The *Telstar* Experiment

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The papers that follow describe in depth the satellite and ground systems designed for the Telstar experiment and give the results to date. The purpose of this introduction is to set the scene in which the project was undertaken and to state some general conclusions.

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

In 1960, with the launching of a large aluminum-coated balloon by the National Aeronautics and Space Administration, the famous Echo experiments[1] were conducted between a transmitting and receiving station set up by Bell Telephone Laboratories at Holmdel, New Jersey, and a companion station at Goldstone, California, designed and operated by Jet Propulsion Laboratory.

The Echo experiments produced the first two-way telephone conversations via satellite. They also confirmed predictions of the radio path loss to be encountered, the stability of the radio medium, and the low noise picked up by a well designed antenna pointing at the sky.

These results were studied at Bell Laboratories in the context of the Bell System's long-term interest in overseas communication. The first New York-London commercial voice circuit was established by long-wave radio in 1927 and was followed by short-wave (HF) circuits in 1929. Over the years, a network of some 240 radio circuits has been constructed, connecting the United States to 140 countries.

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 worldwide communication that was developing. It was clear also that because of physical limitations inherent in the very nature of the radio transmission medium, the reliability and quality of the resultant telephone circuits would leave something to be desired.

At this time the development of repeatered, multi-channel submarine cable was pressed forward. The first transatlantic cable of this type was placed in service in 1956,[2] followed in rapid succession by many others. The submarine cable network is expanding rapidly, providing high quality and reliable communication service.

The Echo experiments opened the possibility of applying microwave radio relay technology to transoceanic links. The line-of-sight transmission characteristic of microwaves had prevented their use over the oceans until the possibility of a "microwave repeater in the sky" appeared.

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. Transistors and diodes, solar cells, low-noise maser amplifiers, long-lived traveling-wave tubes, horn-reflector antennas, FM-feedback receivers — these and other essential tools were available.

It was recognized that there was a long step in development needed to fit these essential but separate elements into a coordinated working system. Also, numerical knowledge of the characteristics and magnitude of radiation in the Van Allen belt was not adequate as a basis for design of a long-lived satellite.

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

In setting the objectives for the experiment, the desideratum was the simplest experiment that would answer the really critical questions, leaving until a later round of design the optimization of trade-offs and the development and construction of a commercial operating system. Thus, the objectives were:

1. To look for the unexpected.

2. To demonstrate the transmission of multichannel two-way telephony, television, data and facsimile via satellite.

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

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

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

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

It was decided to install a microwave repeater in the satellite. While the passive reflector of the Echo type has advantages, calculations indicated that the transmitter power required for television bandwidths would be excessive unless balloons of a size well beyond the present state of the art were used.

Study of available boosters led to the Delta configuration of the Thor as the simplest and most reliable rocket for these purposes. Its relatively limited lifting capacity set a bound of about 180 pounds for a useful orbit. This was established as: apogee 3450 miles, perigee 575 miles, inclination to equator 45°. The apogee is high enough to give good mutual visibility between northeastern United States and western Europe. Calculations for a working worldwide system indicate the desirability of circular orbits at 6000–8000 mile elevations; however, these were not achievable with the Delta vehicle.

The weight restriction now forced the decision to install only a single, one-way amplifier in the satellite, rather than two. This permits one full-band signal to be sent one way, or two (or more) narrow-band signals to be sent two ways. Also, the solar cell power supply capacity was limited to less than that required to operate all of the electronic circuits continuously. It was necessary, therefore, to use a nickel-cadmium storage battery to handle the peak loads, with means to turn the amplifier on and off by command from the ground.

If the satellite presented one face to the earth at all times, it would be possible to use 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 fitted 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 payload is thus spinning at the time of ejection.

It was decided that the satellite antennas should receive and transmit circularly polarized waves, so as not to require polarization tracking by the ground system. Consideration of the geometrical relations between the earth and the spinning satellite in an inclined, elliptical orbit indicated the desirability of omnidirectional antennas if communication is to be maintained unhampered at all times and places. Such a design is not possible; thus the design objective was to achieve the broadest coverage obtainable. Calculations indicated that with the antenna pattern attainable and with the satellite launched with its spin axis perpendicular to the sun line, its aspect with respect to locations in the northern hemisphere would be satisfactory for long periods.

To gain more numerical understanding of the distribution of radiation in the Van Allen belt, it was decided to include a rather complicated array of sensors and measuring devices in the satellite. Clearly, to return this information to earth required radio telemetry. Parts of some and all of other orbits are not visible from the BTL stations. Thus it was made part of the cooperative agreement with the National Aeronautics and Space Administration that their Minitrack stations around the world would collect telemetry from the satellite. For this reason, the telemetry frequency was chosen in the band around 136 mc for which the Minitrack stations were already equipped.

The necessity to turn the communication repeater on and off (because of power capacity limitations) established a need for a radio command channel. Further consideration of the over-all problem indicated the desirability of additional command capability. Since it seemed likely that it might be desirable for some Minitrack stations to issue commands, it was decided to use a frequency near 120 mc for this purpose, and to use a command format for which the Minitrack stations were equipped.

The choice of frequencies for the communications 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. The newcomer, satellite communication, has to work its way into this established pattern. This presents a complex international question which is not yet resolved.

In the meanwhile, 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,[3] 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 frequency bands 3700–4200 mc and 5925–6425 mc.

It was decided to use the 4000-mc band for the down direction, from satellite to ground, so as to minimize the deleterious effects of rain on the received signal and noise. 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. The A.T.&T.Co. applied for and received from the Federal Communications Commission research-experimental licenses for satellite and ground stations.

Sharing of frequencies with terrestrial systems had an effect on the choice of the site for the ground station. A location in the northeast part of the United States was wanted, so as to minimize the great circle distance to western Europe. Separation from large cities and from existing or probable microwave radio relay stations operating in the 4000- or 6000-mc bands was desirable.

Fairly flat ground was desired for the installation of initially one, and later several, large 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 nearby. All of these were found at a location near Andover, Maine.

Study of the over-all system parameters lead to the conclusion that a large ground antenna with minimum power in the satellite was the economical choice. Research work at the Bell Laboratories Holmdel Radio Research Laboratory had culminated in the construction of a horn-reflector antenna with 400 square feet of aperture. 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 broad-band, it can be designed so that the receiving equipment does not move with elevation motions of the horn.

It was decided to design and build a horn-reflector antenna 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 preserve the accuracy of the antenna, and to permit it to operate in all kinds of weather (including the 90 inches of snow to be expected in Maine), an air-inflated covering or radome was added.

Study of the antenna-pointing problem led to the conclusion that the satellite should radiate a low-level microwave signal whenever the communications transmitter is turned on. This has two uses. It permits very precise tracking of the satellite, and hence accurate determination of its orbit. Also, it facilitates the design of an autotrack system that automatically optimizes the pointing of the ground antenna once its beam is placed on the satellite.

It was decided to design for tape-controlled pointing of the antenna, as well as for slaving to a small, precise autotracking dish. The objective was to acquire knowledge of the advantages and limitations of several methods of antenna pointing.

To receive telemetry at 136 mc, and to transmit commands at 120 mc, it was decided to construct a directional antenna with autotrack capability. This would lock on to the 136-mc telemetry carrier normally radiated from the satellite. The relatively broad beam (about 20°) of this antenna facilitates finding the satellite in space, even with quite crude orbit prediction. It was decided to arrange for slaving of the precision tracker to the command antenna, so that we could go through the sequence of acquiring the satellite with the 20° command antenna, having it direct the 2° beam of the precision tracker to the right position, and then have the precision tracker give instructions to the horn-reflector antenna.

To make the most of the very good noise performance of the horn-reflector antenna, the communications receiver was designed to use a traveling-wave maser operating in liquid helium. Also, to improve the breaking point of the receiver, (i.e., to permit the receiver to reach deeper into noise for very weak signals) the technique of FM-feedback is used. This method was invented at Bell Telephone Laboratories some years ago, and was applied very successfully in the Echo experiment.

Thus the main outlines of the Telstar experiment were established. The plans were discussed in considerable detail with the communication agencies in England, France and Germany. All three decided to build ground stations to work with Telstar; the German station was planned for operation in 1963 or 1964, while the British and French set it as an objective to be ready on or near the time of the first Telstar satellite launching. In the meanwhile, NASA discussions led to the agreement that the Bell System, British and French stations would be equipped to operate with Project Relay, along with other stations such as those planned in Italy, Brazil, and elsewhere. To simplify the hardware situation at the ground stations, it was agreed to have Project Relay use the same frequency plan as Telstar for the downward direction.

GENERAL CONCLUSIONS

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

Andover, Maine. Also the first transmission of a telephoto picture was achieved. The procedure was also televised for the national networks. In the midst of this program, word was received that the French station at Pleumeur-Bodou was receiving picture and sound perfectly. The British station at Goonhilly was receiving the signal, but was not able to utilize it because of a turnover in polarization at the antenna.

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

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

During the fourth week of November, 1962, the command channel began to act erratically. Increasing difficulty was encountered in having it accept commands. Since it seemed possible that control might be lost, arrangements were made to leave the telemetry on continuously rather than switching it on and off. Also, the traveling-wave tube was not energized at all, lest loss of control should leave this heavy drain on continuously and thereby ruin the batteries. After the 1242nd orbit on November 23, 1962, the command channel ceased responding.

It was known from previous studies[4] that radiation may produce important effects on transistors. Telstar telemetry data indicated that the density of electrons of high energy was much higher than had been anticipated. The working hypothesis was formed that the command circuit failure was caused by radiation damage to certain of the transistors in the command decoder. Careful study of previous data indicated that one of the two command decoders had failed in August of 1962.

During November, our command stations in the northern hemisphere were addressing the Telstar satellite near the perigee of its orbit, while it was traversing the worst part of the Van Allen belt. The possibility existed that the radiation damage effects would be less serious while the satellite was nearer apogee. Thus attempts were made to command the satellite from the Minitrack station at Johannesburg, South Africa, but without success.

In the meanwhile, laboratory tests had pointed to certain transistors as being the most likely sources of trouble. Special codes were devised to take advantage of certain circuit features that would permit by-passing these particular transistors. On December 20, 1962, one of these modified codes was successfully transmitted to the satellite. In subsequent operations, all voltages were removed from the command decoders. As had been predicted, this action allowed recovery of the transistors. On January 4, 1963, during orbit 1628, public demonstrations of live television to and from Europe were concluded. Telstar by then was responding properly to all normal commands.

On February 14, 1963, there began to be indications that the operation of the command system was beginning to degrade again. The satellite began to take longer and longer to respond to the normal command codes. By February 20, it did not respond to the normal codes. During this period, the response to the modified codes was solid.

On February 21, the satellite misinterpreted a command and operated the relay that disconnects most of the electronic system from the power plant. Since then to the present writing (March 18), the Telstar satellite has not responded to even the modified commands.

The results of the Telstar experiments are given in detail in the following papers. Two general conclusions can be drawn:

1. Design of a second-generation Telstar satellite could be approached by Bell Telephone Laboratories with confidence as an engineering project. Where uncertainties exist, they have to do with the conditions existing in space.

2. Problems of the ground station are clearly understood. The usual design trade-offs and optimizations can be made with real understanding. The second-generation ground station will be considerably simpler than the first experimental station at Andover.

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