Bell Laboratories **RECORD**

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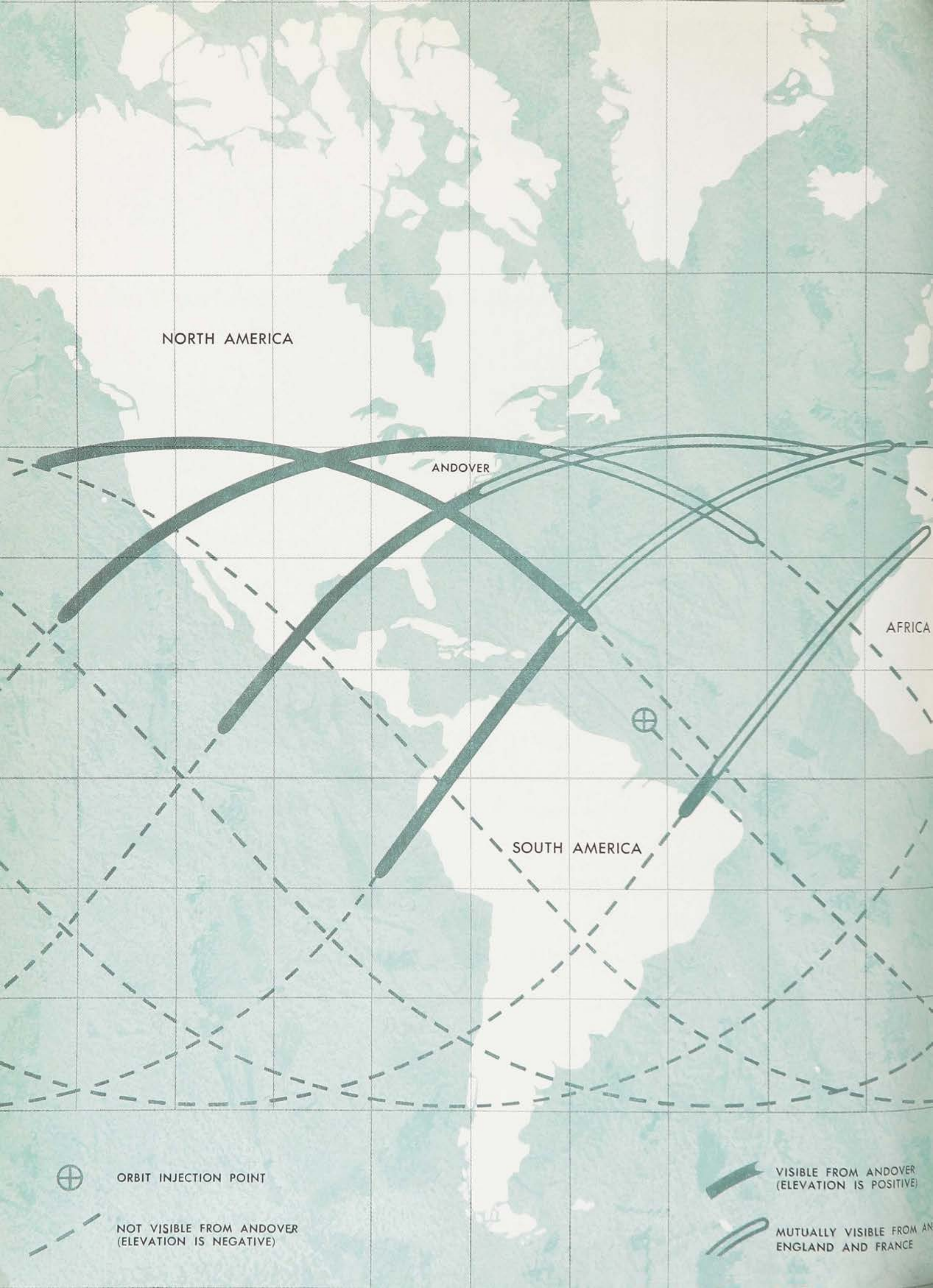
Contents

"A Message for Mankind From Telstar"

On August 12, 1962, historian Arnold J. Toynbee wrote under the above title of the Telstar experiments: "...nothing could have been more timely than a further invention that promises to turn the whole face of the planet into a common home of the united human family.

"...To get to know each other on a world wide scale is the human race's most urgent need today; and this is where Telstar can help us. It can make it possible for each section of the human race to become familiar with every other section's way of living; and once this mutual familiarity is established, there is some hope that we may all become aware of the common humanity underlying the differences in our local manners and customs."


NORTH AMERICA
ANDOVER
AFRICA
SOUTH AMERICA
ORBIT INJECTION POINT
NOT VISIBLE FROM ANDOVER
(ELEVATION IS NEGATIVE)
VISIBLE FROM ANDOVER
(ELEVATION IS POSITIVE)
MUTUALLY VISIBLE FROM AN
ENGLAND AND FRANCE

A. C. Dickieson

This article "sets the stage" for the discussion of the Telstar experiment, which culminated in the transmission of television across the Atlantic on July 10, 1962.

Project TELSTAR

Its Aims and Purposes

THE STORY OF PROJECT TELSTAR began in the Research Department of Bell Telephone Laboratories. In 1955, two years before any man-made satellites circled the earth, Dr. John R. Pierce published calculations showing the usefulness of satellites to communications. He discussed the relations among power, bandwidth, antenna gain, receiver performance, and orbit parameters. Then, in 1957, Sputnik I started the long procession of man-made satellites.

When the National Aeronautics and Space Administration decided to launch a large aluminum-coated balloon to study the effect of various phenomena on orbit stability, Dr. Pierce proposed the now-famous Echo experiments, to investigate the use of passive orbiting reflectors for satellite communication. Bell Laboratories set up a transmitting and receiving station of unusual design at Holmdel, N. J., to work with a companion station at Goldstone, Calif., designed and operated by Jet Propulsion Laboratory.

The Echo experiments began in August, 1960, and produced the first two-way telephone conversations via satellite. They also confirmed predictions of the loss to be encountered in the radio

Map shows portions of early orbits during which the Telstar satellite was mutually visible between the U. S. and Europe, and for Andover-Andover use.

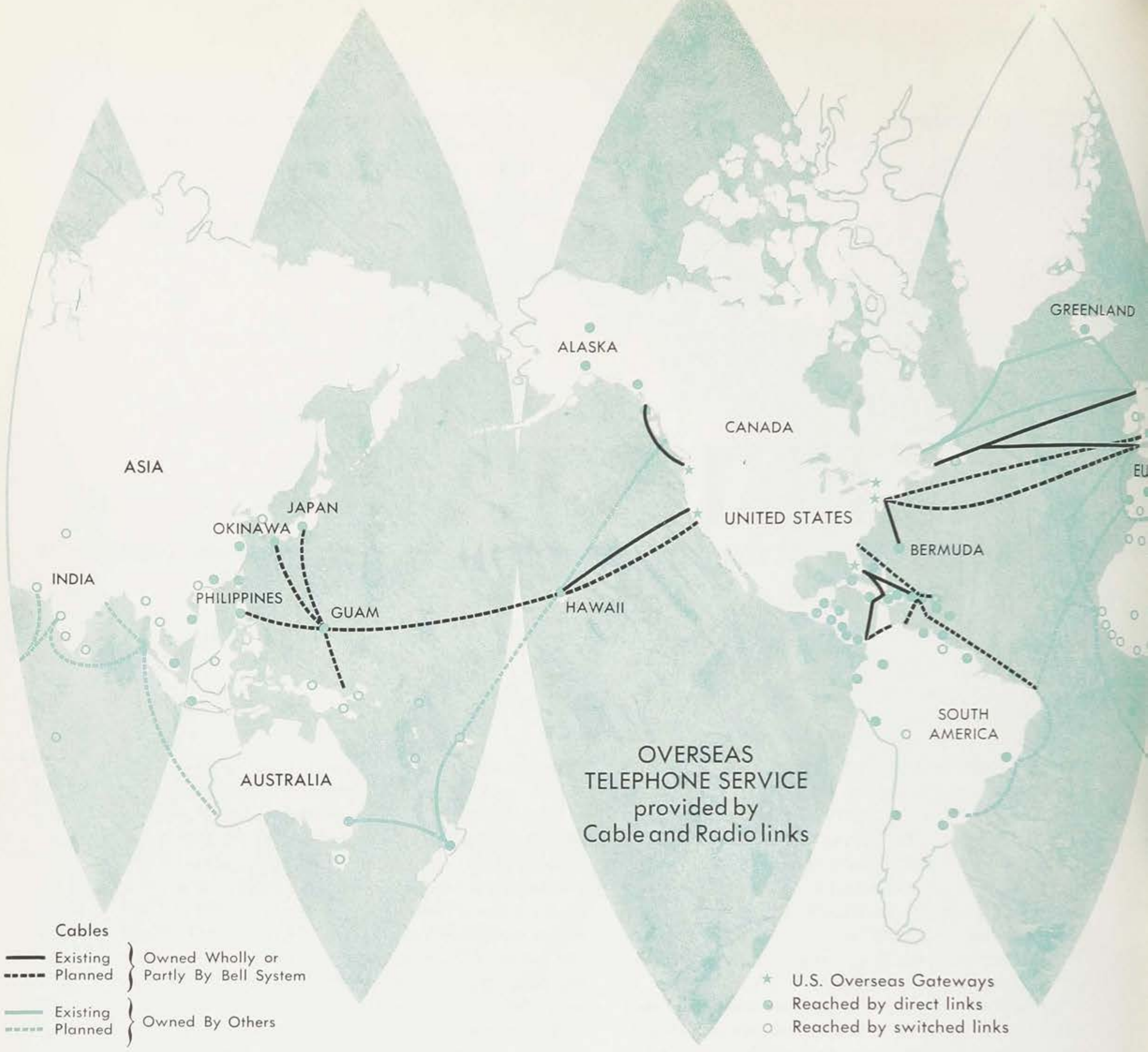
path and the stability and wide band performance of the radio medium (RECORD, *September* 1961).

The results of these experiments were studied at the Laboratories in the context of our long-term interest in overseas communications. We had established our first New York-London commercial circuit by long-wave radio in 1927, followed by short-wave (HF) circuits in 1929. Over the years, a very large network of radio circuits has been built, connecting the United States to foreign countries, as shown in the map on page 118.

By the end of the late 1940's it had become evident that the frequency space available in the HF range was not sufficient to support the volume of world-wide communication that was developing. It was also clear that because of physical limitations inherent in the very nature of the radio transmission medium, the existing telephone circuits in this range could not be made as good nor as reliable as desired.

Therefore, the development of repeatered, multichannel submarine cables for telephone communication was pressed forward, based on research and development work which went back to the 1920's. The first trans-Atlantic telephone cable was opened in 1956, followed in rapid succession by many others. The network of present and planned submarine cables is also shown above.

The Echo experiments opened the possibility of



applying our microwave radio relay technology—widely and successfully used overland in the Bell System—to use in transoceanic links. The line-of-sight transmission characteristic of microwaves requires repeaters on towers at frequent intervals, and this prevented our using it over the oceans. Satellites, however, could provide a "microwave repeater in the sky" making transoceanic microwave transmission a possibility.

As we studied the problem of satellite communication, it became apparent that we had most of the tools to do the job in the fruits of previous research and development in widely scattered fields. The transistor and its solid-state cousins, solar cells, low-noise maser amplifiers, plus long-lived travelling-wave tubes, horn-reflector antennas, FM-feedback receivers—these, and other essential tools were at hand. However, there is a long step between the essential, separate elements and the coordinated, working system. We have learned by long experience that designers face up to and solve all of the design problems only when their products are to be put to the test of actual operation. In earlier phases, it is all too easy to set the tough problems aside for later consideration.

It was decided, therefore, to design and build an actual experimental satellite communication system. To this end, the American Telephone and Telegraph Co. entered into a cooperative agreement with NASA; AT&T to design and construct a satellite, NASA to launch it into space, with AT&T paying its own development and

construction costs plus reimbursing NASA for the cost of launching and use of the Minitrack Stations.

In setting the objectives for the experiment, we were careful not to fall into the trap of attempting to run before we walked. What we wanted was the simplest possible experiment that would answer the most critical questions, leaving until later the "optimization of trade-offs," and the development and construction of a commercial operating system. Thus, the objectives set up for the experiment were:

1. To look for the unexpected.
2. To demonstrate the transmission of multichannel, two-way telephony, television, facsimile and data 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 get 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 electronic equipment for long life and reliability in the space environment.

Accomplishing The Objectives

Study of available boosters led us to the Delta configuration of the Thor as the simplest and most reliable rocket for our purposes. Its relatively limited lifting capacity set a bound of about 175 pounds for a useful orbit. The desired limits on the orbit were established as: apogee (or furthest departure from earth)—3000 nautical miles; perigee (closest approach to earth)—503 nautical miles, inclination to equator 45 degrees. This orbit is depicted on the next page. The apogee is high enough to give good mutual visibility between northeastern United States and Western Europe. Because of the precession, or gradual rotation of the ellipse about the earth, the mutual visibility would vary with time after launch as shown on page 121.

Calculations for a working world-wide system indicate the desirability of circular orbits at 6000-8000 mile elevations; however, the Delta vehicle does not have sufficient thrust to achieve this orbit with the payload we felt necessary, so the compromise described was accepted as most suitable.

As a result of the Echo experiments the decision had been made to install an active microwave repeater in the satellite. While the passive Echo reflector has certain advantages, calculations indicate that the transmitter power required for television bandwidths would be excessive unless balloons of a size well beyond the present state of the art are used.

The weight restriction now forced the decision to install only a single, one-way broad-band amplifier in the satellite, rather than two. This single amplifier, however, not only permitted one full band signal to be sent one-way, but, alternately, two or more narrow band signals could be sent two ways as well. Also, the solar cell power supply was limited, so it was necessary to turn the amplifier on and off by command from the ground to limit the duty cycle.

Ideally, the satellite should present one face toward the earth at all times. This would permit the use of directional antennas, with consequent gain in signal strength. While such arrangements exist as concepts, it was not practicable to apply them in this experiment. It was decided to stabilize the position of the satellite by spinning it around one axis, like a child's top. This fit well into the Delta vehicle—the third stage of the Delta is a solid-fuel rocket which is spun during firing for reasons of stability and equalization of thrust. The pay load is thus spinning at the time of ejection.

The simple, spin-stabilized satellite calls for an omnidirectional antenna with circular polarization if we are to communicate at all times. No design to achieve this exists. It was decided, therefore, to design for as much antenna coverage as we could achieve. Controlling the aspect of the satellite in launching so as to preserve a favorable attitude with respect to the sun would present a suitable part of the antenna pattern while the satellite was in the northern hemisphere.

It was known from previous experiments that there are electrons and protons of various intensities trapped in space in the earth's magnetic field, in vast belts called the Van Allen belts. It was also known that such radiation could seriously reduce the life of solar cells, as well as that of other semiconductor devices. However, the data available on the Van Allen belt radiation were not sufficiently detailed to permit us to design a satellite on an engineering basis. We therefore decided to include a rather complicated set of sensors and measuring devices to fill out our numerical knowledge of space radiation, for use in future experiments.

Clearly, to get this information and other useful data back to earth required radio telemetry. Since we wanted data from parts of the orbit not visible from the Bell Laboratories stations, it was made part of the cooperative agreement with NASA that their Minitrack Stations around the world, perhaps most commonly known for their use in Project Mercury, would collect telemetry data for us. Thus, the telemetry frequency was chosen in the band for which the Minitrack Stations were already equipped, around 136 mc.

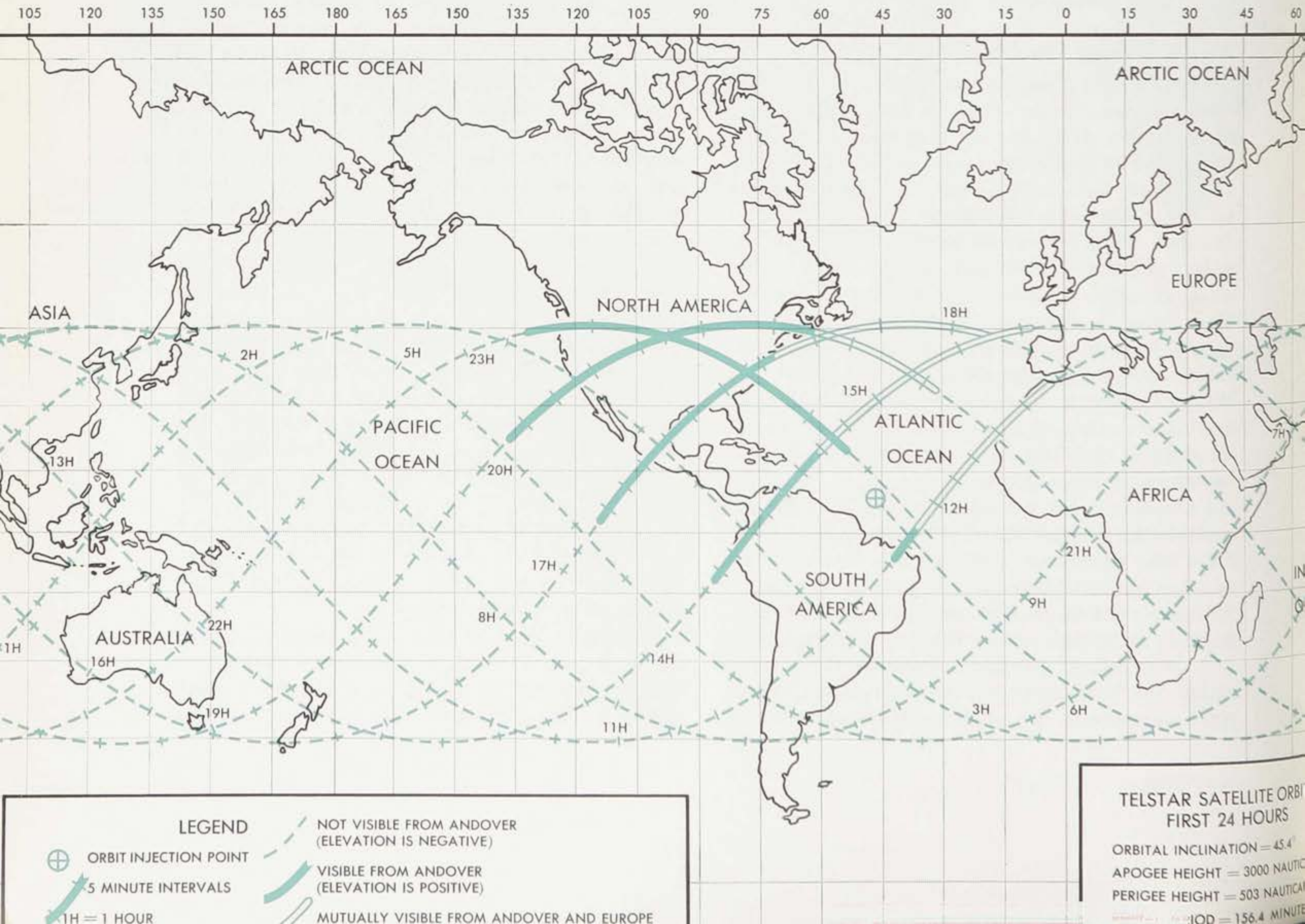
At the same time, the 136-mc carrier radiated from the satellite serves as a beacon which the ground stations can use for finding the Telstar satellite in the sky, as well as for rough tracking purposes by an antenna that locks on and follows automatically—"auto tracks." The same antennas, using a frequency around 120 mc, are used to send commands up to the satellite, for turning the microwave repeater on and off and for other functions.

The choice of frequencies for the communication repeater was more complicated. Previous research had indicated that the preferred frequencies lie between 1000 and 10,000 mc. In the United States, and generally in the rest of the world, these frequencies have all been allocated for various terrestrial uses, with a few narrow bands available on a "shared basis" for space research. Satellite communication, the newcomer, had to work its way into this established pattern. The provision of adequate frequency bands for development of worldwide satellite communication services presents a complex international problem, but good progress is being made toward a solution by the work of the International Telecommunications Union and its subsidiary technical organization, the International Radio Consultative Committee (CCIR).

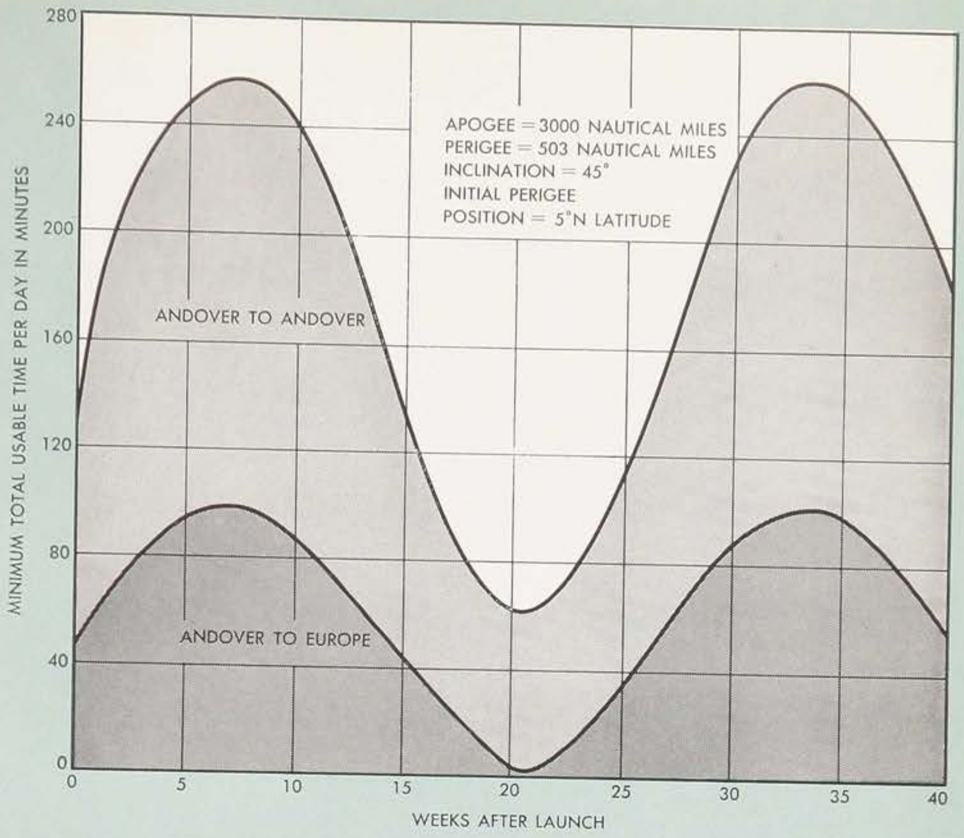
In the meantime, though, it seemed most practical to assume that, at least initially, satellite communication of the Telstar type would have to share frequencies with terrestrial systems; hence it became important to examine the conditions of compatibility. After considerable study, and consultation with various foreign communication agencies, it was concluded that, for a start, it was most practical to share frequencies with the point-to-point, common carrier microwave relay systems. These are the frequencies in the 4000 mc range used by our TD-2 systems, and in the 6000 mc range by TH. As a result, the AT&T applied to the Federal Communications Commission for research-experimental licenses for satellite and ground stations, and received them.

It was decided to use the 4000-mc band for the

Orbits of first nine passes of the Telstar communication satellite on July 10, 1962.



Graph shows variations in the time available for transmission via the Telstar satellite for both intercontinental and "up-and-down" transmission.



down direction, from satellite to ground, so as to minimize the deleterious effects of rain on the received signal. The 6000-mc band is used for the up direction. The wide frequency separation between the two directions simplifies sharing of the ground antenna, and minimizes interference effects in the satellite.

Sharing of frequencies with terrestrial systems obviously had an effect on the choice of sites for ground stations. We wanted to be in the northeast part of the United States, to minimize the great circle distance to Western Europe. This would yield the greatest usefulness of a satellite in the orbit already selected. We wanted to be relatively far from large cities, and from existing or probable microwave radio relay stations.

Fairly flat ground was desired for the initial installation of one, and later several, large ground antennas. For best protection against interference, the site should be ringed by hills. Finally, the site should have road access, power, water, and living facilities near by. The Long Lines Dept. of AT&T found all of these at a location near Andover, Maine.

Study of the over-all system parameters led to the conclusion that a large ground antenna with minimum power in the satellite would be the economical choice. Research work at Holmdel had culminated in the construction of a horn-reflector antenna with an aperture 400 square feet in area. This was used very successfully in the Echo experiments. The particular virtue of the horn-reflector type is that it has very low side lobes; hence it does not pick up extraneous noise from the ground when it is pointed even a few degrees above the horizon. Besides being very broadband, it can be designed so that receiving equipment remains in essentially fixed position, while the antenna is pointed freely in all directions.

It was decided to design and build a horn-reflector antenna much larger than the Holmdel version—with 3600 square feet of aperture. The very sharp beam of such an antenna would stretch our ability to point it accurately at the satellite. To perserve the accuracy of the antenna, and permit it to operate in all kinds of weather (including the 90 inches of snow to be expected in Maine), an air-inflated radome was added.

Study of the antenna pointing problem led to the decision that the satellite should radiate a low level microwave signal or beacon whenever the communications transmitter is turned on. This has two uses. It permits very precise tracking of the satellite, and hence good determination of its orbit. Also, it permits us to design an auto-track system that automatically optimizes the pointing of the big horn-reflector once its beam is placed on the satellite.

We now had the main outlines of the system planned. There remained the work of designing, constructing and testing the hardware. This very large effort is described in the following papers.

To insure reliable communication with the Telstar satellite, Laboratories engineers conceived a ground-based antenna structure of unusual size and accuracy. This is the story of its mechanical design and construction.

Design and Construction Of the Horn Antenna

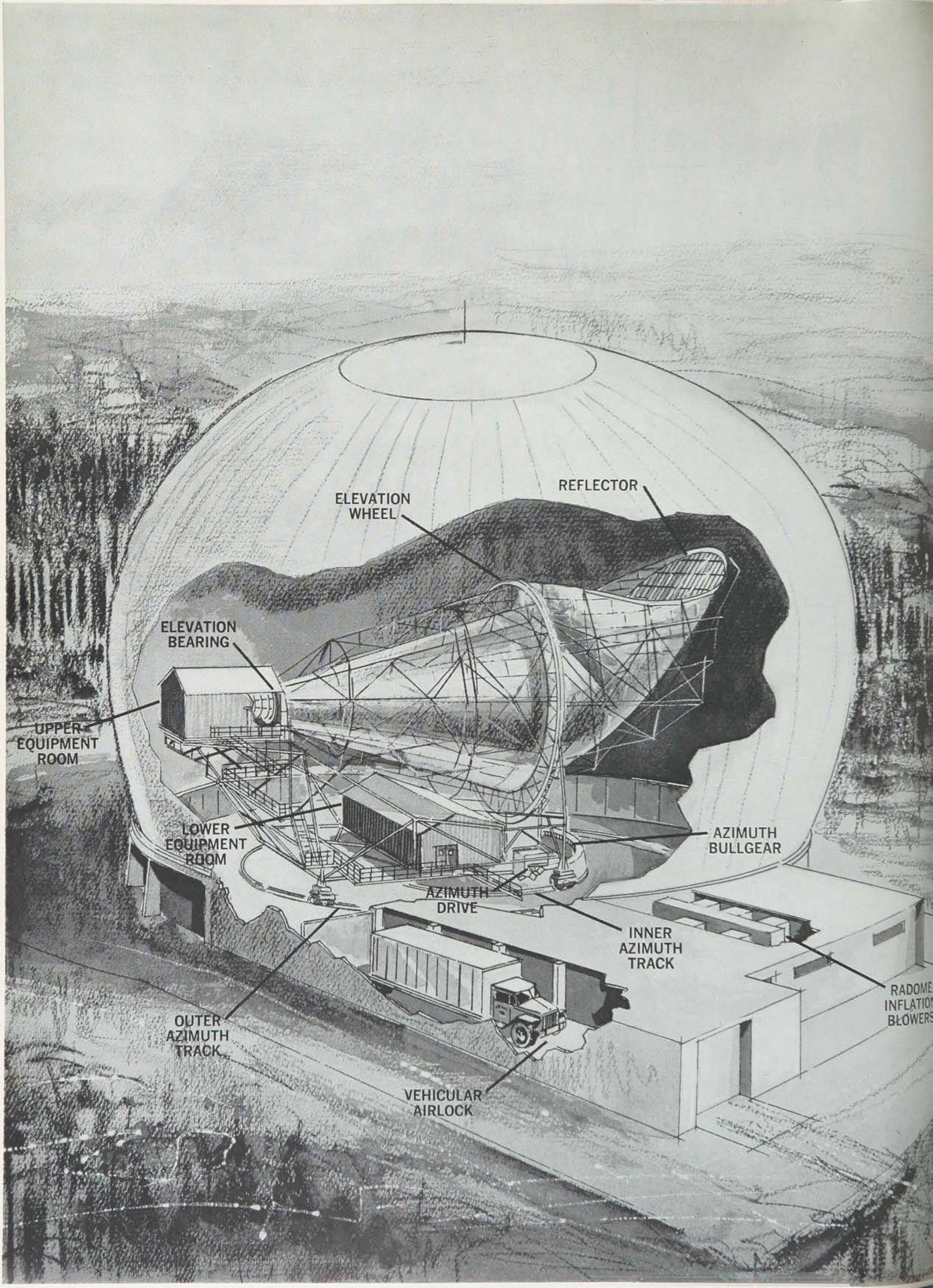
R. W. Blackmore

ON A SNOWY DAY in March, 1961, two Laboratories engineers, in the midst of a timberland tract near Andover, Maine, witnessed the driving of a stake through two feet of snow to establish ground zero for the first Telstar communication antenna. This was an important milepost in a chain of events extending back to early 1960 and culminating in the history-making trans-Atlantic television transmission via the Telstar satellite in July, 1962.

The horn-reflector antenna at Andover can best be visualized as two separate structures: an elevation structure rotating about a horizontal axis, and an azimuth structure rotating about a vertical axis. The elevation structure supports a conical horn approximately 90 feet long. At the horn's apex is a room, or cab, containing the transmitting and low-noise receiving equipment; at its large end is a reflector—a sector of a paraboloid enclosed by a cylindrical shield forming an aperture about 68 feet in diameter.

As shown on page 124, the rotation of the elevation structure around the axis of the conical horn is provided for by a circular track at the large end and by a 10-foot-diameter ball-bearing near the horn apex. Four "trucks" running on two concentric tracks support the azimuth structure. The entire antenna structure—177 feet in length, 94 feet high, weighing approximately 380 tons—is covered by an air-supported radome 210 feet in diameter. The performance characteristics of the antenna are listed in the table on page 127.

During the spring of 1960, Laboratories engineers were busily engaged in feasibility studies of a greatly enlarged version of the horn-reflector antenna already under test and later used so successfully in the Project Echo experiment. The Echo antenna has an aperture of approximately


REFLECTOR
ELEVATION
WHEEL
ELEVATION
BEARING
UPPER
EQUIPMENT
ROOM
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EQUIPMENT
ROOM
AZIMUTH
BULLGEAR
AZIMUTH
DRIVE
INNER
AZIMUTH
TRACK
OUTER
AZIMUTH
TRACK
VEHICULAR
AIRLOCK

400 square feet. The proposed 3600-square foot aperture for the new antenna would require a structure approximately 27 times the cubic size of the Echo antenna. Initially, the new antenna was to have been erected at Crawford Hill near the Holmdel Laboratories—the same location as the Echo antenna.

Antenna Function

The original plan was to use the new antenna only as a research device. However, by December, 1960, it was decided to use the antenna as a prototype satellite communications terminal with the capability of working—via an active satellite—with antennas overseas. This change had a significant effect on the initial planning. First, while the Holmdel location was satisfactory so far as radio interference was concerned for the frequencies specially selected for the experimental operation, it did not provide an adequate degree of isolation for the 4- and 6-kmc bands assigned for satellite communication. Proximity to Europe was also a consideration. Accordingly, soil test borings in progress at Crawford Hill were discontinued, and the Long Lines Department of AT&T began an extensive search for a suitable site.

This change in function had a direct effect on the design of the antenna. If it were to be employed only as a research facility it could operate on a "weather-permitting" basis. However, as a part of a prototype satellite-communication link, the antenna would have to operate around-the-clock. An analysis of the effects of wind, snow, ice, and solar heating on the pointing accuracy of the system indicated the need for a protective radome for the antenna.

Based on extensive experience with radomes for military radar antennas, the Laboratories felt that the only type of radome of the required size and electrical properties capable of being designed and fabricated within the allotted time would be an inflatable structure. Accordingly, in December, 1960, requests went out to a number of concerns for proposals for what was to become the largest radome ever constructed. Concurrently, tests were begun at the Laboratories to evaluate the transmission loss and noise contribution of various materials considered for the envelope of the radome. With the decision to cover the antenna with a radome, every effort was made to keep the turning diameter to a minimum.

Considering its size, the horn-reflector antenna at Andover, Me., has the same tolerances as a precision-made watch. It is covered by a radome weighing 30 tons—the largest radome ever built.

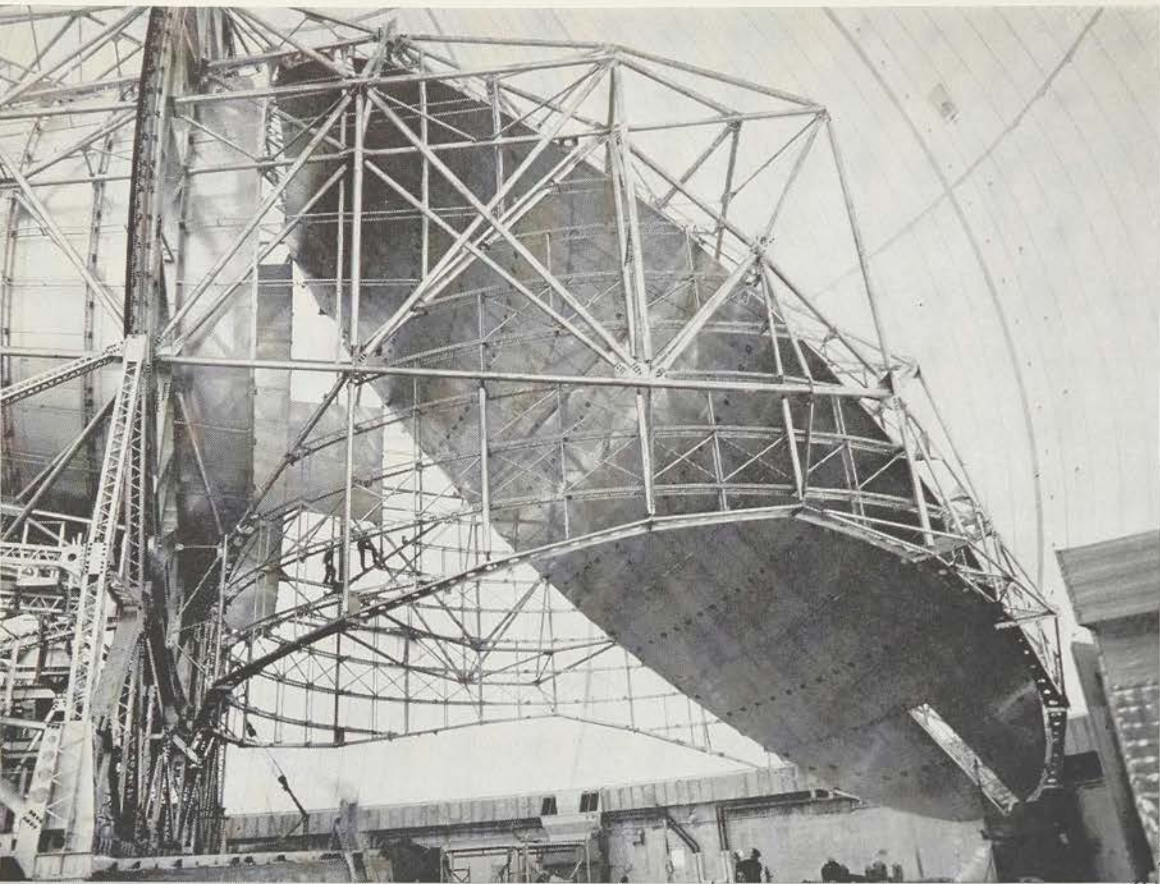
Another effect of the change in antenna function was a considerable increase in the amount of electronic gear that had to be mounted on the structure. As a research instrument, the antenna would have required a moderate amount of electronic equipment in the cab at the horn apex; now it became necessary not only to increase the size of the cab, but also to provide a lower room on the rotating structure beneath the horn for additional electronic equipment.

Schedule considerations played a dominant role in nearly all of the engineering decisions during late 1960 and early 1961, since the project time table afforded little opportunity for extensive investigation and exploratory development programs. Laboratories engineers selected hydraulic servo drives to power the elevation and azimuth motions because of the proven performance of these drives on other large precision antenna mounts. They decided to use positive gear drives for elevation and azimuth rather than rely on wheel-to-rail friction values. The concept of a pintle bearing, fixed at the azimuth axis, was developed as the most satisfactory means of constraining the structure to an accurate circular path during azimuth rotation. If this bearing were to support any appreciable portion of the structure's weight, its design would become unduly complicated. Accordingly, a diaphragm, which had ample resistance to horizontal reactions but little to vertical, was provided to connect this bearing to the structure. Opposing drives were provided in both elevation and azimuth with the dominating drive system always being resisted by a "back-pedalling" drive system which eliminated all back-lash from the drive gear trains.

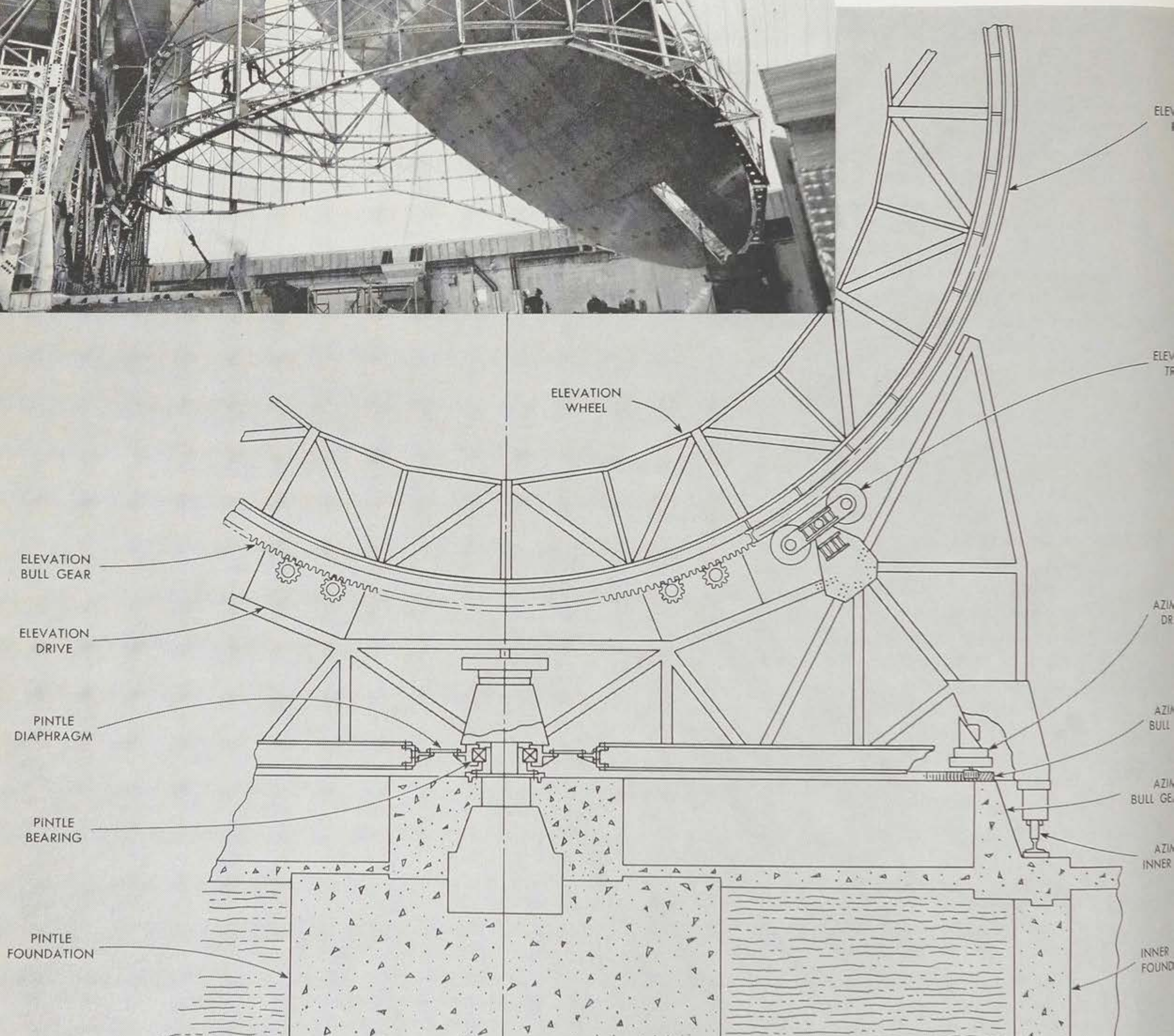
Construction Materials

Steel was used for the basic antenna structure because of its relatively low cost and its availability in the numerous structural shapes needed to obtain maximum rigidity with minimum weight. Laced-box girders, fabricated from angle sections by welding, were selected as the basic elements for the azimuth structure. Because of more stringent weight-deflection requirements, welded-steel tubing was used for the elevation structure forming the framing for the cone, shield, and reflector. High-tensile strength bolts were used for field-assembly of shop-welded subassemblies to facilitate erection and assure an antenna structure of maximum rigidity.

Aluminum honeycomb panels were used for the horn, shield, and reflector surfaces. These panels, consisting of two .020-inch sheets of aluminum



The photo to the left shows the reflector with most of the aluminum honeycomb panels installed. Features of the azimuth and elevation support and drive systems are shown in drawing below.



AZIMUTH AND ELEVATION SUPPORT AND DRIVE SYSTEMS bonded to an aluminum honeycomb core, offered the best combination of physical properties. Their use resulted in a surface rigid enough to meet all deflection requirements yet weighing only about one pound per square foot.

Other decisions made by Laboratories engineers at this time were:

(1) to use conical azimuth truck wheels to permit pure rolling contact between azimuth wheels and rails,

(2) to restrain the rotating elevation structure horizontally by the large ball bearing at the cone apex and to provide ball splines at the elevation truck wheels to accommodate any differential movement resulting from temperature differences between the elevation structure and its supporting cradle, and

(3) to determine the size of the vehicular air lock for the radome—keeping in mind that all equipment, materials, and components involved in the erection of the antenna would have to pass through it.

Site Planning And Structural Considerations

By February, 1961, AT&T located a 1000-acre site near Andover, Me., for the Telstar ground station. In early March, at a conference at the AT&T offices in White Plains, N. Y. Bell System experts and subcontractors were assigned the responsibilities for clearing, surveying, test boring, and providing access roads and rough grading. Project engineers described the site and reviewed a plan for accomodating the initial horn antenna and as many as four future antennas, all to be deployed around a central control building.

Meanwhile, structural analysts endeavored to design a structure sufficiently rigid to satisfy basic deflection limitations but at the same time staying within a reasonable weight limitation so that wheel, rail, and bearing sizes already selected would not have to be increased. At this time, the complement of electronic gear to be mounted in the upper and lower equipment rooms was not completely defined, and accurate weight estimates of most of the items were not available. In the case of the upper equipment room particularly, increased equipment weights could have resulted in increased beam sizes carrying down through the entire structure. Thus, each member had to be re-examined to evaluate its capability of sustaining the augmented structure above it. In these structural considerations, not only did stiffness, weight, and natural frequencies for the entire structure have to be determined, but even the resonant frequency of individual members was examined. The concern here was that vibrations of individual members might excite larger portions of the structure.

HORN-ANTENNA PARAMETERS	
Transmission Characteristics	
Typical signal	2000 watts
Frequency	6.4 kmc
Gain	61 db
Beamwidth	0.16 degrees
Receiving Characteristics	
Typical signal	1×10^{-12} watts
Frequency	4 kmc
Gain	58 db
Beamwidth	0.22 degrees
Pointing Accuracy	0.019 degrees
Maximum Velocity	
Azimuth	0.025 radians/sec
Elevation	0.020 radians/sec
Maximum Acceleration	
Azimuth	0.007 radians/(sec)^2
Elevation	0.002 radians/(sec)^2

One step taken to keep structural weight to a minimum concerned the wall thickness of the steel tubes comprising the elevation structure. The conventional practice in a design using members of this type is to allow for a certain reduction in effective wall thickness (brought about by internal corrosion) by specifying a wall thickness greater than actually required. The increased weight resulting from applying this practice to the hundreds of tubular members of the elevation structure was prohibitive. Consequently, to prevent corrosion, Laboratories engineers devised a means of purging (with dry nitrogen) and sealing each tubular member.

In another instance, substantial weight reduction was achieved by a reconsideration of the reaction forces associated with the azimuth-drive system. The structure proposed for carrying the drive pinions down to the level of the bull gear mounted adjacent to the inner azimuth track was found, upon analysis, to be too flexible. Rather than "beef up" the structure to meet the stiffness requirement, the designers raised the level of the entire bull gear by constructing a wall to a four-foot height above rail level. In this manner, critical rotating structure weight was traded off for noncritical foundation weight.

The estimated weight for the complete antenna as of the end of February, 1961, was 344 tons; the final weight was 380 tons. That the estimate could be within 10 per cent at that time appears remarkable in view of the fact that final electronic equipment requirements were not established until months later and structural detailing had not yet been started.

Foundation Construction

By mid-May, excavations for the antenna foundation began at the Andover site. The most critical portion of the foundation is that supporting the inner azimuth rail which, because of the configuration of the antenna structure, assumes about two thirds of the entire 380-ton load. Vertical deflections of this rail must be minimized for pointing accuracy and servo-drive considerations. Test borings and preliminary excavations indicated the presence of granite bedrock between 15 and 20 feet below the surface and a water table close to the surface. In view of these soil conditions and minimum deflection criteria, it was originally decided to carry the rail foundations to bedrock by driving steel piles. When pile driving proved impractical because of the number of large boulders, the entire area was excavated and the concrete foundation was poured on the bedrock.

In addition to the rail supports, the other main elements of the foundation are the pintle portion and the wall to which the inflatable radome is secured. As mentioned earlier, all horizontal reactions of the antenna structure are absorbed by the pintle bearing. Because the antenna might, under extreme conditions, such as the collapse of the radome, be subjected to horizontal wind loads of 300,000 pounds, it was decided that the pintle foundation should also be anchored directly to bedrock.

The top of the radome foundation was established as 14 feet above azimuth rail level to provide a radome-foundation interface all in one plane (most favorable condition for uniform stress distribution within the radome fabric) and to provide the required head room in the vehicular air lock. With a maximum wind load of 100 mph and maximum inflation pressure of 0.175 psi, the radome foundation must withstand an aerodynamic lift of 844,000 pounds, an inflation pressure lift of 730,000 pounds, a drag of 221,000 pounds and an overturning moment of 8,700,000 pound-feet.

In late May, it became apparent that some sort of construction shelter would be required to assure that the erection of the antenna could proceed throughout the autumn months without being delayed by bad weather. Such a shelter would also provide a suitable environment for certain critical operations such as rail welding and grinding, and reflector-panel alignment. In addition, the shelter, when pulled down to a partially inflated condition, would serve as an excellent "shoe horn" for slipping the final radome over the structure. Procurement of the shelter by late September appeared feasible in view of the fact that the shelter did not have to meet the rigorous electrical and mechanical requirements imposed on the radome.

Work on the foundation proceeded satisfactorily, and, by the end of August, the first member of the antenna structure—the pintle bearing assembly—was emplaced on the foundation. The inflation blower rooms, air locks, and mounting arrangements for the construction shelter were ready by the end of September and during the night of September 29, when the wind had subsided, the shelter was inflated without incident. The blowers, handling 3.8 million cu. ft. of air in the process, completed the job in about two hours.

Antenna Erection

Installation of the interface hardware between antenna foundation and structure now proceeded in good order, and towards the end of October, the azimuth trucks were placed on the rails and the azimuth structure framing began to take shape. In early November, the six segments comprising the elevation wheel were laid out horizontally on timber "cribbing" from which the assembled wheel would be lifted into its final position. The segments were bolted together and the 12 elevation rail sections installed and welded. Then began the critical operation of grinding the 220-foot circumference of the rail to provide a continuously smooth and concentric supporting track upon which the elevation structure would roll as it rotated.

The stage was now set for the most spectacular phase of the erection of the antenna—the lifting of the assembled 70-foot diameter wheel (weighing some 50 tons) into position on the supporting elevation trucks. This operation was performed in two stages. First, three cranes, lifting at the 10, 12, and 2 o'clock positions of the wheel, raised it to a nearly vertical position. Then, after the cranes were redeployed, the entire structure was lifted some 12 feet upward and positioned on the supporting trucks. The elapsed time for the first operation was about five hours, for the second, three hours. Both operations had to be conducted with painstaking caution to make sure that the movements of the three cranes were synchronized. For while the concerted capacity of all three was adequate to handle the wheel weight, any uncoordinated action on the part of one of the three crane operators which might cause his rig to assume either more or less of its proper share of the total load could have led to disaster.

With the successful erection of the elevation wheel, the rafter structure for the cone could be started. By mid-December, the cone structure was rotated to establish the geometric axis for installation and alignment of the cone panels. In late December, workers erected the reflector rafter structure.

Meanwhile, the azimuth rail segments were welded together and the welds ground to form two continuous and smooth rail systems. Then, using rail-leveling jacks, the tracks were leveled to within 1/32 inch. After being tested by rotating the fully loaded antenna structure, the tracks were later re-checked and re-leveled.

In mid-January, the elevation structure was rotated to determine the center of rotation of the reflector support structure so that reflector-panel installation could be started. This procedure is somewhat analogous to determining the center of a room before starting to lay floor tiles. The panel-alignment procedure involved the sighting of targets on panels from two theodolite positions, feeding observed angles into a computer, and adjusting panels in accordance with correction factors produced by the computer program.

Four points on every other 3 by 12-foot panel were "shot," computed, and adjusted. The intervening panels were faired-in with the adjusted panels. Schedule considerations did not permit exactly meeting the desired .040-inch tolerance for the entire reflector surface, but the surface quality achieved proved more than adequate in directing and concentrating radio energy to and from the Telstar satellite. For the alignment procedure, the elevation structure was oriented with the reflector surface pointing downward to facilitate optical sighting from the theodolites positioned on the floor of the radome arena. At this point, the antenna structure was essentially complete. With the final adjustment of the drive and data-gear meshes, it was made available in mid-February to engineering groups responsible for tuning the antenna servo-drive systems and making preliminary radiometry measurements.

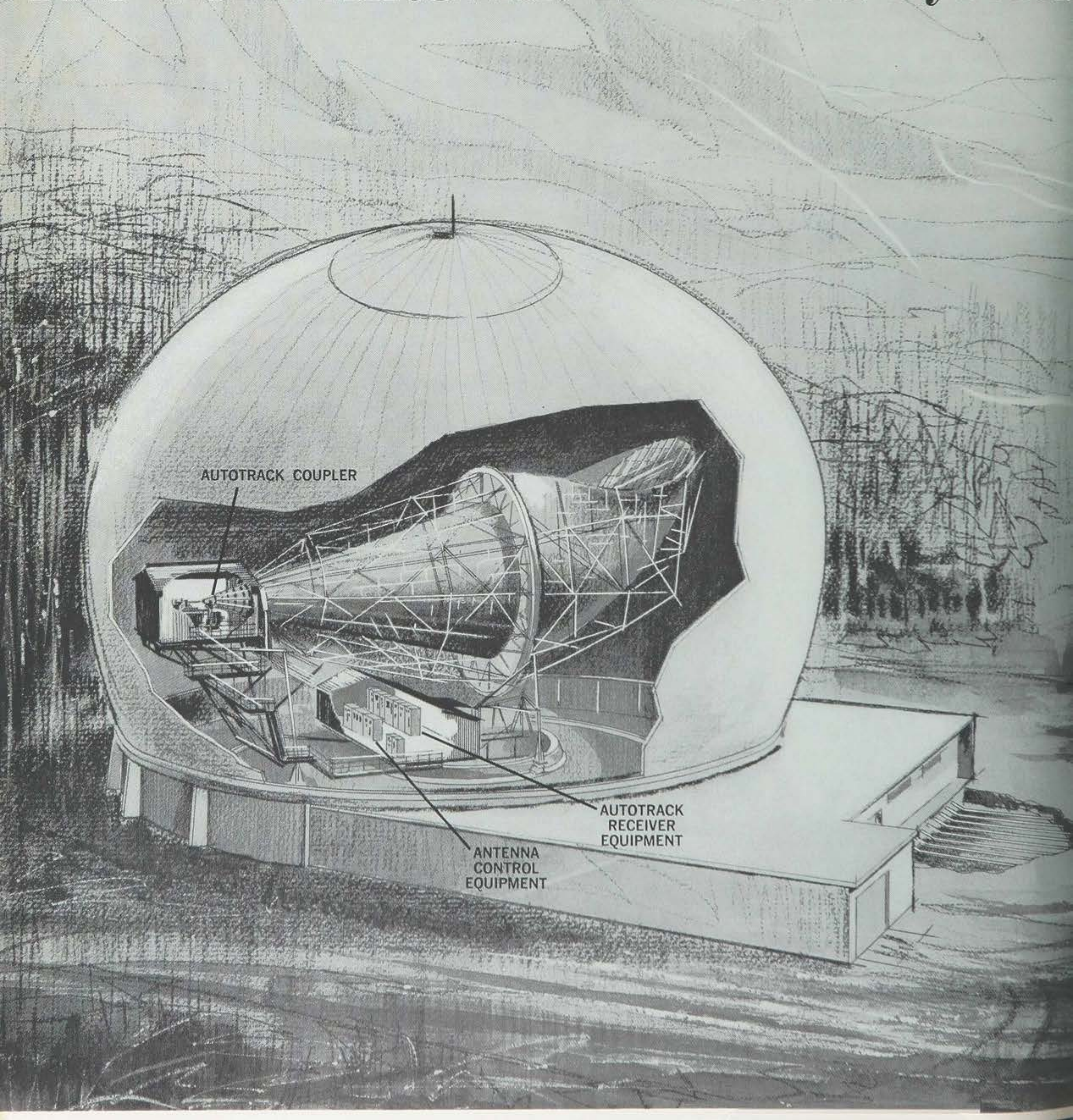
In mid-April, with the arrival of the permanent radome on the site, the construction shelter was reefed to approximately half of its full height, and the 30-ton radome was installed over it and inflated. The construction shelter was then deflated and removed in sections. The stage was now set for final antenna calibration which Laboratories engineers accomplished by training it on radio stars. These sources of radio energy, some of whose locations are known to an accuracy of 0.005 degree, permitted checking antenna-pointing angles to well within the required 0.019 degree tolerance and made the acquisition of the Telstar satellite as it cleared the Andover horizon on the evening of July 10 a matter of routine.

Here, then was the final payoff for over two years of intense Laboratories engineering effort, from conception of design to surveillance of panel alignment—all dedicated to the completion within the allotted time of an antenna structure of unprecedented size and accuracy.

Maneuvering the 50-ton elevation wheel into position—the second phase of an eight-hour operation.

R. Klahn and E. R. Byrne

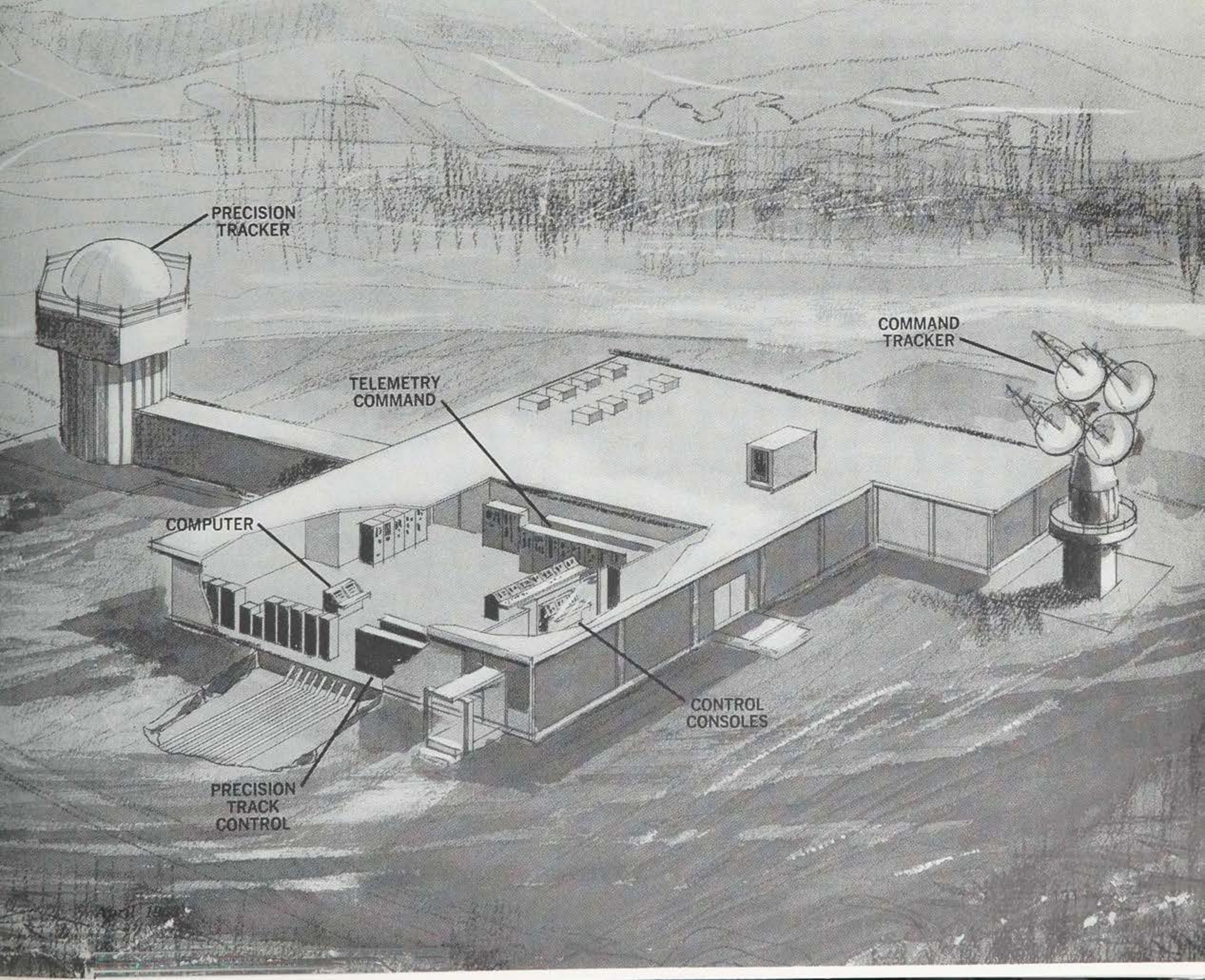
The Horn-Antenna Direction System

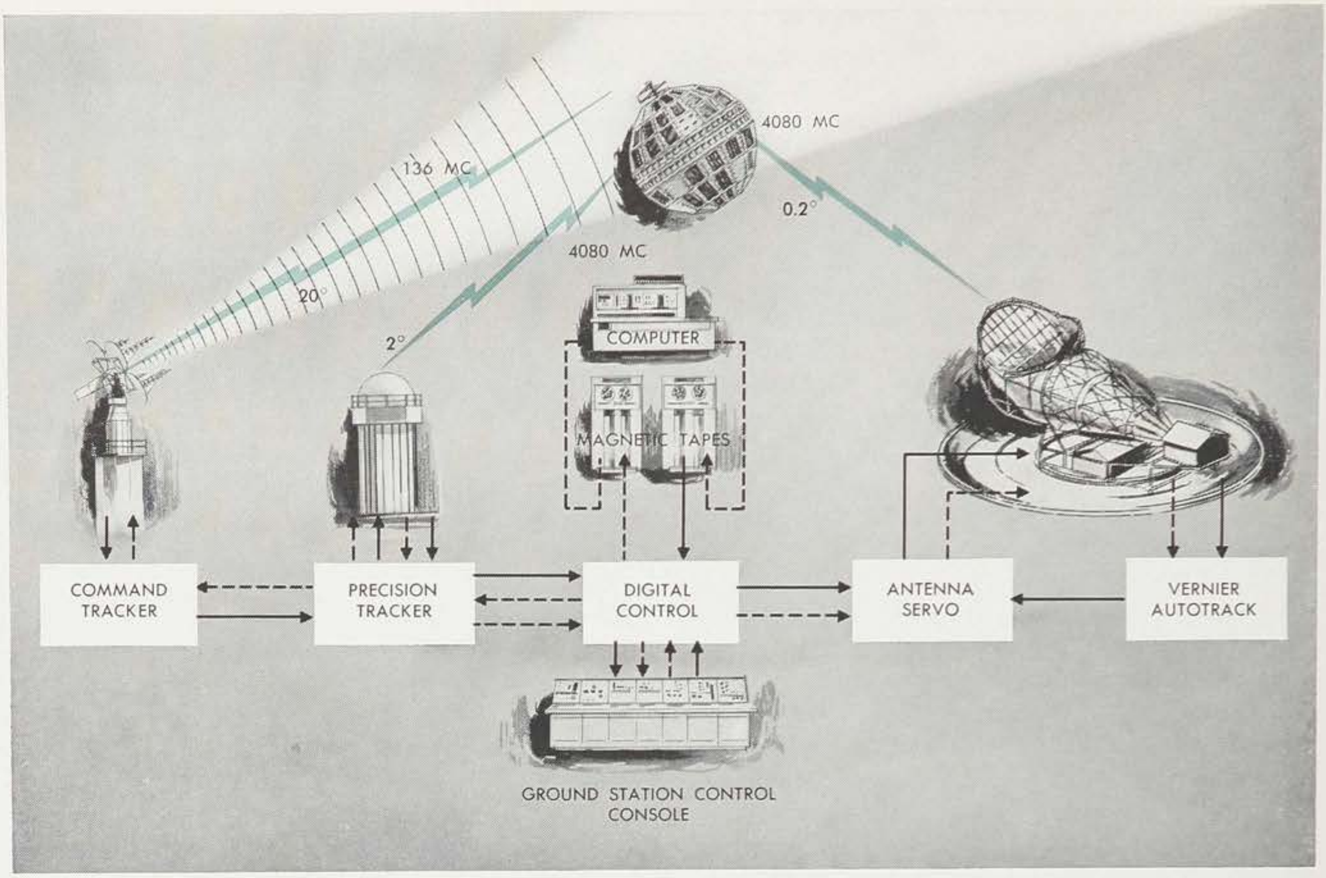


THE TELSTAR SATELLITE is a 34-inch sphere which moves through space at speeds exceeding 16,000 miles an hour. During periods of communication, its orbit carries it to altitudes of 3500 miles and as far as 7000 miles from the ground stations. In spanning these great distances, less than a billionth of the 2¼ watts of power radiated by the satellite reaches a ground station. Communication to and from this satellite requires an antenna system of unparalled sensitivity. To establish such a system, the designers of the Telstar satellite system combined the low-noise maser amplifier, the superior signal-to-noise performance of frequency modulation with feedback reception techniques, and a huge horn-reflector antenna at the ground station.

The horn antenna concentrates the signals transmitted to the satellite in a very narrow beam and captures the weak signals coming from it. In other words, the narrow beam insures that an adequate amount of power reaches the satellite; at the same time it means that the antenna receives signals from only a small part of the sky. Although this narrow beam is highly desirable from a transmission standpoint, it necessitates an extraordinarily accurate method of pointing the antenna. To prevent pointing errors from degrading the quality of transmission, the huge horn must be pointed at the satellite with errors of less than 0.06 of an angular degree during each transmission period. This requires a precise knowledge of the satellite's position and control equipment to move the 380-ton antenna with watch-like accuracy.

Tracking the satellite and controlling movements of the horn antenna are the specific tasks of the antenna-direction system. To create this system, Laboratories engineers drew on the experience they gained from the Echo I satellite experiments where orbit-prediction techniques were used to produce pointing instructions for the ground-station antennas. These techniques involve the following fundamental steps: First, the positions of the satellite are measured and recorded. Next, based on these recordings, precise calculations are made to determine the basic





Acquisition and tracking data flow diagram for antenna-direction equipment. The solid lines indicate the flow of information for acquiring a recently launched satellite; the dashed lines indicate the flow of information for tracking a satellite whose orbit is well determined.

geometric characteristics of the satellite orbit. These data are then used to predict the position of the satellite and to calculate antenna-pointing angles. In the case of Echo I, radio measurements from the NASA Minitrack network and photographic observations were used to determine the satellite's position. NASA's Goddard Space Flight Center then computed the orbital characteristics of the satellite, and antenna-pointing instructions were sent to the participating ground stations (RECORD, *April,* 1961).

The antenna-direction system developed for the Telstar experiment is, in essence, modeled after the system used for Echo. However, the tasks of tracking and orbit determination are performed at the Andover ground station. This permits the use of new techniques of orbit determination developed at the Laboratories.

The processes of satellite tracking, orbit determination, and antenna control require considerable equipment at the Andover ground station, as well as the inclusion of certain features in the Telstar satellite itself. To test the satellite shortly after it is placed in orbit, an operations plan was adopted to insure communication experiments on the earliest viewable pass. Certain features of the tracking sequence for a recently launched satellite are omitted once a satellite orbit is well determined. To discuss this operation, let's review the sequence of tracking events which begins a few minutes before the satellite rises over the mountainous horizon around Andover.

Sequence of Operation

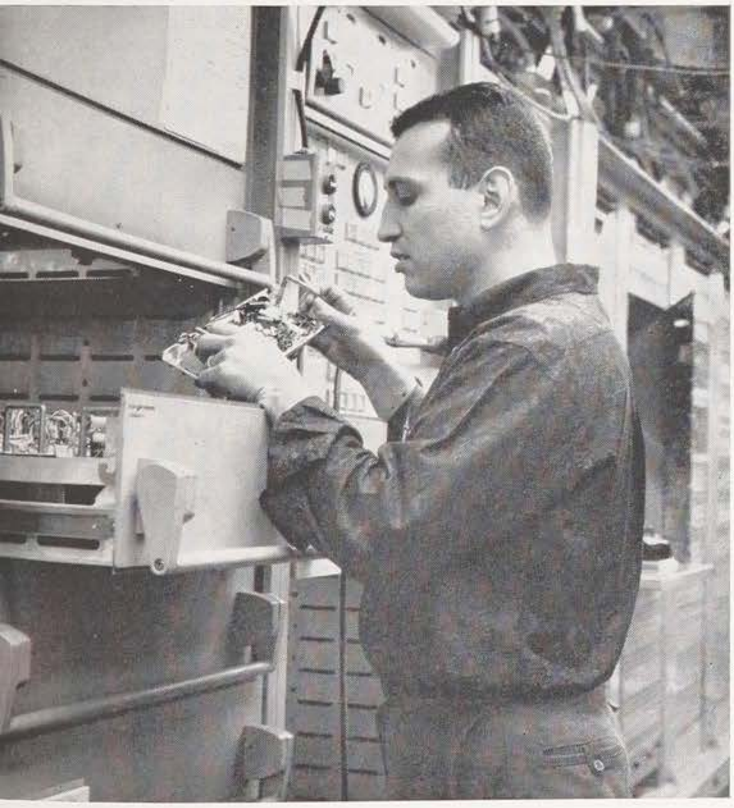
For the first few passes after launch, the sequence begins with a rather small antenna called the command tracker. Aided by data obtained during the launch from Cape Canaveral, operators at a control console in Andover position the command tracker to the point where the satellite is expected to appear. This antenna establishes the first contact with the satellite when it picks up a steady 136-mc signal which was turned on before launch. The command tracker's "quad helix" antenna elements give it the ability to find the satellite anywhere within a 20-degree area of the sky. Its receiver then locks onto the signal and automatically drives the antenna to track with an error of less than 1 degree. Having determined that the command tracker has received the

136-mc signal, operators at the Andover ground station control center send the satellite the first of several command signals over a 120-mc transmitting channel.

The first command energizes telemetry equipment within the satellite so that measurements of its power supply and other circuits can be sent to the ground station on the 136-mc channel. Decoding equipment and special displays permit the operators to interpret this information rapidly and assess the "health" of the satellite. If all is well, the operator applies a sequence of commands which activate the remaining circuits in the satellite, including the traveling-wave tube which amplifies and transmits the broadband telephone or TV signals.

With the traveling-wave tube on, the satellite begins to transmit a 4080-mc beacon signal. A second antenna, the precision tracker, picks up this beacon signal and "locks on" to the satellite. This antenna can acquire a signal within a cone 2 degrees wide; it is pointed in the direction of the satellite by a "slaving" connection from the command tracker. Once it locks on to the 4080-mc beacon signal, it can track with an accuracy of about 0.01 degree. Precision angle-measuring devices included on this antenna mount provide the basic data needed for orbit determination.

George Colom of Bell Laboratories checks servo amplifier in a portion of the control equipment for the horn-reflector antenna at Andover, Maine.



Digital data-processing equipment in the control building collects samples of the precision tracker angles twice per second and records the station time with each sample. This information is stored on magnetic tape for subsequent use by general-purpose digital computers at the ground station. During the first few passes, there is not time to gather enough data to accurately determine the orbit, so an alternate connection is used to provide pointing instructions to the horn-reflector antenna. Pointing angles from the precision tracker are fed directly to the horn through this connection. Within a few days after launch, sufficient data is gathered so orbits can be accurately determined. Pointing instructions are then computed for the horn antenna before the pass and placed on magnetic tape.

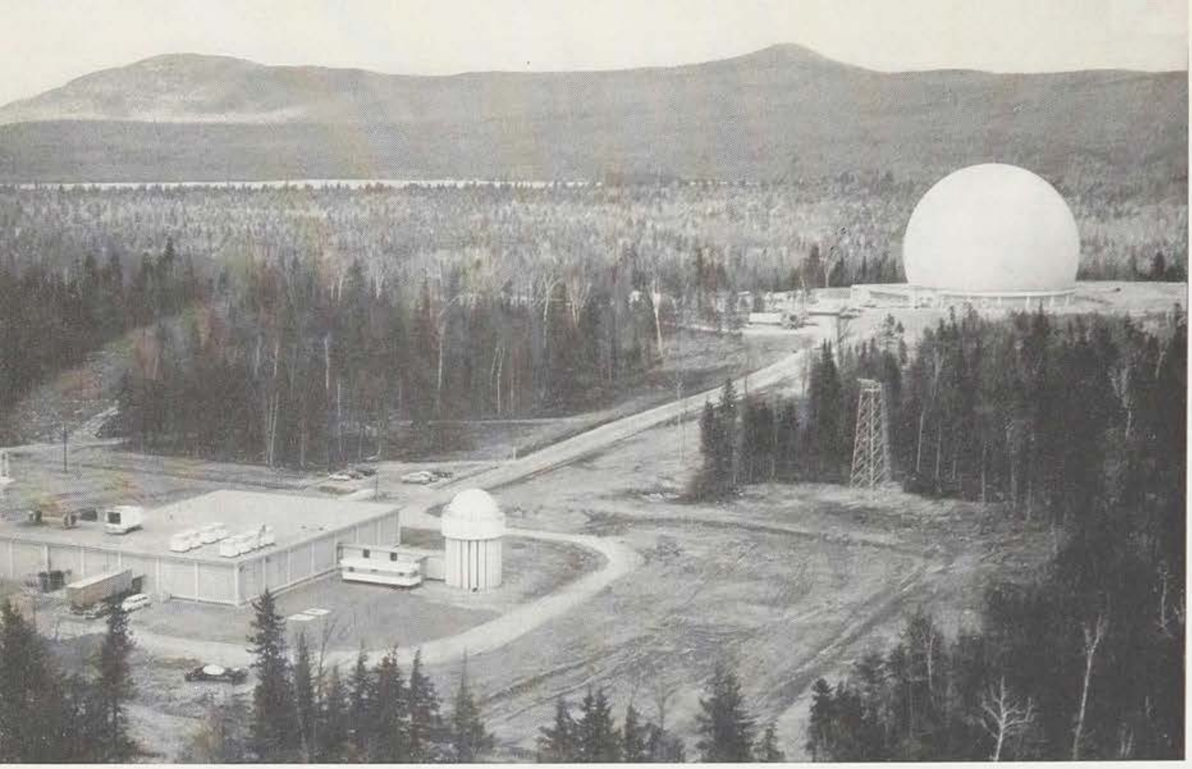
In either event, precise pointing data is sent to the antenna-control equipment housed in the lower equipment room on the horn structure. The primary function of this equipment is to use pointing commands furnished by either the precision tracker or magnetic tape to control the horn's motion. It does this by comparing the antenna's position to the position indicated by the commands. This comparison produces error signals which control the power of the hydraulic drive units which actually rotate the massive structure.

Control Techniques

Digital data-processing techniques are used to perform the comparison, so that the position of the antenna can be precisely measured. A sophisticated servomechanism is then used to transform the error signals into driving torques which move the antenna smoothly and easily. In determining the drive power, the servo takes into account variations in individual drive motors, tendencies of the big structure to oscillate, and even very small power changes required by slight rail deflections. These and many other problems must be carefully considered to control the antenna with an accuracy of a few hundredths of a degree.

During the early planning of the project, Laboratories engineers realized that the antenna-direction system would be subject to small errors in satellite predictions and misalignments of the horn. After investigating various methods of improving tracking ability, they prepared a unique autotrack system which would allow the horn to track the satellite without impairing the reception of the communication signal.

This system operates in the following manner:



Aerial view of Andover ground station shows relative positions of control center, horn antenna, and command and precision trackers.

When the horn is pointed at the satellite and receives a signal from it, the autotrack system becomes engaged. The autotrack receiver determines small pointing errors by examining the way in which the 4080-mc beacon signal enters the horn. By electrically sampling and comparing these waves with each other, error voltages are generated when the horn is not aimed directly at the satellite. These voltages are amplified and sent through the servo to the antenna-drive motors which respond by re-directing the antenna.

Even minute errors in antenna-pointing direction can be detected by the autotrack system. In fact, once pointed at the satellite by the antenna-control equipment, the autotrack can lock on and keep the antenna radio beam directed at the satellite without further assistance from the digital-pointing commands. By thus permitting the horn antenna to generate its own tracking commands (for this is what the autotrack does), many possible sources of tracking errors—such as erroneous tracking data, antenna misalignment or distortion—are automatically eliminated.

The operation using three antennas allows the horn's beam to be pointed at the satellite during the earliest passes—well before accurate predictions of the satellite position are available. In the meantime, precision-tracking data is used to compute the satellite's orbit, so that within a few days after launch the normal mode of operation is used in which predicted information serves as the primary pointing information. To establish this mode, ground-station operators connect magnetic tape units to the precision-tracker control and the horn-antenna control equipment. The computed list of pointing data then drives both these antennas. At the same time, the slave connection between command and precision trackers is reversed so that, in effect, the digital-pointing instructions also place the command-tracker beam on the satellite. Once the initial orbit is determined, the precision tracker continues to provide data which is used to refine certain values of the slowly changing orbit.

The antenna-direction system met all of the operational objectives. This is perhaps best indicated by the fact that during the experiments, no loss in signal level could be attributed to tracking error. The swift acquisition and tracking ability afforded by the slaving of the three antennas enabled the communications experiments to begin even before accurate predictions of the orbit were obtainable. Later, when accurate data were produced, the horn could be pointed automatically and station operators, relieved of much of the tracking task, directed their attention to more complex experiments.

The flexibility provided by the various tracking modes allowed operators to perform tests on the antenna direction system itself, and experiment with alternative acquisition and tracking procedures. For example, by temporarily removing the autotrack connections, operators deliberately introduced pointing errors in the predicted commands, and measured the effects of these offsets on the received signals. One series of tests indicated that it was possible to position the horn along the expected path of the satellite, and then lock on to the autotrack beacon as the satellite passed through the antenna beam. By making these tests, the performance limitations of specific parts of the system were determined, and optimum procedures for acquiring and tracking the satellite were worked out.

The objectives of the ground station transmitter and receiver are similar to conventional FM microwave systems. However, their use in satellite communications imposed a number of additional design considerations.

The Ground Station Transmitter and Receiver

J. Schill and A. F. Perks

THE FACT THAT the Telstar satellite is basically a "microwave tower in space" brings with its advantages a few problems. Not only does its orbital location make transoceanic communication possible, but it brings about the two major problems in the design of the transmitters and receivers for the system — large distance between transmitter and receiver, and a very low level of the received signal.

To overcome these problems, Laboratories engineers have had to design special circuits, devices, and structures for both the ground-based transmitter and receiver. Many of the design approaches are unique. In the transmitter, the output power was stepped up tremendously, compared with conventional microwave systems, and coupled with an extremely narrow-beam transmitting antenna. The receiver cannot depend on a strong signal from the satellite, since the satellite power supply had to be limited. So an extremely sensitive, low-noise amplifier, coupled with the same narrow-beam antenna is used.

The basic objectives of the Telstar transmitter system are quite similar to most conventional FM microwave systems. However, the application to satellite communications has placed additional requirements and considerations on transmitter design techniques. Since the transmission paths in ground-to-satellite communications systems are obviously quite long, noise is an ever-present limitation of satisfactory communications. The ground transmitter developed is a high index FM, wide-band system with low distortion and high power, which considerably reduces the limitation imposed by the distance. Obviously, in a communication system such as this, special consider-

OVER-ALL SYSTEM TRANSMISSION PARAMETERS			
TRANSMITTER		RECEIVER	
Frequency	6390 mc	Frequency	4170 mc
Output Power Range	0.2 to 2000 w	Input Signal Range	−70 to −100 dbm
RF Bandwidth	> 32 mc	Noise Temperature	32°K
Peak Deviation	±10 mc	Over-all Bandwidth	25 mc
Deviation Sensitivity	20 mc/v	Baseband Width	2 cps to 3 mc
Baseband Width	2 cps to 5 mc	Output Impedance	124 ohms balanced
Input Impedance	124 ohms balanced		

Over-all system parameters for the ground transmitter and receiver at Andover.

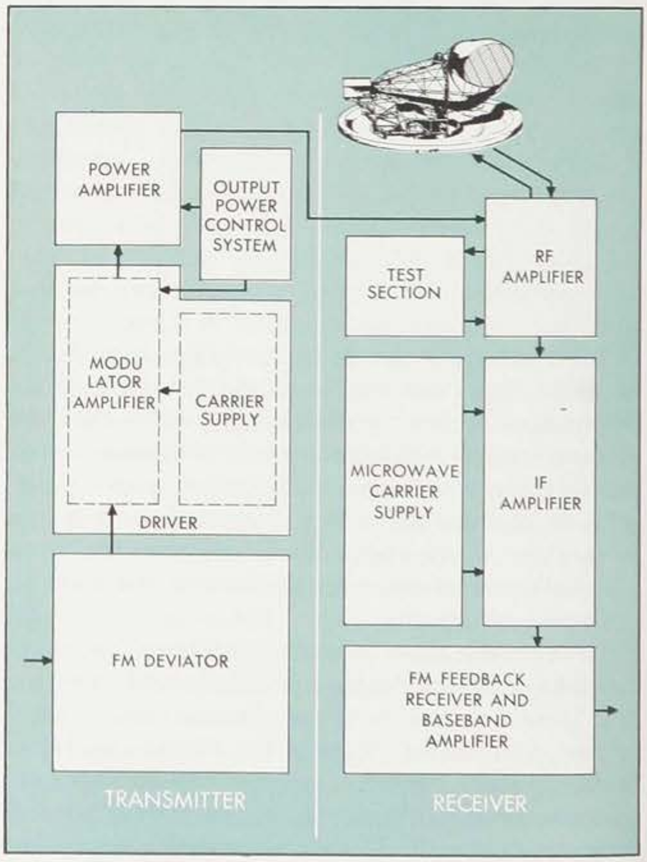
ation has been given to reliability. The outage time of the transmitter has been kept to a minimum by using a variety of trouble reporting circuits and electromechanical safeguards.

The transmitter is subdivided into three functional subsystems, as shown at right. An FM deviator receives information in the form of video or telephone multiplex signals and translates them to a frequency-modulated signal centered about 74 mc. This is the first step in our transmission process. The 74-mc signal is then passed to a driver unit. The driver translates the incoming 74-mc signal to a frequency-modulated signal centered about 6390 mc, the transmitting carrier frequency, in the common carrier band. The output of the driver is then passed to a power amplifier where the signal is amplified to the proper power level. The signal is now ready for transmission. The output of the power amplifier is then sent to a diplexer and on to the horn antenna for transmission to the satellite.

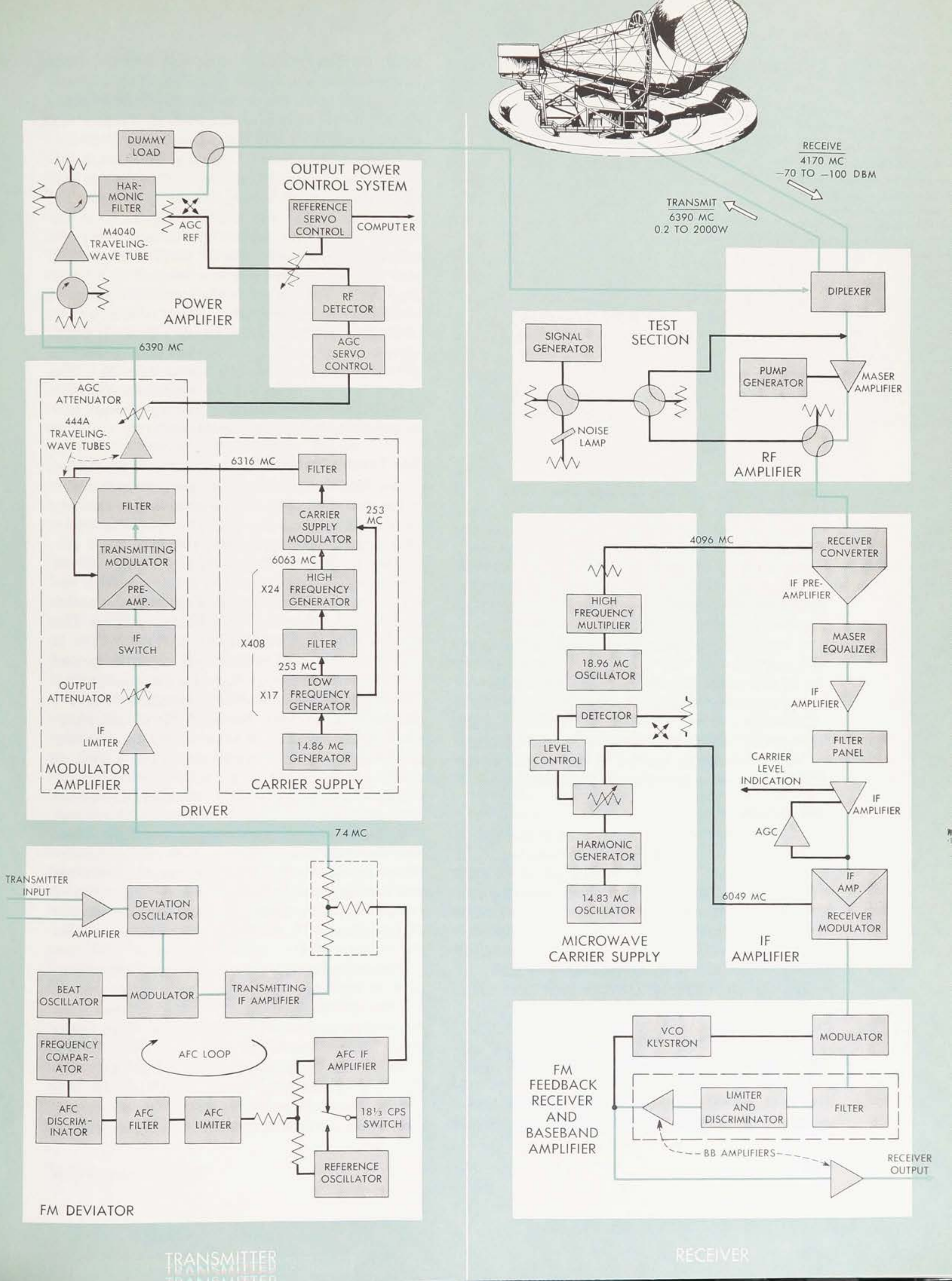
The FM Deviator

The FM deviator, the first functional subsystem of the ground transmitter system, has as its prime function the translation of incoming television or telephone multiplex signals to a frequency-modulated signal centered at 74 mc. It consists of a TH terminal transmitter (RECORD, *November*, 1962), modified to meet the special transmission requirements of a satellite communications system. Some of the objectives of the modification program were: increased signal deviation, adequate automatic frequency control, and compatibility in transmitting both European and American television.

The input signal to the deviator is applied to a balanced video amplifier, modified for increased gain. This amplifier is a high-gain, low-distortion, wide-band device. The output of the amplifier is then applied to the repeller of a deviation oscillator (DO) klystron whose rest frequency is 6174 mc. Since the oscillating frequency of a klystron is a function of repeller voltage, a frequency-modulated signal results. The DO klystron output is mixed with the output of a beat oscillator (BO) klystron operating at 6100 mc. The difference frequency signal, centered about



Functional subsystems in transmitter and receiver. Simplified drawing above is key to that at right.


DUMMY LOAD
HAR-MONIC FILTER
M4040 TRAVELING-WAVE TUBE
AGC REF
POWER AMPLIFIER
OUTPUT POWER CONTROL SYSTEM
REFERENCE SERVO CONTROL
COMPUTER
RF DETECTOR
AGC SERVO CONTROL
6390 MC
AGC ATTENUATOR
444A TRAVELING-WAVE TUBES
6316 MC
FILTER
TRANSMITTING MODULATOR
PRE-AMP.
IF SWITCH
OUTPUT ATTENUATOR
IF LIMITER
MODULATOR AMPLIFIER
CARRIER SUPPLY MODULATOR
253 MC
6063 MC
X24
HIGH FREQUENCY GENERATOR
X408
FILTER
253 MC
X17
LOW FREQUENCY GENERATOR
14.86 MC GENERATOR
CARRIER SUPPLY
DRIVER
74 MC
TRANSMITTER INPUT
AMPLIFIER
DEVIATION OSCILLATOR
BEAT OSCILLATOR
MODULATOR
TRANSMITTING IF AMPLIFIER
FREQUENCY COMPAR-ATOR
AFC LOOP
AFC IF AMPLIFIER
AFC DISCRIM-INATOR
AFC FILTER
AFC LIMITER
18⅓ CPS SWITCH
REFERENCE OSCILLATOR
FM DEVIATOR
RECEIVE
4170 MC
−70 TO −100 DBM
TRANSMIT
6390 MC
0.2 TO 2000W
DIPLEXER
SIGNAL GENERATOR
TEST SECTION
NOISE LAMP
PUMP GENERATOR
MASER AMPLIFIER
RF AMPLIFIER
4096 MC
RECEIVER CONVERTER
IF PRE-AMPLIFIER
HIGH FREQUENCY MULTIPLIER
18.96 MC OSCILLATOR
MASER EQUALIZER
IF AMPLIFIER
DETECTOR
LEVEL CONTROL
FILTER PANEL
CARRIER LEVEL INDICATION
IF AMPLIFIER
AGC
HARMONIC GENERATOR
6049 MC
IF AMP.
RECEIVER MODULATOR
14.83 MC OSCILLATOR
MICROWAVE CARRIER SUPPLY
IF AMPLIFIER
VCO KLYSTRON
MODULATOR
FM FEEDBACK RECEIVER AND BASEBAND AMPLIFIER
LIMITER AND DISCRIMINATOR
FILTER
BB AMPLIFIERS
RECEIVER OUTPUT
TRANSMITTER
RECEIVER

74 mc, is then converted, and amplified by a three-stage wide-band (32 mc) IF amplifier. The frequency-modulated signal is subsequently applied to the driver unit. The modification to the automatic frequency control (AFC) system of the FM deviator for Project Telstar was quite extensive because of the increased deviation requirements (as much as ± 10 mc), and the need for American-European transmission compatibility. This placed more stringent demands on the AFC system than in normal TH operation. The modified control circuits will keep the carrier frequency within the desired limits for drifts of as much as 10 mc of the DO and BO difference frequency. This is accomplished without degradation to the intentional modulation.

Automatic frequency control is accomplished by comparing the klystron difference frequency with a closely controlled crystal oscillator operating at 74 mc. This comparison is done at an 18 1/3 cps rate to facilitate both American and European television transmission. The combined pulsed signals are sent through a wide-band limiter and then a modified TH discriminator. The 18 1/3 cps square wave voltage appears at the output of the discriminator. The discriminator is extremely linear over a 20-mc bandwidth; therefore, the amplitude of the 18 1/3 cps square wave signal is proportional to the average frequency drift of the klystron difference frequency.

A narrow-band filter follows the discriminator and extracts only the fundamental of the 18 1/3 cps square wave, thereby excluding any undesired signal frequencies present. The resulting signal is then sent through a modified TH frequency comparator, where it is amplified, rectified, filtered, and subsequently applied to the repeller of the BO klystron as a frequency-correction voltage.

The Driver

As mentioned earlier, the frequency-modulated signal output of the FM deviator is centered about 74 mc. We must now upshift this signal to 6390 mc (common carrier band), the transmitting frequency of the ground transmitter system. This is done in the driver, which consists of a carrier supply and a modulator amplifier. The equipment is essentially the same as that used in TH.

The carrier supply generates a high level, 6316-mc RF beat frequency. This signal is then passed through a traveling-wave tube (TWT) amplifier, and added to the 74-mc frequency-modulated signal from the FM deviator in a transmitter modulator.

The 74-mc signal from the FM deviator is applied to an amplifier-limiter located in the modulator amplifier, which removes any amplitude modulation of the signal. The signal is then passed through an IF switch to the transmitter modulator. The IF switch serves both as a safety and remote control device. Operation of the IF switch will remove the 74-mc IF signal which subsequently removes the RF output signal. The transmitter modulator receives both the 74-mc signal from the FM deviator and the 6316-mc signal from the carrier supply simultaneously. These signals are mixed (in a balanced varactor modulator) and the sum frequency, 6390 mc, is extracted by a band-pass filter. The signal is then passed through a 444A traveling-wave tube, which is identical to that used for the carrier supply signal. The amplified 6390-mc RF signal is then passed through an AGC attenuator to the power amplifier. The output level of the modulator amplifier is approximately +37 dbm (5 watts). The signal must now be amplified before transmission.

The Power Amplifier

The final subsystem of the ground transmitter is the power amplifier. It consists of five cabinets which are interrelated with the operation of its high-power, wide-band traveling-wave tube, designated the M4040. This tube is the "heart" of the power amplifier. As used, the power amplifier has a gain of approximately 26.5 db and the entire transmitter system has a bandwidth of 32 mc. The maximum output level of the power amplifier is approximately 2000 watts. This signal is passed to the horn antenna by way of a diplexer.

The design of the M4040 traveling-wave tube is unique. The demand for high-power traveling-wave tubes has been predominantly for military pulsed radar system applications. The advent of satellite communications, and of the Telstar satellite experiments in particular, has offered the first real application and need for a broadband, CW, high-powered TWT communications amplifier. Basically, the TWT is a 48-inch long cylindrical structure with a cathode at the lower end and a collector at the upper end. A large solenoid completely surrounds the central portion or body of the tube; both the collector body and magnet are water cooled.

The conventional helix "slow wave structure" used in most traveling-wave tubes is inadequate for the M4040 TWT, because of the poor heat dissipation qualities of a helix at average power levels greater than 1000 watts.

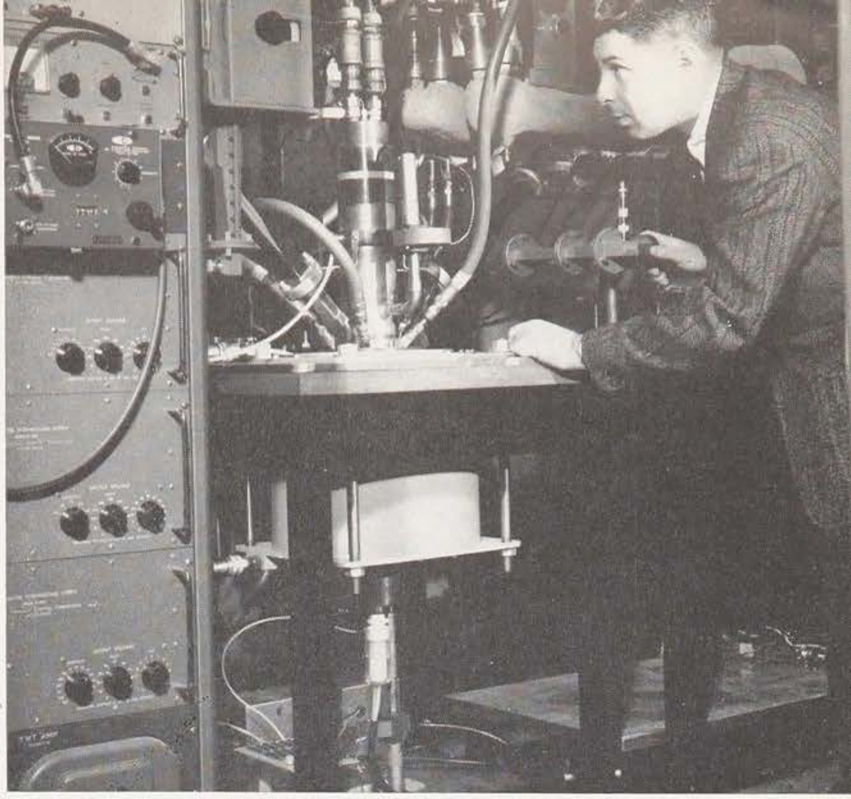
Therefore a design employing a disc-loaded circular waveguide "slow wave circuit" is used. This circuit is also commonly called a "coupled cavity" interaction structure. Since this RF structure is directly connected to the outer shell, heat dissipation problems are vastly reduced. The slow wave structure is called the "body" section of the tube and consists of 30 equal-sized cylindrical chambers separated by circular metal diaphragms each with a small hole in its center for the electron beam and a port for the electromagnetic wave. Each chamber acts as an individual waveguide section or cavity resonator. Spurious oscillations are prevented by isolating the two center cavities with a diaphragm having no electromagnetic coupling port. An RF termination is attached to each of these two cavities to absorb the forward and reflected waves. The signal information is transmitted on by means of the modulated electron beam.

Because of the extremely high voltages present in the power amplifier, numerous safety precautions such as mechanical interlocks and gravity operating switches have been designed into the equipment to safeguard personnel. The equipment itself is protected mainly by devices which sense abnormal operating conditions. Timers and relays are used to ensure proper turn on and shut down sequences.

In the power amplifier, as shown in the drawing, the output of the driver (modulator amplifier) is applied to the input of the TWT cabinet through an input circulator. The high-power output signal of the TWT can either be switched to an RF output port which subsequently goes to a diplexer, or to an RF "dummy load" used for test purposes.

AC power is supplied to the over-all system by two separate three-phase lines. The primary voltages are subsequently distributed to the various parts of the equipment. The high-voltage supply has an electronically regulated dc output that may be remotely controlled. This output supplies the beam voltage for the M4040 traveling-wave tube. The low voltage supply delivers all the remaining dc potentials for proper operation of the traveling-wave tube. All voltages not directly related with the operation of the traveling-wave tube are supplied by auxiliary low voltage supplies.

The automatic output power control system is essentially a self-correcting servo-system with solid-state circuitry, as used throughout the Telstar ground transmitter equipment. The output power control system can automatically vary the output power to any level within the range of 0.2 to 2000 watts. This is done from computer commands and is dependent on satellite slant range. In addition, if the antenna is driven below the horizon line, the output power will automatically be turned off. The automatic output power control



R. J. Collier with "hot testing" apparatus for M4040 traveling-wave tube used in transmitter.

system will also maintain the necessary output power selected at a constant level until the computer command calls for a change.

Ground Station Receiver

The prime objective of the receiver in any communication system is to reproduce the transmitted signal faithfully. Two of the main effects working against this goal are low carrier levels and low carrier signal-to-noise ratio at the receiving end. In a satellite communication system, several of the techniques usually used on terrestrial systems to overcome these obstacles—using high-power transmitters, reducing the distance between the transmitter and receiver, and using highly directional antennas—are ruled out by the inherent nature of the orbiting repeater. Therefore, the designers had to resort to a different technique, use of a very low noise receiver. This receiver should add the minimum amount of noise possible to the weak incoming signal and also be able to "pick out" the information from a signal with a low signal-to-noise ratio. Using something old and something new, Bell Laboratories engineers designed such a receiver for Project Telstar.

The "something old" was the FM feedback receiver invented by J. G. Chaffee at Bell Laboratories in the early 1930's. Figuratively, it waited on the shelf until its first real application in the Project Echo experiments, where it proved its worth. The receiver used at Andover extends the threshold of the detection of an FM signal by 4 to 5 db, thereby still producing a usable information signal when the conventional FM receiver output

CONTRIBUTOR	HORN ANTENNA ELEVATION			
	90°	30°	15°	7.5°
Dry Atmosphere	2.4°K	4.8°K	9.2°K	18.4°K
Dry (Wet) Radome Absorption	3.0(12)	3.0(12)	3.0(12)	3.0(12)
Dry (Wet) Radome Scattering	7.4(18.5)	6.0(15.0)	4.1(10.2)	1.4(3.5)
Antenna Sidelobes	1.0			
Diplexer	12.2			
Direction Coupler (23 db)	2.0	19.2°K (total of Antenna Sidelobes through 2nd Stage)		
Maser	3.5			
2nd Stage	0.5			
Total (Measured)	32.0°K	33.0°K	35.5°K	42.0°K

Contributors to noise temperature in the receiver.

would be considered unsatisfactory. (In an FM system, threshold is a point where a disturbance becomes noticeable and increases rapidly if the input signal should degrade further. In a single channel telephone signal this would be heard as "popping," while in a TV transmission, black and white dots called salt and pepper, would appear on the reproduced picture.) An improved transistorized model of Mr. Chaffee's receiver, with bandwidth sufficient to handle TV signals, was designed for use in the Telstar receiver.

The "something new" is the use in a communications receiver of a high-gain maser amplifier, a product of the most recent advances in quantum electronic devices, which has a noise temperature of only 3.5 degrees K. This compares to conventional amplifiers with noise temperatures of 3000 degrees K. This extremely low noise temperature makes possible the amplification of very weak signals.

The receiver-system noise temperature is dependent on the elevation angle of the ground antenna and weather conditions. The chart above shows these dependencies, and also the various contributors to the receiver-system noise.

A simplified block diagram of the ground receiver is also shown on page 137. The low-level signal received by the horn is fed through the diplexer to the maser amplifier. The output of the maser is converted to a 74-mc signal and further amplified by an IF amplifier before being converted to a 6-kmc signal. This 6-kmc signal is then demodulated in the FM feedback receiver. This demodulated signal is then amplified in the baseband amplifier, and is ready for processing. (The conversion of the 74-mc signal in the IF amplifier to 6 kmc and then promptly back to 74 mc in the FM feedback receiver allows the use of a klystron with a very linear frequency versus voltage characteristic in the feedback loop of the FM feedback receiver.)

The RF amplifier consists of three subsystems: the diplexer, the maser amplifier and the pump generator. The diplexer is a group of waveguide components which allows the simultaneous use of the horn antenna for transmitting and receiving communication signals. The signal received from the satellite at 4170 mc is a left-hand circularly polarized wave. The diplexer converts this wave to a vertically polarized wave, and directs the signal through low-loss waveguide circuits to the maser amplifier. At the same time, it accepts the vertically polarized high-energy 6390-mc signal from the ground transmitter and launches it as a right-hand circularly polarized wave into the antenna. (The 6390-mc signal "sees" only a high-loss path toward the receiver.) The use of the left- and right-hand circularly polarized waves for the received and transmitted signals helps to separate the two frequencies at both the ground station and the satellite.

Low-Noise Maser Amplifier

The maser amplifier used in the ground receiver is a traveling-wave maser, whose active element is a ruby crystal. It has a gain of 40 db, a 3-db bandwidth of 16 mc, and a noise temperature of approximately 3.5 degrees K. This low-noise temperature is maintained by cooling the amplifier to the temperature of liquid helium using a double dewar—essentially two large vacuum bottles, one within the other. The outer bottle is filled with liquid nitrogen and the inner with liquid helium. The ruby crystal is then submerged in the liquid helium. The two vacuum jackets are connected and maintained at a vacuum of 10^{-8} mm of mercury by continuous pumping by an ion pump.

The maser does not use a conventional dc power supply; it must be powered at a frequency much higher than the signal frequency (RECORD, *July, 1958*). The pump generator is the power supply for the maser. A klystron oscillator is used as the pump frequency source, operating at a frequency of 30 kmc with a power output of 100 milliwatts. An automatic frequency control (AFC) loop holds the frequency to within ±1.5 mc. Monitor circuits continuously check the power output and the frequency of the klystron and will issue an alarm if either varies beyond its prescribed limits.

A power meter, a frequency meter and the klystron power supply are integral parts of the pump generator.

The amplified output of the maser is applied to the input of the receiver converter at a power level of —61 to —31 dbm. A second microwave frequency from the microwave carrier supply is used as a "beat frequency" to produce a 74-mc output. A 3-stage preamplifier, a subunit of the receiver converter, amplifies the 74-mc signal with an overall conversion gain of 7 db. The signal then passes through the maser equalizer which effectively widens the transmission characteristic from the 16 mc of the maser to an over-all bandwidth of 25 mc.

The wide-band 74-mc signal is then amplified by a 3-stage amplifier with a gain of 21 db. The output of this amplifier is fed to a filter panel where either a 2-db pad or a narrow-band filter is inserted, depending on the type of transmission; for one-way TV transmission the pad would be used, and for a two-way telephony transmission the narrow band filter would be used to filter out the signal coming from the other ground station while attenuating the transmission from the local transmitter.

Additional amplification is provided by a 7-stage wide-band IF amplifier. The input power to this amplifier may vary from —52 to —22 dbm. An AGC circuit holds the output power at +7 dbm over this range of input variation. The AGC voltage is used to indicate received carrier level.

The 74-mc signal is now converted to a 6-kmc signal by the receiver modulator. The input power to this unit is adjusted by a variable attenuator for a 6-kmc output of —5 dbm. The modulator consists of a single-stage, wide-band amplifier and a mixer. The microwave frequency output is produced in the mixer by the addition of the 74-mc signal and a constant power 6-kmc signal from the microwave carrier supply. A constant power beat frequency is necessary to keep any variation of the output level restricted to a function of the 74-mc input power.

The output of the receiver modulator is applied to a modulator in conjunction with a signal from a klystron voltage-controlled oscillator (VCO) in the feedback loop of the FM fedback receiver. The frequency of this oscillator has a definite relationship to the frequency modulation of the incoming signal; it is controlled by the varying output voltage of the FM feedback receiver. The incoming frequency-modulated signal has a maximum frequency swing of ±10 mc; because of the varying frequency of the VCO, the output of the modulator has a maximum frequency swing of about ±1 mc. This, in effect, converts a wide-band FM signal into a narrow-band FM signal. Consequently, the bandwidth of the following circuitry may be considerably narrowed, thereby reducing the noise power while leaving the signal power unaffected. The threshold of detection is therefore improved by 4 to 5 db.

The output signal of the modulator is applied to a narrow-band filter and then to a limiter and discriminator where the baseband signal is recovered. A two-stage video amplifier increases the baseband signal level to —16 dbm.

The baseband signal is then amplified to a level of 0 dbv by a video amplifier. This amplified signal is the output of the ground receiver, which is then sent via the TD-2 microwave system to its ultimate destination.

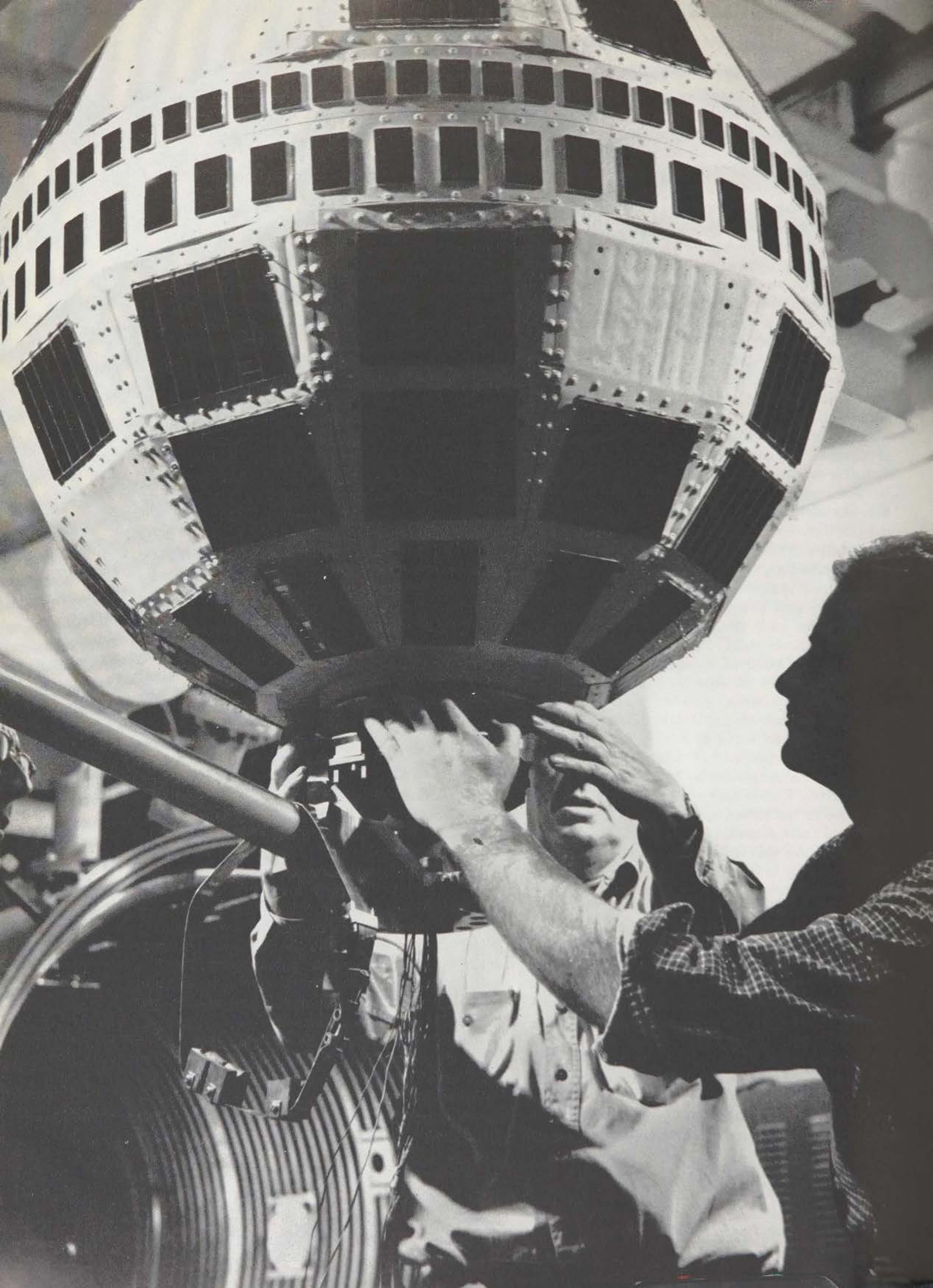
The microwave carrier supply generates the two microwave frequencies needed for the receiver converter and the receiver modulator. The 4-kmc signal is generated from a 18.96-mc crystal oscillator by multiplying the base frequency by 216 in a string of frequency multipliers. The 6-kmc signal is derived by multiplication and addition of its basic frequency source. The 8th and 9th harmonics are generated from a 14.83-mc oscillator by frequency multipliers, and then added to get the 17th harmonic. This is then multiplied by 24, producing the 408th harmonic of the crystal frequency. Both microwave generators have long term frequency stabilities of better than 10 parts per million.

The 6-kmc output is stabilized by using in its output a ferrite variolosser whose loss is controlled by a feedback circuit.

A test section is built into the receiver. It includes the test equipment necessary to make transmission characteristic, gain, and noise temperature measurements of the receiver. Most of the equipment is housed in one of the bays of the main receiver cabinet.

Much of the equipment described in this paper was originally designed for other communication systems. For instance, the receiver converter and the 4-kmc generator were designed for the TD-2 radio system, while the baseband amplifier was designed for the A2A video system. The TH radio system provided the IF amplifier, IF main amplifier, receiver modulator, 6B modulator, and the 6-kmc generator.

The final results of the design effort of the Telstar ground transmitter and receiver have been most gratifying. The original design requirements have been met in all cases, and at present, the equipment is continuing to operate in a most satisfactory manner.



R. E. D. Anderson,
G. W. Meszaros,
and D. F. Ciccolella

Ground-based microwave stations have their own generators or bring in operating power on cables from power stations. The satellite must be self-sustaining. It makes electricity from the light of the sun to operate all the systems it contains.

The Satellite Power System

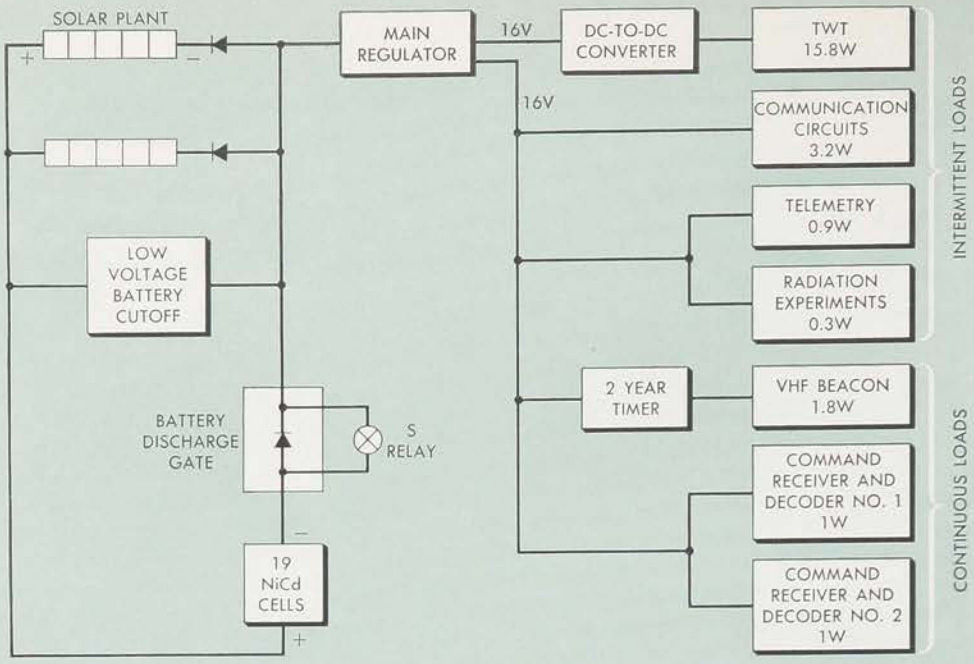
As a herald of a new era in the science of communications, the "power" of the Telstar satellite is immeasurable. The electrical power that operates the satellite, however, is quite easily measurable—it averages not much more than that of an ordinary night-light for a child's room. While it is transmitting, the satellite needs 35 watts. At other times, when most of the equipment is turned off by command from the ground, it needs only 5.4 watts. Normally then, the average power needed to operate the Telstar satellite in orbit is 10 to 12 watts.

To provide even this small amount of power for a long time in the hostile environment of outer space is a difficult job. A two-year life was originally planned for the Telstar satellite, and it was calculated that during this time it would use about 200 kilowatt hours of power. A chemical battery large enough to store that much power without being recharged would be too big and too heavy for the satellite. What was needed, then, was a way to convert the energy available in space to electricity, and a means to store that energy for use during periods of eclipse and periods when the satellite is operating at its full load. The power system of the Telstar satellite thus combines the energy-converting feature of solar cells with the energy-storing capability of rechargeable batteries.

The solar-cell plant is the primary power source. It provides the average power needed—including all losses—to operate the satellite. A sealed nickel-cadmium storage battery is wired in parallel with the solar cell array. Depending on the state of charge of the battery, the magnitude of the connected load, and the incident sunlight, the output of the solar cell-battery system ranges from 20 to 29 volts. During light load periods the output is held at the voltage of the fully-charged battery.

The other elements of the power system are the voltage regulator and dc-to-dc converter. To achieve optimum performance and the highest reliability, the electronic circuits in the satellite must be supplied with well-regulated dc power. Semiconductor devices are used as active elements in the Telstar satellite circuits to the complete exclusion of electron tubes (except for the traveling-wave tube), so that only one voltage is required and this can be delivered by the voltage regulator. The regulator, which uses transistors operating as time-modulated switches, provides 16 volts at over 90 per cent efficiency at peak load. The converter, which also employs semiconductor devices, derives the high and low potentials for the traveling-wave tube from the 16-volt regulator output.

The first consideration for the designers of the power system was, of course, the power drain im-



Block diagram of the power system showing the drain imposed by the various systems. The programming of these systems results in a drain on three major levels which are divided between continuous loads and intermittent ones.

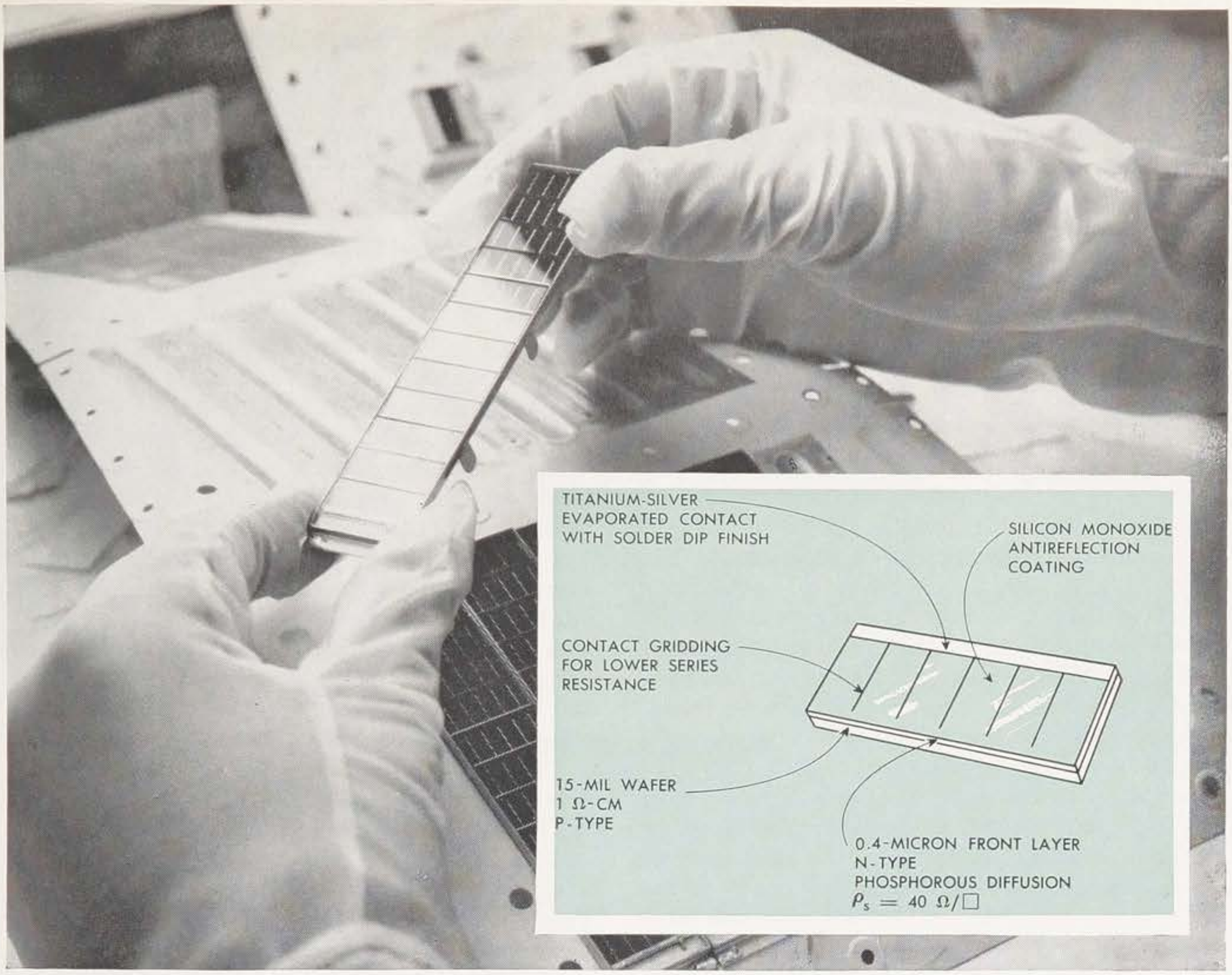
posed by the various systems in the satellite. (See the diagram on page 144.) Not all these systems operate continuously; their operating time is programmed and this results in a power drain on three major levels. The first is the continuous drain of the VHF beacon transmitter and command system—a total of 3.8 watts. The second level includes telemetry, radiation level monitors, and radiation damage experiments. These may be commanded "on" by any of several ground stations, and they need a total of 1.2 watts. The third level is the microwave communications system. It is controlled by only a few of the ground stations and requires a total of 19 watts. All these drains and the losses of the power supply add to a total of 35 watts. This, therefore, was established as the maximum power output requirement of the solar cell-battery power system.

Several other system requirements were significant to the power system design: First, to put the satellite precisely in the desired orbit with the available launch vehicle, weight had to be reduced in every possible way. Second, for a simple and reliable solar cell and antenna configuration a spin-oriented satellite was dictated. Third, because the satellite would be exposed repeatedly to the maximum radiation of the Van Allen belts, critical components had to be shielded. Fourth, a minimum useful life of one year was required, and two years was thought to be possible depending on the rate of degradation in space. Finally, because of the limits to size and weight, the designers emphasized highly reliable circuits and components instead of system redundancy.

Although Bell Laboratories is an old hand with problems of reliability, the Telstar satellite presented a new challenge because its life would be lived in outer space, and there was little experience with operational satellites. At the beginning, certain solar-cell power system arrangements, such as unfolding paddle wheels, were rejected as insufficiently reliable even though they may convert more sunlight to electricity than the arrangement actually used on the Telstar satellite.

Concerning the reliability of the solar cells themselves, the expected radiation damage was the main problem. Its elliptical orbit (an apogee of 3,502 and a perigee of 593 miles) destined the Telstar satellite to repeated exposure of the maximum electron and proton radiation of the Van Allen belts. These two belts of natural radiation encircle the earth at the magnetic equator like two huge doughnuts (RECORD, *February*, 1963). Their altitudes extend from about 1,000 to 20,000 miles or higher with a maximum intensity at about 2,000 miles and again between 12,000 and 16,000 miles. Early man-made earth satellites were orbited at altitudes generally under 1,000 miles and so were not exposed to such severe amounts of radiation. The Telstar satellite, however, needed a higher orbit in order to present simultaneous line-of-sight transmission paths to ground stations on both sides of the Atlantic.

The first solar cells developed in 1954 and 1955 (RECORD, *July*, 1955) were p-n cells—a p-type layer diffused into n-type silicon. At that time, n-p



The make-up of the Telstar solar cell. The drawing is inset in a photograph showing solar cell modules being assembled on the skin of the satellite during development of the satellite at Hillside, N.J.

cells were also studied, but their efficiency was lower than that of p-n cells. The latter type could be made with as much as 11 per cent efficiency, and from 1956 to 1961 all commercial solar cells manufactured in the United States were that type. In 1960, just about the time the Telstar project was getting under way, the United States Army Signal Research and Development Laboratory announced that they had developed an n-p solar cell that resisted radiation damage better than p-n types. Investigation at the Laboratories and at other places confirmed this.

Radiation mainly reduces the lifetime of the minority carriers in silicon and thus shortens their diffusion length. The carriers produced by long wavelength (red) light are lost before they reach the junction. However, electrons have a greater diffusion length than holes in silicon; therefore, to overcome the loss, the electrons should be the minority carriers and the body of the solar cell should be p type—in other words, an n-p cell. The output loss due to radiation even in this type of cell is produced primarily by the losses at the red end of the light spectrum. An extremely shallow junction, however, increases the collection efficiency of carriers generated by short wavelength (blue) light. The choice of n-p cells for the Telstar satellite, then, was obvious.

The junction, or n layer, of the Telstar solar cell (see the inset drawing above) was made almost incredibly thin—0.4 micron, about 1/250th the thickness of an average human hair. A new contact of evaporated titanium with a cover layer of silver was also developed. This adheres quite tenaciously to the surface of the silicon and thus makes a mechanically strong and electrically good connection and it does not penetrate the thin n layer. To reduce the resistive losses of this thin layer, several parallel metallic "fingers" extend over the surface of the cell and connect to its negative terminal. Also, an antireflection coating of silicon monoxide was developed to reduce reflection from the surface of the cell to a minimum.

The Telstar solar cell is a rectangle about 1 centimeter by 2 centimeters by about 0.04 centimeters thick. The surface of the satellite contains 3600 cells distributed more or less uniformly in 50 electrically parallel groups; each group contains 72 cells in series. Each string of 72 cells is made up of six modules; each module contains 12 cells of matched outputs which are rigidly connected together by the device of slightly overlapping their edges, like shingles on a roof. The process, however, is far more precise than shingling; each overlap is made so that the underside, or positive terminal, of one cell covers only the upper contact surface of the next cell and does not project over and shield the active part of its upper surface. Transparent sapphire plates, 0.030-inch thick, cover each cell, and are a shield against electron and proton radiation. The plates are also protection against micrometeoroid abrasion.

Actually, a simple arithmetical calculation based on the initial output of a solar cell in the normal rays of outerspace sun indicates that much fewer cells would produce the average power for the satellite. A typical cell has an initial output of 22 milliwatts, thus 500 cells will produce 10 to 12 watts. Why 3600 cells? First, because the cells are mounted on the surface of the spherical satellite only half of them can be illuminated at any time. Moreover, only a small number of the illuminated cells get the full power of the sun's rays; the angle of incidence of the rays considerably reduces the output of the rest of the cells. Second, solar-cell output is temperature dependent, decreasing with increasing temperature. Third, the output of all cells will, in time, be somewhat reduced by radiation despite the design, the precise fabrication, and any preventive steps that can be taken. Fourth, cells must be added to compensate for the loss of output from the solar cells when the satellite is in eclipse. Finally, an engineering safety factor must be included in the calculation of the number of cells needed to supply the average power.

The performance of the solar cell array was calculated for various angles of illumination and for the differences in skin temperature distribution on the satellite. Because the satellite is spin stabilized, the skin temperature distribution changes according to the attitude of the satellite in relation to the sun. Its spin rate—180 rpm—is high enough to insure a symmetrical temperature distribution about the spin axis. For example, when the satellite is in sunlight and its polar band is turned to the sun, the skin temperature at its illuminated hemisphere ranges from about 156 degrees F. at its polar band to about 55 degrees F. at its equatorial band. The skin temperature at the opposite (dark) hemisphere of the satellite in these conditions is about −173 degrees F. If the equator of the satellite is turned to the sun, the skin temperatures at its polar and equatorial bands are about 27 degrees F. and 34 degrees F., respectively.

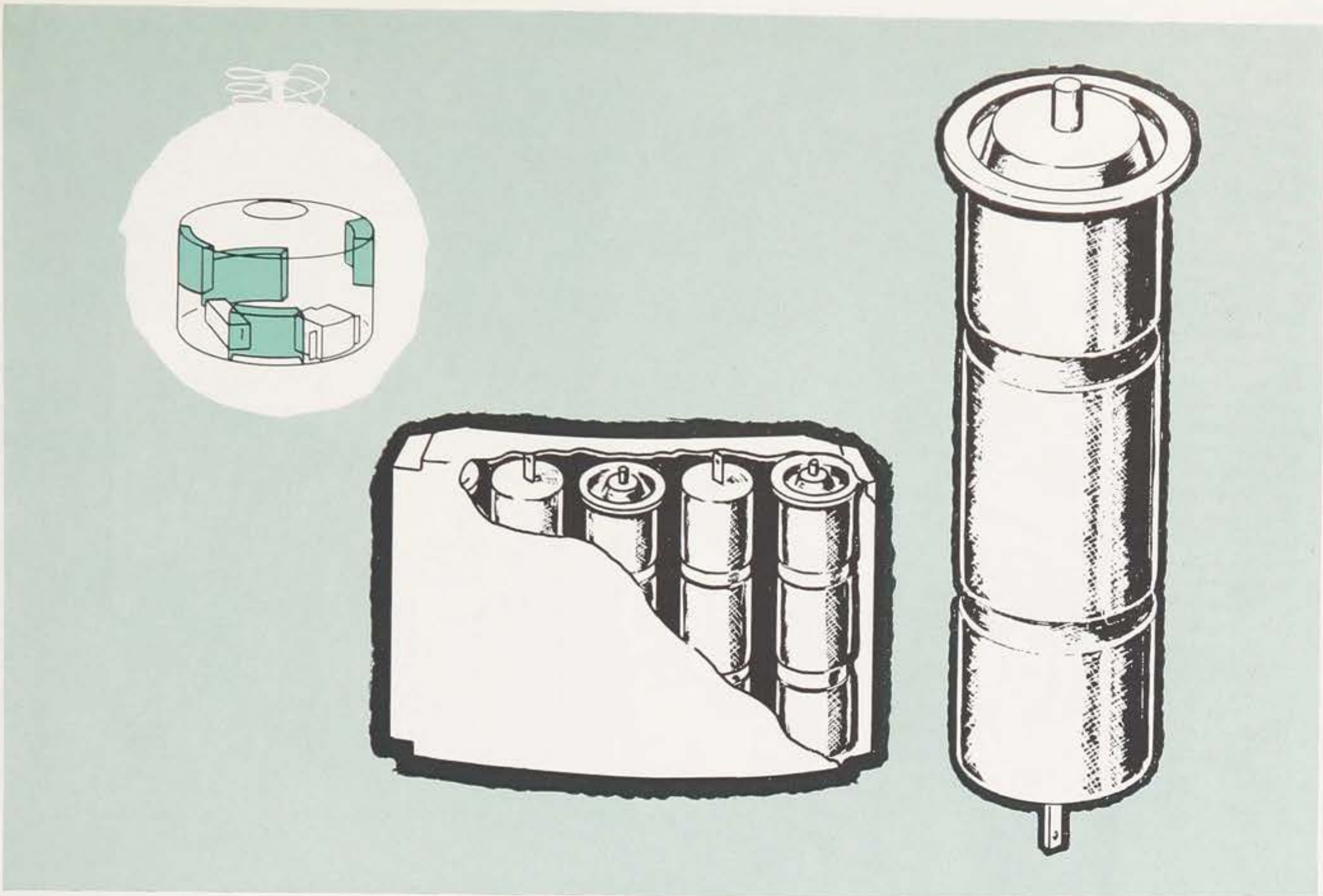
Power Supplied During Eclipse

During part of most of its orbits—up to 45 minutes of the 158-minute orbital period—the Telstar satellite is eclipsed by the shadow of the earth. Solar cells cannot function in eclipse periods and it is up to the battery to furnish power during these periods. A flexible program of radiation experiments and communications experiments of varying duration depends directly on the energy that the battery can supply at any time. The available energy is determined by: (1) the average solar power over 24 hours which depends on the length of the eclipse period and the orientation of the satellite; (2) the state of charge of the battery; (3) the allowable depth of discharge of the battery; and (4) the probability that the satellite will be in eclipse during an experiment.

To correlate the charging energy available from the solar array over a 24-hour period with the energy requirements of the electronic packages in the satellite, the power system designers analyzed the energy flow equations of the battery. This analysis established a firm footing from which to plan an experimental program that accounts for different battery depths of discharge. Families of curves were calculated for different values of available solar power, orbit eclipse time, and battery depth-of-discharge. Although the power system was designed to operate with maximum loads and the minimum voltage limit of an 18-cell battery, one extra cell was added for series redundancy.

The 19 nickel-cadmium cells (see the drawing on page 147) are arranged in three groups of five and one group of four. The cells are made of nickel cans with ceramic seals. Nickel was used because it resists caustic attack from the alkaline electrolyte and it is relatively easy to weld by the method of resistance welding. Each cell is 4.6 inches long, 1.3 inches in diameter, weighs 8 ounces, and has a nominal capacity of 6 ampere hours. A high alumina ceramic insulator bonded to a Kovar pin and cover provides a hermetic ceramic-to-metal seal. The cover is resistance welded to the case so that no cracks or holes are created near the weld.

Because the battery is alternately charged and discharged its terminal voltage varies. Ambient temperature also affects the voltage. The maximum variation anticipated (including one shorted



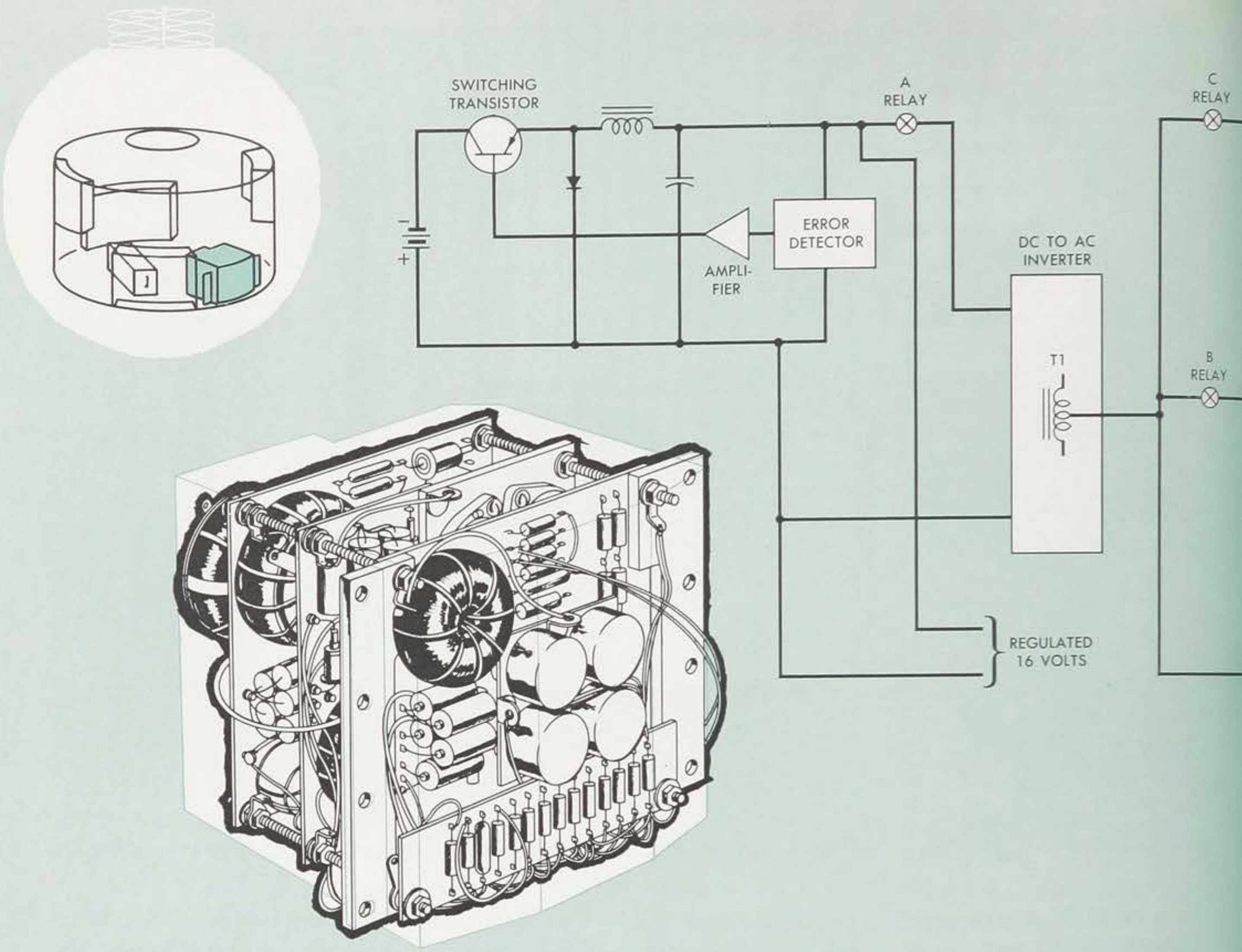
The Telstar batteries, showing how they are mounted in the satellite. The four-cell group was mounted in the quadrant with the most weight as an aid in the dynamic balancing of the satellite.

cell) was 20 to 29 volts. This variable voltage is applied to the input terminals of the main voltage regulator (see the drawing on page 148) which then supplies a regulated 16-volt output to the electronic circuits. Its output load varies from 0.2 ampere when none of the experiments are in progress to 2.0 amperes when they all are.

Besides these input voltage and output load variations, the regulator had to meet several other rigid requirements. Its efficiency had to be as high as possible; its weight had to be kept to a minimum; and it had to function in temperatures ranging from 25 degrees F. to 95 degrees F. Another requirement stemming from the outer space environment of the satellite was survival through a two-year period of proton radiation (about 1.5 x 10^{12} protons per square centimeter). For the utmost reliability under these conditions the regulator has a minimum number of components all of which operate well within their ratings. Finally, because obviously there could be no replacement of parts after launch, the circuit had to be able to tolerate anticipated variations in the parameters of the various components stemming from normal aging and radiation damage.

Series or shunt-type regulators which regulate by controlling the dissipation of power are fairly well known to power systems designers. A new development, the switching regulator, regulates through a switching mode. With ideal components, it can approach lossless regulation. Therefore, it was a natural choice for the Telstar satellite. Unfortunately, a switching regulator creates rectangular waves which must be filtered before they are applied to the various dc output loads. Efficient filtering can be attained with L-C low pass filters which are quite heavy. L-C filtering, however, is more effective at high frequencies than at low. Thus, to minimize the weight of the Telstar regulator, it had to be designed to switch at a relatively high frequency, in the order of 20,000 cycles. Even at these frequencies the L-C filter accounts for more than half the weight of the entire regulator.

The highest frequency at which the regulator can be made to switch efficiently depends on several practical factors. A switching power transistor alternating between cutoff and saturation (open and short) creates rectangular waves. Although the transistor dissipates little power

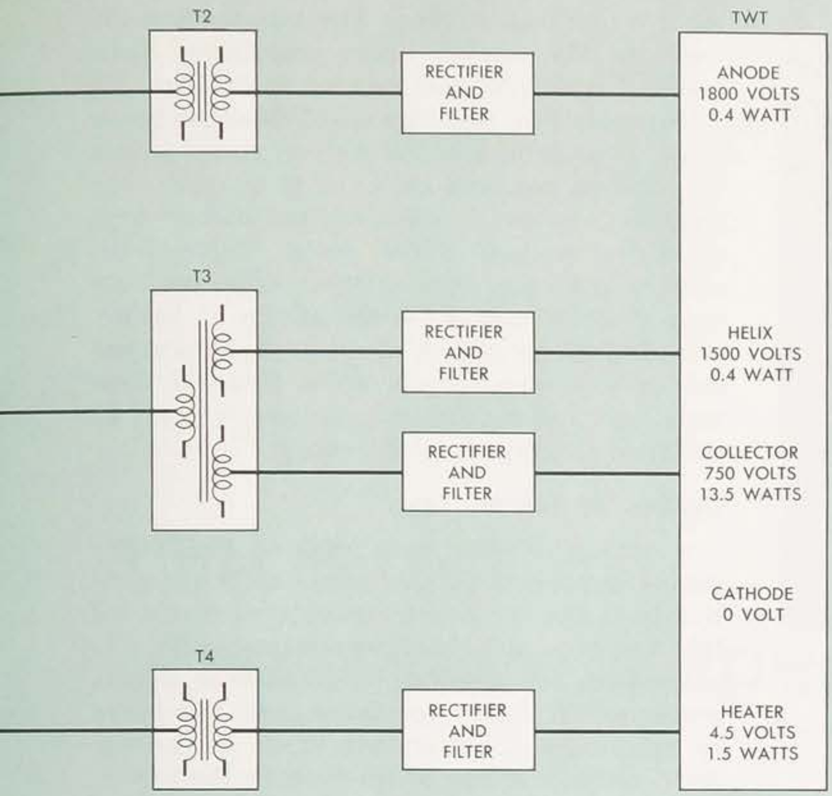


The voltage regulator (left), a fully transistorized unit, is made up of three glass-fiber filled polyethylene boards. The low voltage inverter section of the dc-to-dc converter is mounted with the regulator.

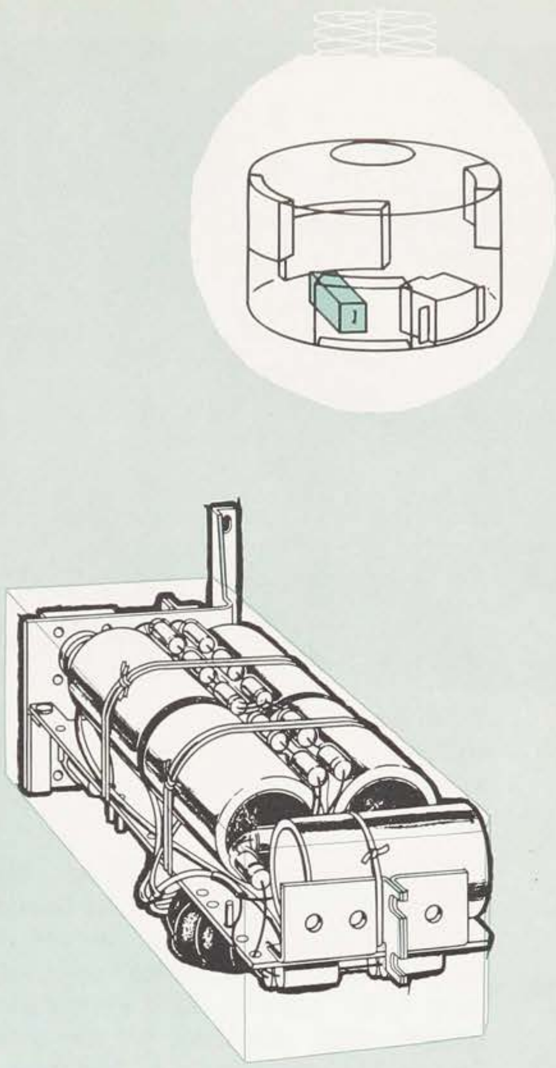
in the cutoff and saturation states, a large amount of power is dissipated during switching. However, the switching times are very short compared to the on-and-off intervals and the average power loss is small. At a regulator frequency of 20,000 cps, the switching power transistor actually spends only 1 microsecond in each 50 in switching (off and on). An alloy-diffused germanium power transistor was used for this switch because it has fast rise and fall times and a low saturation resistance.

Losses were carefully accounted for and every possible step was taken to minimize them. For instance, the input inductor of the main filter has frequency-dependent losses. To keep these as small as possible, that component was toroidally wound on a core of powdered permalloy.

The actual efficiency of the regulator is 92 per cent at maximum load and 85 per cent at minimum load. The package, which includes six control relays and the low voltage part of the converter, weighs 4.2 pounds. All flyable units were tested at temperatures from 15 degrees F. to 105 degrees F. The components are mounted on irradiated polyethylene boards filled with glass fiber. Transistors and diodes that require heat sinks are mounted on light-weight beryllium-oxide boards. The electrical insulation of these boards is that of a ceramic, but they have heat conduction properties that are similar to metal. These are connected thermally to the canister for maximum heat transfer with minimum size and weight. To guard against radiation damage, all transistors in the regulator are shielded by ⅛-



The schematic diagrams show how the output of the regulator is applied to the high-voltage section.



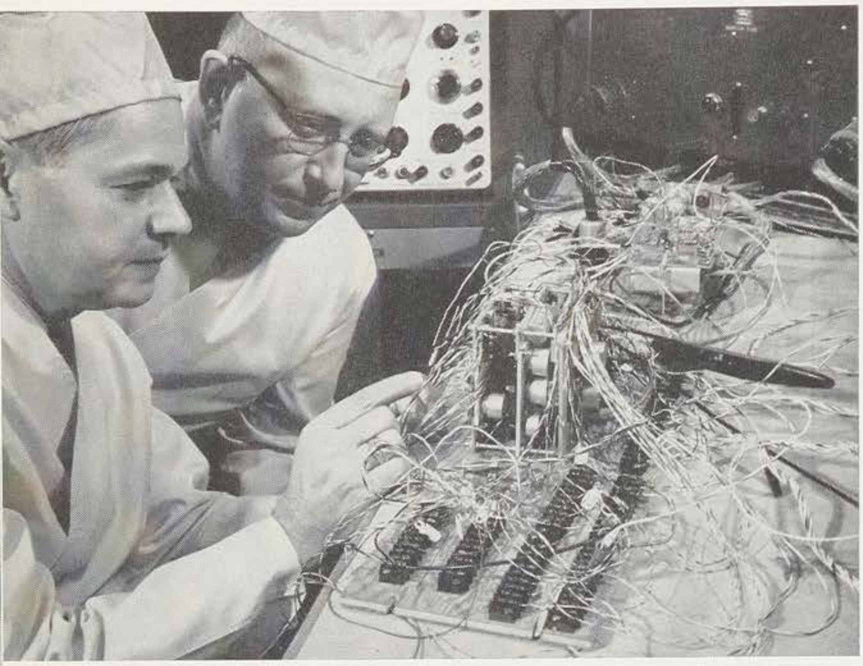
The high-voltage section is mounted separately, adjacent to the traveling-wave tube.

inch thick aluminum caps which supplement the shielding provided by adjacent equipment, the canister, and the outer shell of the satellite.

During communications experiments the dc-to-dc converter (see the drawing at the left) is also energized. It receives the 16 volt output of the regulator and, in turn, supplies accelerator, helix, collector, and heater voltages to the traveling wave tube. These voltages are supplied in sequence—first the heater voltage, then the helix and collector voltages, finally, at least three minutes after the heater is energized, the anode voltage. The voltages are removed in reverse order. This method of operation trades some power supply efficiency, weight, and size for maximum tube life. The converter is unregulated but there are only small changes in its output because the traveling-wave tube load is constant and the input is well regulated.

To eliminate the possibility of interference from the Telstar satellite VHF beacon if ground-command capability is lost, the satellite contains an electro-mechanical timer. This device consists of an electronic oscillator driving a precision gear train that operates a turn-off switch. It is driven by a button-type mercury cell. The timer was turned on just before launch, so that if ground command is lost after the two-year period the beacon will be turned off automatically.

In the final analysis, there was only one way to insure that the satellite would have the kind of reliability it had to have to function in outer space. That was through a rigorous program of tests carried out on all its systems down to their



P. W. Ussery (left), and B. Litwack of Bell Laboratories, Hillside, N. J., sort out spaghetti-like wires in the Telstar satellite's power regulator.

smallest components; no part was considered insignificant. The power system was first tested with a dummy load. Then, before the satellite was assembled, it was tested with the traveling-wave tube. Further tests were made after the systems were assembled in the satellite space frame. (Life tests already had been performed on components.) Telemetry data and transmission from the traveling-wave tube were evaluated during tests of the power supply operating in the completely assembled satellite. Then, vibration tests and environmental tests were performed as well as simulated orbital operations tests. Also, an extensive system test was performed before the launch to gather as much data as possible on the traveling-wave tube. During this test an external power supply was used instead of the satellite power supply. Thus, there was no drain on the fully-charged satellite batteries.

During the development of the Telstar solar cell extensive studies were made to determine the extent of damage from electrons and protons of various energies; to determine the cell short-circuit current for a set of standard cells under space illumination; and to devise correlation techniques which would allow simple laboratory measurements to represent the conditions of outer space. These studies showed that long-life solar plant performance could be achieved by covering the solar cells with the sapphire plates that have been described. Spectrum analysis and current, voltage, and temperature measurements were made on individual cells. The modules actually used on the satellite were constructed from matched individual cells selected from these.

To evaluate the performance of the entire power plant, a simulated solar cell-battery power system was devised and tests were run to determine the effects of changes in solar cell and battery temperature, available solar power, depth-of-discharge, and eclipse time. Other extensive tests were made to determine the effects of battery charging during periods of constant sunlight and during maximum eclipse orbits. Some of these tests were run continuously for over a year; all indicated satisfactory performance.

Variety of Battery Tests

A variety of tests were made on the battery during its construction. After extensive pre-selection tests the dry active elements were inserted into the cans and the covers were welded into place. Each cell was then surrounded by helium, evacuated through a tubulation, and leak-tested by examining the evacuated gases for helium. Next, electrolyte was added through the tubulation and the cell was back-filled with a mixture of oxygen and helium. It was then pinch-sealed and resistance-welded and the tubulation was tested for leaks by a helium "sniff" test.

Electrical tests on all cells included measurements of capacity, overcharge characteristics, self-discharge rate, and internal resistance. Repeated cycling tests were made as well as environmental, vibration, and acceleration tests. A group of several hundred cells was selected and from these 19-cell batteries were made from cells with matched characteristics. Before the launching, approximately 500,000 cell-operating test hours were accumulated on batteries of this type.

To date, the performance of the Telstar power system has been very close to what was planned in its design. The average solar plant output was measured at about 13.1 watts shortly after the launch. This is within 2 per cent of what was anticipated. Even under peak load and maximum use, the battery voltage range has been within 23.6 to 28.6 volts, and battery temperatures have ranged from 65 degrees F to 77 degrees F. The power conversion equipment has performed perfectly in an ambient approximating the battery temperature. On the basis of telemetered data it appears that after two years in orbit, the solar plant current should still be about 70 per cent of its initial value. Barring a catastrophic failure, the satellite power system could provide adequate power for experiments for a long time to come.

The chief function of the Telstar satellite is to receive signals from the ground, amplify these signals 10 billion times, and retransmit them on a different frequency to another ground station.

The Satellite Microwave Repeater

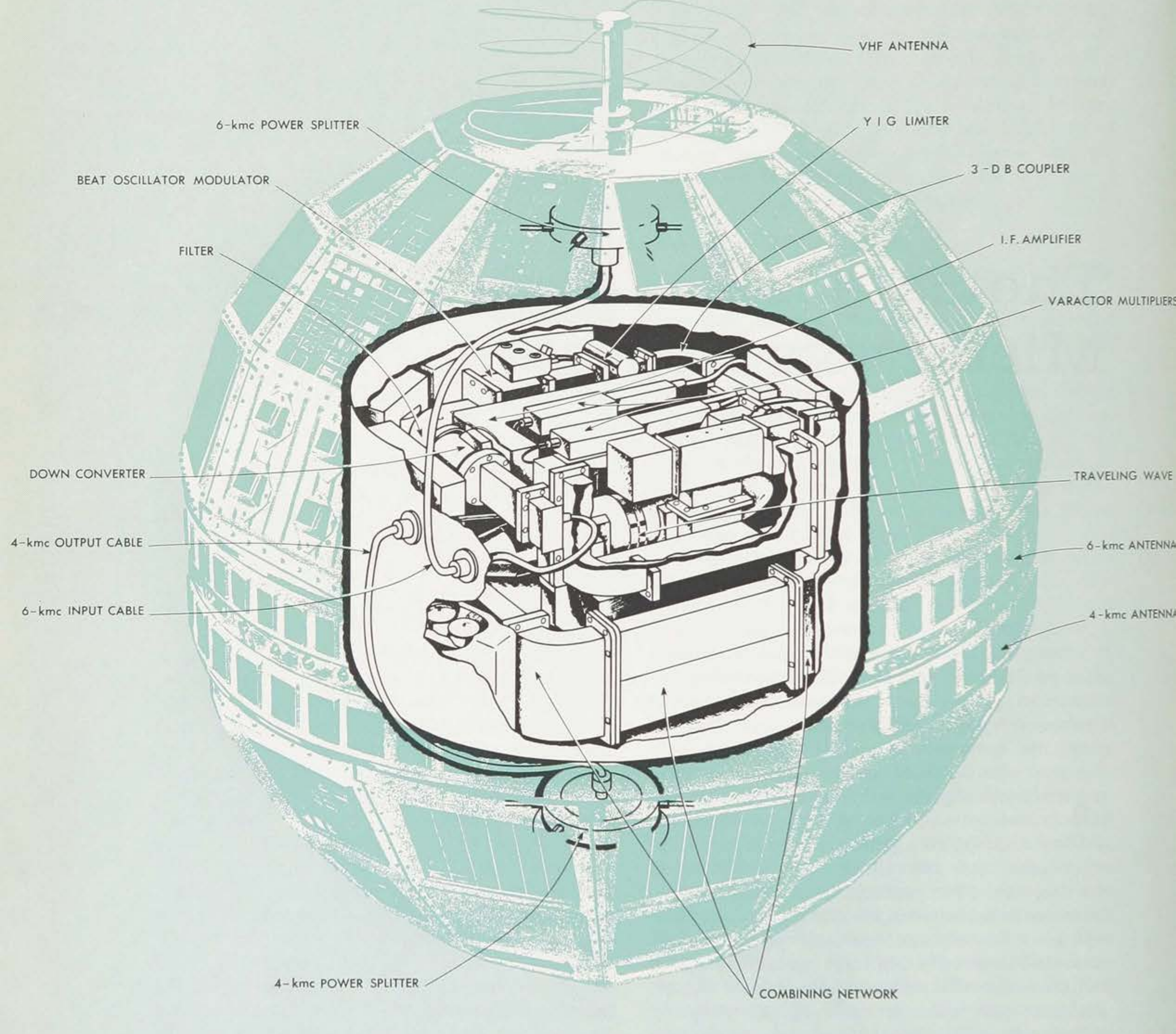
P. T. Hutchison

INTRODUCTION—The Telstar satellite's repeater is an electronic circuit capable of receiving and transmitting one-channel television, multichannel two-way telephony and high-speed data while orbiting the earth at altitudes to 3500 miles. This repeater receives FM signals centered at 6390 mc, shifts the signals to 90 mc for amplification in a transistor amplifier, shifts the signals to 4170 mc for further amplification by a traveling-wave tube, and re-radiates the signals to all visible points. The repeater, shown on page 152, includes the transmitting and receiving antennas, which are located near the equator of the shell of the satellite, and the centrally located electronics canister. The electronics canister houses the repeater proper which is made up of waveguide components, solid-state devices, and one electron tube—the traveling-wave tube amplifier.

Aside from the fact that it operates as an earth satellite, its function as the focal point of a communication system is little different from that of a microwave repeater on earth. To extend the concept of say, TH repeaters, from a continental system to a global one would be a justified comparison (RECORD, *February*, 1961). In the remainder of this section certain electrical features and design considerations peculiar to satellite communication repeaters are discussed.

Because the satellite is moving with respect to the ground station, it must transmit a microwave beacon whose frequency is extraordinarily stable to be tracked by ground station antennas. (The method of tracking the satellite is discussed in the article which begins on page 131.) Gyroscopic action keeps the satellite stabilized so that its axis of rotation is almost fixed with respect to the spin axis of the earth. To achieve satisfactory trans-oceanic communication with this orientation, the satellite's receiving and transmitting antennas must be as nearly isotropic as possible so that they can "see" all points on earth visible to them. Each microwave antenna consists of a belt of radiating ports spaced around the equator of the satellite and provides an almost isotropic radiation pattern.

Other differences between the Telstar satellite


VHF ANTENNA
6-kmc POWER SPLITTER
Y I G LIMITER
3 - D B COUPLER
BEAT OSCILLATOR MODULATOR
FILTER
I. F. AMPLIFIER
VARACTOR MULTIPLIERS
DOWN CONVERTER
TRAVELING WAVE
4-kmc OUTPUT CABLE
6-kmc ANTENNA
6-kmc INPUT CABLE
4-kmc ANTENNA
4-kmc POWER SPLITTER
COMBINING NETWORK

repeater and conventional repeaters are of a physical rather than an electronic nature. The Telstar satellite repeater had to withstand not only the stresses of launching, but it had to operate at high radiation levels and in the vacuum of space. All parts of the communications repeater except the antennas are housed in an electronics canister which is mechanically connected to the satellite frame by nylon lacing cord which greatly reduces the vibration experienced by the canister during launch. In addition, all subassemblies, which have been tested individually, are supported by hardened polyurethane foam which fills the canister and makes it mechanically strong. The hermetically sealed canister shields the electronics components from some particle radiation, and keeps the pressure inside the canister high enough to obviate any corona problems associated with the high voltages needed to operate the traveling-wave tube. Thermal shutters on the canister keep the temperature inside near 70 degrees F, but all circuits were designed to operate over a wide temperature range because of possible malfunctions of the thermal shutters.

The question of reliability is of utmost importance. The circuits are built almost without consideration of repair since repair is very difficult after the canister has been foamed and impossible after launch. All active and passive circuit elements in the satellite operate well below their power or voltage capacities. Before they are placed into the circuits, these elements are carefully screened and tested. After the elements are assembled, the circuits are tested again.

The size and weight of the satellite are important because these factors determine the type of launch vehicle used and the satellite orbit. Magnesium waveguides were used to reduce weight. The circuit arrangement, as shown in the photo and drawing on these pages, indicate the compactness of structure.

Circuit Operation

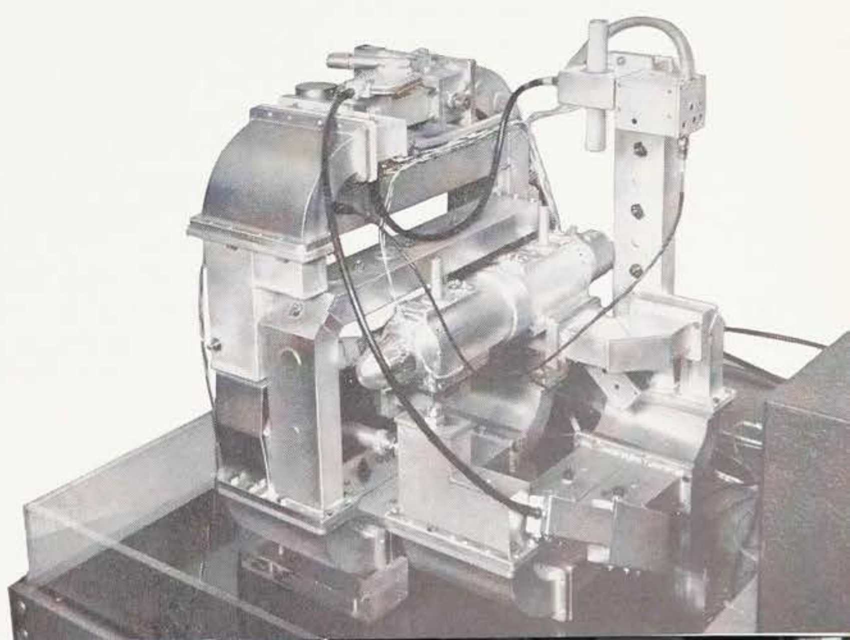
The FM signal arriving at the satellite from the ground transmitter has a center frequency of approximately 6390 mc. The nominal power level of this signal at the input to the repeater is about one nanowatt (10^{-9} watts). There may be variations in received power level (from 0.1 to 10 nanowatts) caused by changes in the satellite's range and orientation in space, and the repeater will function normally. However, the transmitted power from the ground can be programmed to compensate for these changes. The position of the satellite relative to the ground station affects reception because—as pointed out before—the antenna radiation pattern is not truly isotropic.

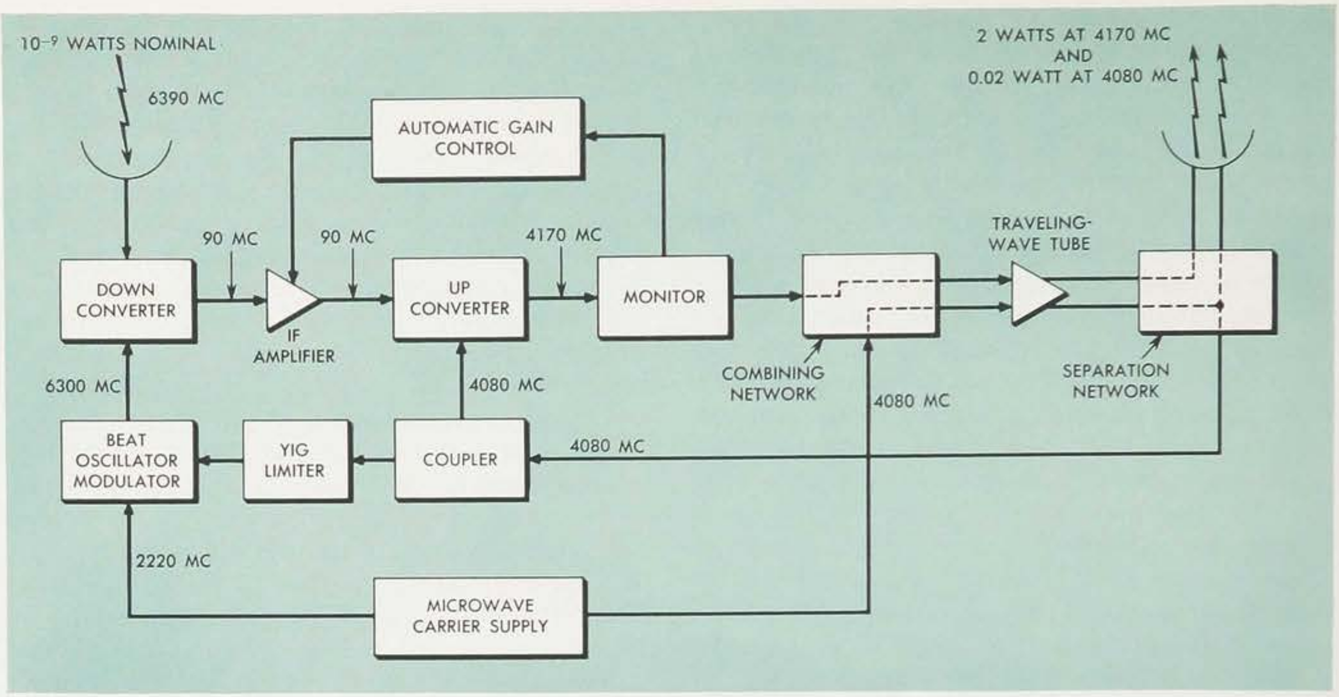
As shown on page 154, the received signal passes from the receiving antenna into a nonlinear down converter where it is combined with a continuous wave (CW) signal. As its name implies, the down converter shifts the frequency of the signal—in this case from 6390 mc to 90 mc. The signal was shifted to 90 mc because low-noise amplifiers at 4 kmc are complicated and impractical compared to amplifiers at lower frequencies. A 14-stage transistor amplifier boosts the power of the intermediate-frequency (IF) signal to about one-half a milliwatt. An up converter combines the 90-mc IF signal with a CW signal of 4080 mc to produce an output of 4170 mc.

A waveguide filter in the output of the up converter allows only the FM signal centered at 4170 mc to pass into the microwave monitor. Silicon diodes in the monitor rectify a sample of this signal to produce a dc voltage which is proportional to the microwave power level. This dc voltage is fed into an automatic-gain-control circuit which—by regulating the flow of current through two variolosser diodes—controls the gain of the IF amplifier. The automatic-gain control-circuit keeps a constant RF power drive to the traveling-wave tube which is connected to the output of the monitor. The traveling-wave tube amplifies the input signal about 5000 times and feeds the output through a separation network to the transmitting antenna. The power radiated in the 4170-mc band by the transmitting antenna is slightly greater than two watts.

A description of what happens as the communications signal goes through the repeater would, in general, hold true for most repeaters with, of course, appropriate changes in frequencies and

The compactness of the microwave repeater is evident in the photograph below. Unit is housed in electronics canister 20 in. wide and 12 in. long.





Block diagram of the microwave repeater. The possibility of circuit oscillation introduced by the closed loops is minimized by use of extra filters and special requirements for up and down converters.

power levels. One feature of the Telstar satellite repeater that makes it unique is the method used to obtain the local oscillator signals at 4080 mc and 6300 mc for the up and down converters. In a conventional repeater, the relatively high local oscillator signals are furnished directly to the converters by the microwave-carrier-supply circuit. Such a circuit requires, from a satellite viewpoint, a prohibitively large dc power, so the Telstar converter signals are obtained by using a reflex circuit in conjunction with a microwave-carrier supply which furnishes weak signals. In the reflex circuit, the weak signal at 4080 mc is amplified by the traveling-wave tube and part of the amplified output is fed through a separation network to act as the local oscillator for the up converter. Part of the 4080-mc output of the traveling-wave is combined in the beat oscillator modulator with a weak signal at 2220 mc to give the 6300-mc signal for the down converter. The power at 4080 mc which goes into the beat oscillator modulator is held constant by a yttrium-iron-garnet (YIG) limiter. The remainder of the 4080-mc output of the tube goes to the microwave transmitting antenna to become the microwave beacon needed by the ground tracking equipment to track the moving satellite accurately.

There are several closed loops, as shown above, which are unfortunate by-products of the reflex circuit. Closed loops in an electronics circuit always introduce the possibility of circuit oscillation. These closed loops are feedback paths, but they do not provide the usual advantages of negative feedback. The presence of these loops required the use of extra filters and special requirements on the up and down converters. While the problems associated with the loops caused more trouble than almost any part of the circuit, the final circuit has a good margin against any type of oscillation.

The microwave circuits are "woven" together as shown on page 153. Special techniques are required to get the microwave circuitry into the small allotted space. All waveguide filters are of the direct-coupled type to give minimum filter lengths. One filter is made with a 90-degree (metered E-plane) waveguide bend in the center of one of the cavities, and another filter has a relatively sharp H-plane bend. Also, there are five 3-db couplers in this circuit which have 90-degree bends. The circuitry is designed so that every section of straight waveguide 1½ in. or longer is part of a filter, a transducer, an attenuator or a modulator. There are no flexible waveguide sections, but flexible coaxial cables are used.

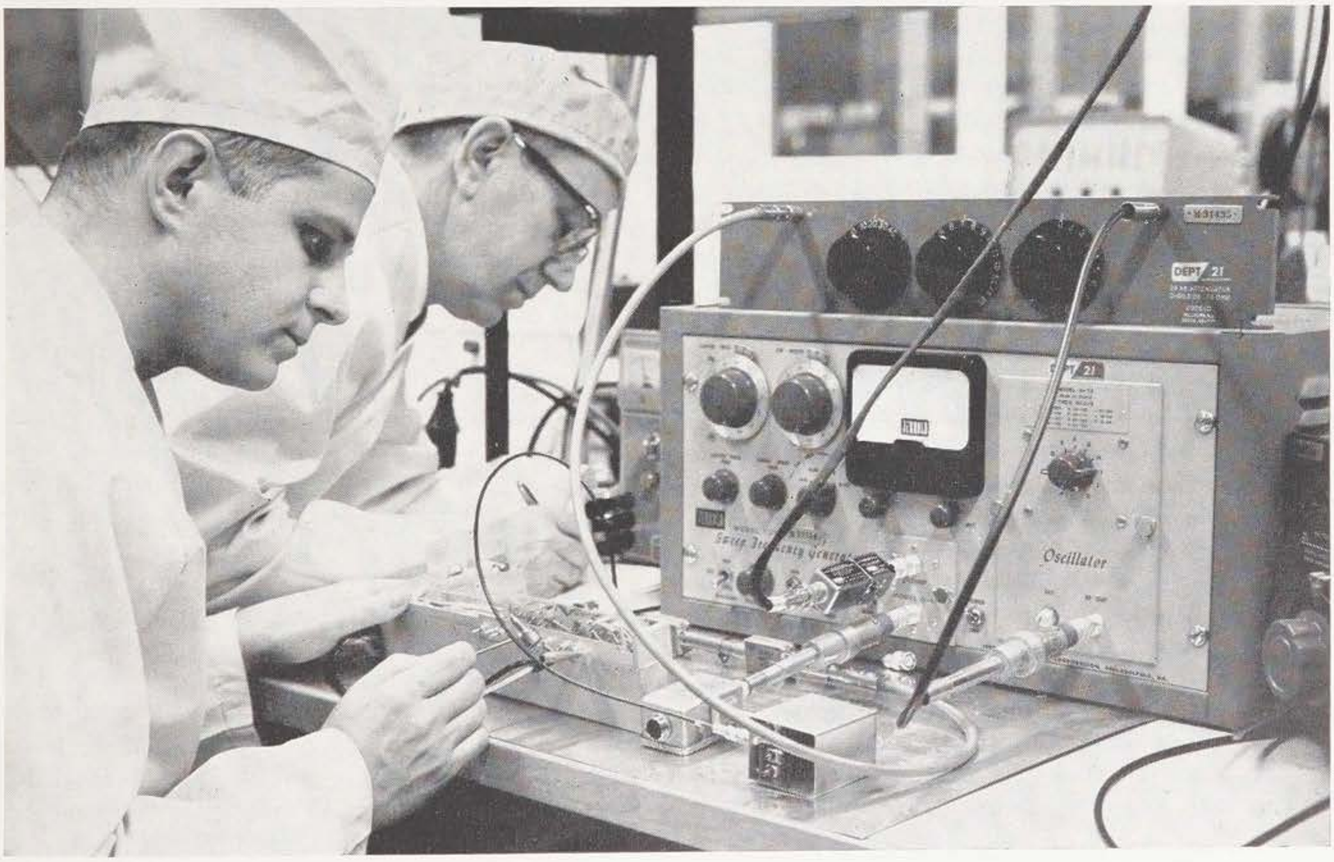
The electronics canister is made by welding domes on the top and bottom of a cylinder about 20 in. wide and 12 in. long. After the domes are welded, the canister acts as a big echo box. Consequently, the problem of reducing the couplings between units to acceptable levels becomes very difficult. For example, the power supply contains one square-wave generator operating at a fundamental frequency of 2.5 kc and another operating between 25 and 50 kc depending on the load on the power supply. Also, there are five crystal oscillators that are used to produce the microwave-carrier-supply signals at 2220 and 4080 mc, the VHF beacon signal at 136 mc, and the local oscillator signal at 128 mc for the command receiver. The frequencies of the crystal oscillators (15.9364, 17.3426, 17.0063, and 31.9750 mc) and their harmonics plus all the harmonics of the square-wave generators create a "noise" spectrum that can cause trouble in the IF amplifier and the converters. The problems associated with the myriad couplings in the canister were solved with extensive shielding, filtering, and patience.

Fourteen telemetry channels monitor the traveling-wave tube currents, temperatures, and critical power levels in the microwave repeater. The readings of these channels provide data to check on the "health" of circuits. Two of these channels are important from an operational standpoint. One channel measures the variolosser current which controls the gain of the IF amplifier so that the rf power drive to the traveling-wave tube is constant. The variolosser current is calibrated in terms of the received signal at 6390 mc; thus, this information is helpful in programming the power radiated from the ground transmitter.

The second channel monitors the power level of the 4080-mc signal at the up converter. This channel provides a direct record of any change in the level of the 4080-mc power (the microwave beacon) and an indirect measure of the changes in the power at 4170 mc. The traveling-wave tube is driven into partial saturation by the communications signal at 4170 mc so any change in the output of the tube at this frequency will be inseparably connected with a change in the level of the other and weaker (4080-mc) signal also amplified by the tube. Thus, this telemetry channel monitors the power at 4080 mc and tells when there is a change in the output power at 4170 mc.

The telemetry readings from all the channels monitoring the communications repeater show that there was no damage during launch and there were no measurable changes in the circuit during the first six months of operation.

W. E. Ballentine (left) and J. J. Gainey of the Laboratories conduct transmission tests on the intermediate-frequency amplifier for the Telstar satellite microwave repeater at Hillside, N. J.



Remote as it is in outer space, the Telstar satellite is responsive to the control of men on the ground. The command and telemetry systems are the instruments of this control.

Satellite Command and Telemetry System

E. P. Moore and W. J. Maybach

If the Telstar satellite had a battery large enough to store a two-year supply of power without being recharged, it would not need a command system except as required to turn off the emission in case of interference with other services. However, the solar plant and the battery together can supply only about 28 watts and the battery must be recharged when the communications circuits—the largest power drain in the satellite—are not operating. The command system is primarily a means of turning these high-drain circuits on and off. But since it must be included in the design, we can take advantage of the full capabilities of this system and assign other functions to it. In the Telstar satellite the command system is also used for attitude control, to check the operation of each command channel, and to switch the telemetry encoders.

The telemetry system is actually a separate subsystem. It monitors the general health and environmental conditions of the satellite and is the feedback link for control of the satellite. More precisely, the function of the telemetry system is to measure various parameters in the remote satellite and to convert the measured quantities to a representative signal that can be transmitted to the ground and conveniently interpreted. These measurements are of basic importance, because physical quantities and phenomena cannot be studied, understood, or, indeed, even talked about intelligently unless they can be quantitatively measured. Now, even in a well-equipped laboratory it is a highly complex task to measure temperatures, currents, and voltages accurately. Yet for Project Telstar, these measurements are made in a sphere that is only 34 inches in diameter and they must be transmitted without appreciable error to a point 6000 miles away.

Command and telemetry functions are performed at VHF frequencies. The elements of the satellite VHF system are shown in the drawing at the top of the column on page 157. The VHF carrier, which transmits telemetry to the ground, is also used as a low frequency beacon tracking signal. A single antenna serves both the 136-mc beacon and the 123-mc command frequencies. The command system consists of a receiver, a decoder, and magnetic latching relays with their associated drivers. For reliability, both the receiver and the decoder are duplicated and either decoder output can operate the relays.

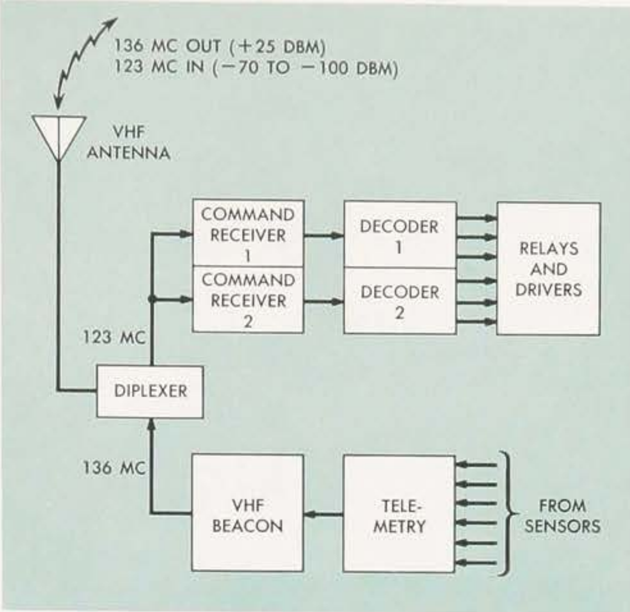
The antenna atop the satellite—a multiturn helix—would be circularly polarized if it were electrically isolated. The surface of the satellite, however, acts as a ground and hence the antenna is almost linearly polarized. Relative to an isotropic antenna, its gain is +2 db to —8 db depending on the spin angle of the satellite. Signals to and from the antenna pass through a diplexer unit, made up of low-loss lumped element tuned circuits, which isolates the beacon and command frequencies from each other. In the command frequency antenna arm the diplexer provides a minimum loss of 80 db at 136 mc and less than 3 db at 123 mc. In the beacon arm, loss is 20 db at 123 mc and less than 1 db at 136 mc.

Command information is contained in the 5 kc subcarrier of the amplitude modulated 123 mc signal. A typical word, or command, (see the middle drawing opposite) consists of eight time slots of four units duration. Each command word contains a guard space (four units long), a "sync" pulse (three units long), and six code bits each containing three ones (two units long) and three zeroes (one unit long). The code structure and the carrier and subcarrier frequencies were chosen to be compatible with the command facilities that existed at the NASA Minitrack Stations. The three-out-of-six code permits twenty unique commands; the Telstar satellite uses fifteen.

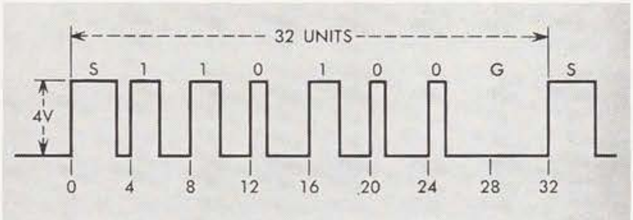
The strength of the command signal at the input to the satellite receiver ranges between —70 dbm and —100 dbm depending on the range and orientation of the satellite. The receiver amplifies the signal to a usable level, recovers the pulse-coded command, and provides a constant amplitude signal to the decoder over the range of input levels. The decoder translates the pulses into usable instructions.

The receiver (see the bottom drawing opposite) is basically a superheterodyne type with a crystal-controlled local oscillator, two RF stages ahead of the mixer, a 5-mc IF section, two detectors, and an automatic gain control (AGC). The RF section provides 10 db of image rejection. It has sufficient gain so that its noise figure is dominant, and this leads to an overall noise figure of 6 db. Most of the receiver gain stems from the IF section which has a gain of 50 to 80 db depending on the level of the input signal. The AGC adjusts the emitter current in the first three IF stages to maintain a constant 4-volt peak-to-peak signal at the receiver output. Two detectors are used; the first removes the 5-kc subcarrier, the second recovers the command signal.

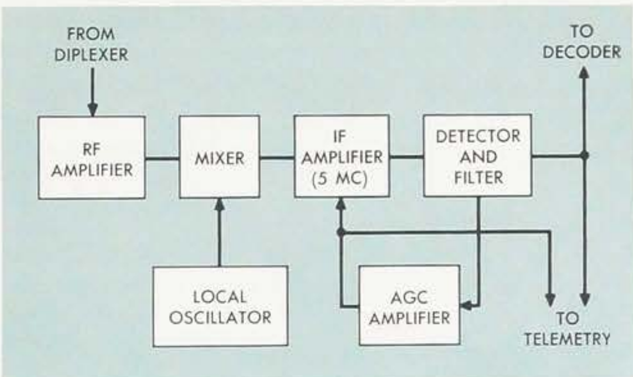
In the decoder (see the drawing on page 158) signals are first put through a shaping network that has a threshold fixed at half the normal pulse amplitude, and then through a translator that ascertains the pulse width. A shift register stores indications of a zero or a one for each code bit and converts the binary code from serial to par-



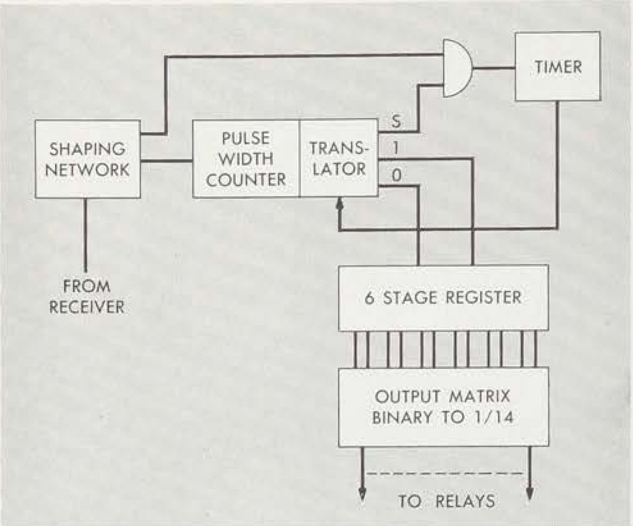
Block diagram of the Telstar satellite VHF system. The VHF carrier has two functions. It not only transmits telemetry to ground stations, but is also used as a low-frequency signal for tracking.



Format of typical 32 unit (eight time slots of 4 units duration) word used in satellite command system. This format permits 20 possible commands.



The basic components of the command system superheterodyne-type receiver. For greater reliability, the Telstar satellite system includes two radio receivers to receive the pulse-coded commands.



The command system contains two decoders for greater reliability. The two channels operate in parallel and either one can be commanded off or on when there is trouble or to check the operation.

allel form. This is then translated from a binary code to a one-out-of-fourteen code to drive the magnetic latching relays. A timer, started by the sync pulse of each command word, operates on all consecutive pulses in the word to prevent the inadvertent joining of two code fragments. Both command channels operate in parallel. To disable a path so that the operation of the other channel can be checked, or to remove it from service if there is trouble, a command is sent through one decoder. This command causes the first decoder to operate a relay which disables the second. The relay drops out in 15 seconds to restore the decoder to normal operation.

Two telemetry channels monitor each of the receivers and report on their operation. One channel monitors the AGC voltage. This voltage indicates the level of the received signal. Alternatively, readings at known received levels can be compared for changes in circuit operations. The second channel samples the signal at the output of the receiver to ascertain the amplitude of the pulse supplied to the decoder and to measure the signal-to-noise ratio.

The telemetry system (see the drawing on page 159) can be viewed as a digital voltmeter that can measure 118 parameters within accuracies of one per cent and transmit the measurements to the earth. Each parameter is assigned to a separate channel (see the table on page 160) and thus one frame of telemetry transmission consists of the information from 118 channels. Although it is a PCM system, it can handle both analog and digital information. Because most quantities telemetered in the satellite vary quite slowly, the system can use a slow scanning rate—only one frame a minute—which is compatible with the data rate. In addition, the slow scanning rate and narrow bandwidth lead to improved noise performance and reduced power drain.

Information telemetered from the satellite can be divided broadly into four categories. The first can be called "housekeeping telemetry"; it is the monitor of the general health of the satellite. It includes internal and external temperatures, pressures, and solar aspect. The second is status information—the state of control switches and the condition of the power plant, for example. The third consists of currents and voltages associated with the microwave repeater; traveling-wave tube currents, modulator biases, and AGC voltages are typical. The fourth is associated with the radiation experiments. It includes, among other things, the outputs of radiation particle detectors and of transistor damage and solar cell damage experiments.

Before these quantities can be coded for transmission, they must be converted to voltages. Many of them are initially in the proper form, such as voltages and currents in the power plant, communication repeater, and radiation experiments. Thermistor-type transducers convert temperatures to voltages while pressure transducers convert pressure to voltage. The analog outputs of the various sensors then enter the multiplex portion of the telemetry system where they are connected to a common bus in a time sequence that corresponds to the word rate (channel rate) of the system. For coding, the amplitudes of the samples that appear on the common bus must be constrained within a range of 0 to −5 volts. Many channels are normally within the range. Those outside it must be amplified, or attenuated, depending on their respective levels. Transistor gates select the channels in proper sequence for coding. The gates are pulsed on in the correct sequence by a square-loop magnetic core matrix. Vertical and horizontal shift registers step the matrix.

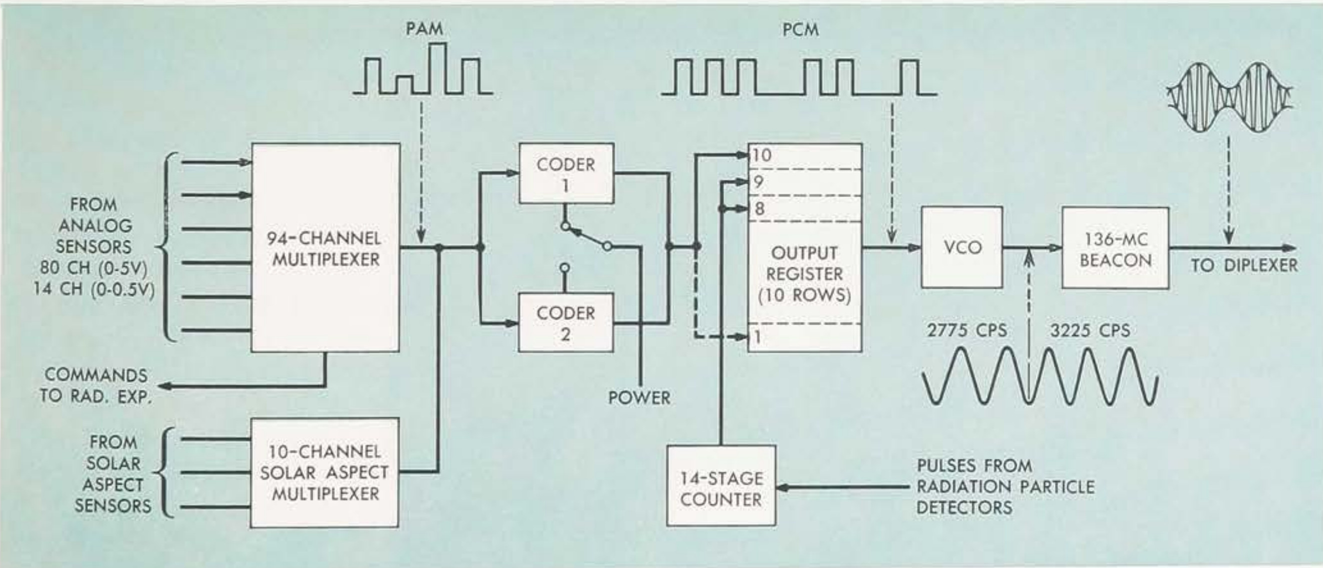
The samples that appear on the common bus are applied to either of two digit-at-a-time coders where they are converted to seven-bit binary words. (Two alternate coders are provided for greater reliability. Either one can be put in operation by command from the ground.) Each analog sample can be quantized into 128 (2^7) levels, or codes. Coding is performed in 50 microseconds and the binary words, which are generated in parallel form, are normally stored in the top row of the output register. In special circumstances this mode of operation is changed and the

William Gianopulos tests a subassembly that switches various circuits for the command system.

data are stored in the bottom row of the register. An eighth, synchronizing, bit is added to each word and the words are shifted out of storage to form a serial PCM train that has a bit rate of 16 pps. The pulse train then shifts the frequency of the 3-kc voltage-controlled oscillator. This operation is similar to FSK telegraph: A zero in the pulse train shifts the frequency to 2775 cps and a one shifts it to 3225 cps. This frequency-shifted subcarrier amplitude modulates the 136 mc beacon carrier. Basic timing and synchronizing for the entire telemetry system are derived from a 32 cps oscillator. The 16 bps bit rate and the 2 cps word rate are obtained by counting down from the basic 32 cps frequency of the oscillator.

Processing information from the radiation experiments on the satellite is facilitated by the fact that the outputs of the particle detectors are pulses that can be processed by simple digital circuitry, thus bypassing the complex coding operations. Command pulses from the telemetry multiplexer control the gating of outputs from the various detectors into a 14-stage binary counter that has a capacity of 16,383 counts. The command pulses to the radiation experiment switch the different gates and biases on and off. Seven times a frame, the commands transfer the contents of the counter to rows 8 and 9 in the output registers. The data in these rows are then shifted up and out of the register at the normal word rate. During insertion and read-out of the register, the coder is inhibited.

The solar aspect part of the "housekeeping" telemetry is actually a separate subsystem. Solar aspect is the angle, measured with respect the upper hemisphere of the satellite, between the spin axis and the line from the sun to the satellite. Six solar cells, mounted so that they face into orthogonal parts of space, are solar aspect sensors. These sensors and four other solar cells, which are part of the radiation damage experiment, are sampled and stored during an 1100 microsecond period near the end of each telemetry frame—rather like a snapshot reading. A multiplexer in the solar aspect subsystem is actuated by a command from



Telemetry system of the Telstar satellite. Inputs from sensors on the satellite skin are converted to a Pulse Amplitude Modulated train which is then translated to Pulse Code Modulated signals.

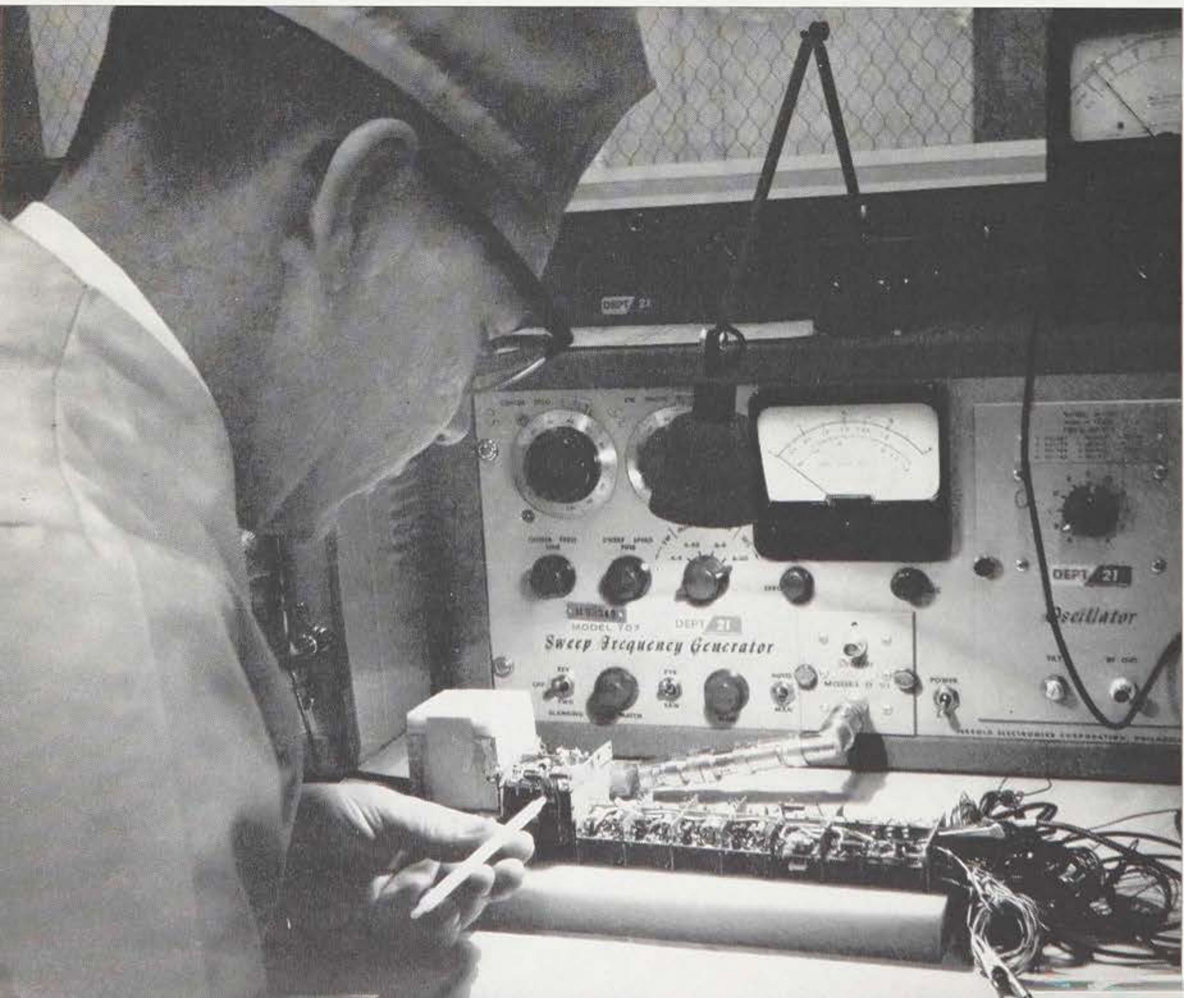
	Number of Channels
Radiation Experiment	37
Internal Temperature	24
External Temperature	16
Microwave Circuit	13
Power Supply	9
Relay States	4
Command System	6
Canister Pressure	2
Calibration	1
Frame Synchronization	2
Unassigned	6
Total	120

the regular telemetry multiplexer. After the outputs of the ten channels are coded, they are stored in rows 1 to 10 of the output register and then shifted up and out at the uniform word rate.

To facilitate handling the serial PCM signal on the ground, a word synchronization pulse is added to each word in the top row of the output register. To synchronize the telemetry frames, a unique code and its complement are placed in rows 8 and 9 of the register. These codes are shifted up and out at channel times 119 and 120.

To give the ground tracking receiver a steady carrier to track, the telemetry information is carried in the sidebands 3 kc above and 3 kc below the 136 mc carrier. The carrier itself is obtained by multiplying a 17 mc crystal-controlled frequency by a factor of eight (three doublers). A final output of approximately one-quarter watt is reached through a transistor power amplifier. The modulator section—a push-pull amplifier—modulates the main carrier to 50 per cent.

The very sensitive role of the command and telemetry systems was indicated late last year when the Telstar satellite temporarily stopped functioning because of radiation damage to a transistor in the command circuit. To restore it to operation, a special kind of binary code was devised to trigger the command decoder circuits into operation. When the normal command function was finally restored the satellite transmitted television pictures as crisp as those on its first passes. In February of this year, the command system again stopped functioning. Although the possibility of a catastrophic failure does exist, it is likely that radiation damage is again the cause. The circuits may recover from radiation damage, so the Laboratories is continuing its attempts to command the satellite. If these attempts are not successful, the experimental life of the first Telstar satellite is ended.



J. C. Oefelein makes adjustments to the command receiver during development of the Telstar satellite at Hillside.

Only with exhaustive tests can we safely predict the performance of many electronic components and materials if they are to operate in an atmosphere other than earth's. The electronic canister is designed to transport the earth's atmosphere to outer space.

Thermal Design Of the Electronics Canister

P. T. Haury

ALMOST ALL THE ELECTRONIC ASSEMBLIES of the Telstar satellite are contained in a single cylindrical unit called the electronics package. This cylinder, only 20 inches in diameter and 12 inches in height, occupies the central volume of the satellite's 34-inch sphere. Yet, the electronic assemblies it contains can perform essentially the same functions as those of a ground microwave repeater station which might occupy several hundred square feet of building space. For this reason, the Telstar satellite has been called a microwave relay station in orbit around the earth.

In broad terms, an earthbound repeater station comprises microwave repeater equipment (usually for several channels), a system of microwave carrier supply, a source of primary power and a local power plant, and antennas on a tower. There are also some very important auxiliary items for operation and maintenance. An "alarm, indication, and order" system, for example, is a link through which maintenance personnel get reports and exercise corrective action or interrogate the station for more information.

The Telstar "station" includes a power plant with a storage battery, a microwave repeater (though for only one basic channel) and its associated microwave carrier supply, a telemetry system (for alarms and indications), and a command system (for orders). These are the "normal" elements. The satellite also contains a diagnostic experiment in the radiation monitors and their related circuitry. The only significant departures from a ground station are the method of "installation" and the problem of "repair."

The only electrical items not contained in the electronics package are the solar battery, the antennas, and those portions of the radiation experiments necessarily placed on the outer skin. Beside

The electronics package, completely foamed and sealed, must meet rigid weight requirements.

the waveguide circuitry and the associated traveling-wave tube, there are seventeen major wired subassemblies and nineteen nickel-cadmium storage cells in the package. The wired subassemblies contain a total of approximately 7100 semiconductor and passive components. A very efficient over-all packaging design was achieved, despite the variety of the circuits and the limitations of time and mechanical constraints.

While the packaging design must satisfy the factors of space and launch environments, it must also satisfy its own reason for being. In this case the objective was to provide an orbiting microwave repeater station of small size and light weight. Design techniques for such equipment, even in substantially miniaturized form, are widely known for ground-based equipment. To permit adaptation of these techniques to the Telstar electronic equipment on as broad a base as possible, a basic design philosophy was chosen in which the design problems were the more familiar and more easily soluble ones. This was, in essence, the choice of a method whereby earth's environment could be transported into space. To accomplish this, an hermetically-sealed container was proposed. Further, it was decided to obtain the mechanical support needed to withstand the prelaunch and launch environments by the extensive use of rigid foam encapsulation. Such encapsulation methods have been used with considerable success by Laboratories engineers in the missile-born equipment for radio controlled missile guidance (RECORD, *January,* 1963). In the electronic package, the encapsulation was carried a step farther in that the assembled package was filled almost completely with the rigid foam. The final result, (see the photograph above) is a monolithic sort of structure with a high degree of mechanical ruggedness. Of course, each succeeding step of assembly makes repair more problematical. This, however, is consistent with the over-all reliability objectives and surely cannot affect maintenance problems after "installation" in space.

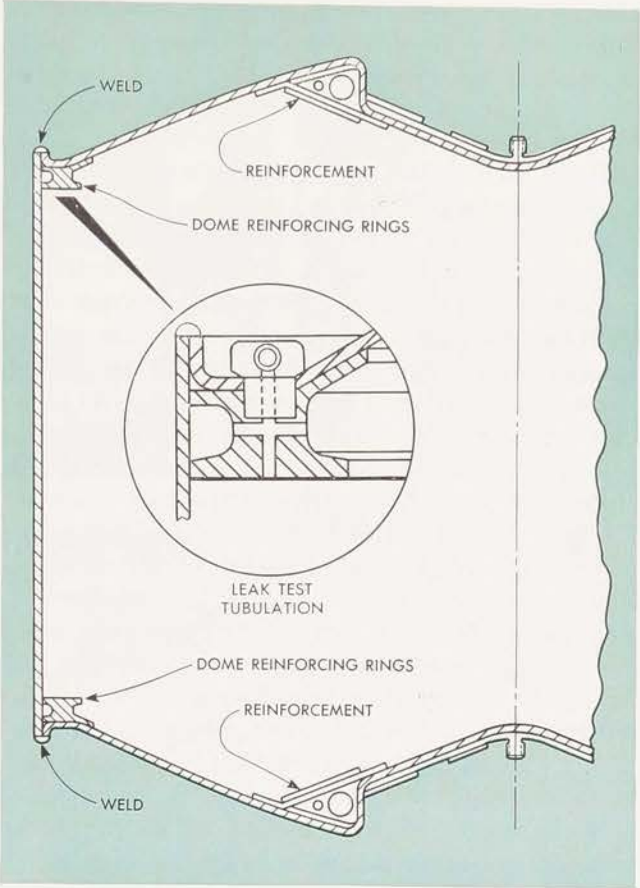
The sealed container (hereafter the canister) can easily be judged the most important single item in the mechanical design of the electronics package. On it and the hermetic seals provided by it rested success or failure, since the high-voltage supply to the traveling-wave tube could not operate in the partial atmosphere that might be caused by a critical leak. Also, materials could be chosen for use within it without regard to their "outgassing" and contaminating critical surfaces of the outer spacecraft structure. Another advantage, thought at the time to be fortuitous, but now recognized as most valuable, is the radiation shielding provided by the metal enclosure.

The drawing at the right is a cross-section of the canister, through its cylindrical axis. Fabricated of aluminum alloy in 1/16-inch thickness for both the cylinder and domes, the enclosure is finally sealed on a specially constructed automatic welding machine by two 60-inch welds. The completed package has a diameter of 20⅛ inches and an over-all height of 16 inches. The recess in each dome provides for the mounting of the thermally actuated bellows controlling the package temperature. With the pressure in the canister being finally set at 10 pounds per square inch absolute, the force acting on a dome in the orbital vacuum is about 3000 pounds. It was, therefore, necessary to reinforce the bellows recesses as shown in the drawing. Similarly, a heavy reinforcing ring was required at the periphery of each dome, the reinforcements being solidly brazed to the spun dome section. The use of the heavy peripheral ring does not represent the most efficient design from a weight standpoint. However, achieving a lighter weight would have required a more difficult welding design and, more important, the weld could not be removed and another weld made. The welding method chosen (the drawing shows a weld atop the upturned dome lips) can be milled off and repeated once or twice. This feature has been most valuable in the repair of those models that developed faults after sealing.

Electrical access to the contents of the package also introduced sealing problems. Six penetrations are required in the cylinder wall; three for coaxial feed-throughs of the VHF and microwave circuits and three for multipin headers connecting to external sensors, solar plant, etc. Their circular openings are reinforced by rings welded into the wall. Ultimately, solder plating is applied to the ring seats and the glass-seal feed-throughs are soldered in place. The seals are individually leak tested by helium detection methods at the time of installation and again before filling the package with foam.

Leak Testing Is Critical

Leak testing of the completed package is a most critical step in its construction. The volume within the package that is not occupied by the rigid foam or hardware provides a reservoir of about 10 liters of gas at 10 psia. A conservative design objective was chosen of permitting a leak that would allow the pressure to drop to 5 psia in the two-year life of the experiment. This represents an average loss of 5 liters of gas in the two years or about one cup per month. This established a permissible initial leak rate of about 8×10^{-5} standard cc/sec with an 8:1 safety factor.



A cross-section of the canister through its cylindrical axis showing details of the dome reinforcing ring and the leak test tubulation.

To measure the initial leak rate the package was first exhausted through a tubulation inserted in the top dome and refilled with argon at 10 psia. The tubulation was then pinched off to seal it and the complete package was placed under a bell jar. The bell jar was then evacuated and the exhaust from it was monitored with a detector for argon. Comparison of the argon reading of the detector with that for a calibrated leak allowed determination of the maximum leak rate with an accuracy 100 times better than the permissible leak. After all environmental testing had been completed, the argon, because of its low ionization breakdown potential, was pumped out and replaced by dry carbon dioxide. The tubulation was then pinched off and this pinch-off was leak tested by measuring the rise in pressure from it into a known evacuated volume.

In the course of development, prototypes of the canister were subjected to overstresses by hydrostatic pressure and exposure to vacuum with an internal pressure in excess of that encountered in orbit. Two such models were loaded with dummy weights to represent the final assembly and exposed to complete qualification-level vibration and shock tests. Leak tests were made before and after the qualification runs to verify the adequacy of the seals and the structural design of the canister.

The thermal balance and thermal control of the electronics package as related to the complete spacecraft is discussed in the article beginning on page 167 in this issue. Within the electronic package, it was a part of the basic approach that the heat dissipated be transferred to the domes by conduction. This resulted from the use of the foam encapsulation, which essentially blocks radiation transfer and prevents appreciable convection flow in the gas reservoir. Early recognition of these factors and attention to the major power dissipation loads in the course of designing the over-all assembly satisfied design objectives with little or no penalty in weight or by compromise. The thermal flow is aided considerably by the presence of the relatively heavy waveguide and its intimate coupling to the traveling-wave tube. Heat flowing to the waveguide is conducted to the canister by brackets that are welded to the wall and securely bonded to the waveguide. The waveguide also serves as a support and heat sink for units with modest dissipations up to a watt or two.

Of special concern were the nickel-cadmium battery cells and the power supply regulator, which are mounted directly to the cylinder wall to limit temperature rises within them. The battery cells are so mounted because the entire 14-watt initial output of the solar plant might be dissipated for long periods as overcharge in the cells. Within the individual units, transistors operating at high power are mounted on beryllium-oxide heat-sinks which are soldered to the chassis structure. In addition, laboratory experiments were run on foam encapsulated components in typical mounting situations to evaluate their temperature rises.

Analog Circuit Aided Development

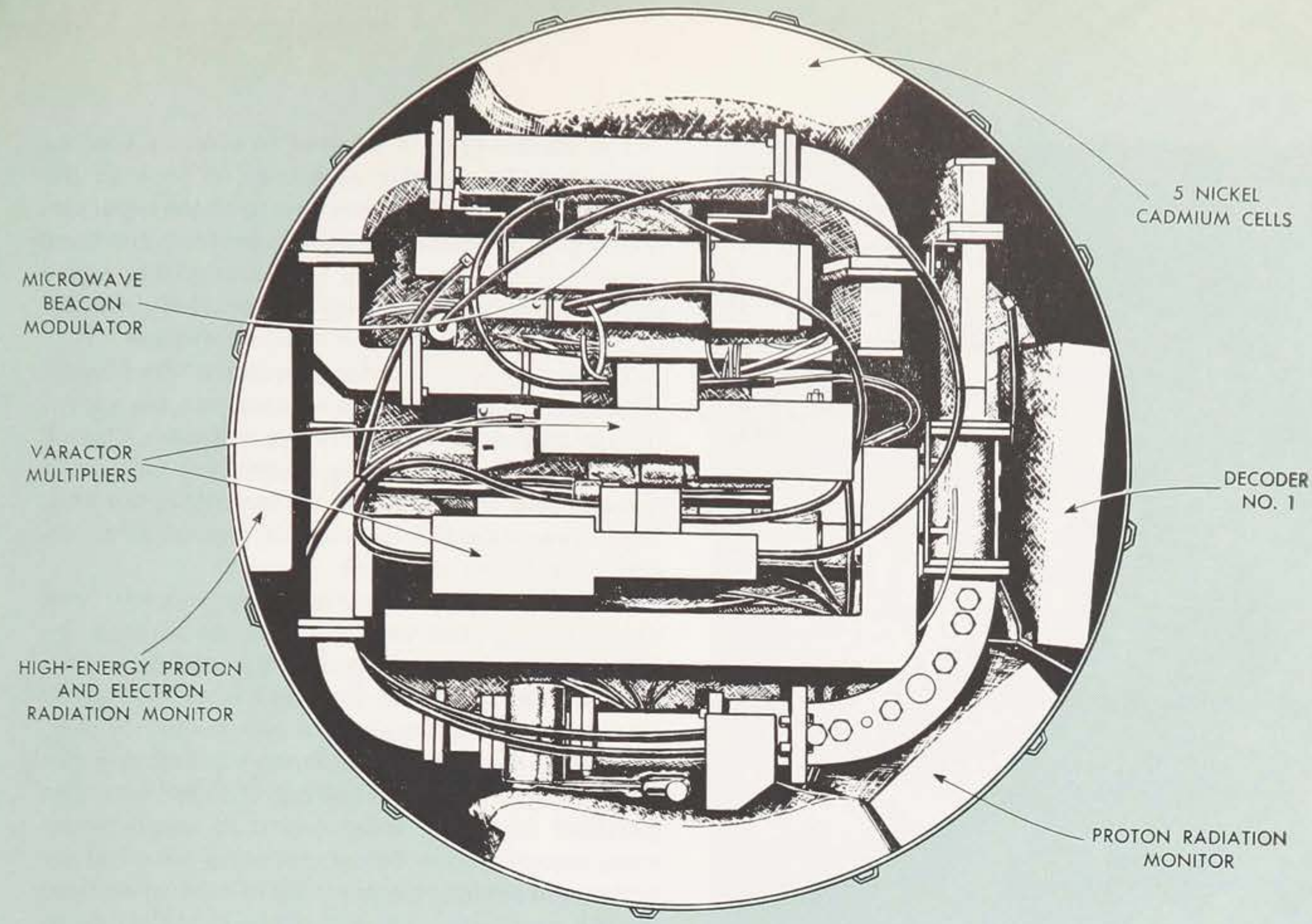
Prior to completion of the first model of the electronic package, an electrical analog circuit of the thermal conduction paths was assembled. This circuit permitted prediction of temperature rises at all power dissipation points in both steady-state and transient conditions. It also indicated one minor design change which improved heat conduction. Actual tests on the prototype showed a very good correlation with the analog predictions, the analog showing higher temperature due to conservative assumptions in its design. Thermal characteristics of the electronics package in orbit are the same as were found in the tests on earth. This illustrates a significant advantage of the thermal conduction design method in that completely valid tests of the package can be made in the laboratory.

Satellite Was Spin Stabilized

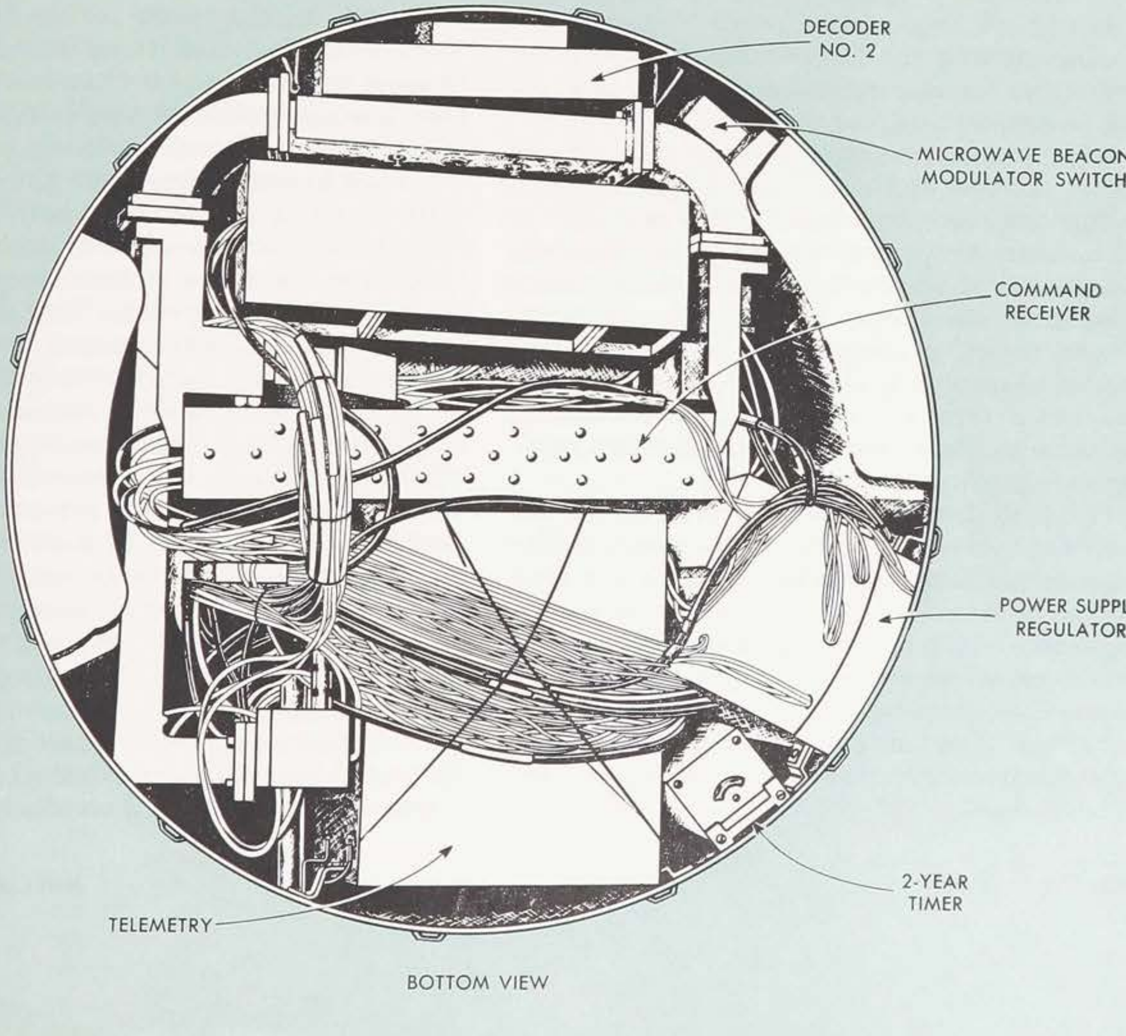
Thermal and electrical problems were not the only factors influencing the disposition of units within the package. Another was the use of spin stabilization for the satellite. This method of stabilization dictated that the completed package assembly be essentially balanced about the spin axis and that the major moment of inertia be about the same axis. If this were not done, an excessive amount of dead weight would be required to achieve the final spin-balance of the fully assembled spacecraft or to obtain the required ratio of pitch-axis to spin-axis moments of inertia. In the course of laying out the over-all assembly, a running analysis was made, as designs were refined and weights firmly established, to keep a check on the resultant moments. Units were reshaped and fitted into available spaces as necessary to obtain the best results. Components with the greatest densities, such as the traveling-wave tube amplifier and battery cells, were placed nearly symmetrically about the spin-axis and the cells were placed as far away from the axis as possible. The final design placed the package center of gravity at 0.4 inch from the spin-axis. This offset multiplied by the 85 pound weight of the package produced a resultant of 30-inch-pounds. Most of this was balanced by components mounted on the outer frame as parts of the radiation experiment and magnetic moment balancing.

The drawings opposite are top and bottom views of the still-open package with assembly and wiring completed, ready for final encapsulation. The waveguide portion appears in a squared-circle configuration, which contains the equivalent of about 12 feet of one-inch by two-inch guide. Only one foot of this serves as simple transmission line, all other parts being filters, directional couplers (in the corner bends), attenuators, etc. The four groups of nickel-cadmium cells are foam encapsulated at an early stage to protect them during later assembly and wiring. Several of the units are not rigidly mounted, but are simply tied or wedged into position until they

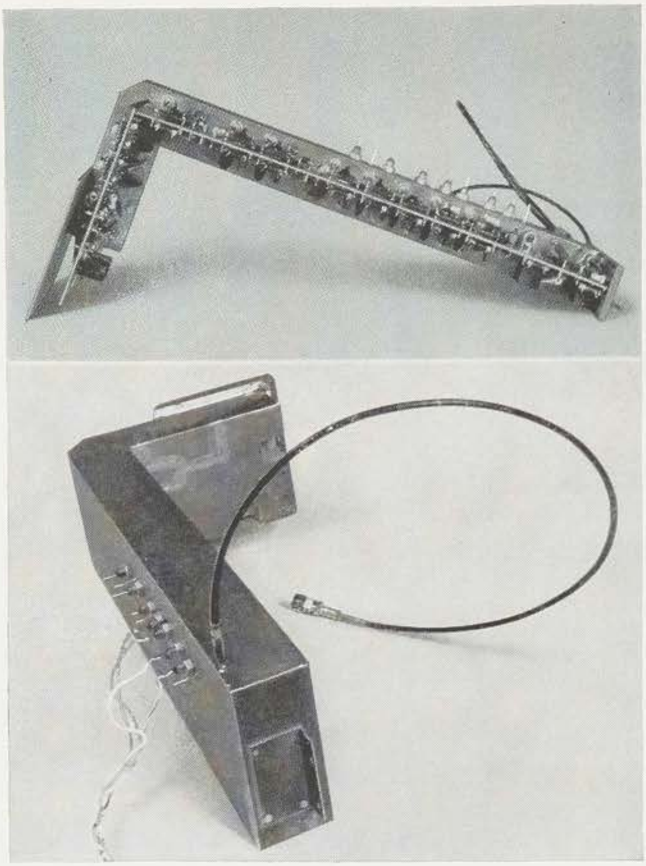
Top and bottom views of the Telstar satellite. This drawing represents the package with assembly and wiring completed, and ready for final encapsulation.



TOP VIEW



BOTTOM VIEW



The intermediate frequency amplifier: top photo shows the structure with all components mounted; lower shows it after it has been encapsulated and covered with aluminum shielding.

are entrapped by the final encapsulation. The decoders and varactor multipliers are examples of this treatment.

Interconnecting wiring between units is almost entirely spliced with crimped-sleeve joints. Connectors are used only on coaxial cables in which splices were impractical. Sub-units for the various transistorized circuits take several forms, depending on the factors involved. These include weight, shielding against high frequency interference, heat dissipation, types of components, and shape factors controlled by mounting arrangements. From these, three basic design categories evolved:

For high frequency circuits such as the IF amplifier (see the photos above) and beat oscillator supply, a fabricated aluminum chassis is used in conjunction with epoxy-glass boards for mounting. After wiring and testing, the structure is encapsulated with certain areas of the chassis exposed. Electrical shielding is then completed by a .003 inch aluminum cover. Cover and chassis are gold-plated to facilitate soldering the shield to the exposed chassis.

The second type is devoted to circuits lending themselves to modular construction such as the decoder. Small modules are encapsulated separately and grouped on unit boards to perform the more complex functions. After interconnection, board and modules are again encapsulated. Heat transfer is not a significant factor in these designs.

The last type is best described as a "free-form" structure to accommodate components too varied in size and shape for strict organization. One or more insulating mounting boards are used with a single step of encapsulation completing the unit. The power supply regulator is typical of these, and is shown on page 149.

When assembly and wiring were completed and thorough electrical tests had been performed, the package was placed on a special fixture for the final foam filling. The filling process was carried out in several pours and the circuits were energized periodically to be sure that no damage occurred as the filling progressed. Energizing in this way also provided telemetry information on temperature rises caused by the foam-producing chemical reaction and avoided overheating of critical sections by the exotherm. After further electrical tests, coupled with temperature cycling, the domes were welded in place and leak checks were completed. The package was then ready for assembly into the spacecraft frame.

Construction Program

The reliability program for the Telstar design was a major factor in its success. An important phase of reliability was the construction program and its organization. At the Hillside, N. J. shop of the Western Electric Company—already notable in Bell System history as the site on which submarine cable repeaters were built for the first trans-Atlantic system—the Telstar electronic units were assembled under whiteroom conditions and the spacecrafts completed. Carefully controlled handling, workmanship, testing, and inspection were instituted with close attention by the design engineers. Special stocking arrangements were setup for the flyable components with meticulous recording of in and out movement. Each unit proceeded through the shop in accordance with prescribed routines laid out by the engineers. Route sheets were placed into containers of parts selected for construction of a unit to stay with the unit to completion. Each step was verified by the responsible personnel and the route sheet was initialed after a step was satisfactorily completed. This careful procedure has paid off handsomely in providing a striking and valuable experiment, a tribute to outstanding team effort.

A room temperature environment for its electronics circuitry and a stable attitude control are among the first requirements for the satellite. How to ensure these is part of the problem of . . .

Space Hardware Aspects Of the Satellite

J. W. West

SPACE IS A HOSTILE ENVIRONMENT, opposed to man and to the electronic systems he sends beyond the earth's atmosphere. As the Telstar satellite orbits the earth it is continually exposed to the intense ultraviolet light of the sun and it is bombarded by high energy protons and electrons. There is no atmosphere, so heat cannot be dissipated by convection. The earth's magnetic field sets up eddy currents and torques that can change a satellite's orientation. Under these conditions, the first thing that must be considered is the rather grim problem of survival: How should a satellite be designed and what protection does it need so that it can live in the rigors of space? In fact, the threat to the life of a satellite starts even before it arrives in space; it starts at launch when the satellite is subjected to tens of G's of acceleration and thrust from the rocket.

We might first briefly consider the temperature problem. A satellite's surface temperature is determined by radiation only: The energy it receives from the sun and earth, and the energy it radiates to space. Hence, surface coatings must be chosen to give a proper thermal balance to the satellite during both sunlit and eclipse periods. Imprudent selection of surface coatings could result in a skin temperature as high as 500 degrees Fahrenheit or as low as—225 degrees Fahrenheit. Yet, the temperature at which electronic components operate is a major factor in determining their life and reliability. Almost all life test data on components are obtained in a room temperature environment. To subject components to widely fluctuating temperatures caused by full sunlight and eclipse conditions would adversely affect their life and performance. What must actually be done is to control the environment which houses the seven thousand electronic components so that it closely approaches the conditions of fabrication and testing.

The two major space hardware objectives were to provide a near room temperature environment for the electronics components and to provide a stable attitude control for the satellite. A stable attitude control was required to assure that communications could be conducted without interruption due to antenna dead zones. There were also many other objectives, such as operation of the solar cell power plant at efficient temperatures, design of shell components to withstand wide temperature cycling and survival during launch. This last requirement illustrates the paradoxical conditions that often must be resolved in a space system, for though an orbiting satellite is weightless, during the brief period of launch its structure must support forty times its own weight.

The Telstar satellite was launched by a Delta space vehicle, the most suitable vehicle available to put the satellite into a precise orbit for experimental international communications. The capabilities of this vehicle placed certain restrictions on the physical characteristics of the satellite — its weight was limited to 170 pounds and it had to fit into the shroud that carried the payload and protected it from overheating as the rocket sped through the earth's atmosphere.

Since the third-stage rocket of the Delta vehicle is spun, it was quite naturally decided to utilize spin stabilization as the attitude control method. The spin axis of a satellite, which must also be the symmetry axis of the antenna, remains nearly constant relative to the sun. Hence, for a satellite in an inclined orbit, the antenna pointing direction changes in relation to the earth because of precession of the orbital plane. Therefore, spin stabilization in an inclined orbit required a nearly isotropic antenna pattern so that antenna dead zones would not interrupt communications.

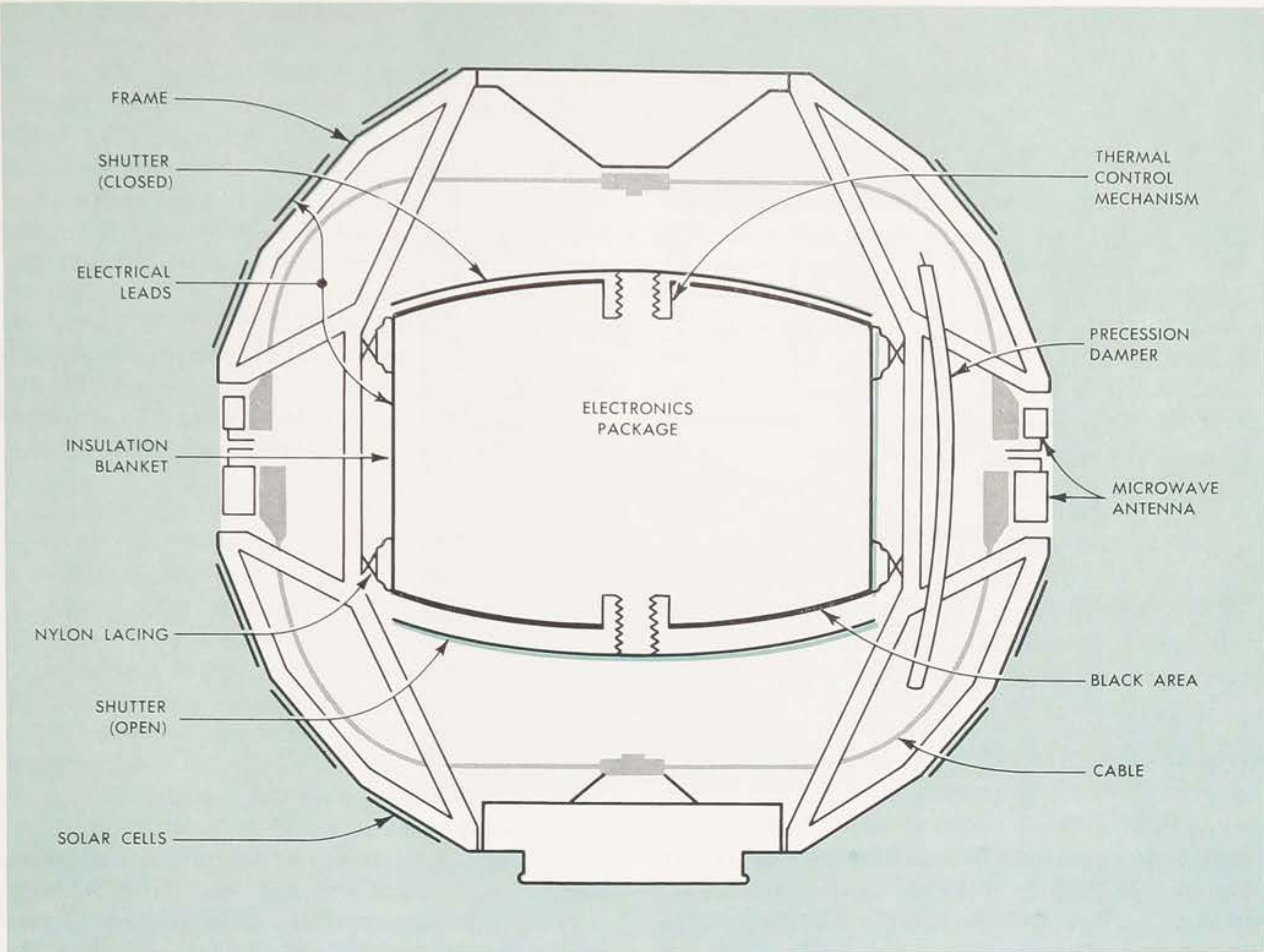
The spherical shape of the satellite has two advantages. First, it allows a nearly isotropic antenna pattern. Second, it permits an isotropic solar cell array. Arranged in this pattern, solar cells will provide power in any orientation of the satellite to the sun. The outer shell is plane-faceted with solar cells arranged in strings of 72 series-connected cells. A string will not produce power unless all its cells are illuminated by the sun. With plane-faceting, all cells in a string are illuminated simultaneously. The few facets that are not covered with solar cells are used for radiation experiments and attitude control sensors. Since the solar cell surfaces tend to absorb considerable solar energy, the remaining parts of the skin are coated with special material to control of the temperature of the satellite.

As we have said the temperature of a satellite in space is determined by the energy it receives from the sun and the earth and the energy it radiates to space. The energy it receives from the earth is divided into: (1) the sunlight reflected from the earth (albedo), (2) the earth's infrared radiation. These two factors vary inversely as the square of the distance between the satellite and the earth. The direct solar flux accounts for 84 per cent of the energy received by the Telstar satellite. Electrical power from the solar cell plant, which is dissipated in the electronics chassis, has a negligible influence on the satellite skin temperature. For example, the solar energy incident upon the satellite is over 1,000 watts in contrast to 14 watts dissipated in the chassis.

To convert sunlight into electrical energy with the highest possible efficiency, solar cells should operate at as low a temperature as possible. Accordingly, the satellite's outer shell was designed to operate near 32 degrees Fahrenheit. the outer skin was coated with aluminum oxide which has low absorptivity for solar radiation and a high emissivity for the heat radiated from the satellite surface which is in the infrared. Absorptivity is an index of the amount of total radiation, of a given kind, that a body can absorb; emissivity governs the rate at which heat energy is radiated from the surface of the body. In other words, absorptivity is a function of the temperature of the source of the incident radiation and emissivity is a function of the temperature of the emitting body. It is most important that these optical properties of the coating be maintained in space when subjected to high vacuum, to ultraviolet light, and to particle bombardment. During development, laboratory tests were made on many materials that had the necessary optical properties. Plasma-sprayed aluminum oxide proved to be most resistant to space phenomena. Actually, telemetry data from the orbiting satellite have shown that the solar cells are operating at the expected temperatures.

The fact that the electronic components should be kept in a room temperature environment and the skin of the satellite must be kept near the freezing point of water are at first glance, paradoxical requirements. They are met by a ball-within-a-ball configuration. (See the drawing on page 169.) The electronic components are compacted into the inner ball to present a minimum surface area to the colder skin. The electrical power from the solar cell plant which is dissipated in the electronics provides the heat necessary to keep the electronics close to room temperature. To reduce to a minimum the transfer of radiant heat from the warm electronics package to the cold skin, the package is insulated with many layers of aluminized Mylar alternating with layers of Fiberglas spacers. To reduce thermal conduction from the package to the skin to a minimum the canister is suspended from the shell by Nylon lacing. The lacing plays a dual role; it also isolated the electronics package from the high vibration levels generated during launch. These design features were proved-in in the first thermal development model. This was a complete satellite except the package contained resistors to simulate the power generated by the final electronics.

One recurring cause of sharp changes in temper-



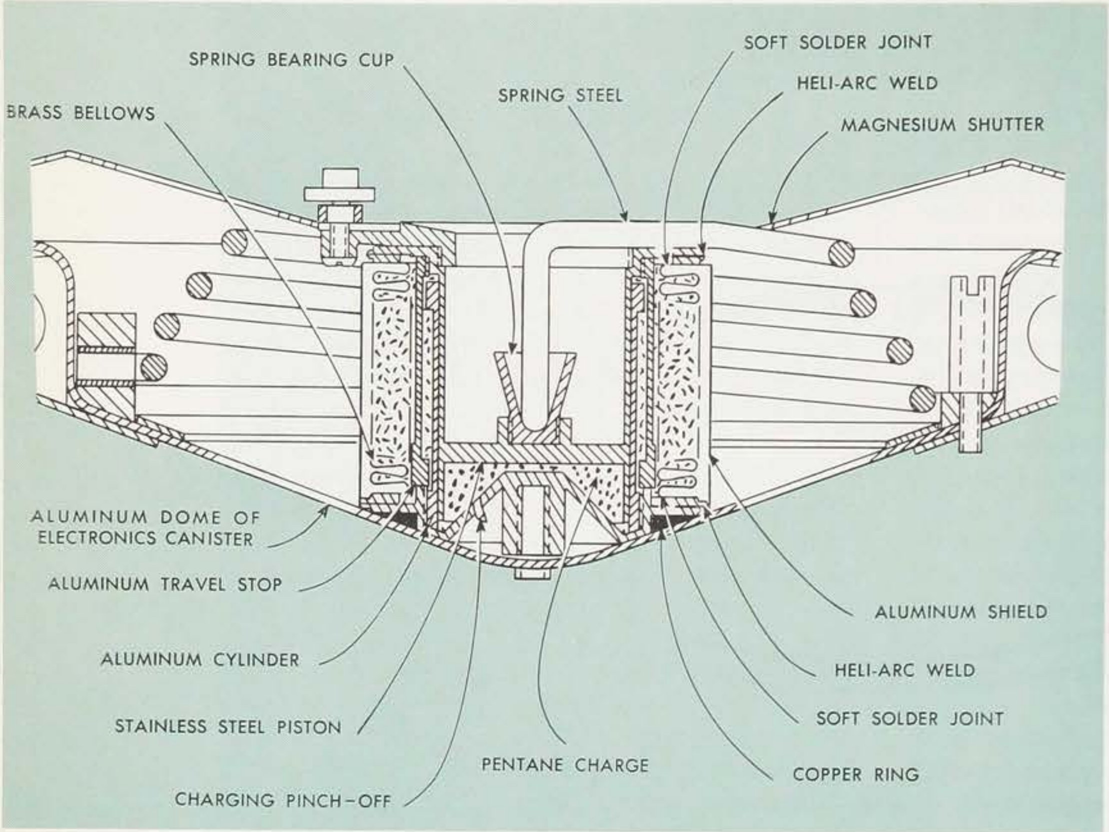
A schematic sketch of the satellite. The thermal shutters, one is shown open and the other closed, automatically control radiative heat transfer between the satellite's electronics package and skin.

ature is the time that the satellite spends in eclipse. This may be up to 45 minutes in an orbit and it varies over the year. In any single eclipse, the skin may cool as much as 80 Fahrenheit degrees. For any orbit in which there is a period of eclipse, the *average* skin temperature may be 30 Fahrenheit degrees lower than it is in a fully sunlit orbit. Because of the high heat capacity of the electronics package, its temperature is practically unaffected by a single period of eclipse; however, it does respond partially to the lower average skin temperature caused by repeated eclipse periods.

Widely fluctuating temperatures can seriously limit the performance, and even shorten the life, of electronics components. The Telstar satellite is equipped with thermally actuated shutters (as shown in the drawing above) that automatically control radiative heat transfer between the electronics package and the skin and thus keep the satellite temperature fairly uniform no matter how much time it spends in eclipse. If the canister temperature drops below 55 degrees F the shutters close fully, holding radiant heat transfer at a minimum. When the canister temperature reaches 75 degrees F, the shutters open fully, exposing a black surface area on the domes of the canister which increases the rate of radiant heat transfer between the electronics package and the colder skin.

The opening and closing of the shutters is controlled by a thermostat (see the drawing on page 170) which is secured to each canister dome. It consists of an internal sliding piston and an external flexible bellows containing Pentane, a fluid chosen for its vapor-pressure-to-temperature relationship. A spring keeps a nearly constant pressure against the fluid to control the opening and closing temperature characteristics of the mechanism. The shutter is moved vertically so that it will completely cover the high emissivity area on the package domes. The mechanism is a rugged one and it has no moving parts exposed to the vacuum of space to cause cold welding problems.

Proof of the effectiveness of this arrangement is, of course, performance: the electronics pack-



The bellows mechanism, essentially a thermostat, controls the opening and closing of the thermal shutter.

age temperature held between 60 degrees and 80 degrees F during the first seven months in orbit. As expected, the temperature of the package varied depending on the per cent of time that the satellite spent in the sun and that spent in eclipse during its orbit. The graph on page 171 clearly illustrates this dependence. The "package temperature" is an index of the thermal environment provided for the electronic components rather than the temperature of the components themselves. Power-generating components and components adjacent to them run at a somewhat higher temperature than the ambient. A design feature of the electronics package has been the use of techniques to reduce internal temperature differentials to a minimum. (See the article beginning on page 161.) The package temperature concept is important in determining the satellite's performance in space.

Just prior to launch, the package temperature was 83 degrees F. and within nine orbits dropped to 74 degrees F. where it remained stable for two weeks while the satellite was in a full sunlit orbit. It will be noted that the variation in package temperature follows very closely the percentage of time that the satellite was in the sun. In January, 1963, the satellite was again in a full sunlit orbit and the package temperature was about 6 degrees warmer than it was in July, 1962.

The change in this package temperature between July and January can be attributed to the cumulative effect of three factors. First, in January, the solar constant was seven per cent higher than it was in July. Second, the absorptivity of the aluminum oxide coating on the skin was probably increased by ultraviolet light and radiation. In fact, when the coating was selected, laboratory tests indicated that these phenomena might increase the absorptivity as much as 20 per cent. Third, the power dissipated in the electronics package decreased from 14 watts in July to 11 watts in January, due to degradation of the solar cells in the Van Allen belts. The first two factors contributed equally to an increase of about 11 Fahrenheit degrees in the package temperature. The drop in dissipated power accounts for a drop of about 5 Fahrenheit degrees in the package temperature.

The thermal performance of Telstar II satellite launched on May 7, 1963 shows excellent agreement with the first satellite. Just prior to launch the package temperature was 85 degrees F; within 10 orbits dropped to 75 degrees F, which is its stable temperature in a full sunlit orbit. This temperature is within 1 degree of the first satellite.

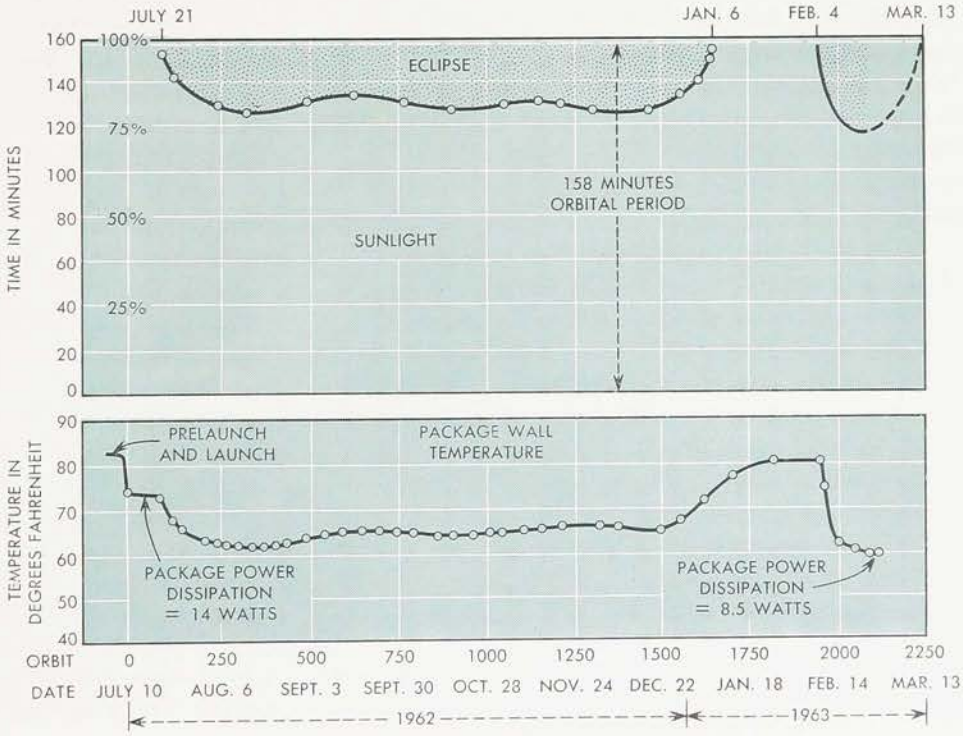
The orientation of the satellite spin axis can also contribute to the level of its temperature. When the spin axis is perpendicular to the rays of the sun the solar energy is evenly distributed about the periphery of the satellite, and the temperature is uniform around the skin. If the spin axis shifts, so that it is parallel to the rays of the sun, the skin around the pole facing the sun will increase to about 145 degrees F, and the opposite pole will become quite cold. The high temperature will reduce the output of the solar plant to about 80 per cent of its normal value, which is still sufficient for communications experiments. However, because the skin is isotropic, the average temperature of the satellite will not be affected. Consequently, the temperature of the electronics package will remain substantially unchanged; the lower power dissipated by the solar plant will be largely compensated for by the active temperature control system.

Initially, the orientation of a spun satellite depends on the time of day of launching and the pointing accuracy of the launching vehicle. The Telstar satellite was launched within a few minutes of a calculated hour and its initial spin axis was within a degree of being perpendicular to the rays of the sun. Interaction of the residual magnetic moment of the satellite with the geomagnetic field, however, causes precession of the spin axis. To reduce this precession to a minimum, the initial magnetic moment of the satellite was nearly cancelled by small magnets which were added to its frame after it was assembled. It was also equipped with a torquing coil which can be used to reorient the spin axis if precession becomes too great. During the first six months in orbit, its spin axis remained within 10 degrees of its initial orientation.

Eddy currents set up in the satellite by the geomagnetic field tend to slow down the spin rate. This is particularly hazardous because of the relatively low orbit that the satellite travels. The effect of eddy current damping is much less on satellites in higher orbits because the strength of the geomagnetic field decreases with the cube of the distance from the satellite to the center of the earth. To counteract the effect of the field, the shell of the satellite was made in two hemispheres, electrically insulated from each other. This cuts down the production of eddy currents and thereby reduces spin decay.

Some spin decay must occur, the double-hemisphere arrangement merely slows down the process. For the Telstar satellite, the time constant (i.e., the time required for a spin decay of 63 per cent) has been calculated at about one year. This means that in two years the spin rate of the satellite will have slowed from 180 rpm to about 20 rpm. If the halves of the shell were not insulated, eddy currents would cause the spin rate to drop to 3 rpm in two years, and the satellite very likely would start to tumble.

Other serious effects could occur if the attitude of the satellite were not precisely controlled. Communications would be interrupted if the spin axis did not coincide with the symmetry axis of the antenna. Further, the satellite would quickly tumble if its axis of maximum moment of inertia did not coincide with its initial spin axis. Moreover, a moment of inertia ratio ($I_{transverse}/I_{spin}$) less than unity is required to assure that the satellite



Dependence of the temperature of the satellite on the time it spends in the sun and the time it spends in eclipse during an orbit.

does not tumble. Detailed calculations predicted a ratio in the order of 0.95; but because of the spherical shape of the satellite small variations, or structural changes, could lead to a larger ratio in different satellites. To be sure that all satellites had the proper ratio, a Laboratories-developed machine was used to measure the ratio to within 0.2 per cent. According to these measurements, all satellites that were built had a ratio of 0.95 or less.

Another disturbing effect on communications is short-time precession or wobble. Three things can cause the satellite to wobble: uneven forces induced by the spring that ejects the satellite from the rocket; a micrometeoroid hitting the satellite; or the use of a torquing coil on the satellite itself. If wobble occurs, it must be corrected immediately because it increases the area of antenna dead zones as seen from the earth.

Precession dampers keep the satellite spinning about its true major axis. These are curved tubes about ½-inch in diameter and 18-inches long; they contain a closely-fitting tungsten carbide ball and are filled with neon. Damping is accomplished by viscous friction as the ball rolls along the tube. When the satellite is spinning on its true axis, centrifugal force holds the balls at rest in the centers of the tubes. The balls also provide rolling friction, but viscous friction is far more effective for damping. Furthermore, gas-filled tubes get around the problem of cold-welding in the vacuum of space. The dampers were designed to reduce a 5-degree wobble to less than 1 degree in a few minutes. Many observations have been made of the satellite in orbit to check this performance. Precession can be measured only to an accuracy of one-half a degree, but from the data gathered from a great number of observations it seems that the short-time precession is even less than the accuracy of measurement. In other words, it is so slight that we do not have the instruments to measure it precisely.

Although launch conditions and the space environment cannot be duplicated exactly, many useful tests can be conducted to determine the space worthiness of the satellite. Thus, we can test the hardware that supports and protects the components, the materials that were adopted, the arrangements to control temperature, and the devices used to control the attitude of the satellite and to absorb the accelerations of launching. Toward this end, special devices were constructed to dynamically balance the satellite, to perform vibration testing, and to perform thermal testing on completed satellites.

The photograph above shows the dynamic balance machine. A spin-stabilized satellite must be both statically and dynamically balanced about its axis of maximum moment of inertia and this, in turn, must be carefully aligned with the axis of the launching vehicle mounting ring so that the third stage of the vehicle will follow its prescribed trajectory. The balance machine is essentially a compound pendulum that can be rotated at variable speeds. Outputs of two mutually perpendicular transducers in contact with the rotating pendulum shaft are translated into the angular position and the magnitude of the unbalance. At each reading, weights are added to the satellite to reduce its unbalance couple. The procedure is repeated until the dynamic axis is within six minutes of arc of the geometric axis. About a dozen weights, totaling about one-half pound are usually required to dynamically balance a satellite.

John Kossyk performing a dynamic spin balance test on the magnesium frame of a satellite model.

To determine the vibrational response of the electronics package, the solar cell panels, the antenna feed, and the frame structure, two vibration test models of the satellite were employed. Accelerometers were used extensively during these tests. The first frame withstood many hours of vibration tests at levels above those which the satellite encounters for only a few minutes at launch.

The graph on page 173 shows the vibration response of the electronics package and the solar cell modules. The 20 G level at 40 cps is due to the Nylon lacing; it is not troublesome because electronic components do not have resonances at such low values. The solar cell modules were subjected to levels as high as 80 to 120 G's at several frequencies. Amplification factors of 5-to-1 and 10-to-1 were recorded; these are due to frame resonances inherent in large structures. During resonance dwell tests, which are conducted at the third stage launching vehicle resonance of 550 to 650 cps, the modules reached levels as high as 200 G with a 42 G input to the vibration table.

The solar cell modules are of a rugged construction which avoids the use of inorganic materials. The solar cells (see "The Satellite Power System" in this issue) are the radiation-resistant n-p type and are protected from 1 mev electron bombardment by 0.030-inch thick sapphire covers. They are soldered to an alumina ceramic plate using a flexible joint which accommodates the expansion mismatch between the silicon solar cell and the alumina plate. The sapphire cover is brazed to a coexpansive platinum frame which is later soldered to the sides of the coexpansive alumina plate yielding a complete module. Beryllium copper tabs fasten the module to the mounting panels. Contact of the platinum frame with the mounting panels provides a good thermal path to the satellite skin. Inorganic fastening of all parts eliminates problems of vaporization in high vacuum or molecular change due to radiation effects.

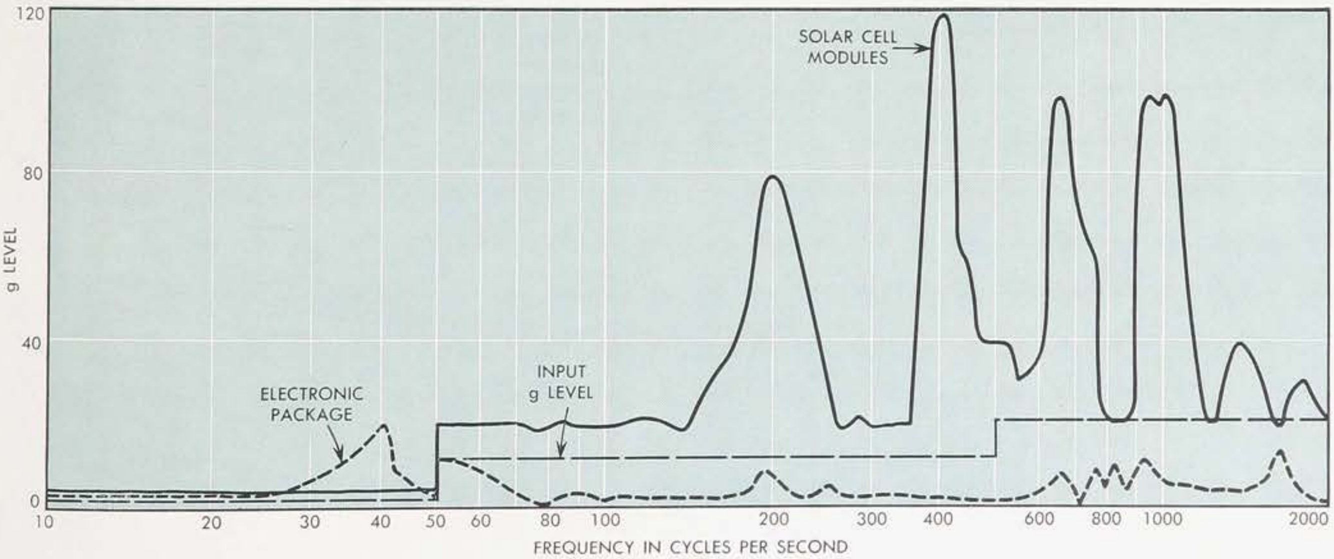
The total weight of the solar cell power plant is 9 per cent of the overall satellite weight. The modules withstand vibration levels of several hundred G's and thermal cycling for dozens of times from +150 degrees F to −150 degrees F. These temperature extremes are well beyond those experienced in space. During six months in orbit, the maximum temperature extremes encountered have been +55 degrees F and −15 degrees F, the latter figure was after a 30 minute eclipse.

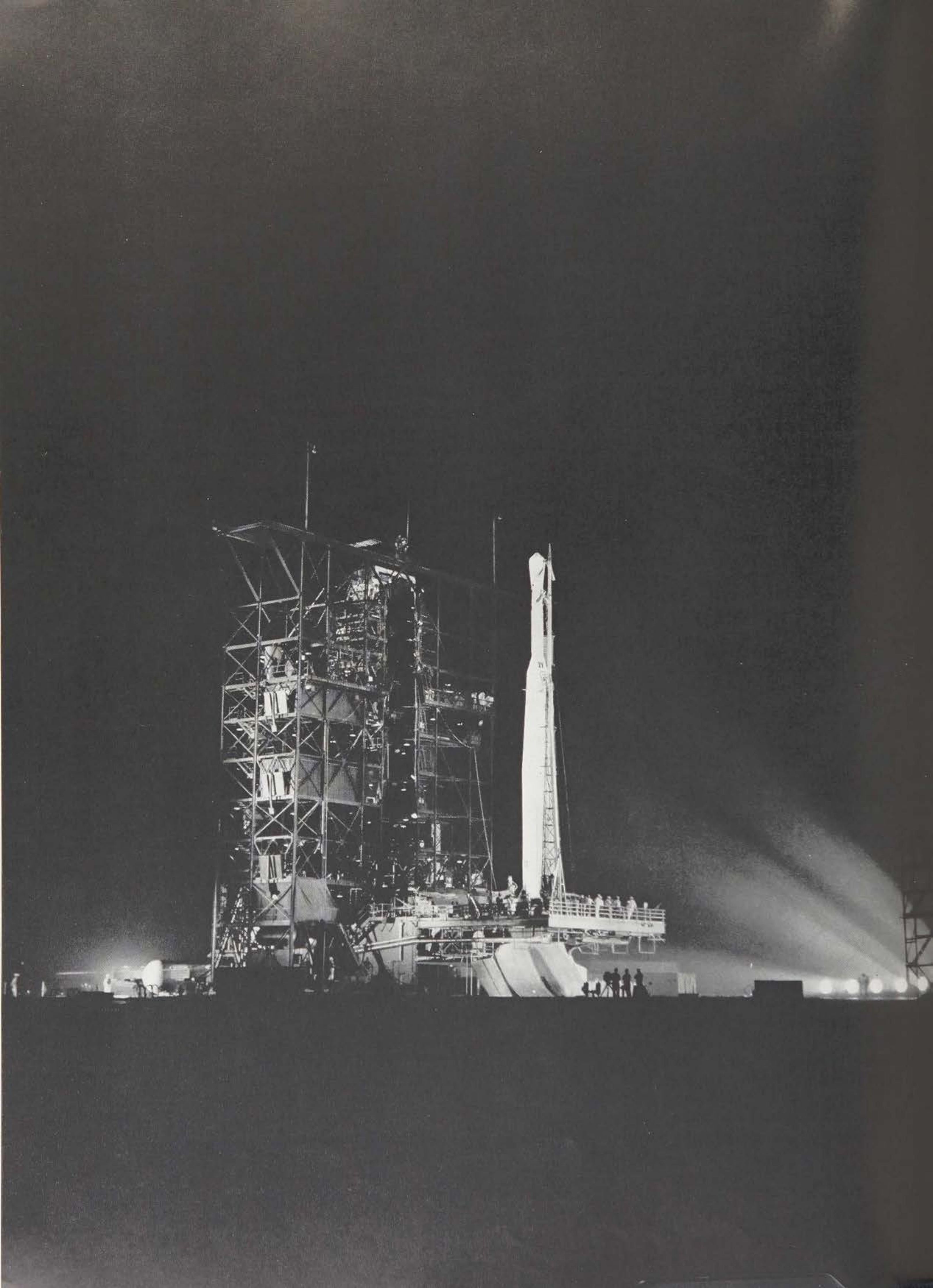
Materials for the outside of the satellite were chosen for minimum weight, resistance to radiation, and low evaporation rates in the nearly perfect vacuum of outer space. The frame is magnesium of welded tubular construction; it weighs 22 pounds. During the simultaneous actions of rocket thrust, vibration, and rocket spin-up, the frame supports the other 150 pounds of components which put a huge total loading on the frame —6,000 pounds vertical loading, 1,000 pounds transverse loading, and 3,000 inch-pounds torsional loading.

During development, extensive tests were performed on several vibration and thermal tester satellites. For thermal testing, a high vacuum chamber with liquid nitrogen cold walls and arc lamp solar source (RECORD, *March*, 1962) was employed to simulate the orbital conditions which the satellite would encounter. Comprehensive materials, mechanical, and thermal cycling tests were performed on all components such as: the thermal control mechanisms, precession dampers, microwave antenna feed components, solar cells, modules, at levels well beyond those expected in use. After development was substantially completed, a mechanical development model, complete except for the electronics package, was successfully subjected to all qualification level tests. The prototype and "flyable" satellites were also mechanically and thermally tested comprehensively before they were accepted for use.

The Telstar satellite space hardware successfully survived launch and is fulfilling all of the objectives set for stabilization, temperature control of the electronics package and the solar cells, and stability of the structural parts and coatings in the space environment.

Vibration response of the electronic chassis and the solar cell modules. Data were gathered from tests on two vibration test models of the satellite. Note the low accelerations on electronics package.





When the designs had been completed and the space craft assembled, when tracking stations had been readied around the world, there remained a last step before the results of this unique experiment in communications could be known.

Launch Operations At Cape Canaveral

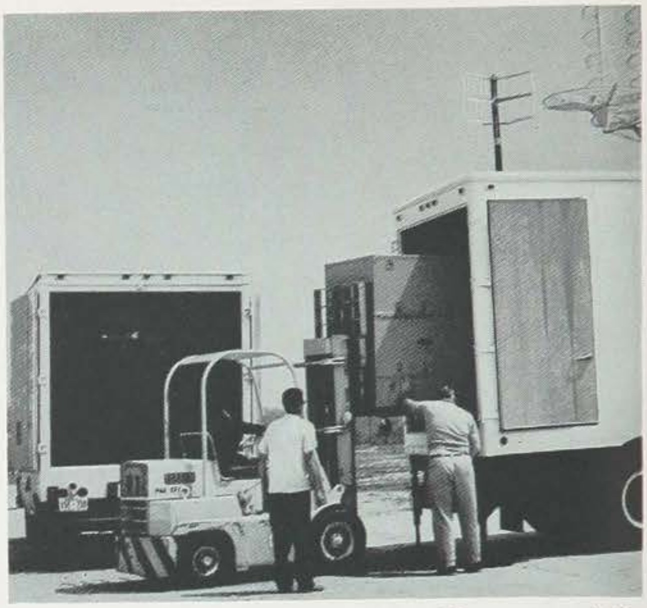
H. N. Upthegrove

SHORTLY BEFORE DAWN on the morning of July 10, 1962, NASA's eleventh Delta rocket stood in readiness on the launching pad at Cape Canaveral. Inside the fairing at the rocket's tip rested the Telstar satellite. Months of preparation were over and numerous pre-launch test procedures had been completed. As the countdown ticked slowly toward "zero," only a breeze from the Atlantic moved on the deserted ramps. Then the booster motor flamed into life, creating clouds of steam from the cooling pool. The rocket, rising slowly at first, rapidly gained momentum, accelerating upward along its arching trajectory until it disappeared from sight. Men in the guidance and tracking stations below followed it to the radio horizon, then waited tensely for the satellite to reappear at the end of its first orbit. Two and one-half hours later it came over the horizon right on schedule, and a new era in communications had begun.

Behind this success lay more than a year of preparation and the close cooperation of many organizations. AT&T signed a cooperative agreement with the National Aeronautics and Space Administration in July, 1961. NASA was to supply as many as four Delta rockets for separate attempts to orbit up to two satellites as well as telemetry information from their Minitrack Stations. AT&T agreed to build the satellites and to reimburse NASA for all identifiable expenses arising from the launch. AT&T would also provide NASA with the immediate results of the experiment, as well as a royalty-free license for any inventions developed as a result.

Soon after the agreement was reached, a two-man team from Bell Laboratories attended a conference for spacecraft representatives at Cape Canaveral where they became acquainted with the launch operations and procedures. The Field Projects Branch of the Goddard Space Flight Center represented NASA for Telstar operations at Canaveral. In the framework of the Delta Program, the Telstar project received the support of all the organizations and facilities of the Atlantic Missile Range, which consists of a series of installations in Florida and on islands and ships extending far down the South Atlantic. The U.S. Air Force Missile Test Center is responsible for the range and has subcontracted daily operation to Pan American Airways. The RCA Service Company provides instrumentation and communication. For Delta launches, Douglas Aircraft Company is the principal contractor. Douglas builds the rocket, integrates its component parts, delivers it to Cape Canaveral, checks out all stages, and launches it. The Rocketdyne Corporation is responsible for propulsion in the first stage, the Aerojet General Com-

These three vans housed the facilities for testing and monitoring the satellite's circuits.



To minimize exposure, each satellite was quickly transferred from the truck to the satellite van.

pany for the second stage and Allegheny Ballistic Laboratories for the third stage.

In Telstar launch operations, Bell Laboratories was responsible for delivering, testing and preparing the satellite for launch at Canaveral. In December, 1961, a full-scale mockup was taken to Douglas in Santa Monica, Calif., for a fit-check to assure that it mated properly with the third-stage rocket and fairing. When the flight satellites were finished and tested at Hillside, N. J., they were trucked to Cape Canaveral, where after a thorough checking they were delivered to NASA and Douglas for mating with the rocket.

The Command Guidance System

For this launch, as for all Delta launches, Bell Laboratories was responsible for the Command Guidance System (RECORD, *November,* 1962). This System had been designed by Laboratories engineers long before the Telstar satellite experiment.

Its function is to guide the Delta rocket until the end of the second stage flight. To accomplish this, a very accurate radar tracking system follows the rocket as it rises. From the time and position data gathered, a ground-based computer derives the speed and direction of the vehicle. These are compared with previously calculated values representing the ideal trajectory. If there is a deviation, the computer recalculates another flight path from the existing position of the rocket. Coded steering commands are then transmitted to the missile on the radar beam, guiding it into this path. An engine cutoff command is sent to the vehicle when the computer is satisfied that appropriate terminal conditions for the desired free-flight trajectory have been met. The accuracy and reliability of this system has been demonstrated in more than 100 successful launches of Titan I, Able Star, Thor Agena, and Delta rockets.

The facilities used for the Telstar launch at Cape Canaveral were relatively few. First there was Launch Complex 17, with its two launch pads, plus fueling, power, and other support facilities. It included a gantry for erecting and servicing the rocket. A blast-proof spin test building was used for mating and dynamically balancing the satellite and third stage. The Laboratories Command Guidance Center was about two miles from the launch site. It contained the computer, antennas, and other devices for tracking and guiding the missile in flight. Specially provided for this launch were three Bell Laboratories trailers, which were equipped to store the satellite prior to launch and to monitor its performance during the ascent trajectory. All of these facilities, serviced, administered and operated by many diverse organizations, combined to achieve the successful Telstar launch.

Telstar Telemetry Vans

When they arrived at Canaveral, the satellites were transferred to the first of the three vans, the Satellite Van. This had a controlled-atmosphere area to reduce the possibility of contamination and minimize fluctuations in humidity and temperature. Two satellites were provided for the launch so that a backup spare was available for delivery to NASA and Douglas if required.

A Telemetry Van is connected to the storage van, serving as the center for prelaunch satellite testing, count-down tests at launch, and telemetry and command activities in post-launch tracking and monitoring. Test equipment in the 40-foot trailer includes receivers, decoders, transmitters, frequency counters, spectrum, analyzers, and teletypewriter facilities. These transmit telemetry between Laboratories locations at Canaveral, Andover, Murray Hill and Hillside.

The third van, the Command Tracker Van, contains equipment for the initial tracking at launch and subsequent operations requiring tracking, sending commands, and receiving telemetry. These three vans, while adjacent to the Command Guidance Center, are completely independent in function from the guidance system.

Dynamic Balancing

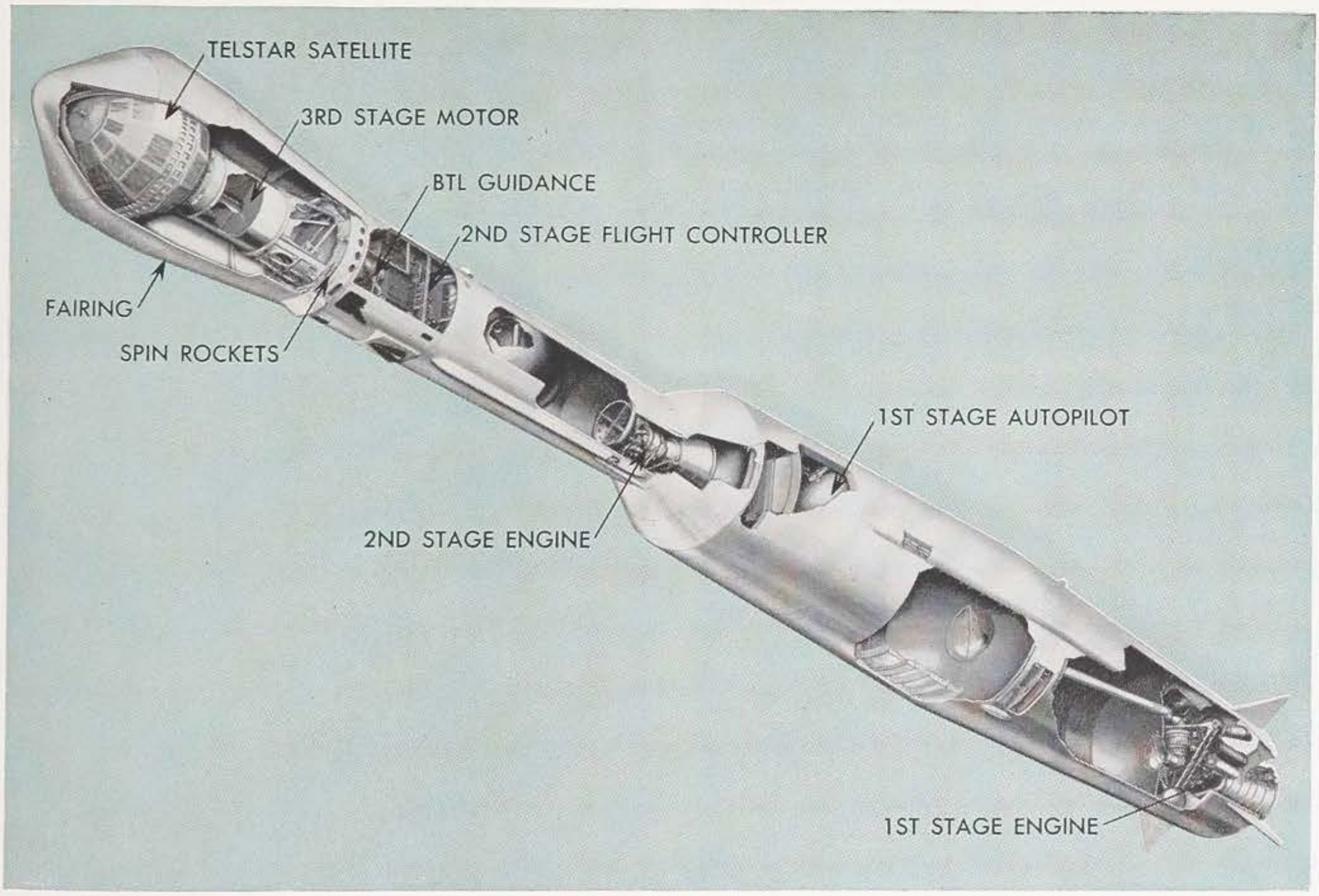
When tests confirmed that the satellite had survived the trip to Canaveral, it was delivered to the spin test building for mating with the third stage of the Delta rocket.

Inside the building, the satellite was hoisted and lowered onto the third stage which contained 500 pounds of live propellant. The weight of the satellite compressed a spring that would later separate the two parts. Electrically-triggered explosive bolts were used to complete the attachment. The whole assembly, the Telstar satellite and the third stage, was then spun to detect any deviation from perfect balance. Engineers added weights at two locations to attain an optimum balance.

Before and after the spin test procedure, Bell Laboratories engineers checked the performance of the satellite's circuits. This systematic checking, which began even before the satellite was fully assembled, continued without interruption throughout every step of the launch procedure, from the satellite's arrival at Canaveral until its disappearance over the horizon on the way into orbit.

Design and Operation of the Delta Missile

The design of the Delta launch vehicle had evolved through a considerable history of missile development. The rocket's first stage is a modified Thor missile, fueled with kerosene and liquid oxy-



This cutaway view of the assembled missile shows the satellite, the guidance system, and the propulsion units of each of the three stages. The fairing is jettisoned at an altitude of about 85 miles.

gen, developing a thrust of 150,000 pounds. A flight controller, employing three integrating gyros, three rate gyros, and a programmer, provides control until the Ground Guidance System takes over approximately 90 seconds after lift-off. Control is achieved by a combination of the gimballed main engine nozzle and two small roll control jets.

The second stage of the rocket is also liquid fueled, a modified version of an early Vanguard stage. Its engine produces about 7,500 pounds of thrust. Steering is again achieved by a gimballed thrust chamber. Four helium jets provide roll control and a nitrogen cold gas system produces reverse thrust to separate the second and third stages.

Both the first and second stages receive steering instructions from the Command Guidance System. Before the separation of the second and third stages, a spin table actuated by small rockets imparts a 180-rpm spin to the third stage. The stages are then separated and the solid propellant in the third stage is ignited. This burns for about 40 seconds and is followed by a coasting period until the possibility of residual "chugging" from the motor is past. Finally the explosive bolts are fired and the spring separates the satellite.

A Fiberglas fairing, initially provided at the tip of the rocket to protect the satellite and third-stage motor from aerodynamic heating and buffeting, is jettisoned at an altitude of about 85 miles during the first stage burn. Thus the Telstar satellite, when finally freed from the third stage, is to remain spinning alone on its long orbit about the earth.

Launch Preparation

Douglas engineers began preparation of the booster and second stage many weeks before the launch. These were gone over carefully in the Douglas hangar. Many vital parts were disassembled, checked, calibrated, and reassembled. Then a truck carried the first stage to the launch pad.

The erection procedure for this rocket is unique among the larger launch vehicles. At the beginning, the ten-story service tower stands fully withdrawn from the actual launch site and the truck parks below it. As a crane at the top of the tower lifts the tip of the missile upward, the tower moves over the truck. The rocket rotates on a pivot in the truck bed. When the rocket is vertical and its base released from the truck, it is drawn up into the tower. Then the whole tower moves forward over the launch pad, lowering the missile into place. The second stage was added to the first in the same manner, and the missile stood ready for the combined satellite and third stage.

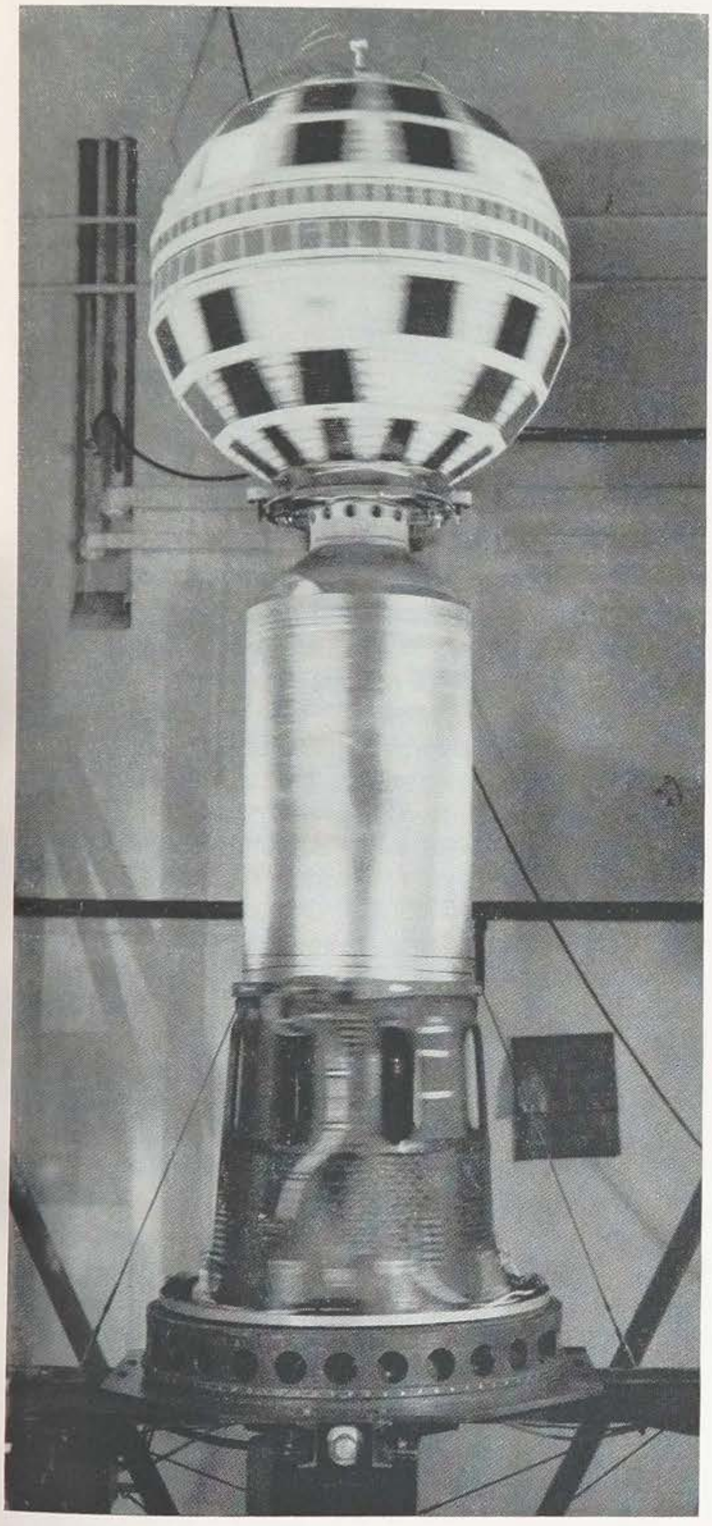
Before it received the actual flight model, prototype satellite and dummy third stage were fitted to the rocket. This was done as part of a test of the compatibility of all radio systems. These include guidance, spacecraft, range safety, telemetry, and communications. The radio systems were turned on in sequence and in various combinations to determine that there would be no interference. At this time, the launch team also practiced a simulated launch which included rolling back the gantry, checking the equipment, and rehearsing firing sequences.

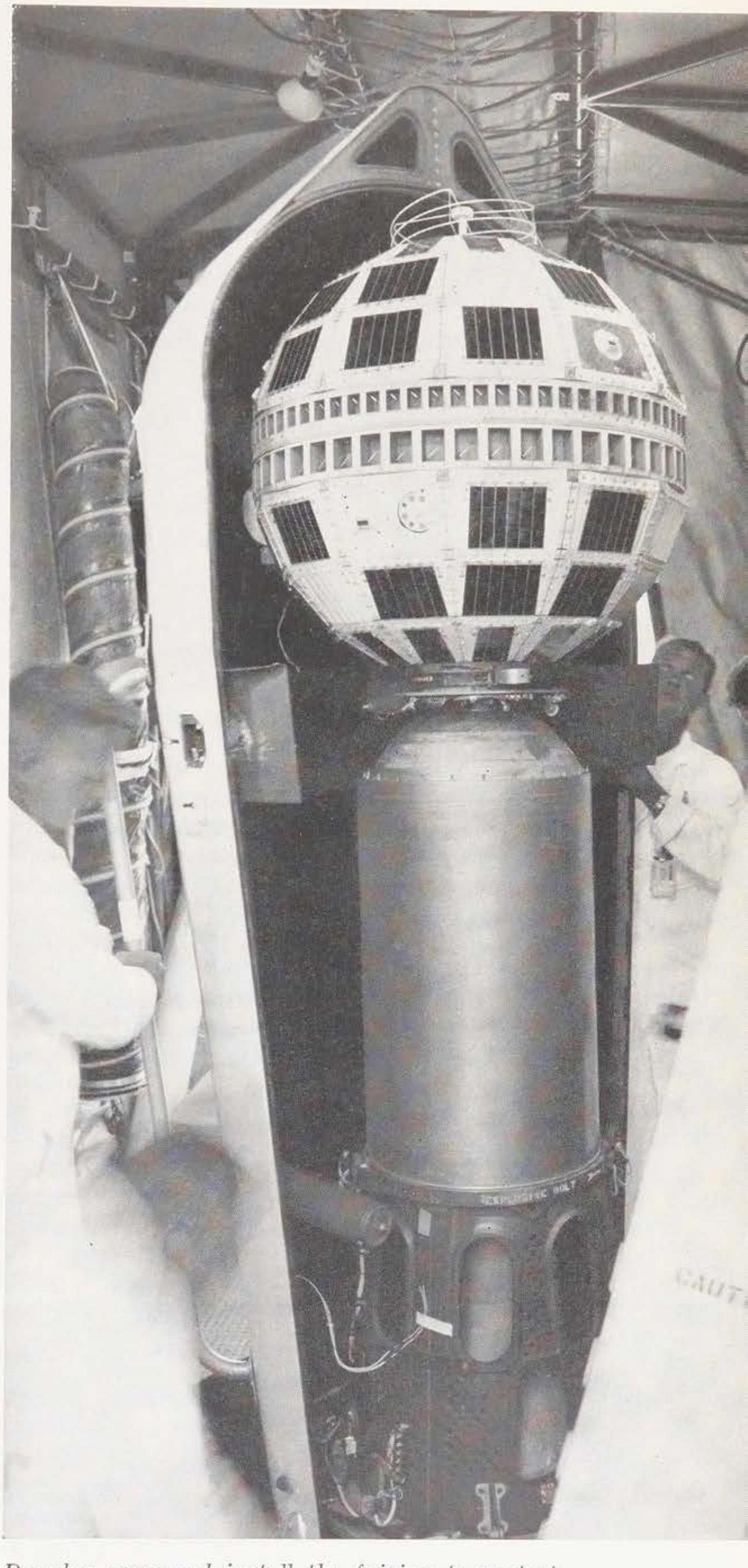
A week before launch, Douglas engineers completed the dynamic balancing at the spin test building. The flight satellite and third stage were then moved to the service tower and secured to the rocket. A special housing with air conditioning was placed around them for protection from exposure. Once the satellite was installed, the tests that had been performed on the prototype satellite were repeated.

On "F minus one" day, the countdown began. All stations were manned eighteen hours in ad-

The first stage of Delta 11 pivots on a specially designed truck bed during the erection procedure.

After adding correction weights to combined satellite and third stage, dynamic balance is checked.





Douglas personnel install the fairing to protect satellite from aerodynamic heating during ascent.

From control console in NASA's Mission Control Center the procedures of the Telstar launch are monitored.

vance of firing. NASA's Mission Control Center coordinated the entire launch operation. Reports from Minitrack Stations, the Blockhouse, Telstar Control, Bell Laboratories Guidance Control, and the Andover Ground Station provided the Mission Control Center with data on the readiness of the far-flung facilities required for the Telstar experiment. Procedures of the launch itself were controlled from the Blockhouse at Complex 17.

As the launch time approached, the first and second stages were fueled and final ordnance checks completed. Boresight adjustments were made on the guidance antenna. The checks and tests on electrical and hydraulic systems continued methodically. Before firing, the service tower was rolled back, leaving Delta 11 standing alone with the "umbilical tower." The countdown continued by minutes, then seconds, until at 3:35 A.M. on July 10, 1962, the Delta rocket, carrying its complex cargo, rose into the sky.

The Telstar experiment requirements called for an orbit of 500 miles perigee, 3000 miles apogee, and 45 degree inclination. Reports from Minitrack sites around the world and the Andover Ground Station indicated that the satellite achieved an orbit of 514 miles, 3040 miles, and 44.8 degree inclination. This was the tenth consecutive successful launch of the Delta vehicle.

On the next day, July 11, 1962, a trans-Atlantic telecast by way of the Telstar satellite provided final confirmation that the combined efforts of so many men and organizations had been rewarded. What future use this achievement will find remains for history to reveal. The success of this first step, however, brings closer the highest goal of communications development: that the communities of man can get to know one another and thus, in Toynbee's words, "become aware of the common humanity underlying the differences in our local manners and customs."

Telstar II Satellite Launched

A second Telstar satellite was launched from Cape Canaveral on May 7. An improved Delta rocket, more powerful than that used for the Telstar I satellite, placed Telstar II in an orbit with a higher apogee where it will encounter less radiation.

According to preliminary NASA data on May 7, Telstar II's elliptical orbit takes the satellite from 604 miles at perigee to 6713 miles at apogee, at an angle of inclination of 42.7 degrees. Its predecessor's orbit ranges from 592 miles to 3531 miles. Telstar I now takes 158 minutes to orbit the earth. Telstar II's orbital time is 225 minutes.

The higher apogee of Telstar II provides longer mutual visibility between the Bell System's ground station at Andover and ground stations in Europe. It also will give some mutual visibility between Andover and Japan, where ground stations are now under construction.

The difficulties with the Telstar I satellite were diagnosed by engineers and scientists as ionization of gases in transistors in the command decoders. To prevent this in Telstar II, "evacuated" transistors were used in one of the decoders. Without any gas in the cap enclosure there should be no ionization.

The two satellites are basically the same in appearance and equipment. A radiation-measuring package has been changed so that it can measure electrons in an energy range from 750,000 to 2 million electron volts. This compares with measurements from 250,000 to 1 million electron volts in the Telstar I satellite.

Telstar II's telemetry reports on some 118 items each minute. Telstar I made 112 such reports. The principal additions include measurements of the command circuit and a more precise check on pressure inside the satellite.

Telstar II is capable of sending its telemetry reports on the same microwave frequency (4080 mc) used for precision tracking of both satellites. It will also use the VHF beacon (136 mc) on which Telstar I sends telemetry. The new arrangement of using the microwave signal for telemetry means that at the end of two years, when the VHF beacon is automatically shut off, telemetry can continue over the microwave channel.

Some changes also have been made in the ground station at Andover. The tracking operation has been made simpler. Adjustments also have been made in the receiver equipment at Andover to handle the telemetry sent on the microwave beacon.

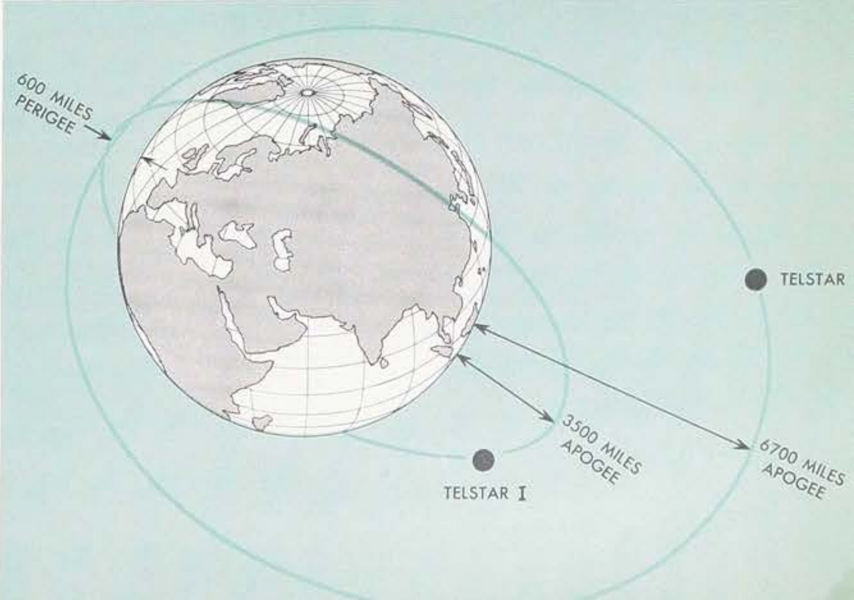
Ground stations in England, France and Italy will participate in the Telstar II experiment as they have done with Telstar I. Telstar II successfully transmitted television to ground stations in Europe on its fourth pass, when Britain and France received video-taped talks by E. J. McNeely, President of AT&T, and James B. Fisk, President of Bell Laboratories.

During its tenth orbit, Telstar II transmitted color and black and white television successfully. The French station reported "excellent" reception of both the color and the black and white programs. Sound was "very good and clear," although it was raining in France and the weather could have introduced "noise." The British station reported that reception of both the color and the monochrome pictures was a little weak. On pass 11, the British transmitted a five-minute television film; the Andover station monitored these tests and said reception was "good."

By the end of the year, the West German station near Munich also is expected to be in operation. Experiments are planned between Andover and Japan after the first Japanese ground station near Tokyo is completed. The International Telephone and Telegraph Company's ground station near Rio de Janeiro, Brazil will be able to receive telephone, data and facsimile signals from Telstar II.

Bell Laboratories ground station at Holmdel, N. J., is not participating in the communications aspect of the Telstar II experiment.

Differences between orbits of Telstar I and II.



AUTHORS

A. C. Dickieson

Alton C. Dickieson, author of "Project Telstar, Its Aims and Purposes," is a native of New York City, and studied electrical engineering at Brooklyn Polytechnic Institute. In 1923 he joined Western Electric's Engineering Department, which later became Bell Telephone Laboratories. In 1929 he was a member of the engineering staff of the Fox-Case Corporation; then rejoined Bell Laboratories in 1930 as a supervisor in a group developing long distance communications systems. During World War II, Mr. Dickieson led the development of carrier telephone communication systems for the Signal Corps, a sonar system for the Navy, and electronic guidance systems for acoustically steered torpedoes. Since the war he has specialized in transmission systems development, and became Executive Director of the Transmission Division in 1961. Bell Laboratories work on the Project Telstar has been carried out under his general direction. He served as director of air defense planning in 1953 and was in charge of planning the communication and detection systems used in the first DEW line stations in the Arctic. Mr. Dickieson and Dr. J. R. Pierce of Bell Laboratories were awarded the General H. H. Arnold Trophy by the Air Force Association in 1962; he and Dr. Pierce have also been awarded the General H. S. Vandenberg Award for 1963 by the Arnold Air Society. Mr. Dickieson holds 28 patents and is a registered professional engineer in New York State. He is a Fellow of the IEEE

R. W. Blackmore was born in Cleveland, Ohio, and attended Case Institute of Technology where he was a member of Tau Beta Pi, Blue Key, and a varsity letterman in fencing. He received his B.S.M.E. degree in 1940 and joined the staff of Bell Laboratories in 1941. He was initially assigned to the Apparatus Development Department. Since 1953 he has supervised a number of

R. W. Blackmore

mechanical design groups concerned with flight instruments and guidance sections for NIKE missiles and with the development of optical instrumentation for aligning and evaluating the tracking performance of precision radar antennas. For the Telstar Project, Mr. Blackmore supervised a group responsible for structural analysis and portions of the mechanical design of the horn-reflector antenna. This group also provided technical direction to the various subcontractors involved in the detail design, fabrication, and field erection of the horn antennas in Maine and France. Mr. Blackmore is the author of "Mechanical Design and Construction of the Horn Antenna."

R. Klahn

Richard Klahn, co-author of "The Horn-Antenna Direction System" in this issue, supervises a group responsible for real-time data-processing techniques. Mr. Klahn, a native of Buffalo, N.Y., is a 1957 electrical engineering graduate of the University of Buffalo; he received his Masters degree in electrical engineering from New York University in 1960. Since coming to Bell Laboratories in 1957, Mr. Klahn has engaged in a variety of military systems studies and development programs and was active in the Echo I experiment in 1959. He was appointed to his present position in November, 1962. From 1948 to 1955, prior to coming to the Laboratories, he was employed in the Long Lines Department of the AT&T Company. He is a member of the IRE.

Edward R. Byrne was born in Buffalo, New York. He attended Notre Dame University and received B.S. and M.S. degrees in Electrical Engineering in 1954 and 1955. From 1955 to 1957 he served as a lieutenant in the Air Force, joined the staff of Bell Laboratories in 1957. He has worked on various aspects of digital real time systems. He contributed to the computational and digital portions of the ground stations for the Echo and Telstar I experiments and currently supervises a group concerned with digital com-

E. R. Byrne

puter organization and logical design studies. He is currently working toward a Ph.D. degree in Electrical Engineering at Brooklyn Polytechnic Institute and is a member of the IEEE and ACM. Mr. Byrne co-authored the article on "Telstar's Antenna-Direction System" in this issue.

Joel Schill was born in Newark, N. J. During the Korean War, he served in the U.S. Marine Corps as a radar technician and instructor at Quantico, Va. Mr. Schill holds an Associate Engineering degree from Newark College of Engineering and is completing his senior year there. In 1954, Mr. Schill joined the Laboratories and worked on the evaluation of portable microwave equipment for black and white and color television transmission. Later, he transferred to the TH radio group where he worked on the development of the TH terminal transmitter and receiver. Mr. Schill is co-author of "Ground-Station Transmitter and Receiver."

J. Schill

Arthur F. Perks, co-author of "Ground-Station Transmitter and Receiver," was born in Lowell, Mass. During World War II he served in the U. S. Navy aboard an LST. After the war, he received his technical training from Capital Radio Engineering Institute, Washington, D. C. From 1947 to 1952 he was employed in the radio and television broadcasting field and then spent a year at the Research Laboratories for Electronics at MIT. Mr. Perks joined the Laboratories in 1953, and was first engaged in the development of the Compandor of the XP-1 carrier system. He later transferred to the TH Radio Group working on the Microwave Carrier Supply and the Automatic Protection Switching for that system. He is an associate member of the IRE.

A. F. Perks

R. E. D. Anderson, co-author of "The Satellite Power System" in this issue, was born in Minneapolis, Minn. He received the B.S.E.E. degree from the University of Minnesota in 1947, having completed two years at the University of Wisconsin, and joined Bell Laboratories where he was assigned to the trial installations group and later to the toll circuit analyzation group. In 1951 he was transferred to the Power Systems Development Department. There he was concerned with the electronic circuit design of rectifiers and regulators for a number of submarine cable systems and for the trial installation of the Electronic Central Office in Morris, Ill. Since 1960 he has supervised a group in the Power Systems Engineering Department that is responsible for planning power system developments. Mr. Anderson is a member of Tau Beta Pi and Eta Kappa Nu, an associate member of the IEEE and a licensed Professional Engineer in New Jersey.

R. E. D. Anderson

G. W. Meszaros, a native of New York City, started his Laboratories career in the Systems Drafting Department in 1926. Later,

G. W. Meszaros

AUTHORS (CONTINUED)

just before he received the B.E.E. degree from the College of the City of New York, he joined the trial installations group. In 1941, after a short time in several engineering divisions of the Systems Department, he transferred to the Power Development Department. Here he has been concerned with electronically controlled power circuits, for several submarine cable systems. Mr. Meszaros is currently in charge of a group designing transistorized power supplies for electronic switching systems, microwave radio relay systems, and for several military projects. He is the co-author of "The Satellite Power System" in this issue.

D. F. Ciccolella, co-author of "The Satellite Power System," joined the Laboratories in 1930 shortly after being graduated from Rensselaer Polytechnic Institute. His early work was in the Apparatus Development Department, in the development of quartz crystal filter elements and crystal networks. About a year before Pearl Harbor, Mr. Ciccolella was called to active military duty in the National Guard which lasted through the war and he was separated as a Lt. Colonel. In 1946, Mr. Ciccolella rejoined the Laboratories and resumed his work in the Crystal Development group where he worked on the development of ethylene diamine tartrate crystal elements. In 1951 he was transferred to the

D. F. Ciccolella

Semiconductor Device Laboratory where he has been engaged in the development of transistors, diodes, and solar cells. Mr. Ciccolella, a native of Albany, N. Y., is a Senior Member of the IEEE.

P. T. Hutchison, author of "Telstar's Microwave Repeater" in this issue, is a native of Tupelo, Miss., and graduated from Mississippi State University in 1944. He received his M.S. degree from the California Institute of Technology in 1947, and his Ph.D. from Georgia Institute of Technology in 1960. Mr. Hutchison joined the Laboratories in 1960 and worked on microwave reflectometers used in the TH Radio

P. T. Hutchison

Relay System and microwave components in the communications receiver used in the Telstar experiment. Since 1961, Mr. Hutchison has supervised a group which has designed and developed the communications repeater in the Telstar satellite and is now developing a microwave repeater suitable for use in future satellite systems. Mr. Hutchison is a member of the IEEE and Sigma Xi.

W. J. Maybach, the co-author of the article on Command and Telemetry Systems," joined Bell Laboratories in 1954 as a member of the Transmission Development Department. He was initially concerned with development of microwave radio systems, more particu-

W. J. Maybach

larly with the TH radio relay system. More recently he has been engaged in the development of telemetry systems for communications satellites. Mr. Maybach was born in Clarence, New York. He received a Bachelor of Science in Electrical Engineering from the University of Buffalo in 1954 and graduated from the CDT Program in 1958. Mr. Maybach is a member of the IEEE.

E. P. Moore, a native of St. Joseph, Missouri, received the A.S. degree from St. Joseph Jr. College in 1950 and the B.S. in E.E. from the University of Colorado in 1954. During this period he also served in the United States Navy from 1945 to 1947 and again from 1950 to 1952. Mr. Moore joined Bell Laboratories in 1954 and completed the CDT Program in 1957. Later he participated in the design of the TASI System

E. P. Moore