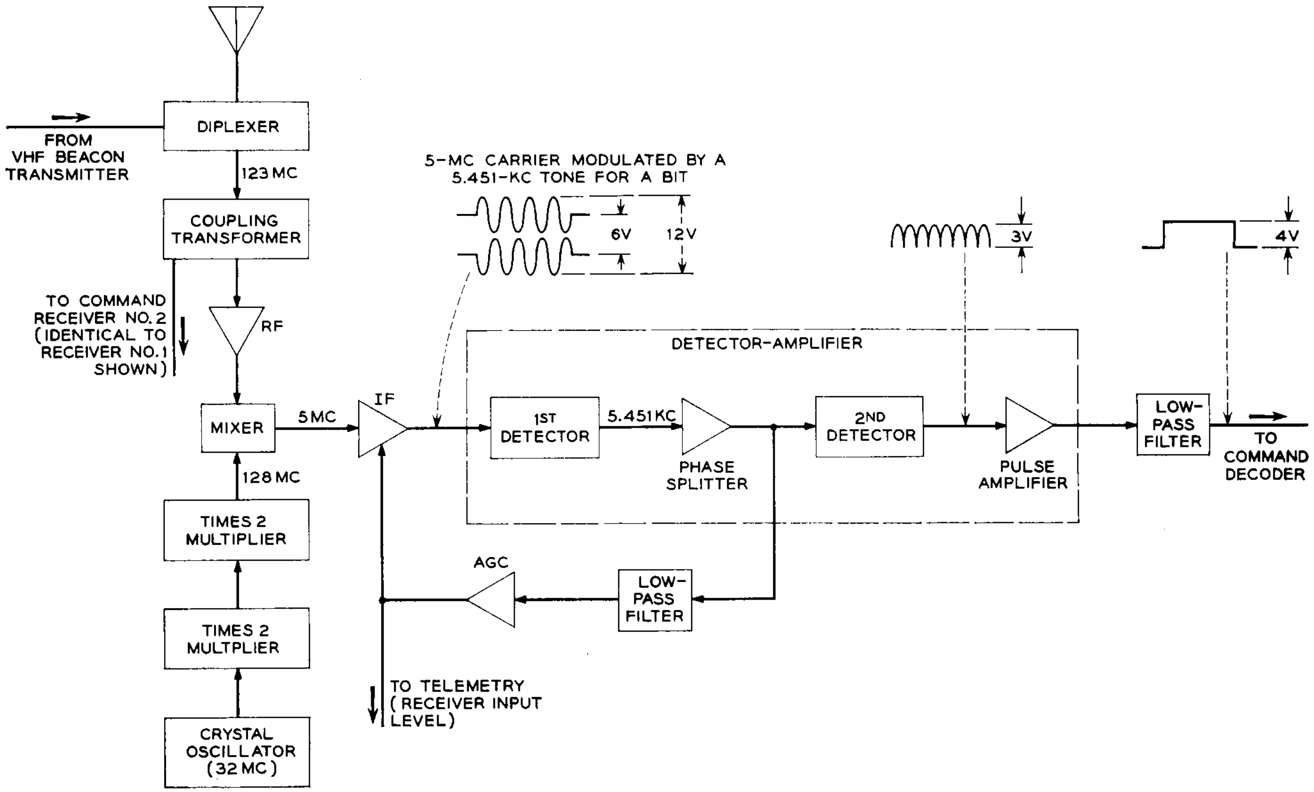

Fig. 10 — Command receiver.

Because of the use of a subcarrier, double detection is necessary. The first detector recovers the 5.451-kc subcarrier. An amplifier supplies a signal to the AGC loop and to the second detector, which consists of a full-wave rectifier followed by an amplifier and a low-pass filter, having a 500-cps cutoff with a 6 db per octave slope. The output signal is a train of pulses having an amplitude between 4 and 4.5 volts and containing less than 1 db of ripple.

6.3.2 *Command Decoder*

A simplified block diagram of the command decoder is shown in Fig. 11 and the timing relationships are shown in Fig. 12. The command receiver output signal is detected in the shaping network. Because the receiver has AGC, the shaping network threshold level is fixed at the average-signal, half-amplitude value. The detected signal permits the gated multivibrator pulse generator to free run for the length of time that the signal exceeds the threshold level. The pulse generator will generate three, two, or one pulse(s) for a start, one, and zero input respectively. The output of the shaping network is also used for readout and reset functions. The pulse width counter and digit gates (zero, one and reset) translate the ternary code to a pulse on one of three output leads. The counter and gates are "reset" by the detected signal. To prevent the inadvertent joining of two code fragments, a consecutive pulse timer controls the one and zero gate outputs. The loss of a word bit resets the timer, thus preventing further one and zero gate outputs. Because of the positive feedback aspects of this circuit, the timer inputs are controlled by the shaping network output.

A detected start pulse at the R gate output is used to reset the flip-flop stores and the digit counter. It also starts the consecutive pulse timer. The combined zero and one outputs drive the digit counter. The digit counter and the counting gates form a series-to-parallel converter for the detected ones. With the inclusion of the flip-flop stores, the combination forms a shift register. The output gates translate the stored binary code to an output pulse on one-of-fourteen leads. To restrict power consumption and to control the output gate readout time, a strobe unit applies power to these gates. The strobe, in turn, is controlled by the digit counter and will generate an output when the digit counter has counted to six. Since the strobe is internally ac coupled, the power to the gates is applied for only a few milliseconds.

To permit disabling of a decoder, the strobe ground can be removed by sending a ground command through its companion decoder. Each decoder can be disabled for approximately 15 seconds by sending the

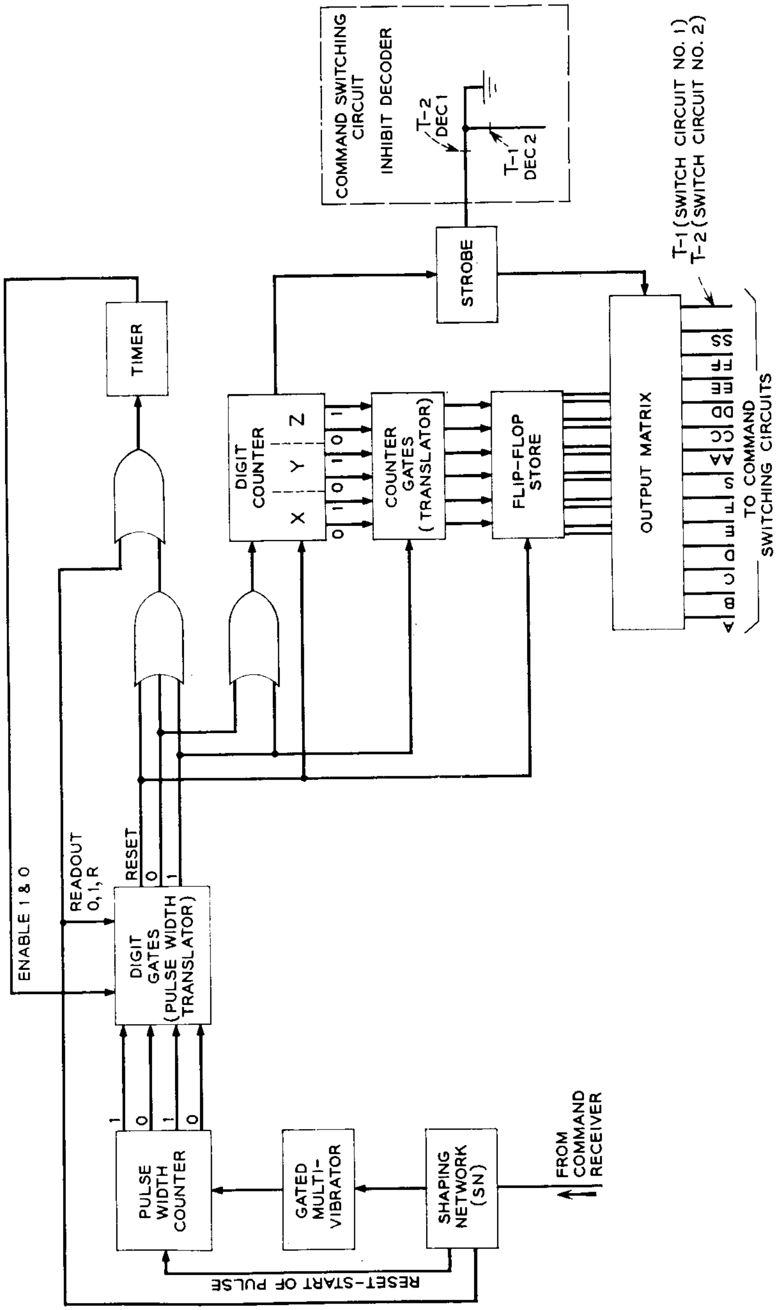

Fig. 11 — Command decoder.

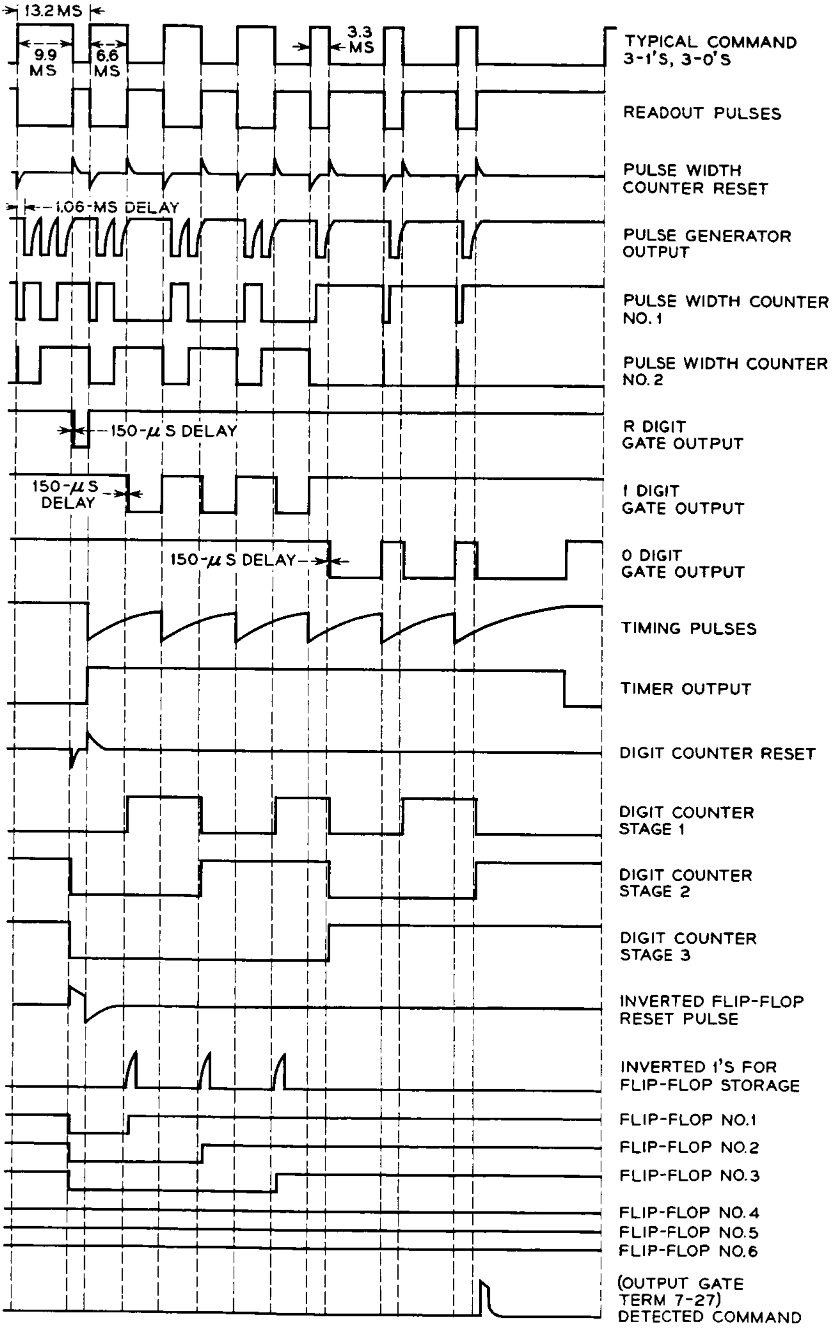

Fig. 12 — Command decoder waveforms.

appropriate (T) command to the other decoder. Thus, if a decoder is detecting a command falsely, it can temporarily be removed from service.

6.3.3 *Command Switching Unit*

The switching unit (Fig. 13) is subdivided into two parts. Each channel performs the same function, thereby providing two separate paths for command execution (except for the T-1 and T-2 commands). Monostable multivibrators provide the necessary amplification and pulse stretching. Driver outputs are combined in OR gates to activate each relay. Single letters designate "set" operations while double letters designate "reset" operations.

As mentioned previously, the S relay is a safety device. Although it can be set and reset by ground command, it can also be reset by the low-voltage trigger circuit. Whenever the battery supply reaches 19.6 volts ± 0.4 volt, the low-voltage trigger circuit responds, thereby triggering the SS driver. Resetting of the S relay resets all other relays except the F (choice of telemetry encoders) and removes ground command control from the A, B, and C relays. The S relay cannot be prematurely reset while the low-voltage condition persists. These features are incorporated to avoid damage to the battery and the TWT.

To avoid permanently disabling the satellite because of failure of a single low-voltage trigger circuit, an override feature is incorporated. The T-1 and T-2 relays inhibit the operation of the SS-2 and SS-1 drivers, respectively, thus permitting the S relay to be set by command during the 15 seconds deactivation of the faulty trigger circuit. Since T-1 and T-2 cannot be transmitted simultaneously, overriding of a legitimate low-voltage condition cannot occur.

VII. TELEMETRY SYSTEM

7.1 *Over-All Description of Telemetry System*

In the satellite, the signals to be telemetered are time multiplexed by sampling gates, encoded into PCM, frequency modulated on a 3-kc subcarrier, amplitude modulated on the 136-mc beacon, and radiated to the earth by the VHF antenna. On the ground, the signal is picked up by the VHF command-tracker antenna, amplified, and amplitude detected; then frequency discriminated to recover the PCM, decoded, and decommutated; and fed to a printout, punch-out, and various displays.

Figs. 14 and 15 show in block diagram form the principal functional

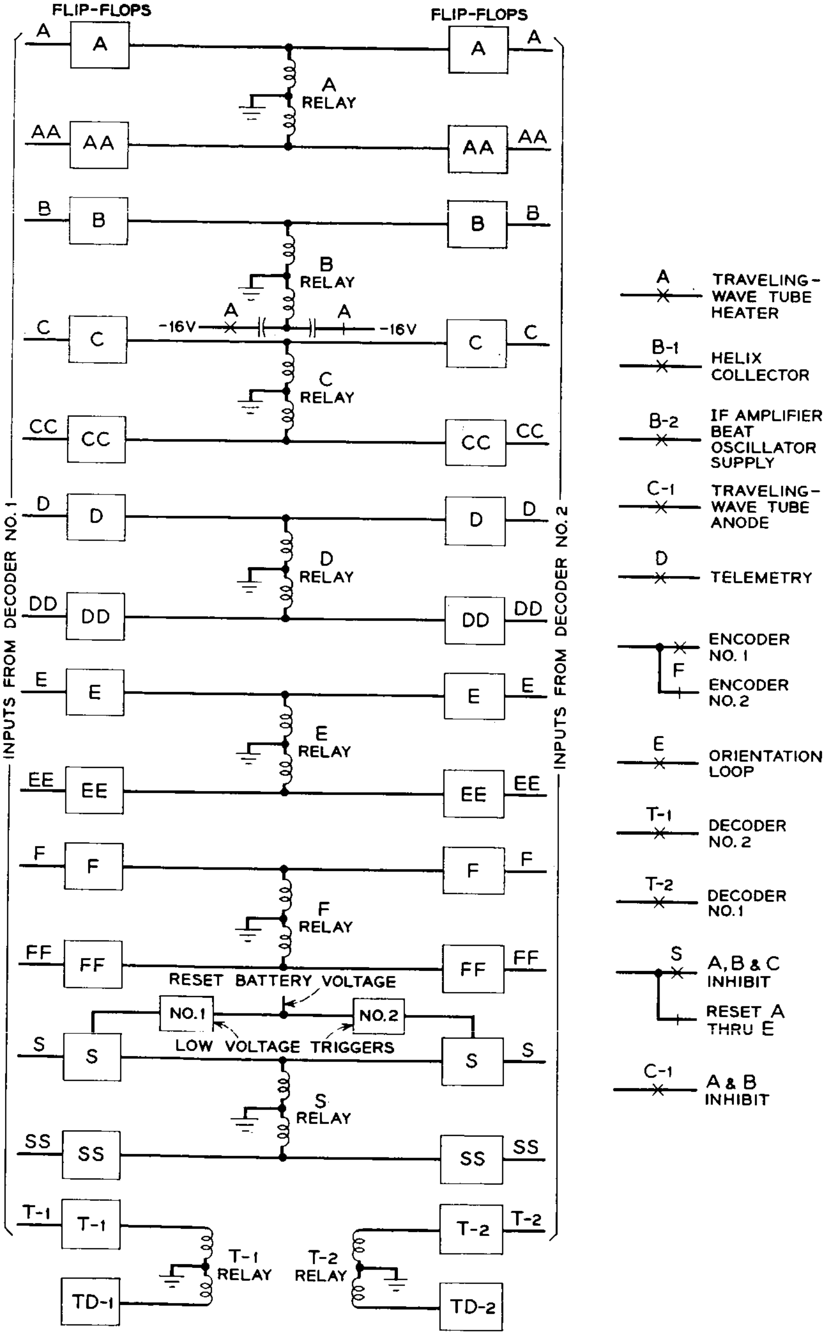

Fig. 13 — Command switching unit.

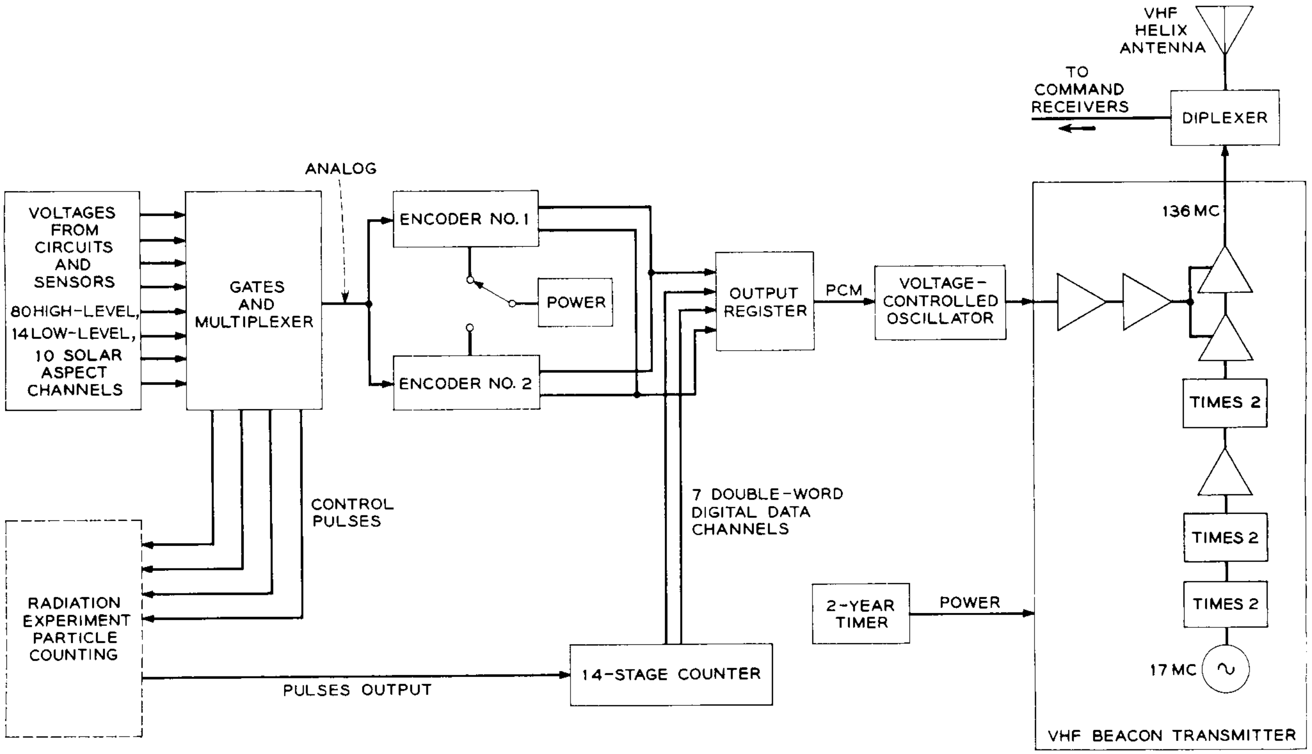

Fig. 14 — Satellite telemetry system.

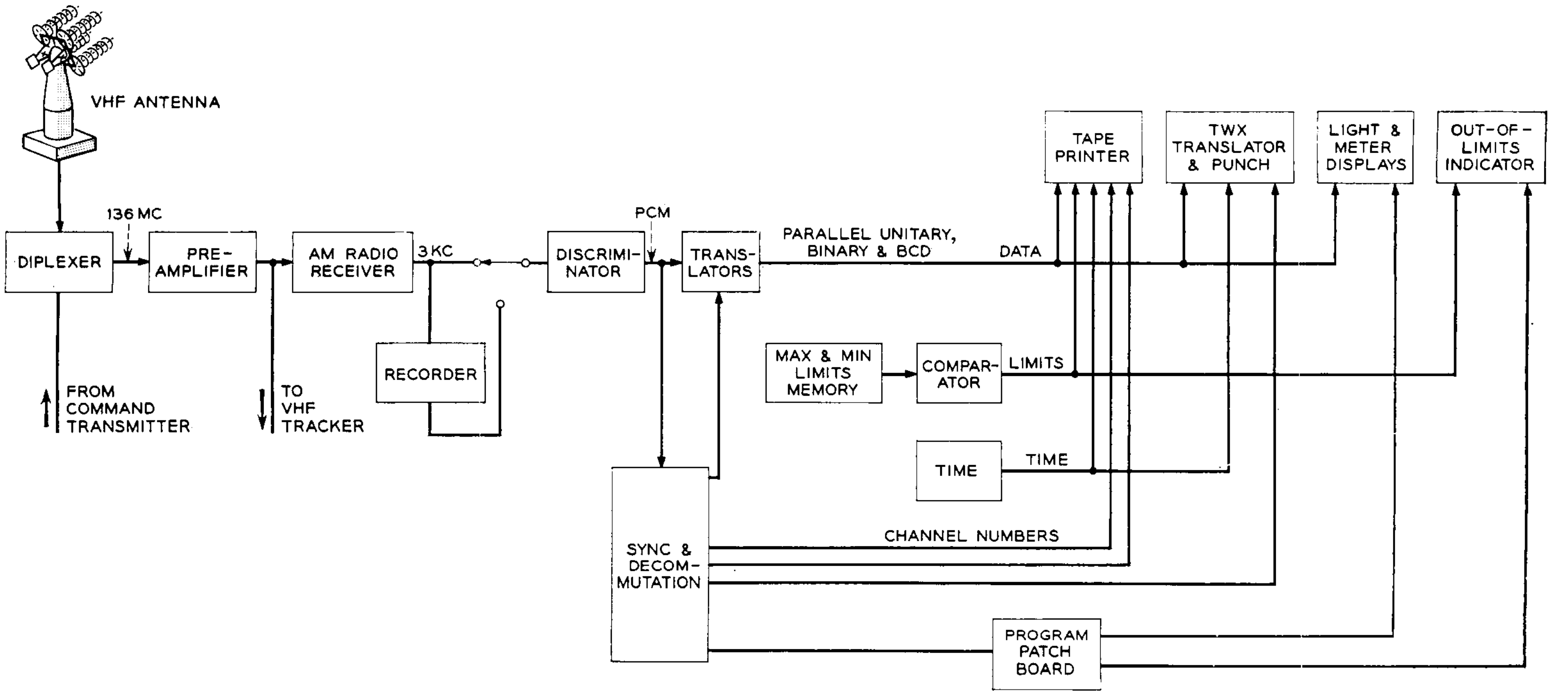

Fig. 15 — Ground telemetry system.

portions of the satellite and ground telemetry systems, respectively. For the satellite system, the portion of the circuit including multiplexer, redundant coders, registers, and voltage-controlled oscillator was developed and constructed for Bell Laboratories by Radiation, Incorporated, of Melbourne, Florida. The ground telemetry, except for the antenna and preamplifiers which are part of the VHF tracker, was supplied by Electro-Mechanical Research, Incorporated, of Sarasota, Florida.

7.2 *Types of Information Telemetered*

The information telemetered falls into several categories as listed in Table II.

The radiation experiment is discussed in detail in another article in this issue.[5] Of the telemetry channels, 16 are used for electron and proton energetic particle counts, 4 for bias of counting detectors, 7 for transistor damage, 4 for solar cell damage, and 6 for solar aspect. In addition to handling the count or measured values of the radiation experiment, the telemetry circuit also provides synchronized pulses for gating on and off the particle-counting circuits and for shifting their thresholds.

Internal temperatures are measured at a number of points in the electronics canister. These are distributed throughout the structure to give both a general temperature picture and to follow certain items of special interest such as battery and traveling-wave tube temperatures. External temperatures are measured at strategic points just under the outer skin and at points associated with the radiation experiment.

TABLE II — TELEMETERED INFORMATION

	Number of Channels
Radiation experiment	37
Internal temperatures	24
External temperatures	16
Microwave circuit	13
Power supply	9
Relay states	4
Command system	6
Canister pressure	2
Calibration	1
Frame synchronization	2
Unassigned	6
Total	120

Various items of the microwave circuit that are monitored via telemetry include the traveling-wave tube accelerator, collector and helix currents, the TWT heater voltage, converter biases, and the IF amplifier AGC. These are of special interest both for the operational control and for the monitoring of performance of the communications repeater. Of the power supply items monitored, perhaps the most important are the solar plant current and the battery voltages. Also monitored are key voltages of the regulator.

Command relay state monitoring is important from an operational standpoint in checking the turn-on and turn-off steps for the traveling-wave tube, the status of the torquing loop, and monitoring the responses to two special commands, T-1 and T-2. Both input and output signals of the command receiver pairs are monitored.

Canister pressure is checked to see whether it is above or below discrete levels of 5 and 1 psia.

7.3 *Types of Telemetry Channels*

To handle the various items to be telemetered, several ranges and types of channels have been employed as listed in Table III.

Where possible, high-level channels were employed. Low-level channels were employed for small signals and differential inputs. The solar aspect channels, in addition to being still more sensitive, are sampled quasi-simultaneously. The digital data channels are for the radiation experiment energetic particle count where the input consists of pulses to be counted. In all cases, the channels are sampled once every minute and converted to binary PCM for transmission.

7.4 *Satellite Telemetry Sending System*

7.4.1 *Sensors*

Except for the so-called digital data channels of the radiation experiment, all the items to be telemetered are first converted to voltages

TABLE III — TYPES OF CHANNELS

Number	Type of Channel	Input
80	High-level	0 to −5 volts analog
14	Low-level	0 to −0.5 volt analog
10	Solar aspect	0 to −0.1 volt analog
14	Digital data (7 pairs)	0 to 16,383 pulses
2	Frame synchronization	

which are subsequently converted to PCM by the encoder. In some cases the analog signal is simply an existing voltage, such as a bias, or a rectified wave, derived directly from the circuit to be monitored. In other cases, transducers or sensors such as thermistors or pressure switches and auxiliary circuits are used to convert the physical quantity to be measured, such as temperature or pressure, to a dc analog signal.

7.4.2 *Multiplexer*

Each analog signal to be telemetered is sampled through sampling gates once every minute and its value encoded into a seven-bit binary code. Channel gates are matched pairs of transistors that are pulsed on in proper channel sequence by transformers of the multiplexer matrix. The 8 × 14 matrix of square-loop magnetic core transformers is driven by horizontal and vertical shift registers and control counters which, in turn, are driven at the word rate. Basic timing at word and bit rate is obtained from a 32-cps oscillator and counters.

In addition to controlling the channel sampling gates, the multiplex matrix also provides timing pulses for the control of the radiation experiment, synchronized with particular word positions. Internal telemetry circuit commands tied to the channel format are also derived from the matrix.

Multiplexing of the solar aspect channels is accomplished by a separate multiplexer operating at high speed in order to effect quasi-simultaneous acquisition of the data. For this, a blocking oscillator, triggered by the main multiplexer, drives a counter and diode matrix which, in turn, drives the transformer-coupled transistor gates.

High-level channel output of the matrix is fed directly to the encoder. Low-level channel output is fed through a 10:1 amplifier and solar aspect channel output is fed through a 50:1 amplifier before going to the encoder. Thus, in all cases, the analog input signals leaving the multiplexer are adjusted to a common 0 to -5 volt range for the encoder to handle.

7.4.3 *Encoders*

To improve reliability, two encoders have been incorporated in the system. Either encoder can be put in operation by ground command (F or FF). The timing circuit oscillators, which are closely linked to the encoders, are also redundant.

For normal high- and low-level channels, each analog signal is sampled once per minute at a rate of one channel each half second. The encoding of each analog signal is accomplished in approximately 50 μsec.

Through consecutive half-amplitude comparisons, the signal is encoded into a 7-bit binary code representing the input signal to an accuracy of ±1 per cent of full scale range for high-level channels and ±2 per cent for low-level channels. Thus, each channel input signal is quantized into a code representing one of 127 levels. The binary-coded information is stored in the output register for readout. A word sync pulse is added at the end of the 7 information slots, resulting in an 8-bit word which is then read out at the normal transmitting rate of 16 bits per second.

To conserve power, the encoders are energized in a pulsed-power mode for approximately 170 μsec during each word time.

For solar aspect and solar cell damage measurement, however, essentially simultaneous sampling of ten channels is required. Practically, this has been accomplished by sampling and encoding all ten of these channels in 1100 μsec, during which time the satellite will have rotated approximately one degree. The ten encoded signals are stored in the output register matrix until they are read out at the uniform output rate of 16 bits per second, or one word per half second.

7.4.4 *Digital Data Channels for Radiation Experiment*

Another article[5] in this issue discusses the radiation experiment particle count circuitry. The telemetry system is linked with that circuitry by supplying to it timed control pulses for turning on and turning off various gates and biases at the appropriate times relative to the telemetry frame progression. The result of this is that the particle experiment pulse groups to be counted and telemetered are time multiplexed into seven different time intervals and are fed to a 14-stage counter. Seven times in the course of each frame, corresponding to the seven digital data channel pairs, the 14-bit digital data counter is read in parallel form into the output register, from which the data are read out sequentially as two adjacent channel words. Each pair of these digital data channels can handle pulse counts ranging from 0 to 16,383.

7.4.5 *Output Register*

The sampling, encoding or counting of channel data takes place at several different rates. In order to transmit it at a uniform rate, an output storage register is used. This register has 10 rows and 7 columns of square loop magnetic cores appropriately interconnected with read-in, set, shift and read-out windings. In all cases the final serial read-out for transmission is taken from the top row (row 10). High-level and low-level data are read into the top row on the completion of encoding. The ten solar aspect channels are read into the bottom row (row 1) one word at a time and shifted upward, filling the register in approximately 1100 μsec. The data are then read out of the top row at the normal read-out rate, shifting the stored words up at word rate. Digital data counts from the 14-bit register are read into rows 8 and 9, which are subsequently shifted up for read-out.

Synchronization information is introduced into the format in the output register. A word sync pulse is added at the end of each group of seven information bit time slots, giving an 8-bit word length in which the most significant bit comes first. Frame synchronization is introduced by putting out an invariant train of pulses in the 16 time slots of the last two word slots of each frame. This pattern of frame sync pulses is read into rows 8 and 9 of the output register by energizing set windings on the appropriate cores. The frame sync words are then shifted up and read out in the normal fashion.

7.4.6 *Voltage-Controlled Oscillator*

The resulting output train of pulses from the output register is sent to the voltage-controlled oscillator (VCO) where it is converted into a frequency modulated signal. The voltage-controlled oscillator is a 3-kc oscillator in which frequency is changed by switching in and out an incremental capacitance in the tank circuit. For a zero bit the frequency stays at 2775 cps for the full one-sixteenth of a second. For a one bit, the frequency is shifted up to 3225 cps for one thirty-second of a second and returned to 2775 cps for the remaining half of the bit time slot.

7.4.7 *VHF Beacon*

The 136-mc beacon has the dual functions of providing a signal for tracking at VHF and serving as the RF carrier for the telemetry 3-kc subcarrier. The beacon can be turned off and on by ground command (S), but it is normally kept on at all times, regardless of the state of telemetry. The beacon will also be shut off automatically if the satellite battery voltage drops below a predetermined low-voltage danger point. Power for the beacon is drawn through contacts of a precision timer which will automatically and irrevocably shut off the VHF beacon at the end of two years. This latter feature is to keep the satellite from indefinitely occupying this spot in the radio frequency spectrum.

The 136-mc frequency is produced by starting with a crystal oscillator at 17 mc and multiplying successively by factors of two. The crystal is a third-overtone AT-cut quartz unit having a ruggedized mount and is used in a Pierce oscillator circuit using the transistor in a common emitter configuration and operating the crystal as a positive reactance at a frequency slightly above series resonance. Initial frequency adjustment was within ±1 part per million. Frequency variation with temperature over the anticipated range is less than $\pm\frac{1}{4}$ part per million, and aging is expected not to exceed 1 part per million.

The oscillator is followed immediately by two stages of doublers in which the transistors in common emitter mode are operated as class C amplifiers into collector tank circuits tuned to the second harmonics. Following this is a buffer amplifier and the last stage of multiplication, in which a transistor with common emitter is operated class C into a second harmonic tuned tank, thus producing the final desired frequency of 136 mc. Next, the power level is raised by a driver stage using a common base transistor. Final amplification is obtained in a power amplifier using a transistor in a common base configuration. All stages of the circuit are transformer coupled.

The frequency modulated 3-kc subcarrier from the telemetry VCO is fed to a driver stage and thence to a power amplifier using a pair of transistors in common emitter push-pull. This signal is fed to the collectors of the driver and power amplifier stages of the beacon, producing 50 per cent modulation of the carrier. The signal is then fed to the diplexer which connects the VHF helix antenna to both the beacon and the command receiver while providing isolation between them. The signal is radiated approximately isotropically and linearly polarized from the antenna at a level of 250 milliwatts.

7.5 *Ground Telemetry Receiving System*

7.5.1 *Antenna and Diplexer*

On the ground, the 136-mc signal is picked up by the command tracker antenna. This is a circularly polarized antenna; hence, effective signal strength is not dependent on the orientation of the linearly polarized wave from the satellite. From the antenna the signal goes to the diplexer which permits the use of the single antenna for simultaneous transmitting and receiving purposes without interference. From there, the incoming signal goes to a preamplifier with a noise figure of 3.5 db. The total effective gain of the ground system to this point, including antenna gain, diplexer, and cable losses, is 18 db.

7.5.2 *Preamplifier, Receiver, Discriminator, and Recorder*

After preamplification, the signal goes from the antenna pedestal to the telemetry radio receiver, which recovers the 3-kc subcarrier by AM detection. The 3-kc signal is then fed to a phaselock discriminator which recovers the original pulse train PCM signal. The subcarrier is also fed to a magnetic tape recorder which serves as a back-up to make possible the recovery of telemetry data at a later time in the event of a failure in the ground system beyond this point. The tape can be played back into the discriminator and processing continued in the normal fashion should this be necessary.

7.5.3 *Synchronizer, Translator, and Decommutator*

From the discriminator, the pulse train goes to the synchronizing, translating, and decommutation equipment. Bit rate, word sync, and frame sync are sought and recovered, synchronizing the rest of the equipment. This takes place automatically, progressing from a search mode to a tentative sync or check mode, to a full sync mode. In the event of loss of sync, the circuit automatically reverts to the next lower mode in order to effect recovery. Adjustable controls permit presetting of sync error rate limits at which this reversion takes place. Thus, if desired, the equipment can, in effect, be programmed to accept limited numbers of errors and tide synchronization over temporary fading or interference. After synchronization, the signal is decoded or translated into forms suitable for the several read-out options. Channel numbers are generated in step with the data, and strobing pulses are made available to decommutate the data into selected channel readouts.

7.5.4 *Print-out*

All channels are printed out sequentially with data and corresponding channel number by a Hewlett Packard tape printer. Time is also printed on this record at the spot where the frame sync words would appear (channels 119 and 120). The data read-out is virtually a real time read-out, being delayed by approximately one and one-half seconds. It serves as the primary source of information on all channels.

7.5.5 *Data Limits*

When a channel value is either above or below preset limit values, an out-of-limits mark is printed next to the data. Both maximum and minimum limit values can be set up in a plug board memory for each of the 118 channels individually. The values are set in binary code with plug-in diodes.

7.5.6 *Teletypewriter Punch*

All channel values are also punched in teletypewriter tape, along with appropriate format information to give a page print-out. The teletypewriter tape can be read out and transmitted to other locations either immediately or at a later time.

7.5.7 *Light and Meter Displays*

In addition to the all-channels printed displays, there are also a limited number of binary light displays, analog meter displays, and decimal light displays which can be connected to any of the channels. The choice of channels to be displayed is set up on a program patch board. Out-of-limits relays for remote indicators and command interlock are also connected to the desired channels by means of this program board.

7.5.8 *Operational Considerations*

In the normal mode of operation, the numeric print-out tape is used by an operator to monitor all channels. Commands are marked on the tape at the channel times corresponding to their transmittal by the operator. Remote indicators at the ground station console display the states of the TWT (A, B and C commands) relays as deduced by telemetry. Operating decisions are made with the help of telemetry data thus supplied.

In addition to the VHF ground facilities at the Andover, Maine, station the command and telemetry ground equipment is duplicated at the Bell Laboratories station at Cape Canaveral. The Cape facilities were, of course, used for prelaunch and launch operations and are now used for monitoring of passes. A third telemetry bay, located in New Jersey, was used for satellite manufacturing testing. This bay has modifications which permit it to decommutate magnetic tape recordings at speeds four and eight times real time, and this facility is used to process telemetry subcarrier recordings made by Minitrack stations.

By means of audio tie-lines and teletypewriter lines, the telemetry facilities at these three locations may be interconnected in various ways to provide mutual back-up.

7.6 *Performance*

The telemetry system has been used in the satellites at all stages of its life: during manufacturing tests, launch operations, and in orbit. Thus far, it has been performing normally and is supplying the desired data.

VIII. ACKNOWLEDGMENTS

As is usual on a project of this magnitude, the work represents the combined efforts of a large number of people, with key roles played by so many as to make individual listings difficult. The authors of this article have been fortunate in being a part of the team and wish to thank all who have had any part in making this work successful.

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