A Delayed-Repeater Satellite Communication System of Advanced Design*

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Summary—This paper describes a delayed-repeater satellite communications system consisting of an orbiting delayed-repeater radio-relay station which passes over terminal ground stations located within the viewing area of the satellite.

Messages are exchanged between the satellite and a ground station operating in the 2-kmc band utilizing both polarization and frequency diversity techniques to provide a continuous transmission circuit regardless of the satellite attitude.

Data storage in the satellite is accomplished by the use of newly-developed magnetic tape recorders.

Signals in the band near 108 mc provide telemetry and command control functions. The telemetry used is a modified standard FM/FM system, while the command control circuit enables selection of satellite control functions. Power for the satellite electronics is derived from solar energy using solar cells which charge nickel-cadmium batteries.

Each of the ground stations consists of radio transmitting and receiving equipment and an automatic-tracking 28-foot-diameter parabolic antenna. Each station will acquire the satellite and track it during a pass over a station. Data from the satellite are transmitted (tape loading) to the ground station upon command. Simultaneously, data for the other two stations are transmitted to the satellite (tape unloading) from the ground station. Message sorting in the satellite is accomplished by use of the appropriate tape recorders, which in turn are activated by ground commands.

In the ground stations, teletype messages on paper tape are converted to a serial pulse train at a 50-kilobit-per-second rate by a paper-tape reader and a magnetic recorder-reproducer. This message-train frequency modulates a 1-kw UHF transmitter and is transmitted to the satellite where the information is deposited.

A quadruple-diversity UHF receiving system using low-noise parametric preamplifiers is used to receive the down-traffic from the satellite. The 100-watt VHF ground transmitter provides for the transmission of initial commands to the satellite and a phase lock VHF receiver on the ground provides for beacon acquisition and telemetry reception.

I. Introduction

On December 18, 1958, a new era of radio communication began with the Atlas launching of the U. S. Army Signal Research and Development Laboratory Project SCORE[1] satellite payload. For the following two-week period, teletype and voice traffic were transmitted by ground stations to the satellite, stored there, and later retransmitted to earth. Through the use of a rudimentary satellite-borne radio relay station employing tape-recorder memory and four companion ground stations, communication was begun by means of delayed-repeater satellite intermediaries. This project represented the first step of an evolutionary program to develop communication satellite systems for use by the military services. This paper describes the form that one type of an advanced design of satellite communication system might take, using the delayed-repeater technique.

II. System Concept and Parameters

The use of earth-orbiting satellites as delayed-repeater radio stations which receive, store, and retransmit messages has been the subject of considerable study by various groups and individuals, since the operational application of these devices offers attractive means of overcoming present-day circuit congestion on existing world communication networks. One needs only to review present and projected traffic growth patterns of current systems to appreciate fully the impact of satellite communication systems on future communication net planning and the promise held forth by future satellite-supplemented global communication networks.

The interrelation of the ground-station locations, communication service areas, and duration and frequency of service is illustrated by the following discussion.[2] An equatorial radio-relay station orbiting at 300 miles above the earth provides 11 minutes of possible communication to ground stations located on the equator once every 95 minutes. Service can also be provided to stations less than 1500 miles north or south of the equator with the same frequency but with diminished communication time. The same satellite orbiting in a plane which intersects the equatorial plane at an angle of 50° can provide communication over a much larger global surface. However, the frequency of service between the equatorial stations is reduced to approximately two or three satellite "passes" every twelve hours.

Considering any probable deployment of ground stations and choice of orbit altitude, a variation in slant range from 100 to 3300 statute miles between a ground station and the satellite has been used as a criterion for system design. The satellite would accommodate five ground stations and not require attitude stabilization. Table I summarizes the salient system parameters prescribed for the purposes of this paper; carrier-to-noise ratio calculations follow, based on these parameters and on others mentioned below for all of the radio links required in such a system. These computations do not include allowances for fading but do allow for equipment degradation over an assumed one-year period of operation.

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[1] S. P. Brown, M. I. Davis, H. C. Hawkins, and G. P. Senn, "The ATLAS-SCORE communication system," *Proc. Natl. Conv. on Military Electronics*, Washington, D. C., June, 1959, pp. 401–409.

[2] For a more comprehensive discussion, see, for example, J. R. Pierce and R. Kompfner, "Transoceanic communication by means of satellites," Proc. IRE, vol. 47, pp. 372–380; March, 1959.

A. List of Symbols and Units

C/N = carrier-to-noise ratio at receiver in db
B = bandwidth in mc
d = slant range in statute miles = 3300 miles maximum
f = frequency in mc = 130 and 1800 mc for calculations shown below
G_r = receiving antenna gain in db
G_t = transmitting antenna gain in db
L_a = antenna polarization loss in db
L_{du} = duplexer loss in db
L_{di} = diplexer loss in db
L_t = tracking loss in db
L_T = total RF plumbing loss between antenna and parametric-amplifier terminals
L_x = cable and rotary joint loss in db
NF = noise figure in db
P_n = noise power in dbw
P_r = received carrier power in dbw
P_t = transmitted carrier power in dbw
T_a = antenna temperature in °K
T_e = effective receiving system temperature in °K
T_r = effective receiver temperature in °K
K = Boltzmann's Constant $= 1.38 \times 10^{-23}$ watt-second/°K

B. Ground-to-Satellite VHF Link

$$P_r = P_t + G_t + G_r - 37 - 20 \log f - L_{di} - L_a - 20 \log d$$
$$P_r = 18.5 + 19 - 4 - 37 - 70 - 42 - 0.5 - 3 = -119 \text{ dbw}$$
$$P_n = -144 + 10 \log B + NF$$
$$P_n = -144 - 15 + 8 = -151 \text{ dbw}$$
$$C/N = -119 + 151 = 32 \text{ db}$$

TABLE I

SYSTEM PARAMETERS

Frequencies:	1.7–2.3 kmc and 108–150 mc
Effective message transmission rate:	50,000 bits/second
Satellite storage:	15,000,000 bits/station
Stations accommodated:	5 maximum

UHF CIRCUITS

	Satellite	Ground Station
Power output	8 watts	850 watts
Noise figure	14 db	—
Noise temperature	—	640°K
IF bandwidth	550 kc	100, 200 or 500 kc
Antenna gain	−4 db	41 db
Antenna polarization	linear	circular transmission, diversity reception

VHF CIRCUITS

	Satellite	Ground Station
Standby power output	50 mw	—
Active power output	1.5 watts	85 watts
Noise figure	8 db	4 db
Standby IF bandwidth	30 kc	1 kc
Active IF bandwidth	30 kc	6 kc
Antenna gain	−4 db	19 db
Antenna polarization	circular	linear transmission, diversity reception

C. Satellite-to-Ground VHF Link—Beacon Mode[3]

$$P_r = P_t + G_t + G_r - 37 - 20 \log d - 20 \log f - L_x - L_{du} - L_a$$
$$P_r = -13 - 4 + 19 - 37 - 70 - 42 - 1.5 - 0.2 - 3 = -152 \text{ dbw}$$
$$P_n = -144 + 10 \log B + NF$$
$$P_n = -144 - 30 + 4 = -170 \text{ dbw}$$
$$C/N = -152 + 170 = 18 \text{ db}$$

D. Satellite-to-Ground VHF Link—Active Mode[3]

$$P_r = P_t + G_t + G_r - 37 - 20 \log d - 20 \log f - L_x - L_{du} - L_a$$
$$P_r = 1.8 - 4 + 19 - 37 - 70 - 42 - 1.5 - 0.2 - 3 = -137 \text{ dbw}$$
$$P_n = -144 + 10 \log B + NF$$
$$P_n = -144 - 22.2 + 4 = -162 \text{ dbw}$$
$$C/N = -138 + 162 = 25 \text{ db}$$

E. Satellite-to-Ground UHF Link

$$P_r = P_t + G_t + G_r - 37 - 20 \log d - 20 \log f - L_x - L_{du} - L_t$$
$$P_r = 9 - 4 + 41 - 37 - 70 - 65 - 1.5 - 0.2 - 0.5 - 1 = -129 \text{ dbw}$$
$$P_n = KT_eB$$
where $T_e = T_a + (L_t - 1)\ 290 + L_t T_r$
$$T_e = 130 + (1.74 - 1)290 + 1.74(170) = 640\text{°K}$$
$$P_n = -168.6 + 28.1 - 10 = -151 \text{ dbw}$$
$$C/N = -129 + 151 = 22 \text{ db}$$

F. Ground-to-Satellite UHF Link

$$P_r = P_t + G_t + G_r - 37 - 20 \log d - 20 \log f - L_{di} - L_t - L_a$$
$$P_r = 28.5 + 41 - 4 - 37 - 70 - 65 - 1 - 1 - 3 = -112 \text{ dbw}$$
$$P_n = -144 + 10 \log B + NF$$
$$P_n = -144 - 3 + 14 = -133 \text{ dbw}$$
$$C/N = -112 + 133 = 21 \text{ db}$$

These calculations indicate reasonably strong signal paths at the worst case of 3300 miles slant range.

The system includes ground-station complexes which simultaneously perform the tracking, data-exchange, and telemetry functions in conjunction with the space-borne radio relay station. The tape recorders aboard the satellite store messages from the ground stations, and (upon command) the satellite retransmits the messages to provide communication to another ground station once acquisition is accomplished and the UHF and VHF links are established. In an exchange of messages between the satellite and a ground station, the data stored on magnetic tapes are transmitted to the satellite serially at an effective 50 kilobit-per-second rate and stored by the satellite tape recorders assigned to other ground stations. Readout of data from the satellite is accomplished (upon command) simultaneously with the transmission of data to the satellite. A combination of frequency-diversity transmission

[3] This calculation assumes a satellite attitude in which polarization is 45° displaced between antennas.

from the satellite and polarization-diversity reception by the ground station is used to reduce errors in delivered messages caused by signal fading. A combined output of both diversity systems is derived to feed the ground-station message-recovery equipment. Tracking and acquisition of the satellite are accomplished by the 28-foot dual-feed tracking antenna. Concentric beams at approximately 130 and 1800 mc are generated by the antenna system in such a manner as to provide E and H plane outputs for both of these bands.

The 18° VHF beam of the antenna is used for beacon acquisition. The "up" and "down" circuits as well as automatic tracking are established via the one-degree microwave beam. During a typical satellite "pass" over a ground station, initial contact is made by the reception of signals transmitted from the beacon operating in its "standby" mode of operation. The ground station then commands the satellite to become active. Sector scanning of the antenna is initiated upon reception of a command acknowledgement that the satellite has switched to the "active" mode during which the satellite's microwave transmitters are activated. As the satellite rises through the plane formed by sector scanning the one-degree ground antenna beam, the antenna automatically locks on the satellite signal when the received signal exceeds the threshold level. This signal is received at the ground station by low-noise high-gain parametric front-end receivers which provide the sensing signals for the automatic tracking antenna servo-drive system. The conical scan system used to derive the azimuth and elevation error signals is provided by a rotating RF lens ahead of the microwave feed. Automatic coast features are built into the antenna tracking circuits to minimize the problems of re-acquisition should this be required during a message exchange with a ground station. Establishment of the up and down microwave circuits, as well as the telemetry VHF link, is required to accomplish properly a message exchange during a "pass." If both ground-to-satellite links are disrupted after acquisition for a period greater than 20 seconds, the satellite will revert to its "standby," low-power mode of operation, and the re-acquisition of the satellite is required. Approximately, three minutes are expended for acquisition, equipment-warmup time, and operational dead time.

The condition of the satellite batteries, which are charged by solar cells, is an essential parameter which must be determined after acquisition and prior to a message exchange. This is available over the telemetry link, and the possibility of a data exchange is dependent on this parameter. Further solar charging is required before a message exchange can be accomplished if the battery charge is too low. The solar charging cycle is dependent on orbit considerations. This system requires charging during approximately 60 per cent of the total orbit time to provide 44 watts of instantaneous power from a 19,000-cell solar generator aboard the satellite. The satellite power supply furnishes approximately 600 watt-hours of energy per day, based on 10 per cent losses caused by micro-meteorite erosion after one year and 15 per cent by solar cell mismatch to batteries, 80 per cent battery efficiency, and solar cell illumination 60 per cent of orbit time. For a duty cycle of 10 per cent (2.4 hours per day), an average of 250 watts are available from the power supply during active periods. Peak loads during a data-exchange cycle plus the power required during standby and acquisition time are estimated to average only 225 watts over the active periods.

Fig. 1 shows the sequence of events during a typical satellite acquisition. Initial acquisition of the satellite is achieved by manual tracking of the signal received by a ground station from the VHF beacon transmitter operating at a 50-mw level. Messages at a ground station are stored on magnetic tapes which have sufficient capacity for a five-minute transmission to the satellite. During this period, data are transmitted over the UHF up circuit at a rate of 55 kilobits per second. A total of 16.5 megabits is capable of being transmitted during this period, but dead time in data processing reduces the total to approximately 15 megabits. In order to exchange this data on sequential orbit passes, the ground tape recorders must be reloaded between "passes." The message-processing equipment that would be required at a ground station would depend upon the communication service to be provided. This would be more or less conventional equipment and is not particularly perinent to the satellite relay system design.

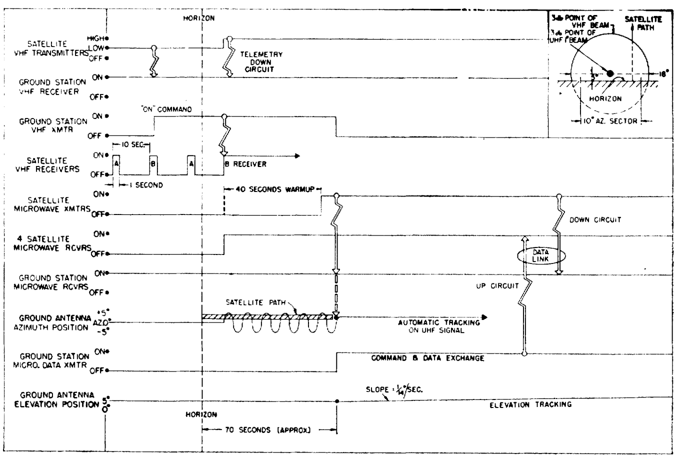

Fig. 1—Satellite acquisition sequence chart.

Telemetry of satellite parameters to the ground station prior to and during message exchange is accomplished over the VHF down circuit. Seven subcarriers are used in an FM/FM System. Commutation on the subcarriers is required to accommodate all telemetry data. Each channel is time-sequenced to provide three seconds for positive calibration, one second for negative calibration, and two seconds for each of five parameters.

Data received from the ground station are stored in the satellite on magnetic-tape recorder reproducers. A storage unit is assigned to each ground station with provision for switching in either of two spare storage units. A simultaneous recording and reproducing capability during a pass is possible because of this manner of assignment of storage units and the fact that only one ground station is in contact with the satellite at one time.

To provide a continuous circuit on the microwave data link, a tracking capability is required in the ground antenna system. The satellite elevation velocity on a zenith pass is in the order of 0.06° per second at the horizon. For a five-degree screening angle, the elevation velocity increases to approximately 0.08° per second, as it comes into line-of-sight with a ground station. This elevation rate is compatible with the automatic acquisition features of the antenna system, since the 3° per second sector scan rate provides approximately six opportunities to intercept and lock on the transmitted satellite signal. Angular error data for the servo drive system are derived from the conical scan modulation on the UHF down signal which is preserved in the ground station receiver and phase-referenced with a reference source. Severe tracking accuracy requirements are not imposed, except for restriction of off-target limits of the tracking beam to minimize the "down" circuit amplitude variations caused by tracking errors to 1 db or less.

The above paragraphs have given a description of an advanced delayed repeater satellite communication concept. However, the reader has probably noticed the minimizing of "art-advancing" techniques within this concept. The operational parameters chosen for the system, particularly satellite parameters, were selected with ease of attainment and an evolutionary advance over the SCORE experimental system as key considerations. A short discussion of some of the more challenging system-design aspects follows.

A collateral choice of operating frequency and satellite size places severe limitations on methods of establishing message circuit continuity regardless of satellite attitude. The operating frequency was selected in the 2-kmc region because of noise, propagation, and component considerations. Since the satellite is a sphere limited in size by assumed vehicle considerations, this combination of conditions rules out any known method of getting the required omnidirectional coverage from a single antenna array. The solution to the problem is the use of antenna apertures capable of providing hemispherical coverage when mounted on the sphere, and the non-phase-coherent use of these apertures. This arrangement provides a satellite radiation pattern which is linearly polarized in random orientations, depending upon the particular satellite orientation existing at any instant. Described more fully in subsequent paragraphs, this method is employed in conjunction with ground-station circular-polarization transmission and quadruple-diversity reception. The frequency and polarization diversity techniques used in the ground receiver, which employs low-noise parametric amplifier front ends, ensure the continuity of the message circuit and minimize the message-error rate.

Use of a 28-foot diameter parabolic antenna at frequencies in the 2-kmc region results in a beamwidth of one degree. Acquisition of the satellite with an antenna beam of this size requires accurate ephemeris data or some other mode of assistance. The evolved acquisition technique permits the system to operate independent of externally-supplied tracking data. Frequencies in the 108-150-mc band were chosen for the VHF links based on the availability of completely transistorized satellite receivers and transmitters in that band. The VHF ground antenna beamwidth of approximately 19° is more than adequate for implementing the acquisition procedure.

Frequency modulation is used throughout the system because it appears to offer the best compromise among equipment simplicity, reliability, and circuit performance. Modulation indexes approximating unity are used in all circuits. The use of FM techniques minimizes the satellite power needed to produce a baseband signal-to-noise ratio of approximately 20 db in the ground stations and allows the use of existing equipment and techniques. Ground station receivers incorporate AFC circuitry; and, accordingly, IF bandwidths are predicated only on the anticipated received signal spectrum and AFC signal centering characteristics. Satellite receivers do not employ afc circuitry and; hence, the IF bandwidths of these receivers include allowances for receiver and ground transmitter drift, Doppler shift, and the anticipated received signal spectrum.

III. Satellite Design

To accomplish its primary mission, the satellite must be capable of transmitting, receiving, and storing ground-originated messages. In support of this mission, the satellite transmits a beacon signal, telemeters internal data to the ground station, implements valid commands, and acknowledges commands. Fig. 2 is a simplified block diagram of the satellite system.

Physically, the satellite would be spherical with a solar-cell surface density of approximately 70 per cent. The solar cells, which are shingled together with a special ad-

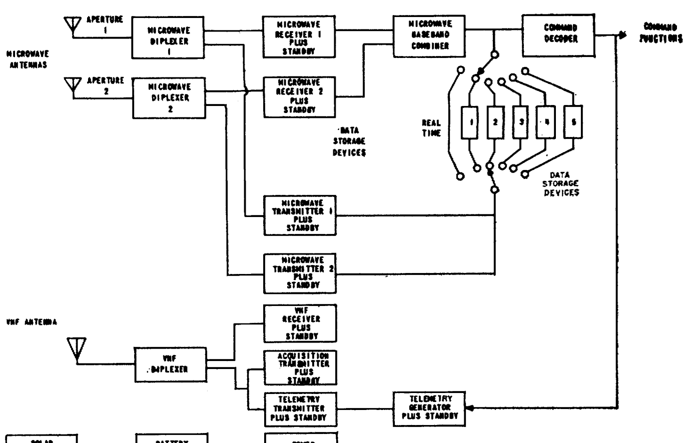

Fig. 2—Satellite, block diagram.

hesive and mounted on the satellite in modules, number about 19,000. Four VHF antenna assemblies are equally spaced around the satellite's equator. Each assembly consists of a probe extending beyond the outer surface of the satellite and containing a flexible section to permit folding when the satellite is placed in its shroud. Two UHF slot antennas, both of which are mounted to ground planes fabricated in a single structure from sheet magnesium alloy, are located at antipodean points on the satellite equator. To provide a uniform reflective area, all solar cells are mounted outside the reflective ground plane areas. Shell material consists of honeycomb fiberglass sandwiched between two thin fiberglass layers, with a conducting metal surface sprayed on the fiberglass but covered with another fiberglass layer. The inner structure, composed of platforms mounted on aluminum-tubing truss members, supports the various components in the satellite. The platforms are also made of the above-mentioned sandwich material to effect an over-all weight reduction without reducing the strength of the structure.

The UHF antenna apertures, one of which is shown in Fig. 3, provide continuous coverage through a solid angle exceeding a hemisphere. At no point within the hemisphere is the response poorer than 4 db below an isotropic radiator. The method of achieving spherical coverage is through a non-phase-coherent employment of the aperture pair. Separate UHF receivers detect signals present at each aperture, while separate transmitters operating on frequencies spaced approximately one per cent apart broadcast from each aperture. Received intelligence is combined at baseband, and transmitted intelligence is fed jointly to both transmitter modulators.

Each UHF slot antenna is fed by a coaxial-line probe which bridges the gap formed by the walls of the notch. As a transmission-line element, the antenna may be regarded as a tapped quarter-wave line used to transform the radiation resistance appearing at the apex of the fin to that of the coaxial line. From the standpoint of the radiation pattern, the antenna is a half-wave slot cut in a

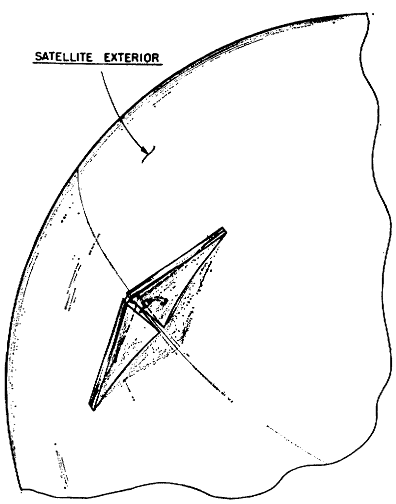

Fig. 3—Linearly polarized antenna.

ground screen which is then folded up into a fin with the E-plane center line of the slot becoming the apex of the fin. This results in broadening the H-plane pattern without affecting the already sufficiently broad coverage of the E-plane pattern.

Simultaneous use of the antenna apertures with companion transmitting and receiving apparatus is accomplished through the use of a pair of microwave diplexers. These diplexers provide antenna-to-receiver and antenna-to-transmitter insertion losses of under 1 db, decoupling loss between the transmitter and receiver of greater than 50 db, and transmitter-to-antenna isolation at the receiver frequency of approximately 20 db.

The primary and standby UHF receivers indicated in Fig. 2 are operated simultaneously during the satellite's active intervals. This method of operation sacrifices 3 db of received RF signal when contrasted to a system capable of switching between the primary and standby units. However, it enhances the reliability of the satellite design. Each UHF receiver is a single-conversion superheterodyne receiver employing a three-pole passive preselector, second harmonic mixing, and 30-mc IF amplification. These completely transisitorized receivers have the following characteristics:

Noise figure	14 db
IF bandwidth	550 kc
Frequency stability	0.002 per cent
Spurious rejection	> 50 db
Power consumption	1.5 watts
Volume	200 cubic inches

Baseband combination of the four microwave receiver outputs is accomplished in a separate completely transistorized unit. Through the use of circuitry that senses out-of-band noise power, each receiver's contribution to the composite output is varied to optimize the baseband signal-to-noise ratio. Since the use of out-of-band noise as a combining criterion does not permit distinction between receiving a very strong signal and a defective receiver, a ground-originated pilot tone is employed as a fail-safe feature. Any receiver that produces an unacceptable pilot-tone output is automatically removed from the combining circuit. In addition to serving its prime mission, the baseband combiner implements other functions within the satellite. These include providing an analog voltage for a telemetry sensor which is used to allow the monitoring of received-signal strength, and output potentials used to control automatic operation of the command decoder.

The combiner message output is routed to the data-storage devices or the real-time circuit as commanded from the ground station. A portion of this output is also used in the command decoder. Message storage is accomplished through the use of five miniature magnetic tape recorder-reproducer machines. Each machine is capable of recording and reproducing up to five minutes of analog data. A shuttle transport design with a tape speed of 30 inches per second provides opposite-direction recording and playback. While this causes traffic to be read out backwards, it does enable some equalization of phase distortions produced by the recording and playback heads. Erasure of old traffic is accomplished by an erase oscillator circuit that functions during the recording cycle with sufficient effectiveness to assure a 35-db signal-to-noise ratio. Life tests of the magnetic tape employed indicate a high confidence factor for one year of trouble-free operation at duty cycles up to ten per cent. To enhance further the reliability and to minimize driving power, the transport construction employs a constant-tension spring system between the play-out and the take-up reels.

Real-time operation bypasses the tape-recorder data-storage units with a circuit that couples the baseband combiner output to the UHF transmitter modulators. A special circuit designed to suppress the rebroadcasting of commands is placed in this circuit. The purpose of including a real-time capability is to facilitate propagation tests and checkout of the communication link prior to data transmission. It is also used to effect a form of fail-safe satellite operation. Command decoder logic places the satellite in its real-time operational mode upon acquisition. Therefore, if the satellite has not failed in a manner that precludes acquisition, the probability of achieving at least real-time operation is extremely high.

Four microwave transmitters, two primary units, and two backup units generate RF signal outputs for the satellite-to-ground data link. Used in pairs, these units are depended upon for at least 8 watts of output power and are selected by ground station command. In this transmitter design, microwave power is generated by a cavity oscillator equipped with a quick-heating planar power triode. Anode cooling is accomplished through the use of a wax-filled, hermetically-sealed reservoir. The reservoir is thermally connected to the anode of the tube but electrically insulated from it. This cooling system depends upon the intermittent nature of system operation. It provides a heat reservoir of great capacity during the relatively short transmitting periods and effects cooling by conduction and radiation during the off period. The large energy storage provided by this device results from the change of state of the wax from solid to liquid when it is heated. The cathode and grid seals of the tube are cooled by conduction through metal collets so that the cavity becomes the short-period heat sink, which is cooled by the conduction of heat to its surroundings during the off periods. Two tuned cavities are used in this grid isolation oscillator, one for the plate circuit and the other for the cathode circuit. The plate cavity is of radial design, operating in the $TM_{0,1}$ mode. It is tuned by means of two threaded plugs introduced through the cylindrical cavity wall 180° apart. Power is coupled to the load by means of a pickup loop capable of being adjusted to obtain optimum loading of the oscillator. The cavity design includes a plate bypass capacitor, which permits the dc power to be shunt-fed to the plate. The cathode circuit is tuned by a ¾-wavelength coaxial-line type cavity operating in the TEM mode. The grid-isolation circuit is inherently stable and will not oscillate unless feedback is deliberately introduced between plate and cathode circuits. In this transmitter, the feedback is obtained by means of four loops in the cathode cavity, equispaced around the wall common to both cavities. The free ends of these inductive loops pass through individual holes in the common partition, and project into the plate cavity where they act as capacitive probes.

Frequency modulation of the oscillator is obtained by coupling a reactance into the cathode cavity whose magnitude varies with the modulating voltage. This is accomplished by utilizing the changes in characteristics of a reverse-biased crystal diode when the bias voltage is modulated. This modulator is connected to the cavity through an adjustable length of tuned coaxial transmission line, and an adjustable coupling probe inserted into the cavity opposite the high-voltage point on the center conductor of the cavity.

The frequency drift present in the self-excited oscillator is compensated for by an automatic frequency control system. A crystal-controlled 50- to 70-mc oscillator is used as a frequency standard. A multiplier chain provides a local oscillator signal at the eighth harmonic of the crystal. A filter inserted between the multiplier chain and the crystal mixer eliminates unwanted responses. In the crystal mixer, a sample signal from the transmitter beats against the fourth harmonic of the local oscillator signal, translating the sample signal to an intermediate frequency in the above 50- to 70-mc range. The IF signal is then passed to an electronic switch controlled by a 400-cps square-wave oscillator. A signal from the crystal oscillator is also fed to the switch so that the switch output consists alternately of the transmitter sample and the crystal oscillator signal, commutated at the 400-cycle rate. The commutated output of the switch is then fed to a limiter-discriminator, which delivers a square-wave output whose amplitude depends upon the frequency difference existing between the transmitter sample and the reference signal. The phase of the square wave depends upon which of the two signals is higher in frequency. The output signal from the discriminator is ac-coupled to an audio amplifier, which is used to drive one phase of a two-phase motor. The motor, with its second phase powered by the 400-cycle source, is used to vary a tuning screw mounted in the cathode resonator. The UHF transmitter, with its automatic frequency control (AFC) disabled, has an initial drift of from 6 to 14 mc, depending upon the planar triode selected. The frequency stabilizes to within one megacycle of the operating point after approximately two and one half minutes. With AFC, the transmitter can be locked into frequency in 40 seconds and the frequency can be maintained to within 0.005 per cent over a temperature range of 0 to 130°F.

VHF satellite circuitry supports system requirements for a tracking beacon, telemetry, command acknowledgement, and initial satellite acquisition. The major units supporting these requirements are shown in Fig. 2. The VHF antenna consists of four quarter-wave whips spaced and electrically fed in quadrature. This configuration gives an antenna pattern that is circularly polarized along an axis normal to the plane of the whips, and elliptically polarized over most of the remaining sector. Since the satellite diameter is approximately one half wavelength in the operating frequency band, nulls would be experienced in the coverage.

A VHF diplexer, consisting of complementary filters with distributed inductances and lumped capacitances, permits simultaneous receiver and transmitter operation. Salient characteristics of this unit follow:

Reception insertion loss	0.5 maximum
Transmission insertion loss	0.2 db maximum
Transmitter/receiver isolation	60 db minimum
VSWR	1.25 maximum
Transmitter decoupling	30 db minimum

The VHF receiving system consists of primary and standby receivers that alternately search for an RF signal from the ground station. A battery-saver circuit causes the receiver pair to operate in the following cyclic fashion. First, one receiver is on for one second; next, both receivers are off for nine seconds; then, the other receiver is on for one second; and lastly, both receivers are again off for nine seconds. This operation reduces standby satellite power without unduly compromising reliability because of fail-safe features incorporated in the system. While the satellite is active, the VHF receiver first intercepting a signal is locked on and used to effect automatic functions within the command decoder circuitry.

Each receiver is a single-conversion superheterodyne unit including a transistor RF amplifier. By use of the inherent capabilities of the diplexer, a 50-db image rejection is attained. Noise figures of 8 db have been measured. The local oscillator is crystal controlled and provides a mixing signal higher in frequency than the operating frequency with a stability of $\pm$ 0.002 per cent over the anticipated temperature range. The IF amplifier frequency is 10.7 mc with a 3-db bandwith of 30 kc. The narrow bandwidth is achieved through the use of a crystal filter following the first stage of amplification. Six stages of IF amplification are used, providing nominal gain of 15 db per stage. The first five stages provide enough gain to raise a threshold signal of -112 dbw to the limiting level in the last stage. All IF amplifier stages following the narrow-band filter include diodes for limiting. Limiting occurs in the last IF stage on threshold signal levels, and, as the signal level increases, additional stages reach the limiting level. Following the last IF amplifier stage, a discriminator driver stage and a crystal discriminator are used. A video amplifier which follows the discriminator uses two stages of voltage amplification, followed by an emitter follower for impedance matching. The voltage amplifiers use two transistors connected in the compound Darlington configuration to provide very stable gain characteristics over a wide range of temperature. Degenerative feedback from the second-stage collector to the first-stage emitter is employed for added stability and a convenient gain control. The outputs of both VHF receivers, the active unit and the standby unit, are connected in parallel to the input of the decoder. The output of the emitter follower stage is designed to present a high impedance when the transistor is not active. In this way, no appreciable power is lost and switching of the two outputs is avoided.

The functions of providing RF energy to serve as a beacon signal and to convey telemetry data are divided among an acquisition transmitter, a telemetry transmitter, and their respective backups. All are completely transistorized, the former delivering 50 mw from its output stage and the latter delivering 1.5 watts. Frequency is maintained to within ± 0.002 per cent through the use of crystal-controlled oscillators. The acquisition transmitter emits a cw signal during satellite standby periods, and the telemetry transmitter is frequency modulated by subcarrier oscillators to provide data when the satellite is active.

The first seven channels of the I.R.I.G. FM/FM telemetry standards[4] are employed as subcarriers. These subcarriers are 400, 560, 730, 960, 1300, 1700, and 2300 cps respectively. Channels 2 through 7 are commutated to provide a positive and negative calibration level and five data samples. The positive calibration consists of three seconds during which the subcarrier oscillators, deviated a positive 7.5 per cent, are at their maximum frequencies. A one-second negative calibration period places each subcarrier oscillator frequency at its minimum due to a negative 7.5 per cent deviation. Mid-range calibration is not believed to be required on a regular basis. However, it is available to the operator, through selective commanding of the satellite and observance of the command acknowledgement signals. Data are modulated on the commutated channels during five two-second intervals. These data consist of the following:

Battery voltages
Solar charging currents
Load current
Temperatures
Magnetic-tape positions
Transmitter power outputs
Receiver signal strength levels

Primary satellite power is derived from approximately 19,000, 2×1 centimeter, nine per cent efficiency solar cells. These cells are individually optically coated, assembled in shingles on metal skins curved to fit the satellite, and distributed about the surface. To prevent shaded cells from loading the power circuit, each group of shingles is diode blocked from other shingles. A pair of diode-blocked 28-volt nickel-cadmium batteries is used for power storage. The combination of diode-blocked solar-cell shingles operating with dual battery supplies is used to en-

[4] "Telemetry Standards for Guided Missiles," Inter-Range Instrumentation Group, White Sands Missile Range, N. M., Document #103-56; October, 1956.

hance power supply reliability. Fig. 4 illustrates the important features of the power-supply arrangement. Each battery complement, charged by the solar power converters to which it is connected, is capable of supporting the 220-watt active and 4.5-watt standby power consumption of the satellite for approximately a 10 per cent duty cycle. In order to minimize interference and voltage breakdown problems associated with launching, the satellite is not activated until it is injected into orbit. The activating switches are microswitches that sense the presence of the upper stage of the missile. Upon injection, these switches close, thereby providing redundant turn-on. The umbilical circuit provides launch-site control of the payload. Through the wiring provided, it is possible to charge and discharge remotely each battery supply and to operate the satellite electronics with both internal and external power.

One of the major satellite design problems is that of ensuring that the payload can withstand the thermal environment in which it must operate. In order to control the internal temperature of the satellite, it is necessary to consider two distinct environments. The first is encountered during the launch phase when the satellite will be subjected to the thermal environments resulting from the aerodynamic heating of the missile nose cone; a maximum skin temperature of approximately 300°F may be experienced for less than four minutes during this period. Hence, satellite skin materials and solar cells capable of withstanding this temperature are used, and thermal isolation is provided between the outer surface of the satellite and internal components to effect a time lag which prevents damage to internal components for that amount of time. The second phase is during its life in orbit when the satellite is subjected to the extremes of intense heat and cold of space. The degree of heating to which the satellite components are subjected during the launch phase depends on the trajectory of the launch vehicle through the earth's atmosphere, selection of satellite materials, and structure of the nose cone, as well as the internal conducting paths, and radiation geometry between the nose cone and the satellite.

IV. Ground Equipment Design

Each ground station is comprised of three semi-trailers of operating equipment, test equipment, and maintenance parts, in addition to a 28-foot parabolic dish-type tracking-antenna system. The control semi-trailer houses complete operating facilities for the entire ground station, including a control console, command generator, message-processing equipment, master timing unit, and telemetering data-processing and display equipment. The radio semi-trailer contains all the required VHF and UHF transmitting and receiving equipment. All maintenance parts and test equipment required for the equipment in the other semi-trailers are included in the maintenance semi-trailer. The antenna system consists of a 28-foot dish mounted on a 40-foot tower with both VHF and UHF feeds and associated RF hardware. A shelter enclosed within the tower

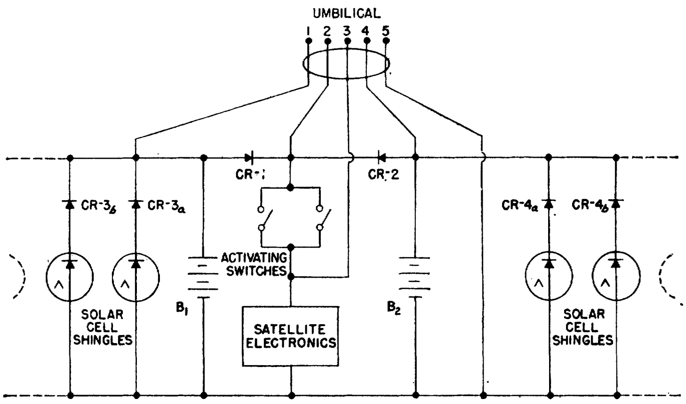

Fig. 4—Satellite power supply, simplified diagram.

contains the servosystem and antenna control equipment.

A layout diagram for a ground station is shown in Fig. 5. All equipment is contained within a 100 × 200-foot area with the exception of the antenna boresight tower, which is located outside the fenced-in area at an appropriate site. Three-phase four-wire wye-connected, ac power is used. This 120/208 volt 60-cps power will be supplied by a commercial concern, and four 45-kva engine generators are provided as backup to ensure uninterrupted power for the installation. A control box facilitates changeover between commercial and backup power. All power lines within the area shown are buried. An "00" isolated ground wire used throughout the ground station reduces ground currents. The antenna is mounted on a reinforced concrete pad and is designed to withstand wind velocities up to 150 mph. The ground station is a semi-fixed installation which may be transported and reassembled at another properly prepared location.

A simplified block diagram for the entire ground station is shown in Fig. 6. Teletype messages on perforated paper tape are read out by the paper-tape reader prior to recording on magnetic tape at a slow speed. The magnetic tape is then played back at a faster rate by the magnetic tape reproducer. This output signal is used to frequency modulate a UHF carrier which is transmitted to the satellite. Repeated messages from the satellite are received by the quadruple-diversity receiving system. The received signals are recorded on magnetic tape at a fast rate and played back by the magnetic-tape reproducer at a slower speed. The paper-tape perforator then punches a paper tape usable by the teletype receivers. A combined agc signal from the UHF receiving system, retaining the amplitude-modulated tracking signal obtained from conical scanning with the ground antenna, is demodulated and compared with the reference generator signal to obtain error signals for automatic tracking and positioning of synchros, controls, and indicators. The VHF system provides for the transmission of initial commands to the satellite and for the reception of beacon and telemetry signals from the satellite. Telemetry data processing, a master timing system, and recording equipment are integrated as shown. Coarse positioning of the relatively wide VHF beam from

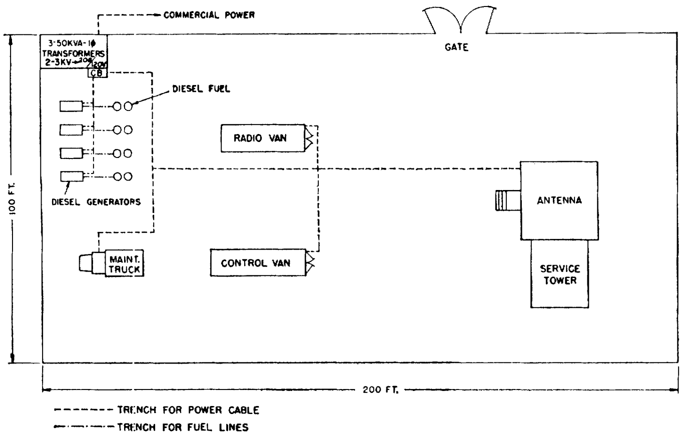

Fig. 5—Power layout of ground station.

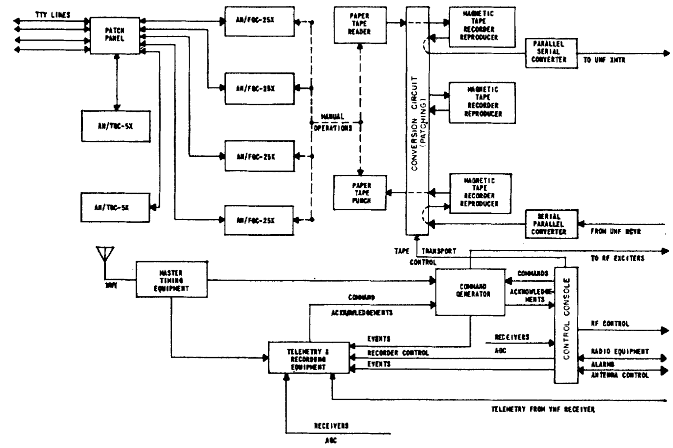

Fig. 7—Control center, block diagram.

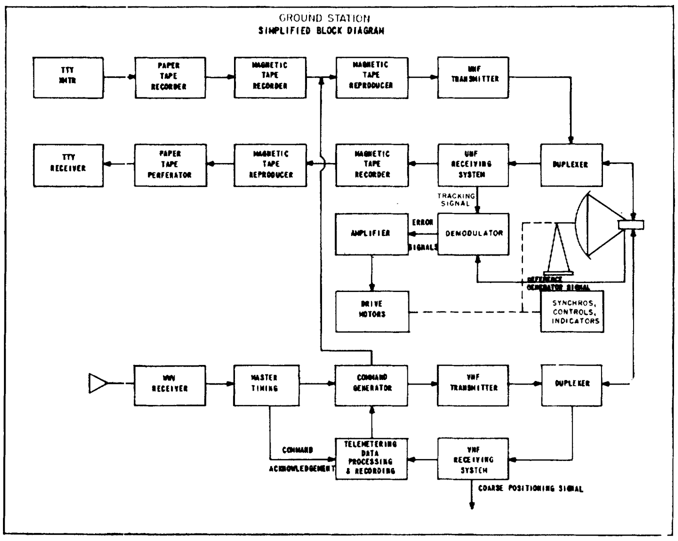

Fig. 6—Ground station, simplified block diagram.

the antenna is accomplished by peaking a meter indication of the AGC signal from the dual-diversity VHF receiver.

The ground station may logically be divided into three major subsystems as follows: the control center, the radio system, and the antenna system. A simplified block diagram for the control center equipment is shown in Fig. 7. Four AN/FGC-25X and two AN/TGC-5X teletypewriter sets provide for simultaneous transmission and reception of teletype messages. The AN/TGC-5X, a torn-tape relay, is capable of operating in conjunction with two AN/FGC-25X machines. Messages may be initiated with the AN/FGC-25X from a keyboard, electrical signals, or a standard punched tape; but the AN/TGC-5X requires punched tape or electrical signals and does not have a keyboard. Various combinations of the six teletypewriter sets are obtained through the patch panel, thus providing a suitable message generating and receiving capability for an experimental system. Connected for 60-wpm operation, the teletypewriters employ the standard five-unit start-stop Baudot code.

Teletype tapes, manually transferred to the photoelectric paper-tape reader, are read out at a speed of 200 characters per second. A 10 per cent guard space is allowed between characters to accommodate deterioration in the speed control of the electromechanical teletype machines and tape reader for a one-year period of time. The reader output consists of parallel pulse trains which are fed to any of three identical tape machines. These machines are used for both speed-up and slow-down of the message rate. Each transport has six speeds: 60, 30, 15, 3.36, 1.68, and 0.84 inches per second. However, in normal operation, the 1.68 and 60 inches per second speeds are used to speed up to and slow down from 55 kilobits per second. Maintained to an accuracy of $\pm$ 0.5 per cent, the tape speed has a maximum cumulative peak-to-peak flutter of 0.1 per cent from 2 to 500 cps at 30 inches per second.

Each character of the message is recorded in parallel on six tracks of the magnetic tape which are played back at a faster rate to the parallel-to-serial converter. The seventh or stop bit of the character is inserted in the parallel-to-serial converter. The parallel method of message-rate conversion is used to allow operation of the paper-tape reader and magnetic-tape machines at speeds sufficiently slow to minimize excessive mechanical wear caused by high speeds. The converter stores the five code bits of a character in a buffer flip-flop store which holds them until a pulse from a diode-matrix output gate causes a transfer of the character to the diode matrix. These five bits, plus the start and stop bits of the character, are then read out as a serial pulse train from the diode matrix by a count-of-seven counter and are amplified and routed to the UHF transmitter.

Incoming traffic from the UHF receiver is converted to parallel form by the serial-to-parallel converter. The signals received by the radio equipment in the form of gaussian pulses are first shaped by the serial-to-parallel converter to obtain full-bauded rectangular pulses. Since the bit rate of the messages received from the satellite is affected by the speed variation of satellite tape machines and, to a lesser extent, ground station tape machines, a local clock is operated at a frequency corresponding to the bit rate of the incoming mesages. To accomplish this, a local oscillator is frequency controlled by an error signal developed by comparing the incoming-message signal frequency with the local-oscillator frequency. The local oscillator in conjunction with a start-stop pulse synchronization circuit controls a binary matrix which provides six outputs to be stored serially in a buffer. These outputs correspond to five teletype code bits and a control bit. All six bits go through pulse generators to obtain signals within the bandwidth of the magnetic-tape machines, and they are then read out in parallel for recording on the selected machine. A more than adequate frequency response of 100 to 100,000 cps is obtained by recording at 60 inches per second. The magnetic tape is then played back, at a rate of 1.68 inches per second, to the paper tape punch which operates at a rate of 200 characters per second. The output paper tape is then converted by the teletypewriters to teletype tapes and/or printed pages.

The control console contains the necessary equipment for the operation of a ground station from one point. Front panel controls are provided for magnetic-tape machines, antenna positioning, selection of commands, events recording, and radio equipment control. Teletypewriter sets and paper-tape equipment are operated manually in an off-line manner and are not controlled from the console. The console also displays UHF and VHF receiver AGC signals, command acknowledgements, transmitter alarms, and other critical signals. Commands selected by the console are generated by the command generator and transmitted to the satellite by the radio equipment. The FM/FM telemetry signal from the satellite is recorded on magnetic tape and also separated into its seven channels by subcarrier filters. Discriminators with a linearity of approximately 0.2 per cent are used to obtain dc voltages representing the telemetered data. These data are suitable for strip-chart real-time recording. The chart recorders are also used to record time and events and AGC voltages from the UHF and VHF receivers, which are FM/FM telemetered from the radio equipment semi-trailer. A master timing system provides a time base for the telemetry recording and command generator equipment. The master timer counts down from a 1-mc crystal frequency to obtain the pulse time base required for the ground station, and is stable to within one part in 10^8 per day. The timing unit can be synchronized with signals received from WWV if required.

The radio equipment includes the UHF and VHF transmitting and receiving systems and the necessary duplexers, diplexers, and harmonic filters. The UHF equipment (see Fig. 8) receives the serial pulse train from the message-processing equipment, and the signal spectrum is limited to 50 kc by an approximately Gaussian-shaped filter having a low pass cutoff of 300 cps. After amplification, the pulse train frequency modulates a stabilized 70-mc carrier frequency. A tuned discriminator is used in the modulator AFC circuit. The modulator signal output is then mixed with a crystal-controlled local-oscillator frequency of 1700 to 2230 mc to obtain the desired carrier frequency to be transmitted. The mixer-amplifier output is at the 5-watt level with a carrier frequency stability of 0.0005 per cent per day. The power amplifier uses a CW four-cavity tuneable klystron to amplify the power level to approximately 1100 watts. A harmonic filter in conjunction with the duplexer reduces transmitted harmonics to 80 db below the carrier signal level. The transmitter output signal is then divided into two paths which are used to provide the horizontally and vertically polarized antenna outputs. A phase shifter in one path provides the 90° phase shift necessary to effect circularly-polarized radiation from the ground antenna.

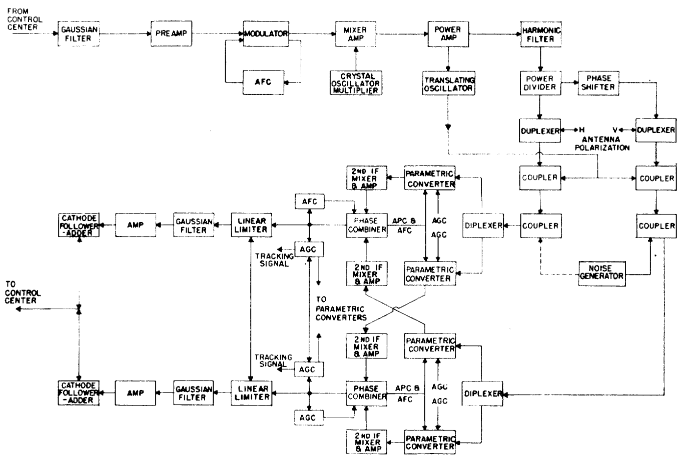

Fig. 8—UHF radio equipment, block diagram.

The two UHF power duplexers permit both circularly polarized transmission and polarization diversity reception. Each duplexer handles 500 watts at present but is capable of handling the full transmitter output to allow linearly polarized transmission, if desired. The pass-band insertion loss for each duplexer is approximately 0.2 db. A translating oscillator and mixer, which shifts the transmitted signal frequency to the expected received signal frequency, facilitates checking of the UHF system for maintenance purposes without receiving a signal from the satellite. When using this self-checking feature, the derived signals are coupled to the received signal paths as shown in the diagram, and a noise generator is coupled to either signal path to simulate a noisy received signal.

A quadruple diversity UHF receiving system is necessary to prevent losing the signal transmitted from the satellite due to nulls and variations in polarization of this signal caused by the nonisotropic satellite antenna. Both predetection and postdetection combining are used since separate noncoherent transmitter modulators are used in the frequency diversity satellite transmission. A predetection phase combiner is not used to combine all four IF signals since the signals to be combined must be approximately phase coherent.[5] Two diplexers with insertion losses of approximately 0.5 db are used and in conjunction with the

[5] For comprehensive discussions of diversity combining techniques, see D. G. Brennan, "Linear diversity combining techniques," Proc. IRE, vol. 47, pp. 1075–1102; June, 1959, or numerous other articles.

parametric converters provide a spurious response of 80 db below the input signal level.

The receiving system is a double conversion superheterodyne system with a dynamic range of -140 to -100 dbw. Received signals of either linear polarization are separated on a frequency basis by the diplexer filters and are accepted by the four parametric converters. These lower-sideband up-conversion units employ hermetically sealed variable-capacitance silicon diodes and an X-band klystron pump generator to obtain a 2-db noise figure with a gain of approximately 20 db and a 5-mc bandwidth. Each parametric converter is a dual unit with one path for the received signals and the second, containing a tunable local oscillator, for accommodating a wide variation of input frequencies. Both the signal and the local-oscillator converters are pumped by the klystron, and the converter outputs are mixed in a conventional X-band balanced mixer to provide the 70-mc IF signals. Summed automatic phase and frequency control voltages from the phase combiner control the local-oscillator frequency. The AGC signals derived from the phase combiner outputs are used in the 70-mc IF amplifiers following the mixers. The first IF signals are then routed to the second IF strips, as shown in Fig. 8, to allow polarization diversity phase combining of the intelligence on each of the received carrier frequencies. The second mixer heterodynes the 60.2-mc local-oscillator frequency with the first IF frequency to obtain a 9.8-mc frequency. Replaceable Gaussian-type bandpass fiilters allow selection of detection bandwidths of 100, 200, or 500 kc. The amplified second IF signals are then combined in pairs in two phase combiners.

Automatic phase control (APC) voltages, derived by comparing the signals from the 9.8-mc amplifiers to the common combiner output in respective phase discriminator circuits, are added to AFC signals derived from separate discriminators, and the sum is applied to the respective first local oscillators to maintain a constant phase relation. The second IF signals are added in pairs in the combiner hybrids, and since they are in phase and the noise is random, an improvement in signal-to-noise ratio is effected. The AFC signals are used to allow frequency tracking of incoming signals to an accuracy of ± 0.001 per cent of the carrier frequency which may vary in frequency as much as ± 150 kc because of Doppler shift, satellite transmitter frequency shift, and receiver local-oscillator drift. The phase combined outputs are then fed to the linear limiters and also to AGC circuitry. The AGC signals are combined to obtain the tracking signal for the antenna servo system and are used to maintain constant amplitude signals in all four receiver channels. The AGC combining is effected by cross-coupled detectors with emitter followers outputs.

Baseband frequency diversity combining is accomplished by the linear limiters and cathode follower-adders. The baseband combiner linearly controls the amplitudes of the respective limiter outputs in accordance with the ratio of the input signal levels and maintains the sum of the amplitudes approximately constant. Controlled bias voltages for conventional diode limiters are used to vary the limit level. The control voltages are obtained by detecting and amplifying the input signal levels to the limiters. By the use of diode cross-coupling between the linear limiter outputs, the signals are limited to a fixed amplitude, but the ratio of the outputs may still vary. Gaussian-shaped 50-kc low-pass filters reject frequencies outside of the baseband. The baseband signals are then amplified to the level needed by the message processing equipment and added prior to cathode follower output circuits. As indicated in Fig. 8, the receiving system output signal may be taken from either of the cathode follower-adder circuits as selected by relays not shown. This allows the receiving system to be operated on a two-channel polarization diversity basis if only one frequency is transmitted from the satellite.

The VHF radio equipment, which receives signals from the command generator in the control center, is shown in Fig. 9. These signals are amplified and used to phase modulate a crystal-controlled oscillator frequency of approximately 4.5 mc. This modulated signal is then frequency multiplied to the final VHF carrier frequency resulting in a carrier frequency stability of better than 0.001 per cent per day. The power level is amplified from 5 to approximately 110 watts by the power amplifier. A harmonic filter in conjunction with the duplexer attenuate transmitted harmonics to 80 db below the carrier frequency power level. Two duplexers are used to allow switching the transmitter output from one linear antenna polarization to the other and still allow polarization diversity reception. Two tunable band-pass filters joined to the common antenna cable by a tee are used in each duplexer, and an insertion loss of 0.2 db is realized in each duplexer. A translating oscillator and mixer provide a self-checking capability in the same manner as described for the UHF radio equipment.

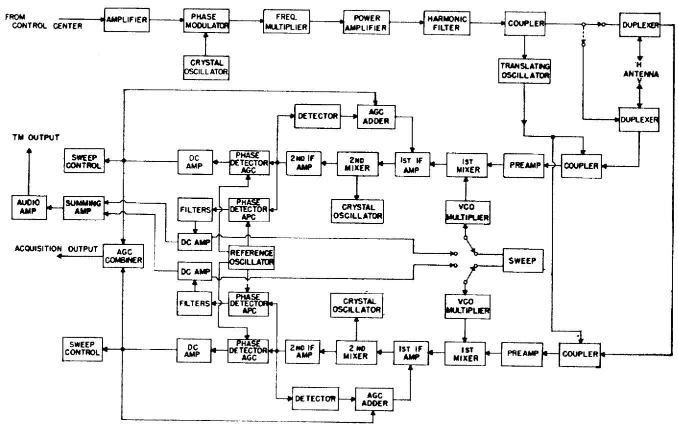

Fig. 9—VHF radio equipment, block diagram.

The VHF receiving system is a double superheterodyne polarization diversity system with a dynamic range of -155 to -110 dbw for beacon signals and -145 to -90 dbw for telemetered signals. Appropriate filters are automatically selected for optimum beacon or telemetery reception. Phase-lock techniques allow the use of relatively narrow detection bandwidths of 1000 to 6000 cps for beacon and telemetry reception, respectively. The system noise figure is reduced to 4 db by the preamplifiers, and spurious response is maintained better than 80 db down by the selectivity of the duplexers and receiving system. The amplified signals are mixed with signals from frequency multiplied voltage controlled oscillators, which are independently swept at a rate of one cycle per second until phase lock is accomplished on both channels. The resulting 21.4-mc IF signals are amplified and mixed with 16.9-mc crystal-controlled oscillator signals in the second mixers. The 4.5-mc IF signals obtained are then amplified and detected. A noise amplitude detected signal is obtained in each receiver channel and added to a phase-detected combined AGC signal to maintain effectively equal gain in both receiver channels for telemetry operation. During beacon operation, the AGC signals for the first IF amplifiers are derived independently. A common 4.5-mc crystal controlled reference oscillator is used for both AGC phase detectors and also for both APC detectors. The 4.5-mc IF output signals go through buffer amplifiers as shown in Fig. 9. The AGC phase-detector outputs go through low-pass filters and then dc amplifiers, prior to combining. The dc-amplifier outputs also operate the sweep control circuits which disable the 1-cps voltage-controlled oscillator sweeps when a phase lock has been accomplished in that particular channel. The combined AGC output is displayed at the control console in order to facilitate manual positioning of the antenna as indicated by obtaining a peak reading on the meter. The buffer amplifiers in the APC phase-detector circuits also shift the signal phases by 90° so that the phase-detector outputs may be used to maintain the two channels in phase for summing.

These APC phase-detected signals are spectrum-limited by the beacon or telemetry filters, which are automatically selected when a 15-db change of received-power level is sensed at the audio output after the satellite switches from the beacon to the telemetry transmitter. The filtered signals are then amplified and summed to provide an audio telemetry output. The dc amplifier outputs are also used to provide a dc signal to the voltage controlled oscillators for use in automatically tracking the carrier frequencies in both channels. The sweep control circuits, therefore, select either the dc-amplifier outputs or the sweep outputs for frequency control of the voltage-controlled oscillators.

The antenna system includes the UHF and VHF feeds, the parabolic reflector, the drive mechanism, the rotary joints, and the tracking system. The UHF feed system is comprised of waveguide and a waveguide feed, a lens, a lens drive motor, a radome and the reference generator. The horizontal and vertical RG-105/U aluminum waveguide lines are joined to a length of circular waveguide at the feed, which is supported such that its center is at the reflector focal point. A four-element ridged waveguide antenna is mounted within the circular waveguide. The elements are fed independently in pairs by coaxial lines from the horizontal and vertical waveguides to provide two linear orthogonal fields of the $TE_{1,1}$ mode. The ridged-waveguide elements are arranged in space quadrature around the circumference of the drive shaft for the rotating lens, and each element is continuously tapered from the circular-waveguide surface at the input end to the shaft at the lens end. An isolation of better than 20 db is maintained between the two polarizations. Then lens, rotated by its drive motor to effect conical scanning at a 30-cps rate, is an artificially-loaded dielectric hemisphere whose dielectric constant is tapered across the waveguide aperture to provide the required phase shift for the transmitted and received signals. The reference generator is driven by the lens drive motor and supplies the phase reference signal for the automatic tracking loop. The VHF feed system is comprised of a crossed dipole antenna with a disk-type reflector. Since the UHF feed system is more critical, the VHF feed center is slightly displaced from the reflector focal point, thus defocussing the VHF antenna system. However, the resulting 45° phase error and ¼-db gain decrease are not large enough to affect significantly ground system operation.

A 28-foot parabolic reflector with an F/D ratio of approximately 0.4 is used. The reflector surface is perforated to reduce wind loading. Four steel spars support the feeds. The UHF signals between the antenna system and the radio equipment are propagated in a horizontal and a vertical waveguide with flexible sections used at the radio equipment junctions to allow for slight misalignments. Ridged waveguide sections provide the required transitions between waveguide and coaxial lines to allow coaxial rotary joints. Both the horizontal and vertical lines entering the antenna system go through two quadruple-rotary joints before reaching the feed. Coaxial lines are used throughout the VHF system which employs the other two channels of the azimuth and elevational rotary joints. Both the UHF and VHF systems have total transmission-line and rotary-joint losses of 1.5 db or better. The maximum VSWR presented to the radio equipment is 1.5.

An electromechanical servosystem (see Fig. 10) automatically points the high-gain, narrow-beam antenna system and tracks the satellite. The antenna is driven in azimuth and elevation by dc generators which control the servo drive motors. One prime mover is employed for both generators. The error signals, power amplified by the magnetic amplifiers, are derived from the combined agc voltage from the UHF receiving system. This AGC signal has a dc component which varies in amplitude with the received signal strength from the satellite and an amplitude-modulated ac signal resulting from the conical scanning of the antenna. The dc component is used to operate relays in both angle control loops to switch from the sector scan to the automatic tracking mode of operation when the signal level exceeds the threshold value. The ac signal goes through a low-pass filter to reduce 60-cps interference with the 30-cps AM signal. The filtered signal is then compared with the 30-cps reference generator signal and separated into azimuth and elevation error signals in the phase demodu-

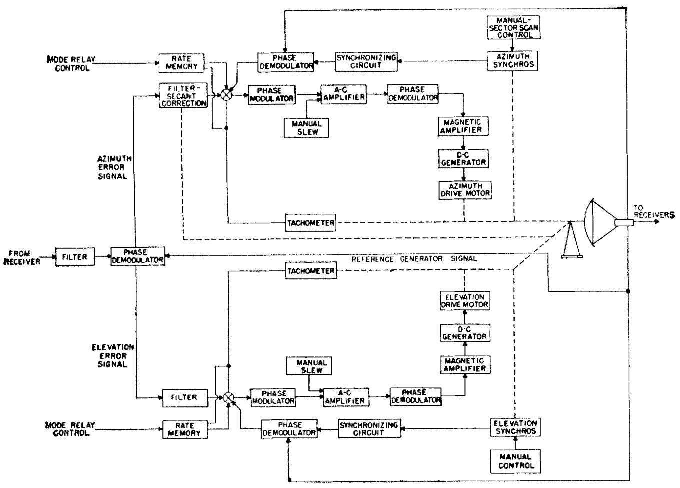

Fig. 10—Ground antenna servosystem, block diagram.

lator. The error signals are both filtered to remove 30-cps components and used as inputs for the servo control loops. A correction voltage proportional to the secant of the elevation angle is used to increase the azimuth-loop gain as the elevation is increased up to 85°, in order to compensate for the fact that a given angular error at high elevation angles is primarily azimuth error. Consequently, the azimuth servo response will lag if its loop gain is not increased. The 85° limit is set by practical limitations which preclude increasing the gain to infinity in accordance with the secant function.

The error signals are summed with tachometer feedback signals at the servo inputs. Rate-memory voltages are applied to the servo loops in lieu of the error signals, during automatic tracking, when the mode relay control is caused to operate by the falling of the dc-signal level below its threshold value. At that time, the rate memories cause the servo loops to drive the antenna at the angular rates at which it was operating prior to the reduction of received-signal level. During the manual mode of operation, the azimuth and elevation handwheels position two-speed synchro systems. The synchro voltages as selected in the synchronizing circuits are compared with the reference voltage in demodulators, whose output voltages are then used as error signals for the servo loops. The synchronizing circuits choose either the 36:1 or 1:1 speed synchro voltage depending on whether angular error is small or large, respectively. An azimuth-sector scan mode is used after the antenna has been positioned manually, during the acquisition phase of operation. An azimuth sector of $\pm 5°$ can be scanned at a rate of 30° per second, and the position control error signals in the sector scan mode are derived from the synchro voltages as described above. When the dc component of the AGC signal exceeds its threshold value, the mode relay control causes the elevation channel to go immediately into automatic tracking mode. The azimuth channel, however, does not go into the automatic mode immediately because of its considerable inertia from sector scanning. The azimuth motion is decelerated at its maximum of 12°/second/second subsequent to the shorting to ground of the azimuth servo amplifier by the mode-relay control. When the rate, sensed by comparing the tachometer output with a reference voltage in a coincidence circuit, is $\frac{1}{4}°$ per second, the azimuth channel switches into the automatic tracking mode.

The dc error-signal sums are modulated and demodulated to allow using high-gain ac amplifiers. A lead-lag compensation network is used at the input to the magnetic amplifiers, and the resulting velocity constant for both channels is approximately 30 second^{-1}. Manual slew capability is provided in both channels by applying variable ac voltages to the ac amplifiers to drive the antenna at faster than normal tracking rates. Maximum tracking and slewing rates are both 15° per second.

Conclusion

Communication satellites, operating in the microwave region, possess the capability to handle reliably a large portion of the world's ever increasing communication requirements. Many systems are being designed in an attempt to harness this capability; employing delayed repeater, real-time repeater, and passive reflector techniques. This paper has given a broad view of an advanced delayed repeater satellite communication system concept.

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