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COMMONWEALTH OF AUSTRALIA

POSTMASTER - GENERAL'S DEPARTMENT
HEADQUARTERS
ENGINEERING DIVISION

INFORMATION BULLETIN
NO. 1
RESEARCH LABORATORIES

RADIO COMMUNICATION VIA SATELLITES

RESEARCH LABORATORIES, 59 LITTLE COLLINS STREET, MELBOURNE C.1.

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FOREWORD

The spectacular successes attained in recent years by Scientists and Engineers engaged in rocket development have now made it possible to consider seriously the possibility of communication over long distances with the aid of repeaters carried by artificial earth satellites. Bandwidths of several megacycles are in prospect for systems spanning inter-continental distances so that if present hopes are fulfilled, the way will be opened for a large expansion of world-wide communication traffic in telephone, telegraph, television and data services.

So far, only very modest pilot experiments have been carried out to prove some of the theoretical predictions but the potentialities of this communication development seem so extensive that many proposals for commercial systems have been put forward. Some of the suggested schemes have been worked out in considerable detail and are based on sound scientific and engineering reasoning but other suggestions are frankly speculative and assume equipment or methods beyond the boundaries of present knowledge.

The major purpose of this information bulletin is to survey the known factors which will influence the design of satellite communication systems and to interpret the published information in terms applicable to this Department's requirements. A commercial channel must be stable and reliable and above all, compatible with the existing extensive communication network. For this reason the performance standards likely to be attained must be examined closely.

It must not be thought that the prospect of widespread application of satellite communications makes present plans for expansion of cable networks redundant. The two techniques are likely to prove complementary. On long-haul circuits such as from the United Kingdom to Australia the inherent time delay complicates the design problem for telephone applications. This disadvantage does not, of course, affect one-way traffic such as telegraphs, picturegram or television relay.

The Department is closely following overseas development in this subject and in addition to a survey of the literature, projects are being carried out in the Research Laboratories which have a direct bearing on the problems to be expected on satellite systems.

A/g. Engineer-in-Chief.

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RADIO COMMUNICATION VIA SATELLITES

1. INTRODUCTION.

1.1 This information bulletin surveys the more important factors relevant to the planning of communication facilities which include earth satellites in the transmission path. It also sets out views on the present and future prospects for such systems.

1.2 The main text is a summary of available information and this is supplemented by a bibliography followed by more extensive coverage of particular aspects in Appendices to which reference is made at appropriate points.

2. HISTORICAL.

2.1 The idea of using artificial satellites as relaying devices for communication purposes was suggested in 1945 (ref. 1) and this was followed in 1955 by calculations (ref. 2) which showed that such a scheme would be quite practicable from a radio engineering point of view. However, it is only in the last two or three years that rocket technology has demonstrated the ability to place the required hardware in suitable orbits.

2.2 Experimental repeaters now in orbit have confirmed that practical satellite communications are possible. The ECHO project uses a 100 foot diameter balloon as a reflector in a near-circular 1000 mile altitude orbit to provide a part time 3 KC/s channel used for testing between Holmdel (New Jersey) and Goldstone (California). Project SCORE and its successor COURIER were delayed transmission repeaters, picking up a signal when within range of the sending station, recording on magnetic tape and relaying the signal on command from the receive station. The COURIER satellite weighs 475 lbs* and was capable of a maximum message rate of about 68,000 words per minute. Messages were transmitted from Fort Monmouth (New Jersey) to Salinas (Puerto Rico) using the satellite which was in orbit at an altitude of about 800 miles. The life expectancy was one year, but unfortunately the transmitter went off the air after two weeks. So far as is known, it has not been possible to ascertain the cause of this failure, but it does illustrate the need for more knowledge of the factors controlling the reliability of radio equipment in space.

3. REPEATER TYPES (Appendix No. 1)

3.1 Satellite repeaters have been classified into two main types - passive and active. Passive repeaters are merely reflectors and therefore may be used by many services simultaneously without mutual interference. However, the high radio path loss restricts the passive repeater to low altitude, small capacity systems so there is a trend favouring the active type of repeater.

Characteristics of the two types are as follows.

3.2 Passive Repeaters. The passive repeater is an inert object which works by virtue of the energy reflected from its surface. Various configurations have been suggested such as large flat plates; corner reflectors (as used for radar purposes) and a cloud of resonant dipoles (needles).

This last suggestion has the advantage that a very efficient reflecting surface would be provided. However major disadvantages are:

(i) Multipath effects due to reflections from several parts of the cloud will restrict system capacity. In a large capacity telephone system the effect will show as intermodulation noise.

(ii) The large cloud of needles may obstruct the free use of other services, such as radio astronomy.

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*Weight before launch as, when in orbit, a body is in "free fall" and hence weightless.

The most favoured form of passive repeater is the large sphere.

This may be readily folded into a small cannister for carriage in the rocket and on arrival in orbit is easily inflated.

Furthermore, no orientation is required as, with a sphere, reflection is equally effective for signals from all directions.

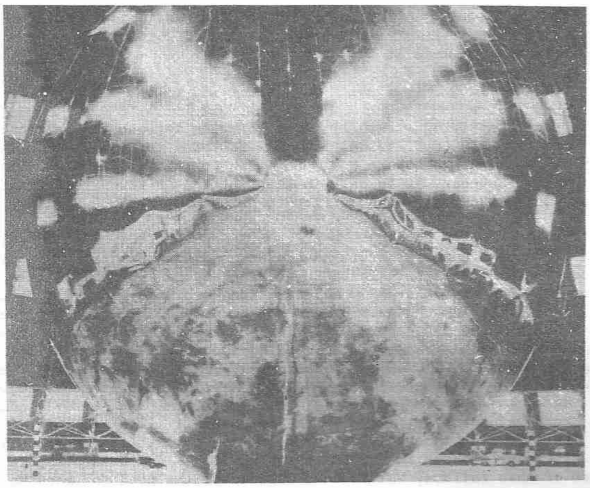

FIG. 1. PROJECT ECHO BALLOON SATELLITE.

Passive repeaters possess the great advantage that all the electronic equipment required for a system is located on the ground. Thus for as long as the structure and surface finish of the satellite can be maintained intact, its performance will remain unchanged. Considering inflated balloon satellites in orbit above atmospheric limits, it is thought that collision with micro-meteorites will be the only likely destructive agency. Puncturing of the balloon is a possibility against which partial precautions were taken in ECHO by supplying enough crystals to continue the inflating process by sublimation for a period of up to one month. (The balloon was inflated slowly by crystal vapour pressure to prevent bursting from suddenly applied pressure.) Also, erosion of the surface finish by micro-meteorites will affect the reflecting properties of the sphere. So far, little data is available on the rate of deterioration expected from this cause.

3.3 Active Repeaters. Delayed re-transmission repeaters of the COURIER type are unlikely to become a part of a public communication network, so only direct transmission types will be considered. The major components of an active repeater are receivers and transmitters together with the necessary power supplies and aerials. In addition and depending on the types of aerials used, it may be necessary to control the attitude of the satellite. The simpler method is to employ omnidirectional aerials, but should higher-gain aerials be necessary, directional control to keep the terminals within the aerial beams would be required. The forces required to effect this control may take the form of small gas jets supplemented by a flywheel for fine setting.

The receivers and transmitters may be of convential electrical design with the major part of the gain being provided by a transistor intermediate frequency amplifier at 70 MC/s. Travelling wave tubes are favoured for radio frequency amplification with a life expectancy of at least 5 years (50,000 hours).

Power supplies to date have all been based on solar cells backed up by storage batteries. Such a power supply can be built for a minimum weight of roughly 1 lb per watt of capacity. Alternative types of power supplies which have been suggested include solar powered turbine installations, thermo-electric generators and nuclear sources using radio-active isotopes, but compared with solar batteries, such power supplies are in a very early stage of development. Fig. 2 shows a proposed active satellite.

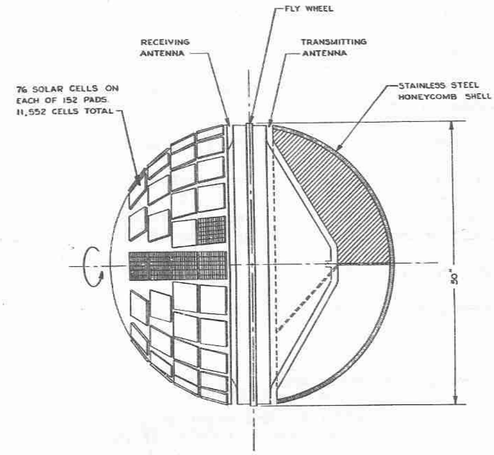

FIG. 2. PROPOSED ACTIVE SATELLITE.

There are still many difficulties left to solve before the engineering design of active repeaters can be undertaken confidently. Some of the relevant factors are:

(i) Erosion by micro-meteorites will reduce the efficiency of solar cells at an unknown rate.

(ii) Protection is required by solar cells and transistors against high energy radiations and temperatures greater than about 60°C. Cases are known of the efficiencies of solar cells being reduced, from the normal 12% to 15% down to 5% in a time of a few weeks.

(iii) In the high vacuum conditions present in space, convection cooling of heat dissipating components such as valves etc. is not possible. Thus all surplus heat must be conducted to a cooling surface and from there radiated into space.

(iv) In addition to long life, the components and assembly of the active repeater must possess the ability to survive the high accelerations experienced in the launching phase.

4. ORBIT CONDITIONS (Appendix No. 2)

4.1 Subject to the well known laws of mechanics, either type of satellite repeater may be placed in any orbit desired. The orbit plane may be inclined at any angle to the equatorial plane, the special case where this angle is zero being termed an "equatorial orbit" and in the case of the angle being a right angle the description "polar orbit" is applied. The only fundamental restriction is that the centre of the earth should be in the plane of the orbit so that for example, (except for an equatorial orbit) any orbit plane including the plane defined by a parallel of latitude is inadmissible.

For convenience, possible orbits have been considered in terms of three classes. Two of the classes concern circular orbits one class being of relatively low altitude (in the range 1,000 to 6,000 miles) the other being the synchronised or stationary orbit at an altitude of 22,300 miles. The remaining class covers particular types of elliptical orbit which could be advantageous under certain conditions.

It is likely that the early communications systems will employ the low altitude circular orbit as there are problems in attitude control and station keeping which have not yet been overcome sufficiently to ensure the successful use of either of the other two classes of orbits.

The factors relevant to each class of orbit are as follows.

4.2 Low Circular Orbits. This is the only practicable orbit for a system using passive repeaters, as, even at the low altitude of 1,000 miles, the path loss between two ground stations will be about 250 db when the repeater is a 100 ft. diameter balloon. Also, choice of low orbit allows the launching of a satellite weighing up to $\frac{3}{4}$ of a ton with available rockets. Within this weight limit, a two way repeater with necessary power supplies can be built.

Other advantages given by low orbits are that transmission delay problems are reduced and because of the limited service areas, interference and jamming possibilities are restricted.

The disadvantages of low orbits are:

(i) A large number of satellites are required to give reliable coverage. As an example it has been worked out (ref. 3) that for a 2,500 mile path with satellites randomly placed in a 3,000 mile altitude optimum orbit (i.e. normal to the great circle between terminals) 12 satellites would give coverage for 90% and 24 would give 99% time coverage. For a world-wide system the number of satellites required could be as high as 50.

(ii) Elaborate steering equipment is required for the ground station aerial installations. In a typical case, the aerials may have to follow the satellite from horizon to horizon in a time of 20 minutes or so. Even with an active satellite in use, the path loss will be around 180 db or 40 db higher than a typical average microwave repeater section of 35 miles so that aerials of 30 to 60 feet diameter will be normal.

(iii) Distortion of the signal may be caused by doppler frequency shift and/or multi-path effects due to more than one repeater being in the aerial beams simultaneously. The former effect is due to movement of repeater and will show up as a carrier frequency shift of the order of some tens of kilocycles/sec.

One factor which must be considered in relation to this class of orbit (also in the case of elliptical orbits covered in 4.4 below) is the location of the Van Allen belts of radiation which are caused by charged particles trapped in the earth's magnetic field. The radiation builds up to two maxima of intensity located in the range of altitudes 1,500 to 4,500 miles and 8,000 to 12,000 miles (ref. 4) though the exact locations of the field intensity contours are not precisely known nor is the variation to be expected with time. The importance of these radiation zones may be appreciated from the fact that the rates registered on Gieger counters at maxima are over 5,000 times the dose that a human being can safely absorb.

4.3 Stationary Orbit. If a satellite is launched in the correct direction (West to East) into an equatorial orbit at an altitude of 22,300 miles its orbital angular velocity will be equal to the angular velocity of rotation of a point on the earth's surface. Viewed from the earth it will therefore appear stationary and would be within sight of nearly half of the earth's surface. Thus only three satellites would be required to provide communication over substantially all populated areas and the other disadvantages of low orbit satellites (4.2 (i) to (iii) on page 8) would also not apply. (Fig. 3.) However, the long time delay, which amounts to about $\frac{1}{4}$ second between terminals or $\frac{1}{2}$ second for delay return echo per hop, could be serious. (This limitation is discussed further in 8.2.)

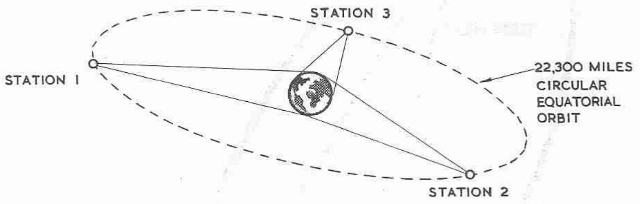

FIG. 3. WORLD-WIDE COVERAGE WITH THREE SATELLITES IN 24-HOUR ORBIT.

Balancing advantages and disadvantages, the stationary orbit seems to be a most attractive one. However at present it cannot be considered a practicable engineering proposition for the following reasons.

(i) Rockets available today are not capable of placing in this orbit a payload of more than about 200 lbs. weight. This is not considered adequate to provide the facilities required in an active repeater which, because of the long path, will be necessary.

(ii) Using three satellites spaced 120° degrees apart in longitude implies that each satellite must be placed at a position in orbit with a tolerance of not more than a degree or so in phase (or longitude) and maintained in station despite perturbations due principally to the earth's equatorial bulge (or polar flattening). Perturbations will also be caused by smaller effects due to solar and lunar gravitional attractions. The list of disturbing forces may be increased considerably but enough has been included to illustrate that from time to time correcting propulsion means on the satellite must be operated to ensure correct station-keeping. A reliable means of ensuring such station-keeping over extended periods has yet to be demonstrated.

(iii) To prevent radiation of the satellite transmitter power into space and to overcome the extra path loss due to the long distance, it is desirable to install an aerial in the satellite whose beam just includes the observed area of the earth. At the frequencies of interest this implies an aerial gain of about 18 db and requires that the attitude of the satellite be controlled. So far as is known, the longest period over which such attitude control has been maintained is about three weeks so this problem cannot yet be considered solved.

4.4 Elliptical Orbits. The general orbit of an earth satellite considered as a "two-body problem" (i.e. ignoring the sun, moon, etc.) will be an ellipse with the centre of the earth located at one focus. (Fig. 4.)

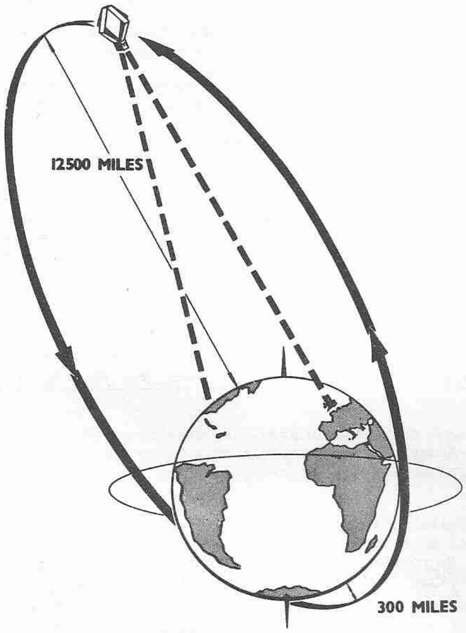

FIG. 4. A PROPOSED ELLIPTICAL ORBIT.

When the radius (distance) from the earth's centre to the satellite is a minimum the satellite is located at the perigee of its orbit and when the radius is a maximum the satellite is located at apogee. The circular orbits (4.2 and 4.3 on previous pages) are special cases of elliptical orbits where perigee and apogee distances are equal and the eccentricity (Appendix 2) is zero. Now it is a property of elliptical orbits that the radius sweeps out equal areas of the orbit in equal time intervals and it follows therefore that the satellite travels faster through perigee than through apogee. The low apogee velocity may be exploited to give a more effective time usage of the satellite.

Consideration of these facts has led to a suggestion (ref. 5) that an elliptical orbit with a perigee height of 300 miles and an apogee height of about 13,000 miles could be used to make most efficient use of a rocket's payload. With available rockets a payload of 700 lbs. weight should be possible, which is sufficient for an active repeater. Also with this particular orbit advantage can be taken of the known perturbations to allow significant reductions in the number of satellites required. However, as in the case of the stationary orbit, this elliptical orbit proposal cannot be considered practical engineering till the problems of station-keeping and attitude control are solved.

5. SYSTEM GROUND STATION REQUIREMENTS.

5.1 The equipment required at a ground station will depend on the type of repeater and orbit chosen and on the reliability required of the system. For a system which is part of a public network, continuous service with a reliability of at least 99% is desirable and the equipment required is discussed below in the light of this assumption.

5.2 Transmitters. When an active repeater is used the ground transmitter power required will typically be of the order of 1 KW for a wideband system. This power is higher than is required in the satellite transmitter (typically of the order of 1 watt) because it is possible to use ground receivers which are much more sensitive than is practicable in a satellite receiver. A passive repeater on the other hand would necessitate a ground transmitter of many kilowatts rating and some of the systems suggested call for Megawatt ratings to ensure success.

In general at least two transmitters will be required at each station to ensure continuity of service.

5.3 Receivers. Because of the long transmission paths and the limited satellite transmitter power available, ground receivers for satellite communications must be as sensitive as possible. For this reason such receivers will almost certainly include masers or parametric amplifiers to provide low noise amplification. As can be seen from Appendix 6 the performance of these devices is so good that receiver noise factor is no longer necessarily the factor limiting sensitivity and noise pickup in the aerial system becomes of increasing importance.

5.4 Aerials. To overcome the 40 db or more excess path loss over a typical earth-bound microwave repeater section, and bearing in mind the low gain aerials possible in satellites, it is necessary to use ground aerials of 30 to 60 ft. diameter. Passive satellites would make even larger aerials necessary. Except in the case of an accurately maintained 24 hour satellite orbit, all aerials must be steerable from the zenith to within 5° of the horizon in all directions. Fig. 5 shows the project echo transmitter and receiver at Holmdel, New Jersey.

FIG. 5. PROJECT ECHO TRANSMITTER AND RECEIVER AT HOLMDEL, NEW JERSEY.

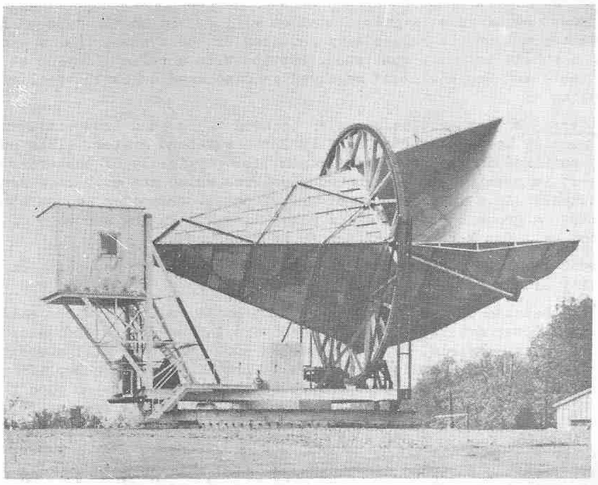

FIG. 6. PROJECT ECHO HORN REFLECTOR AERIAL.

Parabolic dish aerials are suitable for transmitting purposes but for use in conjunction with low noise receivers, the back and side lobe responses of this type of aerial are too great. As a result large horn-parabolas have been developed of 50 ft. square aperture with a secondary lobe response of the order of 60 db down on the main lobe. This ensures that noise pickup from unwanted directions such as the earth or lower atmosphere as well as other interfering signals are reduced to the greatest practicable extent.

For low orbit multi-satellite systems it will generally be necessary to install two complete sets of aerial equipment at each ground terminal under the control of radar beacon or other suitable tracking equipment, backed up by computer facilities. Thus at any given time one aerial system to which the operating radio equipment is switched will be following a satellite within range and as this drops towards the horizon, the tracking equipment will search for the next satellite due to appear. The second aerial system will then be beamed towards the new satellite and the radio equipment switched over to ensure continuity of service. Some form of overall system control will also be required to ensure that two pairs of ground stations cannot simultaneously attempt to use the same active repeater but so far little indication has been given as to how this control is to be organised.

6. COSTS (Appendix No. 3)

6.1 Estimates of cost of satellite communication systems are much less precise than the engineering design estimates but it is certain that some of the very low charge rates which have been quoted are too optimistic. They are based only on the cost of providing and maintaining the satellites and ground terminal stations.

Estimates on the cost of this bearer provision range over the following limits:

Capital Costs	-	£50 million to £150 million
Annual Charges (for satellite replacement)	-	£2½ million to £19 million

The differences between these figures show the order of uncertainty in the final cost. Until a pilot system has been built and tested and the average life of satellite repeaters is known with greater certainty any estimate of cost is extremely unreliable.

7. UTILITY.

7.1 The important property offered by satellite communications is the ability to provide broadband bearers over ranges up to 10,000 miles in one hop. Bandwidths of 5 Mc/s are envisaged at present but there is no theoretical limitation to prevent even broader bands being possible.

The alternative method of H.F. radio will provide equivalent range but bandwidth is limited severely by the reflecting medium (the ionosphere). Reflection or re-transmission from a satellite can be made independent of frequency but reflection from the ionosphere which takes place at heights up to 1,000 miles or so is dependent on frequency (which gives effects observed as selective fading) and is critically dependent on variable solar phenomena. In practice therefore, an H.F. radio system is restricted to a maximum of four voice channel loading and the number of R.F. channels is severely restricted due to congestion in the H.F. band. The reliability varies but better than 90% is difficult to achieve.

Ionospheric scatter radio can provide reliable (99.9%) channels up to a maximum range of 1,500 miles but because of practical limits on aerial size, multi-path effects from the reflection volume in the ionosphere restrict the possible bandwidth to a few voice channels. Frequency allocation difficulties also make only a limited number of systems possible.

Tropospheric scatter radio can provide wide bandwidths (up to 5 - 10 Mc/s) with high reliability over ranges up to 500 miles. Very high transmitter powers and very large aerials are required for this performance and in many cases lowered transmission standards are accepted for economic reasons or simply to provide service. Also a multi-link broadband scatter system would probably give a very poor circuit though it could be used effectively for a substantial number of telephone channels (ref. 6).

Satellite communication systems may provide telephone, telegraph, data transmission, sound programme and television relay facilities.

The number of telephone channels which can be provided depends on various factors including the diameter of the satellite in the case where it is used as a passive reflector. Estimates using different design parameters show that the development of suitable vehicles, repeaters and ground equipment would allow up to 100 channels to be provided over 2,500 mile links with low orbit passive reflectors and 500 to 1,000 channels over distances up to 10,000 miles with active satellites.

Television relay should be practicable with active repeater systems but would be difficult with passive reflector schemes.

Television broadcasting appears to be impracticable for a passive reflector system because of the highly complex and expensive receiving aerial required to track the satellite and the special receiver necessitated by the low signal strength.

With active satellite systems, use for television broadcast is limited by the power of the transmitter required in the satellite to produce sufficient signal over the service area to permit relatively simple aerials and receivers. Power levels of 10 to 100 KW are required which at present are quite impracticable. (See Appendix 5.)

8. OPERATIONAL DIFFICULTIES. (Appendix No. 4.)

8.1 There are two major operational problems to be solved before satellite communications can be integrated into public networks. The problem of transmission time delay is an engineering one which requires research effort to overcome while the problems of frequency allocation will require administrative solutions. The relevant factors in each case are.

8.2 Time Delay. The time delay difficulty is most serious in the case of 24 hour orbit systems where the transit time per hop is about $\frac{1}{4}$ second. The round trip echo delay is thus $\frac{1}{2}$ a second and as up to two hops may be necessary, a round trip echo delay of up to about one second is to be expected.

Relatively long time delays are inherent in satellite communications because of the long path lengths involved (up to about 48,000 miles earth - satellite - earth per hop) so that echo suppressors will be essential on telephone circuits. The hangover time would be in the region of 0.35 to 0.40 seconds which would cause difficulty to users because of the clipping of initial syllables of speech. Another difficulty would be the relatively long time for which subscribers would wait for replies to remarks made.

The Bell Telephone Laboratories are conducting controlled experiments to show subscriber reaction to echo delays of 0.2; 0.6 and 1.2 seconds (ref. 7). Published results are not yet available but it has been indicated that at delays of 0.6 and 1.2 seconds conversation is sometimes completely stopped due to both parties attempting to speak together. The problem is thus shown to be a serious one, though it was also stated that experiments now in progress using slow acting echo suppressors show promise that a working solution may be found.

This difficulty does not arise in uni-directional systems, used for sound and video relays or telegraph and data transmissions. It would be a serious limitation however, if error correction equipment is required. Such equipment appears to be alsmost a necessity on high speed data channels.

8.3 Frequency Allocations. Frequencies in the range 100 to 10,000 Mc/s are suitable for satellite communications but for various reasons the preferred range is 2,000 to 6,000 Mc/s. There are many services located in this band but it has been possible to repeat allocations with geographical separations of a few hundred miles so that congestion has not yet become very acute. The advent of satellite transmitters with interference potential over nearly half the earth's surface will alter this situation and serious problems are likely to arise. The position will be aggravated by proposals to use modulation systems which obtain noise reduction at the expense of wider effective bandwidth occupancy such as negative frequency feedback or pulse code modulation methods.

It is expected that frequency allocations will be discussed in Conference by I.T.U. (International Telecommunications Union) in 1963.

9. TIMING.

9.1 Available information indicates that American Sources think that it will be possible to launch one active satellite for trans-Atlantic television relay tests this year (1961). A pilot communication system could therefore be established in three to five years with satellites at an altitude of 6,000 miles. United Kingdom authorities estimate that five to ten years would be required after that date to establish a working system.

To exploit the 24 hour orbit, it will be necessary to complete the development of more powerful rockets. One such, with a projected thrust of 1,500,000 lbs. is estimated to allow a payload of 8,000 lb. in stationary orbit. This is described as a "long range programme" and estimated completion dates are not given (ref. 6).

As both active and passive type satellites have already been established in low altitude orbits, it would seem possible that a pilot scheme could be established in the near future.

10. CONCLUSION.

10.1 Perusal of current literature indicates a wide diversity in what can be achieved by satellite communications, at what time it can be achieved, at what cost and technical standards. The diversity of views is influenced to an appreciable extent by sectional interests of particular groups concerned with different parts of the problem and this is reflected in views within Australia. Emphasis on satellite vehicles and programmes can tend to distort the communication aspects. Furthermore, there is a tendency to confuse requirements for defence and for commercial purposes and ignore the technical and commercial operating standards that have been built up with conventional systems over many years. It is not always appreciated that there can be wide differences in standards between a defence point to point requirement where communication at any cost is essential and commercial circuits, which have to fit into a complex network and satisfy a wide range of public demand.

Despite the high capital costs and annual charges of satellite systems, the method could be economic for international communications and could supply broadband facilities not otherwise possible. However, no change is justified in the present programme of laying repeatered submarine cables between many points on the earth's surface to meet current demand (ref. 8).

Low orbit systems with link distances of the order of 2,500 miles could have application to trans-Australia communication problems, but direct television broadcasts via satellites do not appear to be practicable.

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APPENDIX 1.

PATH ATTENUATION FOR PASSIVE AND ACTIVE REPEATERS.

The radio path attenuation is considered below in terms of the loss between isotropic aerials. Thus aerial gains, feeder losses, etc., must be included with the path loss figure to obtain the attenuation from transmitter output to receiver input terminals.

For satellite communication systems the aerial gain factor will be large and is most conveniently calculated in terms of the effective aperture area. The relation is -

$$\text{Gain over an isotropic aerial in (dB)} = 10 \log \left(\frac{4\pi A}{\lambda^2}\right)$$

Where A = Effective area of aerial aperture (usually between one half and two thirds of the actual area).

λ = Wavelength.

Consistent units (sq. metres and metres or sq. ft. and feet, etc.) must be used in the above. Figure 7 shows the aerial gain in terms of the above relation.

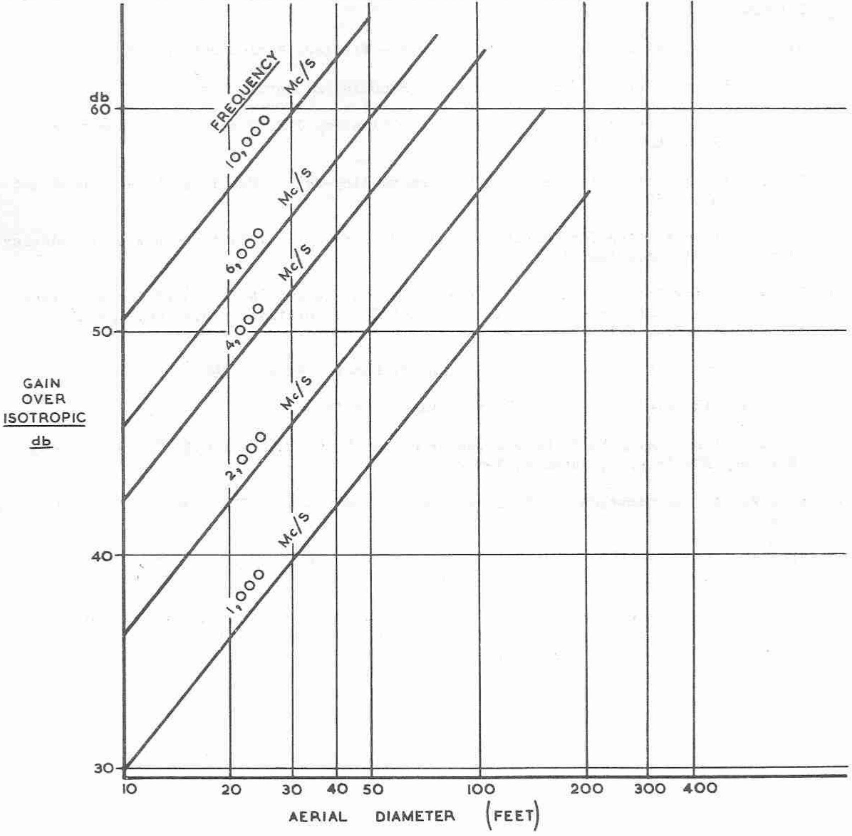


FIG. 7. AERIAL GAIN OVER AN ISOTROPIC RADIATOR.

The path conditions are different depending on whether passive or active satellites are used. The two cases are therefore treated separately below.

Passive Repeaters. In this case the path loss is considered between isotropic aerials at the transmit and receive ground terminals and the attenuation calculation must therefore include the effect of the reflector performance. The reflecting properties of many possible types of passive repeater have already been evaluated for radar purposes so the standard radar equation may be used to work out the path loss. In the case of a spherical reflector, which is the type most likely to be used, it is convenient to use the equation -

$$\text{Path Attenuation between isotropic aerials (in dB)} = 20 \log \left(\frac{16\pi}{\lambda} \frac{d_m^2}{D}\right)$$

Where d_m = Geometric mean of the distances between the satellite and the two terminals.

D = Diameter of the satellite.

All quantities must again be in consistent units. Figure 8 shows this relation over a typical range of conditions.

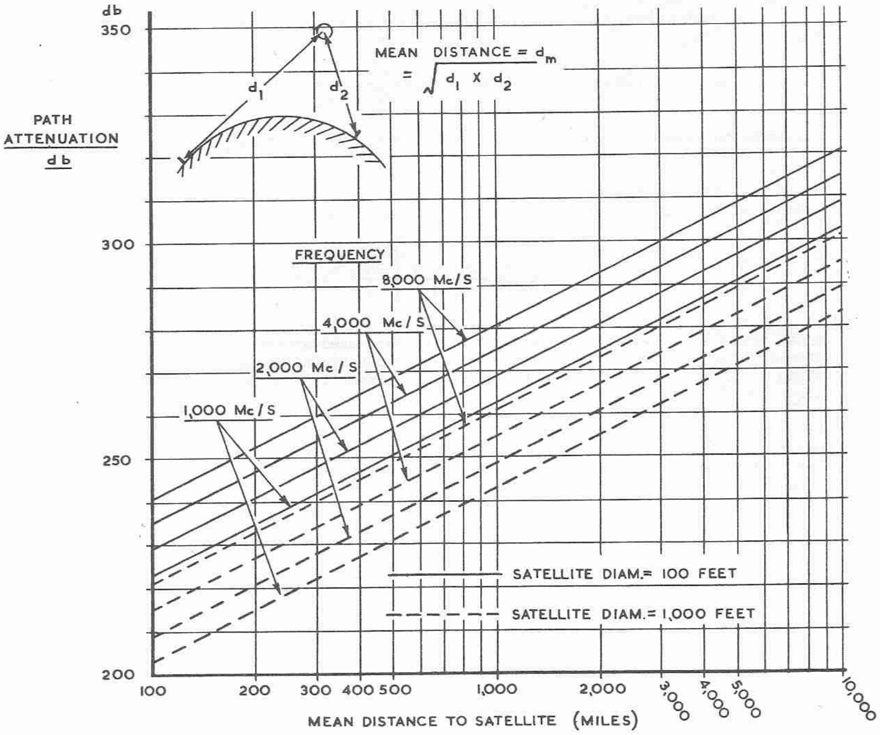


FIG. 8. ATTENUATION BETWEEN ISOTROPIC TERMINAL AERIALS USING PASSIVE SATELLITE REPEATER.

As an example consider a satellite of 100 ft. diameter located at a distance of 1,000 miles from one terminal and 2,250 miles from the other. The geometric mean distance = $\sqrt{1{,}000 \times 2{,}250} = 1{,}500$ miles and assuming the frequency is about 1,000 Mc/s wavelength of 1 foot. The path loss is then -

$$20 \log \frac{16\pi}{1} \times \frac{(1{,}500 \times 5{,}280)^2}{100} = \underline{270 \text{ db}}$$

If ground aerials of 60 ft. effective diameter were used in conjunction with this satellite each would provide a gain of about 45 dB so the attenuation from transmitter to receiver, ignoring feeder and filter losses etc. would be around 180 dB.

Active Repeaters. In this case, each section of the path is considered separately and the attenuation worked out from the transmit terminal to the satellite and then from satellite to ground receive terminal. The methods familiar in connection with conventional microwave systems are used, the relation for propagation in free space being -

$$\text{Path attenuation between isotropic aerials (in dB)} = 20 \log \left(\frac{4\pi d}{\lambda}\right)$$

Where d = Length of path under consideration.

Distance and wavelength must be in the same units. This relation is plotted in Figure 9.

For an example, let us assume an active satellite at 22,000 miles distance and as in the example of the passive satellite above, a wavelength of one foot. The path loss is then -

$$20 \log \frac{4\pi\ (22{,}000 \times 5{,}280)}{1} = \underline{183 \text{ db}}$$

If the same 60 ft. (effective) diameter aerial were used at the ground terminal and the satellite aerial were equal in gain to an isotropic aerial an aerial gain improvement of 45 db would be expected. The attenuation from transmitter to receiver would therefore be about 138 db.

Comparison of this result with that obtained from the passive repeater example illustrates the justification for intensive research and development to make a reliable active repeater.

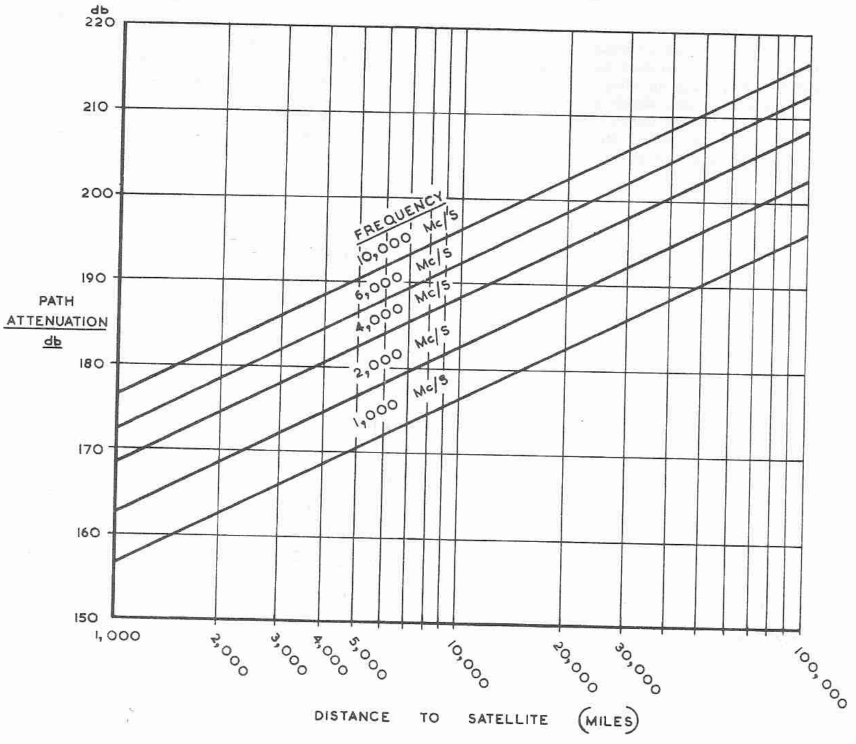


FIG. 9. ATTENUATION BETWEEN ISOTROPIC AERIALS AT GROUND STATION AND ACTIVE SATELLITE.

APPENDIX 2.

ORBIT CONDITIONS.

At the altitudes of interest for communication purposes, the only force acting on a satellite is due to the earth's gravitational attraction. The satellite is therefore constantly falling towards the centre of gravity of the earth and since the mass of the satellite is completely negligible compared with the earth's mass, the earth may be considered to be stationary.

Referring to Figure 10 assume that the satellite is propelled horizontally from A with a velocity v. (The function of the rocket and guidance system is to provide this initial impetus in the correct direction.) If the velocity is of the correct value, after any given time, such as when the satellite has reached position B, the satellite will have fallen a distance which exactly compensates for the curvature of the earth and will be in a stable circular orbit. We may therefore equate the acceleration of the satellite towards the centre of the earth (centripetal acceleration) with the constant acceleration due to gravity and this allows the orbit time to be easily calculated.

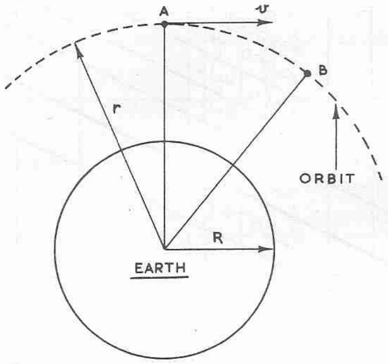


FIG. 10. CONDITIONS FOR CIRCULAR ORBIT.

If r is the distance from the earth's centre to the satellite, the centripetal acceleration $= \frac{v^2}{r}$.

The acceleration due to gravity is inversely proportional to the square of the distance from the earth's centre, so taking the conventional surface value of 32.2 ft./sec./sec.

the acceleration due to gravity at the satellite $= 32.2 \frac{R^2}{r^2}$ (where R is the radius of the earth).

$$\text{Thus } \frac{v^2}{r} = 32.2 \frac{R^2}{r^2} \text{ ft./sec./sec. (R and r in feet)}$$

$$\text{So } v = 5.7 \frac{R}{\sqrt{r}} \text{ ft./sec.}$$

It is convenient in calculations to express the distance to the satellite in terms of ratio to the earth's radius so, converting the units to miles and seconds and using a value for R of 3,960 miles the velocity may be written as -

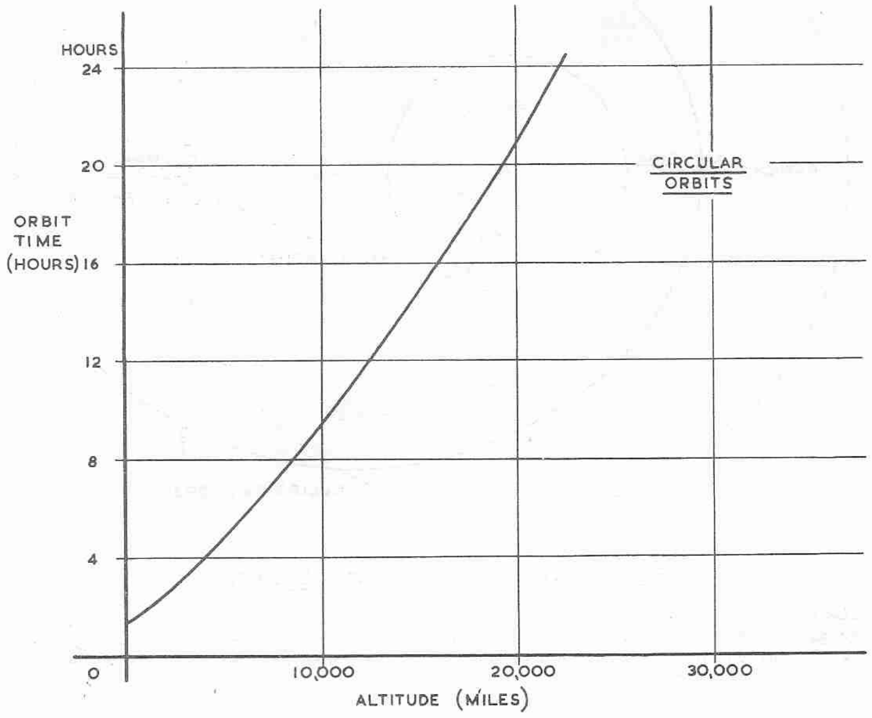
$$v = 4.91\sqrt{\frac{R}{r}} \text{ miles per second} \qquad \ldots(1)$$

The distance around a circular orbit is given by $2\pi r$ so the orbit time, T, may be calculated by dividing this distance by the velocity. The result is:

$$T = 1.34 \frac{r^{3/2}}{R} \text{ minutes}$$

$$\text{or } T = 84.4 \left(\frac{r}{R}\right)^{3/2} \text{ minutes} \qquad \ldots.(2)$$

Figure 11 shows orbit time as a function of altitude for circular orbits.



<u>FIG. 11.</u> <u>ORBIT TIME FOR CIRCULAR ORBITS</u>.

If the initial velocity of the satellite at A in Figure 10 differs from that required at the altitude of A to ensure a circular orbit one of three things will happen. If the velocity is much too low, the satellite will spiral down to earth and fail to go into any repetitive orbit. On the other hand if the velocity is higher or slightly lower than required for a circular orbit, the satellite will move in a stable elliptical orbit. For the higher velocity, point A on the figure, where it has been assumed that the initial impetus is given, will become the perigee (point nearest to the earth) while the apogee (point furthest from the earth) and the two focal points of the ellipse will be located as shown in Figure 12. For the lower velocity, the perigee and apogee will be located opposite to those shown on the figure.

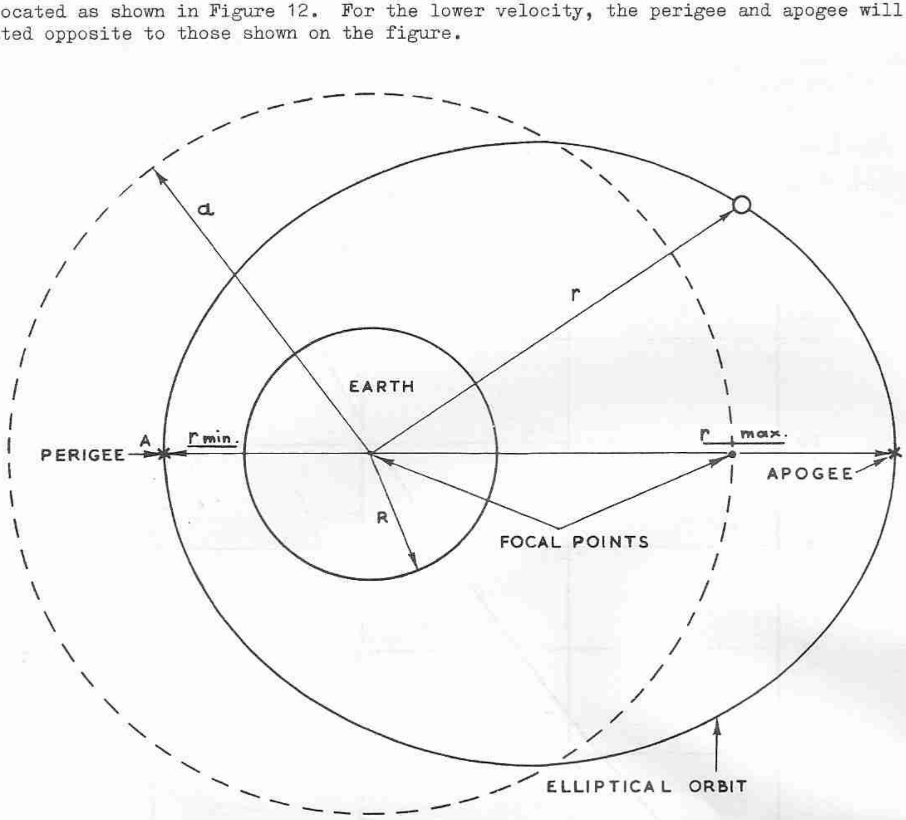


FIG. 12. DESCRIPTION OF ELLIPTICAL ORBIT.

The velocity of the satellite will vary around the orbit in accordance with the law of Kepler which states that the radius vector (r) sweeps out equal areas of orbit in equal times. The extent of the variation depends on the eccentricity of the ellipse which is defined by the equation

$$e = \frac{r\ \mathrm{max} - r\ \mathrm{min}}{2a}$$

where $a = \frac{1}{2}(r\ \mathrm{max} + r\ \mathrm{min})$ or the average distance of the satellite from the earth's centre. The velocity at any point and the orbit time can be easily calculated by introducing this average distance into equations 1 and 2, the results being -

$$\text{Velocity } v = 4.91\sqrt{\frac{2R}{r} - \frac{R}{a}} \text{ miles/second} \qquad \ldots.(3)$$

$$\text{and Orbit Time } T = 84.4\left(\frac{a}{R}\right)^{3/2} \text{ minutes} \qquad \ldots.(4)$$

For communication purposes it is necessary to know the distance and time over which a satellite is visible.

The distance over which the satellite is visible at any time is a circle on the earth's surface centred immediately below the satellite (at the "sub-satellite" point P), as shown in Figures 13 and 16. The diameter of this circle is the section of great circle D whose length is given by $2R\theta$ where θ is the angle in radians subtended at the earth's centre as shown. Thus the diameter

$$D = 2R \operatorname{Cos}^{-1} \left(\frac{R}{r}\right) \text{ miles} \qquad \ldots.(5)$$

where r and R are in miles and $\operatorname{Cos}^{-1} \left(\frac{R}{r}\right)$ is in radians.

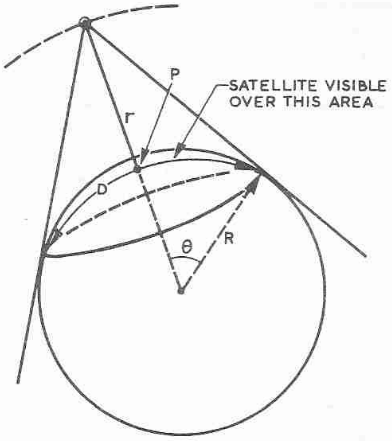


FIG. 13. GEOMETRY DEFINING SATELLITE VISIBILITY.

Thus the diameter D depends only on satellite altitude and the variation with this is shown in Figure 14.

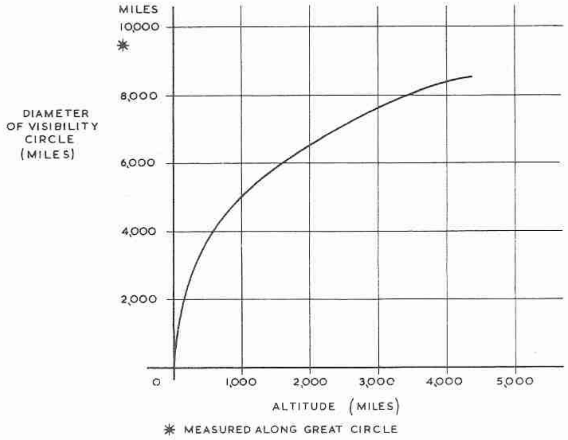


FIG. 14. CALCULATION OF AREA VISIBLE FROM SATELLITE.

The time a satellite is visible over any point on the earth's surface depends on where the point is situated relative to the movement of the centre of the circle shown in Figure 16 and the velocity and altitude of the satellite. The time will be a maximum when the centre of the circle passes through the point, i.e., when the satellite passes directly overhead. For circular orbits, where the velocity and altitude are constant, this maximum duration of visibility is shown as a function of altitude in Figure 15.

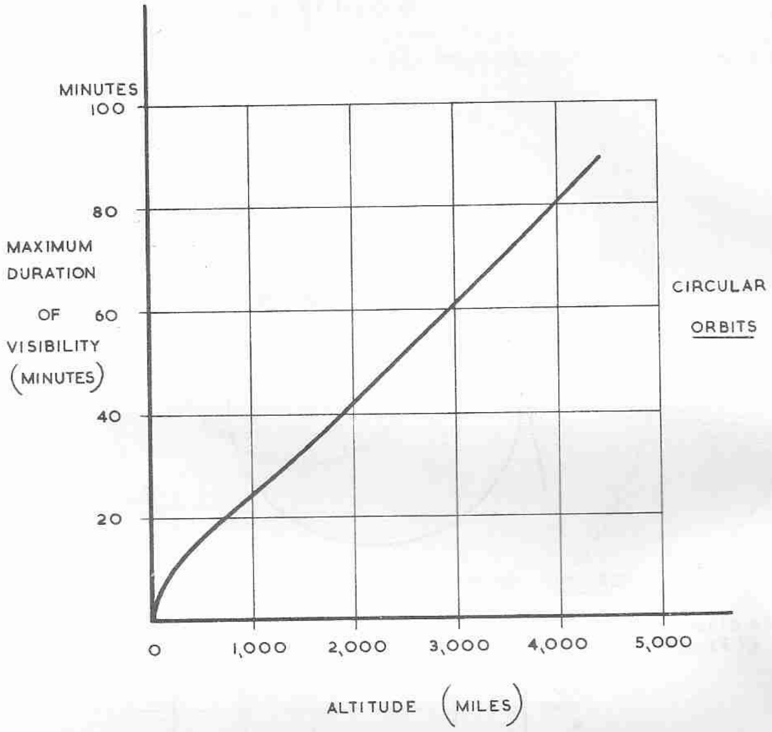


FIG. 15. VISIBILITY DURATION FOR CIRCULAR ORBITS.

If the centre of the circle does not pass through the point it is only during a portion of the maximum period that the satellite will be visible as shown on the plan diagram in Figure 16. Consider first the point shown at A. The satellite will be visible from this point for the proportion of the maximum time that the chord CC is to the diameter of the circle or,

$$\text{Duration of visibility} = \text{Maximum duration} \times \frac{\text{length (A1 to A2)}}{\text{length (D1 to D2)}}$$

The more interesting case is where two points, such as A and B, must communicate via the satellite. This can only happen when A and B see the satellite simultaneously so the above procedure must be applied twice. Thus A sees the satellite when the sub-satellite point is located between A1 and A2 while B sees the satellite over the range B1 to B2. The common visibility range in this case is A1 to B2 so

$$\text{Duration of common visibility} = \text{Maximum duration} \times \frac{\text{length (A1 to B2)}}{\text{length (D1 to D2)}}.$$

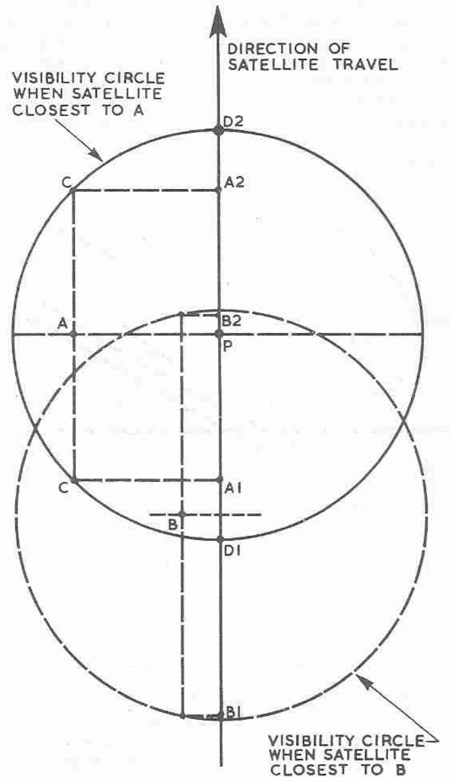


FIG. 16. CALCULATION OF VISIBILITY DURATION.

The above simple theory is adequate to assess the suitability of an orbit for a particular communication system but to allow estimates of the number of satellites required for any system and to appreciate the advantages claimed for particular elliptical orbits (ref. 5), it is necessary to consider the major perturbations to be expected.

It has been assumed above that the earth is a perfect homogeneous sphere so that the gravitational attraction is constant anywhere at a given radius from the centre and that drag due to the atmosphere is negligible. At the altitudes of interest for communication satellites (1,000 miles and over) the second assumption is permissible even though the air drag is increased greatly by a retarding effect due to electrified particles, but gravitational variations do have a marked effect on the satellite's motion.

The earth is markedly flattened at the poles the dimensions being (ref. 4).

Equatorial radius = 3963.18 miles

Polar radius = 3949.89 miles

This polar flattening, or as it is more often termed, the equatorial bulge, causes a variation in gravitational force from equator to poles and is the most important perturbing agency being some 10,000 times more effective than the gravitational forces due to the sun and the moon. The effect is to impress two distinct motions on the orbit as described below. Terms to be used are indicated on Figure 17.

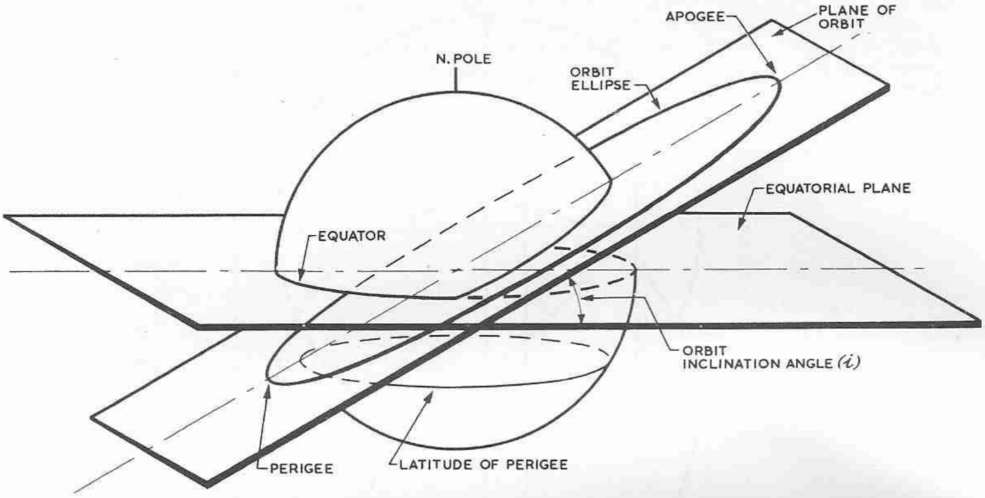


FIG. 17. TERMS USED TO DESCRIBE ORBITS.

In the absence of the equatorial bulge the plane of the orbit would remain fixed in direction and the earth would rotate around its axis as shown once per day. Each successive pass of the sub-satellite point would be located westward on the earth's surface from the preceding one by the number of degrees of longitude corresponding to the orbit time (15° per hour).

The first effect of the equatorial bulge is to cause the plane of the orbit to precess around the earth's axis. The angle of inclination of the orbit to the equator, i, does not change, while the orbital plane rotates slowly around the earth's axis in the opposite direction to the satellite's motion. If this is from West to East as is usual to take advantage of the earth's angular velocity to reduce the rocket thrust required, the orbital plane rotates from East to West. The approximate rate of rotation is given by -

$$\text{Rate of rotation} = X = 9.97 \left(\frac{R}{a}\right)^{7/2} \text{Cos } i \text{ degrees per day}$$

where R and a are as previously defined.

The rotation varies from 0°/day for a polar orbit to 8°/day for a low equatorial orbit.

The second important effect is that the orbital ellipse rotates steadily on its own plane, forward (in the same direction as the satellite motion) for near equatorial orbits and backward for near polar orbits. The perigee thus moves forward (or backward) and the latitude of the perigee is constantly changing. The rate of rotation of the ellipse is given by -

$$\text{Rate of rotation} = 4.98 \left(\frac{R}{a}\right)^{7/2} (5 \text{ Cos}^2 i - 1) \text{ degrees per day.}$$

The rate varies from 17°/day forward for low equatorial orbits through zero at $i = 63.4^\circ$ to approximately 4°/day backward for low polar orbits. Further information on these perturbations may be obtained from the reference (4).

It is possible to exploit these perturbations to give economy in the number of satellites required as has been suggested recently in connection with the use of highly elliptical orbits (ref. 5). This takes advantage of the long time spent in the vicinity of apogee (where the velocity of the satellite is at a minimum) and by arranging the orbital constants such that the perturbations keep the apogee on the sunlit side of the earth where traffic is expected to be heaviest, the most effective time utilisation of the satellite is obtained.

APPENDIX 3.

COSTS OF SATELLITE COMMUNICATION SYSTEMS.

Estimates vary greatly depending on the assumptions adopted. Several examples follow (converted to £A) -

(a) Weisner (Massachusetts Institute of Technology) - (ref. 9)

24 hour orbit; 100 Mc/s baseband width -

Launching cost per system - £M 34
Ground Equipment - £M 11
Total Capital - £M 45

Replacement Cost £M 9 per annum.

(b) I.T and T. - (ref 6)

24 hour orbit; 500 telephone channels -

Launching Cost for first system - £M 100
Ground Equipment - £M 54
Total Capital - £M 154

Replacement Cost £M 9 per annum.

(c) De Havillands - (Unpublished Paper)

Low orbit; 100-1,000 telephone channels -

(40 year development)

Launching Cost - £M 60
Ground Equipment - £M 35
Total Capital - £M 95

Replacement Cost £M 2.5 per annum (average)

(d) C.T.B. Report (TTM/1960/2) - (ref. 8)

Low orbit; 100 telephone channels -

Launching Cost - £M 31
Ground Equipment - £M 31

Total Capital - £M 62

Replacement Cost £M 19 per annum.

(e) A.T. and T. - (ref. 10)

Low orbit; 600 telephone channels -

Launching Cost - £M 22
Ground Equipment - £M 29

Total Capital - £M 51

Additional cost to add 1 TV channel to above

Launching Cost - £M 22
Ground Equipment - £M 2

Total Capital - £M 75

No replacement cost figures are given. However estimated life of satellite is 10 years, so as 50 satellites are envisaged, average replacement rate can be estimated at 5 per annum.

Replacement cost therefore about £M4½ per annum.

The above costs compare with the estimated cost of £970,000 for the Melbourne-Adelaide conventional microwave system. This cost includes buildings, power and two both-way channels (one standby) suitable for 960 telephone channels but not including channelling equipment. Each additional 960 channel bearer would cost about £170,000. There is thus little likelihood of the application of satellite relay on routes which can readily be served by standard microwave or coaxial cable methods and where frequent drop-out facilities are required. In Australia this applies to the eastern States (Cairns to Adelaide and Tasmania and country spurs) and the main possible use for internal communication by satellite repeater would be a broadband system from Adelaide to Perth.

APPENDIX 4.

TRANSMISSION ASPECTS.

The appropriate transmission standards to be applied to satellite communication proposals have not yet been agreed but a discussion of some of the technical factors involved follows -

(a) Noise. For systems up to 25,000 Km in length, an allowable noise power in a telephone channel of 4 pW per Km has been laid down (CCITT, New Delhi, 1960). Since this would permit a noise level of - 40 dbm on the longest circuits, it has been recognised that this standard is worse than is desirable and Australia in particular has advocated an objective of 1 pW per Km. Some qualification would be required before this figure could be applied to satellite systems, as the radio path length does not bear any fixed relation to the distance between terminals. Likewise the CCIR recommendations on mainline radio systems (286, 287, 288 and 289 Los Angeles, 1959) based on 3 pW per Km for systems up to 2,500 Km cannot be directly applied.

Until an agreed standard is evolved, the end-to-end performance required by the CCIR 2,500 Km hypothetical reference circuit could be used as a guide to satisfactory practice, regardless of path length and ignoring the sets of channel, group and supergroup modulators called for in the hypothetical circuit. Using this method, the allowable noise is specified on a statistical basis, but can loosely be described as requiring the noise power in a telephone channel (at a point of zero relative level) to be lower than -50 dbm for 99% of the time and in a 625 line television channel requiring a ratio of peak-to-peak signal (excluding sync pulses) to RMS random noise of at least 52 db when measured, using the procedure specified.

It appears to be possible in a satellite system to obtain performance of this general standard for a large block of telephone channels or a single television channel provided active repeaters can be used. However, with passive reflectors, channel signal to noise ratios better than about 40 db would require uneconomical, if not impracticable, ground equipment.

(b) Transmission Delay. The finite time of transmission could be a major problem in the application of satellites to two-way telephony and to high speed data channels where error correcting devices are required. The propagation time gives a delay of about 5.4 milli-seconds per 1,000 miles of radio path length so that echo from the far end terminal is delayed by 10.8 milli-seconds for each 1,000 miles of path. Delays of more than a second would therefore be incurred on a two-hop path using satellites in 22,300 mile orbit and it is by no means certain that this would allow commercial telephone circuits to be derived.

Delay time has been considered by the CCITT in connection with conventional means of providing service and it has long been recommended that a magnitude of 250 milli-seconds one way delay time should not be exceeded. 100 milli-seconds of this is assigned to end connections so the recommended maximum delay on an International line is set at 150 milli-seconds, giving a maximum echo delay of 300 milli-seconds.

The route United Kingdom to Australia is an important one where, because of the long path length, the time delay will be large. The shortest possible loop or echo delay of 120 milli-seconds would be given by propagation along the surface at the speed of light. For comparison, the loop delay through the proposed cable via Canada will be about 280 milli-seconds. Using satellites, the delay will depend on the altitude and number of hops required. A satellite at low altitude is only visible over a comparatively small area, so that a large number of hops would be needed. The path length is therefore not much greater than the distance over the surface. If, on the other hand, a lesser number of higher altitude satellites are used, the path is covered in a lesser number of hops, but the total path length is longer.

Atmospheric drag and heating, which cause short satellite life makes it impracticable to consider seriously the use of very low altitudes such as say 250 miles. An additional reason against this low altitude solution is the consequential need for a large number of satellites, with a correspondingly large number of ground stations. The theoretical sites for some of these would fall in oceans or unavailable territories. The lowest satisfactory altitude would probably be in the range 3,000 to 4,000 miles with say 4 or 5 ground repeater sections employed. Adding 100 milli-seconds for terminal networks, the minimum echo delay will amount to about 0.5 and 0.6 seconds respectively, or about twice the recommended maximum for international circuits.

(c) Bandwidth Required (Radio Frequency). Statements have been made (notably by Pierce and Kompfner) that for a 5 Mc/s signal bandwidth, an RF band of over 100 Mc/s is required. This requirement arises from the desire to use a particular modulation scheme, i.e., negative frequency feedback (ref. 11).

The modulation system to be used in a satellite communication project deserves careful consideration as by suitable design, noise performance improvements can be obtained. Negative frequency feedback is one such system though others are available two examples being pulse code modulation and the so-called "high sensitivity reception" techniques developed by Nippon Electric. This latter system uses phase detection with a local oscillator controlled by the incoming signal and shows promise though the signal bandwidth limitations have not yet been completely assessed.

(d) Frequency Allocations. Any frequency not affected by the atmosphere or ionosphere is useful for satellite communications. This puts the range from say 100 to 10,000 Mc/s, with a broad optimum between 2,000 and 6,000 Mc/s. Below 2,000 Mc/s cosmic noise becomes increasingly troublesome while above 6,000 Mc/s atmospheric absorption increases the path attenuation. Satellite systems will be vulnerable to interference since the ground receivers must work at the limits of possible sensitivity and the safety margins allowed on standard microwave systems cannot be afforded. Interference to the satellite system can be caused by a variety of factors both natural and man-made. Radio emissions from the sun and other objects can affect the noise performance of masers and parametric amplifiers as also can the thermal emission from the atmosphere when the aerials are at low elevation angles (up to 5-7½° above the horizon). Reduction of the effect of such natural interference requires refined aerial design to prevent pickup from undesired directions. Prevention of accidental man-made interference from electrical noise and other services is relatively simple but deliberate jamming is more difficult to counter. Low orbits, because of reduced service area, will be less vulnerable and circuits can be protected by suitable coding schemes. Such protection may however be difficult or impossible for broadcast services and in any case cannot theoretically be infallible.

(e) Secrecy. Telephone channels will no doubt be derived using standard frequency division multiplex which by itself will prevent accidental "eavesdropping". More positive measures to ensure secrecy would require the application of equipment developed and used for the same purpose on HF radio systems.

(f) Reliability. The reliability of the complete system depends on the separate reliabilities of the radio path and the equipment.

The attenuation of the radio path will remain relatively constant while a satellite is above the horizon by more than about 5° as seen by the transmitting and receiving terminals. This has been demonstrated by the Echo experiment, the radio path being described as "very stable". When the satellite is not in sight, the path attenuation is, for practical purposes, infinitely high so the reliability of the radio path will depend on the number and locations of the satellites in orbit. Using a fixed satellite (22,300 miles) the reliability will be 100% on this basis, but in the case of low orbit satellites the reliability will vary. As an example (ref. 3), considering a 2,500 mile path with satellites randomly placed in a 3,000 mile altitude optimum orbit (i.e. normal to the great circle between the terminals), 12 satellites would give 90% reliability; 15 would give 95% and 24 would give 99%. (See Appendix 2 for orbit times and visibility distances).

Equipment reliability cannot be predicted with such accuracy. Satellites, both active and passive, are subject to various destructive agencies which may cause either catastrophic failure or a gradual deterioration in performance. Until these factors are known with reasonable certainty, it will not be possible to predict likely failure rates and hence the number of satellites required for replacements over a given time. Engineering effort at present is aimed at a satellite lifetime of the order of 10 years and components are expected to be available shortly with this life potential.

APPENDIX 5.

TELEVISION BROADCASTING USING SATELLITES.

Suggestions have been made that the broadcasting of television programmes from satellites would be advantageous because of the large area which may be served from one transmitter. While such projects are theoretically possible, equipment available or in prospect does not allow any firm engineering proposal to be made. Two examples follow -

(a) Using Low Orbit Passive Satellites. A domestic installation much more complicated (and therefore expensive) than is at present considered desirable would be required. Calculations then show that transmitters of from 500 KW to 5 Mega Watt rating with steerable aerials of the order of 100 feet diameter are necessary for the required 5 Mc/s bandwidth.

Transmitters of such power ratings in the U.H.F. band are not yet available and in view of the relatively low efficiencies and small physical size associated with such frequencies it is by no means certain that such high powers are possible in one unit. Thus the parallel connection of a multiplicity of smaller units with attendant phasing problems may be necessary to obtain the required power. New problems such as radiation hazard would also need to be considered as the equivalent radiated power would be up to 50 million KW from a steerable aerial. (The recommended safety level of exposure is set at a maximum radiation level of 100 milli-watts/sq. cm.)

(b) Using Active Satellites. In this case one can assume a domestic installation similar to those in common use today. It would probably be feasible to mass produce U.H.F. receivers at an economic price requiring a signal of around -100 dbW for satisfactory performance. A path attenuation of 170 dB would be a typical figure, so assuming a satellite with aerial beams just covering the service area (implying a gain in the range 20 to 10 dB), the transmitter powers required would range from 10 to 100 KW. Such powers are not yet in sight for satellite-borne equipment, though future developments in rockets and nuclear or other power supplies may make such a scheme practicable.

APPENDIX 6.

A NOTE ON RECEIVER AND AERIAL RATING BY EFFECTIVE TEMPERATURE.

It is common practice to rate receiver noise performance in terms of the well known Noise Factor.

This Noise Factor (or Noise Figure) is the ratio by which the input signal/noise ratio is degraded by the receiver and for the better class of receiver a few years ago was typically about 10 db.

In a perfect receiver, the input noise power consists wholly of thermal noise generated in the resistive components of the source impedance. It is not necessary to know the actual value of this resistive component when the concept of Available Noise Power is introduced as the available Noise Power depends only on temperature and bandwidth. In a two terminal network, Available Noise Power (in Watts) = k T B -

Where k = Boltzmann's Constant = 1.38×10^{-23} joules/°K

T = Temperature in °K (= °C + 273)

B = Noise Bandwidth in cycles/sec (Approximates to "3 db bandwidth")

From this reasoning, it can be seen that noise factor measurements include temperature as a prime parameter.

For conventional types of receiver, noise factor measurements usually assume a room temperature of 20°C (i.e. 293°K) since most signal sources (signal generators, aerials, etc.) are in thermal equilibrium with an environment of this temperature. The source resistance thus generates an available noise power of 4×10^{-21} Watts/cycle of bandwidth. Thus for a 4 kc/s bandwidth, the power would be 1.6×10^{-17} watts or 168 db below a watt (dbw). The noise power at the input of an imperfect receiver appears to be greater than this by a multiplying factor equal to the noise factor of the receiver.

This method of rating receiver performance may be used to calculate directly the sensitivity of receiving systems in all cases where the ultimate sensitivity of the system is limited by receiver performance. However, in cases where other sources of noise are significant the Effective Temperature (or Apparent Noise Temperature) is a more convenient parameter which can be applied to the aerial system as well as to the receiver. There are two main reasons behind the use of this idea.

One reason is that in modern receivers using masers or parametric amplifiers the noise contribution from the receiver is extremely low (i.e. the Noise Factor is close to unity). Thus variations in the source temperature are very important since the receiver-generated noise no longer swamps the source noise by a factor of 10 or so as in conventional receivers.

The other reason follows from the advent of Radio Astronomy and Satellite Communications where the signal source is an aerial pointing into space. The volume of space or the objects included in the polar pattern of the aerial may be much lower or higher in temperature than the earth and it is no longer realistic in system design to use room temperature in noise calculations. The net radiation into the aerial from all directions (main beam, side and back lobes) will generate a signal across the aerial terminals and this signal is used in noise calculations.

The measured value of noise power (N) generated by the amplifier, or at the aerial terminals due to radiation pickup, is substituted in the formula N = k T B to obtain a value of T which we call the Noise Temperature. A value of 30°K is readily obtainable at the present stage of development from a maser amplifier. This is some 20 db lower in noise level than the typical conventional receiver of 10 db noise factor previously cited (equivalent to an effective temperature of 3,000°K).

The noise temperature of an aerial system depends on the direction in which it is pointing as well as on its polar pattern. The earth itself is a thermal emitter with an effective source temperature of around 150°K so that if the main beam is too low in elevation angle an appreciable fraction of this noise will be picked up. The background level of cosmic noise varies with frequency, being most serious at low frequencies, but even at 1,000 Mc/s this accounts for noise from a source of effective temperature up to about 30°K. These sources and any others present may be added and plotted in terms of frequency, time of day and direction to give the effective noise temperature of the aerial. Details of a method and application to a particular system design are given in the reference (12).