The Research Background of the *Telstar* Experiment

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

I. INTRODUCTION

The Telstar satellite communications experiment, like all achievements in technology and engineering, has many roots. Some of these roots are as broad and old as science itself; others are rather recent and include modern rockets, missile guidance, and general space technology. Other more modest but essential roots grew from an early appreciation of the potential of satellite communication and the steps taken in the area of communication technology to foster its growth.

Bell Telephone Laboratories interest in the possibility of using artificial earth satellites for communication purposes began in 1955 with the publishing of the article on "Orbital Radio Relays"[1] by J. R. Pierce. It is significant, however, that some of the research which was relevant to the success of the satellite predated this publication by a decade or more.

The material presented here consists of a summary of scientific and technological knowledge and advances which were important to the satellite program. It also contains the pertinent parts of a memorandum dated August 24, 1959, which summarizes the background and views that led to work toward a particular sort of experimental communication satellite. This memorandum expresses better than could be done retrospectively the thinking that led to the course of research activity which followed.

Bell Laboratories activities which followed the publication of Pierce's article and which culminated in the Telstar satellite experiment can be divided into five rather distinct periods of approximately one year each:

(*i*) 1958 Preliminary studies
(*ii*) 1959 Initiation of research and development programs
(*iii*) 1960 Experimentation and verification
(*iv*) 1961 Intensive development
(*v*) 1962 System construction and test.

The year 1958 was one for imagination and invention. The activities consisted principally of paper studies of the many system possibilities which were made possible by satellites, and resulted in a number of memoranda and published papers[2,3,4,5] which provided guide-lines for subsequent activities. Systems proposed in Bell Telephone Laboratories were conservative by many standards but relatively realistic if we judge by the fact that most of the factors which have so far proven to be important to the problem were well evaluated at that time. The most notable exceptions have been the unforeseen radiation hazard and the degradation of two-wire circuits with echo suppression by delay, which has dampened an early enthusiasm for 24-hour "stationary" satellites.

During 1959 several research and development programs were initiated which led directly to the Telstar experiment. An ad-hoc group containing people from many disciplines throughout the organization was formed to initiate activities in the areas which needed attention. It is principally the early work of this group which is described in this paper.

By 1960 laboratory work was well under way on several of the problems. During the year, the Project Echo experiment[6] was carried out and provided valuable experience with many of the elements inherent in a satellite communication system. Prototype models of the traveling-wave tube used in the Telstar satellite were built and put on life test, and life tests on batteries and other components were also started. Discussions with others working in the field led to an appreciation of the environmental problems and the necessity of radiation shielding. During this time, studies of radiation damage to solid-state devices were undertaken in cooperation with Brookhaven Atomic Energy Laboratories, which led to the design of the radiation-sensing package and the radiation protection used on the satellite. A general electrical-mechanical configuration of the satellite was also proposed, although many important problems remained to be worked out.

Early in 1961 intensive development of the satellite began and is described elsewhere in this issue. The present paper discusses the more important parts of the research program which preceded the development project.

II. RESEARCH LEADING TO THE STATE-OF-THE-ART

If the Telstar satellite had been built using the state-of-the-art of a decade ago, it would have been a very different satellite. The evaluation of the sky noise temperature, the development of the low-noise maser amplifier, the appreciation of the low-noise properties of the horn-reflector antenna, and the solving of the problem of demodulation of large-index frequency modulation using feedback combined to reduce the power requirement on the satellite by two or three orders of magnitude (about 20 db in effective noise temperature and 5 db in FM threshold improvement). Similarly, advances in solid-state electronics reduced power requirements, size and weight enormously. In the following pages, we will outline some of the more significant parts of the general research activities which produced the state-of-the-art upon which the Telstar satellite was built, and we then will describe work done more recently, specifically to implement satellite communication. Less attention will be given to a number of areas which were of vital importance to the success of the experiment, such as the development of solid-state electronics, microwave electronics and large computers, since these are covered in other papers.

2.1 *Low-Noise Receivers*

Research leading to the understanding of the effective temperature of the sky has gone on intermittently for several decades and has yielded important results, culminating in the determination of the now well known relationships[7] of sky noise temperature vs frequency and elevation angle. These relationships were vital to the choice of frequencies for space communication, and the realization that these very low effective sky noise temperatures existed revealed the possibility of utilizing the properties of masers and low-noise antennas.

Most work on antennas in the past has been directed toward producing high area efficiency in terms of the gain or directivity of the antenna, properties which are not uniquely related to the noise properties. However, the horn-reflector antenna,[8,9] developed for terrestrial microwave relay systems, was found to have an effective noise temperature of only one to two degrees Kelvin.[10]

The low-noise character of sky-directed antennas would be of little use were it not for the extremely low-noise microwave amplifiers which came into being just as satellite communications became a possibility. The microwave maser amplifier,[11] having a noise temperature of two or three orders of magnitude lower than the best previously existing amplifiers, grew out of a decade or more of physical research in microwave molecular spectroscopy and paramagnetic resonance in solids. The parametric amplifier, similarly, was the product of years of work in solid-state physics and nonlinear circuit theory.[12,13]

Research and development in these three low-noise areas were greatly stimulated by the prospect of satellite relays. Research on atmospheric absorption and radiation, particularly in the presence of high humidity and rainfall, was intensified because of this prospect.[14] Traveling-wave masers played key roles in both the Echo[15] and Telstar experiments; those used in the Telstar Project were among the first masers with truly broadband capability. Antenna development (larger horns and Cassegrainian antennas) was likewise spurred by the fact that new low-noise and large-size requirements had to be met.

2.2 *Electron Devices*

Perhaps the most remarkable contribution to the state-of-the-art came from solid-state physics. Few components used in the satellite or on the ground are not at least in part the product of research in this area of physics. The maser and parametric amplifier have already been mentioned. All of the active elements in the satellite, except the traveling-wave tube, are solid-state devices, none of which was beyond an early state of development a decade ago. The availability of the reactance diode used in the frequency multipliers and the high-frequency transistor could scarcely have been more timely.[13]

Microwave tube development was likewise timely. Five years before the Telstar experiment there were no CW microwave tubes of adequate power for ground station operation, and the long life and reliability required in space were just beginning to be obtained. These efforts, directed toward more conventional applications, were almost directly applicable to the space problem.

Development in other areas, such as missile tracking and computers, as well as the chemistry of plastics and adhesives, also helped to provide a state-of-the-art conducive to the development of satellite communications; but it is perhaps more appropriate to consider those problems which were newly posed by the new prospect. These problems ranged from satellite components and construction to considerations of celestial mechanics and geography necessary to establish probability statistics of mutual visibility between stations.

III. THE SATELLITE RESEARCH PROGRAM

In the face of a bewildering variety of options, it was necessary in 1959 to settle on a particular plan of action which would define the next nearest goal and the steps needed to attain it. This plan had to be sufficiently concrete to make it possible to identify the various problems and to help in getting people interested in solving them; at the same time it had to be flexible to allow for unexpected discoveries and developments.

Such a plan, embodying much of the thinking of Bell Laboratories at that time, was presented in an unpublished company memorandum dated August 24, 1959. In view of the influence of this memorandum on the subsequent course of events, we feel that the readers' interests are best served by reproducing below the relevant parts of this memorandum,* including even those parts about which we might feel differently now. It will be seen that while a number of important choices and decisions were made at a relatively early date and were adhered to subsequently, there were other choices, such as the traveling-wave tube power level, the modulation bandwidth and the choice of frequencies, which had to be changed to meet new requirements.

An important change in outlook has resulted from tests of the effect of long delays and echo suppressors on telephone users. The degradation due to delay has not been precisely defined over the total range of interest in satellite communications, but present evidence strongly favors an approach which minimizes the delay. Thus our initial enthusiasm for a 24-hour system as an ultimate goal has been considerably dampened, and the low-altitude system, proposed in the memorandum as the first experiment, has become more attractive.

The fact that the document reproduced here was a plan, a program of action only and conditioned by the time it was written, should be kept clearly in mind by the reader.

* Only sections which are pertinent to the subsequent activities and which led to the Telstar experiment are included here.

Active Satellite Repeaters: Interim Report I

By L. C. TILLOTSON

ABSTRACT

An experiment employing an active repeater in orbit at an altitude of about 2500 miles is discussed. The system would provide an experimental circuit having a bandwidth of 5 mc and suitable for TV or multiplex telephony between the U.S.A. and Europe for periods of up to 30 minutes. Broadband frequency modulation would be used to ease power requirements on board the satellite. Possible interference between the space system and existing services is discussed briefly. Some of the problems which must be solved before such a system can be considered feasible are outlined.

Active versus Passive Repeaters

As the title indicates, we are here concerned primarily with active repeaters. This comes about in part because passive repeaters are already receiving considerable attention at Bell Telephone Laboratories* and in part by the writer's conviction that passive satellites are best for military systems, particularly if the orbiting body is chosen for its immunity to enemy action, and that active satellite repeaters will be more useful in civilian activities.

For long-haul point-to-point service, a repeater in a synchronous (24-hour) equatorial orbit is very attractive. The main disadvantages, in addition to the large distances involved, are the $\frac{1}{4}$-second round trip delay and the fact that the satellite is not visible near the north and south poles. The latter is more important to military than to civilian communications. An unoriented passive reflector at this altitude is prohibitively large. On the other hand, if it is to be successful, an active repeater must be built from *reliable* components. Herein lies the challenge....

Frequency Allocations

Space-borne repeaters will obviously have to compete with other types for frequency allocations. This problem could be considerably reduced if bands presently assigned to the common carriers are also used for common carrier activities in space, the only real difference being that the satellite radio repeaters would be located on very high altitude platforms. If a given frequency band is to be used for space and earth-based repeaters simultaneously, several possible interference paths must be studied and controlled.† These are:

* Both passive and active satellite repeaters are considered at some length a memorandum by C. C. Cutler dated 1/12/59. Many of the proposals in this memorandum are based in part on this work. [Later published, Ref. 5.]

† Since we also propose to use the same frequency for several satellite repeaters, relying upon spatial separation and antenna discrimination for protection, this subject must also be investigated but it is not part of the present consideration.

1. Interference to earth-based receivers caused by satellite-borne transmitters.
2. Interference to earth-based receivers caused by space system ground-terminal transmitters.
3. Interference to space system ground-terminal receivers by earth-based transmitters....

Proposed Experiment

A system with a 5-mc baseband and a snr of 40 db which uses a repeater circulating in a 2500-mile polar orbit could provide a TV circuit to Europe with a common visibility time from Holmdel and Paris of up to 30 minutes. The communication system parameters are listed in Fig. 2 [Table I in this

TABLE I—ACTIVE SATELLITE REPEATER SYSTEM PARAMETERS
(Fig. 2 of 8/24/59 memorandum)

Experimental path	USA (Holmdel)—Europe (Paris)
Satellite, altitude	2500 miles
orbit	circular polar
period	2 hours 55 minutes
velocity	14,450 mph (4 mps)
Mutual visibility time, best pass	approx. 30 minutes $7\frac{1}{2}°$ above horizon
Maximum range to satellite	4600 miles
Maximum path loss	130 db
Minimum range to satellite	2500 miles
Minimum path loss (reference value)	125 db
Ground antenna effective area	1700 ft² (60-foot dish)
Temperature of ground receiver	30° Kelvin
Noise in 10-mc band	−144 dbw
Power of ground transmitter	1 kw
Satellite antenna	isotropic −3 db
Temperature of satellite receiver	3000° Kelvin
Noise in 100-mc band	−114 dbw
Power of satellite transmitter	1 watt
With satellite at *maximum* range:	
Margin relative to system objective	−1 db
Margin about FMFB threshold (C/N = 12 db)	2 db
Modulation	Large-index FM
Improvement factor	21 db
Baseband	5 mc
RF band (30 db down)	104 mc
Radio frequency	6 kmc
S/N for TV, p.t.p. signal to rms noise	48 db
Noise in message channel	38 dba at zero level
Number of message channels	500 to 1000

paper]; possible repeater arrangements are described in a later section entitled "Satellite Microwave Repeaters".

The philosophy used in the design of the experiment is as follows:

(*i*) *Minimum requirements on the propulsion and guidance equipment used to inject the payload into orbit.* Thus the satellite is assumed to be either completely unoriented and hence tumbling through space or, at most, spin-stabilized, and hence precessing only very slowly. This choice must be determined by further study of the satellite antenna and orbit injection problems.

(*ii*) *Minimum possible payload size and weight.* This is achieved mostly by limiting the experiment to a single one- or two-way channel and by using a receiver which trades bandwidth for snr in an advantageous manner. This makes it possible to keep the satellite transmitter power down to one watt. Special care will also need to be taken in the design of the microwave tube to achieve maximum efficiency. Since one of the larger components of the payload weight will be solar cells and storage batteries, this will be reflected directly in the total weight of the package.

(*iii*) *The space-borne apparatus must be compatible with our long-range objectives.** Since the path loss to an unoriented satellite at 2500 miles altitude is nearly equal to that for a 22,300-mile attitude-stabilized repeater with a 19-db antenna, the satellite electronics can be essentially the same at both altitudes. This is very desirable since even a "minor" change in the design of long-life apparatus may mean starting over.

(*iv*) *The space-borne apparatus must have maximum possible life.* Almost every design parameter must be considered here. Some of the most important are:

(a) *Low transmitter power.* Tubes in the one- to ten-watt power range have a longer operational life than those in the 100- to 1,000-watt range. As shown in a memorandum† by D. A. Chisholm et al, tube life decreases rapidly as cathode current density is raised. High-power tubes call for high cathode current densities. It is expected that a one-watt TWT can be built with a cathode current density not to exceed 50 ma/cm^2. Such a tube would have an "expected" life of 10 to 20 years. Low power is also important in the satellite because waste heat dissipation is a problem at best.

(b) *Only one microwave tube per repeater channel and maximum use of solid-state devices operated in a conservative manner.*

(c) *Simplest possible repeater circuit arrangements consistent with a useful communication capability.* It seems clear that components left out will never cause trouble. However, this must be achieved by straightforward design rather than by resorting to "trick" circuits which make repeater performance unduly sensitive to component characteristics.

(d) *The space electronics must not quickly become obsolete because of advances in the art.* We propose a "straight-through" repeater having a

* Soon after this memorandum was issued, experiments with delay on a two-wire telephone circuit indicated that there is a very serious problem in the use of a synchronous satellite in two-way telephony.

† Contents of this memorandum are presented in Ref. 16.

bandwidth of 100 mc and providing a minimum cnr of 15 db at the earth-based receiver....

Satellite Microwave Repeaters

Although there are many possible apparatus arrangements which could be used for satellite repeaters, there are only two broad categories. The first type puts out what it receives, but at higher level and perhaps shifted in frequency. This is essentially a broadband straight-through amplifier which will handle any signal within the range of its performance characteristics. Such an arrangement has two outstanding advantages.

(*i*) Great changes in ground-based apparatus, modulation techniques, etc., can be made with no reaction on the satellite repeater. This will help to avoid obsolescence caused by advances in the state of the art, which is an important consideration when development of very reliable apparatus which takes years to complete is being started.

(*ii*) Since the signal handling at the satellite is simple, i.e., just amplification, simple circuit arrangements and relatively few components can be used. In spaceborne apparatus this is a vital consideration, at least for the present.

The second type processes the signal during its passage through the repeater. Examples are: demodulating-remodulating repeaters, or receivers and transmitters connected back to back; pulse-regenerating repeaters, receivers which employ a correlation detector feeding a local transmitter; and very advanced types which include on-board computers for error correction, key stream generation, path selection (antenna pointing), orbit parameter control, etc. The disadvantages of this type are rather obvious:

(*i*) We must decide the system mode of operation in considerable detail before launching. Any important change will require a new satellite.

(*ii*) Most of these schemes require an untenable amount of complication in on-board apparatus.

Since even the simplest schemes will require a major effort to achieve adequate reliability in the space environment, we shall consider only the simplest possible versions of each of the two basic repeater types.

Straight-Through IF Repeater

Two variations of a possible IF type repeater are shown in Figs. 8 and 9 [Figs. 1 and 2 in this paper]. In type I the IF amplifier, up and down converter, frequency shift oscillator and local (microwave) oscillator, would all be realized by using solid-state devices. Since a real microwave transistor is doubtful, especially on the required time scale, local oscillator power would need to be obtained by harmonic generation from a transistor oscillator operating at several hundred megacycles. Of course, if all this can be achieved, the repeater will require only one microwave tube. If not, then repeater type II, shown on Fig. 9 [Fig. 2], is a possibility. This arrangement exploits the bandwidth of the TWT to provide a microwave oscillator at a different frequency, but at the same time it is being used as a

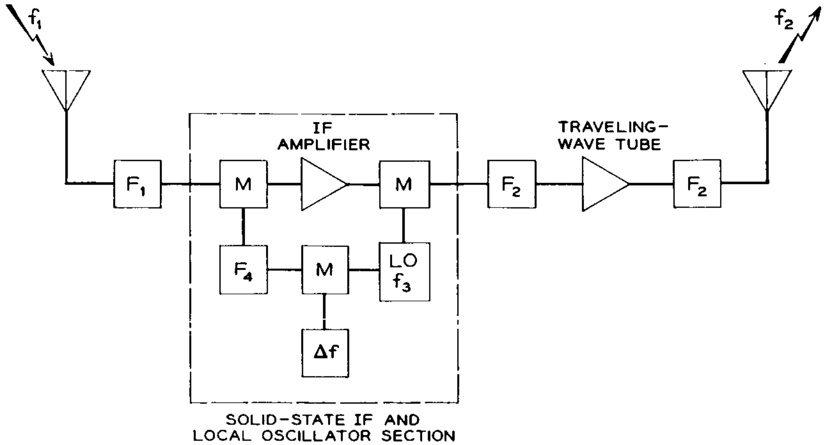

Fig. 1 — IF repeater type I (Fig. 8 of 8/24/59 memorandum).

signal amplifier. There are intermodulation troubles here, too, but the local oscillator power can be kept 20 db or more below the signal power, which should be very helpful in solving this problem.

At present, the most likely choice appears to be an IF repeater of type I or II, as shown in Figs. 8 and 9 [Figs. 1 and 2]....

Satellite Repeater Design

(*i*) *Life.* While launching costs are expected to decrease markedly as the operation moves from R and D into an operational phase and as more effi-

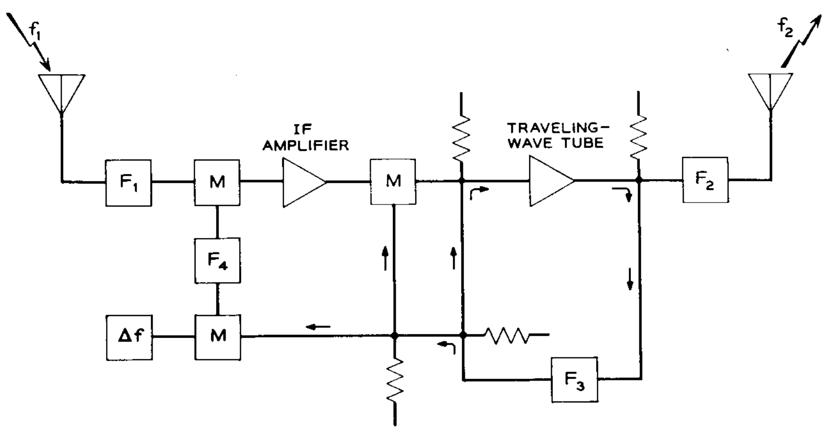

Fig. 2 — IF repeater type II (Fig. 9 of 8/24/59 memorandum).

cient propulsion systems become available, the cost of placing a repeater in orbit seems likely to remain as a major item of expense. Even if this were not so, it would still be important that the repeater last as long as possible in order to avoid cluttering up space with unusable derelicts. Hence, both for economic and political reasons, a long-life repeater appears essential. It is suggested that our goal be the same as for undersea cables — 20 years. More knowledge of the space environment than we now possess is likely to be required before such an ambitious goal can be achieved, but it is not too early to define our objective. Also, in order to make the first experiment appear successful, from both economic and psychological points of view, the first satellite should not be launched until it has a high expectancy of living at least one year.

(*ii*) *Size and Weight.* Clearly, both size and weight should be held down, but not at the price of compromising on performance. The successful launching of a device which then fails to operate will avail us less than nothing. An over-all weight in the vicinity of 100 pounds and a surface area of 20 square feet for solar cells appears reasonable from both the propulsion and electronic subsystem viewpoints. As propulsion systems with greater capabilities become available, they can be used to launch a multichannel repeater or several satellites at one time, or both. The basic repeater design can remain unchanged, if it is right in the first place. For example, the experimental single-channel one-way repeater discussed above could be used to build up a multichannel two-way repeater....

* * *

About the time the memorandum reproduced above was written, work was started on a number of problems defined therein in several places, both within the Research Division and in other Divisions of Bell Telephone Laboratories. Since much of this work is treated in considerable detail in this issue and elsewhere, we shall treat each topic with only the amount of detail appropriate to this historical introduction.

3.1 *Project Echo*

Early in 1959 preparation was begun for the Project Echo experiment,[6] and this work dominated our satellite communication activity for a time. Interest in the passive satellite was spurred by realization of the magnitude of the job of building an adequate active satellite, and the desire to gain early experience with systems. It was also believed that a system based on passive satellites might be created before the reliability of active satellites could be proven.

Bell Laboratories cooperated with the National Aeronautics and Space Administration, Jet Propulsion Laboratories, Naval Research Laboratories and others in formulating and carrying out the communication part of the Echo experiment. For this purpose a ground station with transmitter, receiver and satellite-tracking facility was established at

Holmdel, New Jersey. As is now well known, single-channel two-way voice communication, facsimile transmission, etc., were demonstrated over transcontinental paths; transmission characteristics were measured; and valuable operational experience was obtained using the 100-foot aluminized balloon reflector. This work spurred large ground station tracking and control and receiver development, and contributed valuable assurance that there were no propagation anomalies except for atmospheric refractive effects at low elevation angles. Experience with the large horn-reflector antenna with its complement of low-noise components, experience with orbit prediction and tracking, and experience with wide-index feedback FM demodulators were of considerable value in subsequent design of the much larger ground station used for the Telstar experiment. Portions of the ground station constructed for Echo were also eventually used in connection with the Telstar experiment.[17]

3.2 *Satellite Electronics*

The most critical component of the spacecraft itself was considered to be the traveling-wave tube. Fortunately, the development of tubes for terrestrial microwave relay systems had recently demonstrated as much as a five-year life span for such tubes, and their use in missile systems had shown that they could be made light and rugged enough. To design and build a tube for particular performance objectives — frequency, gain and power level — and with an aim toward even longer life, was no trivial task, and it was felt that at least a two-year lead time would be needed. To complicate the matter, the assignment of frequencies for an experiment with communication satellites could not be rushed. Consequently, some long guesses had to be made, and work on a one-watt tube at 6000 megacycles was started because this seemed a most likely possibility. The eventual change to two watts at 4000 megacycles was not so great as to void much of the work that was done. A full account of this work is presented elsewhere in this issue.[16]

Experience with an experimental light-route radio relay gave confidence that the solid-state devices and microwave circuitry used therein could be adapted to the design of a broadband repeater in space, and there was considerable experience upon which to draw. Several repeater circuit configurations were considered, and the straight-through IF configuration was favored because it made more straightforward use of existing circuitry.

3.3 *Satellite Power Supply*

Since the satellite power supply accounts for an appreciable part of the total satellite weight, it was essential that the most efficient design be used. While several schemes, including nuclear reactors and isotope power supplies, had been proposed, the only feasible means (1959–1960) was to use solar cells and a storage battery, together with a solid-state converter to change the low battery voltage to the various potentials required by the electronic circuitry. Study of the solid-state power converter, which was started at this time, benefited from considerable related experience with dc-to-dc converters for terrestrial microwave systems and for various military applications. The main problem was one of reliability. How this was obtained is described elsewhere in this issue.[18]

A storage battery of suitable design was not available; existing cells suffered from a lack of control during the manufacturing process and from a tendency to leak. There was also considerable question about cell life under continuous deep cycling and the effects of a long continued overcharge. Some of the early results obtained from a fundamental investigation started at this time have been published.[19,20,21] Early work on solar cells consisted mostly of radiation damage studies, since this was expected to be the most crucial problem; considerations were also given to temperature control and mounting arrangements.

3.4 *The Satellite Antenna*

The satellite antenna posed a difficult problem because of the conflicting mechanical and electrical requirements. Since the satellite diameter would inevitably be many wavelengths at the operating frequency, severe shadowing would occur if a nondirectional antenna was mounted near the surface. Erection of extensible arms in space had proven risky at best; and even if this were achieved, a sufficiently flexible low-loss microwave transmission line was not available.

A solution to the electrical problem was to divide the spherical satellite into two parts, separated by a radial transmission line which fed a circumferential slot radiatior. This antenna configuration was studied analytically and checked experimentally and found to produce a pattern acceptable for a spin-stabilized satellite.[22] However, this basic structure, consisting of two hemispheres insulated from each other by a small slot, posed severe mechanical and thermal problems in the satellite design. A multiplicity of closely spaced "boxes" fed in-phase by an array of coaxial cables and arranged to radiate circular polarization[23] provided an acceptable solution which was adopted in the development models of the Telstar satellite.

3.5 *The Satellite Structure*

Since it was desired to build a satellite which would have a long useful life, and there was no assurance of being able to provide attitude control, it was important that the satellite not be dependent upon orientation relative to the sun or the earth. For this reason an approximately spherical shape was chosen, and solar cells were distributed more or less uniformly so that the power generated would not depend upon solar aspect.

The early work was on a larger framework than used on the Telstar satellite, because continuous operation was envisaged, but work on the structure, heat flow and vibration damping paved the way for the later design.[24]

3.6 *Mutual Visibility Problems*

A crucial factor in the design of satellite communication systems is the problem of mutual visibility statistics. It was easy to derive a first-order approximation to the operational statistics for particular ground terminals and satellite orbit. To get a more general solution was a good mathematical problem which was solved in an interesting fashion.[25] It is clear from this work that a practical real-time, low-altitude satellite system for use between the United States and Europe should use polar, or at least steeply inclined, orbits at an altitude of several thousand miles. Other orbits are more suitable for other paths, and it appears that a global system would make good use of both polar and equatorial orbits. Before the radiation hazard was appreciated, it was thought that a 2,500-mile orbital altitude represented a logical compromise between the many factors involved, but to ease the radiation problem, and for other reasons, higher altitudes are now favored. The 24-hour synchronous satellite was, of course, expected to be much better from this point of view, but was ruled out of early consideration because of the more severe technical problems.

3.7 *The Delay and Echo Problem*

A most interesting research problem has been that of the delay and echoes inherent in long two-wire telephone circuits. The literature of a generation ago has a lot to say on this subject, and set a limit on the largest acceptable delay in a two-way, two-wire telephone circuit.

Heretofore, it has not been too difficult to stay within such a limitation, but it was soon clear that any double-hop, low-altitude system or single-hop synchronous satellite system would exceed this standard by a considerable amount. Early (1959) and simple experiments indicated that delay alone (in four-wire circuits) was not a problem, but that eliminating the echo in the presence of a delay up to 0.6 second was not a trivial problem.

It was soon apparent that this problem strongly involved user psychology as well as some severe technological problems. Circuits were devised which worked very well with some individuals and very poorly with others. Accordingly, in addition to work on specific apparatus for echo suppression, a user preference testing program was inaugurated. Tests were conducted over several years using a number of echo suppression techniques, including those of competitive companies. The user reaction to circuits with the best available echo suppressors and delays corresponding to only a single 24-hour satellite link is of serious concern in commercial telephony. This question still remains a fruitful area of research.[26]

3.8 *The Ground Station Antenna*

During the early planning for an active satellite experiment, it became evident that a low-noise antenna larger than any then in existence would be required. Design, construction, and test of the 20 × 20-ft horn reflector for Project Echo were sufficiently advanced to make clear that such an antenna would also be acceptable for use with an active satellite. Hence, plans were initiated for a 60 × 60-ft horn-reflector antenna of similar design. It was suggested by the mechanical designers that a conical horn might ease some of the structural problems. As a result of this suggestion, an analysis and an experimental check were made of the gain and pattern of such an antenna[27] which showed that performance equal to that of the older rectangular horn-reflector antenna could be obtained.

With antennas of the size contemplated, it is desirable that steering (autotrack) information be derived from the antenna itself. Prior research on waveguide modes provided a solution to this problem[28] and a multimode autotrack system was developed which contributed greatly to the Telstar operation.[29]

3.9 *Modulation*

A large number of possible modulation methods were considered for both passive and active satellites. During the Project Echo experiment amplitude modulation, phase modulation, single-sideband and frequency modulation (FM) were used. When complexity, power requirements on the satellite, and frequency spectrum limitations were all considered, it was not difficult to settle on wide-index FM as the most desirable. FM seemed desirable even for spectrum conservation because the relative freedom from interference greatly reduces the required geographical separation of stations sharing the same band.

The desirability of FM was greatly enhanced by the promised advantage of feedback in reducing the receiver threshold power.[30] Early attempts to use feedback demodulation failed to demonstrate the expected advantage, because of the seeming conflict between the IF band-shape requirements of the noise elimination and feedback stability criteria. A considerable amount of rather difficult theoretical and experimental work was necessary to resolve this difficulty, and the improvement obtained,[31,32,33] first for Project Echo and later in the broadband Telstar receiver, was very near the amount expected on more intuitive grounds.

IV. TRANSITION FROM THE RESEARCH TO THE DEVELOPMENT PHASE

Up to 1960, Bell Laboratories activity in satellite communication centered in an ad hoc group representing many parts of the organization. No large expenditure had been committed, and in fact it was not known at this date when, if ever, a satellite for other than government purposes would be launched. The work was undertaken because of a firm conviction of its eventual importance to the Bell System and because it posed problems which the technical staff found interesting and challenging. It was made possible by the freedom granted to the research groups to enter new areas which they found promising, long before it was possible to evaluate the commercial importance of the new field of activity.

Where does research end and development begin? It must be clear to the reader that there is as much "development" described in the foregoing paragraphs as there is research. However, there came a time in the course of events when a clear-cut change in the nature of the effort took place. Prior to the fall of 1960, "research," motivated primarily by the desire to solve crucial and interesting problems, dominated the Bell System activities in this field. After the fall of 1960, the activities were dominated by the dedication and commitment to produce a working experimental system in the shortest possible time. This paper covers only the earlier effort when activities were based on a hope rather than a commitment, were directed toward components more than toward a system, and before most of the people who made the Telstar experiment work had become involved. In the two years that followed, a number of important changes in the plan took place, and the pace accelerated many fold. The earlier contributions seem pale beside the later achievement, but small as the beginnings were, they played an important part in getting the Telstar satellite program under way.

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