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Waveguide Systems for Telecommunications

W. J. Bray, M.Sc. (Eng.), A.C.G.I., D.I.C., A.M.I.E.E.

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CONTENTS

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I. INTRODUCTION.

This paper is essentially a survey of the published information on S.H.F. radio and waveguide systems, prepared with a view to introducing engineers of the Department to these aspects of communications.

S.H.F. systems are those operating in the range 3,000 to 30,000 Mc/s, 10 to 1 cm. wavelength; even higher frequencies, for example 40,000 to 80,000 Mc/s, 0.75 to 0.375 cm. wavelength, may be used in waveguide systems.

A study of the information now available on the characteristics of wave propagation and techniques for generating and amplifying waves in the S.H.F. range suggests that such systems may enable multichannel telephony and television signals to be transmitted effectively, economically, and reliably. A valuable feature of S.H.F. systems is that once a network of relay stations has been established, the wide frequency bands available would permit a considerable increase in the number of telephony channels transmitted with a relatively small amount of additional equipment, a feature which contrasts with the limited bandwidth available on a coaxial cable.

That great interest is being shown in these developments is evident from the considerable amount of research in the S.H.F. field being carried on in the laboratories of the Bell System (1) (2)*, the Radio Corporation of America (3) (4) (5), Western Union (6) (7) and the International and Federal Telecommunications Laboratories (8) (9) in America, in the Laboratoire Central de Télécommunication in France (10) (11) and in various organisations in this country.

Two main types of S.H.F. relay system will be discussed:—

(i) radio systems employing highly directional aerials and space-wave propagation (Section 2),
(ii) waveguide systems using waves guided by metallic pipes (Section 3).

These systems have several features in common, for example there is the same need to generate, modulate, amplify and demodulate a S.H.F. carrier and there are similar problems to be solved in connection with the signal-to-noise and crosstalk ratios; the chief differences are concerned with the nature of the transmission paths.

The overall performance of a relay system for multi-channel telephony must be adequate from technical aspects such as:—

(i) signal-to-noise ratio,
(ii) linearity of the input/output amplitude response characteristic,
(iii) gain stability, and
(iv) uniformity of the frequency/response characteristic.

A relay system for television signals must satisfy additional requirements such as:—

(v) uniformity of the phase-delay/frequency characteristic, and
(vi) freedom from echo signals.

Reliability, ease of maintenance and economy of construction and operation are also of great importance. Of the technical factors the signal-to-noise ratio is probably the most important since it controls the spacing of the repeaters, the transmitted power and the size of aerials required in a radio system. The signal-to-noise ratio in an audio or vision frequency channel depends on the modulation system adopted, *e.g.*, amplitude, frequency or pulse modulation, as well as on the carrier-to-noise ratio in a R.F. or I.F. band. By using a suitable modulation system the wide frequency band available at S.H.F. may be utilised to reduce the transmitted power required for a given signal-to-noise ratio; for this reason some attention has been given (Section 4) to the various possible modulation systems.

A brief description has also been given (Section 5) of existing techniques for generating, amplifying and filtering S.H.F. waves.

2. S.H.F. RADIO RELAY SYSTEMS.

2.1. General Principles.

The basic elements of a S.H.F. radio relay system are shown in Fig. **1**, such a system comprises two terminal stations and a chain of repeater stations spaced at intervals of some 20 to 40 miles. (The significance of the dotted lines in Fig. **1** will be referred to later.) At the terminal station a radio frequency (R.F.) carrier is generated, modulated by the multi-channel telephony or television signal to be transmitted, and after amplification is applied to a highly directional aerial for radiation to the first repeater station. At the repeater station the R.F. signal is received on a highly directional aerial, is amplified and possibly changed in frequency and is re-radiated to the second repeater station and so on. The R.F. signal at the distant terminal station is, after amplification, demodulated and the multichannel telephony or television signal recovered.

The path between the transmitting and receiving aerials of a S.H.F. radio link must be free from obstructions such as hills and buildings and should clear the intervening terrain by at least 100 ft. Under these conditions the path-attenuation, *i.e.*, the ratio of the transmitted to the received power is, to take a specific example, about 60 db for a 25 mile link operating at 4000 Mc/s with aerials of size 6 ft. by 6 ft.

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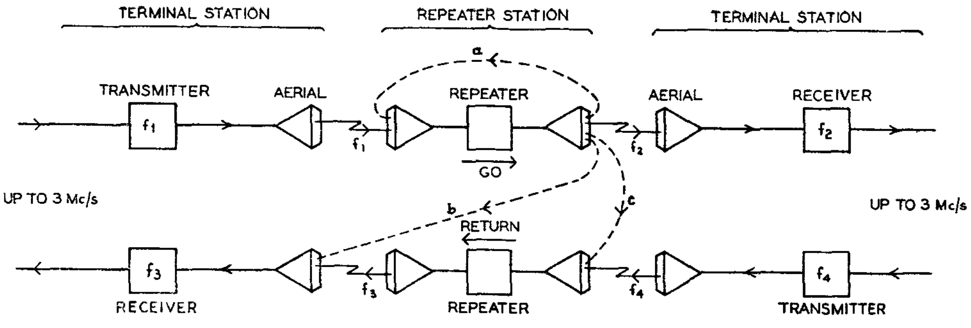
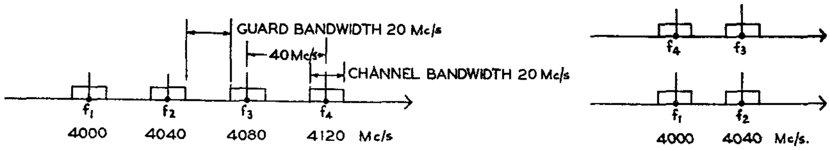
* Numerical References are to the Bibliography at the end of the Paper.



(a) SCHEMATIC



(b) FREQUENCY PLAN 1 (c) FREQUENCY PLAN 2

FIG. 1.—S.H.F. RADIO RELAY SYSTEM.

This relatively low value of the path-attenuation compares favourably with that on coaxial cables, for example, four 6 mile repeater sections of 3/8in. coaxial cable would have a total attenuation of about 160 db at 3 Mc/s. In the absence of fading a path-attenuation of 60 db would enable a carrier-to-noise ratio of 50 db to be obtained with transmitted powers of about 0.1 W, assuming a bandwidth of 10 Mc/s. However, fading due to the inhomogeneous and variable nature of the atmosphere may make it desirable to increase the transmitted power to a few watts in order to ensure that a carrier-to-noise ratio exceeding 50 db is obtained consistently. It should be made clear at the outset that by using techniques such as amplitude limiting with frequency modulation the signal-level at the output of a relay system may be held constant within a fraction of a decibel, the effect of fading being confined to varying the noise level. Since the characteristics of wave propagation influence the design of radio relay systems to a marked degree they will be considered in somewhat greater detail before proceeding to a discussion of equipment techniques.

2.2. Characteristics of radio wave propagation at S.H.F.

The propagation over an unobstructed S.H.F. radio link with adequate ground clearance is usually such that the average received signal level closely approaches the free-space value and it is useful to consider this case as a starting point.

2.2.1. *Path-attenuation with Free-space Propagation.*

It can be shown(12) that the ratio of the received power W_R to the transmitted power W_T with free-space propagation is given by

$$\frac{W_R}{W_T} = \frac{A_T A_R}{\lambda^2 d^2} \quad . \; . \; . \; . \; . \; . \quad (1)$$

where A_T A_R are the effective areas of the transmitting and receiving aerials,
λ is the wavelength,
and d is the distance between the transmitter and the receiver.

The corresponding path-attenuation is

$$10 \log_{10} \left[\frac{W_T}{W_R}\right] \text{ db.}$$

Equation (1) shows that for a given transmitted power, link length and size of aerial the received signal power varies inversely as the square of the wavelength, *i.e.*, the received power increases as the square of the frequency. In practice losses due to water vapour in the atmosphere, rain and fog set an upper limit to the usable frequency range around 10,000 Mc/s (λ=3 cm.).

Fig. 2 shows the variation of path-attenuation with

TRANSMITTED POWER W_T = 1 WATT
EFFECTIVE AREA OF AERIALS $A_T = A_R$ = 3SQ METRES
BANDWIDTH B = 10 Mc/s
NOISE FACTOR N_F = 10db

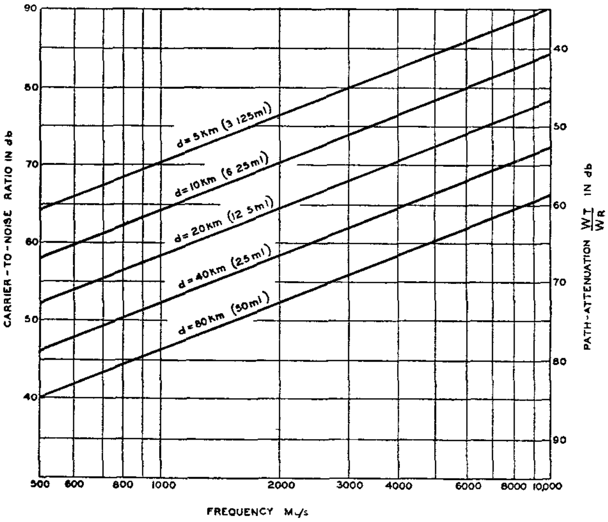


FIG. 2.—VARIATION OF CARRIER-TO-NOISE RATIO AND PATH-ATTENUATION WITH FREQUENCY AND LINK LENGTH.

frequency for various link lengths and for aerials of 3 square metres effective aperture. It should be noted that the effective area of practical S.H.F. aerials of the paraboloid reflector or lens horn type is approximately 60 per cent. of the physical area of the aperture.

The path-attenuation is of interest since it is equal to the minimum gain required in the repeaters to make good the loss in the preceding link, additional gain usually of the order of 20 db is necessary to allow for fading.

2.2.2. *Carrier-to-noise Ratio with Free-space Propagation.*

For frequencies in the S.H.F. range atmospheric noise is generally negligible and the noise level in the radio system is determined by the noise level inherent in the early stages of the receiving equipment. A convenient datum for the noise level is that due to thermal agitation of electrons in a resistance equal to that of the aerial at the ambient temperature, this datum level is given by

$$W_N = KTB \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

where K = Boltzmann's constant (1.37×10^{-23} joule/deg.),

T = ambient temperature (deg. abs.),

and B = bandwidth of receiver (c/s).

For a bandwidth of 10 Mc/s, $W_N = -134.0$db relative to 1 watt.

The noise output of the receiver may be regarded as due to a source having the same resistance as the aerial but in which the available noise power is $N_F W_N$, N_F being the "noise-factor" of the receiver(13). The noise factor of S.H.F. receivers is usually in the range 10 to 15 db and tends to increase with frequency.

The carrier-to-noise voltage ratio for a single link is given by

$$\left[\frac{\text{Carrier}}{\text{Noise (1 link)}}\right] \text{RMS} = \sqrt{\frac{W_R}{N_F W_N}} = \sqrt{\frac{W_T A_T A_R}{N_F W_N \lambda^2 d^2}} \quad (3)$$

Fig. **2** shows the variation of carrier-to-noise ratio with frequency for various link lengths ; the effective area of the aerials is assumed to be 3 square metres, the noise factor 10 db and the transmitted power 1 watt.

When several links are connected in tandem the noise contributions from the various links add on a power basis at the output of the system, if there are *n* similar links the carrier-to-noise ratio in the *n*th receiver is

$$\left[\frac{\text{Carrier}}{\text{Noise } (n \text{ links})}\right] \text{RMS} = \sqrt{\frac{W_R}{n N_F W_N}}$$

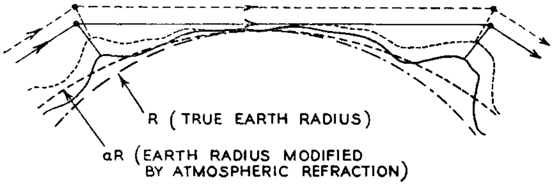
$$= \sqrt{\frac{W_T A_T A_R}{n N_F W_N \lambda^2 d^2}} \quad . \; . \; . \; . \; . \quad (4)$$

Thus, for a 240 mile system consisting of 8 similar 30 mile links, the overall carrier-to-noise ratio is 9db less than on a single link.

2.2.3. *Effects Due to the Atmosphere and the Surface of the Earth.*

(*a*) *Fading.*

The atmosphere under average conditions and when in a well-mixed state causes slight downward bending of the ray paths, *i.e.*, refraction, an effect which is usually allowed for by increasing the radius of curvature of the earth in the ratio "a" when plotting path-profiles to determine the ray clearance above the intervening terrain, as in Fig. **3**(*a*). For a "standard" atmosphere(14), one with average gradients of humidity and temperature with height, the modified radius of the Earth is about 1.33 times the actual radius, *i.e.*, $a = 1.33$, and the direct ray clearance is increased. Exceptionally the distribution of humidity and temperature may be such that "*a*" varies appreciably above and below the standard value 1.33 giving rise to variations of the received signal level due to interference between direct and reflected waves, as shown in Fig. **3**(*b*). When "*a*" is small the atmospheric refraction is sub-standard, and the direct ray path may be intercepted by the curved surface of the earth, so producing a large increase in path-attenuation. Such a possibility is minimised by avoiding long links and by making the aerial height as large as practicable. The aerial heights should be such that the ray paths clear the intervening terrain by at least 50 ft. on 20 mile links and 200 ft. on 40 miles links, under standard atmospheric conditions(15). Fading may also occur due to wave interference produced by reflections from atmospheric layers of different humidity and temperature, or from the partial trapping of rays in atmospheric ducts. The magnitude of the variations of



(a) EFFECT OF ATMOSPHERIC REFRACTION ON RAY CLEARANCE ABOVE GROUND

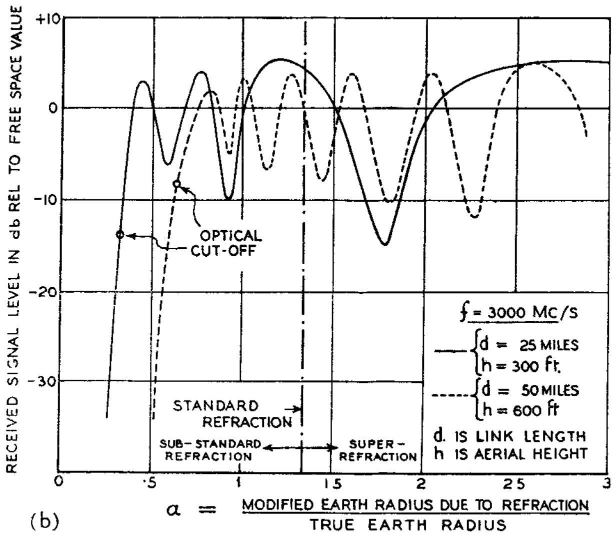
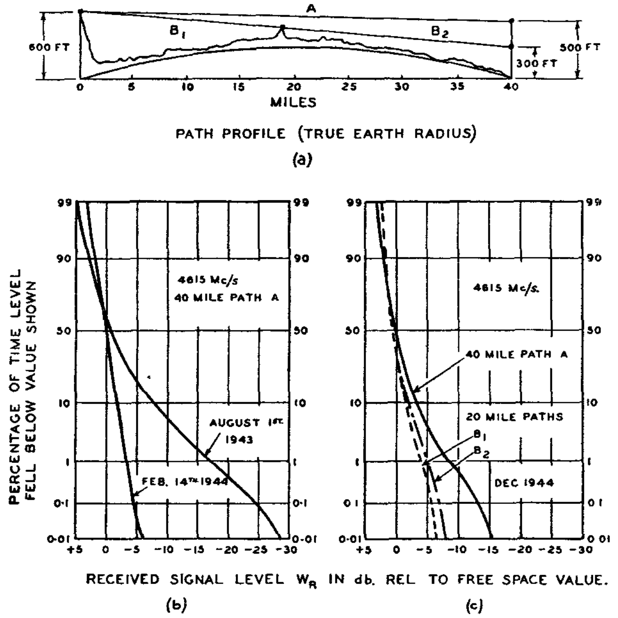


FIG. 3.—ILLUSTRATING THE VARIATION OF RECEIVED SIGNAL LEVEL DUE TO VARYING ATMOSPHERIC REFRACTION.

received signal level due to the above causes is best assessed by long-term propagation tests, some typical data(15) is shown in Fig. **4**. This data illustrates the wider fading range experienced in summer as compared with winter, Fig. **4**(*b*), and the reduction of the fading range by approximately one half on a 20 mile path as compared with a 40 mile path, Fig. **4**(*c*). In planning S.H.F. radio systems operating at frequencies in the range 4000-8000 Mc/s it is estimated from published data(15) that an increase of path-attenuation of some 15 db should be allowed for on a single 20 mile path and 30 db on a 40 mile path ; fortunately the probability of deep fades occurring simultaneously on all the links of a multiple link system is extremely remote and allowances of 10 db and 20 db for 10 link systems with 20 and 40 mile links respectively would probably suffice.



(a)

(b) (c)

FIG. 4.—FADING DATA FOR 20 & 40 MILE PATHS. (BELL TELEPHONE LABORATORIES TESTS.)

(*b*) *Changes of Wave Arrival Direction.*

The variable bending of the ray paths due to changes in the distribution with height of the refractive index of the atmosphere give rise to variations of the direction of arrival, these variations are predominantly in the vertical plane and may amount to 0.25° and 0.50° on 20 mile and 40 mile paths(16). This fact limits the directivity and therefore the maximum size of aerial which can be used in practice to about 5 square metres aperture at 10,000 Mc/s (beamwidth 1°) for a 40 mile path, larger aerials could be used at lower frequencies and on shorter paths.

(*c*) *Highest Usable Frequency.*

The highest frequency which can be used effectively on a S.H.F. radio link is of the order of 10,000 Mc/s and is determined by the increase of the path-attenuation due to rain, and to a less extent fog, hail and snow. The absorption due to rain has been calculated by Ryde(14) and is shown in Fig. **5** for various rates of precipitation. Cloudburst rainfall (exceeding 59 mm/hr) is only likely to occur over an area of about 6 km. diameter for a few minutes some two or three times a year in this country. Such rainfall would give rise to an increase of path-attenuation of about 1.5 db/km. or 9 db for 6 km. at a frequency of 10,000 Mc/s. The absorption due to water-vapour and the permanent gases of the atmosphere has been calculated by Van Vleck(17) and is shown in Fig. **5**, the peak at (*a*) being due to water vapour and that at (*b*) to oxygen. It is evident that these causes of absorption are less serious than rain and fog.

(*d*) *Echo Signals.*

For television signal transmission it is necessary to consider the echo characteristics of radio paths since echoes of time delay exceeding 1 picture element (0.25 microsecond in a 405 line system) and of level exceeding —40 db relative to the direct signal are undesirable. Similar requirements apply to multi-channel telephony systems using time-allocation multiplex with pulses of less than 1 microsecond duration since prolongation of the pulses by echoes may produce inter-channel crosstalk.

Echoes may occur as a result of reflections from buildings, hillsides, aircraft, etc., and at S.H.F. may have an amplitude equal to, but not often exceeding that of the incident wave. Reliance must, therefore, be placed on the sharp polar diagram of the aerials for excluding such echoes. Echoes exceeding a given time delay T are produced by a reflecting surface lying outside an ellipse having the transmitter and receiver at its foci, the breadth of the ellipse being

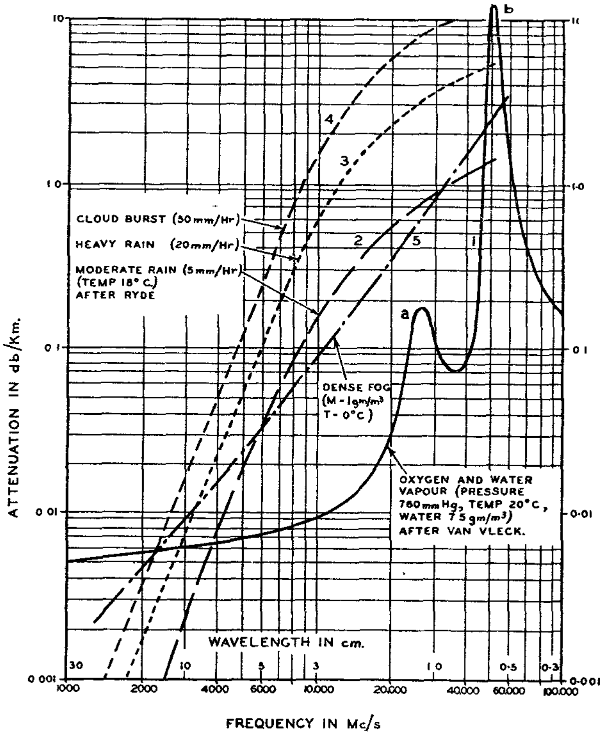


FIG. 5.—INCREASE OF PATH-ATTENUATION DUE TO WATER VAPOUR AND OXYGEN IN THE ATMOSPHERE, RAIN AND FOG.

$b = \sqrt{2dcT}$, where d is the path length and c is the velocity of light (3.10^8 m/sec.), and the angular width $\theta = \sqrt{\frac{2cT}{d}}$ radians. An ellipse is shown to scale in Fig. 6 for $d = 25$ miles and $T = 0.25$ microsecond, for this case $b = 3.92$ miles and $\theta = 7.0°$. Echoes from " mid-path " points such as " a " are excluded if the polar diagram width is less than θ; echoes from points near to the transmitter or receiver such as " b " are sufficiently suppressed if the major-to-minor lobe ratio of the aerial exceeds 40 db. These requirements of the aerial polar diagram are readily met for example by the 4000 Mc/s shielded lens horn aerial described later. Reflections from objects within the ellipse, *i.e.*, of delay less than 0.25 microsecond, do not give rise to echoes as such, their chief effect is to change the level of the received signal.

The foregoing considerations apply of course to reflections from aircraft and it is unlikely there would be any difficulty from this cause provided that the aerial directivity is sufficient to exclude echoes exceeding 0.25 microsecond time delay and the automatic gain control or limiting action in the receiving equipment is sufficiently rapid to absorb the fluctuations of level due to reflections from an aircraft flying within the ellipse.

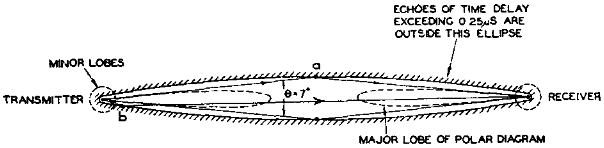


FIG. 6.—REJECTION OF ECHO SIGNALS BY DIRECTIONAL AERIALS (ELLIPSE IS APPROXIMATELY TO SCALE FOR 25 MILE PATH).

2.2.4. *Noise from External Sources.*

(*a*) *Noise from Ignition Systems.*

There is, as yet, comparatively little data available on the field strength of ignition interference at frequencies above about 1000 Mc/s. However, a preliminary examination of the problem based on the assumption that the field strength at 4000 Mc/s is not greater than the values measured at 1000 Mc/s suggests that ignition interference is not likely to be significant in a radio link operating at 4000 Mc/s or higher frequencies, provided that the aerials have beamwidths of less than about 6° and the minor lobes are at least 40db below the major lobe. If such an aerial is elevated for example 400 ft. above the surrounding terrain, as shown in Fig. 7, the area " seen " from the aerial is at least $1\frac{1}{2}$ miles away and the field strength of the ignition interference at the receiving aerial is correspondingly low.

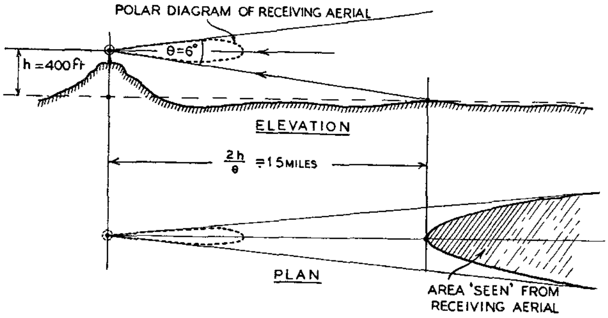


FIG. 7.—ILLUSTRATING THE LIMITED AREA " SEEN " FROM A HIGHLY DIRECTIONAL RECEIVING AERIAL.

(*b*) *Noise from Cosmic and Solar Sources.*

Cosmic noise (radio noise emanating from the Milky Way) does not appear to be significant at frequencies in the S.H.F. range although it is readily detectable at frequencies of the order of 100 Mc/s(18).

The sun radiates noise(19) of a more or less constant level superimposed on which are bursts of high intensity at times of sun spot activity. The steady noise level is such that at 3000 Mc/s a receiver having a noise factor of 10 db would be degraded by 2 or 3 db when connected to a large aperture (10 square metres area) aerial pointing directly at the sun, at 10,000 Mc/s the increase of noise level would be about 10 db. Most of the work on the noise bursts associated with sun-spot activity has been done at frequencies of the order of 100 Mc/s, but there is some evidence to show that short duration bursts may cause a deterioration of noise factor of up to 20 db at 3000 Mc/s. Fortunately the time a highly directional fixed aerial points at the sun is limited to a few minutes at sun-rise or sun-set at certain times of the year for links lying in approximately EW or WE directions and the probability of interference due to sun-spot activity is therefore extremely small and confined to a limited number of specific cases.

2.3. Equipment Techniques for Radio Systems.

The equipment techniques referred to in this section are those special to radio systems; the general techniques for generating, modulating and amplifying S.H.F. carriers and which to a large extent are common to radio and waveguide systems are discussed in Sections 4 and 5. The equipment techniques special to radio systems are mainly those applicable to aerials and repeaters.

At a radio repeater station the possibility exists of an echo signal due to feed-back from the transmitting aerial to the receiving aerial appropriate to the same direction of transmission, along a path indicated by the dotted line " a " in Fig. 1(a), there is also the possibility of crosstalk between the go and return systems along paths such as " b " and " c " in Fig. 1(a).

If the path-attenuation over a link is 60 db and the unwanted carrier level is to be at least 55 db below the level of the wanted carrier, the attenuation required along paths " a," " b " and " c " is $60 + 55 = 115$ db. If there is appreciable fading a somewhat greater attenuation may be required. The permissible ratio of unwanted to wanted carrier level will be determined partly by the modulation system adopted, since certain modulation systems such as F.M. tend to suppress the interfering signal.

If the radio system uses the same frequency for all links the attenuation between a pair of aerials placed back-to-back should be at least equal to the sum of the path-attenuation and the desired ratio of the wanted to the unwanted signal level, *e.g.*, at least $60 + 55 = 115$ db. The attenuation between a pair of aerials placed side-to-side should also be at least 115 db and the front-to-back attenuation of a single aerial should be at least 55 db.

These attenuation requirements can be minimised by displacing the sent and received frequencies on the go and return systems, as in Fig. **1**(*b*), and providing part of the discrimination by filters in the receiving side of the equipment.

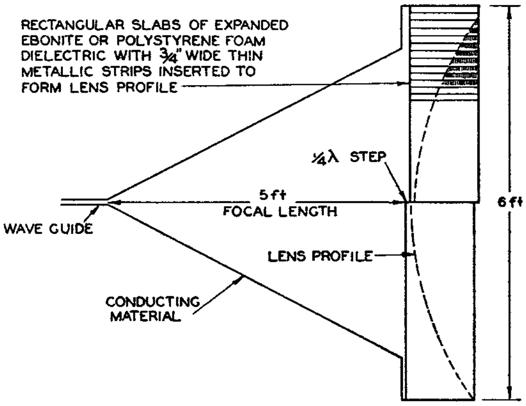
As a compromise the frequency plan shown in Fig. **1**(*c*) may be used; in this arrangement two allocations are employed, the two outgoing frequencies at a given station being identical but the frequencies on the go and return sides of a given link are different. In this case the front-to-back ratio of each aerial must exceed 55 db, in the example referred to above, if crosstalk via path "*b*," Fig. **1**(*a*), is to be adequately rejected.

2.3.1. *Aerials.*

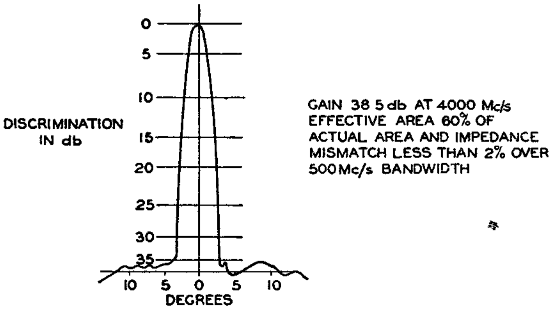
The requirements of aerials for S.H.F. relay systems may be summarised as follows :—

(i) the effective area should be large in order to reduce the path-attenuation and thus the transmitted power required for a given signal-to-noise ratio,
(ii) the directional properties should be good in order to minimise interference from other transmitters and to other receivers, the beamwidth must not however be less than the variations of wave arrival direction,
(iii) the impedance match between the aerial and its feeder should be good in order to minimise reflections which may distort the transmitted signal or produce echoes,
(iv) the required standard of performance should be obtained without critical mechanical tolerances, and
(v) the bandwidth over which the aerial is effective should be as broad as possible in order to permit the transmission of several radio channels on a single aerial.

These requirements are met to a large degree by the shielded lens-horn aerial developed by W. E. Kock of the Bell Telephone Laboratories(20)(i), following earlier work by N. M. Rust of Marconi's Wireless Telegraph Company(20)(ii). This aerial consists of a metallic horn, usually of square section, fed from a waveguide and having an artificial dielectric lens in the aperture, Fig. **8**(a). The radio lens functions similarly to the lens used in optics, *i.e.*, it converts a spherical wave-front in the horn to a substantially plane wave-front immediately outside the horn, and it does so because of the reduced phase velocity in the lens material which results in slowing down the wave-front near the axis where the lens is thickest. The lens-material is an artificial dielectric made of rectangular slabs of expanded ebonite or polystyrene foam in which thin strips of metal some ¾ in. wide are inserted in parallel rows, as in Fig. **8**(*a*) which shows the strips end-on. Such a material has a refractive index of about 1.5 and results in a lens 16 in. thick for a 6 ft. aperture at 4000 Mc/s. The impedance mis-match of the aerial to the waveguide feeder is determined by reflections from the lens back into the throat of the horn, these are minimised by slightly tilting the lens and by using a quarter-wavelength step so that reflections from the upper and lower halves of the lens tend to cancel. In practice an impedance mis-match of less than 2% for a band 500 Mc/s wide around 4000 Mc/s is claimed. The horizontal plane directivity of this aerial is shown in Fig. **8**(*b*), the symmetry of the major lobe and the suppression of the minor lobes being apparent. The gain of the aerial (38.5 db at 4000 Mc/s relative to an isotropic aerial) corresponds to an effective area equal to 60% of the actual area of the aperture. Because of the excellent shielding which this type of construction permits and the low levels of the minor lobes the front-to-back attenuation of a pair of aerials is of the order of 125 db and the side-to-side attenuation is 85 db.



(a) CROSS SECTION OF 6ft APERTURE SHIELDED LENS-HORN AERIAL



(b) HORIZONTAL PLANE DIRECTIVITY DIAGRAM OF SHIELDED LENS-HORN AERIAL

FIG. 8.—SHIELDED LENS-HORN AERIAL. (BELL TELEPHONE LABORATORIES.)

(*a*) *Maximum Permissible Size of Aperture.*

The maximum size of aperture which can be used in practice depends on the variations of wave aerial direction which may be 0.5° on a 40 mile path. The beamwidth θ, 3 db below peak, is related to the aperture width "w" by the formula

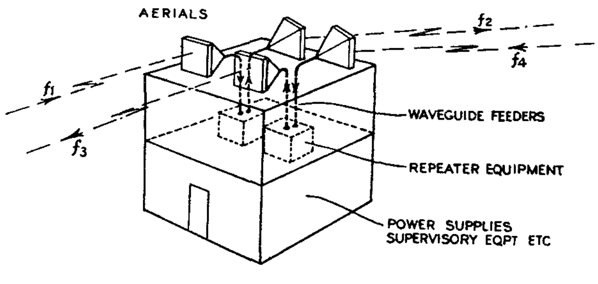
$$\theta \doteqdot \frac{67\lambda}{w} \text{ degrees} \quad . \quad . \quad . \quad . \quad (5)$$

where λ is the wavelength.

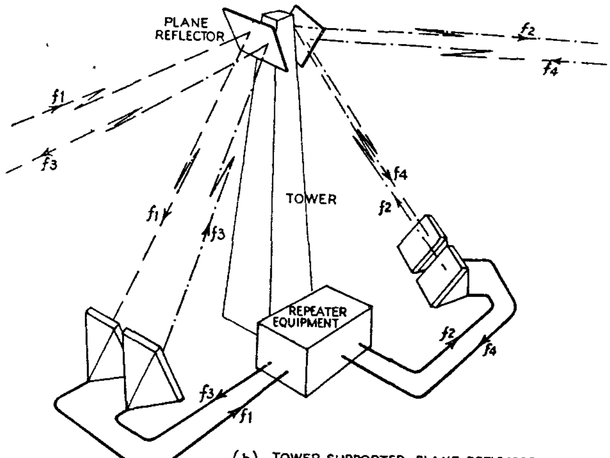
Thus if θ is to be 1.0°, the maximum permissible width of aperture at 10,000 Mc/s ($\lambda = 3$ cm.) is about 2 m, at 4,000 Mc/s ($\lambda = 7.5$ cm.) it is about 5 m.

(*b*) *Arrangement of Aerials at Repeater Stations.*

Where hills are available to elevate the repeater station above the surrounding terrain, the type of layout shown in Fig. **9**(*a*) is suitable. Here the aerials are mounted on the repeater station roof and the signals are fed to and from the repeater equipment by means of waveguides.



(a) HILL TOP REPEATER STATION



(b) TOWER SUPPORTED PLANE REFLECTOR SYSTEM

FIG. 9.—ARRANGEMENTS OF AERIALS AT REPEATER STATIONS.

If adequate height is not available by means of hills, towers must be used and in this case there is a choice between arrangements in which

(i) the aerials and the repeater equipment are at the top of the tower,

(ii) the aerials are at the top of the tower and the signals are fed to and from the repeater equipment at the ground by means of waveguides, and

(iii) the aerials and the repeater equipment are at ground level and plane reflectors are provided at the top of the tower as in Fig. **9**(*b*).

Arrangement (i) is probably to be preferred from the point of view of performance of the equipment since the feeders are short and impedance irregularities are therefore less troublesome.

Arrangements (ii) and (iii) are more convenient from the maintenance aspect, particularly (iii) since all the equipment is at ground level. A possible disadvantage of (iii) is a slight impairment of the aerial directivity due to scattered radiation from the tower and reflectors.

(*c*) *Feeders.*

Waveguides are used in S.H.F. systems in preference to coaxial feeders in view of their much lower losses. They are usually rectangular section copper tubes, typical sizes and losses being :—

(i) 3600-4200 Mc/s. 2.5 in. × 1.25 in (outside) × 0.064 in.
Attenuation 0.72 db/100 ft. at 3900 Mc/s.

(ii) 5850-7050 Mc/s. 1.5 in. × 0.75 in. (outside) × 0.064 in.
Attenuation 1.79 db/100 ft. at 6450 Mc/s.

2.3.2. *Repeaters.*

(*a*) *Repeaters with Intermediate Frequency Amplification.*

Existing S.H.F. repeaters obtain most of the required gain at an intermediate frequency of some 60 Mc/s, a technique made necessary by the lack of readily available low-noise R.F. amplifiers at the present time.

A typical repeater(1) of this type is shown in Fig. **10**. The two modulators employ crystal valves, the first being a low noise, low conversion loss type which, in conjunction with a low noise I.F. amplifier, enables a noise factor of 14 db to be achieved (22). The R.F. amplifier in this repeater uses four double-resonator klystron amplifiers in tandem, to produce a gain of 20 db and a power output of about 0.25 watt. Automatic gain control is used to stabilise the level at the output of the I.F. amplifier. The overall maximum gain is 77 db and the bandwidth 10 Mc/s for a substantially uniform response. Of special interest is the technique used to shift the outgoing frequency f_2 some 40 Mc/s from the incoming frequency f_1. This is achieved by taking part of the output from the R.F. oscillator feeding the first modulator, modulating it with 40 Mc/s and selecting one sideband. The sideband, after amplification and filtering then supplies the second modulator at a frequency 40 Mc/s away from the frequency of the supply to the first modulator. An important advantage of this system is that the stability of the outgoing frequency, relative

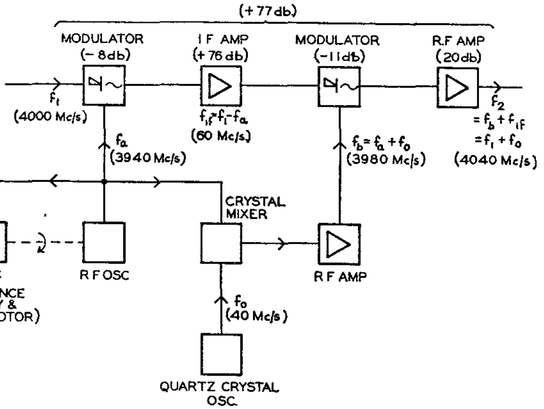
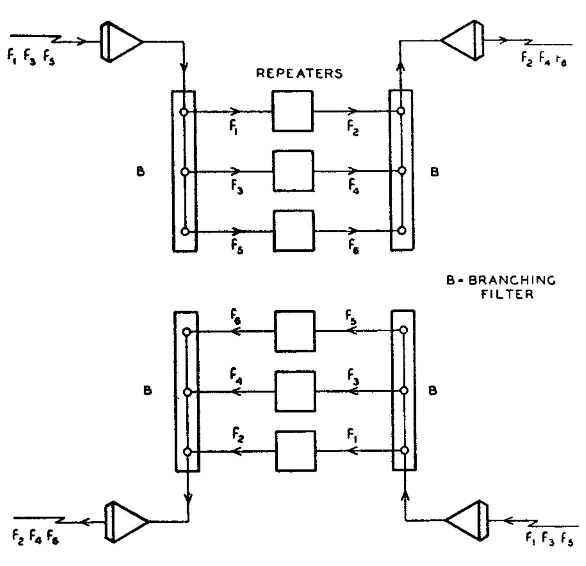


FIG. 10.—REPEATER IN WHICH MOST OF THE GAIN IS ACHIEVED AT I.F. INPUT & OUTPUT FREQUENCIES DIFFER BY THAT OF A RELATIVELY LOW FREQUENCY QUARTZ CRYSTAL CONTROLLED OSCILLATOR.

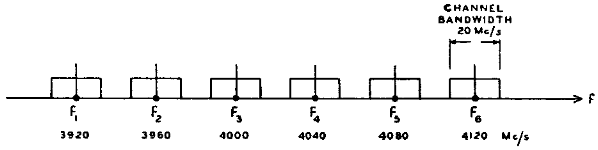
to the input, is dependent only on that of the 40 Mc/s oscillator which can be crystal controlled. Thus the only frequency errors which are cumulative in a long relay system are those for the 40 Mc/s oscillator and these can be made very small. The R.F. oscillator frequency must however be maintained within about 0.5 Mc/s of a specified value in order to ensure correct alignment of the signal in the I.F. channel; this is ensured by an automatic frequency control system (23) in which a resonant cavity provides a reference frequency and the oscillator tuning is adjusted by a servo-motor.

(*b*) *Multiple R.F. Channel Systems.*

It is possible to transmit several R.F. channels over a given relay system using the same aerials for the various channels, a three-channel system is shown in Fig. **11**(*a*). The separation of the signals from the aerials into the various repeaters without significant loss is achieved with a "branching filter" (24). The frequency plan for a three-channel system is shown in Fig. **11**(*b*).



(a) SCHEMATIC



(b) FREQUENCY PLAN.

FIG. 11.—SYSTEM WITH THREE GO AND RETURN R.F. CHANNELS.

(*c*) *Repeaters with R.F. Amplification Only.*

It is now possible to produce in the laboratory valves of the travelling-wave type in which the noise factor is of the order of 10 db and the gain 20 db in low-power valves operating at 4000 Mc/s; valves with power outputs of about 1 watt but higher noise-factor have also been made. These valves are remarkable for their wide bandwidths, several hundreds of megacycles per second have been achieved at 4000 Mc/s.

It is interesting to consider the simplification these valves may introduce into S.H.F. relay systems. For example, Fig. **12**(*a*) shows a possible repeater in which all the gain is achieved at R.F. A low noise R.F. amplifier is preceded by a waveguide filter, Section 5.3, to reject interfering transmissions; this stage is followed by a modulator stage in which the carrier is modulated by a 40 Mc/s crystal controlled oscillation. Such a modulator may consist for example of a travelling-wave valve in which the beam-current is modulated by a 40 Mc/s oscillation applied to an electron gun anode. The appropriate sideband of the modulated signal is selected in a second waveguide filter and is amplified to the required power level by one or more travelling-wave valves.

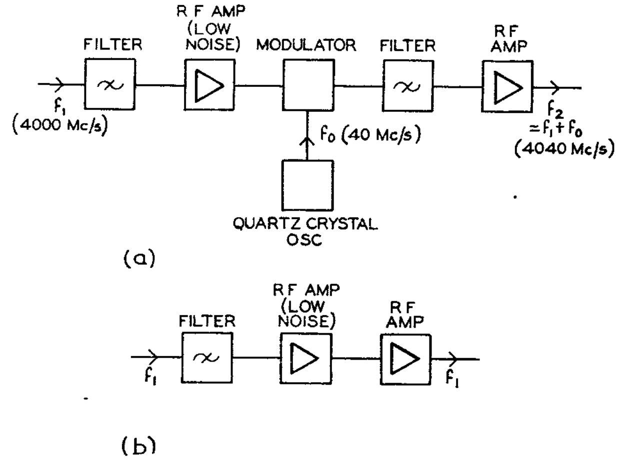


FIG. 12.—REPEATERS IN WHICH THE GAIN IS ACHIEVED AT R.F.

As a further step in simplification the straight R.F. amplifier shown in Fig. **12**(*b*) may be considered. Since the outgoing and incoming frequencies are identical in this system the back-to-back attenuation of the aerials at a given repeater station must exceed the sum of the path-attenuation and the desired ratio of the wanted to the unwanted signal level, *e.g.*, 115 db in the example considered earlier. Whether this is consistently possible is not at present clear but there is a possibility that the shielded lens-horn type of aerial may meet this requirement.

Finally, there is the possibility of the "common aerial" system shown in Fig. **13**. In this system the same aerial is used for transmission and reception, different frequencies f_1 and f_2 being used for the go

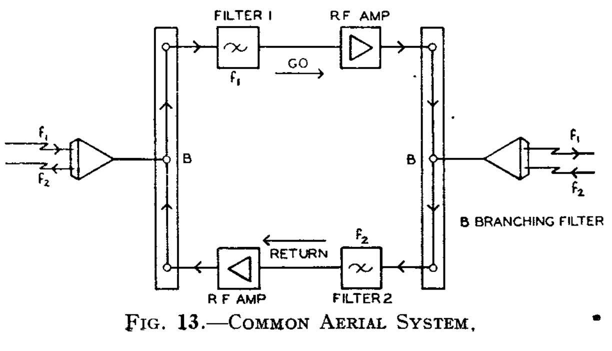


FIG. 13.—COMMON AERIAL SYSTEM.

and return paths. This system necessitates not only a back-to-back attenuation of some 115 db for the aerials but a similar discrimination in filter 1 at frequency f_2 and in filter 2 at frequency f_1, there is no reason however to suppose that this is outside the capabilities of waveguide filter technique provided that the ratio of the channel spacing to the channel bandwidth is 3 or more to 1.

(*d*) *Very Wide-band Systems.*

If systems with R.F. channel bandwidths in the range 3 to 30 Mc/s are designated " wide-band " systems it is convenient to describe those with bandwidths of 30 to 300 Mc/s as " very wide-band " systems, following the generally accepted system of notation for the frequency spectrum.

Very wide-band systems are made possible in principle by the advent of the travelling-wave amplifier and the lens-horn aerial, both of which may have bandwidths of several hundreds of megacycles per second.

It is possible for example that R.F. bandwidths of 200 Mc/s might be utilised to transmit signals having modulation frequencies up to 15 Mc/s, that is high definition or colour television signals or groups of some 3000 telephony channels, by means of a frequency-modulated carrier with a deviation of ± 60 Mc/s, the wide deviation being used to improve the signal-to-noise ratio.

However, before the practicability of such systems can be established it will be necessary to investigate in detail not only the equipment designs but also the transmission characteristics of the radio paths. With high modulation frequencies and wide-deviation signals the echo characteristics of the radio path assume greater importance and it may be necessary to reduce the path length to some 10 to 15 miles and to use higher directivity aerials in order to exclude echo signals.

3. S.H.F. WAVEGUIDE RELAY SYSTEMS.

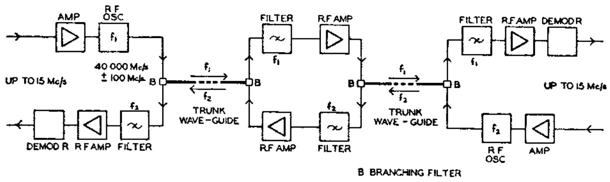
3.1. General Principles.

A waveguide (25) is essentially a metal tube used for transmitting S.H.F. electromagnetic waves along its inside without an additional conductor. The theoretical investigations of Lord Rayleigh in 1897 showed that electromagnetic waves could be propagated inside conducting tubes but it was not until 1936 that the experimental work carried out by Dr. G. C. Southworth and others (27) of the Bell Telephone Laboratories established the matter on a sound practical basis. By 1940 waveguides had come into widespread use as a simple and efficient means for transmitting waves of wavelength 10 cm. or less in radar equipments. A " Glossary of Terms used in Waveguide Technique " is published as Supplement No. 1 to B.S. 204.

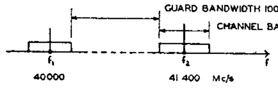
For reasons which will be discussed later it would appear that a S.H.F. waveguide relay system* should operate on a frequency of the order of 40,000 Mc/s in order that a sufficiently low attenuation may be achieved with a waveguide of reasonable size. For example at 40,000 Mc/s an attenuation of 2.6 db/mile is theoretically possible in a cylindrical copper tube of 2in diameter. If this attenuation is in fact realisable it would permit spacing the repeater stations some 10 miles apart, assuming that a carrier power of 0.1 watt is available and a carrier-to-noise ratio of 46 db in a 400 Mc/s band is sufficient (a noise-factor of 20 db is assumed).

At 40,000 Mc/s the attenuation varies but slightly over a band a thousand or more megacycles per second wide and it would be attractive to make use of this wide bandwidth (*a*) to improve the signal-to-noise ratio for example by using a frequency modulated carrier with a deviation of some ± 100 Mc/s and (*b*) to use the same waveguide to transmit the go and return channels. Thus we may visualise a S.H.F. trunk waveguide system, Fig. **14**(*a*), in which the go and return channels are about 400 Mc/s wide and are spaced 1400 Mc/s apart, Fig. **14**(*b*), in order to ease the problem of separating the R.F. channels.

In the schematic Fig.**14**(*a*), the repeaters have been shown as straight R.F. amplifiers operating at 40,000 Mc/s and having a bandwidth of 400 Mc/s. Although this may seem a somewhat optimistic extrapolation from the characteristics of existing valves, preliminary theoretical studies suggest that the proposal is by no means impracticable.



(a) SCHEMATIC



(b) FREQUENCY PLAN

FIG.14.—S.H.F. TRUNK WAVEGUIDE SYSTEM.

3.2. Characteristics of Propagation in Waveguides.

3.2.1. *Propagation in Uniform Rectangular Waveguides.*

The simplest mode of propagation in rectangular guide is known as the " transverse " electric or TE_{01} mode. It has the electric and magnetic field structure illustrated in Fig. **15**(*a*), the electric field consisting of straight lines across the short dimension of the guide(27). The longest wavelength which can be transmitted is twice the broad dimension of the guide ; the attenuation at shorter wavelengths passes through a minimum as shown in Fig. **15**(*b*) for a 1 in. × 2 in. copper waveguide, the attenuation being due to the finite conductivity of the walls of the waveguide. It is evident that the minimum attenuation for a 2 in. × 1 in. waveguide used in the TE_{01} mode, 0.8 db/100 ft. at 8000 Mc/s, is too high for use in a waveguide

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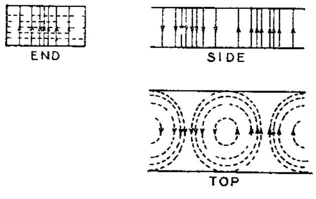
* Proposals for a trunk waveguide relay system have been made by Professor H. M. Barlow (26)(i) and J. Kemp (26)(ii).

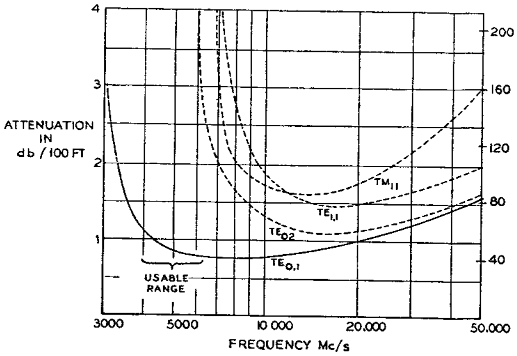
relay system although it is small enough for waveguides of this size to be used in lengths of 100 or 200 ft. as feeders connecting the aerials and equipment of S.H.F. radio relay systems.

Other more complex modes of propagation exist in rectangular waveguides but these have higher attenuations than the simple TE₀₁ mode, as indicated by the dotted curves in Fig. **15**(*b*). The usable frequency band must be chosen to avoid these unwanted modes as well as the high attenuation region, this band is also shown in Fig. **15**(*b*).



(a) TE$_{01}$ MODE IN RECTANGULAR WAVEGUIDE

ELECTRIC FIELD
MAGNETIC FIELD



(b) VARIATION OF ATTENUATION WITH FREQUENCY FOR 2" x 1" RECTANGULAR COPPER WAVEGUIDE

FIG. 15.—PROPAGATION IN RECTANGULAR WAVEGUIDE.

3.2.2. *Propagation in Uniform Cylindrical Waveguides.*

The TE₀₁ mode in a cylindrical waveguide has the electric and magnetic field distribution shown in Fig. **16**(*a*), it possesses the remarkable property that in a perfectly uniform waveguide of finite conductivity the attenuation decreases with increasing frequency (27) (28), as shown in Fig. **16**(*b*).

For a 2 in. diameter cylindrical copper waveguide the theoretical value of the attenuation is 2.6 db/mile at 40,000 Mc/s, a value which is suitable for a waveguide relay system. The higher order modes, such as those indicated by dotted curves in Fig. **16**(*b*), have attenuations which exceed that of the TE₀₁ mode at 40,000 Mc/s by a large margin. If these higher modes are excited in the waveguide they would therefore be rapidly attenuated compared with the TE₀₁ mode.

On tests carried out at the Bell Telephone Laboratories a TE₀₁ wave at 10,000 Mc/s was transmitted over an equivalent distance of some 30 km. by multiple reflection from the ends of a 100 m. length of straight cylindrical copper waveguide of 12 cm. diameter, the attenuation was found to be only about 30% greater than the theoretical value.

3.2.3. *Absorption due to Liquid Water, Water Vapour and the Permanent Gases of the Atmosphere.*

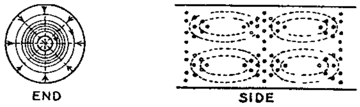
Examination of Fig. **5** shows that the absorption to be expected from a normal atmosphere is less than 0.15 db/mile at 40,000 Mc/s, this frequency being conveniently located between the water-vapour absorption peak " *a* " and the oxygen peak " *b*."

Measurements of the absorption due to liquid water in a waveguide have shown that at 3,000 Mc/s the loss due to a thin film of water is about 0.003 db/ft, that due to a heavy film with small drops is about 0.10 db/ft while puddles of water a foot long can produce losses of the order of 1 db. The losses would probably increase with frequency, the data quoted above therefore underlines the importance of keeping long waveguides free from moisture.

So far as is known nitrogen is free from absorption bands up to at least 100,000 Mc/s and a waveguide filled with dry nitrogen under pressure might be used at frequencies exceeding 40,000 Mc/s.

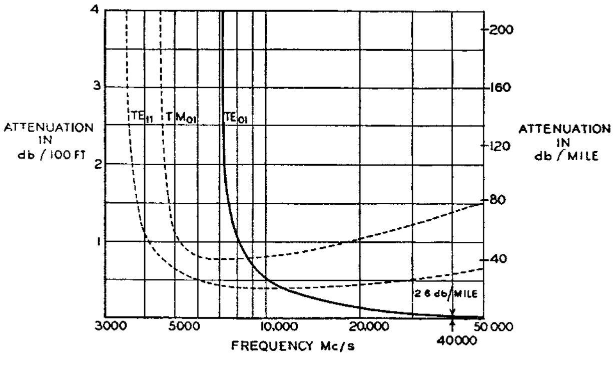
3.2.4. *Effects of Waveguide Imperfections.*

A theoretical analysis of the increased attenuation due to elliptical distortion of a nominally circular waveguide has been made by Chu (28). His results show that if the ellipse eccentricity (major-to-minor axis ratio) departs from unity by 0.1 or less the attenuation increases by less than 1 db/mile for a 2 in. diameter waveguide, moreover the TE₀₁ mode is stable and does not degenerate into higher order modes of greater attenuation. The effect of other irregularities and imperfections of the surface of the waveguide is not known at present ; it is however clear that the connection of individual lengths of waveguide must be carried out in such a manner that reflections from the joints are far less than is possible with any of the techniques in use at present, if the



(a) TE$_{01}$ MODE IN CYLINDRICAL WAVEGUIDE

ELECTRIC FIELD
MAGNETIC FIELD



(b) VARIATION OF ATTENUATION WITH FREQUENCY FOR 2 IN DIA CYLINDRICAL COPPER WAVEGUIDE

FIG. 16.—PROPAGATION IN CYLINDRICAL WAVEGUIDE.

accumulated effect of these reflections is to be negligible.

3.2.5. *Effects of Bends.*

It has been shown by Jouget (42) that a transverse electric TE_{01} wave in a cylindrical waveguide is transformed into a mixed transverse electric and magnetic wave at bends and the attenuation is considerably increased. If however a circular bend is employed between two straight cylindrical waveguides inclined at a critical angle θ given by

$$\theta = \frac{310n\lambda}{d}, \text{ degrees} \quad . \quad . \quad . \quad (6)$$

where n is any integer, λ is the wavelength and d the diameter of the waveguide, then the mixed wave in the bend is converted to a pure TE_{01} wave at the output of the bend and the attenuation is small. For example, if λ = 0.75 cm. and d = 7.5 cm., θ = 31°, 62° or 93°.

4. MODULATION SYSTEMS.

The R.F. bandwidth potentially available in S.H.F. systems is so large that the question arises—" how may these wide bandwidths be most effectively utilised for telecommunication purposes " ?

The answer to this question must be considered in relation to the type of signal to be transmitted, for present purposes this may be defined as :—

(i) assemblies of 10 to 1000 telephony channels requiring total (signal) bandwidths of 40 kc/s to 4 Mc/s, and
(ii) 405 line and higher definition or colour television signals requiring bandwidths of 3 Mc/s and possibly 15 Mc/s respectively.

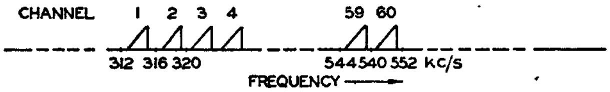
It is apparent that some of the S.H.F. systems discussed earlier have R.F. bandwidths considerably in excess of the bandwidth of the signal to be transmitted. Fortunately this large available bandwidth may be used to reduce the transmitter power for a given signal-to-noise ratio or in some systems to improve the signal-to-crosstalk ratio.

It is necessary therefore to consider the various possible modulation systems, not only in relation to the signal-to-noise and crosstalk ratio but also in terms of simplicity, flexibility, economy and reliability of the equipment required and the suitability for inclusion in the trunk network.

4.1. Transmission of Multi-channel Telephony.

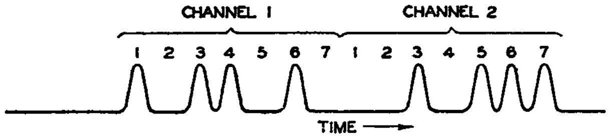
The more important modulation systems to be considered are shown in Table 1, they may be divided into continuous wave and pulsed-wave systems.

Continuous wave carriers are best suited to modulation in amplitude, frequency or phase (11), (29), (30) by a signal consisting of the various telephony channels arranged at regular intervals along the frequency scale, as in the frequency-allocation multiplex (f.a.m.) shown in Fig. **17**(*a*). The individual telephony signals are of the suppressed-carrier single-sideband type, the frequency spacing used in the Department's carrier and coaxial cable systems being the standard 4 kc/s recommended by the C.C.I.F. (31). The minimum bandwidth B required for an " n " channel A.M. system is $2nf_a$, where f_a is the highest audio frequency to be transmitted ; for F.M. and Ph.M. systems with an equivalent frequency deviation of $\pm \Delta f_c$, B is $2nf_a + 2 \Delta f_c$.



(a) FREQUENCY-ALLOCATION MULTIPLEX

(b) TIME-ALLOCATION MULTIPLEX



(c) PULSE-CODE MODULATION

FIG. 17.—FREQUENCY AND TIME-ALLOCATION MULTIPLEX AND PULSE-CODE MODULATION.

TABLE 1.
MODULATION SYSTEMS FOR MULTI-CHANNEL TELEPHONY.

BASIC SYSTEM.	TYPE OF MODULATION.	TYPE OF MULTIPLEX.
Continuous-wave (C.W.) ...	(i) Amplitude (A.M.) (ii) Frequency (F.M.) (iii) Phase (Ph.M.) (iv) Modulation of a carrier by (i), (ii), or (iii) using a sub-carrier modulated by (i), (ii) or (iii)	Frequency allocation (f.a.m.).
Pulsed-wave (P.W.)	(v) Pulse-amplitude (P.A.M.) (vi) Pulse-length (P.L.M.) (vii) Pulse-position (P.P.M.)	Time or frequency allocation (t.a.m. or f.a.m.).
	(viii) Pulse-frequency (P.F.M.)	Frequency allocation (f.a.m.).
	(ix) Pulse-code (P.C.M.)	Time allocation (t.a.m.).

Pulsed-wave carriers (32), (33), (34), (35) are, in general, best suited to time-allocation multiplex (t.a.m.) shown in Fig. **17**(*b*). Here the pulses 1, 2 . . *n* are modulated in amplitude, length or position according to the instantaneous level of the telephony signals in channels 1, 2 . . . *n* respectively. In such systems the repetition frequency of the pulse train must be at least twice the highest audio frequency to be transmitted, so that for an " *n* " channel system the pulse frequency f_p is at least $2nf_a$ and the minimum bandwidth B is $4nf_a$.

A frequency-allocation multiplex may, however, be used to modulate the individual pulse signals so that pulse systems are not exclusively confined to time-allocation multiplex.

In pulse-code modulation (36) each channel signal consists of a train of *m* pulses, Fig. **17**(*c*), each train forming a " code " corresponding to the presence or absence of certain pulses in the train, much as in the 5 unit teleprinter code. With $m = 7$, $2^7 = 128$ different signals are available, each of which may be identified with a separate step of level in the speech range to be transmitted. It is found that in practice a system which transmits 128 finite steps of level is more than adequate for telephone quality speech. The pulse frequency f_p for an *n* channel system must be at least $2nmf_a$ and the minimum bandwidth B is $4nmf_a$; for systems with many channels P.C.M. needs wide bandwidths, for example if $n = 60$, $m = 7$ and $f_a = 4$ kc/s, B is 7.5 Mc/s.

A comparison of the various modulation systems on the basis of signal-to-noise-ratio with the assumptions of equal mean carrier powers, equal overall bandwidths and numbers of channels leads to the following tentative conclusions.

Excluding pulse-code modulation the best signal-to-noise ratio is achieved with a phase-modulated continuous-carrier system using f.a.m. A frequency-modulated continuous-carrier f.a.m. system is only slightly inferior (by 4.7 db in the highest frequency channel and less in lower frequency channels). The superiority of the frequency- and phase-modulated systems to pulsed-carrier systems from the signal-to-noise aspect is partly due to the fact that they are well suited to frequency-allocation multiplex and this permits full advantage being taken of the intermittent and variable level of speech to increase the fraction of the total frequency deviation which can be allocated to each channel.

The R.M.S. carrier-to-R.M.S. noise voltage ratio required in the R.F. band of a multi-channel F.M. f.a.m. system for a given signal-to-noise ratio in an A.F. channel is given by

$$\left[\frac{\text{Carrier}}{\text{Noise}}\right]\text{R.M.S.} = \frac{\sqrt{2}f}{m\Delta f_c}\sqrt{\frac{f_a}{\text{B}}}\left[\frac{\text{Signal}}{\text{Noise}}\right]\text{R.M.S.}, \quad (6)$$

where *m* is the fraction of the deviation Δf_c allocated to each channel and *f* is the mid-band frequency of the channel (33). *m* is inversely proportional to the square-root of *n*, the number of channels, when *n* is large; for a system in which the over-load point is to be exceeded for less than 0.01% of the time and only one-third of the channels are active at a given time $m \doteqdot 0.4/\sqrt{n}$.

The degree to which the noise reducing properties of F.M. can be used to reduce the R.M.S. carrier-to-R.M.S. noise ratio required for an A.F. channel signal-to-noise ratio of 60 db is shown in Fig. **18** for various numbers of channels from 24 to 960. The bandwidth B in this diagram is the minimum R.F. bandwidth required to accommodate the frequency-modulated carrier.

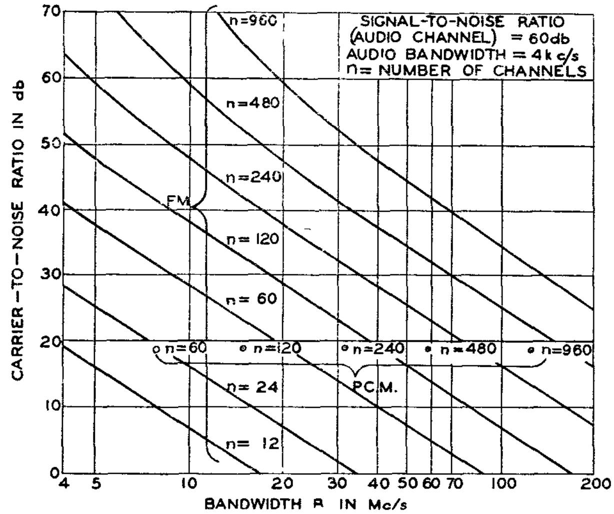


FIG. 18.—CARRIER-TO-NOISE RATIO FOR AUDIO CHANNEL SIGNAL-NOISE RATIO OF 60 DB. IN FREQUENCY MODULATION AND PULSE CODE MODULATION SYSTEMS.

With pulse-code modulation it appears that a carrier-to-R.M.S.* noise ratio of 18 db is sufficient to ensure that the signal-to-noise ratio in the audio channel is better than 60 db; the circled points in Fig. **18** show that this system is superior to F.M. by some 15 db for equal numbers of channels and R.F. bandwidths. A further advantage of P.C.M. is the possibility it offers of regenerating the pulses and so removing the accumulation of noise and distortion in a long relay system.

Detailed analysis of the various modulation systems from the crosstalk aspect has not as yet been made and only general statements are possible. Amplitude modulation is not favoured since it requires a high degree of linearity of the R.F. input/R.F. output response characteristic of the repeaters. Frequency and phase modulation multi-channel systems are not dependent on the linearity of the R.F. input/R.F. output response but do require a high degree of linearity of the phase/frequency characteristic, a requirement which is shared with systems for transmitting television signals. Pulsed-wave systems may be less critical in their phase-frequency requirements, the primary need is for adequate bandwidth so that the pulses build-up and decay sufficiently rapidly to avoid over-lapping in time.

4.2. Transmission of Television Signals.

The selection of a modulation system for relaying television signals is in practice restricted to a choice of amplitude or frequency modulation of a continuous carrier; although in principle it is possible

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* R.M.S. value of the pulsed carrier at its maximum height.

to transmit a television signal by a pulsed carrier system this technique has not yet been investigated. Since television relaying necessitates a fairly high degree of linearity of the overall amplitude response of the system, frequency-modulation is preferred to amplitude-modulation.

The minimum bandwidth B of an F.M. system used for television signal transmission is $2f_v + 2\Delta f_c$ where f_v is the highest vision frequency to be transmitted and $2\Delta f_c$ is the total frequency-deviation of the carrier between synchronising pulse tip and the white level, as shown in Fig. **19**.

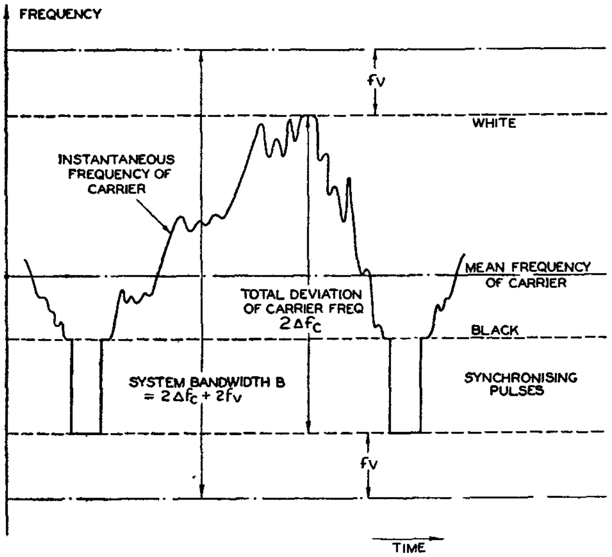


Fig. **19**.—Carrier Modulated in Frequency by a Television Signal.

The R.M.S. signal-to-R.M.S. noise ratio required in television signal transmission is of the order of 50 db, the corresponding carrier-to-noise voltage ratio is given by

$$\left[\frac{\text{Carrier}}{\text{Noise}}\right]\text{R.M.S.} = \frac{1}{\sqrt{3}} \cdot \frac{f_v}{\Delta f_c}\left[\frac{\text{Signal}}{\text{Noise}}\right]\text{R.M.S.} \qquad (7)$$

For example, if the deviation ratio $\frac{\Delta f_c}{f_v}$ is 5, the carrier-to-noise ratio required is 31.3 db for a signal-to-noise ratio of 50 db. If $f_v = 3$ Mc/s, the R.F. bandwidth B is 36 Mc/s.

4.3. Preferred Modulation System.

Phase or frequency-modulation systems are considered to have many practical advantages :—

(i) suitability for use with existing frequency-allocation multiplex terminal equipment,
(ii) suitability for use with television signals,
(iii) modulating and demodulating equipment is of a relatively simple kind, and
(iv) repeaters are not required to operate linearly, level stabilisation may be achieved with simple amplitude limiting.

For certain multi-channel telephony applications where the signal-to-noise and signal-to-crosstalk ratio requirements are difficult to meet using phase or frequency-modulation, pulse-code modulation may be preferred. Furthermore pulse-code modulation has important advantages from the privacy aspect since the " code " can be changed at will.

5. GENERATION, AMPLIFICATION AND FILTERING OF S.H.F. WAVES.

It is not possible in the space available to do more than describe a few typical examples of S.H.F. techniques. In practice a wide range of techniques is available, most of which have been developed for radar purposes but which can be adapted for telecommunications.

In general it will be preferred to use low power oscillators in the transmitters followed by R.F. amplifiers to give the required power output, since a low power oscillator is more readily modulated and stabilised in frequency than is an oscillator of higher power operating directly into an aerial as in radar. Low power oscillators are also needed for use as the beating (frequency-change) oscillators in superheterodyne receivers.

Although the power output required from R.F. amplifiers is relatively small it is desirable for the efficiency to be at least a few per cent, in order to reduce the power required from the high tension supply. With conventional valves of the space-charge control type the power output, efficiency and gain decrease as the frequency is increased, owing to limitations imposed by the transit time of the electrons and the effects of the inductance of leads to the electrodes. These limitations can be minimised by the use of the grounded-grid triode type of valve with very small clearances between the electrodes, but for practical purposes it may be said that at present the upper useful limit of frequency is about 1500 Mc/s for amplifiers capable of some few watts output with adequate efficiency, satisfactory low-power grounded-grid triode oscillators have been produced for frequencies up to about 3000 Mc/s.

Although some improvement in these figures may be expected it is apparent that for frequencies much above 3000 Mc/s methods of operation other than conventional space-charge control are necessary if adequate gain, power output and efficiency are to be obtained. Fortunately above about 1500 Mc/s it is possible to use valves of the velocity-modulation type as amplifiers and oscillators, the magnetron is also available as a high-efficiency oscillator.

5.1. Amplifiers.

5.1.1. *Velocity-modulation Klystron Amplifier.*

The basic elements of a double-resonator klystron amplifier(37) are shown in Fig. **20**, it consists of two

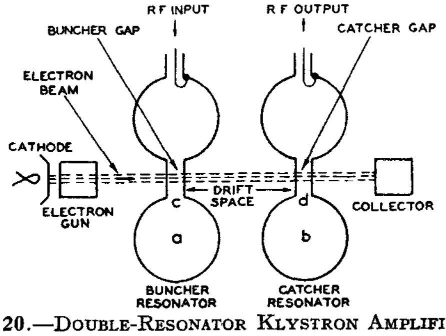


Fig. **20**.—Double-Resonator Klystron Amplifier.

cavity resonators (*a*, *b*) termed the " buncher " and " catcher " respectively, which are traversed by an electron beam. Each resonator consists of an enclosure with two plane surfaces separated by narrow gaps (*c*, *d*) at the centre, the surfaces being perforated by holes to permit the passage of the electron beam.

When the buncher is excited by radio frequency power, fed in by means of a suitable coupling loop or probe, a relatively strong alternating electric field exists across the narrow gap, provided that the frequency of the applied carrier is equal or close to the resonant frequency of the buncher. Under these conditions the velocity of the electrons is varied by the electric field, some electrons being accelerated when the direction of the electric field is opposite to that of electron flow and others retarded when the field reverses. Thus some electrons leave the buncher gap with greater than average velocity and others with less. As the electrons pass along the space between the buncher and catcher—the " drift " space—the faster moving electrons overtake the slower electrons and form bunches or groups with greater than average density. The time of transit through the buncher gap is a small fraction, usually about one-third, of a radio-frequency cycle. The time of transit through the drift-space is much longer and may amount to several radio frequency cycles in order to obtain effective bunching. The average time spent in the drift-space depends on the average velocity of the electrons and therefore on the direct accelerating potential between the cathode and anode, *i.e.*, between the resonators which are normally earthed and the cathode which is usually held below earth potential by some 1000 to 3000V.

The electron beam is thus modulated in intensity at the applied radio frequency and its harmonics; the effect of passing such a modulated beam through the output or catcher resonator is to excite the latter at the fundamental frequency and to produce a corresponding radio-frequency electric field across the gap. Electrons passing through the gap are retarded during the half of the radio frequency cycle for which the field is in the same direction as the motion of the electrons and therefore give up energy to the resonator, other electrons which pass through when the field is in the reverse direction are accelerated and absorb energy from the resonator. Many more electrons pass through the gap when the field is retarding than when it is accelerating and the nett result is a considerable absorption of energy from the beam. Under suitable operating conditions more radio frequency power can be taken from the catcher resonator than is applied to the buncher, *i.e.*, the valve is an amplifier. The difference between the R.F. output power and the R.F. input power comes from the power in the electron beam (*i.e.*, the product of the beam current and the accelerating voltage); only a fraction of the beam power is, however, abstracted at the catcher and the remainder appears as heat due to electron bombardment of the electrode on which the beam is finally collected.

The gain of a klystron amplifier can be improved by using three resonators in cascade along the same electron-beam, the second resonator being also tuned to the signal frequency but not connected to an external circuit. One advantage of this type is that it can be designed to yield maximum power output with comparatively small drive-power; with a small amount of driving power the bunching at the first gap is not complete but additional bunching occurring at the second gap enables optimum bunching to be obtained at the output gap. A triple-resonator klystron amplifier is shown in Fig. **21**, its characteristics are given below.

Characteristics of Klystron Amplifier.

	Narrow Bandwidth.	*Wide Bandwidth.*
Operating frequency (Mc/s)	3000	3000
Bandwidth (3 db below maximum) (Mc/s)	3	10
Beam voltage (V)	3000	3000
Beam current (mA)	80	80
Maximum R.F. power output (W)	10	10
Gain (under linear conditions) (db)	20	10
Efficiency (%)	4	4

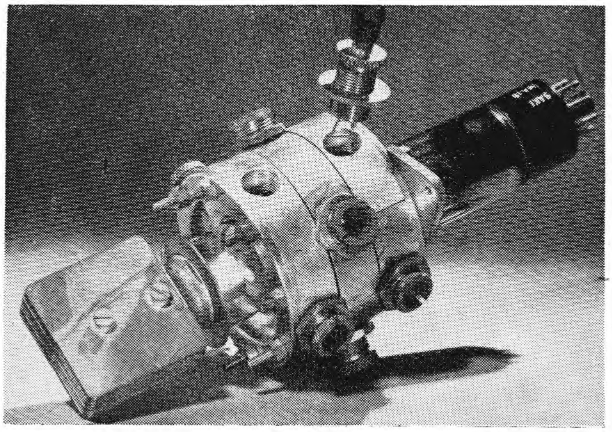


FIG. **21**.—TRIPLE-RESONATOR KLYSTRON AMPLIFIER.

The noise factor of a typical (3000 Mc/s) klystron is of the order of 30 db compared with about 15 db for a super-heterodyne receiver operating on the same frequency and in which the first stage is a crystal mixer. Thus it appears that at present the klystron amplifier is not suitable for use as the input amplifier in receiving equipment, although, of course, it is of value for use as a power amplifier in transmitting equipment.

The performance data given above does not by any means represent the best performance which can be achieved with klystron amplifiers and it is known that appreciably greater bandwidths, efficiency and gain can be achieved for example by using annular electron beams(38).

5.1.2. *Travelling-wave Amplifier.*

The first travelling-wave amplifier(39) was developed by Kompfner working at the Clarendon Laboratory, Oxford, during the period 1942-1944. The feature of major interest in the travelling-wave valve is the remarkably wide bandwidth, for example some 800 Mc/s at 3000 Mc/s ; because of this feature the valve is now being studied intensively.

The travelling-wave valve is relatively simple in construction—it consists primarily of a closely wound helix along which the R.F. electro-magnetic wave is propagated. An electron beam is made to traverse the helix axially, an axial magnetic field produced by a direct-current carrying solenoid being used to focus the electron-beam so that most of the current in the beam is received by a collector electrode. When the velocity of propagation of the R.F. wave along the helix is nearly the same as the velocity of the electrons in the beam, interaction between the wave and the beam occurs, with the result that under suitable conditions the amplitude of the wave increases progressively after a certain point on the helix.

A travelling-wave amplifier is shown in section in Fig. **22**, which indicates the wave-guides used to transmit R.F. power on to and away from the helix and the solenoid for producing the magnetic field for focusing the electron-beam.

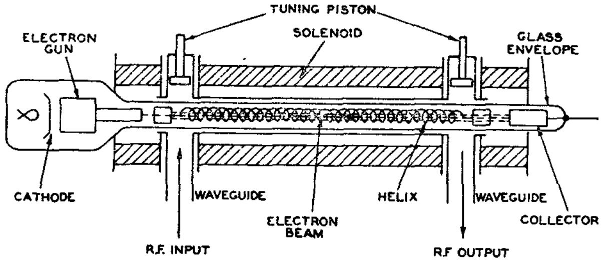


FIG. 22.—TRAVELLING-WAVE AMPLIFIER.

The characteristics of a typical valve designed by J. R. Pierce and L. M. Field (40) are given below.

Characteristics of Travelling-wave Amplifier.

Beam voltage	1670 V
Cathode current	8 mA
Collector current	6 mA
Gain at 3600 Mc/s	23 db
Bandwidth (3 db)	800 Mc/s
R.F. power output	0.2 W
Efficiency	1.5 %

Noise arises in travelling-wave amplifiers due to fluctuations of the electron stream, as in the klystron amplifier. Valves for low noise output should be operated with a small beam current ; Kompfner has described a valve with a noise-factor of 11db, the beam current being 50 microamperes (39). The noise-factor of this valve is appreciably better than that of existing klystron amplifiers and compares favourably with the overall noise-factor of receivers using crystal mixers.

Structures other than the helix, *e.g.*, corrugated waveguides, may be used with the object of improving the efficiency by increasing the axial R.F. electric field for a given R.F. power input. Structures of the corrugated waveguide type also have the advantage that they are more readily scaled down in size for use at higher frequencies than is the case with the helix. In one type of corrugated circular waveguide the corrugations are formed by metal discs with large and small central holes, assembled alternately on a common axis, along which the electron beam passes. Such a valve bears a close resemblance to a klystron amplifier in which there are many resonators, in fact the operation of the travelling-wave valve may be explained in terms of velocity modulation and electron bunching as in the klystron amplifier.

At present the power output and efficiency of the helix type of travelling-wave valve are rather low, power outputs of 1.5 W at about 2% efficiency have been reported. Large power outputs require large beam currents which lead to difficulties in the cathode and gun design, and in focusing the beam through the long solenoid. The coupling between beam and helix is not large and this is a contributory factor in lowering the efficiency. It seems probable however that efficiency and power output will both be raised considerably in the near future with valves using the corrugated waveguide technique, although probably at the expense of bandwidth.

5.2. Oscillators.

5.2.1. *Reflex Klystron Oscillator.*

Although the double-resonator klystron amplifier may be made to oscillate by providing a suitable feedback path, the single-resonator reflex klystron oscillator is preferred because of the ease of tuning and simplicity of construction. In a reflex klystron oscillator the electron beam traverses the resonator twice, firstly in a forward direction from the cathode and secondly in the reverse direction after reflection from an electrode held at a negative potential with respect to the cathode. The beam becomes velocity modulated in the first transit and subsequently bunches of electrons form in the retarding field around the reflector electrode. The drift-time is determined by the anode (resonator) voltage and the reflector voltage relative to the cathode, since the former determines the electron velocities and the latter the distance they travel in the drift-space. By suitable adjustment of these voltages the drift time may be made such that each bunch arrives in the correct phase to give up energy to the resonator, a condition which is fulfilled if the drift-time is $n + 3/4$ periods of the oscillation (n being an integer usually in the range 2 to 10). Oscillation occurs if the energy extracted from the beam is equal to, or exceeds, the losses in the resonator and the load circuit.

Since the frequency of oscillation may be varied over a limited range by adjustment of the reflector-cathode voltage (the reflector current being negligible), the reflex klystron is particularly useful as an electronically tuned beating oscillator in a receiver or as a low-power frequency-modulated source.

The characteristics of a typical low-power reflex klystron oscillator for use in the frequency range 2930 to 3130 Mc/s are given below.

Characteristics of Reflex Klystron Oscillator.

Beam voltage	250 V
Reflector/cathode voltage	100-175 V
Beam current	32 mA
R.F. power output	150 mW
Efficiency	2%

The variation of frequency with reflector/cathode voltage is such that a linear variation of frequency of some ± 5 Mc/s for ± 5 V variation of the reflector/cathode voltage can be achieved with negligible variation of output. Measurements of the modulating voltage required at various frequencies for constant frequency deviation have shown that modulating frequencies up to at least 10 Mc/s may be applied for a variation of deviation of less than 10%.

5.2.2. *Magnetron Oscillator.*

Magnetrons are not only suitable for high-power pulse operation as in radar but also as highly efficient low-power C.W. oscillators. They are not suitable for linear amplitude modulation but may be frequency modulated by varying the current in one or more auxiliary electron beams passed through the cavities of the magnetron (41). The characteristics of a typical C.W. magnetron for use at 4000 Mc/s are given below.

Characteristics of Frequency-modulated C.W. Magnetron.

Operating frequency	4000 Mc/s
R.F. power output	25 W
Efficiency	50%
Anode voltage	850 V
Anode current	60 mA
Frequency deviation	±2.5 Mc/s

5.3. Filters.

Filters for use at S.H.F. may be constructed from lengths of waveguide in which are inserted diaphragms with circular or dumb-bell shaped apertures. Such diaphragms are equivalent to tuned circuits and may be tuned to a required frequency by means of adjusting screws projecting into the aperture. An example of a 4000 Mc/s band-pass filter of this kind is shown in Fig. **23**(*a*) and the insertion-loss/frequency characteristic in Fig. **23**(*b*).

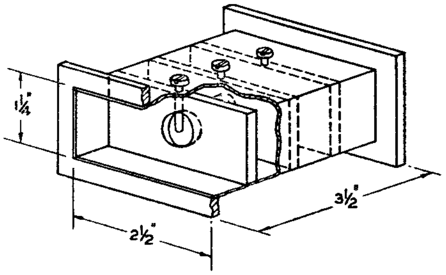
S.H.F. filter design is at present in the early stages of development but it would appear that many of the principles of design which are used at much lower frequencies are also applicable in the S.H.F. range and that a wide range of useful filters is possible.

6. CONCLUSIONS.

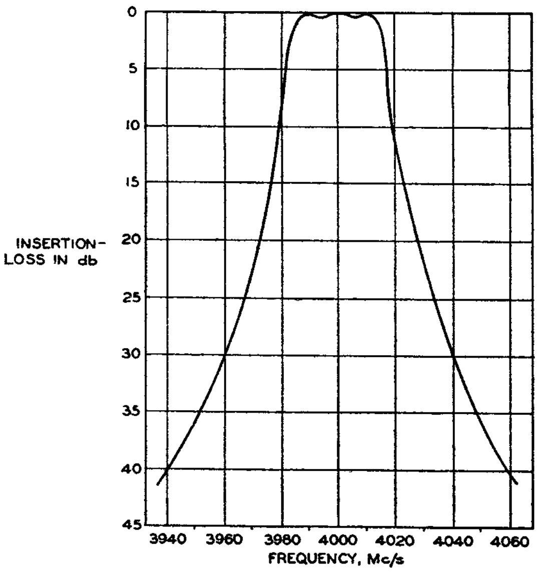
It is considered that radio relay systems operating in the frequency range 4000-8000 Mc/s offer the earliest prospects of exploiting for telecommunication purposes the wide frequency bands available at S.H.F. The reason for this is that in broad outline the characteristics of the transmission paths are known and the principles of equipment design have been established. However, before such systems can take their place in the trunk network much work remains to be done in order to produce equipment that has the necessary high standard of performance and reliability. There is considerable scope for development in valves using the velocity-modulation principle, in particular the power output and efficiency of travelling-wave valves should be capable of improvement and it is by no means certain that the optimum noise-factor has as yet been obtained.

The development of suitable S.H.F. filters, in conjunction with valves of the travelling-wave type, may be expected to lead to relatively simple repeaters in which S.H.F. oscillators and the associated frequency control equipments are unnecessary.

Some experimental evidence is available to show that the theoretically predicted low attenuation of the TE_{01} mode wave in cylindrical waveguide can in fact be substantially realised in practice. Thus a frequency band ranging from 40,000 to 80,000 Mc/s may become available on a single 2 in. diameter waveguide, so providing a trunk system the bandwidth capabilities of which would meet the largest demands of communication engineers for the foreseeable future.



(a) CONSTRUCTION



(b) INSERTION-LOSS FREQUENCY CHARACTERISTIC

FIG. 23.—WAVEGUIDE FILTER FOR 4000 Mc/s.

7. ACKNOWLEDGMENTS.

The thanks of the author are due to Capt. C. F. Booth, Mr. H. T. Mitchell and to other colleagues for much helpful advice and discussion during the preparation of this paper.

8. SUMMARY OF DISCUSSION AT THE LONDON CENTRE ON 8th NOV., 1948.

The discussion was opened by the Engineer-in-Chief, *Sir Archibald Gill,* who drew attention to the pioneering work of Dr. G. C. Southworth of the Bell Telephone Laboratories on waveguide transmission systems ; he also referred to the possibility of using the wide bandwidths available on radio relay and waveguide systems to lower the cost of the terminal equipment for multi-channel telephony, for example, by increasing the frequency spacing between telephony channels, so simplifying the filter design. *Captain C. F. Booth* said that radio relay and coaxial cable systems both had a place in the trunk network of the country, and the relative advantages and disadvantages would only be decided after experience had been obtained with both systems ; the radio relay link for television installed between London and Birmingham would provide valuable experience on the operation of a radio link on a commercial basis.

Several speakers stressed the importance of reliability and the need for equipment to be designed for easy maintenance. Some doubts were expressed as to the wisdom of transmitting very large numbers of telephony channels on one repeater, there was a general feeling that about 1,000 channels was the maximum desirable.

Reference was made to some earlier work of M. Jouget's which predicted that very large radii of curvature would be needed for bends in waveguide systems if excessive attenuation was to be avoided. It appears that later work of M. Jouget's has established the fact that relatively sharp bends are practicable provided that the angle of the bend is adjusted to one of certain critical values (see Section 3.2.5 of the paper).

The status of the TE_{01} mode wave was questioned and it was asked whether experimental evidence as to its stability was available. In reply it was said that recent work in the Bell Telephone Laboratories, U.S.A., in the General Electric Company, England, and in the Centre Nationale des Etudes en Télécommunications, France, had confirmed the existence and stability of this mode and had shown that attenuations only slightly above the theoretical value were realisable.

A speaker asked whether consideration had been given to the use of lens aerials as passive repeaters. In reply it was said that such repeaters cannot compete with free-space propagation unless they are spaced by relatively small distances and are very low-loss.

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