Long-Wave and Medium-Wave Propagation

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BBC Engineering Training Department

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FOREWORD

THIS booklet is based on a series of lectures given by the author at the BBC Engineering Training Department to students specialising in the operation and maintenance of transmitting stations. It is now offered to a wider public because it is believed that many radio engineers and students will find it useful to have the information readily available in a concise form.

The author desires to express his thanks to his colleagues in the Engineering Division of the BBC for their assistance in preparing the text of this book, and to make the following acknowledgments:

Figure 2 is based upon a curve given by H. P. Williams in "Antenna Theory and Design" published by Sir Isaac Pitman & Sons, Ltd.

Figures 5, 6, 7, 8 and 9 are based upon curves given in C.C.I.R. Recommendation No. 52 (Volume 1 of the documents of the C.C.I.R. VIIIth Plenary Assembly, Warsaw, 1956, published by the International Telecommunication Union, Geneva).

LONG-WAVE AND MEDIUM-WAVE PROPAGATION

Introduction

The general purpose of this Supplement is to explain the main features of propagation at low and medium frequencies i.e. 30–3000 kc/s, and in particular in the bands used for broadcasting viz. 150–285 kc/s and 525–1605 kc/s. In these bands, the signal at the receiver may have two components: they are

(a) a ground wave, i.e. one that follows ground contours
(b) an ionospheric wave (sky wave) which is reflected from an ionised layer under certain conditions.

In the vicinity of the transmitter, the ground wave is the predominant component, and for domestic broadcasting, the service ideally would be provided by the ground wave only. In fact the limit to the service area is often set by interference from the sky wave.

The magnitudes of the ground wave and sky wave are determined to a large extent by the properties of the transmitting aerial, and hence any discussion of propagation is intimately linked with that of aerials. For this reason, the radiating characteristics of various types of aerial are discussed briefly at the outset. The propagation of the ground wave is next treated in some detail, with particular reference to the attenuation of the wave by absorption of power in the earth over which the wave is travelling.

The propagation of the sky wave is then considered and the limiting of the service area by sky-wave effects is discussed. The principles of ionospheric reflection are not covered, as they are adequately explained elsewhere.[1]

Before beginning the main discussion it is essential to define field strength and state acceptable values for different conditions of broadcasting service and transmitter site.

The field strength provided by a transmitter and aerial system is measured in terms of microvolts per metre (μV/m) or millivolts per metre (mV/m) and is the open-circuit voltage induced in one metre of correctly orientated aerial wire. (With the aerials and couplings generally used, only a fraction of the induced voltage is actually delivered to the receiver).

The field strength for an acceptable medium-frequency service depends on the condition of operation. Under best conditions of transmission on a clear channel during daylight hours noise will be the limiting condition and for a high grade broadcasting service a signal-to-noise ratio of the order of 40 db is desirable. The noise may be generated by electrical apparatus or by electrical storms, and with either method of generation the noise interference will tend to decrease with increase of transmitter frequency. Noise due to electrical apparatus will naturally tend to be greatest in metropolitan areas and least in rural areas; the difference may be of the order of 20 db. As far as atmospheric noise is concerned a summer evening tends to give the noisiest conditions though local storms can give very much greater noise levels. After nightfall reflection takes place from the ionosphere causing interference of the sky wave with the ground wave and this can only be overcome by increasing the ratio of ground-wave to sky-wave field strength. For a given aerial system this means an increase in the minimum acceptable field strength, i.e., a reduction in service area. An 'anti-fading' transmitting aerial, which increases the ratio of ground-wave to sky-wave radiation, will obviously be desirable under these conditions. A still further increase in minimum field strength will be necessary when the transmission channel is shared with other stations even when they are part of a synchronised group carrying the same programme. Table 1 below indicates the order of acceptable field strengths required for different conditions.

TABLE 1

Field strength necessary for an acceptable service under typical conditions

DAY		NIGHT		
Single transmitter	*Synchronised group*	*Single transmitter*		*Synchronised group*
4 mV/m	Whichever is the greatest of: (i) 4 mV/m (ii) 4 times an unwanted signal carrying the same programme (iii) Up to 600 times an unwanted signal carrying a different programme	Assuming a good anti-fading transmitting aerial, 5 mV/m	Assuming a poor transmitting aerial, 9–10 mV/m	May be as high as 12 mV/m if the wanted signal is to be 4 times greater than an unwanted signal carrying the same programme

Note: Interference from the Continent may entirely upset any of these figures

The minimum figure shown in Table 1 of 4 mV/m is generally sufficient to give a ratio of 40 db between the signal and the electrical noise of a metropolitan area. In rural areas this signal-to-noise ratio could be maintained with a much lower field strength of about 0·5 to 1 mV/m, but at this field strength the receiving site may be outside the fade-free range after nightfall.

Aerials

Nearly all transmitting aerials used on low and medium frequencies for domestic broadcasting consist of vertical wire or mast radiators often with inductive or capacitive loading. Such aerials produce a vertically polarised wave.

The field strength provided by such an aerial depends upon the aerial radiation pattern and the power input to the aerial. Assuming that the earth is flat and perfectly conducting, and that the current distribution in the aerial is sinusoidal, the radiation pattern in the vertical plane of a short aerial, i.e. one whose height is for example less than 0·125λ, is approximately a semicircle, as shown in Fig. 1. As the aerial height is increased the vertical

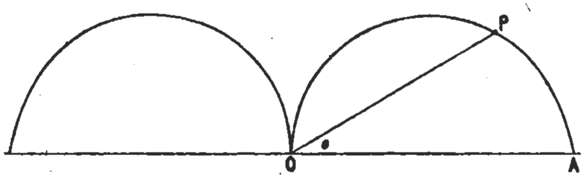


Fig. 1. Vertical radiation pattern for short aerial

radiation pattern tends to flatten with increase of energy along the ground and a reduction of the energy directed skywards. When the height is increased beyond about 0·5λ secondary lobes of high-angle radiation appear and eventually there is a decrease of energy directed along the ground. There is therefore an optimum value of height giving maximum ground-wave field strength and as shown in Fig. 2 it occurs for a height of about 0·625λ. It should, of course, be noted that the height referred to above is the equivalent electrical height and is greater than the actual physical height due to an extension of the electric field beyond the end of the aerial. The physical height will be of the order of 5 to 10 per cent less than the equivalent electrical height. It is the same kind of 'end' effect which is encountered with open-ended organ pipes. The increase in high-angle radiation from the aerial when height exceeds about 0·5λ can be a disadvantage since the sky wave may be reflected back to earth at some distance from the transmitter so interfering with the ground wave. The limit of the service area is usually taken as the boundary at which the magnitude of the reflected sky wave (assuming the ionosphere to be a perfect reflector) would equal that of the ground wave. The condition for maximum range under these conditions occurs when aerial height is of the order of 0·55λ and such an aerial is termed an anti-fading aerial.

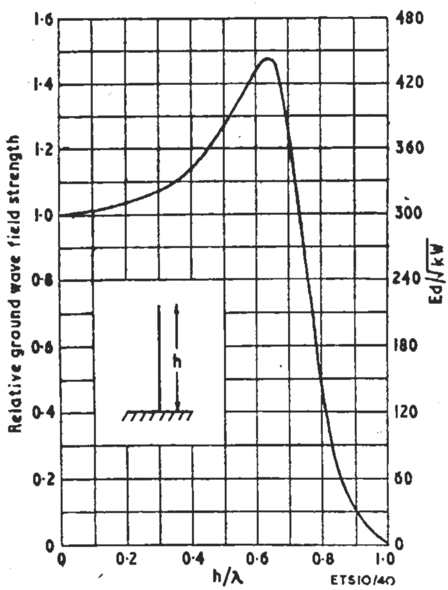


Fig. 2. Showing the variation of ground-wave field strength with transmitting aerial height

The field strength due to the ground-wave signal at any distance, assuming the earth to be perfectly conducting, is given by

$$E = E_1/d$$

where E_1 is the field strength at a horizontal distance of 1 kilometre from the aerial and d is the distance in kilometres.

E_1 is usually designated the 'unattenuated field strength at 1 kilometre'. It is of fundamental importance in propagation problems. E_1, however, varies directly with the square root of the power delivered to the aerial, and is thus only indirectly an indication of the efficiency of the aerial itself. If, however, E_1 is divided by $\sqrt{kW}$ the result is a figure of merit for the aerial proper. By noting that $E = E_1/d$ this figure of merit becomes $Ed/\sqrt{kW}$, and is usually quoted as 'Ed per root kilowatt'. It is equal to the field strength in mV/m at a distance of 1 kilometre when the power fed to the aerial is 1 kilowatt, and the aerial is situated over a perfectly conducting earth. Its variation with aerial height is shown in Fig. 2.

Whilst the figure of merit varies primarily with the height of the aerial, it is also dependent on the form of the aerial (i.e. whether it is a wire or mast radiator and whether it is loaded). It is also affected by the presence of nearby objects.

There is a further factor in that some aerials are partially directional such as Postwick and Start Point (Home Service); Burghead, Westerglen, Moorside Edge and Brookman's Park (Light Programme); for these aerials the maximum value of $Ed/\sqrt{kW}$ is quoted together with the direction in which this occurs.

The value of $Ed/\sqrt{kW}$ for a short aerial is 300 m/Vm, and this is often used as a reference figure for assessing the performance of other aerials. Masts or aerials effectively much longer than $\lambda/4$ can give appreciably higher values of $Ed/\sqrt{kW}$. The best figures approach 400 as for the mast radiator at Daventry (Third Programme).

In practice the earth losses cannot be assumed to be zero and some loss of efficiency occurs. In extreme cases the losses may be so high that when 1 kW is applied to the aerial the field strength at 1 km may be as low as 100 mV/m.

Ground-wave Propagation

When the surface of the earth can be assumed flat, the ground-wave field strength can be expressed by Sommerfeld's equation:

$$E = \frac{E_1 . A}{d}$$

where E = received field strength

E_1 = unattenuated field strength at unit distance. A table of values for medium- and high-power BBC transmitters is given in Appendix I.

d = distance

A = attenuation factor.

In the Sommerfeld equation the factor A represents the earth losses. With a perfectly conducting earth the ground-wave field strength at any point would be E_1/d. The nearest approach in practice is the propagation curves for low-frequency signals over sea water (Fig. 8). Energy lost from the wave front into the ground is replaced by energy higher in the wave front and hence there is a continuous movement of energy down towards the ground.

The attenuation factor A takes into account the effect of the ground over which the wave passes. It also varies with the frequency of the signal. The ground wave induces a charge in the ground and this charge travels with the wave, constituting a flow of current. The important ground constants are, therefore

(a) conductivity (Symbol σ (sigma)) which governs the loss of energy whilst the charge is moving, and
(b) permittivity (Symbol ε (epsilon)) which influences the production of the charge.

At low and medium frequencies the more important component in ground attenuation is conductivity, permittivity being relatively unimportant. At frequencies above about 1·5 Mc/s permittivity becomes increasingly important.

The conductivity of a material is equal to the conductivity between opposite faces of a cube of 1 centimetre side. As far as propagation is involved the important criterion is average conductivity and it is usually expressed in electro-magnetic units. In the e.m. system of units, the unit of resistance is equal to 10^9 ohms, and hence the e.m. unit of conductivity is equal to 10^{-9} of the practical unit, mhos/cm.

The values of conductivity which affect ground-wave propagation at low and medium frequencies depend upon the nature of the ground down to considerable depths (for example, currents at low frequencies may be induced at depths of over 100 feet). There is close correlation between conductivity and the geological structure of the ground and reference is made to this matter in a later section. Some examples of conductivity and permittivity are shown in Table 2.

TABLE 2

Examples of Conductivity and Permittivity

Surface, and Classification in Conductivity	*Conductivity*	*Permittivity*
Ground, Good	$\sigma = 10^{-13}$ e.m.u. $= 0{\cdot}01$ mhos/metre	$\varepsilon = 4$
Ground, Moderate	$\sigma = 10^{-13\cdot5} \simeq 3 \times 10^{-14}$ $= 0{\cdot}003$ mhos/metre	$\varepsilon = 4$
Ground, Poor	$\sigma = 10^{-14}$ e.m.u. $= 0{\cdot}001$ mhos/metre	$\varepsilon = 4$
Sea Water, Very Good	$\sigma = 4 \times 10^{-11}$ e.m.u. $= 4$ mhos/metre	$\varepsilon = 80$
Fresh Water, Good	$\sigma = 10^{-13}$ e.m.u. $= 0{\cdot}01$ mhos/metre	$\varepsilon = 80$

In order to use the Sommerfeld formula for calculating field strength the attenuation factor A must first be evaluated. Fig. 3 shows the relationship between A and a parameter called the numerical distance (Symbol ρ). If the following conditions prevail:

(1) range is such that the earth's curvature can be ignored,

(2) the frequency is less than 1·5 Mc/s,

(3) the conductivity is greater than 10^{-14} e.m.u.

then the numerical distance can be calculated from the following formula:

$$\rho = \frac{\pi d}{2c} \cdot \frac{1}{\lambda^2 \sigma}$$

where σ = conductivity
d = distance
λ = wavelength
c = velocity of propagation of an electromagnetic wave.

The unit of length is the centimetre if σ is expressed in e.m. units.

When a value for A has been obtained the required field can be found from:

$$E = \frac{E_1 \cdot A}{d}$$

Since the unattenuated field strength at 1 kilometre is usually given, d is the distance in kilometres. A set of graphical solutions for E for various values of d have been prepared by the C.C.I.R., and these are discussed further later.

In practice it is often possible to make a fair assessment of conductivity, as for example, over the areas of clay in the Midlands, but at times the variations are so great that a different method (see page 20) must be used. Two examples where an average value of conductivity can be used are as follows:

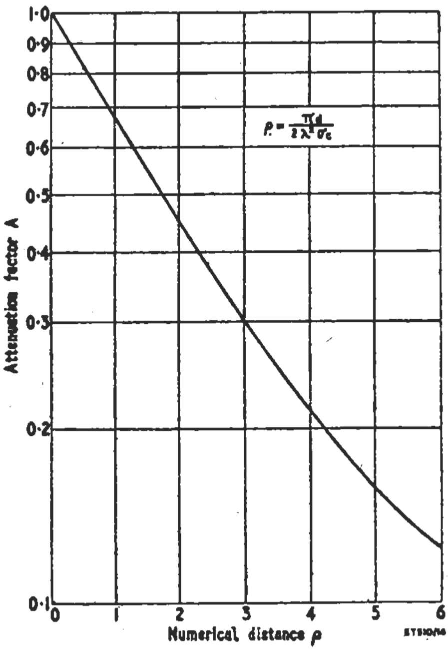


Fig. 3. Showing the variation of the attenuation factor A with ρ, the numerical distance; these factors are used in the evaluation of field strength by the Sommerfeld formula

Example 1

Calculate the field strength at Hull of the Third Programme transmission from Daventry.

The distance d = 183 km = 183 × 10^5 cm.

Conductivity σ has an average of about 12 × 10^{-14} e.m.u. (see Fig. 4).

Velocity of propagation c = 3 × 10^8 metres/sec = 3 × 10^{10} cms/sec.

From Appendix I,

$$\lambda = 464 \text{ metres} = 4{\cdot}64 \times 10^4 \text{ cm}$$

$$E_1 = 4500 \text{ mV/m}$$

$$\text{Then } \rho = \frac{\pi d}{2c} \cdot \frac{1}{\lambda^2 \sigma}$$

$$= \frac{\pi \times 183 \times 10^5}{2 \times 3 \times 10^{10} \times 21{\cdot}5 \times 10^8 \times 12 \times 10^{-14}}$$

$$= \frac{183\pi}{155}$$

$$= 3{\cdot}7$$

From the curve relating A and ρ (Fig. 3)

$$A = {\cdot}236$$

The required field strength

$$E = \frac{E_1 \, . \, A}{d} \text{ mV/m}$$

$$= \frac{4500 \times {\cdot}236}{183} = \text{nearly } 6 \text{ mV/m}$$

The BBC Research Department have produced maps of the field strength coverage of the medium frequency transmissions and that for the Third Programme shows the field strength measured at Hull to be about 7 mV/m.

Example 2

Calculate the field strength at Blackpool from the Droitwich 200 kc/s transmission.

Distance $d = 187$ km $= 187 \times 10^5$ cm.

Conductivity σ has an average of about 10^{-13} e.m.u.

Velocity of propagation $c = 3 \times 10^{10}$ cm/sec

From Appendix I

$$\lambda = 1500 \text{ metres} = 15 \times 10^4 \text{ cm}$$

$$E_1 = 6000 \text{ mV/m}$$

$$\text{Then } \rho = \frac{\pi d}{2c} \cdot \frac{1}{\lambda^2 \sigma}$$

$$= \frac{\pi \times 187 \times 10^5}{2 \times 3 \times 10^{10} \times 225 \times 10^8 \times 10^{-13}}$$

$$= \frac{187\pi}{1350}$$

$$= 0{\cdot}435$$

From the curve relating A and ρ (Fig. 3)

$$A = 0{\cdot}84$$

The required field strength

$$E = \frac{E_1 . A}{d} \text{ mV/m}$$

$$= \frac{6000 \times 0{\cdot}84}{187} \text{ mV/m}$$

$$= 27 \text{ mV/m}$$

As shown on the Light Programme coverage map, the measured field strength at Blackpool is about 25 mV/m.

Geological Correlation

When considering low- and medium-frequency propagation a knowledge of the nature of the ground is extremely important.

The depth of penetration of radio-frequency currents depends, for example, not only on frequency but also on ground constants. Table 3 shows the depth in feet at which the current is one tenth of its value at the surface, the relationship being:

$$\frac{\text{current density at depth } d}{\text{current density at surface}} = e^{-pd}$$

d = depth in cm

$p = \sqrt{(4\pi^2 \times f \times \sigma \times 10^6)}$ (approximately, when f is less than 1·5 Mc/s)

f = frequency in Mc/s

σ is in e.m.u.

TABLE 3

Depth of penetration in feet (Current density = 10% that at surface)

Surface Constants	0·2 *Mc/s*	1 *Mc/s*	1·5 *Mc/s*
Sea Water = 4×10^{-11} e.m.u.	4·3	1·9	1·6
Good Soil = 10^{-13} e.m.u.	85	38	31
Poor Soil = 10^{-14} e.m.u.	270	121	99

Penetration to these different depths may involve different strata. Consequently the estimation of conductivity by field strength measurement may produce different figures over the same path if different frequencies are used.

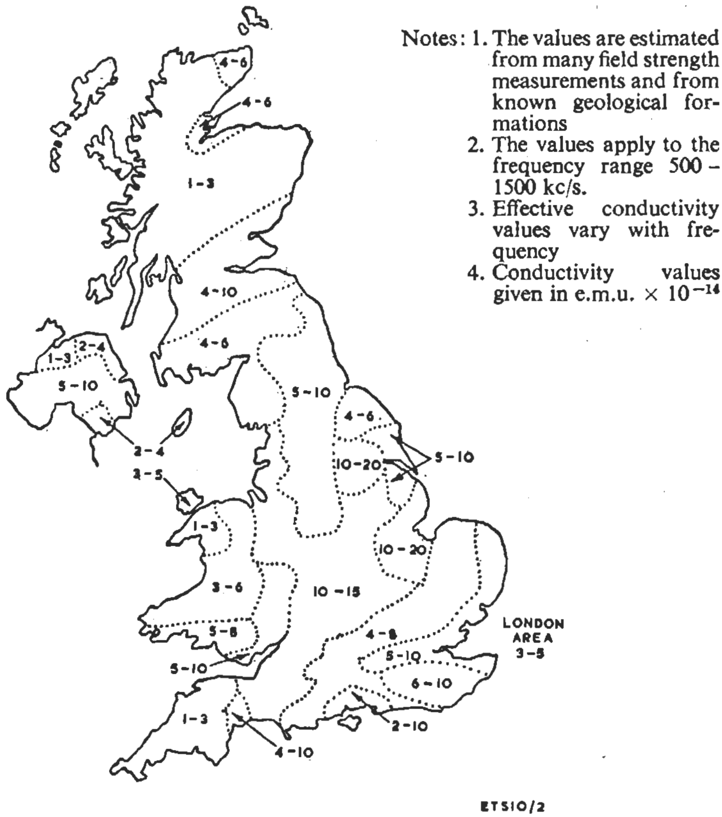


Fig. 4. Ground conductivity map of the British Isles

For example, if the conductivity be measured around a station transmitting on two frequencies two figures for conductivity will probably result, that at the lower frequency should be the lower figure since deeper penetration usually means penetration into older and less conductive rock.

The results of a large number of measurements are shown on the map of conductivity Fig. 4 produced by the BBC Research Department. Some of the correlation between conductivity and the nature of the ground is shown in Table 4, taken from Research Report[3] K062 1944/10.

TABLE 4

Some measured average ground conductivities in the British Isles and their geological correlation

General Classification of Underlying Rock Structure (from the Geological survey)	*Geological Subdivision*	*Surface Drift (where known)*	*Conductivity* $\times 10^{-14}$ e.m.u.	*Conductivity classification*
Quaternary	Recent	Alluvium	20	good
Tertiary	Pliocene	Boulder clay	14	good
	Eocene	Gravel sand	7	moderate/good
		London clay	12	good
Cretaceous	Chalk	Sand and gravel	4	moderate
	Wealden		10	good
Jurassic	Oolitic	Kimmeride clay	13	good
	Liassic	Limestone near surface	10	good
Trias	Keuper Marl	—	11	good
	Bunter Sandstone	Sands and boulder clay	6	moderate/good
		Deep boulder clay	10	good
Palaeozoic	Coal	Boulder clay	8	good
	Millstone grit	Various shallow drifts	3	moderate
	Carboniferous limestone	Sandstone, shale, grit and boulder clay	5	moderate
	Old red sandstone	—	2·5—4	moderate
	Silurian	Sands and boulder clay	4	moderate
	Ordovician	Sands and boulder clay	4	moderate
		Deep boulder clay	10	good
Archaean	Mica schist, gneiss shallow drift	—	2	poor
Igneous	Granite	—	1	

In very general terms, the distribution of conductivity is:

ENGLAND AND WALES

North and west of a line drawn from Teignmouth (Devon) to Tynemouth (Northumberland) the conductivity is generally poor to moderate; south and east of this line it is generally moderate to good, occasionally very good.

SCOTLAND

Central Lowlands area moderate and the rest poor.

NORTHERN IRELAND

Generally moderate but poor around Londonderry.

Propagation Curves

It is apparent that the use of the Sommerfeld equation for the purpose of estimating coverage can be a lengthy and tedious affair, although it is a most useful tool for a few spot calculations.

To facilitate estimation of coverage, propagation curves have been drawn and examples are shown in Figs. 5 to 9 inclusive. These curves have been taken from the Documents[3] of the VIIIth Plenary Session of the Comité Consultatif International des Radiocommunications (C.C.I.R.) and refer to what is called an 'unattenuated field strength of $3 \times 10^5/D$ μV/m' (i.e. $300/D$ mV/m) when D is the distance from the transmitter in kilometres. The unattenuated field strength at 1 kilometre, the factor we have used earlier is thus taken as 300 mV/m. This field corresponds to that from a vertical aerial, shorter than one quarter wavelength with 1 kW applied.

The curves are shown for selected frequencies, three conditions of conductivity for land, poor ($\sigma = 10^{-14}$ e.m.u.), moderate ($\sigma = 3 \times 10^{-14}$ e.m.u.) good ($\sigma = 10^{-13}$ e.m.u.) and for sea ($\sigma = 4 \times 10^{-11}$ e.m.u.), for ranges up to 200 km. Additionally, a set of curves for ranges up to 2,000 kilometres has been prepared by the C.C.I.R. These curves are not all reproduced in this supplement, as their value is somewhat limited for the present purpose because of the relatively short ranges used in the United Kingdom. One specimen curve, that for $\sigma = 10^{-13\cdot5}$ e.m.u. is, however, reproduced in Fig. 9, and can be used for longer distances on lower frequencies. Field strengths are quoted in microvolts/metre in powers of 10 and in decibels relative to 1 μV/m. The db scale will be found most useful when considering mixed path propagation.

A study of the curves shows the effect of frequency on propagation. A comparison of Figs. 5 and 8 (curves for poor land and sea water) shows that for very low frequencies the attenuation is almost independent of conductivity. The effect of conductivity becomes greater with increase in frequency, as shown by the curves (for example, for 1·5 Mc/s).

To use the curves for estimating field strength over a given path the procedure is to select the appropriate curve, i.e. that drawn for the nearest figure of conductivity and, interpolating for frequency where necessary, estimate the reference field strength at the distance concerned. To convert this figure to actual field strength multiply by $E_1/300$. Two examples are given.

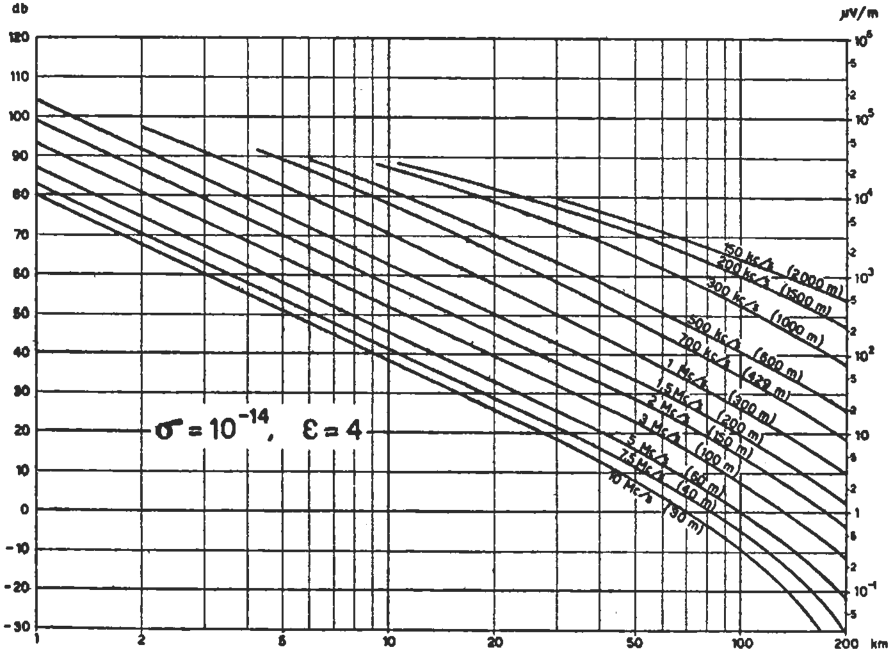


Fig. 5. Propagation over land of poor conductivity (conductivity $\sigma = 10^{-14}$ e.m.u., dielectric constant $\varepsilon = 4$ e.s.u.) $E_1 = 300$ mV/m

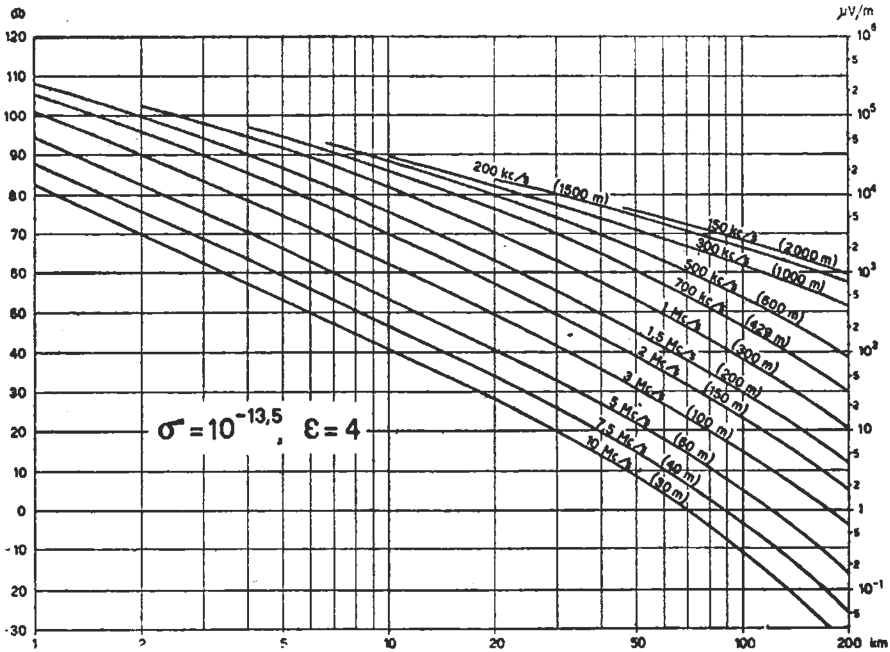


Fig. 6. Propagation over land of moderate conductivity (conductivity $\sigma = 10^{-13\cdot5}$ e.m.u., dielectric constant $\varepsilon = 4$ e.s.u.) $E_1 = 300$ mV/m

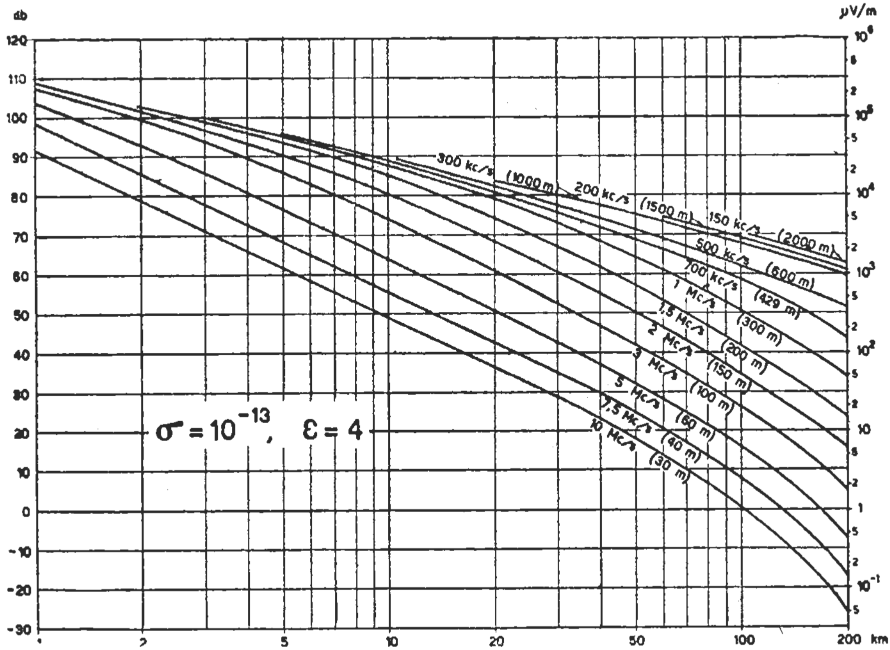


Fig. 7. Propagation over land of good conductivity (conductivity $\sigma = 10^{-13}$ e.m.u., dielectric constant $\varepsilon = 4$ e.s.u.) $E_1 = 300$ mV/m

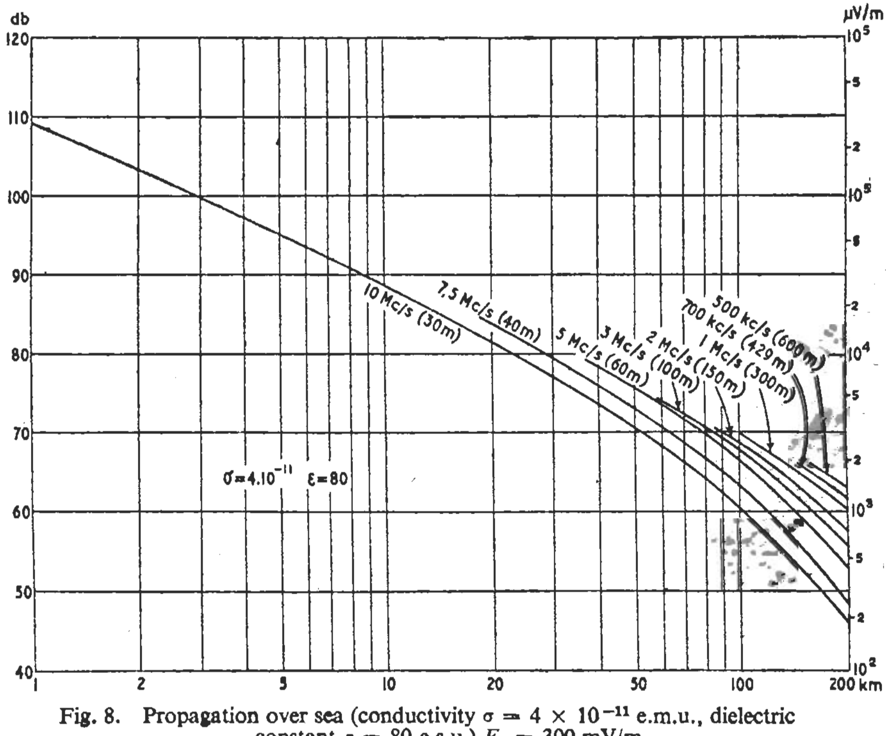


Fig. 8. Propagation over sea (conductivity $\sigma = 4 \times 10^{-11}$ e.m.u., dielectric constant $\varepsilon = 80$ e.s.u.) $E_1 = 300$ mV/m

Example 3

Estimate the field strength at Leicester of Droitwich Midland Home Service transmission.

Distance = 50 miles = 80 km.

Conductivity = 12×10^{-14} e.m.u. The nearest curve is for $\sigma = 10^{-13}$ e.m.u. (Fig. 6) hence an error is bound to be introduced, the estimate being low.

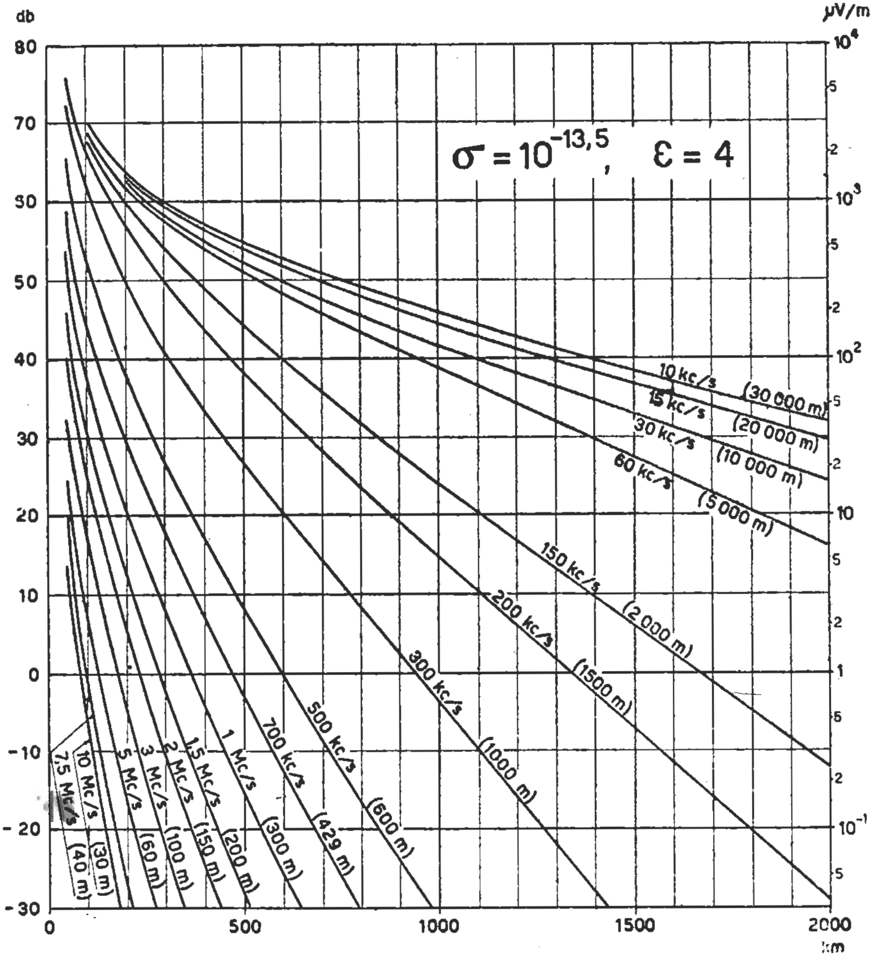


Fig. 9. Propagation over land of moderate conductivity (conductivity $\sigma = 10^{-13.5}$ e.m.u., dielectric constant $\epsilon = 4$ e.s.u.) over long distances. $E_1 = 300$ mV/m

From Appendix I

$$\text{Frequency} = 1088 \text{ kc/s}$$

$$E_1 = 4200 \text{ mV/m}$$

The propagation curve for $\sigma = 10^{-13}$ e.m.u. gives a field strength at 80 km of about 0·5 mV/m for a frequency of about 1 Mc/s.

$$\text{Hence field strength} = \frac{4200 \times 0{\cdot}5}{300} \text{ mV/m}$$

$$= 7 \text{ mV/m}$$

The Home Service coverage map shows the field strength at Leicester to be about 8 mV/m.

Example 4

Estimate the field strength at Fishguard of the Welsh Home Service transmission from Towyn.

Distance = 56 miles = 90 km.

Conductivity = 4×10^{-11} e.m.u. (sea path).

From Appendix I

$$\text{Frequency} = 881 \text{ kc/s}$$

$$E_1 = 550 \text{ mV/m}$$

From the propagation curve of Fig. 8 ($\sigma = 4 \times 10^{-11}$ e.m.u.) the field strength is given as 3 mV/m.

$$\text{Hence field strength} = 3 \times \frac{E_1}{300} = 3 \times \frac{550}{300} \text{ mV/m}$$

$$= 5{\cdot}5 \text{ mV/m}$$

The Home Service coverage map shows that there is a field strength of about 5 mV/m at Fishguard.

The Recovery and Loss Effects

When a signal passes over material of uniform conductivity the rate of attenuation becomes characteristic of that material. Assume that the signal then crosses a fairly definite boundary and passes over material of different conductivity. Eventually the rate of attenuation will become characteristic of the new material. In other words, the propagation of the signal at some distance beyond the boundary is as if the new material had stretched back to the transmitter, with the radiated power modified accordingly.

At the boundary, however, the balance between the movement of energy down the wavefront and the loss of energy in the ground material is disturbed. If the change of material is to one of higher conductivity then the disturbance in balance results in an increase in field strength at ground level immediately beyond the boundary, and this is known as the Recovery Effect.

If the change of material is from high to low conductivity then the disturbance at the boundary produces a reduction in ground level field strength and this is referred to as the Loss Effect. The greatest change in field strength is produced by the greatest change in conductivity, i.e. the deviation from the expected field strength is a maximum over land-sea or sea-land boundaries.

Mixed-path Propagation

Owing to the complex geological structure of the United Kingdom, most of the transmission paths cover zones of different conductivities. Consequently estimation of field strength is made more difficult by Recovery and Loss Effects. Field strength estimation by fitting together two appropriate propagation curves leads to inaccuracies, the estimation being low over a poor to good boundary and high for the converse. Several methods have been devised for mixed-path calculations, the one now in use being due to Millington[4].

The method involves two estimations, one forward (i.e. the normal path) and one reciprocal (i.e. exchanging transmitter and receiver sites). One path gives a result which is high and the other one which is low. The geometric mean of these two values is taken as the correct estimate.

The method can be illustrated by considering a given sea-land path such as shown in Fig. 10 where a signal from a transmitter T travels over AB km of sea and BC km of land to receiver R.

Had the path been all land of conductivity σ_2 then the propagation curve for this frequency would be as shown by curve DJK. But the path AB is over sea and the appropriate curve for this part is shown as DG. Thus the signal would be stronger at boundary B by GJ and will be stronger at C by the same amount. Curve G to H is drawn parallel to JK, and curve DGH gives the field strength in the forward direction; let this be called E_F.

Repeat this procedure using the reciprocal condition, i.e. the transmitter T at C and receiver R at A, shown in Fig. 10 (b). Had the path been all sea, of conductivity σ_1, the propagation curve would have been represented by LMN. But the path CB is over land and the propagation curve is represented by curve LP and the signal at the boundary B is MP lower because of this. The signal at A is lower by the same amount, shown by drawing PQ parallel to MN. The reciprocal field strength is called E_R.

The final figure of field strength for the transmission from A to B is the geometric mean of the forward and reciprocal figures.

$$\text{Field Strength} = \sqrt{(E_F E_R)}$$

When E_F and E_R are expressed in db relative to 1 μV/m then the final figure is the equivalent to the arithmetic mean,

$$\frac{E_F + E_R}{2} \text{ db}$$

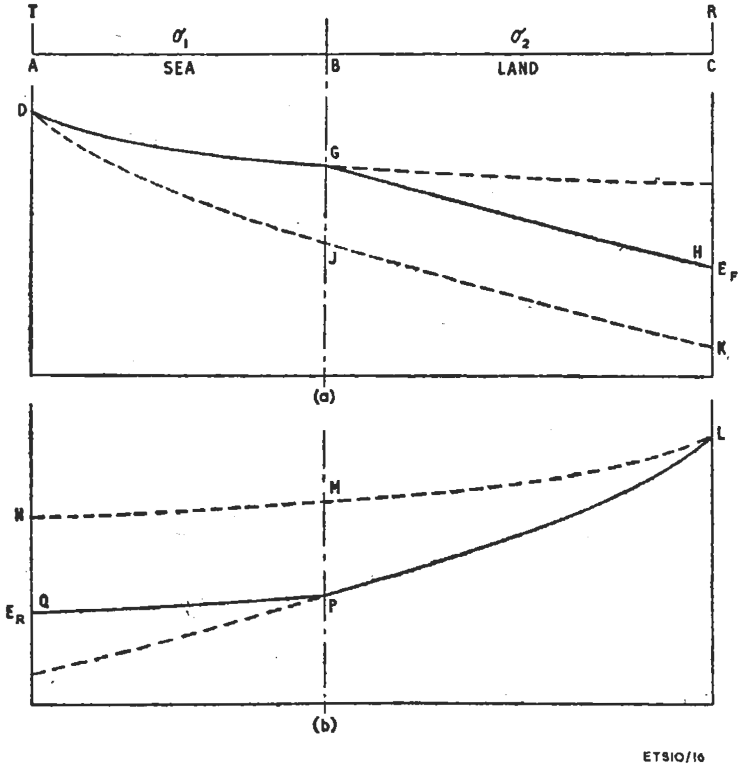


Fig. 10. Mixed-path propagation. (a) Forward transmission over sea-land boundary. (b) Reciprocal transmission over land-sea boundary

Land-sea paths do occur in practice but sea-land paths are used far more often. Examples of the former are Droitwich to the Isle of Man (Light Programme) or Moorside Edge to the Isle of Man (Home Service), and of the latter are Burghead to Ross and Cromarty and Sutherland (Home Service) and most of the Home Service coverage in Wales.

Estimates of field strength can be made without actually drawing the curves and two examples will be given to demonstrate the procedure.

Example 5

Estimate the field strength at Salisbury from the Start Point transmission. From Appendix I

$$\text{Frequency} = 1052 \text{ kc/s}$$

$$\max E_1 = 3300 \text{ mV/m}$$

In the direction of Salisbury E_1 may be assumed to be 3000 mV/m. The path represents a length of 171 km with a sea-land boundary 87 km from Start Point. The land has a conductivity approaching 10^{-13} e.m.u. The conditions are illustrated in Fig. 11. Using the appropriate propagation curves Figs. 7 and 8, and expressing field strength in db relative to 1 μV/m, the procedure is as follows:

Forward Transmission

Field strength at boundary over 87 km of sea = + 70 db (from Fig. 8).
Field strength at boundary had this been land = + 53 db (from Fig. 7).
Therefore gain due to 87 km sea path = + 17 db.
Had the whole path been land the field strength at Salisbury would have been = + 38 db (from Fig. 7).
Hence $E_F = +38 + 17 = +55$ db.

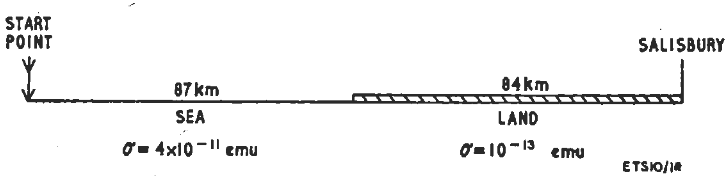


Fig. 11. Mixed-path propagation example. Start Point to Salisbury

Reciprocal Transmission

Field strength at boundary over 84 km land = + 54 db (from Fig. 7).
Field strength at boundary over 84 km sea = + 71 db (from Fig. 8).
Therefore loss due to 84 km land path = 17 db.
Had the whole path been sea field strength = + 62 db (from Fig. 8).
Hence $E_R = +62 - 17 = +45$ db.

The correct reference field strength is the mean of E_F and E_R (arithmetic mean since they are expressed in db).

$$\text{Reference field strength} = \left(\frac{E_F + E_R}{2}\right)$$

$$= +50 \text{ db} = 0{\cdot}32 \text{ mV/m}$$

$$\text{The field strength} = 0{\cdot}32 \times \frac{E_1}{300} \text{ mV/m}$$

$$= 3{\cdot}2 \text{ mV/m}$$

Example 6

Estimate the field strength at Carmarthen from the Washford transmission.

This is a mixed path of 68 km over the sea plus 39 km over land of conductivity assumed to be $\sigma = 10^{-13 \cdot 5}$ e.m.u. ($\simeq 3 \times 10^{-14}$ e.m.u.).

From Appendix I

$$\text{Frequency} = 881 \text{ kc/s}$$

$$E_1 = 3000 \text{ mV/m}$$

The conditions for the path are shown in Fig. 12.

Forward Transmission

Field strength over 68 km of sea = + 72 db (from Fig. 8)
Field strength over 68 km of land = + 50 db (from Fig. 6).
Therefore gain by having a sea path = + 22 db.
Had the whole path been over land, field strength = + 40 db (from Fig. 6).
Hence field strength over mixed path = + 40 + 22 = + 62 db (E_F).

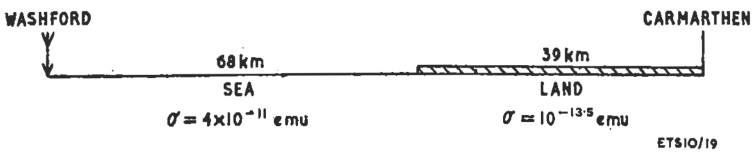


Fig. 12. Mixed-path propagation example. Washford to Carmarthen

Reciprocal Transmission

Field strength over 39 km of land = + 60 db (from Fig. 6).
Field strength over 39 km of sea = + 77 db (from Fig. 8).
Therefore loss over land path = 17 db.
Had the whole path been over the sea, field strength = + 67 db (from Fig. 8).
Hence the field strength for the reciprocal path = 67 − 17 = 50 db (E_R).
The reference field strength is equivalent to

$$\frac{62 + 50}{2} = +\ 56 \text{ db} = 0{\cdot}65 \text{ mV/m approximately}$$

The field strength is thus ($E_1/300 \times 0{\cdot}65$) = 6·5 mV/m approximately.

Sudden changes in conductivity over a land-land boundary are not common but an example of the effects of such is given in Fig. 13 which shows the ground-wave propagation due north-west from Westerglen (Home Service). The signal passes over 25 miles of ground of moderate conductivity, sandstone and limestone for which $\sigma = 10^{-13.5}$ e.m.u. is a good approximation. At the commencement of the Trossachs the conductivity changes abruptly to a value of $\sigma = 10^{-14}$ e.m.u. approximately. Fig. 13 was obtained by a series of forward and reciprocal calculations and the change in signal strength due to change in conductivity is quite well defined. The calculated field-strength figures agree closely with those on the Home Service distribution map.

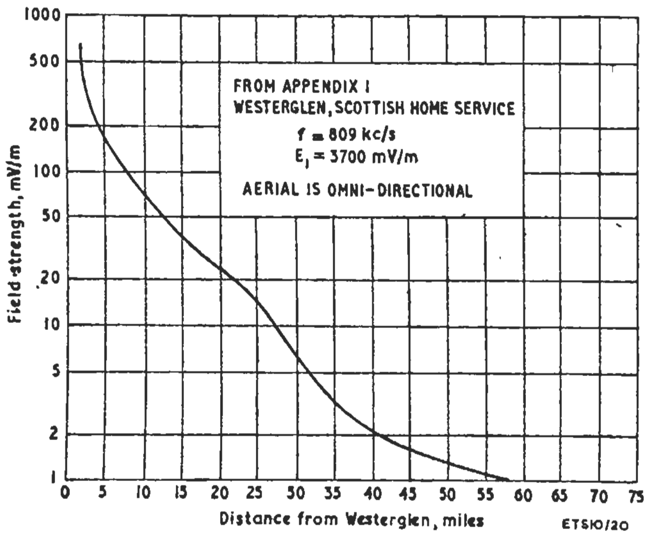


Fig. 13. Mixed-path propagation. Calculated ground-wave field strength along path due North-West from Westerglen

Synchronised Group Working

With one exception all BBC medium-frequency transmitters work in synchronised groups, i.e. there is more than one transmitter on each frequency. This is necessary in order to give the maximum coverage with the limited number of frequencies available in the waveband. The use of synchronised working however imposes limitations on the service areas of the individual transmitters forming the group, because some areas will receive comparable signals from two or more transmitters and unless there is exact synchronism between the two or more carrier frequencies taking the same programme, interference and programme distortion will tend to occur. At night sky-wave reflection will occur and still further limit the area over which satisfactory reception is possible by tending to increase the signals(s) from the 'distant' synchronised transmitter(s).

Since the geographical spacing between BBC transmitters is small, those sharing a frequency must take the same programme, the only exception being the low power transmitters using the International Common Frequency of 1484 kc/s. Thus a large number of listeners may receive, for example, the Regional Home Service simultaneously from two or more sources, and whether the result is a satisfactory service or not depends upon the ratio of the signals and the degree of synchronism of the transmitter drive units. If the main signal being received is called the wanted signal and the smaller one called the unwanted signal, then a first-class service requires a ratio of wanted to unwanted signal of about 5 to 1 and a secondary service requires a ratio of about 3 to 1, provided the two transmitters are synchronised to BBC standards (i.e. a maximum total frequency difference of about 5 parts in 10^8).

It is found convenient when considering ionospheric reflections, to which reference is made later, to take the average of these ratios and to say that an acceptable service is one in which the ratio of wanted to unwanted signal must be at least 4 to 1.

If transmitters share a frequency but have different programmes, then to avoid a background of a second programme, the ratio of wanted to unwanted signal goes up to 200 : 1, and the transmitters using such a system, e.g., Barrow and Ramsgate with the International Common Frequency of 1484 kc/s, are restricted to a power of 2 kW. Hence the range of such transmitters is severely restricted.

The ratio of field strength required for a good service increases rapidly if there is a slight difference in frequency between the transmitter drives. The relationship between the required field strength ratio and the frequency difference is shown in Fig. 14, taken from Proc.I.R.E., 1931, page 1351. It is seen that a frequency difference of 2 cycles per second increases the required ratio from 4 to 1 (12 db) up to 10 to 1 (20 db). This may produce a serious loss of service area and can be caused by a frequency deviation of 1 cycle per second in each drive unit. At a carrier frequency of 1 Mc/s such a shift would be $\pm$ 1 part in 10^6. Avoiding loss of service area by such slight drifts in frequency calls for the use of precision drive units such as the BBC Crystal Oscillator Unit COU/4.

Curves are not available to show similar relationships when different programmes are used, but it is known that the necessary separation rises from 200 to 1 (46 db) up to about 600 to 1 (55 db) when the frequency difference is such as to produce whistles.

Low-power Installations

Since the cost of the aerial needs to have some economic relation with that of the transmitter, low-power installations have simple aerials. If the construction be over-simplified, however, the efficiency will be greatly reduced. On a well-engineered installation, such as two 100-ft masts supporting a T aerial with a good earth system, an applied power of 1 kW may produce a field strength at 1 km as high as 250 mV/m. For temporary installations, where the aerial system may be a wire supported by a factory chimney, then the field strength at 1 km for an applied power of 1 kW may fall below 150 mV/m.

A reduction in the service areas of low-power installations results from synchronised group working and from their location in built-up areas. When a synchronised group contains a high-power station, the sky wave of the latter can seriously reduce the effectiveness of the small transmitters. If the built-up area is large the effective conductivity is reduced and the electrical noise level at the receiver is likely to be high.

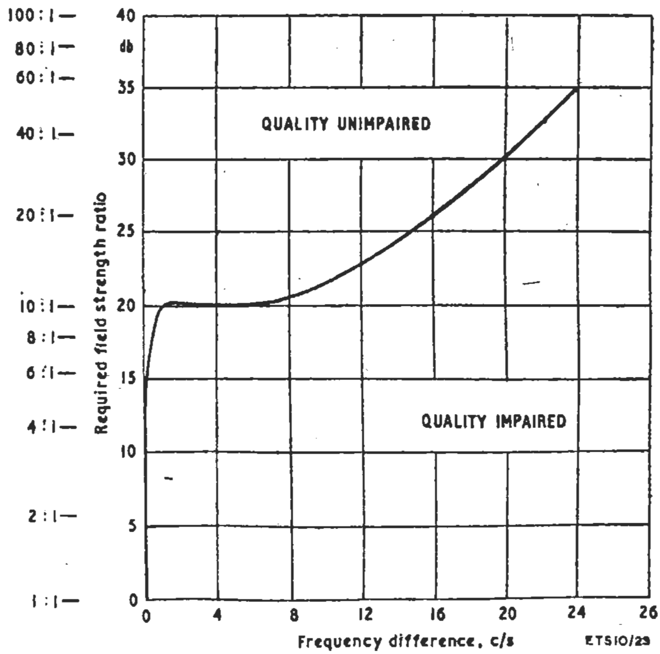


Fig. 14. Relationship between the frequency difference of two signals and the ratio of their field strengths required for good reception

Thus, even in the absence of interference from foreign stations, the useful range of a low-power installation may be limited to ground-wave field strengths as high as 12 mV/m. Taking 8 mV/m as a satisfactory field strength, moderate conductivity ($\sigma = 10^{-13 \cdot 5}$ e.m.u.) and the good T aerial defined above, the useful range (in miles) expected from low-power sites are summarised in Table 5.

TABLE 5

The useful range of average low-power installation in miles

kc/s	½ *kW*	1 *kW*	5 *kW*
500	7½	12	22½
1000	4½	7	12
1500	3	5	8

Ionospheric Reflection

Part of the atmosphere that surrounds the earth is ionised by radiation from the sun. This part is known as the ionosphere and contains a number of layers that affect broadcast signals. The layers that are important to medium frequency broadcasting are the D, E and F_2 layers at heights of the order of 85, 110, and 300 km respectively.

When a signal meets one of these layers, part of the signal is absorbed in the layer, part is transmitted through the layer and the remainder is reflected. During daylight hours, the lowest layer, the D layer, reflects a negligibly small amount of the incident signal, and hence the ground wave is predominant.

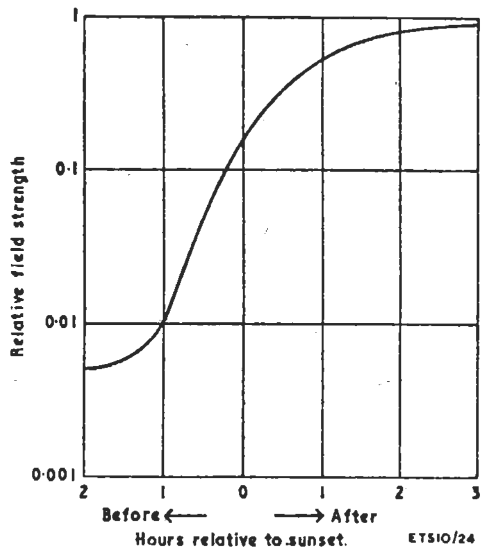


Fig. 15. Variation of sky-wave amplitude over the sunset period

At sunset the ionisation of the layers starts to decrease and the D layer disappears quickly. Then the first layer reached by medium-frequency signals is the E layer and its ionisation is sufficient for a period after sunset to maintain reflections, the duration of the period depending upon the frequency of the signal and angle with which it strikes the layer. The change that takes place over the sunset period is shown in Fig. 15. Eventually, medium-frequency signals penetrate the E layer and reflection from the F_2 layer occurs; such reflected signals are, however, considerably attenuated by passing twice through the lower layers, and will not be considered further here.

At sunrise the ionisation of the layers increase and the D layer is re-formed, and the reflections become of negligible magnitude.

The ionisation of the E region decreases after sunset and this affects the reflecting conditions. The change in ionisation is shown by the variations of the critical frequency (f_0E). The critical frequency is the highest frequency that will be reflected with a wave normally incident on the layer (angle of incidence = 0°). If the angle of incidence be other than zero, i.e., $\theta°$, the signals higher than f_0E will be reflected, the approximate relationship being $f = (f_0E)$ Sec θ where f is the highest frequency that will be reflected. The variation of f_0E in the period after sunset is shown in Fig. 16.

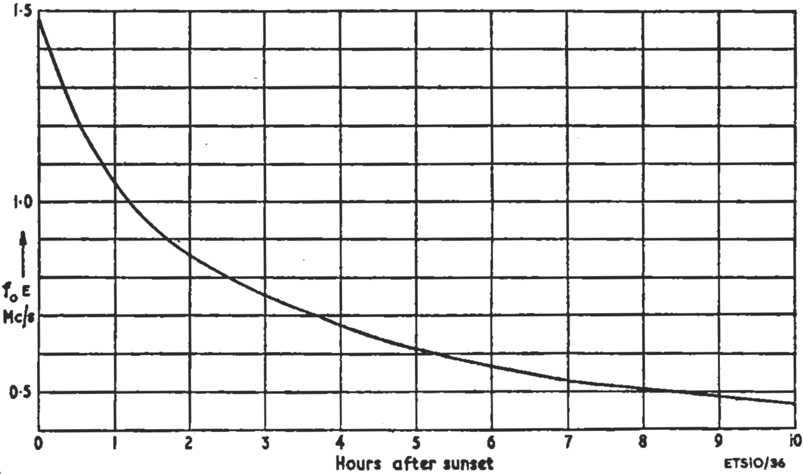


Fig. 16. Curve of critical frequency f_0E (E region) against time

The sky wave may disappear after a certain period of darkness and this period is shown in Fig. 17. To illustrate the use of the diagram assume receivers to be set up 100 km from transmitters radiating on 1·4 Mc/s, 1·0 Mc/s and 0·7 Mc/s. Sky-wave reflection would last for about ½ hour, 1¾ hours and 5 hours respectively for the three cases. If the receivers were then moved to 200 km from the transmitters the sky wave would last for about 1 hour, 2¾ hours and 7 hours respectively. An interesting example of the effect on a synchronised group is to consider the case of the Midland Home Service transmissions on 1088 kc/s from Droitwich and from Postwick, 240 km apart.

The normal service range from Droitwich on this frequency is about 80 km, at which distance E region reflections start to disappear about 1¼ hours after sunset. Over the greater distance to Postwick sky-wave reflection lasts for a longer time, until about 2 to 2½ hours after sunset. Thus the sky wave from a transmission can affect other service areas of its own synchronised group long after it has ceased to affect its own service area.

The disappearance of the sky wave is shown in Fig. 18 relating to the 1457 kc/s group over the period when reflection ceases. Since the signal at the receiver is the resultant of a number of transmissions on this frequency, deep fades will not occur but there are marked variations until reflection ceases.

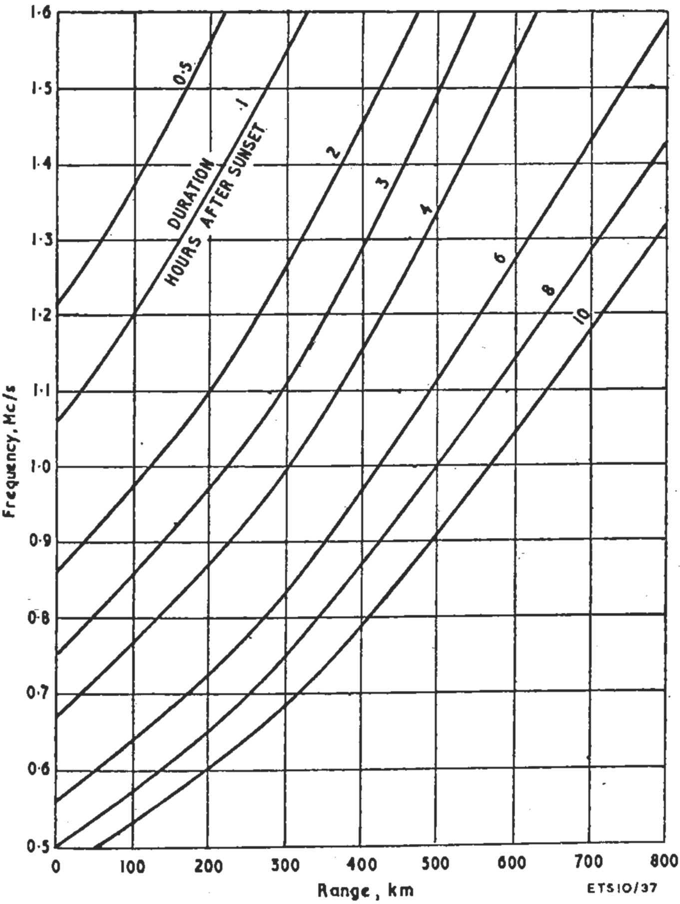


Fig. 17. Approximate duration of E-region reflections during period after sunset

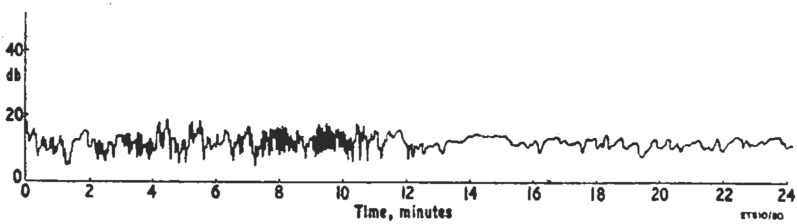


Fig. 18. Field strength due to group of synchronised transmitters, showing the diminution of the effects of sky waves about 2–3 hours after sunset

Fading

If the received sky-wave signal bore a constant ratio to the ground-wave signal, and the relative phase angle between the two waves did not vary, the magnitude of the resultant signal would differ by a constant factor from that of the ground wave alone. There would then be no distortion, and only a change of receiver gain would be necessary to allow for the presence of the sky wave. There is one special exception to this statement, which would occur if the sky wave and ground wave were of equal magnitude, and 180 degrees out of phase; the resultant signal amplitude would then be zero.

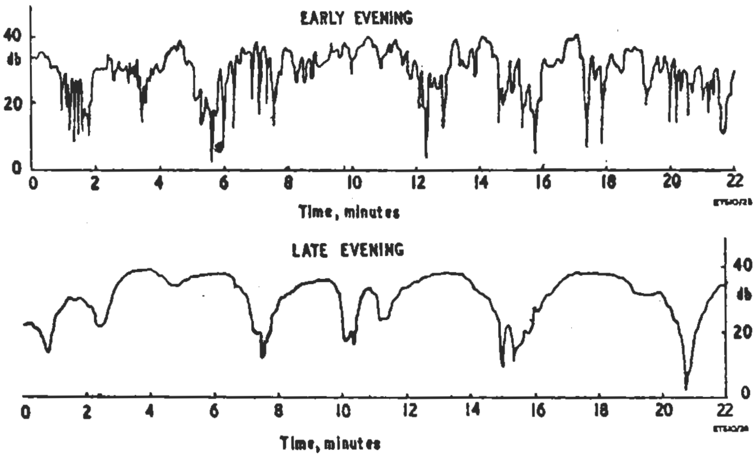


Fig. 19. Radio Luxemburg signal, field strength after sunset

In general, however, the received sky wave is not constant in amplitude or in phase. Thus the resultant signal will exhibit irregular variations of amplitude; this phenomenon is known as 'fading'. If the carrier and sideband components of the sky wave rise and fall together, there is no harmonic

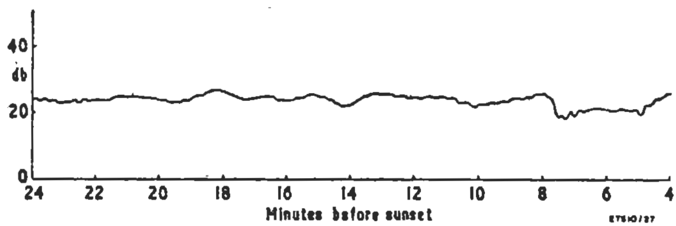


Fig. 20. Signal from Start Point at range of 155 miles, measured over sunset period (continued opposite)

distortion associated with the resultant signal and this type of fading is known as 'group fading'. However, the carrier and sidebands may not be reflected equally. In this case, there is distortion associated with the resultant signal, and this phenomenon is known as 'selective fading'. This form of fading is particularly objectionable, and is one of the main factors limiting the extent of coverage at low and medium frequencies.

The reflecting layer is in a continuous state of change both in height and in density, and as mentioned above, the reflected signal amplitude is continuously changing. The ratio of the reflected signal to the incident signal is a measure of the efficiency of the layer as a 'mirror', and this ratio is termed the 'reflection coefficient'. For perfect specular reflection its value is unity; for calculation purposes, a mean value of 0·25 is often assumed. During a complete sky-wave fade-out the reflection coefficient falls to zero.

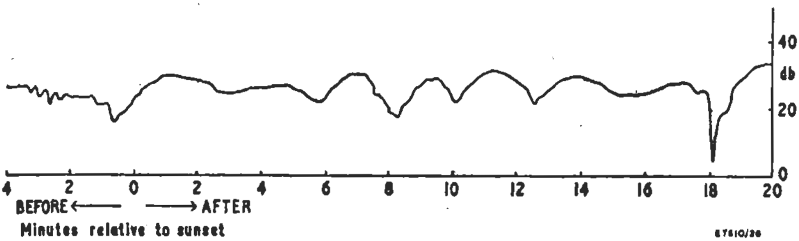
Under somewhat unusual conditions, the reflecting layer has curvature such that it is no longer parallel to the earth's surface, and hence it may act as a focusing mirror; the apparent value of the reflection coefficient may then exceed unity and values over 2 have been recorded.

The deep fading that can occur in a received sky wave is shown by the two recordings of the Radio Luxemburg signal of 1439 kc/s in Fig. 19, taken at a range of about 360 miles; the first was taken soon after sunset when the ionsphere is in a state of rapid change, and the second taken later in the evening when the reflecting conditions had settled down to give slower changes.

The presence of the reflected sky wave after sunset has a considerable effect on the useful ground wave of a transmitter. This is demonstrated by the recording of the Start Point transmission of 1052 kc/s taken at a range of 155 miles shown in Fig. 20. This is a continuous chart over the sunset period. What might be a satisfactory ground-wave signal is interfered with by the reflected sky wave to such an extent that the service would be unacceptable.

Reduction of Service Area by Sky Wave

In order to estimate the reduction in range, the vertical polar diagram of the transmitting aerial must be taken into consideration. Fig. 21 shows the sky-wave field strength at ground level produced by base-fed aerials of varying heights (expressed in terms of wavelength), assuming the ground-wave field strength is the same in each case. The E layer reflection coefficient is assumed



to be unity whereas in practice it is continuously varying and has an average value of about 0·25. It will be seen that the magnitude of the sky-wave changes rapidly for small changes in aerial height above 0·5λ. A mean ground-wave curve is also shown ($\sigma = 10^{-13}$ e.m.u., $f = 1$ Mc/s, $E_1 = 300$ mV/m) and the point of intersection of the ground-wave curve and the sky-wave curve shows the range at which the ground-wave field strength equals that of the sky wave. Allowing for the fact that the reflection coefficient has an

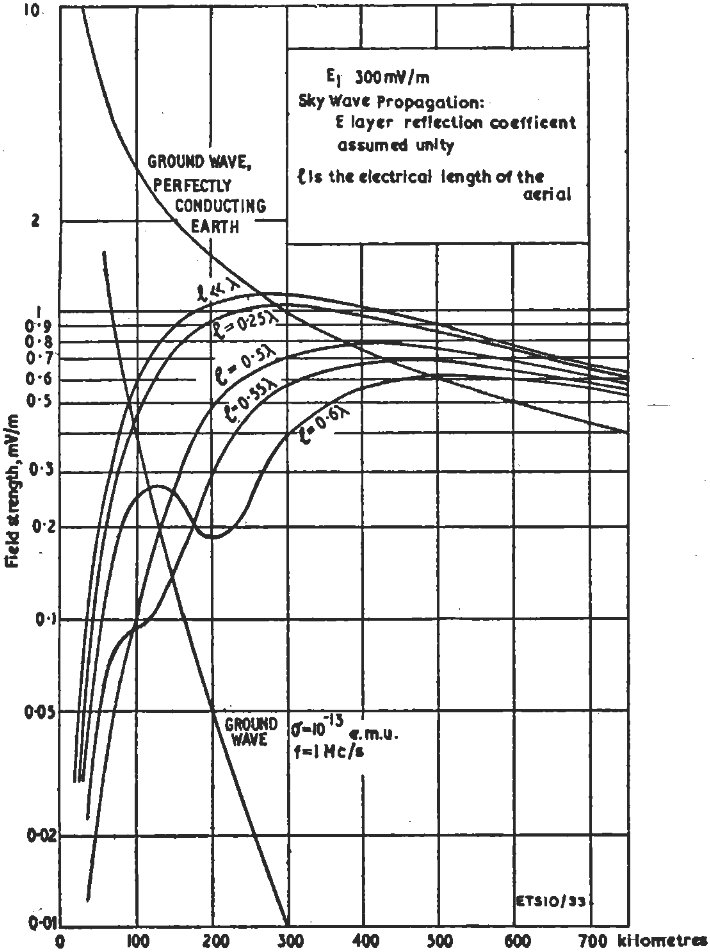


Fig. 21. Sky-wave field strengths plotted against distance for various heights of aerial

average value of 0·25, the intersection shows the range where the strengths of the received signals have a ground-wave : sky-wave average ratio of 4 : 1. This range is usally accepted as the fade-free range of the transmission. In the example shown a transmission would have the following range:

Aerials up to $h = 0{\cdot}25\lambda$	range about 100 km
Aerial about $h = 0{\cdot}5\lambda$	range about 130 km.

Taking the Droitwich Home Service transmission for which $E_1 = 4200$ mV/m, then these ranges occur at ground-wave field strengths of nearly 6 mV/m and 3 mV/m respectively. These figures would appear optimistic when compared with the coverage maps, which take into account the presence of the Postwick transmitter. The best service area is achieved when the curve for the sky wave is at a minimum when it crosses the curve for the ground wave.

In the above discussion the effect of the sky wave has been considered in relation to the service area within which the ground wave tends to predominate. Beyond the area where severe fading occurs due to interference between the two waves, the sky wave predominates and fairly satisfactory reception may be possible. It is subject to some fading because of the variations in reflection coefficient of the ionosphere but may be sufficiently reliable to give a secondary grade of service. A service of this kind is given by the BBC medium-wave transmission in the European service.

Long-range Interference by Sky Wave

A signal may be received at a point well outside its nominal service area by virtue of reflection from the ionosphere. Interference from this cause occurs predominately after nightfall, when ionospheric reflection is most pronounced. The maximum range of propagation by this means is achieved by a signal propagated tangentially to the earth's surface, as shown in Fig. 22.

For example, for night-time reflection from the E layer at 110 km, the maximum range is given by:

$$AEC = \frac{\theta}{360} \times 2\pi r$$

where r is the radius of the earth, 6360 km.

Now $\cos \theta/2 = AD/BD$ and thus

$$\theta = 2 \cos^{-1} \frac{AD}{BD}$$

$$= 2 \cos^{-1} \frac{r}{r + BE}$$

$$= 2 \cos^{-1} \frac{6360}{6470} = 21° \ 10'$$

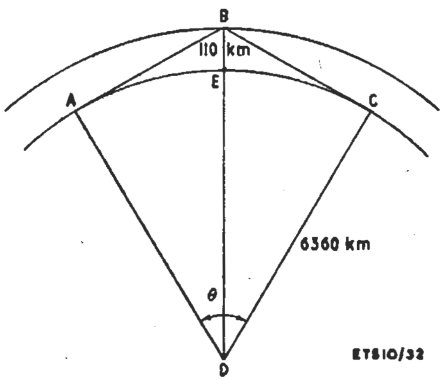


Fig. 22. Diagram showing path of reflected signal for maximum range via E-region reflection

$$\text{Thus the range} = \frac{21{\cdot}17}{360} \times 2\pi \times 6360 = 2350 \text{ km}$$

It is usually considered that the maximum practical range via the E layer is about 2000 km. This means that sky waves from low- and medium-frequency transmitters can be reflected back to earth anywhere up to 2000 km, and sometimes even farther, i.e. when multiple hop transmission becomes possible. Such long-range reflection can cause interference with distant stations on the same or a nearby frequency.

Fig. 23 is a map based on Plett's zenithal azimuthal projection which shows the parts of Europe and Africa within 2000 km of London. Straight lines drawn on this map represent Great Circles. Any medium-wave transmitter outside the United Kingdom up to the distance shown by the circle can produce a sky wave reflected into this country. Tatsfield has listed over 200 such transmissions between 500 and 1500 kc/s.

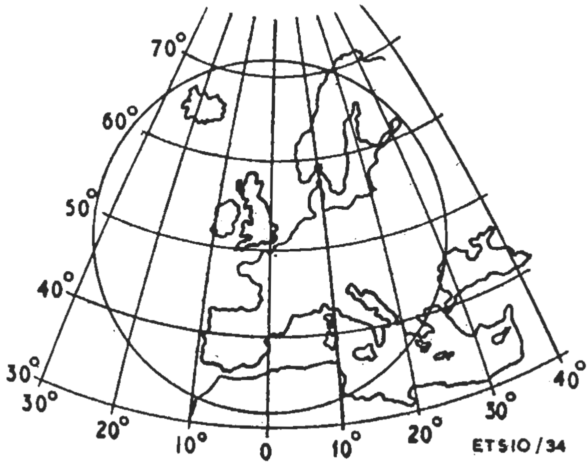


Fig. 23. Map showing circle of 2000 km radius centred on London

The magnitude of the sky wave after dark is shown in Fig. 24, which is based on a C.C.I.R. curve, derived from measurements. The field strength shown is that exceeded instantaneously for five per cent of the time, and is known as the quasi-maximum field strength. The median field strength, i.e. that exceeded fifty per cent of the time, is approximately 0·35 of the quasi-maximum field strength. When the range is over 500 km the amplitude of the sky wave is very little affected by the vertical radiation pattern of the aerial, as the reflected signal leaves at a very small angle with the ground. Thus the strength of the reflected signal at long range varies approximately with E_1, the unattenuated ground field strength at one kilometre. The curve of Fig. 24 is drawn for $E_1 = 300$ mV/m, which corresponds to the field strength of a short aerial fed with one kilowatt. To determine the field strength E' for an aerial of any other length and input power, the field strength E determined from

Fig. 24 must be multiplied by the ratio of the unattenuated field strength at one kilometre E_1 for this aerial to that of the short aerial postulated, 300 mV/m. Thus

$$E' = E.\frac{E_1}{300}$$

As an example, consider a transmitter situated 1000 km from England, radiating a power of 100 kW from a short aerial. This would produce a reflected sky wave in this country of quasi-maximum value of about

$$0{\cdot}3 \times \frac{3000}{300} = 3{\cdot}0 \text{ mV/m}$$

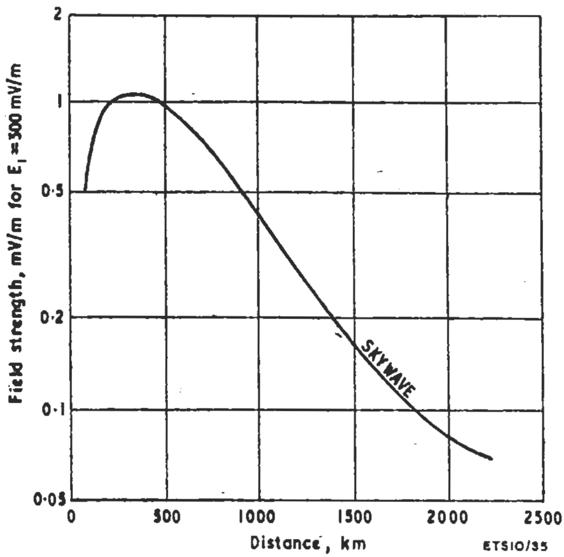


Fig. 24. Quasi-maximum field strength of sky wave at night; the field strengths shown are those exceeded instantaneously for five per cent of the time

The median field strength would be about $3{\cdot}0 \times 0{\cdot}35 = 1{\cdot}05$ mV/m. If the transmitter operates on a frequency used in this country then the useful range of the BBC transmitter for good reception would be restricted after sunset to a ground-wave field strength some 46 db greater than this if exact synchronism occurred, or some 55 db greater if the carrier frequency difference was such as to produce a whistle (see page 2 5). Thus with exact synchronism, interference would occur for five per cent of the time where the BBC field strength was 600 mV/m, and fifty per cent of the time when the field strength was 220 mV/m. With an audible carrier-frequency separation, interference would occur for five per cent of the time when the BBC field strength was 1800 mV/m, and for fifty per cent of the time when 630 mV/m. This order of restriction has been experienced with one of the Home Services.

APPENDIX I

Table of BBC Transmitting Stations as operating in 1957

Pro-gramme	*Station*	*kc/s*	*metres*	*kW*	*Aerial*	E_1 mV/m	$\frac{Ed}{\sqrt{kW}}$*	*Direction*
North	Moorside Edge	692	434	150	500′T	4500	370	omni
Scottish	Westerglen	809	371	100	500′T	3700	370	omni
	Burghead	809	371	100	500′MR	3600	360	omni
	Redmoss	809	371	5	250′MR	850	380	omni
Welsh	Washford	881	341	75	500′T	3000	350	omni
	Penmon	881	341	8	250′MR	900	320	omni
	Towyn	881	341	5	120′T	550	250	omni
London	Brookman's Park	908	330	125	500′MRC	4500	400	omni
Midland	Droitwich	1088	276	150	350′MR	4200	340	omni
	Postwick	1088	276	7·5	126′MR	900	330	max. 90°–130°
Nor.	Lisnagarvey	1151	261	100	475′MR	3500	350	omni
Ireland	Stagshaw	1151	261	100	475′MR	3500	350	omni
West	Start Point	1052	285	95	450′MR	3300	340	max. 330°
	Bartley	1457	206	10	250′MR	1000	320	omni
	Clevedon	1457	206	20	350′MR	1600	360	omni
Light	Droitwich	200	1500	400	700′T	6000	300	omni
	Brookman's Park	1214	247	50	200′T	4200	590	max. 135°
	Moorside Edge	1214	247	50	SVW	2000	280	max. 90° and 270°
	Westerglen	1214	247	50	SVW	2000	280	max 150° and 330°
	Burghead	1214	247	20	126′MR	1600	360	max. 160° and 340°
	Lisnagarvey	1214	247	10	100′T	950	300	omni
Third	Daventry	647	464	150	725′MRC	4500	370	omni

T = a wire aerial, with top loading, supported between masts.
MR = mast radiator.
MRC = centre fed mast radiator.
SVW = spaced vertical wire aerial.
E_1 = field strength measured at 1 km (figures supplied by Research Dept.).

* The figures given in this column are approximations, obtained by dividing the measured field strength at 1 kilometre by the square root of the nominal power delivered to the aerial. The true value of $Ed/\sqrt{}$kW is obtained by dividing the unattenuated field strength at 1 kilometre (i.e. that existing with the aerial situated over a perfectly conducting earth) by the square root of the true power delivered to the aerial. Reference to Figs. 5 to 9 will show that only a small error is involved in assuming the measured value of field strength at 1 kilometre equal to the unattenuated field strength at 1 kilometre at frequencies less than 1·5 Mc/s, except where the ground conductivity is poor, i.e. less than 3×10^{-14} e.m.u.

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