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Satellite Science and Technology

Efforts in any complicated undertaking are based on so many sources that no one can call them his own.

J. R. Pierce

I am neither a historian nor an astronomer, and it would be presumptuous of me to comment at any length either on the life and work of Edmund Halley or on the illustrious men who have delivered the Halley lecture. I cannot help observing, however, the range of interests encompassed in Halley's work, which embraced geomagnetism as well as astronomy; the diligence with which he pursued it; and his bringing, through the publication of Newton's *Principia*, something beyond his own powers to the world of science.

The matters I consider here in connection with satellite science and technology have an even wider range than Halley's work, because science is broader than it was in Halley's day. And, what I discuss is not chiefly my own work, but rather the work of others.

Lest the title of my article be misleading, let me explain that I discuss almost exclusively one sort of satellite among the many that have been launched—that is, satellites intended to explore the possibilities of transoceanic communication. And I further restrict my discussion almost exclusively to two experimental communication satellites: Echo I and Telstar I.

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Yet, in dealing with these seemingly specialized satellites, I have something to say about the earth's atmosphere, both about its temperature and about its density 1000 miles above the earth's surface; about the particles trapped in the earth's magnetic field; about celestial mechanics; about an application of radio astronomy; and about the synchronization of clocks of the Royal Greenwich Observatory at Herstmonceux, East Sussex, and the United States Naval Observatory at Washington, D.C. I also discuss some findings in the field of experimental psychology, and I touch on a remarkable political effect of the Echo and Telstar experiments.

Now all of this is only a small sample of the multitudinous scientific, technological, and social problems which arose in connection with these communication satellites. Yet I believe that this small sample will show that, if science and technology are only a part of the world of thought, they are a remarkably various and yet highly interrelated part of that world.

In dealing with so broad and rambling a subject as the science and technology involved in communication satellites, some sort of organization is necessary.

Since I do not know how else to proceed, I propose to be guided by chronology and to discuss matters in the order in which they became clearly apparent to those connected with the Echo and Telstar programs.

Background

Certainly, none of the technical problems would have arisen had there been no overall communication satellite program. For this we must give due credit to Arthur C. Clarke (*1*), who in 1945 proposed the relaying and broadcasting of electromagnetic communication signals by means of manned "stationary" satellites at an altitude of 22,300 miles. Yet we see that there is a considerable gap between satellite communication as Clarke proposed it and as it has been realized, for while many people have seen television relayed across the ocean by Telstar, the manned space stations which Clarke proposed lie still in the future.

I am sure that echoes of Clarke's words of 1945 had reached my ears (though I had not read the words themselves) when I first thought seriously about satellite communication, in 1954. It seemed clear to me then, as it does now, that the best justification for developing communication satellites would be the linking together of the common-carrier communication systems of various continents. This would, for example, make the 46 million telephones of Europe (I use today's figures) more readily and more quickly accessible to the 83 million telephones of North America.

To broadcast directly to home receivers would necessitate putting heavy, high-powered, complicated equipment in a satellite, but my calculations showed that equipment of very low power could provide for the present rapid growth of international telephone and data transmission and, for the first time, link together the television networks of various continents.

In 1954 I was worried about problems of the life and reliability of any equipment launched into orbit, and I was encouraged to find that it would be possible to relay telephone and television signals by means of a passive, spherical, reflecting satellite. Indeed, for some of my calculations the model was a reflecting sphere 100 feet in diameter, and that is the very diameter of the

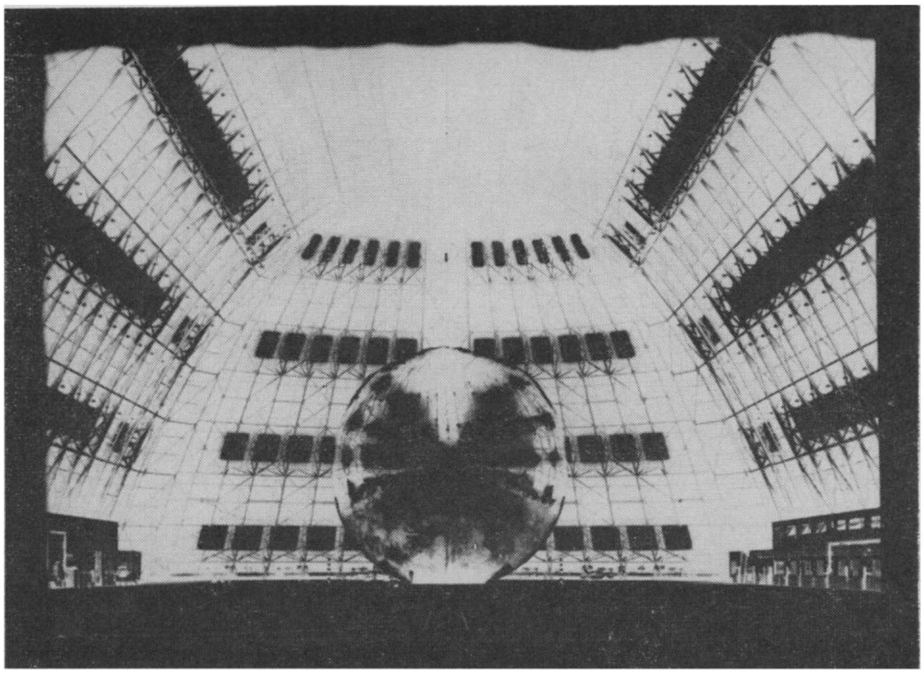


Fig. 1. Experimental 100-foot aluminized balloon.

Echo I balloon satellite which was launched into orbit on 12 August 1960.

Thus, Clarke proposed one thing in 1945 and I had something rather different in mind in 1954, which I published in 1955 (*2*). Something very close to the satellite I described was launched in 1960. Was this a direct result of my 1955 paper?

Oddly enough, the Echo balloon satellite itself was the result of work of a quite different character and purpose. In January 1956, William J. O'Sullivan of the Langley Research Laboratory of the National Advisory Committee for Aeronautics, now incorporated in the National Aeronautics and Space Administration, proposed to launch balloon satellites in order to measure the density of the very tenuous atmosphere at an altitude of around 1000 miles. His work led to the construction of an experimental 100-foot aluminized balloon, shown in Fig. 1.

After the launching of Sputnik late in 1957 and of Explorer I early in 1958, Rudolph Kompfner and I became very much concerned about a practical communication-satellite experiment. We saw in O'Sullivan's balloon the very object I had thought of in 1954 as a communication satellite. Our discussions with NASA led to their Echo program by early 1959. The plan was this. NASA would launch a 100-foot balloon satellite, for measuring atmospheric density *and* for communication. The Bell Telephone Laboratories would construct an East Coast communication terminal at Crawford Hill in New Jersey, and NASA's Jet Propulsion Laboratory would construct a communication terminal at Goldstone, California. All of this was done, and President Eisenhower's spoken message was sent coast-to-coast by way of Echo on 12 August 1960.

Let me note briefly that the density of the atmosphere was duly derived from the orbital behavior of Echo I (*3*). Figure 2 shows a plot of atmospheric density versus altitude in kilometers. R. W. Bryant, from whose work this curve is taken, observes: "It must be pointed out in considering these density values that the atmosphere cannot be considered static at high altitudes. The diurnal effect can produce changes in density of as much as a factor of 30, and the effects associated with solar activity can produce changes of as much as a factor of 4 and possibly much greater. The seasonal effect may be as much as a factor of 1.5."

The Echo Experiment

Let us return, however, to Echo I as a communication experiment. One important problem in carrying out such an experiment was that of pointing the transmitting and receiving antennas at the satellite. This could easily be done visually at night during clear weather when the satellite was in sunlight, but these qualifications are severe limitations. The satellite could be tracked by radar. But Newton's laws of motion and gravitation, which enabled Halley to predict the return in 1757 of the comet of 1682, which now bears his name, would make it possible to predict from data acquired at one time, exactly where the antennas used in the communication experiment should be pointed at another time. Moreover, by using modern electronic gear, the antennas could be made to track the satellite automatically on the basis of the predicted position.

In project Echo, the existing Minitrack network was the chief source of orbital information as long as the 108-megacycle beacon on the satellite remained active. Optical data from the Smithsonian Astrophysical Observatory were also used. Radar data from the West Coast communication terminal of the Jet Propulsion Laboratory at Goldstone, were available during 1960.

In tracking Echo, orbital elements were computed by NASA's Goddard Space Flight Center at Greenbelt, Maryland. From these, elevation and rate of change of elevation and also azimuth and rate of change of azimuth were computed for times 4 seconds apart for each pass. To each such set of four data the time was added, and all the data for a pass were punched on a standard teletypewriter tape. Such tapes were transmitted to Holmdel (New Jersey), Goldstone, and other locations by commercial teletypewriter circuits. At Holmdel, the received tape was put into a digital-to-analog converter. When the clock time coincided with the time written on the tape, the angles and rates of change were automatically read out, converted to analog form, and used to drive the transmitting and receiving antennas.

In the Echo experiment this pointing was accurate to ±0.2 degree under favorable conditions. Such accuracy was not sufficient for Telstar, because the beam width of the Andover antenna is only 0.2 degree. At the Telstar ground terminal at Andover, Maine, a precision tracking antenna, operating on a 4000-megacycle signal radiated by the satellite, supplies data from which orbital elements are computed. It was predicted—and the prediction has been borne out—that data from as few as two successive passes per day would make it possible to predict pointing angles with an accuracy of 0.02 degree for the subsequent 24 hours.

Programs for computing orbital elements and tracking data have been written for both the I.B.M. 7090 computers at the Bell Laboratories' Murray Hill and Whippany, New Jersey, locations and for the two I.B.M. 1620 computers at Andover, Maine. The I.B.M. 7090 makes an orbital determination in a few minutes; the I.B.M. 1620's require about an hour and a half to process the data recorded during a pass, but they can handle data for three satellites in orbit.

We have seen how O'Sullivan's interest in the density of the exosphere was an important factor in the development of satellite communication. We see that the existence of electronic digital computers was essential in bridging the gap between Newton's laws and observations of the positions of Echo I and Telstar I, so that orbital computations could be made in minutes instead of months. As a communication engineer I do, however, propose to say *something* about electrical communication.

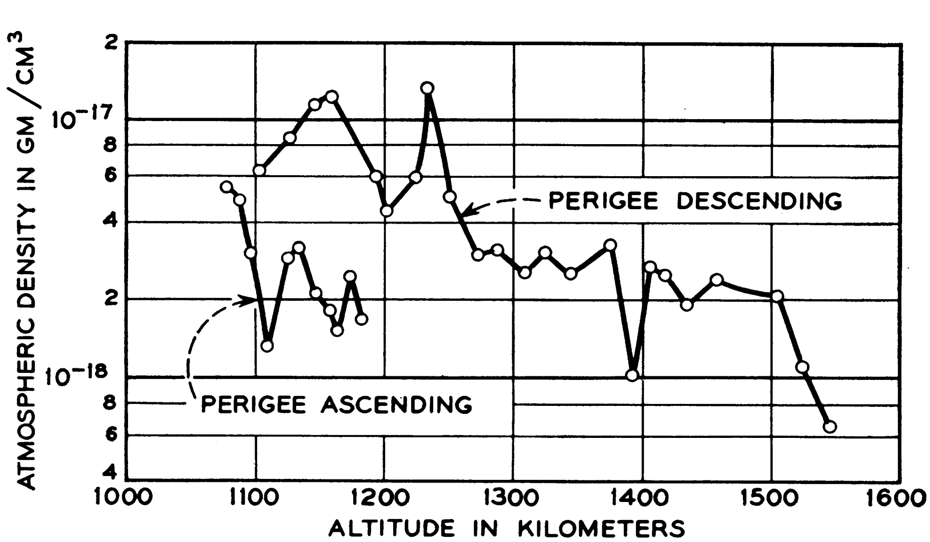


Fig. 2. Plot of atmospheric density versus altitude in kilometers.

Noise

One of the great challenges of the Echo experiment was the fact that the 100-foot balloon reflected into the receiving antenna only about a millionth of a millionth of a millionth (10^{-18}) of the 10 kilowatts beamed at it by the transmitting antenna. The very low signal power received had to compete with noise from various sources. When I first considered satellite communication in 1954, by far the greatest source of such noise was the microwave receiver itself. I assumed that the receiver would introduce a noise equivalent to the Johnson or thermal noise of a body at a temperature of about 900 degrees Kelvin.

Happily, by the time the Echo experiment was carried out, matters had changed drastically. As a result of his studies in microwave spectroscopy after World War II, Townes invented the ammonia maser in 1954. This was followed by the invention of the three-level solid-state maser by Bloembergen, and by the time Project Echo was carried out, it was possible to use as an amplifier a maser which introduced a noise corresponding to the electromagnetic radiation from a body at a temperature of 8 degrees Kelvin, an improvement by a factor of 100 over the receiver I had visualized in 1954.

What would be the advantage of using such a receiver? This would depend on how much noise reached the receiver from the antenna. In 1954 this would have been negligible in comparison with the 900-degree noise temperature of a microwave receiver; in the Echo experiment it could be crucial in comparison with the 8-degree noise temperature of the maser.

The first requirement was that the antenna face, not the warm earth, but the cool sky. Antennas with conventional dish-shaped parabolic reflectors "see" something of the environment to the sides and behind as well as in the direction in which they are pointed. Fortunately, in 1941 Friis and Beck (*4*) had described a "horn-reflector" antenna which is insensitive to radiation from the sides and back.

Let us suppose the antenna saw only the sky; what noise would be received? If the air were perfectly transparent, only noise from space. But, because air

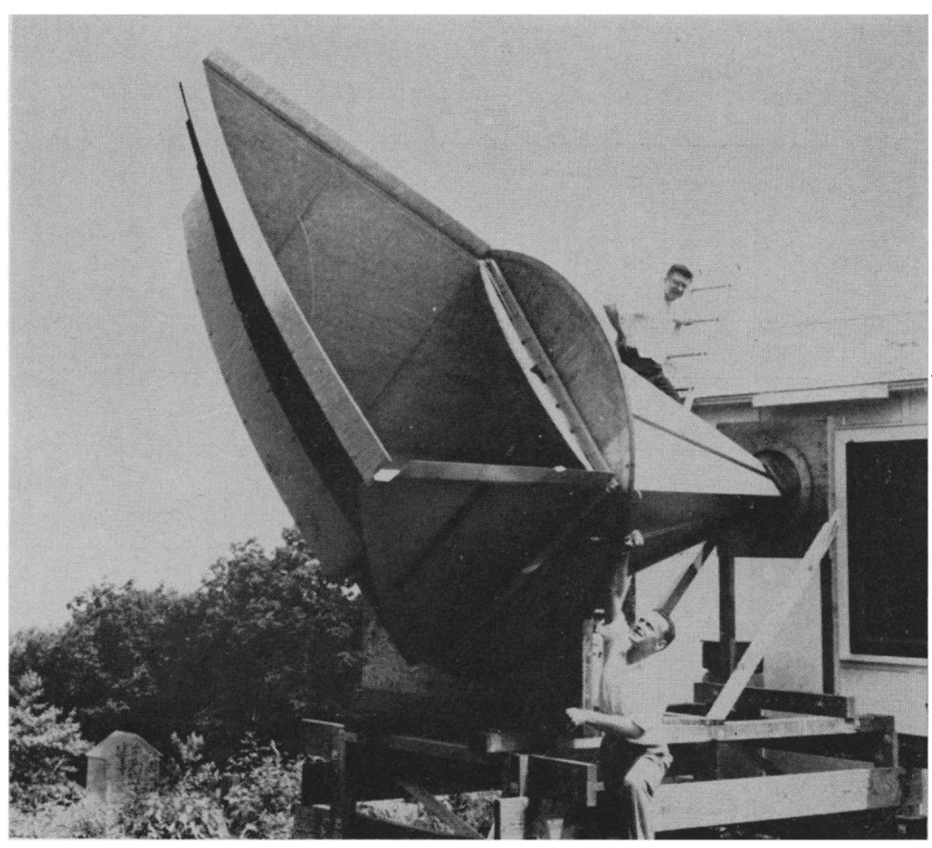


Fig. 3. Maser with small horn-reflector antenna.

is not perfectly transparent, some thermal radiation must be received from it.

In 1947, Van Vleck gave formulas for the absorption of microwaves by oxygen and water vapor. Using these, together with constants which had been determined experimentally and data concerning the density and temperature of the atmosphere, D. C. Hogg was able to compute the thermal noise which should be received at various angles from the zenith as a function of receiver frequency.

However, his values still had to be verfied experimentally. By September of 1959 this had been done, with a maser with the small horn-reflector antenna shown in Fig. 3. Figure 4 shows the close agreement between the theoretical and the experimental values.

There are, however, other sources of noise. Figure 5 shows two sources of noise during rain. The lower curves show thermal noise due to the rain, and the upper curves represent the scattering into the receiving antenna, by the rain, of energy from a microwave transmitter 20 miles away.

The maser was instrumental to the success of Echo and later of Telstar. The sensitivity of the maser made an investigation of sky noise imperative. For this, the horn-reflector antenna was called into use. And the results of the investigation indicated that gains could be made through the use of this type of antenna. Thus, for the Echo experiment a horn-reflector antenna with an aperture of 400 square feet was constructed at Holmdel; this is shown in Fig. 6. Figure 7 shows the 3600-square-foot antenna constructed at Andover for the Telstar experiment.

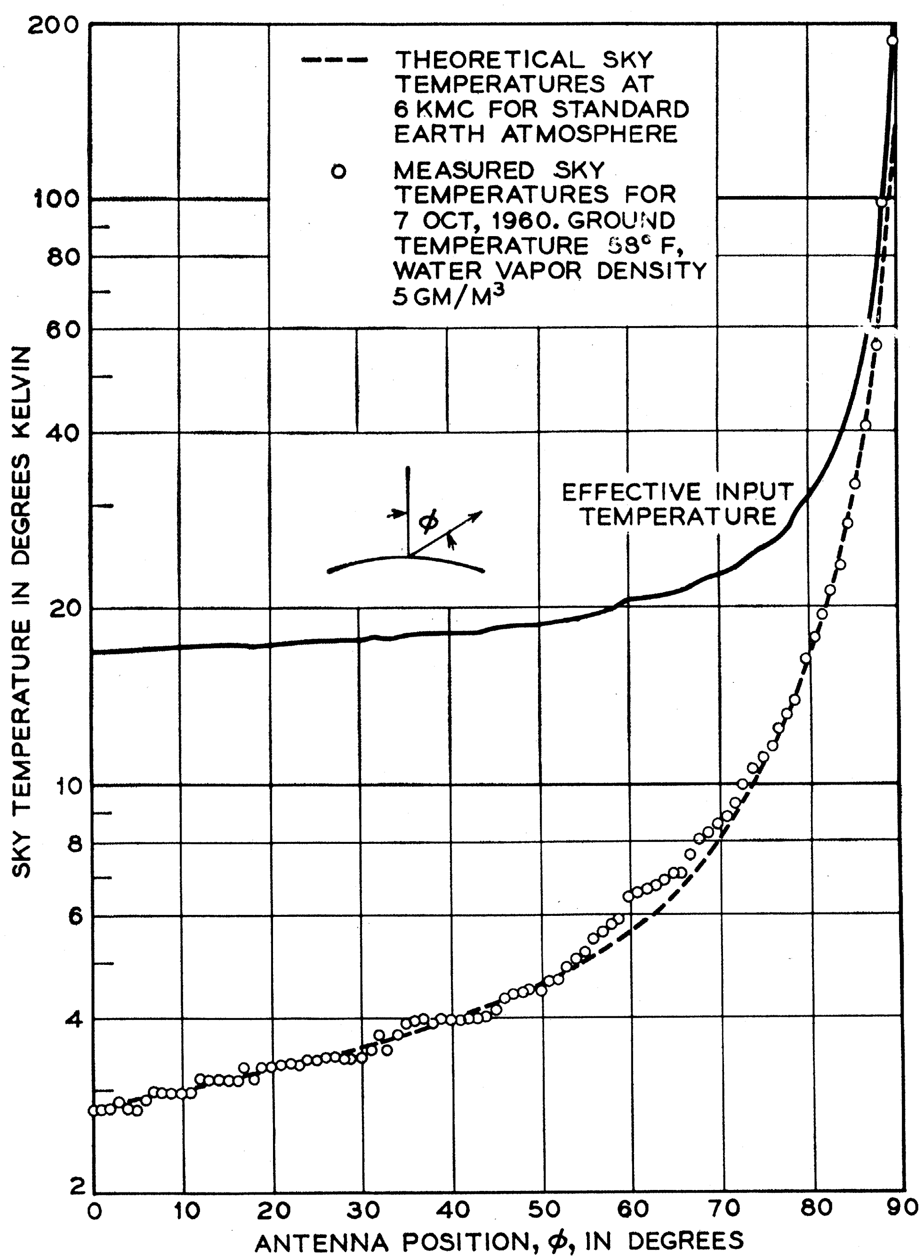


Fig. 4. Graph showing the close agreement between the theoretical values computed by D. C. Hogg and the experimental values for thermal noise at various angles from the zenith as a function of receiver frequency.

Boresighting

The construction of such large antennas led to the problem of boresighting—that is, of determining just where the antenna beam is pointed for various mechanical positions of the structure. This is no easy problem for a large antenna. The electromagnetic point source which is used must lie outside Fresnel zone; this means that it must be at a distance greater than D^2/λ, where D is the diameter of the antenna aperture and λ is the wavelength. Thus, for an antenna 70 feet in diameter and a wavelength of 1/6 foot (a frequency of 6000 megacycles), the source used in boresighting should be more than 3000 feet away. Airplanes and helicopters come to mind, but they are expensive and cumbersome for boresighting.

Happily, radio astronomy has provided us with the locations of a number of sufficiently distant radio sources, which have been identified with optically observed celestial objects. Some of the stronger sources are α Cassiopeiae, α Cygni, α Tauri, and α Virginis. Each of these sources can provide a number of data points as it moves across the sky. In particular, it is very useful to include at least one whose declination is approximately equal to the observer's, for it will then pass very near the zenith and thus become a sensitive indicator for azimuth boresighting.

Early in 1962 the antenna at Holmdel was boresighted by means of stellar radio sources. The tracking equipment was supplied with digital-computer data which would cause it to point exactly at a star and track it if the electrical and mechanical axes of the antenna were exactly aligned. A boresighting correction was obtained by offsetting the antenna in alternate senses by amounts that would reduce the output to a particular chosen value; the true direction of the source was taken as halfway between such offsets in azimuth and elevation. The root-mean-

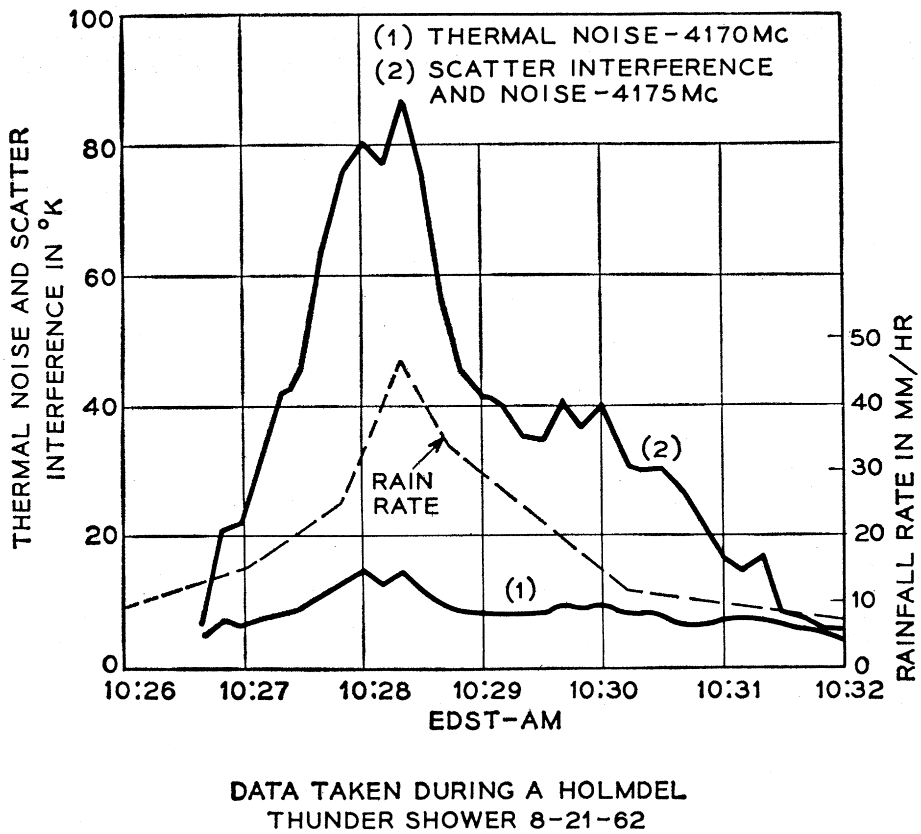


Fig. 5. Sources of noise during rain (see text).

square scatter of the data was 0.01 degree in elevation and 0.025 degree in azimuth. The beam width at 2390 megacycles is 1.4 degrees, so pointing errors could be determined to within 1/60 or less of the beam width.

The Andover antenna was boresighted by the same method.

Contributions to Radio Astronomy

It seems only fair that we communications engineers should try to repay our debt to radio astronomy. At present, A. A. Penzias is working to set a meaningful upper limit to the abundance in space of the OH radical, which has a spectral line at 1677.34 megacycles. The sensitivity of the Holmdel receiver is such that results obtained with it should be more accurate than published results by two orders of magnitude.

Navigation, geodesy, and chronometry were once near the heart of astronomy, and Telstar I has made its contribution in this field. On 25 and 27 August 1962, William Markowitz and C. A. Lidback of the U.S. Naval Observatory cooperated with J. M. Steele of the National Physical Laboratory, who suggested the experiment, in relating, to an unprecedented degree of accuracy, the master clocks of the Naval Observatory at Washington and the Royal Greenwich Observatory at Herstmonceux. This was done by transmitting pulses from the ground stations at Andover, Maine, and at Goonhilly, Cornwall. The difference between time of reception and time of transmission of the pulses was measured at each station.

In addition, the Goonhilly station measured the time of arrival of its own pulses as transmitted by the Andover station. These data furnished both the difference between the clocks, as represented by the two pulsers, and the travel time. The difference between the Andover and Goonhilly clocks was determined to 1 microsecond. This represents nearly a thousand-fold improvement in accuracy of synchronization over the result of previous radio transmissions. The clocks at Washington and Herstmonceux had been related to the Andover and Goonhilly clocks, respectively, to within about 10 microseconds; they can now be related to within 1 microsecond.

The measurements also gave a check on the accuracy of the orbital data; the ephemeris range was found to be accurate to about 1 kilometer.

Radiation Measurement

I now turn to another topic of considerable interest to science. Prior to the launching of Telstar, in July 1962, our knowledge of the spectrum of electron and proton radiation in the Van Allen belt was meager, and we had little knowledge of how this radiation changed with time. Fortunately, a long program concerned with radiation damage to semiconductors and a small but active interest in low-energy nuclear physics had led to the development, from semiconductors, of particle detectors of great simplicity and accuracy. Telstar I was equipped with such detectors. Such detectors have been flown in the Injun and TRAAC satellites and in several Air Force satellites in the past 2 years, but little information is yet available from these experiments.

The detectors are p-n junction devices which, in effect, are small solid-state ionization chambers (*5*). They give output pulses proportional to the energy deposited by an incident charged particle in a disk-shaped active volume a few millimeters in diameter and a few tenths of a millimeter thick. This kind of device has been extensively used in low-energy nuclear physics experiments in the last several years and provides high-energy resolution and relatively high speed. In the Telstar experiment the devices were not used as high-resolution devices or at their maximum speed; nevertheless, the experience gained from the nuclear-physics experiments with these devices was invaluable in designing the satellite experiment.

Three dectectors measure protons in energy regions between 2.8 and 25 Mev, between 26 and 34 Mev, and above 50 Mev. The peak flux of the highest-energy protons in the inner Van Allen belt is very close to the figure given by Van Allen in 1959 (*6*), and the flux of lower-energy protons rises steeply, as had been observed at low altitudes by Naugle and Fichtel (*7*). Quite comprehensive maps of these particles have been made over the range of Telstar's orbit. Protons are responsible for a major part of the radiation damage on the Telstar solar power plant; the damage would be much more serious were it not for the relatively thick sapphire shielding of the solar cells.

A fourth particle detector made from a semiconductor is used in studying the distribution of electrons in the trapped radiation belts. In this case

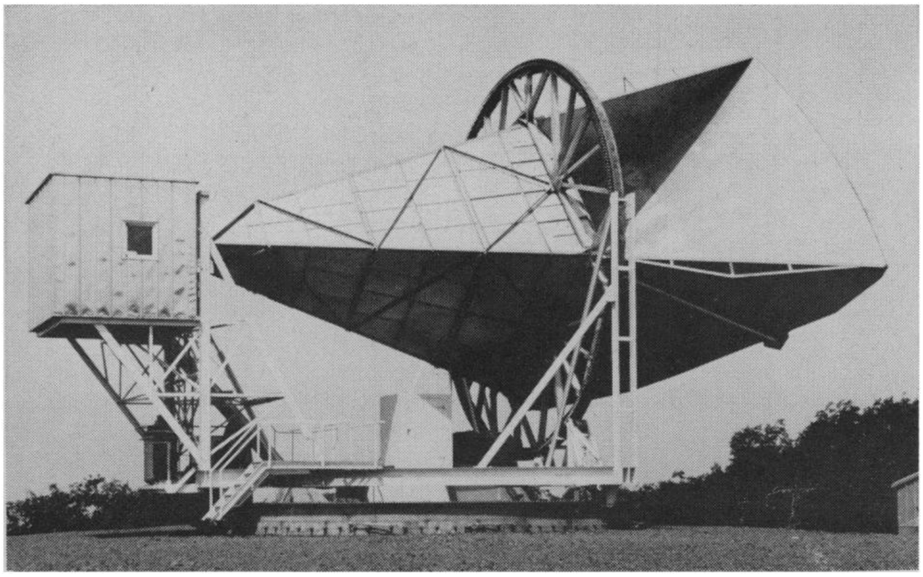


Fig. 6. Horn-reflector antenna with an aperture of 400 square feet, at Holmdel, New Jersey.

particle pulses are introduced into four pulse-height channels below 1 Mev. Because of the nature of the processes of electron energy loss, the detector is also sentitive to electrons of higher energy.

Data on magnetically trapped particles are most naturally presented in coordinates reflecting the basic properties of the earth's magnetic field. Figure 8 shows a collection of points obtained on the electron detector for a 5-day period during July, approximately 2 weeks after Telstar's launch. The data are shown in a magnetic dipole space onto which the irregular magnetic field of the earth has been mapped. The satellite's orbits are clearly visible in the strings of points in some regions. This collection of points has been sorted by computer according to the electron counting rate and has given the contours of constant omnidirectional flux shown in Fig. 9. Provided the electron energy spectrum is appropriate to fission-fragment beta decay, contour 1 corresponds to a flux of a little less than 10^9 electrons per square centimeter per second. The contours are spaced toward lower fluxes at intervals of $(10)^{\frac{1}{2}}$ in magnitude.

Initially, the electron flux measured by Telstar I was about 10 times as great as had been expected, and the electron energy was considerably greater than had been expected. This is generally attributed to the high-altitude detonation of a nuclear device in the megaton yield range in the Pacific the day before Telstar was launched.

The unexpectedly high radiation measured by Telstar, and measured at lower altitudes by the Injun satellite, caused considerable scientific excitement. On 27 October, NASA launched the Explorer XV radiation-measuring satellite. Despite the fact that the despin mechanism failed, this satellite has provided valuable data on the Van Allen belt and has added to our knowledge of the way the belt changes with time.

Satellite Communication

The radiation measured by Telstar I was unexpectedly high. So was the public excitement engendered by the first and by subsequent real-time transatlantic television programs which Telstar I made possible. A United States Information Agency poll showed that in the week after the transatlantic television ceremonies of 23 July 1962, 82 percent of the people of Great Britain were able to identify the Telstar satellite by name, 79 percent knew it was a United States achievement, and 59 percent saw the television program beamed from the United States. In a message broadcast to the people of the Commonwealth, Christmas day, 1962, Queen Elizabeth referred to Telstar as "the invisible focus of a million eyes," and used this new star to draw man's attention to the star the Wise Men of old followed, and to its message.

Telstar was an engineering experiment which took us a step forward in understanding and capability. The interest excited by Telstar made people want to know when satellites would become a regularly functioning part of the world's communcation network, what sort of satellites would be used, and how a satellite communcation system would be brought into being.

When work was started toward developing an experimental active communication satellite in the research department of the Bell Telephone Laboratories late in 1959, we had great enthusiasm for a proposed 24-hour synchronous satellite which would hang stationary above a spot on the equator at an altitude of 22,300 miles. We realized, however, that the time delay in transmission might seriously impair the usefulness of such a satellite for telephony.

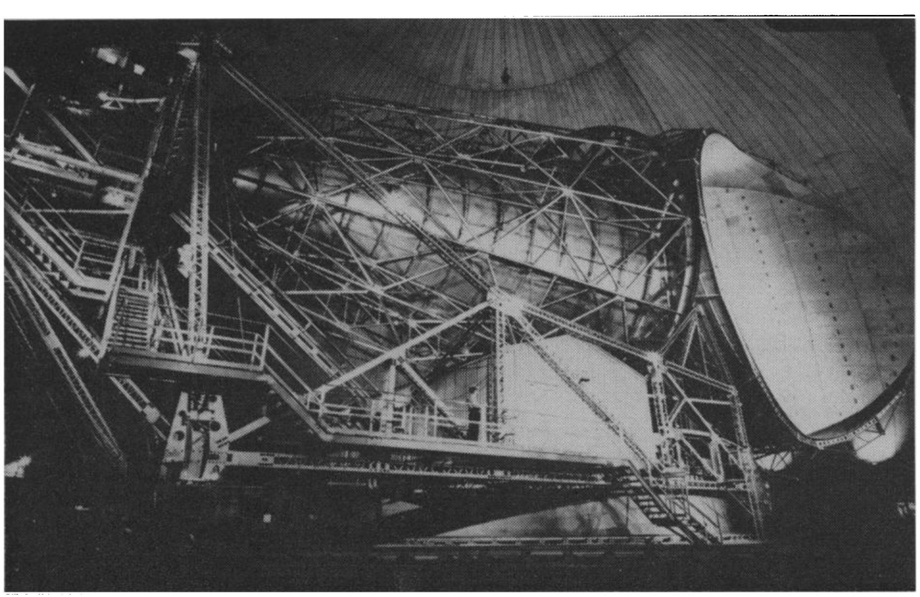
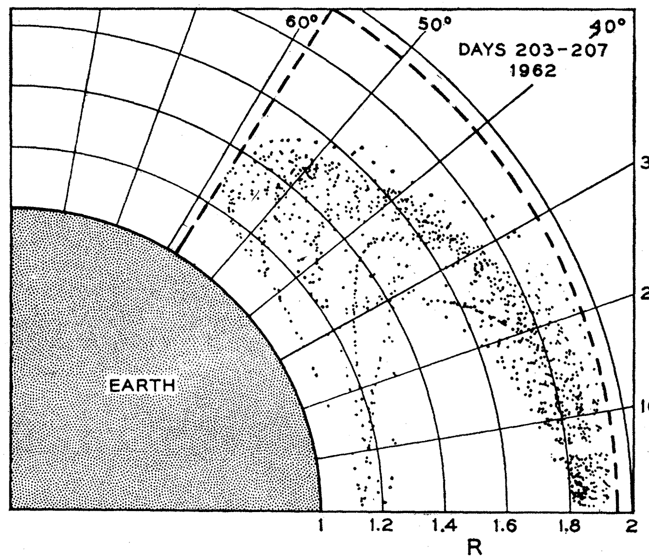


Fig. 7. The 3600-square-foot antenna constructed at Andover, Maine, for the Telstar experiment.



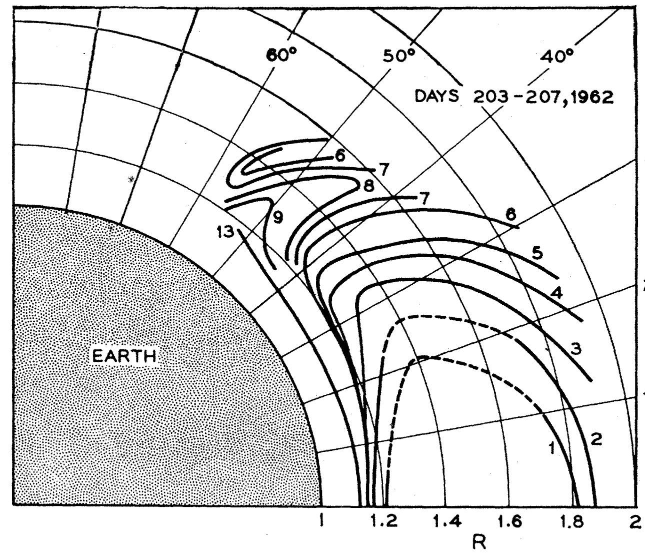


Fig. 8 (left). A collection of points at which data on magnetically trapped particles were obtained with the electron detector for a 5-day period approximately 2 weeks after Telstar's launch. Fig. 9 (right). Contours of constant omnidirectional electron flux derived from the data on counting rate at the points of Fig. 8 (see text).

While long-distance or trunk telephone circuits use separate paths in the two directions, the circuits from switching offices to subscribers send signals both ways over the same pair of wires. Devices called hybrid coils are used to attain some degree of independence of transmission in the two directions. Nonetheless, all of the world's 140 million telephones reflect a small percentage of energy directed toward them. When the person on the phone hears this reflected speech delayed by 0.1 second or more he finds it unpleasant and upsetting. Thus, echo suppressors are inserted at the ends of trunk circuits longer than 1500 miles. These devices turn off the outward path when a signal is present on the inward path. Provision is made for breaking in by talking very loudly.

Echo suppressors are tolerable for handling echo delays encountered in continental telephony and even in transoceanic telephony by way of submarine cable. Would they be tolerable for an echo delayed 0.6 second, as would be the case in talking by way of a synchronous satellite?

This is no easy matter to decide, for the answer could depend on the people involved, on the nature of the conversation, and perhaps on the design of the echo suppressor. Psychologists have been studying this problem at the Bell Laboratories for over 2 years. As in the case of most experiments, answering one question raises another. However, we hope to have some convincing numerical data within a few months. At present I can only say that, under realistic conditions, a delay of 0.6 second, even when the best echo suppressors available are used, proves unacceptable in a substantial percentage of conversations.

This result seemingly flies in the face of the fact that laboratory workers often feel, after casual trails, that a circuit with echo suppressors which has a delay of 0.6 second is quite satisfactory. It is here that we see the difference between experimental science as we know it in our time and the sort of casual experience which was man's sole and inadequate guide in earlier ages.

Legislation

In citing this example of human response to a communication system I have strayed from physics, but I have not departed from the realm of science and technology. Satellite communication itself has stirred other realms. I think I scarcely need describe the somewhat heady, or perhaps I should say dizzy, feeling I had during a period when the President of the United States and members of Congress proposed and discussed legislation engendered by the existence of a communication satellite, a satellite whose very existence depended in part on earlier work of mine. Perhaps the dizziness was caused by the stupendous gulf, physical and otherwise, which separated me from the political scene: I followed events in the newspapers, but I had no direct part in them.

On 31 August 1962 President Kennedy signed a Communications Satellite Act which, after long hearings and much debate and amendment, had passed both houses of Congress. This act sets the pattern for United States participation in any international civilian satellite communication system. The exclusive right is granted to a new corporation created by law for this single purpose.

Traditionally, the communication common carriers have had freedom to use directly, as a part of their very diverse communication facilities, any part of the science and technology which has come to them from so many sources. Thus, their facilities have come to include wire, cable, coaxial cable, submarine cable, short-wave radio, ultrahigh-frequency radio, tropospheric scatter, and microwave radio relay systems.

The Communications Satellite Act and the entirely new corporation which it has created represent a bold venture into completely uncharted waters. Its activities are confined to one particular aspect of common-carrier communication—supplying circuits by means of satellites. The stock is to be owned partly by the general public and partly by communication common carriers. The board of directors is to have members representing the noncommunication investors, who presumably want to make money; the common carriers, who urgently need more transoceanic circuits, whether these be supplied by cables or by satellites; and members appointed by the President, who has strongly asserted that satellite communication should serve the needs of the inhabitants of the least developed areas of the globe. For this new and unique corporation to act successfully in establishing the necessary research and development resources for reaching its various goals in a tricky and scarcely tried field of technology will require unprecedented pluck and ingenuity.

Conclusion

I began by proclaiming myself no historian, and I am certainly no prophet. In closing, let me return to the things I have observed over the few years of my life that have been devoted in part to communication satellites.

I think that the relations I have pointed out between the work on Echo I and Telstar I and work in the fields of upper-atmosphere physics, celestial mechanics, electronic computers, molecular spectroscopy and masers, radio astronomy, and experimental psychology aptly illustrate the fact that the science and technology involved in any complicated undertaking come from so many sources that no one can call them his own. Science and technology belong to no enterprise and to no nation; they are part of the heritage and the work of men throughout the world. Governments and other institutions may support, license, forbid, and enforce conformity, but they can neither legislate the laws of nature out of existence nor prevent men outside of their area of control from discovering and using them.

But the powers that governments exercise can have drastic effects, both on the lives and work of scientists and engineers and on the degree of benefit that society reaps from science and technology. And these powers are as often exercised foolishly and ignorantly as with informed wisdom.

C. P. Snow has spoken of two worlds in modern society—the world of polite learning and the world of science and technology. I myself find a more real distinction between two other worlds. These two worlds can exist even in the thought and action of one individual, though perhaps they more often manifest themselves separately: one in an engineer; the other in a statesman or a religious leader.

One of these worlds has two aspects: it is the world of natural law and of the understanding and application of natural law which are expressed in our science and technology. Some things are possible; some are beyond possibility. At a given time we can in part distinguish between the possible and the impossible. Of those things which are possible, some we can this very day achieve by an effort commensurate with their value. Some we can have, but at far too dear a price. Some, though possible in principle, are beyond our present grasp, however hard we may strive.

This world of our understanding of nature and the power that it gives us varies not only with time but among individuals and institutions. What one can do is beyond the grasp of another. Yet, whatever ephemeral and elusive qualities this world of science and technology may appear to have, it is exceedingly powerful, though extremely obdurate. The possibilities of great things are within our grasp, and men and institutions exist by means of which these great things can be accomplished.

The other world is, let us say, a personal world, the world of our aspirations—of our needs, desires, dislikes, and hates. It is the world of what we would like to accomplish and of how we would prefer to achieve it. The obdurate world of science and technology can sometimes help us to distinguish wishful thinking from what is possible, of fantasy from what will work. It can sometimes enable us to foretell otherwise unexpected and unpleasant consequences of capricious behavior.

Projects and people succeed in the degree that their aspirations are wise and realistic. I believe that our knowledge of the powerful but obdurate world of science and technology can add wisdom and realism to our world of personal and nattional conduct. But I believe that too, too often men and nations expect the laws of nature, the state of technology, and the abilities of people and of institutions to conform to their aspirations, instead of making their aspirations conform to the obdurate world of science and technology.

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