The series that comprise (21) and (22) can be identified as those of the type used to set up the incident fields[2] or identified by a technique described in a recent article;[6] hence (7) and (8) have the form

$$\overline{E}_s = \frac{a}{r} E_0 e^{i[k(r-a)-\omega t]} \left\{ -\left(\frac{1}{kr}\right) \sin\theta\cos\phi\hat{r} - \cos\theta\cos\phi\hat{\theta} + \sin\phi\hat{\phi} \right\} e^{ika\cos\theta},$$

$$\overline{H}_s = \frac{a}{r} \frac{kE_0}{\omega\mu} e^{i[k(r-a)-\omega t]} \left\{ -\left(\frac{1}{kr}\right) \sin\theta\sin\phi\hat{r} - \sin\phi\hat{\theta} - \cos\theta\cos\phi\hat{\phi} \right\} e^{ika\cos\theta}.$$

B. The Poynting Vector

Since the radial component of the far zone fields was neglected, the total Poynting vector has the following form:

$$\overline{S}_s = \tfrac{1}{2}\,\mathrm{Re}\, E_\theta H_\phi^* - E_\phi H_\theta^*]\hat{r}.$$

For the fields calculated in *A* of the Appendix,

$$\overline{S}_s = \left(\frac{a}{r}\right)^2 \frac{kE_0}{2\omega\mu} [(\sin\theta\cos\phi)^2 + (\sin\phi)^2]\hat{r},$$

$$\overline{S}_s = \left(\frac{a}{r}\right)^2 P_0[1 - \sin^2\theta\cos^2\phi]\hat{r}.$$

[6] T. Vea, "Generating functions and the summation of infinite series," to be published in PROC. IRE.

C. Equivalent Gain of the Sphere

The equivalent gain of the sphere over an isotropic scatterer was computed from the pattern volume. For linear polarization,

$$V_L = 8\int_0^{\pi/2}\int_0^{\pi/2}\int_0^{\cos^2\phi} r^2\cos\phi\, dr d\phi d\theta,$$

$$V_L = \frac{64\pi}{105}$$

from which the radius of the equivalent sphere is computed to be 0.77; hence,

$$G_L = \frac{1}{0.77} = 1.30.$$

For the case of circular polarization,

$$V_c = 8\int_0^{\pi/2}\int_0^{\pi/2}\int_0^{1/2(1+\cos^2\theta)} r^2\sin\theta\, dr d\theta d\phi,$$

$$V_c = \frac{16\pi}{35}$$

and the radius of the equivalent sphere was computed to be 0.70; hence

$$G_c = \frac{1}{0.7} = 1.43.$$

Project SCORE*

S. P. BROWN† AND G. F. SENN†, SENIOR MEMBER, IRE

***Summary*—This paper is designed to provide a review and summary of the over-all program of development, construction and operation by the U. S. Army Signal Research and Development Laboratory of the first satellite communication system placed in orbit on December 18, 1958. This effort was part of Project SCORE (Signal Communication by Orbiting Relay Experiment) directed by ARPA. Basically, Project SCORE consisted of designing, constructing, and conducting an actual flight experiment of a delayed repeater type satellite package using an actual stripped down Atlas missile as the satellite container. The major points to be covered are summarized in the following paragraphs.**

A brief historical résumé of the project will cover the preliminary discussions regarding the feasibility of orbiting an Atlas ICBM; the vehicle and weight limitation affecting preliminary system design; mechanical and electrical test problems and ground station installation and on-site training.

The system description will cover orbit data; ground station site location and control; airborne equipment components such as antennas, temperature control and communication electronics; general considerations of system design and design problems; ground station equipment including recording and test equipment and associated ground communication equipment.

The system operation portion of the paper will cover a brief summary of the launch into orbit and actual life of the communications system; actual operating procedures used to achieve maximum benefits from the experiment; a summary of test data obtained with chart and graph presentations; a discussion of test results and the factors affecting the evaluation of test results; and selective comments on equipment reliability.

The final part of the paper will contain conclusions to be made from the equipment and the impact of these conclusions on the planning for future communications satellite systems.

* Original manuscript received by the IRE, December 2, 1959.
† U. S. Army Signal Res. and Dev. Lab., Fort Monmouth, N. J.

STARTING with the development of radio communication equipment suitable for operational use in the VHF and UHF frequencies, system designers and operating personnel alike have been concerned with the problems imposed by line-of-site propagation at these frequencies. Equipment operating on even higher frequencies with corresponding greater communication channel capacity is being developed and placed in operational status. However, no reliable and economic means of providing single-link, wide-band communication facilities over intracontinental and intercontinental distances yet exists.

To fill this communication gap, extensive networks of coaxial line and microwave radio relay systems have been developed and installed in the continental United States during the past decade. The logistics problems attendant upon the installation and maintenance of these systems in the confines of the United States are tremendous, even with a relatively favorable environment. Applying the same techniques to a fluid military situation aggravates the difficulties to produce an almost impossible situation. The economics of the problem of providing multichannel communication under these conditions are such that only the pressure of military necessity justifies the cost. Even in commercial practice, the installation of radio relay and coaxial cable facilities is limited to the land masses of the eastern and western hemispheres. There are no means available to cross the reaches of the Atlantic and Pacific Oceans with economically sound and reliable radio relay or coaxial facilities capable of transmitting, for example, real time television program material.

Many schemes have been proposed, such as circling aircraft, blimps or dirigibles, land stations installed on the islands which dot the subarctic borders of the Atlantic and Pacific Oceans, anchored platforms and cables with sealed-in repeaters. Each of these, except the last, in one form or another has developed flaws, either logistic or technical, which makes them extremely unattractive, if not impossible. The last has been accomplished in recent years for multichannel telephone and slowed-down television; however, it is quite vulnerable to earthquakes, tides and Soviet trawlers.

With the successful launching of man-made satellites, their possibilities as elements in world-wide transmission systems were the subject of considerable speculation. A satellite, quite obviously, has many attractions as a vehicle for an unattended radio relay repeater. It requires no fuel to maintain it on its appointed course. Once in orbit, its position can be predicted with great accuracy and by selection of orbits, with no more than two relay points, any two locations on earth can be linked.

Attractive as these possibilities are for commercial communication systems, they become almost irresistible for world-wide military networks. At the present time the satellite station is practically impossible to intercept. It requires no friendly real estate to house equipment and, powered either by atomic energy or solar radiation, needs no logistic support. Operating as a delayed repeater, a satellite link could give a military system a considerable antijamming advantage.

Naturally, there are some disadvantages. The electronic equipment must be rugged enough to withstand the hazards of launching, one hundred per cent reliable for a time at least sufficient to amortize its initial cost and launching expenses, and capable of withstanding the extreme conditions existing in outer space. None of these appear to be insurmountable at the present time.

It was in an environment of such considerations that the Advanced Research Projects Agency, jointly with the Army and the Air Force, undertook Project SCORE. The object of this project was to place in orbit an eighty-foot long Atlas missile and to use this as a platform for a communication system capable of spanning intercontinental distances. The ultimate goal was to demonstrate dramatically the feasibility of such a system and to explore some of the technical and operational problems that would attend a military satellite communication system. The communications portion of the project was approved and assigned to the U. S. Army Signal Research and Development Laboratory late in July, 1958. The launching date was set for early November, 1958, which required that system and equipment design and installation in the vehicles had to be completed by the middle of October to avoid interference with prelaunch checkouts. Ground stations were required to be installed and operating crews trained by November 1, 1958. This was admittedly an extremely short deadline within which to accomplish project SCORE.

The plans were to install two complete communication packages in the Atlas missile. These each would include a receiver, transmitter, control unit, battery supply tape recorder, and tracking beacon. Ground equipments installed in standard army type V-51 vans with associated support vehicles were to be located at Fort MacArthur, Calif., Fort Huachuca, Ariz., Fort Sam Houston, Tex., and Fort Stewart, Ga. This equipment would include a Quad helix tracking antenna mounted on searchlight base, receiving, transmitting and control equipment along with appropriate recording, telephone and teletype terminal equipment. In addition, the California station would have a direction finder to assist in initial pickup and tracking of the satellite. All ground stations were to be linked by both telephone and HF radio to a system control center at the Deal Area of the Signal Corps Laboratory in New Jersey.

Preliminary calculations indicated that an elliptical orbit with an apogee of between 500 and 800 miles and a perigee of approximately 100 miles might be achieved. The launching was to be from the Atlantic Missile Range at Cape Canaveral with an inclined orbit of 30°. Fig. 1 illustrates the orbit geometry and the location of the four operating ground stations.

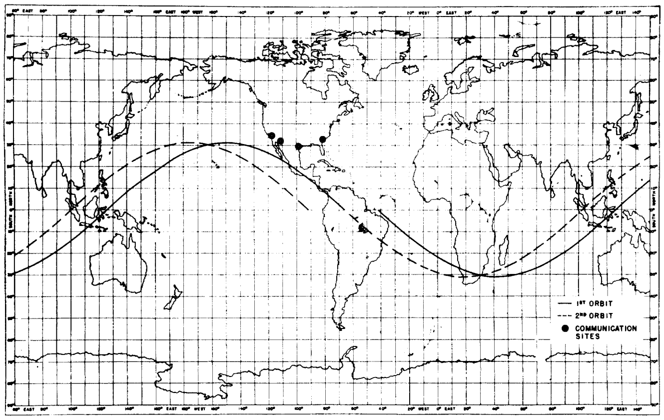

Fig. 1—SCORE satellite orbit.

The design of the system was based on providing two modes of operation; as a delayed repeater and as a real time active satellite repeater. In the delayed repeater mode, the satellite, upon reception of a suitable command signal from a ground station would record information transmitted to it. Upon reception of a different command signal, it would then transmit back to the ground station originating the command the information previously stored. Within the limitation of the storage capacity in the satellite, the information transmission rate, and hence the bandwidth, of the system and the time in view over each of the ground stations, a delayed repeater can provide intercontinental "store and forward" message transmission service.

The second mode of operation, that of a real time repeater, was obtained by the use of yet another command signal which activated the satellite as a radio relay repeater station with the recording mechanism bypassed. Here, the transmission capability of the system is limited by the time the satellite is in view of both stations simultaneously and the system bandwidth. The locations of the four ground stations were based, in part, on providing station separations which would permit testing of the real time capability over varying distances.

The system parameters which were incorporated in the satellite and ground equipments are indicated in Table I. VHF frequencies were used to minimize the effects of cosmic noise and ionospheric propagation while still permitting the use of sensitive, transistorized receiving equipment in the satellite. The power levels employed were consistent with what could be obtained in the time frame of the program. The bandwidths selected were the minimum consistent with frequency stability, Doppler frequency variations, maximum audio frequency and carrier frequency deviation. Allowance was made for ±4-kc variations caused by Doppler shift and ±5 kc for the first-order sidebands of the modulation with the deviation ratio limited to 1.0 at 5 kc. The frequency stability of the satellite components was within ±0.005 per cent. Consistent with the expected apogee of 500 to 800 miles, the system design was based on 1000-miles slant range. Power balance calculations using this value resulted in the fade margins indicated, including allowances for miscellaneous losses in transmission lines, duplexers, filters and ring isolators.

TABLE I

SCORE System Parameters

	Satellite	Ground
Transmit Frequency	132 mc	150 mc
Receive Frequency	150 mc	132 mc
RF Power Output	8 watts	1000 watts
Noise Figure	10 db	6 db
IF Bandwidth	40 kc	40 kc
Audio Bandwidth	0.3–5.0 kc	0.3–5.0 kc
Antenna Gain	0 db	16 db @150 mc
FM Threshold	10 db	10 db
Fade Margin	39 db	19 db

The satellite elements of the system were designed with due consideration for simplicity, the capability to withstand the mechanical environment during powered flight, an adequate thermal design to maintain the electronic components within reasonable temperature limits while in orbit, and redundancy to improve the likelihood of a successful communications experiment. Two complete systems, using slightly different radio frequencies, were installed in the Atlas missile to provide the redundant feature. Table II summarizes the size, weight and power drain for the items comprising the over-all satellite system.

TABLE II

SCORE Component Characteristics

Components	Weight (Pounds)	Size (Cubic Inches)	Power Drain (Watts)
Receiver	0.75	39	0.24
Transmitter	2.5	101	51.3
Beacon	1.0	27	0.36
Control Unit	0.75	37	3.0*
Recorder	3.25	99	1.4
DC-DC Converter	1.0	19.2	—
Battery	21.0	175	—
Mount and Hardware	14.5	—	—
Antenna System	54.0	—	—

* Relay mode only.

The major design areas for the satellite system can be broken down into the following areas which are described below.

The major elements of each of the satellite systems are shown in Fig. 2 as well as the over-all configuration. Fig. 3 indicates the interconnection between the major elements. As shown in Fig. 3, separate antennas were used for the communication receiver and transmitter with a beacon transmitter diplexed with the higher powered communication transmitter.

The communications receiver was a double superheterodyne frequency-modulated all-transistor receiver, a modified version of a commercial type. Considerable improvement in sensitivity was attained by the use of selected transistors in an RF amplifier stage which was included; noise figures in the 10-db to 13-db range were

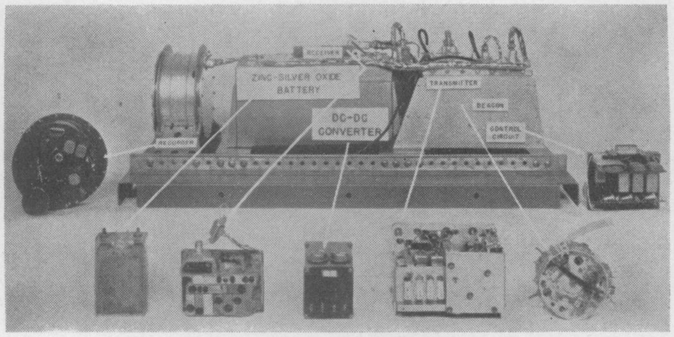

Fig. 2—SCORE system satellite components.

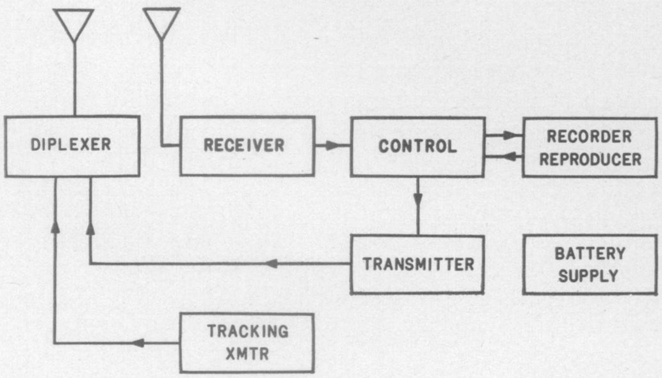

Fig. 3—SCORE satellite interconnection diagram.

realized. Although the receiver power drain was only 0.24 watt, it represented a considerable expenditure of energy over long periods of time if it were permitted to operate continuously. To conserve the limited battery supply, a battery saver circuit was included in the receiver design which, during standby periods between interrogations, turned the receiver on for a period of $\frac{1}{4}$ second each $2\frac{1}{2}$-second period, thereby reducing the power requirement by a factor of 10. This substantial saving in power drain was thereby achieved without introducing appreciable delay in detecting command signals.

The transmitter used vacuum tubes throughout and provided 8-watts frequency-modulated power output. The circuitry used was conventional, in keeping with the urgency of the development cycle. Plate and screen voltages for the transmitter were obtained from a transistorized dc to dc converter operating from the battery power supply. A relatively high conversion efficiency of 82 per cent was obtained with the converter operating with a ripple frequency of 2500 cps.

The control unit consisted of transistorized switching circuits activated by special telemetry type notch filters at frequencies of 3000, 3900 and 5400 cps. These tones corresponded to the record, playback and radio relay modes, respectively, and caused the appropriate connections to be made between the transmitter, receiver and tape recorder. The 5400-cps tone had an alternate capability of disabling the record and playback modes and caused the system to revert to a standby status. This was included to provide a measure of control of the satellite system by the ground stations in the event that the automatic cycling sequence incorporated in the satellite design might fail.

The recorder-reproducer was a miniature type originally designed and built at the Signal Corps Laboratory for a meteorological satellite, but modified for application to the SCORE project. The electronic circuitry including erase, playback and record functions was completely transistorized; the tape drive mechanism was pressurized for reliable operation of the dc motor in the space environment. An endless loop of 75 feet of 1-mil mylar tape, operating with a tape speed of $3\frac{1}{4}$ inches per second (ips) provided 4 minutes of recording or playback time with a 300- to 5000-cps bandwidth. A $\frac{1}{2}$-inch metallic coated section of the tape which momentarily completed an electrical circuit indicated the stopping point on the endless loop. This contact caused the control unit to revert automatically to a standby status at the completion of a record or playback cycle.

The nominal 108-mc tracking beacon used was a modified version of the transistorized type used in Explorer I. One channel of FM-AM telemetry was included in the design to indicate temperature variations in either the missile pod cover or one of the electronic packages. Output power was a continuous 30 milliwatts.

Based on the expected life of the satellite of 21 days, a chemical battery system rather than a costlier and heavier solar cell and rechargeable nickel cadmium battery system was used. Zinc-silver oxide batteries were chosen because of their high capacity (watt hours per pound) and ability to handle occasional peak loads, such as the communication transmitter.

The antennas employed consisted of two simple slot antennas for reception and two for transmission, a receiving and a transmitting antenna being located on each instrumentation pod of the missile. A typical slot antenna is shown in Fig. 4 which was fabricated from fiberglass honeycomb sandwich material with the conducting surfaces applied by means of an aluminum metal spray process.

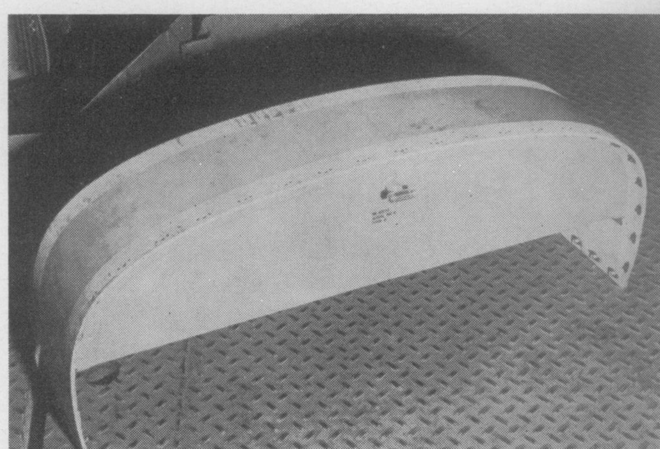

Fig. 4—Slot antenna used with SCORE satellite.

Fig. 5 indicates the manner in which the various components were interconnected; band-pass filters and ring couplers being used to isolate the effects of like units from each other while still providing a low-pass path connection to the antennas located on opposite pods of the missile. The separate transmitting and receiving antennas provided the additional decoupling necessary to eliminate desensitization of the receiving equipment.

The antenna radiation pattern attained was essentially that of a multiwavelength doublet with the attendant deep nulls. The effect of the missile tumbling in its orbital flight was to introduce fades of up to 15 db in the transmission path. The fade margins indicated in Table I were made as large as possible to overcome this effect.

Fig. 6 indicates the over-all configuration of each system mounted on rails on the Atlas missile. The electronic components were coated, where circuit configurations permitted, with a conformal resin coating. All of the major assemblies were further encapsulated in an isocyanate foam, and poured into place within light-weight, polished aluminum canisters. Printed wiring was further used in most units. The finally assembled units, in their canisters, were attached to the mounting rails through isocyanate foam and laminated fiberglass mounts, with the exception of the recorder where solid Kel-F plastic mounts were used. These mounts provided a measure of vibration isolation but, more important, thermally isolated the electronic equipment from the skin of the missile. The over-all configuration withstood accelerations of 10 g from 20 to 2000 cps and $\frac{1}{4}$-inch excursions from 5 to 20 cps.

The thermal design presented unique problems because of the difficulty in providing an adequate thermal environment in the vicinity of the electronic components. A range of +40°F to +120°F was the largest useable, if system performance were to be met. The approach finally decided upon was to use highly polished surfaces on the communication components while the surface of the metallic pod covers were iridited. This was expected to produce a mean temperature of approximately 90°F within the individual packages. The expected low duty cycle of the communication transmitter was not expected to cause an appreciable temperature rise within its canister. Since the temperature compensation problem was not straightforward and was severely limited by payload and development time considerations, the results obtained were not unexpected.

The ground stations were designed to be operated from transportable vans and trucks and included certain minimum requirements. In addition to the radio terminal equipment, including transmitters, receivers, telegraph and telephone terminal equipment, as shown in Fig. 7, it was necessary to provide means for tracking the orbiting satellite with a high gain antenna, recording pertinent signal level and communication data, and automatically sequencing the ground equipment for either transmission or reception with the satellite.

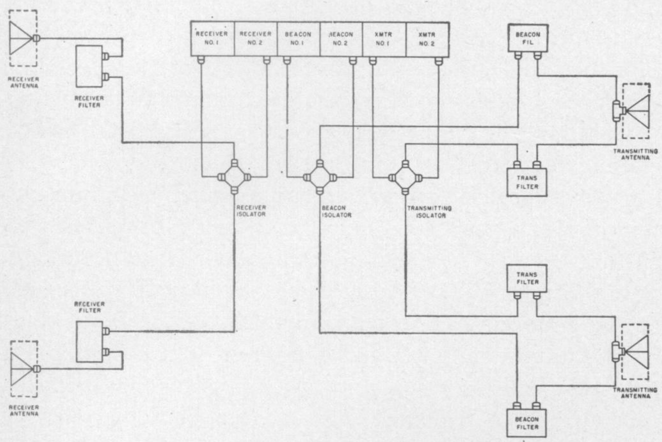

Fig. 5—SCORE antenna connection diagram.

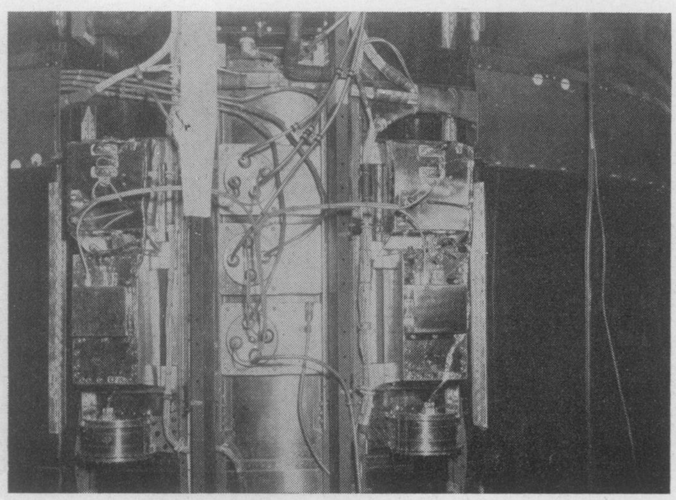

Fig. 6—SCORE satellite components mounted on Atlas 10B missile.

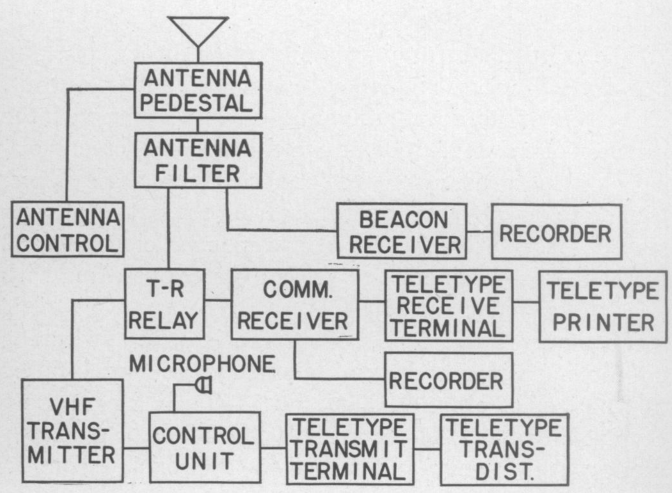

Fig. 7—SCORE ground station interconnection diagram.

The VHF radio terminals were modified commercial types with characteristics as listed in Table I. Backups were provided for all major items in the communications chain with both a 250-watt and a 1000-watt transmitter, for example. These units occupy the center of Fig. 8, an interior view of the operations van. The teletype multiplex equipment was capable of either seven-channel, frequency division multiplex operation or single-channel, 850-cps frequency shift operation. Standard military teletype sets were used for receiving, transmitting and preparing messages on perforated tape.

The control unit shown in Fig. 9 not only originated the command tones transmitted to the satellite, but also automatically accomplished the switching of the receivers, transmitters, teletype machines and other equipment in the proper sequence. At the operators' position, a patch panel was also provided which permitted changing the operating sequence or type of service at a single location.

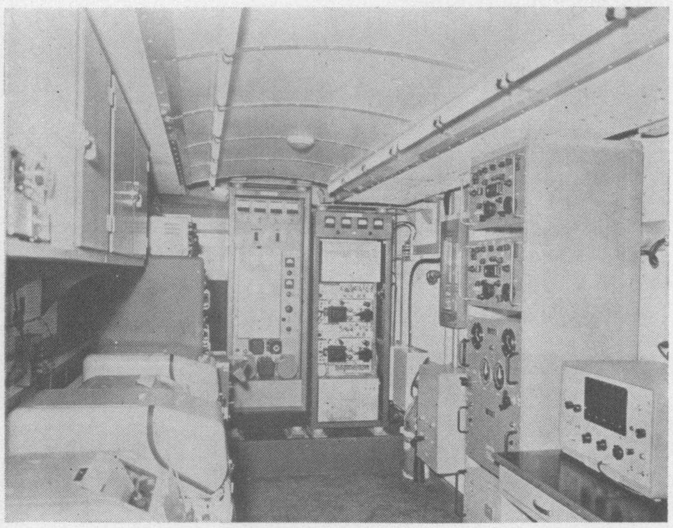

Fig. 8—Interior view of SCORE ground station operations van.

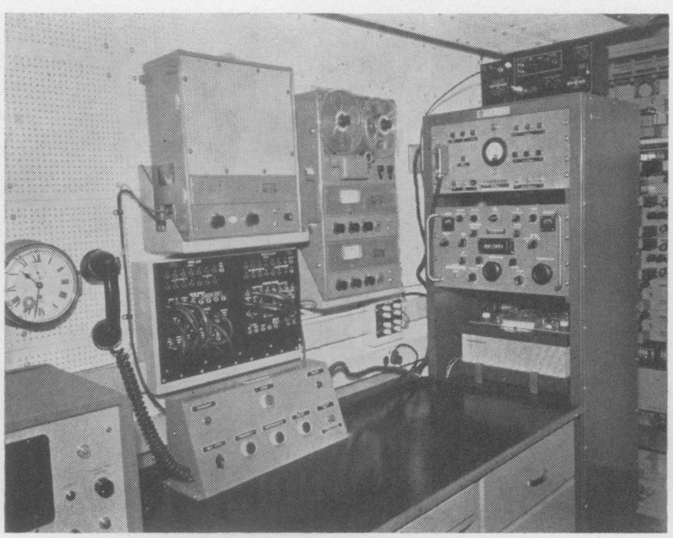

Fig. 9—Operator's console in SCORE ground station.

Recording devices, including magnetic tape recorders and pen recorders, were also supplied to provide permanent records of such things as signal level variations and communication traffic.

The antenna system used (see Fig. 10) was a circularly polarized, quad-helices array with a screen reflector mounted on a modified searchlight pedestal. The gain provided varied from 10 db at the 108-mc tracking frequency to 16 db at the 150-mc communication frequency. Coverage of 360° in azimuth and 90° in elevation was controlled at all but the California station by an operator maximizing the 108-mc signal reception with the antenna positioning controls located near the tracking receivers. At the California station, the azimuth control was slaved to the alidade of an experimental direction-finding equipment while the elevation control was manually varied. Even this partial automation resulted in a marked improvement in tracking accuracy and system performance.

The successful launching of the Atlas missile 10B on December 18, 1958 and the subsequent operation of the communication system installed therein almost instantly assumed importance as an achievement of national and international significance. This fact interfered with the conduct of the technical portions of the project to such an extent that the orderly collection and analysis of data were somewhat neglected for the first week of operation. Therefore, some important clues that might have explained some discrepancies later observed were lost. Qualitatively, the practical operation of a satellite radio relay system capable of spanning intercontinental distances either in real or delayed time was demonstrated conclusively until battery failure occurred on December 30, 1958. For example, communication traffic, both voice, single-channel teletype and multichannel teletype, was carried on a delayed repeater basis in many successive orbits around the earth and was

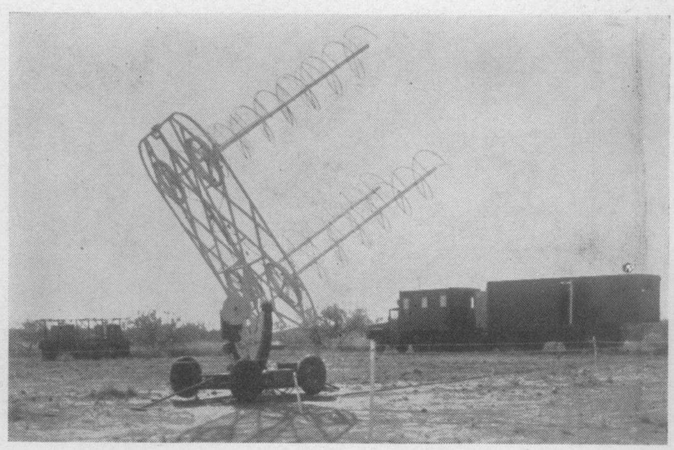

Fig. 10—Exterior view of SCORE ground station showing tracking and communication antenna.

made available individually to the four ground stations at their command.

The ground stations interrogated, received and recorded, for simulated distribution, a total of 78 messages for a total of 5 hours, 12 minutes communication time. Of these, 28 separate messages had been placed in the satellite recorder by ground stations. The remainder were multiple interrogations of previously recorded material. A total of 1 hour and 52 minutes operation of the satellite in the recording mode was involved for these 28 loadings. Eleven real time relays from California to Georgia, a distance of over 3000 miles, were successfully made for a total of 43 minutes of satellite operation. In several instances, unauthorized fortuitous recordings from unidentified stations, with apparently random distribution in the Eastern hemisphere, were received during interrogations by both the California and Georgia stations. In all probability, many fortuitous interrogations of the satellite also were made but there were no means of determining the number of these. This does indicate that a simple tone keyed command system is highly inadequate for future satellite applications.

One set of equipment failed because the tape recorder became inoperative on the first orbit allowing the transmitter to operate continuously and discharge the battery. The other equipment operated exactly as planned other than with somewhat smaller fade margins than had been expected. This satisfactory operation was obtained in spite of the fact that internal temperatures appeared to rise to over 20°F higher than the maximum temperature of 120°F for which the equipment was designed.

This system, which was assembled in record time, demonstrated a world-wide single-voice channel communication capability, over intercontinental distances, in real time, and to and from any point on earth by delayed (store and forward) repeater techniques.

There is no insurmountable barrier to the expansion of the principles demonstrated by this project to the dimensions necessary for an economically practical, world-wide communication system. The communication equipments developments required are well within the state of the art, namely, wide-band transmitters and receivers, a recording facility of complementary capacity and a secure command control system, all capable of providing unattended operation for a year or more by using redundancy and other techniques. It is beyond the purpose of this paper to analyze the bandwidth and time dimensions necessary for economic feasibility, but, in all likelihood, the electronic equipment could be available in about the same time frame as the rocket power necessary to place such a satellite into a proper orbit.