Satellite communications

By K. W. Pearson

The paper gives a short non-technical description of satellite communication systems. It explains the need to supplement existing methods of long-distance communication, and describes the types of satellite systems envisaged. The number of satellites required, and their heights, are discussed. A brief reference is made to the effects of the time-delay associated with satellites in high orbits. Ground station aerial design and low-noise receiver techniques are mentioned. The type of equipment used in a satellite is described. The results of the Telstar experiments are quoted, and an indication is given of the future programme of satellite communications.

The first point of interest is, why are satellites needed for communication? The answer is not—as yet—that data transmission is making enormous demands on circuit capacity, nor that trans-Atlantic TV is essential, but there is no doubt that telephony is. It has been estimated that by 1980 (in the absence of other methods of communication) at least 50 submarine cables of the type recently laid across the North Atlantic would be needed. Even if we allow for the probable improvement in cable techniques, at least 20 cables would probably be needed. Each cable has about 150 amplifiers distributed along its length, so that we would have some 3,000 amplifiers under the ocean, and the reliability and maintenance problems would be very great.

There are, of course, radio systems capable of handling very large numbers of telephone channels, and many are in use all over the world, but these systems use very high radio frequencies which travel in straight lines and are not reflected by the ionosphere, and consequently adjacent stations must be within line-of-sight of each other. They must normally be not more than some 50 miles apart, because of the curvature of the earth and the practical limit to the height of towers. However, by using a satellite as a relay station, line-of-sight transmission over enormous distances becomes possible.

There is the snag that radio equipment in an orbiting satellite is even less accessible for maintenance than the underwater amplifiers of submarine cables, and thus, at first sight, the use of a passive satellite, which is a mere reflector with no radio equipment on it, appears attractive.

There is available one very large and permanent passive satellite, namely the moon, and this has been used as a reflector of radio waves. Unfortunately its surface is rough and it moves relative to the earth, with the result that we get back not one but several reflections from various parts of the surface, and these interfere with each other to produce severe distortion. Another disadvantage is that it takes $2\frac{1}{2}$ seconds for signals to travel to the Moon and back, which makes it rather difficult to conduct a sensible conversation via the Moon. This time delay is not such a disadvantage for one-way data transmission, but it might be necessary to use error-correcting techniques which normally require a return channel, and once again the delay could be troublesome. However, in spite of its disadvantages, transmission via the Moon may well find application. For example, I believe that some military authorities are considering it as a form of last-ditch communication when all else has failed.

Passive and active satellites

On 12th August 1960, an artificial passive satellite was launched. This was Echo 1, which was a 100 ft diameter balloon, inflated after launching. It was quite successful and many experimental transmissions were carried out with it. It is still in orbit, but its shape has become distorted, thereby reducing its efficiency in much the same way as the Moon's roughness does.

The big disadvantage of the passive satellite is that only a minute fraction of the power transmitted from earth is reflected back. For example, if 10 KW were transmitted—which is a fairly large amount of radio power at the frequencies used—the received power would be about 1/100 of a micro-micro-watt. This latter figure is about one millionth of that received by the average TV set.

If the satellite were active, that is, if it contained an amplifier, the situation would be much better, but even so the received power would still be only a few micro-micro-watts, and very sophisticated techniques must be employed in order to make efficient use of a satellite for communication purposes.

Orbits

Satellites may be launched in a variety of orbits—circular or elliptical, in a plane inclined at any angle to the equator. The question of which is the optimum orbit for a given application is very interesting, but space does not permit me to discuss it here. I can, however, say that there is a growing opinion that the circular equatorial orbit offers many advantages for a worldwide satellite communication system.

Now let us consider how high a satellite should be, and how many satellites are required. Clearly the area of visibility from a satellite increases with its height, so that, for worldwide coverage, the higher the satellites are orbiting, the fewer are required. Another point is that the orbital period decreases with height and therefore the satellite is available for longer periods for communication between any two given points on the earth. An interesting case is the circular orbit at a height of 22,300 miles, when the orbital period is 24 hours, so that a satellite in an equatorial orbit at this height, travelling in the same direction as the earth, would appear to be stationary in the sky. From such a height, almost half the earth's surface is visible, and three satellites in this particular orbit (known as the *synchronous orbit*) could provide almost complete world coverage. Moreover, the design and operation of a very large aerial which must track a moving satellite is an expensive business, so that if the satellites were practically stationary the aerial costs could be considerably reduced.

Thus, as I have already pointed out, the higher the orbit, the fewer satellites are required. However, the launching costs increase rapidly with height of orbit, and, moreover, if the height is great, the time delay may become troublesome. Not that it approaches the $2\frac{1}{2}$ seconds delay of Moon relays, but it would be $\frac{1}{4}$ second for the synchronous satellite.

Time-delay effect

The time delay affects a conversation in the following way. Suppose *A* is talking to *B*; *A* stops talking and expects a reply from *B*, and *B* does in fact reply when he hears *A* stop, but owing to the time delay *A* does not hear *B* until $\frac{1}{2}$ second after he himself has stopped talking. Before this, however, *A* has impatiently started to talk again, only to stop when he hears *B*'s reply. Then *B*, hearing *A* apparently breaking in on his speech, also stops. Then they probably start talking simultaneously! This "double-talk" can last for several seconds and can be extremely annoying. Nevertheless, if the delay is known to exist, intelligent people can conduct a normal conversation with very little effort.

Continuity

Another factor governing the number of satellites required is the need for continuity of communication. As a satellite in use moves down to the horizon another must be coming up so that the circuit can be switched to it. Bearing this in mind it will be seen that the minimum number of satellites will be required when they are neatly and evenly spaced around the orbit, so that they appear at regular intervals. It is hoped that this regular spacing, or "station-keeping" as it is called, can be achieved, although it will entail having on the satellites some means of adjusting the orbits, such as little jets of compressed gas which can be operated as required by radio signals from the ground. This is a complication and costs money. Hence there is a choice ranging from many low-level satellites in random positions with fairly low launching cost for each one, to a few high-level satellites with high launching costs plus the cost of station-keeping.

Other factors influence the choice, and there are indications that station-keeping will be used because the ground station arrangements can thereby be considerably simplified. The ultimate development is probably the synchronous station-keeping satellite, of which only three are essential for world-coverage.

Although this may be the ultimate, the very powerful launching vehicles required are not fully developed yet, and the first satellite systems will probably be at lower levels—about 8,000 miles above the earth. It will then be necessary to switch from one satellite to the next about once per hour. The desire for continuity during switching leads to the need to duplicate the ground facilities, so that the next satellite can be acquired before the first goes out of sight. This is a very expensive business, and, in fact, a busy ground station may need as many as five aerials. One will be using a particular satellite for communication to, say, North America, while a second acquires the next satellite prior to switch-over. A third will be using some other satellite for communication to, say, India, while a fourth acquires the next satellite for that direction of transmission. The fifth aerial will be a standby.

This need for switching may affect data transmission more than any other form of communication. The path lengths via the two satellites, and hence the transmission times, are unlikely to be equal at the time of switching, so that there can be a gap in transmission or—more seriously—a few milliseconds of transmission may be lost altogether. However, the time of switching will be known in advance, and it would be possible to stop transmission for a short period during switching.

Receivers and aerials

I have already mentioned the extremely low received power, and the need for sophisticated techniques. The ultimate sensitivity of a receiver is set by its noise level and, fortunately for satellite systems, there have been significant advances in low-noise receiver techniques in recent times, with the introduction of the parametric amplifier and the maser. The latter gives lower noise and its use is essential for a ground station having a large bandwidth, such as television, but the parametric amplifier, which is much simpler in several respects, will probably find application in smaller stations.

With such low-noise receivers, the noise picked up by the aerial itself becomes of importance. Some of this noise originates in outer space and is called *cosmic noise*, and some originates in the earth's atmosphere and the earth itself. When the aerial is pointed straight up it is looking through less atmosphere than when it is directed horizontally, and the noise picked up is less. Cosmic noise decreases as the operating frequency is increased, whereas the atmospheric absorption increases with frequency; there is a broad optimum frequency band ranging from about 2,000 Mc/s to 10,000 Mc/s.

The amount of noise picked up is to some extent dependent on aerial design, particularly at low elevation angles where the side-lobes of the aerial illuminate the earth itself. Considerable efforts have been made to improve aerial systems and probably the most spectacular design is that of the Bell Telephone Laboratories. This is a horn-reflector and was used for the Echo experiments. It has advantages over more orthodox aerials, in that there is nothing in front of the aperture to obstruct the radiation, and it has very little radiation outside the main beam.

For use with Telstar and future systems, the Bell Laboratories made a rather larger horn-reflector which is shown in Fig. 1. The scale may be judged from the size of the man. This structure is 177 ft long and weighs 380 tons. Actually this is a feather-weight compared with the Goonhilly dish which weighs 870 tons, and is shown in Fig. 2. The relatively flimsy horn-reflector must be protected from the force of the weather by a radome, which is now a feature of the Maine countryside. This radome is 210 ft in diameter, 161 ft high, made of rubberized fabric only 1/16 in thick, but has an area of 3 acres and weighs 20 tons. It is held up by air pressure of less than 1/10 p.s.i.

Returning to the satellite, it would of course be an advantage if the aerial on the satellite were directional and could be pointed continually at the earth. However, a satellite left to itself will be spinning or tumbling, and if directional aerials are to be used it must have its attitude stabilized with respect to the earth. Such stabilization is possible, but power must be consumed to do it, and power is at a premium in a satellite.

Telstar equipment

Now let us consider the sort of equipment an active satellite will carry. It must obviously be light and compact to keep the launching costs down. It must be rugged to withstand the shock and vibration of launching. It must be extremely reliable, because there is no hope of sending someone to put it right. To meet these requirements the circuit designers have gone to solid-state devices. For example, in Telstar there is only one thermionic valve, the output travelling-wave tube—all the rest of the circuitry uses transistors and diodes. There are, in fact, about 2,500 transistors and diodes in Telstar, but less than 10% of these are associated with the actual communication channel, the remainder being used in the complex command and telemetry equipment. This is the equipment that accepts instructions from the ground and which transmits information concerning the functioning of the various parts of the satellite. The reason for this complexity is that Telstar is an experimental satellite designed to explore the environment of outer space as well as to provide communication facilities. In a practical satellite system the telecommand and telemetry would be much simpler.

Telstar receives signals from the ground at 6,390 Mc/s and radiates about 2 watts at 4,170 Mc/s. The main aerials are in a ring round the equator of the satellite. A spiral wire antenna is used for the telemetry on 136 Mc/s. The power for the satellite comes from 19 nickel-cadmium cells, rather like torch batteries, which are charged from 3,600 solar cells. Solar power is not particularly cheap—with the sort of solar cells being used it costs about £70 per watt. There are not enough solar cells on Telstar to give 24-hour working. It can in fact operate for only 2 to 4 hours per day, depending on how long it spends in the earth's shadow. Solar cells on satellites designed for continuous operation are usually mounted in large sheets on paddles at various angles, so that at least one set is in direct sunlight.

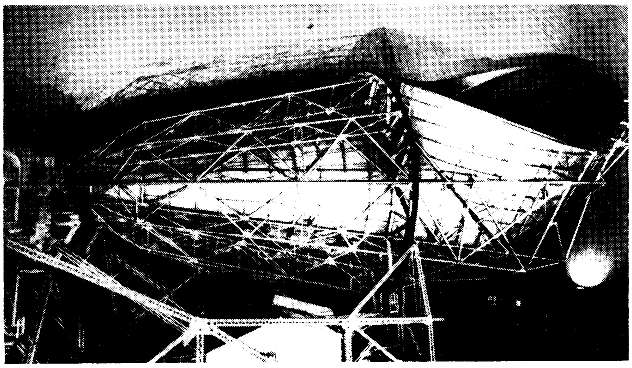

Fig. 1.—The Bell Laboratories horn reflector

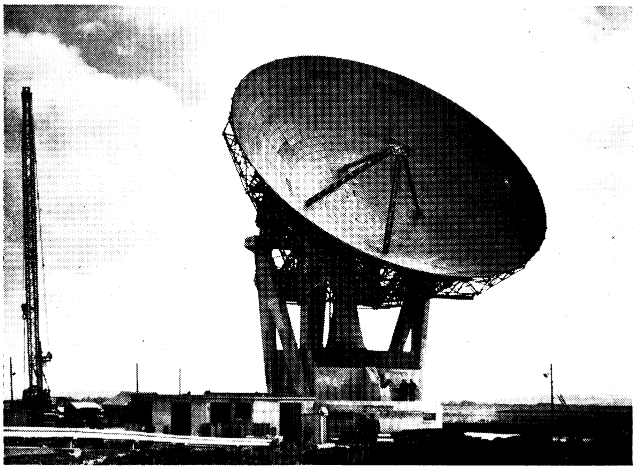

Fig. 2.—The Goonhilly dish

Telstar has of course been very successful. No doubt many of you saw the pictures which were received at Goonhilly, but you will not have seen the test-cards or test patterns which were transmitted. These indicated the high quality of the system and the freedom from unwanted effects.

The future

Finally, what of the future? It is expected that a second Telstar will be launched this year, and also Relay which is a US Government sponsored satellite. This satellite will be in a similar orbit to Telstar's and will be capable of much the same performance. There are plans to launch more Echo type balloons—slightly larger and more rigid—and a 24-hour satellite is being prepared. It will however be some years before a commercial system comes into being, although the success of Telstar has produced some rather optimistic estimates in some quarters. The problems of station-keeping and attitude stabilization have yet to be demonstrably solved.

There is also the small matter of economics. The uncertainties of satellite launching and reliability are such that it is difficult to make sound cost studies of satellite systems. They will be very expensive. Telstar alone has cost the Bell System some 50 million dollars. Nevertheless it does seem that satellites offer an economic method of long-distance communication, and I have no doubt that in ten years' time they will be in use.

I am indebted to the American Telephone & Telegraph Company for Fig. 1, and to the British Post Office for Fig. 2.

Summary of discussion

Mr. A. L. Metcalf (*National Coal Board, Doncaster*): May I ask the speaker from the Bank of Scotland whether he re-runs his tape to prove the accuracy, or whether he leaves it to the computer to discover any error?

Mr. Wilson: We leave it to the computer. On our input process we check the account number in each case for validity. This number embodies a check digit to a particular formula, the computer works out this formula and compares it with the check digit included in the number, accepting numbers which prove correctly and rejecting any which do not. As far as the amounts are concerned, we are checking them entirely on the fact of balancing the proof totals. We have a batch total at frequent intervals and the computer is accumulating individual amounts. If the individual amounts do not agree with the total then it makes a "rejection" entry for the difference. We do not do any re-running of the transmission at all.

Mr. L. R. Crawley (*Standard Telephones and Cables Ltd.*): Could you wait until this information gets into the computer before you have a check? What happens then? Do you have to start off your transmission again, getting a connection, go back to the Branch to find out what error has occurred?

Mr. Wilson: We are dealing with tape to some extent as it comes in during the day, mostly during the afternoons, and if we do find something that shows an error during the afternoon we would go back to the Branch, probably on their final transmission. Of course, in each case the connection is established by voice and we can clear up any simple snags that way, but if it is on the final transmission it may be some time after the Branch has closed down that the error is discovered by the computer. In these cases we automatically put the doubtful entry to the suspense account. The system does depend on having a high proportion of valid tapes, and this is why we do stress the off-line production of tapes and accurate checking of it before it is transmitted. If we can keep the preparation of the tape to a high standard we are satisfied that transmission errors are so relatively few that we do not mind putting them to a suspense account overnight and having them corrected next day, because the Branch does know, first thing the following morning, that they have occurred, and so there is no danger of them providing false information to a customer. It is their first duty in the morning to clear up these errors that have been notified to them.

Mr. E. N. Duke (*A. E. Reed and Co. Ltd.*): My question is addressed to Mr. Pearson: I believe computers are used for the tracking of satellites. Presumably there must be a data transmission link-up between those computers and the stations around the world, which would be of some interest to us.

Mr. K. W. Pearson: There is a network of tracking stations round the world and in the United States, at the Goddard Flight Centre, all this information is collected and analysed; I have no information on the network itself. From the Goddard Flight Centre, information from the orbit is sent, for example, to Goonhilly, by ordinary telegraph line, and at Goonhilly they have another computer, which can interpolate on this data which is given at 2- or 4-minute intervals. I am sorry I have no information on the data transmission.

Mr. K. L. Smith (*IBM (U.K.) Ltd.*): I believe I can provide some information here. The American aerial at Andover, Maine, and the identical French system at Lannion are each controlled by an IBM 1620 computer. These are interconnected by data-transmission links using IBM 7702 magnetic-tape terminals over the transatlantic telephone cable.

Mr. Wilson (*in reply to another delegate, who inquired how the paper tape was prepared*): Originally we used teleprinters with reperforators. Now we are usually using either an adding machine or an accounting machine linked to a tape perforator.

Mr. C. P. Marks (*Ministry of Aviation*): What use is made of the typescript at the transmitting end of the Branch?

Mr. Wilson: Where it is an adding machine that is in use, this is purely a listing operation, listing the account number and the amount of each entry, and this forms part of the internal book-keeping of the Branch. In addition, of course, the printed records from the adding machine are used for a visual call-back of the tape before it is transmitted. In the case of the accounting machines the position is roughly similar except that there the typescript is part of a large record which we call the Journal or "Waste Sheet," through which all the transactions of the Branch pass. Only those which concern customers' accounts are actually punched on paper tape, but the accounting machine itself is producing a full record of all the transactions of the Branch; this is one of the main records of the Branch, but again the portion relevant to the tape is used for a visual call-back to check the accuracy of the tape before it is transmitted.

Mr. S. Bootle (*Friden Ltd.*): Are you putting alpha-narrative on your statements?

Mr. Wilson: Yes, up to now we are providing alpha-narrative, where it is really essential. No bank really wants to add alpha-narrative. It is something, I think, which will eventually disappear, but it is very difficult to eliminate and we have always worked on the principle that every system we used must be able to give alpha-narrative if required.

Mr. B. V. Piggott (*Eastern Electricity Board*): I should like first to thank Mr. Pearson for the very interesting talk which he has given on Telstar, providing information of which I have felt the need for some time. Am I correct that radio waves always travel in a straight line and that hitherto long-distance communications have been achieved by reflecting the waves from some other natural medium? Would the speaker please explain, if so, why these facilities are no longer adequate and how the use of Telstar differs?

Mr. K. W. Pearson: It is true that radio waves travel in a straight line and the HF systems which I referred to, using frequencies below 30 megacycles per second, rely entirely, for long-distance coverage, on the fact that there is above us a layer of ionized atmosphere called the ionosphere or the Heaviside layer, which in fact does reflect such low frequency signals back to earth. It is not a very efficient reflector. It varies in its efficiency between day and night, and with the season, and also with the sun spot activity which goes through an eleven-year cycle. The result is that it is a rather variable means of transmission. It is worldwide in that everything shot up there comes down again somewhere, and there is a great demand for h.f. radio channels because until about five years ago there was no other means of getting very long-distance communications, especially over oceans. As a result the radio spectrum in the h.f. region is terribly congested; in fact if you had a receiver that covered that band and just tuned across it you would be very lucky if you found at any time even one empty space out of hundreds. There should be some spaces because all these transmissions are licensed and controlled, but there are a number of pirates.

Another point is that the ionosphere is an inefficient reflector in the same way as the moon is an inefficient reflector. There is a bandwidth limitation on h.f. radio systems which may restrict them to perhaps two telephone channels or half-a-dozen telegraph channels, which is nothing like enough for the demands of the future. In fact when submarine cables with built-in submerged repeaters came into use three or four years ago they constituted a tremendous advance and those across the North Atlantic carry practically all the traffic now. The h.f. radio is still there, but is only used as a back-up, and I do not think that anyone really wants to go back to it if they can avoid it.

Mr. E. C. Clear Hill (*De Havilland Aircraft Co. Ltd.*): As I understand it, the Ariel satellite has recently become of depleted value because of the recent American experiments. The problem of radiation which could perhaps be introduced by a potential enemy, and the disruption of worldwide communications which might rely heavily on this type of device in the future—does this in fact represent a very real danger? Insurance of alternatives, perhaps at different levels—are these matters being considered?

Mr. K. W. Pearson: It is quite a real danger. In addition, of course, to the American-produced ionized particles, or whatever you like to call them, which have caused trouble to Ariel, there are natural belts of radiation around the earth which are known as the Van Allen belts. Not very much is known about them. They have a name and that is about all. It is believed that the high-energy particles, protons and electrons in these belts can in fact cause deterioration not only to solar cells which are exposed, of course, to radiation, but also to the various solid-state components in satellites. Telstar and Relay, which I mentioned, are both somewhat deliberately designed to travel through the Van Allen belts, and they carry in addition to the solar cells which are to power the communications system on board, a number of other solar cells which are merely there to check this effect. This is done by shielding them with various thicknesses of material so that one can get an idea of the velocity of the attacking particle in each case, or the distribution of velocities. indicating how many particles of greater than a certain energy are striking the satellite. The solar cells which are actually used to charge the batteries which run the communications system are protected to some extent by a layer of synthetic sapphire which has the property of preventing a large number of these particles from damaging the solar cells, without at the same time significantly reducing their efficiency. It is difficult to know just what will happen in the future. I might just add that all permanent practical satellites will probably be outside the Van Allen belts. I mentioned eight thousand miles. This is well above the centre of the inner Van Allen belt and it is hoped that at that level problems of radiation will be much reduced.

One other point is that although solar energy is at the moment the favourite source of energy for satellites because it is readily available, even at a cost, there are, of course, tremendous advances going on in other means of producing power. Nuclear power, for example, is being considered—in fact one satellite is up using a little nuclear power pack—and this may provide the solution to deterioration of solar cells.

Correspondence

To the Editor,
The Computer Journal.

Dear Sir,

I would like to pass on a few comments on D. C. Handscomb's paper of the computation of latent roots of a Hessenberg matrix by Bairstow's method (*Journal*, July 1962).

I have written a program for a Mercury computer which reduces a general square matrix to Hessenberg form by elementary similarity transformations, but then proceeds by obtaining the characteristic equation. The program then tries to find a quadratic factor using Bairstow's method. In some cases this fails to converge; if in these cases the roots of the quadratic factors are inspected, and if it is found that one has converged (the other corresponding to a pair of complex roots) then Newton's method is used to obtain to the required accuracy the one that has converged. When a root or pair of roots is found it is removed from the equation. In order to try to find the roots in ascending order (Wilkinson has demonstrated the advisability of this in his paper on the "Evaluation of zeros of polynomials" in *Numerische Mathematik*, Vol. 1, pp. 150–80), the initial guess in trying to find any pair of roots has been chosen to correspond to a pair of very small roots.

This program, which has been written in double-precision arithmetic (57 bit floating point) to try to overcome the problem of instability, has been successfully used on a number of matrices, including the one of order 22 quoted by Handscomb. For this it took about four minutes to find the roots once it had been reduced to Hessenberg form (as compared with 12½ minutes for Handscomb's program). It agreed on 19 of the roots exactly with Wilkinson's results (as quoted by Handscomb), and on the other 3 the difference was only one in the last place quoted, i.e. for roots 2, 3 I obtained $0{\cdot}2859394 \pm i0{\cdot}06599475$ (5) and for root 16 I obtained $0{\cdot}0000015735$ (6).

These accuracies and times have been obtained on a number of other matrices of this size, and it would thus appear that for a two-level storage machine such as Mercury, working throughout to double precision and reducing to a characteristic equation will be, in general, both faster and more accurate than Handscomb's method, which keeps to single precision throughout.

Yours faithfully,
J. C. F. Payne.

The General Electric Company Ltd.,
Erith, Kent.
6 November 1962.