# The Telstar Experiment

A DEFINITIVE technical report on the Telstar Experiment is presented in the July 1963 three-part issue of the *Bell System Technical Journal* published by American Telephone and Telegraph Co., 195 Broadway, New York 7. The 1100-page report contains 38 papers and includes illustrations, diagrams, numerous references, an index and brief biographies of the 114 contributors. The entire report is priced at $3.75. Each part may be purchased separately at $1.25. Abstracts of many of the papers appear below. These abstracts were selected with the intent of presenting to the reader a general idea of the overall content of the Telstar report rather than the contents of specific papers. With this purpose in mind, some of the abstracts have been slightly abridged, and in other instances additional material from the paper has been incorporated in the abstract. An introduction by A. C. Dickieson, Chairman of the *Bell System Technical Journal's* Editorial Committee describes the purpose and scope of the report. Excerpts from his introduction are given below.

Papers on the Telstar experiment which have appeared in this Society's *Journal* include "Optical Measurements on Telstar to Determine the Orientation of the Spin Axis, and the Spin Rate," by J. S. Courtney-Pratt, J. H. Hett and J W. McLaughlin (*Journal*, June, 1963, pp. 462–484); and "Project Telstar: Communications Experiment," adapted by the Board of Editors from an illustrated lecture presented at the Society's 92d Convention by Hugh P. Kelly (*Journal*, February, 1963, pp. 91–96).

## From Part 1

**The Telstar Experiment,** *A. C. Dickieson*

[This report] describes in depth the satellite and ground systems designed for the Telstar experiment. . . . The purpose of this introduction is to set the scene in which the project was undertaken and to state some general conclusions.

Bell System interest in satellite communication had been aroused when, in 1955, Dr. John R. Pierce published calculations showing the possible usefulness of satellites to communication. Dr. Pierce discussed the relations among power, bandwidth, antenna gain, and orbit parameters. Sputnik in 1957 started the procession of man-made satellites.

In 1960 the famous Echo experiments, conducted between a transmitting and receiving station set up by Bell Telephone Laboratories at Holmdel, New Jersey, and a companion station at Goldstone, Calif., designed and operated by Jet Propulsion Laboratory, . . . opened the possibility of applying microwave radio relay technology to transoceanic links. The line-of-sight transmission characteristic of microwaves had prevented their use over the oceans until the possibility of a "microwave repeater in the sky" appeared.

It was decided to design and build an experimental satellite communication system. To this end, the A.T.&.T. Co. entered into a cooperative agreement with NASA; A.T.&.T. to design and construct a satellite and NASA to launch it into space, with A.T.&T paying its own costs plus reimbursing NASA for the cost of launching and certain tracking and telemetry services. . . .

The objectives were:

(1) to look for the unexpected.

(2) to demonstrate the transmission of multichannel two-way telephone, television, data and facsimile via satellite.

(3) to build a very large ground station antenna and find out how to point its extremely sharp beam very accurately at the satellite.

(4) to gain a firm understanding of the problems of measuring orbital parameters and predicting satellite positions.

(5) to gain a better numerical knowledge of the character and intensity of radiation in the Van Allen belt.

(6) to face the problems of designing for long life and reliability of electronic equipment for operation in the space environment. . . .

*General Conclusions*

The Telstar satellite was launched in the early morning of July 10, 1962. On the first pass from Andover, demonstrations were made of speech and television transmission. These transmissions were carried on between distinguished audiences in Washington, D.C., and Andover, Maine. Also the first transmission of a telephoto picture was achieved. . . .

On the next pass, six two-way telephone circuits were set up through the Telstar system, and various people in Washington and Andover talked to people around the United States. Also, high-speed data messages were sent successfully. On the next day, television signals were received from Pleumeur-Bodou and Goonhilly.



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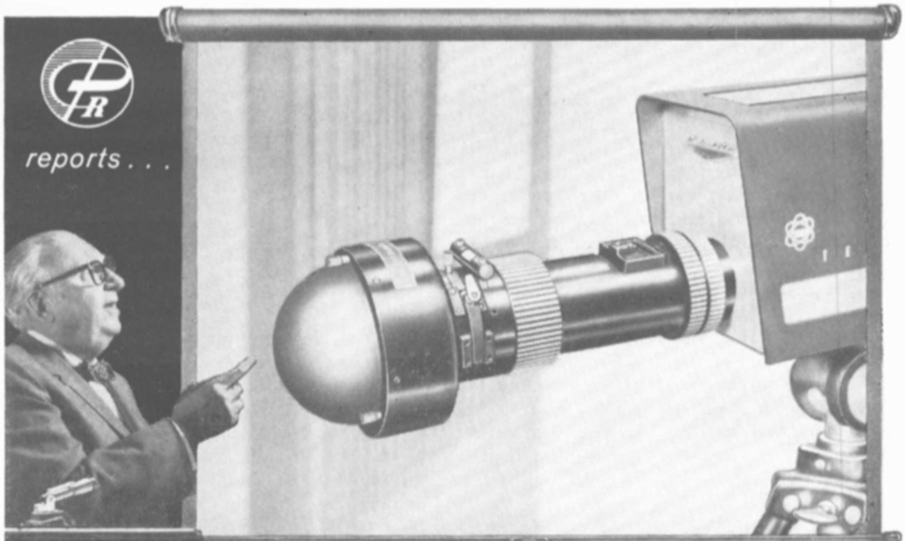
In the next several months, in addition to more than 250 technical tests covering every aspect of transmission, there were some 400 demonstrations. These included multichannel telephony, telegraphy, data, telephoto and other facsimile transmissions. Transatlantic television was demonstrated 47 times, and on 5 of these occasions the transmission was in color. At the same time, a great deal of telemetry data were received, covering conditions in the Van Allen belt, temperatures, degradation of the solar cell plant, spin rate, voltages, etc.

During the fourth week of November, 1962, the command channel began to act erratically. Increasing difficulty was encountered in having it accept commands. Since it seemed possible that control might be lost, arrangements were made to leave the telemetry on continuously rather than switching it on and off. Also, the traveling-wave tube was not energized at all, less loss of control should leave this heavy drain on continuously and thereby ruin the batteries. After the 1,242nd orbit on November 23, 1962, the command channel ceased responding. . . . Laboratory tests had pointed to certain transistors as being the most likely source of trouble. Special codes were devised to take advantage of certain circuit features that would permit by-passing these particular transistors. On December 20, 1962, one of these modified codes was successfully transmitted to the satellite. In subsequent operations, all voltages were removed from the command decoders. As had been predicted, this action allowed recovery of the transistors. [By] January 4, 1963, Telstar responded properly to all normal commands. . . .

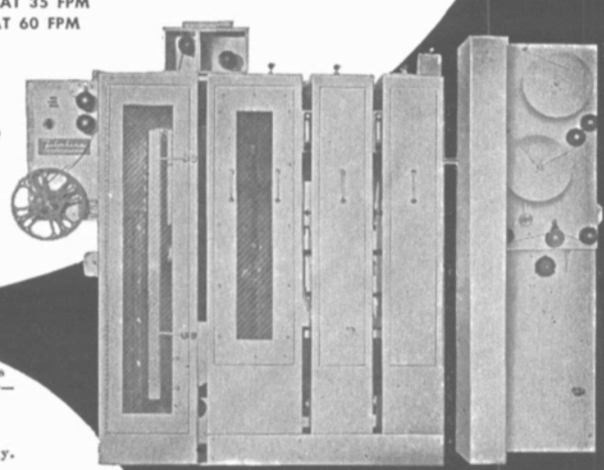
On February 21, the satellite misinterpreted a command and operated the relay that disconnects most of the electronic system from the power plant. Since then to the present writing (March 18) the Telstar satellite has not responded to even the modified commands. (Ed. note: Telstar II, launched during the summer of 1963, differs in certain respects from Telstar I, mainly in the orbit, which has a greater apogee (6,500 statute miles) to avoid regions of high radiation intensity. Also, one of the two command decoders in Telstar II has been modified to use evacuated rather than gas-filled transistors to minimize radiation damage.)

**The Research Background of the Telstar Experiment,** *A. B. Crawford, C. C. Cutler, R. Kompfner and L. C. Tillotson*

For several years before the launch of the Telstar satellite, research effort was directed toward an experiment with an active satellite capable of relaying a broadband communication channel. The intention was to utilize and test a number of novel techniques which had become available, to explore those areas in which the current technology was lacking, and to demonstrate the feasibility of this means of communication. This paper describes some of this work, the background of facts and beliefs on the basis of which a number of important choices were made, and the general state of the radio art upon which the Telstar program was built.







**A General Description of the Telstar Spacecraft,** *R. H. Shennum and P. T. Haury*

The Telstar spacecraft design is discussed with emphasis on the electronics system. The description includes early planning, starting with frequency allocation considerations, and carries the program through electrical and mechanical design, construction and evaluation of the electronics system. The content is aimed at a broad introduction. A description of the Telstar spacecraft is developed chronologically so that the reader may understand how each of the decisions influenced the design and construction which followed. Foremost in practical considerations affecting the satellite design was the selection of the Delta vehicle to launch the spacecraft.

**The Spacecraft Communications Repeater,** *C. G. Davis, P. T. Hutchison, F. J. Witt and H. I. Maunsell*

This paper describes the communications repeater portion of the Telstar satellite. This repeater receives the weak, −60 dbm nominal, FM signal from the earth at a center frequency of 6389.58 mc, shifts the frequency to 90 mc for amplification by the traveling-wave amplifier, and reradiates the signal at a minimum power of 33 dbm. The signals are received and transmitted through separate circularly polarized antennas which are nearly isotropic. The satellite also radiates, for tracking purposes, a very stable microwave beacon signal at a frequency of 4079.73 mc and at a power of greater than 13 dbm. The bandwidth of the repeater is 50 mc, although to date only 25 mc has been used in the experiments because of bandwidth limitations of the maser in the ground receiver.

**The Spacecraft Antennas,** *J. T. Bangert, R. S. Engelbrecht, E. T. Harkless, R. V. Sperry and E. J. Walsh*

The spacecraft employs two microwave antennas for communications and a single VHF antenna for telemetry, beacon and command functions. One microwave antenna centered at 6 gc is used to receive broadband signals from a ground transmitter while the other microwave antenna centered at 4 gc is used to transmit signals to a ground receiver. Each microwave antenna is composed of a large number of circularly polarized radiating elements equally spaced around the equator of the spacecraft and connected to the electronic receiver and transmitter by a complex precision feed system. The VHF antenna is a small multielement helix mounted at the pole of the spacecraft and radiates a linearly polarized signal. All antennas provide nearly isotropic antenna patterns with the axis of symmetry corresponding to the spin axis of the spacecraft. The antenna systems were constructed of light, but rugged, materials and passed extensive electrical, mechanical and thermal tests.

**The Spacecraft Radiation Experiments,** *W. L. Brown, T. W. Buck, L. V. Medford, E. W. Thomas, H. K. Gummel, G. L. Miller and F. M. Smits*

The radiation experiments on the Telstar spacecraft were designed to measure the electron and proton particle distributions in the region of space explored by the satellite orbit and to give information on the integral semiconductor radiation damage produced by these particles. A solar aspect experiment is included with the radiation experiments because of its direct importance to solar cell damage results. The design and the hardware for these experiments are described.

**The Spacecraft Power Supply System,** *D. C. Bomberger, D. Feldman, D. E. Trucksess, S. J. Brolin and P. W. Ussery*

The power supply system in the Telstar spacecraft consists of a solar cell plant to convert solar radiation to electrical energy when the satellite is illuminated by the sun, a 19-cell nickel-cadmium battery to store energy, and a regulation circuit to supply constant output voltages over a wide variation in input voltages. Additionally, the power supply system provides switching to conserve power and allow battery recharging during periods between communications experiments.

**The Spacecraft Structure and Thermal Design Considerations,** *P. Hrycak, D. E. Koontz, C. Maggs, J. W. Stafford, B. A. Unger and A. M. Wittenberg*

This paper covers the general structural and thermal design considerations of the Telstar satellite. The basic objectives were to maintain the electronic components in a near room temperature environment and to protect the electronics package from high-frequency vibration excitation. These objectives were realized by dividing the satellite into two lumped masses, the shell and the centrally located electronics package, and by utilizing nylon lacing for support of the electronics package. The package was provided with an active temperature control, regulating radiative heat flow between the skin and the package. Results of on-the-ground experimental evaluation and of telemetry data are given.

**Command and Telemetry Systems,** *R. C. Chapman, Jr., G. F. Critchlow and H. Mann*

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

**The Ground Transmitter and Receiver,** *A. J. Giger, S. Pardee, Jr. and P. R. Wickliffe, Jr.*

Ground station equipment for the Telstar experiment includes a 6-kmc transmitter and a 4-kmc receiver used for television and telephone channels. This paper describes the overall transmitting and receiving arrangements and presents detailed accounts of the RF and power-supply subsystems. Information is also presented on protection, control and equipment features, and on receiver noise performance.

**The FM Demodulator With Negative Feedback,** *A. J. Giger and J. G. Chaffee*

This paper describes the design and theory of operation of the wideband FM demodulator with feedback (FMFB receiver) used at the Andover, Maine, earth station for Telstar satellite communications tests. Performance data for the FMFB receiver indicate a clear advantage over the conventional FM receiver in many cases. The principal advantage lies in the ability of the FMFB receiver to raise the threshold at which "breaking" occurs for TV and other wideband signals.

# From Part 2

**The Electrical Characteristics of the Conical Horn-Reflector Antenna,** *J. N. Hines, Tingye Li and R. H. Turrin*

The conical horn-reflector antenna was selected for the satellite communication ground station because of its broadband and low-noise properties. Prior to the construction of the full-size antenna, theoretical and model studies of its electrical characteristics were undertaken. These studies consisted of computing gain and radiation patterns for two modes of excitation, constructing of model antennas and measuring them. Results of these studies are presented in this paper together with results of the measurements of the full-size antenna at Andover, Maine.

**Antenna Pointing System: Organization and Performance,** *J. A. Githens, H. P. Kelly, J. C. Lozier and A. A. Lundstrom*

At the Andover, Maine, satellite ground station the 3600-square-foot aperture horn-reflector antenna concentrates the microwave energy in a very narrow beam. This is needed to achieve adequate signal-to-noise ratio in the broadband communications channel provided by the system. Accordingly, it is necessary to provide means for pointing the antenna at the Telstar satellite. The guiding objectives used in engineering and constructing the antenna pointing system are briefly described here.

**The Autotrack System,** *J. S. Cook and R. Lowell*

The autotrack system accurately senses the direction of arrival, at the horn-reflector antenna, of the microwave beacon signal from the communications satellite. When this direction does not coincide with the horn-reflector pointing direction, error correcting voltages are automatically generated to enable the antenna direction system to steer the antenna toward the satellite.

This paper presents a simple analysis of error voltage generation, a description of the system, and a brief discussion of system performance. Measurements at Andover, Maine, have shown that an angular pointing error of less than 0.005 degree is maintained by the antenna when using the autotrack system to follow the Telstar communications satellite.

**Orbit Determination and Prediction, and Computer Programs,** *A. J. Claus, R. B. Blackman, E. G. Halline and W. C. Ridgway, III*

Orbit determination and prediction programs are needed to generate ephemerides for the satellite. Orbit determination is from tracking data consisting of angles only, and is based on a modified version of a method by R. E. Briggs and J. W. Slowey of the Smithsonian Institute. Trends in the data due to perturbations from a Keplerian orbit are removed before this process, and estimates of the orbital elements from individual passes are combined statistically to produce refined estimates. Ephemeris calculation is by a semi-analytic method in which deviations from a Keplerian orbit are obtained by integrating the perturbing forces. The programs to implement these procedures have been written for both the IBM 7090 and the IBM 1620 computers.

**Participation of the Holmdel Station in the Telstar Project,** *William C. Jakes, Jr.*

The facility for satellite communication studies at Holmdel, New Jersey, was originally established to take part in Project Echo. This paper describes the modifications required to participate in the Telstar experiments and the results obtained during operations from July 10 to November 9, 1962. Reception of television from the satellite was successfully accomplished, studies were made of the signal levels, and the changes with time of the satellite spin rate and spin axis orientation were determined.

**Results of the Telstar Satellite Space Experiments,** *P. T. Hutchison and R. A. Swift*

This paper describes how the Telstar satellite has performed in space. Included is information on changes in the temperature, spin rate, spin-axis precession, orbital parameters and power levels of the satellite signals, and comments on the behavior of the electrical circuits in the space environment.

**Results of the Telstar Radiation Experiments,** *W. L. Brown, J. D. Gabbe and W. Rosenzweig*

The data from the particle experiments of the Telstar satellite have been analyzed to provide maps of the distribution of electrons and protons as measured in three of the

Telstar detectors during the period from July through October, 1962. For the protons between 26 and 34 Mev and >50 Mev, the particle distributions are stable in time, but for the electron distribution there is a time decay of the electron flux over most of the region explored by the Telstar orbit. The connection of these observations to the high-altitude nuclear explosion of July 9, 1962, is discussed. The introduction of additional electrons by Russian tests at the end of October was also observed. The particle maps have been used to derive the integral particle exposure of the satellite, which is found to account quantitatively quite well for the radiation damage experiments on solar cells and special damage transistors carried by the satellite. In the main power plant the proton and electron contributions to damage are found to be equal. The integral particle exposure has also been used to compute the level of ionization in different depths of material in order to evaluate the degradation of semiconductor devices in the Telstar canister.

**Results of the Telstar System Communications Tests,** *R. W. Hatch, S. B. Bennett and J. P. Kinzer*

The results of the communications tests on the Telstar satellite system which have been conducted at the Andover earth station are presented. These tests have included successful transmissions of telephone, television and data signals. In addition, measurements of received carrier power, noise, transmission characteristics, linearity, data system errors, absolute delay, and Doppler shift have been made. The results are in good agreement with the expected performance.

## From Part 3

**Component Design, Construction and Evaluation for Satellites,** *D. S. Peck and M. C. Wooley*

Components for a high-reliability system such as the Telstar project are obtained by: (a) design of the component for the required environment, (b) careful control of manufacturing processes, (c) elimination of potential early failures by screening tests, and (d) selection of the most stable components. For passive components, these methods could be applied by using design parameters, suppliers and screening techniques established in the earlier submarine cable program, with consideration being given to the additional effects of the satellite launch and orbit environments.

Semiconductor component designs are selected by qualification tests using accelerated electrical and environmental stress conditions. Screening tests were applied to eliminate early failures, and resulting components were aged from two to six months before selection for the satellite. The recognition of the effect of ionizing radiation on transistors caused the addition of a radiation qualification test, or a screening to assure selection of the least sensitive devices. Tests have shown this screening to be effective for the radiation intensity expected.

Experience with the passive components, and evaluation of the accelerated test results and aging data of the semiconductor devices, indicate that the reliability objective was obtained.

**Nickel-Cadmium Cells for the Spacecraft Battery,** *D. C. Bomberger and L. F. Moose*

The storage battery for the Telstar satellite must undergo frequent charge-discharge cycles; in addition, it is subject to overcharge during a substantial portion of its life. Nickel-cadmium cells were chosen as best capable of satisfactory long-time operation under these conditions. A design and selection program was undertaken to ensure that Ni-Cd cores would meet objectives imposed by battery service conditions, and the cell enclosure was designed to minimize electrolyte leakage. Selection, qualification, and life tests indicated that a storage battery using the cell design would perform satisfactorily. To date, the only failures occurring during continuing life tests have been among cells subjected to 100% discharge daily; this operation is far in excess of the expected duty cycle of satellite cells.

**The Satellite Traveling-Wave Tube,** *M. G. Bodmer, J. P. Laico, E. G. Olsen and A. T. Ross*

The traveling-wave tube amplifier described provides a minimum output power of 3.5 watts at 4.0 to 4.2 gc. Design aspects that lead to lifetimes in excess of 10 years and to tube efficiencies between 35 to 40% are discussed. The tube is focused by an improved version of the single-reversal magnetic circuit. Performance data pertinent to this particular satellite operation are shown. Highlights from the final production run and the subsequent life test serve to illustrate the care with which this TWT has been built.

**The Solar Cells and Their Mounting,** *K. D. Smith, H. K. Gummel, J. D. Bode, D. B. Cuttriss, R. J. Nielsen and W. Rosenzweig*

Objectives in development of the solar plant for the Telstar spacecraft were to provide a power source which would withstand launching stresses and the expected space environment, with optimum end-of-life performance. Radiation damage to the silicon solar cells is the primary factor limiting their useful life; the effect of energetic protons or electrons is the generation of recombination centers in the silicon which reduce the minority-carrier diffusion length and therefore the long-wave response of the cell.

The spacecraft solar cells use the n-on-p structure, in preference to conventional p-on-n structure, to obtain a factor of 3 to 10 increased life expectancy. Response to light in the 0.4- to 0.7-micron range is enhanced by minimum reflectance at 0.55-micron wavelength. Early estimates of electron and proton fluxes in the satellite orbit showed that even the best cells would not give sufficient life without radiation shielding. Therefore the cells are protected against electrons of energy up to 1 Mev by 0.3 gm/cm$^2$ sapphire cover plates. The cell mountings are designed to withstand peak vibration stresses of 200 g and repeated temperature cycles from +65 C to −100 C.

The 3600-cell solar power plant is composed of 300 twelve-cell groups of 1-cm by 2-cm cells, yielding a nominal initial power of 14 watts at 28 volts for any spin-axis orientation relative to the sun. Telemetry information on performance of the solar plant indicates degradation of the shielded solar cells equal to that measured in the laboratory on unshielded cells with a 1-Mev normal incidence flux of 6 by $10^{12}$ electrons/(cm$^2$ day). From this comparison it is estimated that the plant will degrade to 68% of its initial output after two years in orbit.

**The Satellite Ferrimagnetic Power Limiter,** *L. J. Varnerin, R. I. Comstock, W. A. Dean and R. W. Kordos*

To limit the 4080-mc local oscillator signal power input to the beat oscillator modulator of the Telstar satellite communications repeater, a subsidiary absorption limiter was used which consisted of an optically polished sphere of single-crystal yttrium iron garnet (YIG), placed in a resonant transmission cavity between the amplified 4080-mc output of the traveling-wave tube and the BO modulator input. The limiter holds the output power nearly constant above a given input threshold; below this threshold the YIG is linear and introduces only a small loss. The threshold is determined, for a given sample at a given frequency, by the external magnetic bias field. Temperature compensation over the desired range was obtained by orienting the crystal with the d-c magnetic field along a [100] or "hard" axis. The total weight of the limiter package, including the bias magnet and cavity, is 13 ounces.

**The Ground Station High-Power Traveling-Wave Tube,** *R. J. Collier, G. D. Helm, J. P. Laico and K. M. Striny*

The M4040 is a 2-kw CW traveling-wave tube developed specifically for communications applications. It was used as the power amplifier in the Project Telstar ground transmitter. Analytic methods employed in the design of the electron gun, the beam collector, the RF circuit and the output match are presented. Typical performance characteristics and drawings of the tube subassemblies serve to describe the electrical and physical features of the M4040 traveling-wave tube. Methods used to inhibit oscillation and the effects of ion drainage and collector depression on tube performance are also discussed.

**Masers for the Telstar Satellite Communications Experiment,** *W. J. Tabor and J. T. Sibilia*

This paper discusses the sign and characteristics of ruby traveling-wave masers operating at 4 g. These masers, characterized by an average gain of ≈35 db over a bandwidth of 25 mc, are equipped with waveguide input transmission lines, rather than the previously employed