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MEDIUM FREQUENCY PROPAGATION
a survey

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Summary

At medium frequencies, ground waves and sky waves are both of equal importance. Ground waves provide stable signals during the day, when sky waves are weak. At night sky waves propagate to considerable distances with very little attenuation but are more variable.

Published ground-wave propagation curves apply to land which is smooth and of uniform conductivity, but this condition is rarely satisfied in practice. The report describes methods for calculating field strengths along mixed land–sea paths, over irregular terrain and through built-up areas.

An interesting feature of sky-wave propagation arises because the Earth's gyromagnetic frequency lies within the frequency band being considered. This gives rise to polarisation coupling loss, which is of considerable importance in tropical regions and to further coupling loss between hops on multi-hop paths. Enhanced inospheric cross-modulation also occurs at the gyromagnetic frequency.

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MEDIUM-FREQUENCY PROPAGATION: A SURVEY

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MEDIUM-FREQUENCY PROPAGATION: A SURVEY

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1. Introduction

At medium frequencies (300–3000 kHz) ground-waves and sky-waves are both of equal importance. Ground waves, described in Section 2, are used extensively for broadcasting at the lower frequencies in the band. They provide stable signals, especially during the day, when sky-waves are greatly attenuated by the lower ionosphere. At night sky-waves are able to propagate to considerable distances with very little attenuation and can cause severe interference. Sky-wave propagation is described in Section 3, which considers the various factors which influence the strength of the received signal. The combined effect of ground-wave and sky-wave propagation is considered in Section 4.

2. Ground-wave propagation

Ground waves propagate efficiently between vertical antennas close to the ground. The transmission loss between a pair of antennas depends on the ground conductivity and frequency, on Earth curvature and on the roughness of the intervening terrain. It is also influenced by buildings and trees on the propagation path. Before considering these effects in detail, it is instructive to consider propagation between two elevated antennas situated above a plane earth and to see how the transmission loss is modified when the frequency decreases and when the antennas are close to the ground.

2.1. Propagation over a plane earth

Fig. 1 shows two antennas A and B situated above a uniform plane earth. Suppose that A radiates a wave of either polarisation. If the distance AP is sufficiently great, the wave incident at P is indistinguishable from a plane wave, and the Fresnel plane-wave reflection coefficients may be used to calculate the reflected-wave field strength. The voltage induced in antenna B by the direct and ground-reflected waves is then given by

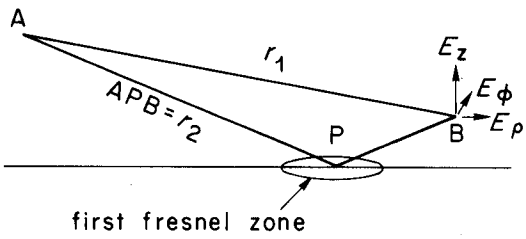


Fig. 1 – Aerials above a plane earth.

$$V = QI\left[\frac{Q_1 e^{-jkr_1}}{r_1} + \frac{Q_2 R e^{-jkr_2}}{r_2}\right] \qquad (1)$$

where I is the current in antenna A, Q, Q_1 and Q_2 are constants and R is the appropriate reflection coefficient, provided the distance between the antennas is large compared with the wavelength λ. The constants Q_1 and Q_2 take account of the vertical radiation patterns of the antennas, and $k = 2\pi/\lambda$.

Before proceeding further, the reflection mechanism must be considered. Antenna A induces currents in the ground; if the ground behaves as a conductor the current is a conduction current and if it behaves as a dielectric the current is a displacement current. Re-radiation by these currents generates the reflected wave.

A useful concept is that of the first Fresnel zone on the ground. This is an elliptical area shown in Fig. 1 which contains the optical reflection point P. Contributions from the boundary of the zone lag behind the contribution from P by 180°. Contributions from within the zone reinforce each other, but contributions from points outside the zone differ widely in phase and tend to cancel. Thus the contributions from within the zone are mainly responsible for the reflected wave, and the size of the zone therefore influences the strength of the reflected wave.

When both antennas are at a finite distance from P the area of the zone is slightly less than it would be if one of the antennas were at infinity. If the reduction in area exceeds, say, 10%, the reflected-wave term in Equation (1) will be in error. In practice it transpires that Equation (1) is nearly always valid at u.h.f. and v.h.f., frequently at h.f. but seldom at m.f. and l.f.

When the use of Equation (1) is not justified a correction term may be added as follows

$$V = QI\left[\underbrace{\underbrace{\frac{Q_1 e^{-jkr_1}}{r_1}}_{\text{Direct wave}} + \underbrace{\frac{Q_2 R e^{-jkr_2}}{r_2}}_{\text{Reflected wave}}}_{\text{space wave}} + \underbrace{\frac{S e^{-jkr_2}}{r_2}}_{\text{Surface wave}}\right] \qquad (2)$$

The direct and reflected waves are together known as the space wave. The correction is called the surface wave because it is the only term which remains when both antennas are very close to the ground.

The factor S in Equation (2) is a complicated function of the ground constants, polarisation and antenna positions. Its derivation, first given by Sommerfeld,[1] is complicated but Sommerfeld's formulae have been arranged in a convenient form by Norton.[2] A more detailed discussion is given by Jordan and Balmain.[3]

When both antennas are very close to the ground, $Q_1 = Q_2$, $r_1 = r_2$ and $R = -1$ for both vertical and horizontal polarisation. Equation (2) then simplifies to

$$V = QI\frac{Se^{-jkr}}{r} \tag{3}$$

where r is distance between the antennas. It can be shown from Norton's equations that S diminishes very rapidly with increasing distance with horizontal polarisation but not with vertical polarisation. Horizontally-polarised surface waves suffer such rapid attenuation that they need not be considered further.

At l.f. and m.f., the use of elevated transmitting aerials is impracticable because the wavelength is of the order of 1 km. Vertical aerials erected on the ground are efficient radiators of vertically-polarised surface waves, known as ground waves. These waves have a vertical electric-field component E_z accompanied by a smaller component E_ρ which acts in the direction of propagation. The wave also contains a transverse magnetic-field component H_ϕ which is approximately equal to $-E_z/\eta_0$, where η_0 is the intrinsic impedance of free space. Of the two electric-field components, E_z predominates. The vector product of E_z and H_ϕ describes the power flow in the direction of propagation. The smaller vector product of E_ρ and H_ϕ corresponds to a downward flow of power into the Earth's surface and accounts for the attenuation of the wave which is additional to that due to the inverse distance term. The attenuation is greatest when the ground is a poor conductor, and it increases as the frequency increases.

The ground wave would be attenuated even if the ground were a pure dielectric, because E_ρ would still be finite and the downward power flow would still occur. The power entering the earth would not be dissipated, however, but would propagate downwards without loss. With a pure dielectric, E_z and E_ρ would be in phase and the wavefront above the Earth's surface would be tilted downwards.

In a further simplification by Norton,[2,4] the modulus of E_z is expressed in the form

$$|E_z| = \frac{300\sqrt{P}}{r}A \tag{4}$$

where A is called the ground-wave attenuation factor and P is the radiated power. Equation (4) then gives the field strength produced by a short vertical aerial radiating P kW; if r is in metres, E_z is in V/m and if r is in km, E_z is in mV/m. The quantity $300\sqrt{P}$ is sometimes called the cymomotive force.

Fig. 2 shows computed values of A expressed in terms of two parameters p and b, called the numerical distance and phase constant respectively. These parameters are defined as follows

$$p \simeq \frac{\pi r}{\lambda x}\cos b \tag{5}$$

$$b \simeq \arctan\frac{\varepsilon_r + 1}{x} \tag{6}$$

where

$$x = \frac{18 \times 10^3\sigma}{F} \tag{7}$$

σ is the ground conductivity in S/m, F is the frequency in MHz and ε_r is the dielectric constant.

To illustrate the application of Norton's method, it is used here to calculate the field strength at a distance of 15 km from a short vertical aerial radiating 10 kW at 1 MHz, assuming the ground conductivity to be 10^{-2} S/m and its dielectric constant equal to 10.

The cymomotive force with which the aerial radiates is $300\sqrt{10}$. In the absence of ground-wave attenuation (i.e. with a perfectly conducting earth), the field strength at 15 km would be $300\sqrt{10}/15 = 63.1$ mV/m.

For the stated ground constants, $\varepsilon_r = 10$ and $x = 180$. Equations (5), (6) and (7) give $p \simeq 0.74$ and $b \simeq 31°$. The ground-wave attenuation factor given by Fig. 2 is 0.51. The actual field strength is therefore $63.1 \times 0.51 = 32$ mV/m or 90 dB relative to 1 μV/m.

2.2. The effect of Earth curvature

Although the theory which has been described above assumes that the Earth is flat, this does not give rise to serious errors at m.f. for distances less

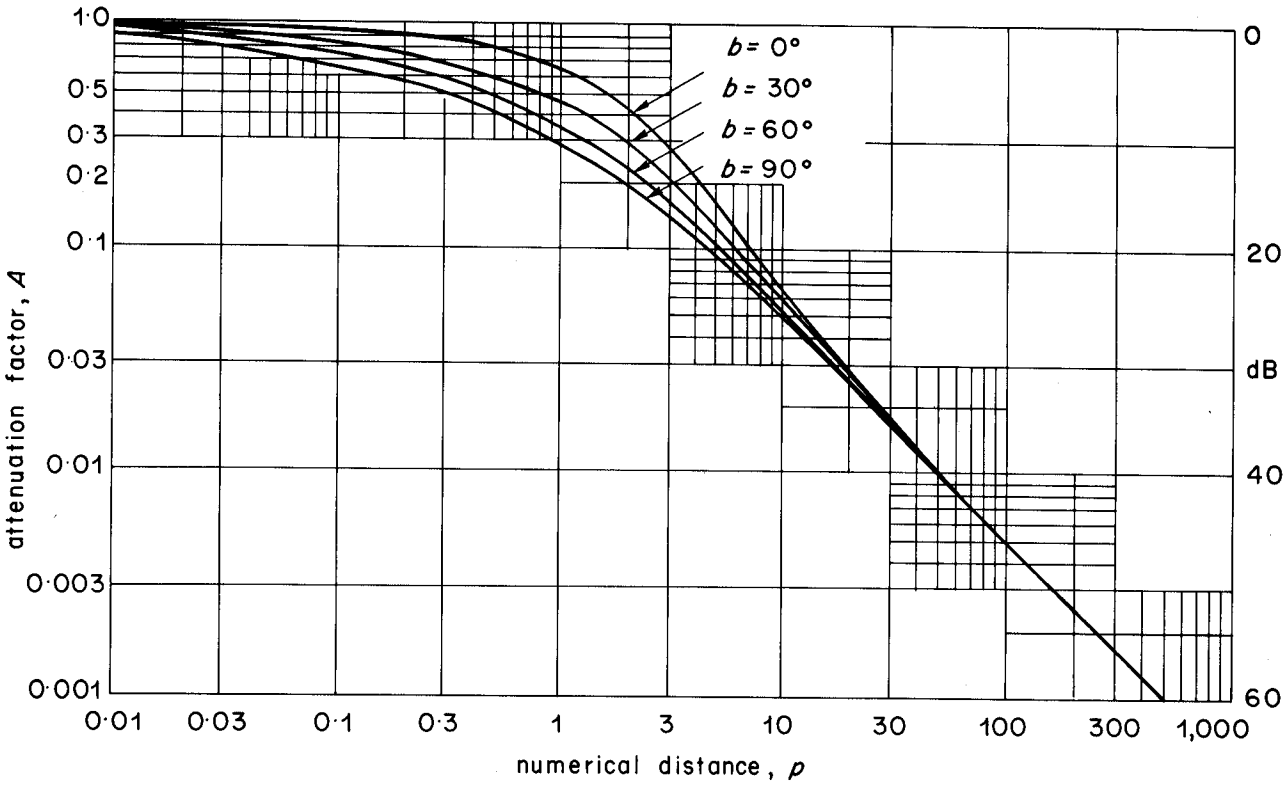


Fig. 2 – Ground-wave attenuation factor.

than 100 km. At greater distances, however, Earth curvature increases ground-wave attenuation.

The formal solution for propagation over a spherical Earth was first derived by Van Der Pol and Bremmer[5] and is extremely complicated. However Norton has again presented the result in a form which can be readily applied; full details are given in Reference 4.

In applying Norton's method, a factor which has to be considered is the effective radius of curvature of the Earth. At v.h.f. and u.h.f., the effect of atmospheric refraction can be taken into account by assuming that the Earth has an effective radius which is 1.33 times the true radius. At very low frequencies, however, the thickness of the atmosphere is small compared with the wavelength and it has no significant effect; at these frequencies, therefore, the true radius must be assumed. At l.f. and m.f. the atmosphere has some effect on ground-wave propagation and it has been shown[6] that this can be taken into account by multiplying the true radius by frequency-dependent factors which are less than 1.33; at 1 MHz, for example, the effective radius is about 1.25 times the true radius.

In practical applications it is more convenient to make use of propagation curves, such as those published by the CCIR,[7] which have been calculated by the methods described above.

2.3. Mixed-path propagation

Published propagation curves are calculated on the assumption that the ground conductivity has a uniform value over the entire path. This assumption is seldom true in practice.

For an all-land path with variable conductivity, sufficient accuracy can usually be obtained by assuming a weighted mean conductivity for the whole path and then using the appropriate propagation curve. This method is not sufficiently accurate for mixed land-sea paths, however, because the conductivities of land and sea differ by a factor of about 10^3.

The following semi-empirical method due to Millington[8] is found to give reliable results for mixed paths and should always be used for mixed land–sea paths. Suppose that 100 km of land is followed by 50 km of sea. For the first 100 km the propagation curve for land must apply; for the remainder of the path the propagation curve for sea can be moved downwards and joined to the land curve, as shown in Fig. 3. The field strength at 150 km is therefore represented by the point Y. If the direction of propagation is reversed, 50 km of sea is followed by 100 km of land. Use of the sea curve for the first 50 km, and the land curve, suitably displaced, for the remainder of the path gives a second field-strength value Y′. The field strength should, however, be

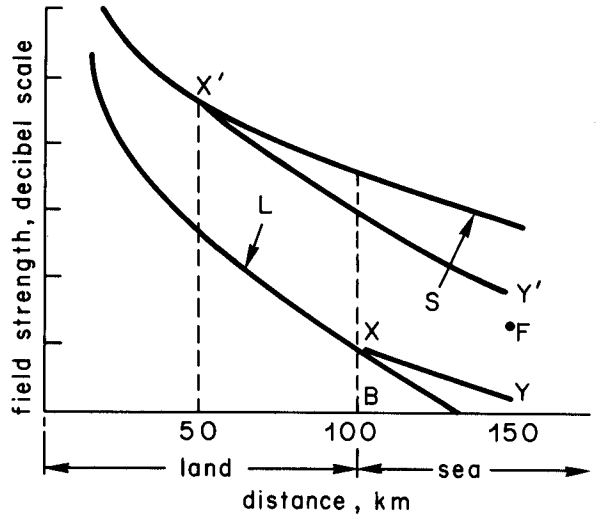


Fig. 3 – Millington's method for mixed-path propagation: L, Land propagation curve; S, Sea propagation curve; XY, Sea curve, lowered; X'Y', Land curve, raised; F, Average values of Y and Y'.

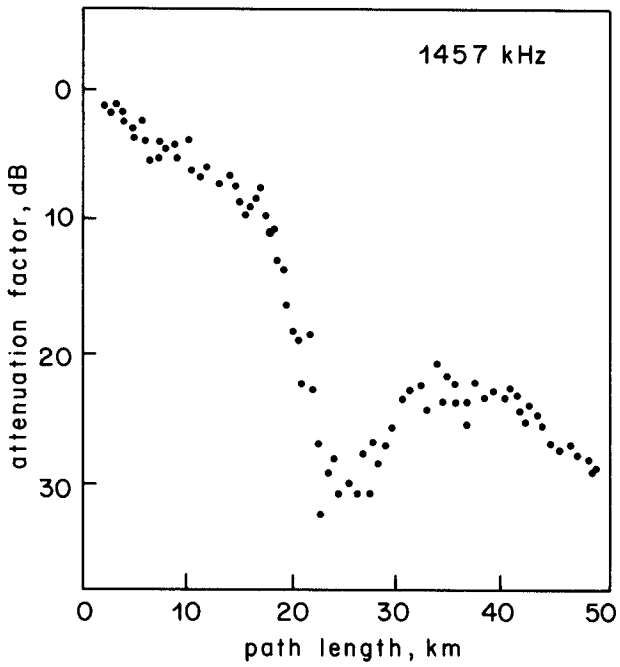


Fig. 4 – Ground-wave attenuation factors measured on a path through London.

independent of the direction of propagation because the principle of reciprocity must apply. Thus neither Y nor Y' is correct, but it has been shown that reliable results are obtained if Y and Y' (in dBs) are averaged, giving the value denoted by F in Fig. 3.

Millington's method may be extended to paths containing more than two sections of different conductivity, by using the appropriate propagation curve for each section of the path in turn. As before, calculations are performed for both directions of propagation and then averaged.

2.4. Ground-wave propagation through urban areas

It has been found that the attenuation of ground waves passing through urban areas cannot be described by assuming that the ground is equivalent to a poor conductor. Furthermore, it is found that the ratio of the electric and magnetic field strengths is not equal to the intrinsic impedance of free space but may be somewhat smaller, because currents flowing in all types of vertical conductors, such as house wiring and plumbing, and even in trees, enhance the magnetic field but tend to reduce the electric field.[9]

Measurements have shown that the ground-wave attenuation factor A does not decrease uniformly with increasing distance (as in Fig. 2) but may fall rapidly to a fairly deep minimum, after which it increases before falling again. Fig. 4 shows ground-wave attenuation factors measured on a typical path through London.

A theory which describes m.f. ground-wave propagation through built-up areas has been developed.[10] Moderately built-up areas, such as residential suburbs, are represented by a randomly-distributed array of vertical unipoles, while more densely built-up areas, such as city centres, are represented by a grooved surface, the grooves corresponding to streets. Both representations are equivalent to an inductive ground plane. If the Sommerfeld–Norton theory is extended to this type of surface it is found that the ground-wave attenuation factor, when represented on the complex plane (see Fig. 4 of Reference 10), contains a zero in the inductive region. If the line representing a path through a built-up area passes near this zero, then the theoretical ground-wave attenuation factor will vary in the same way as the measured values shown in Fig. 4.

2.5. The effect of ground irregularity

An integral-equation method for calculating ground-wave attenuation over irregular paths has been described by Monteath.[11] This method is based on the Compensation Theorem,[12] which leads to an equation of the form

$$G(R) = 1 - \sqrt{\frac{jR}{\lambda}} \int_0^R \frac{\psi + \eta_r}{\sqrt{r(R-r)}} e^{-j2\pi t/\lambda} G(r)\, dr \tag{8}$$

Here $G(R)$ is the complex ground-wave attenuation factor between two antennas A and B separated by

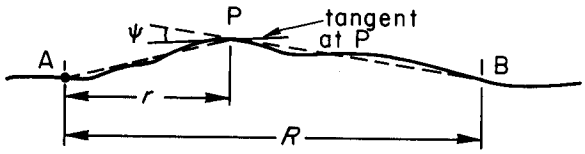


Fig. 5 – Propagation over irregular ground.

irregular ground as shown in Fig. 5; over a plane earth the modulus of $G(R)$ is represented by the quantity A of Equation (4). $G(r)$ is the ground-wave attenuation factor for propagation between A and an intermediate point P. Other symbols in Equation (8) not represented on Fig. 5 are defined as follows:

λ free-space wavelength

η_r relative surface impedance (see Reference 13)

t the path difference APB–AB

The integral of Equation (8) is evaluated numerically. As this requires a knowledge of $G(r)$ for a number of points between A and B, $G(R)$ must be evaluated initially for some minimum distance. The calculation is then repeated for twice this distance, using the value just derived for the intermediate value of $G(r)$. The path is then extended by a further increment, with two intermediate values of $G(r)$ in order to calculate a third value of $G(R)$, and so on. The first value of $G(R)$ is calculated from one of Norton's formulae on the assumption that a uniform plane earth exists over the first integral. Experience with real ground profiles has shown that intervals of 2 km give adequate accuracy at 1 MHz.

In addition to hills and valleys, the method takes both Earth curvature and varying ground conductivity into account. Computations made over idealised ground profiles, for which solutions can be derived by other means, have shown that the method is reliable and accurate. When applied to real ground it has been found that undulations approaching one wavelength in height have very little effect on ground-wave attenuation. Much larger variations in attenuation, however, would be expected in mountainous areas, where the terrain irregularities may be several wavelengths high.

3. Sky-wave propagation

One of the principal characteristics of the 300 to 3000 kHz band is that sky waves propagate efficiently at night but are greatly attenuated during the day. The attenuation occurs in the lower part of the E layer, sometimes known as the D region. At sunset the D region decays rapidly and waves can then be reflected from the E and F layers, with much less attenuation.

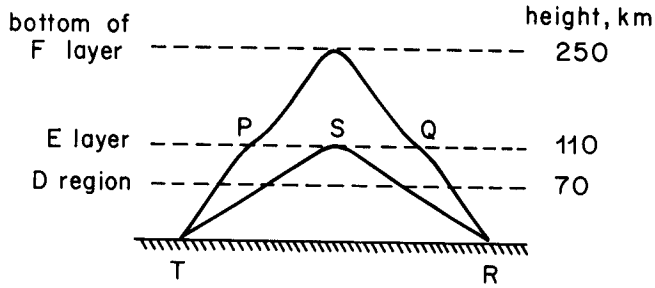


Fig. 6 – Simultaneous E and F-layer reflection.

The critical frequency of the normal E layer is about 1500 kHz at sunset but it then falls rapidly as a result of electron–ion recombination and tends to a value of about 500 kHz late at night. Sky waves may be reflected from the E layer, or they may penetrate the E layer and be reflected from the F layer, depending on the frequency, path length and time of night. Simultaneous reflection by both layers is also possible in some circumstances. This possibility is illustrated in Fig. 6 where waves penetrate the E layer at P and Q but are reflected at S because here the angle of incidence is greater than at P and Q.

Although daytime propagation is relatively unimportant it cannot be entirely disregarded at the upper end of the band, since ionospheric attenuation decreases with the square of the frequency. Nor can it be entirely disregarded at the lower end of the band, where partial reflection from the lower edge of the D region may occur, especially in winter at temperate latitudes.

As the wave propagates from transmitter to receiver it is subject to a number of different types of loss which are illustrated in Fig. 7. Those losses are considered in detail in the sections which follow. To simplify the discussion it is assumed here that all antennas transmit and receive vertical polarisation (VP); most transmitting antennas operating in the 300–3000 kHz band radiate VP and the majority of receiving antennas are more sensitive to the vertically-polarised component of the downcoming wave than to the horizontal component.

Some of the losses described are peculiar to the 300–3000 kHz band because the gyromagnetic frequency lies within this band. Enhanced ionospheric cross-modulation also occurs at and near to the gyromagnetic frequency; this is described in Section 3.7.

3.1. Ground loss at transmitter and receiver

The strength of the transmitted wave, and the voltage induced in the receiving antenna, are both modified by ground loss, which would be zero only if

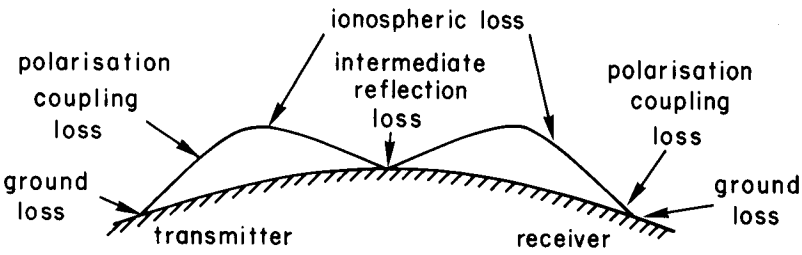


Fig. 7 – Losses on a two-hop sky-wave path.

the ground were flat and perfectly conducting in the vicinity of the antennas. With imperfectly-conducting flat ground the loss in decibels at each terminal would be given by

$$L_g = 6 - 20\log_{10}|1 - R_v(\alpha)| \qquad (9)$$

where $R_v(\alpha)$ is the Fresnel plane-wave reflection coefficient for vertically polarised waves at the radiation angle α being considered. Since R_v tends to -1 at grazing incidence, the loss would tend to infinity at very low angles if the Earth were flat. However the loss is modified by Earth curvature and has a finite value at grazing incidence given by Wait and Conda.[14] Their theory can be used to estimate losses for the negative radiation angles which apply when waves diffract around the curvature of the Earth, as shown in Fig. 8.

The field-strength reduction which would occur if flat perfectly-conducting ground were replaced by an imperfectly-conducting curved Earth is shown in Fig. 9, which was calculated from Equation (9) for radiation angles above 5° and from Wait and Conda's theory for lower angles, assuming the radius of the Earth to be increased by a factor of 1.25 to allow for atmospheric refraction. Fig. 9 should be used in conjunction with Fig. 8, which shows radiation angles for hop lengths up to 3000 km.

On single-hop paths involving diffraction around the curvature of the Earth, it is reasonable to assume that the negative radiation angles at both ends of the path are equal if the ground conductivities at the two terminals are similar. When the conductivities are very different, however, this may not be true but calculations have shown that the total reduction on such paths does not depend critically on the way in which the total diffraction angle is shared between the two ends of the path. The angle may therefore be assumed to be equally divided between the two ends and given by Fig. 8(b) even when the conductivities are dissimilar.

Ground loss may be defined as the field-strength reduction which occurs above a curved Earth when land replaces sea water. Ground loss may therefore be derived from Fig. 9 by subtracting field-strength reductions for sea water from those for ground of the appropriate conductivity. The corresponding increase which occurs when land is replaced by sea water is known as sea gain. Fig. 10, which shows the sea gain which occurs at 1 MHz when land having a conductivity of 10 mS/m is replaced by sea water, has been adopted by the CCIR in a field-strength prediction method.[15] The increase will be doubled if both terminals are near the sea. The increase rises to a maximum when the path length is about 2000 km, because here the one-hop mode predominates and is propagated at a very

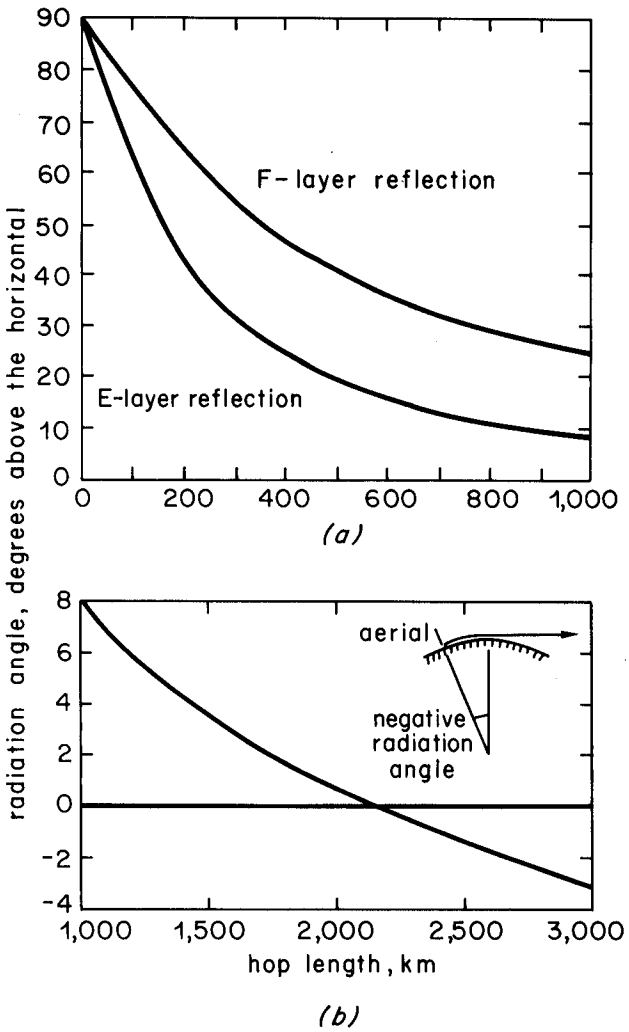


Fig. 8 – Radiation angle: (a) short distances; (b) longer distances: E-layer reflection only.

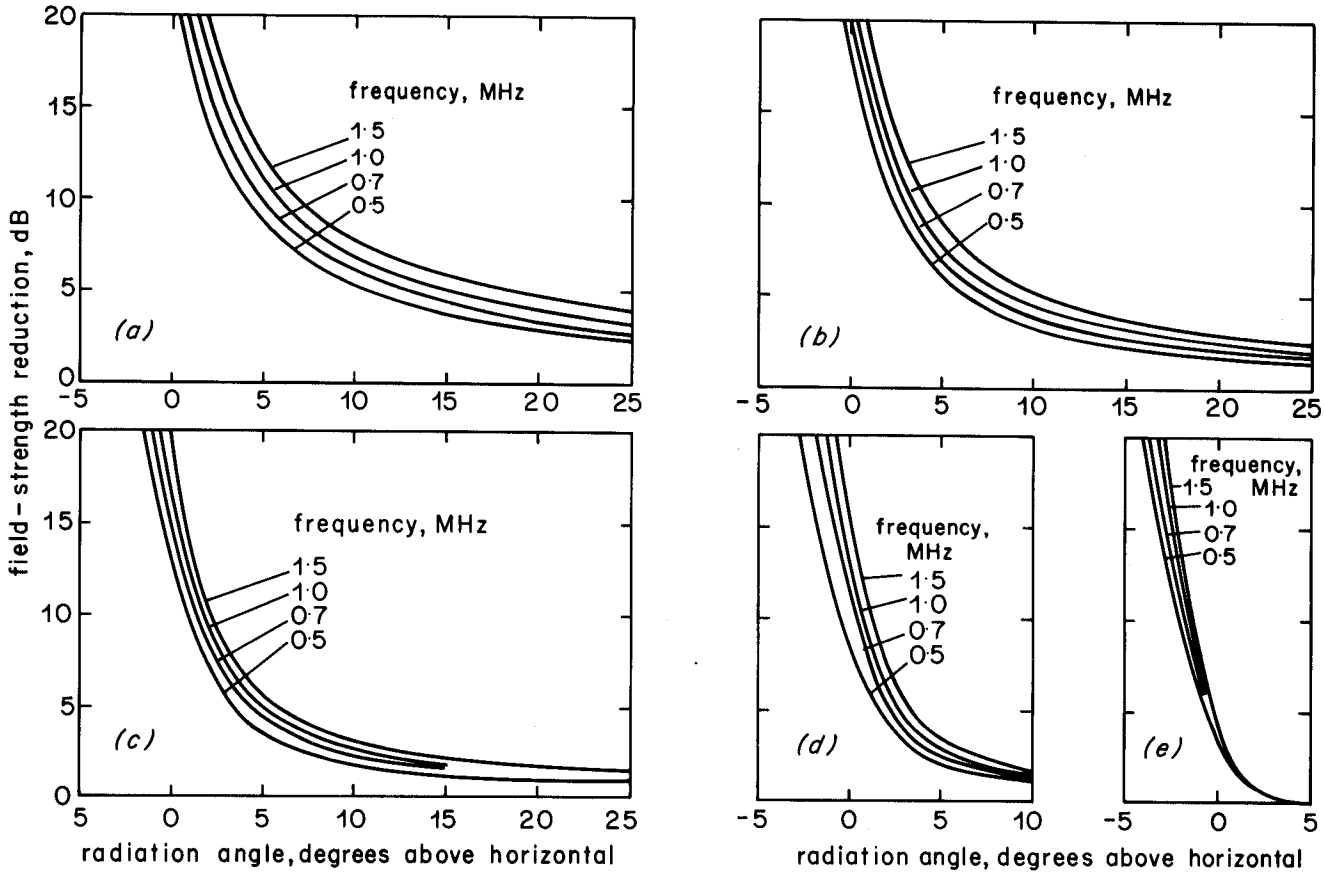


Fig. 9 – Field-strength reduction: (a) ground conductivity 1 mS/m; (b) ground conductivity 3 mS/m; (c) ground conductivity 10 mS/m; (d) ground conductivity 30 mS/m; (e) sea water.

low angle. The increase rises to a further maximum at about 4000 km; here the 2-hop mode predominates.

The full increase shown in Fig. 10 will only apply if the transmitter or receiver is within a few km of the sea. Fig. 11 shows how the field-strength depends on the actual distance from the sea (measured in the direction of propagation) when one terminal of a 1500 km path is moved inland, assuming ground of average conductivity (10 mS/m) and a frequency of 1 MHz. Fig. 11 is calculated from a formula derived by Anderson,[16] and the theory has been confirmed experimentally.[17] The field strength

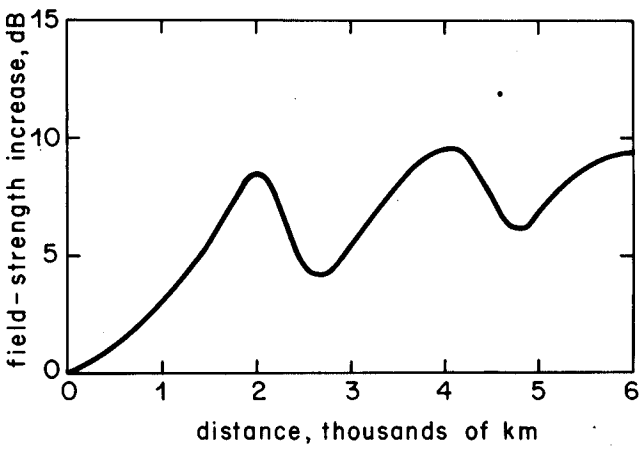


Fig. 10 – Effect of replacing land, at transmitter or receiver, by sea.

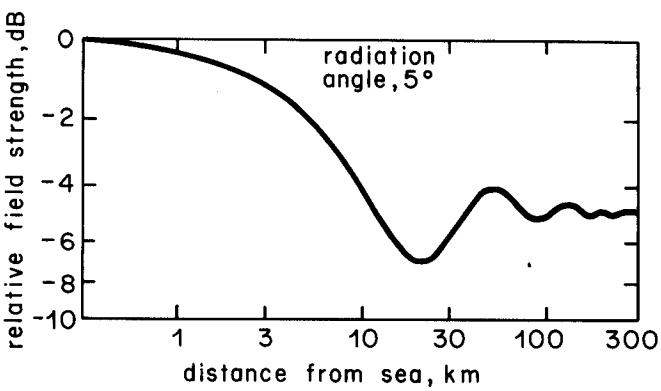


Fig. 11 – Variation of field strength with distance from sea.

falls to a minimum when the first Fresnel zone on the ground lies entirely on land. Then as the aerial moves further inland the field strength tends to the value which would apply if the land were of infinite extent.

Sea gain is also influenced by the extent of the sea; for example, it will be considerably reduced if the sea consists only of a narrow channel. This aspect has also been studied by Anderson but the solution is very complicated. An approximation to Anderson's formula has been derived[18] and has been adopted by the CCIR.[15]

3.2. Polarisation-coupling loss

The gyromagnetic frequency, which depends on the strength of the Earth's magnetic field, varies between 800 kHz in equatorial regions and 1600 kHz near the magnetic poles. It therefore always lies within the band of frequencies being considered in this report. At the gyromagnetic frequency, the extraordinary wave of the magneto-ionic theory[19] is so greatly attenuated that it makes a negligible contribution to the received signal; furthermore the attenuation exhibits a broad maximum centred on the gyromagnetic frequency. As a consequence, the extraordinary wave can be disregarded for all practical purposes within the medium-frequency broadcasting band (approximately 550 to 1600 kHz) and even at 3000 kHz its rate of attenuation is two or three times greater than that of the ordinary wave. In the discussion which follows it will be assumed that the extraordinary wave is completely absorbed.

Conventional aerials radiate vertically-polarised waves. At m.f. the wave which is accepted by the ionosphere and which propagates further, usually has a different polarisation and may not be excited efficiently by the incident wave. The wave which emerges from the ionosphere is in general elliptically polarised and may not excite the listener's receiving aerial efficiently, because aerials near the ground are most sensitive to vertical polarisation.

The fraction of the incident power which is lost on entry into the ionosphere is called the polarisation coupling loss. Further polarisation coupling loss occurs when the wave which emerges from the ionosphere induces a voltage in the receiving aerial. The coupling losses which occur at the two ends of the path are caused by essentially the same mechanism and are unchanged if the direction of propagation is reversed.

It has been shown[20] that when the transmitting aerial radiates vertical polarisation, the coupling loss in decibels is given by

$$L_c = 10 \log_{10} \left(\frac{1 + M^2}{\cos^2 \psi + M^2 \sin^2 \psi} \right) \qquad (10)$$

where M is the axial ratio of the ordinary-wave polarisation ellipse and ψ is the angle by which its minor axis is tilted from the horizontal plane. Formulae for calculating M and ψ in terms of frequency, magnetic-dip latitude, direction of propagation and angle of incidence at the ionosphere are given in Reference 20.

Curves which give polarisation coupling losses at individual terminals are contained in Fig. 12. Although polarisation coupling loss depends to some extent on frequency and angle of incidence at the ionosphere, Fig. 12 may be used with negligible error for all frequencies in the m.f. band and for radiation angles up to 20° from the horizontal. The direction of propagation γ is defined in the inset; on short paths the values of γ for the two terminals tend to be complimentary and the coupling losses are similar. On long paths, however, the coupling losses at transmitter and receiver must be calculated separately because the magnetic dip latitudes and directions of propagation (relative to magnetic north) at the terminals will, in general, be somewhat different.

Since the major axis of the elliptically-polarised ordinary wave which is accepted by the ionosphere, and also that of wave which emerges, is parallel to the direction of the Earth's magnetic field, polarisation coupling losses are low in temperate latitudes, because the Earth's magnetic field is almost vertical. At the magnetic equator, however, the Earth's field is horizontal and polarisation coupling losses on east–west paths are large.

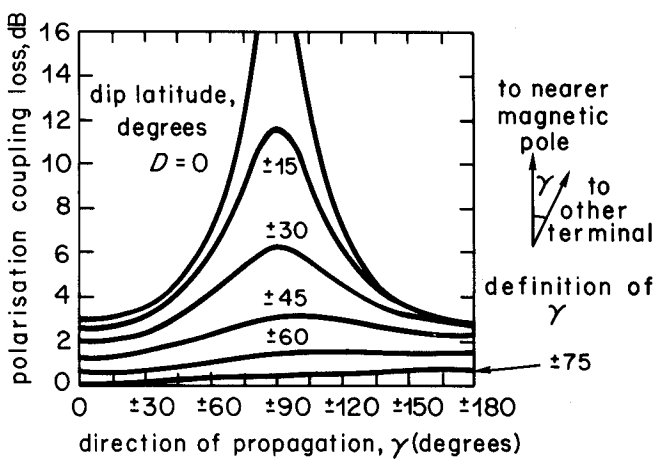


Fig. 12 – Polarisation coupling loss at transmitter or receiver.

In the CCIR field-strength prediction method,[15] polarisation coupling losses in temperate latitudes are assumed to have a fixed value of 1 dB at each terminal and are included in the general propagation formula. An empirical formula which approximates to the curves of Fig. 12 of this report is used in the CCIR method to calculate the additional polarisation coupling loss which occurs in tropical latitudes.

3.3. Ionospheric absorption

The Earth's magnetic field has two distinct effects on the residual ionospheric absorption which remains late at night when solar activity is low. Firstly it is responsible for the auroral zones, regions centred on the magnetic poles where absorption losses are high. Distance from the auroral zone is believed to be of considerable importance; for example, ionospheric losses in North America are known to be greater than in Europe.[21] Secondly the rate of attenuation of a wave in the ionosphere depends on the angle between its direction of propagation and the direction of the Earth's magnetic field, the rate of attenuation being least when these two directions are parallel.

These two effects in combination cause ionospheric losses on north–south paths to be less than on east–west paths. Long north–south paths usually pass through equatorial regions, where propagation tends to be parallel to the Earth's field and auroral effects are absent. On the other hand, east–west paths tend to be transverse to the Earth's field, and some east–west paths (especially those across the North Atlantic) are close to the auroral zone.

The way in which ionospheric losses would vary if auroral effects were absent has been studied by means of an extensive series of ray-tracing computations, using an ionospheric model assumed to be common to all geographical areas.[22] A detailed study was made of propagation from hypothetical transmitters situated in Europe and Africa. In Europe, ionospheric losses were found to be almost independent of direction of propagation; this is to be expected because the Earth's magnetic field is almost vertical. Losses on east–west paths in Europe and Africa were found to be similar; this is also to be expected because east–west propagation tends to be transverse to the Earth's magnetic field at all latitudes.

Ordinary-wave losses computed for the frequency range 500–1500 kHz for single-hop east–west paths are shown by unbroken lines in Fig. 13. Although the losses decrease with increasing frequency, the reduction is less than might be

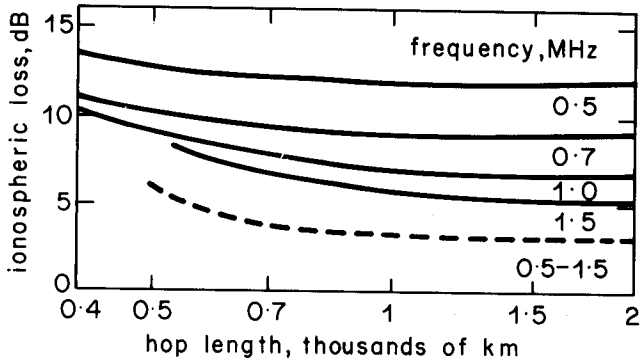


Fig. 13 – Computed ionospheric losses:
——— east–west propagation at all latitudes;
– – – – north–south propagation at magnetic equator.

expected, because waves of higher frequencies penetrate more deeply into the ionosphere and the distance traversed within the ionosphere is greater than at lower frequencies. Consequently the variation of the total loss with frequency is much smaller than would otherwise be the case. Fig. 13 shows that losses for low-angle modes tend to be almost independent of hop length because of the very small variation of the angle of incidence at the ionosphere.

Propagation parallel to the Earth's magnetic field was studied by computing losses on single-hop north–south paths with reflection points above the geomagnetic equator. Although most of the computations involved reflection over Africa, some additional computations were made for other equatorial regions since some dependence on the strength of the Earth's magnetic field was expected. The strength of the Earth's field was, however, found to have negligible influence on the computed losses, which were also found to be almost independent of frequency. The results of the computations for equatorial north–south paths are shown by the broken curve of Fig. 13.

In the auroral zones, ionospheric losses are somewhat greater than those shown in Fig. 13. The auroral zones are centred on the magnetic poles and have an outer radius of about 4000 km. Areas which are affected by increased losses include Canada and the northern USA, the North Atlantic and the northern part of the USSR. In this region, ionospheric losses are independent of the direction of propagation because the Earth's magnetic field is almost vertical.

Fig. 13 does not apply when waves penetrate the E layer and are reflected by the F layer; this is most likely to occur at frequencies above 1500 kHz. Outside the auroral zone the residual night-time absorption loss L_A tends to be independent of path azimuth and is given approximately by the following

semi-empirical formula due to Wakai which has been adopted by the CCIR:[23]

$$L_A = \frac{7 + 0.019d}{10 + F^2} \text{dB} \qquad (11)$$

where d is the path length in km and F is the frequency in MHz.

3.4. Field-strength variation

3.4.1. Short-period and day-to-day variation

The ionosphere is a turbulent medium and sky-wave field strength varies continuously. Short period variations, occurring within periods measured in minutes, usually follow a Rayleigh distribution, although larger variations may be observed if two or more propagation modes are received simultaneously. However, the median field strength measured during a short period generally differs from that measured at the same time on the previous night and it has been found that the day-to-day variation of the median field strength often obeys a distribution which resembles the log-normal.[24] The combined effect of the short-period and day-to-day variation causes the instantaneous field strength to exceed the median value by more than 8 dB for about 10% of the total time, during short periods centred on a specific hour, on a series of nights.

Because sky waves are so variable, field-strength measurements made on a single night are of little value. Even if measurements are made at the same hour for 25 consecutive nights the median field strength may still be 2 dB in error. This variability should always be taken into account.

3.4.2. Diurnal variation

Ionospheric absorption is smallest and field strengths are largest late at night. The absorption increases rapidly at sunrise and decreases from its day-time value almost as rapidly at sunset. Field-strength variations have been measured during the sunset and sunrise periods, and throughout the night, on many paths in different parts of the world. The results have been compared and it has been found that these variations are largely independent of frequency (within the m.f. broadcasting band) and of path length.[24] An average curve which shows the additional absorption which occurs around sunset and sunrise, and during the early part of the night, can therefore be drawn: it has been adopted by the CCIR[15] and is reproduced in Fig. 14.

For single-hop paths, the sunset and sunrise

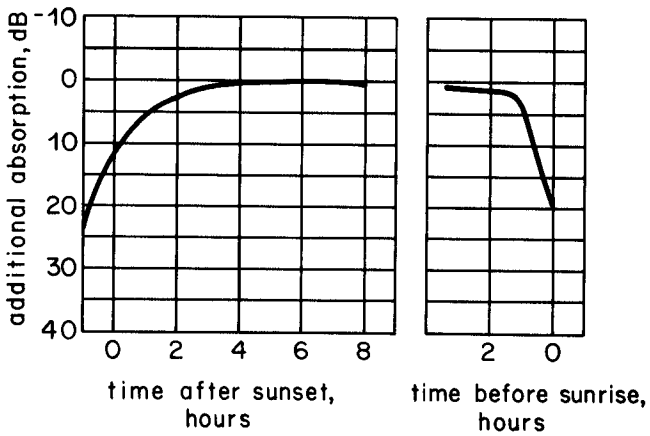


Fig. 14 – Diurnal variation of ionospheric absorption.

times of Fig. 14 are those observed at the path mid-point. For multi-hop paths the absorption variation is mainly controlled by the hop nearest to the terminal where the sun sets last or rises first, because the remainder of the path is then in darkness. Sunset and sunrise times for paths longer than 2000 km are therefore taken at points 750 km from the appropriate terminal.

The absorption rises to a maximum at about mid-day and Fig. 15 shows the corresponding field-strength reduction, measured on a 361 km path in Japan.[25] Fig. 15 shows the tendency for day-time field strengths to be greater in winter than in summer. Measurements made at Helsinki[26] of a large number of European transmissions have shown that sky waves received over single-hop paths near mid-day in December are 20 to 40 dB weaker

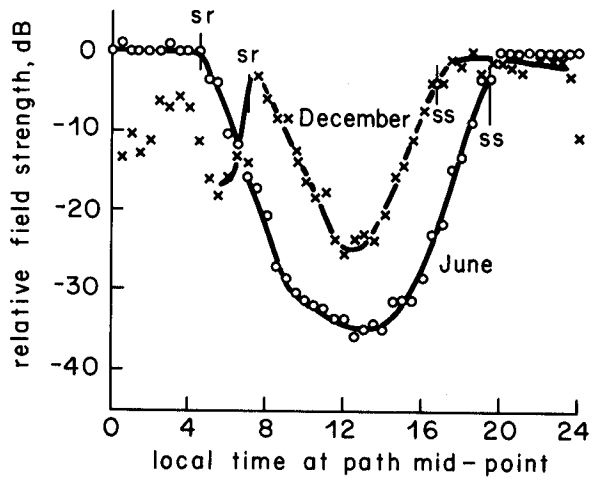


Fig. 15 – Field-strength variation during the day. Measured at 1850 kHz on a 361 km path in Japan (see Reference 25). Each point represents the monthly median value for the time indicated; SR ground sunrise at path mid-point; SS ground sunset at path mid-point.

than at night, throughout the frequency range 500–1600 kHz.

3.4.3. Seasonal variation

As described in the previous section, there is a tendency for day-time field strengths to be greater in winter than in summer. At night there is a tendency for field-strength maxima to occur in spring and autumn, except at vertical incidence, when the maximum occurs in the summer. Considerable differences have been observed from one path to another; for a more detailed discussion see Reference 24.

3.4.4. Solar-cycle variation

There is a tendency for night-time sky-wave field strength to decrease with increasing solar activity. The decrease seems to be most pronounced in North America, where reductions of more than 6 dB have been observed on typical paths at the peak of the solar cycle.[27] Smaller reductions have been observed in Europe and Australia. In tropical regions, there is unlikely to be any appreciable field-strength reduction because ionospheric absorption at night is relatively small.

Regression analysis indicates that the field-strength reduction is proportionable both to sunspot number R and to the path length p, and can be represented by the formula

$$L_R = 10^{-2} bpR \text{ dB} \qquad (12)$$

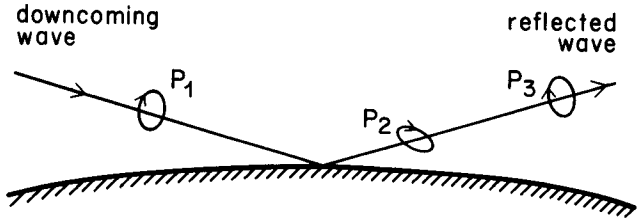
where p is in km and b is a constant which depends on geographic location. According to the CCIR, $b = 4$ for North America, 1 for Europe and Australia and 0 elsewhere.[15]

There is very little information about the effect of solar activity on daytime propagation although measurements made in India at 1550 kHz show field strengths decreasing with increasing solar activity (as at night) because of greater ionospheric absorption.[28]

3.5. Intermediate reflection loss

Intermediate reflection loss occurs between hops on multi-hop paths and is closely related to polarisation coupling loss. It occurs for the same reason i.e. because the extraordinary wave is almost completely absorbed and only the ordinary wave propagates.

The mechanism is illustrated in Fig. 16. When the elliptically-polarised downcoming wave is reflected at the ground its strength is reduced and its polarisation (P_1) is modified. The new polarisation P_2 will not necessarily match the polarisation P_3 which the ionosphere would like to accept for onward propagation of the ordinary wave. The intermediate reflection loss is the sum of the ground reflection loss and the coupling loss between the polarisations P^2 and P_3; these two losses cannot be considered separately.



P_1 polarisation of downcoming wave
P_2 polarisation of wave after ground reflection
P_3 polarisation of wave accepted by ionosphere

Fig. 16 – Intermediate reflection loss: P_1 polarisation of downcoming wave; P_2 polarisation of wave after ground reflection; P_3 polarisation of wave accepted by ionosphere.

There are three situations in which the loss may be large:

1. In temperate latitudes when the downcoming wave is incident at the Brewster angle, because the ordinary wave is essentially vertically polarised.

2. For east–west propagation with sea reflection at 45° dip latitude, when the ordinary wave re-enters the ionosphere as the extraordinary wave and is absorbed.

3. For north–south propagation with sea reflection at the magnetic equator, when the ordinary wave is again converted into the extraordinary wave and absorbed.

Intermediate reflection loss is, in general, non-reciprocal, i.e. its value changes if the direction of propagation between two given terminals is reversed. The non-reciprocal effect is most apparent when waves are reflected from land at angles near the Brewster angle, waves propagating towards the west suffering the greater loss. Waves reflected from the sea, however, have similar losses in both directions of propagation.

A general formula for intermediate reflection

loss has been derived.[20] This loss is a function of a large number of variables and should, ideally, always be computed. To enable losses to be estimated from curves, however, the following simplifying assumptions have been made elsewhere.[29]

1. The dip latitude and direction of propagation at the points where the wave leaves the ionosphere, and re-enters after reflection, are the same as the value at the Earth reflection point, except on north–south paths near the equator, where an allowance has been made for the change in dip latitude.

2. The frequency is approximately equal to the gyromagnetic frequency.

3. The angle of incidence at the ionosphere is 80°; this angle is approximately correct for hop lengths greater than 1000 km.

4. The reflection coefficient for horizontally-polarised radiation is −1.0.

Fig. 17 shows intermediate reflection losses, computed with these assumptions, for five directions of propagation relative to magnetic north and for a range of dip latitudes. The curves are plotted as a function of $\alpha(\sigma/F)^{1/2}$ where α is the radiation angle in degrees, σ is the ground conductivity in mS/m and F is the frequency in MHz. Because of the simplifying assumptions, Fig. 17 should not be used for values of α greater than 10°.

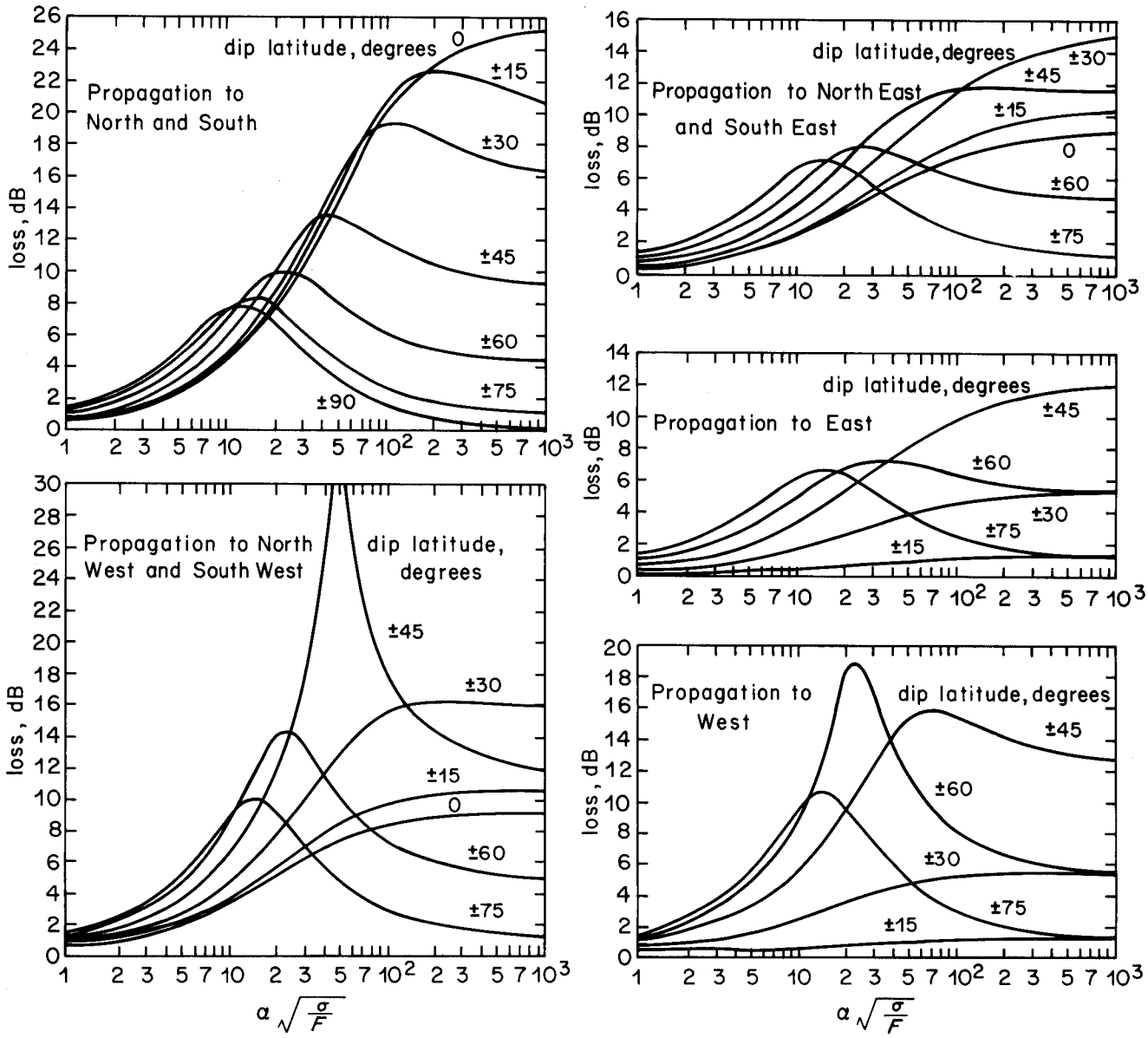


Fig. 17 – Intermediate reflection loss values: α angle of arrival, degrees to horizontal; σ ground conductivity, mS/m; F frequency, MHz.

The theory described above makes no allowance for Earth curvature, which would be expected to have a significant effect when α is less than 2°. Although the effect of Earth curvature on intermediate reflection loss has not yet been studied, it is possible that, at grazing incidence, the loss may tend to a value of about 6 dB under all circumstances. Although greater losses would be incurred with negative radiation angles because of diffraction, multi-hop paths involving negative radiation angles are unlikely to contribute significantly to received signals.

3.6. Field-strength calculation

So many factors are involved in m.f. sky wave propagation that it is difficult to draw a universal set propagation curves. A number of methods can be used to calculate field strengths and to construct propagation curves for particular areas, and directions of propagation.

In the wave-hop method[29] each propagation mode is considered separately. The free-space field strength is augmented by convergence gain[30] and the losses described in Sections 3.1 to 3.5 are then subtracted. Since the various modes arriving at the receiver are randomly phased, they are added on a power basis. The result gives the estimated median field strength for late at night at periods when solar activity is least. Corrections must be applied to derive field strengths for other times of day and for periods of greater solar activity, and to estimate the values exceeded for various percentage times.

The wave-hop method is too complicated and time consuming for planning purposes and a simpler method has therefore been adopted by the CCIR.[15] This is based on a propagation formula derived from measurements made in the USSR[31] which has been found to be reasonably consistent with measurements made elsewhere. Corrections are applied for polarisation coupling loss and sea gain, extending the validity of the formula to tropical regions and coastal areas. Corrections are also applied for diurnal variation and solar activity.

3.7. Ionospheric cross-modulation

Another feature of m.f. propagation which is affected by the Earth's magnetic field is ionospheric cross-modulation. When the region of the ionosphere traversed by a sky-wave is strongly illuminated by a high-power disturbing transmitter, the audio-frequency modulation of the latter may be superimposed on the carrier of the former and cause interference. This cross-modulation, also known as the Luxembourg effect, is caused by a non-linear process in the ionosphere. The mechanism has been fully described by Huxley and Ratcliffe.[32] Briefly, the disturbing transmitter varies the collision frequency of the ionosphere in step with its modulation and this, in turn, varies the attenuation suffered by the traversing wave, leading to cross-modulation.

Ionospheric cross-modulation is mainly confined to the l.f. and m.f. broadcasting bands, and the high-power transmitters which are in common use today may cause serious interference to sky-wave broadcasting services. Because of the large numbers of transmitters in these bands, ionospheric cross-modulation is difficult to distinguish from co-channel interference and even more difficult to measure. Numerous measurements have, however, been made in the past when these bands were less congested.

The depth of the transferred modulation depends both on the modulation depth of the disturbing transmitter and on the strength of the disturbing wave at the base of the ionosphere. To enable measurements to be compared they must first be standardised by calculating the cross-modulation which would have been observed if the disturbing transmitter had radiated with certain specified characteristics.

In a comparison of all known measurements,[33] estimates were made of the cross-modulation levels which would have been observed had the disturbing transmitters radiated from short vertical aerials with a power of 100 kW and been modulated at 300 Hz to a depth of 80%. This relatively low power was adopted as a reference because many of the measurements were made with powers of this order.

Fig. 18 shows the results of this comparison; full details are given in Reference 33. The horizontal frequency scale is normalised to the gyromagnetic frequency F_H because cross-modulation rises to a maximum at the gyromagnetic frequency, the width of the maximum depending on the collision frequency at the height where cross-modulation takes place. If the Earth's magnetic field were absent, cross-modulation would decrease approximately as $1/F_D^2$, where F_D is the frequency of the disturbing transmitter.

The enhanced cross-modulation near the gyromagnetic frequency is a direct result of the high rate of attenuation of the extraordinary wave generated by the disturbing transmitter. As a result an appreciable fraction of the radiated power is dissipated in a relatively small volume, causing electron heating and a significant increase in collision

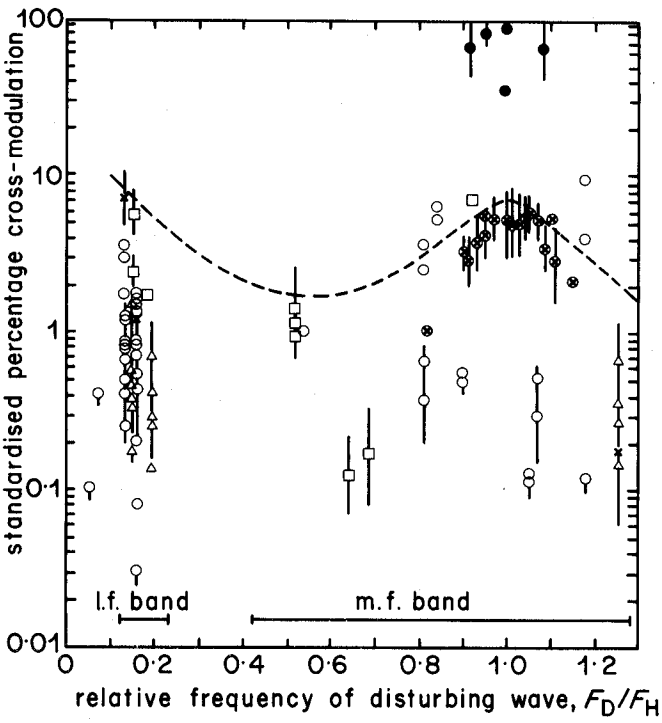


Fig. 18 – Comparison of ionospheric cross-modulation measurements. The measurements are standardised to the values which would have been observed if the disturbing transmitters had radiated 100 kW from short vertical aerials and been modulated at 300 Hz to a depth of 80%. --- semi-empirical upper limit.

frequency. This in turn greatly increases the attenuation of waves traversing the same region of the ionosphere and is responsible for the increased cross-modulation.

4. The combined effect of ground waves and sky waves

At m.f. the ground wave and sky wave can be considered separately because the distance between the ground and the ionosphere is several hundred wavelengths. Interference between the two waves, however, does have to be considered. In some situations the ground wave predominates and at other times the sky wave is stronger.

During the day, sky-wave propagation is relatively unimportant and ground waves provide stable signals. They are therefore widely used for broadcasting. For example a 100 kW transmitter can provide a good service out to a radius of 100 km and a satisfactory service at twice this distance. At night, however, the service is limited by sky-wave interference. The sky-waves may be generated by the same transmitter or they may originate from distant transmitters using the same frequency.

Although sky waves generated by the same transmitter carry the same modulation as the ground wave, it is slightly delayed in time and this gives rise to unacceptable distortion if the two waves are of comparable amplitude. The distortion can be tolerated, however, if the ground wave is at least 10 dB stronger than the sky wave. With a simple transmitting antenna this reduces the radius of the service area to about 80 km at night, regardless of the transmitter power. Some increase in this radius can be achieved by the use of specially designed transmitting antennas which minimise high-angle radiation and so reduce the sky-wave field strength at the edge of the service area, but this is seldom worthwhile today because of the great increase in the number of transmitters sharing the same frequency. Since these co-channel transmitters usually radiate different programme material, careful planning is required to protect ground-wave service areas from harmful sky-wave interference. Ideally, high-power transmitters sharing a common frequency should be separated by at least 1000 km.

Sky waves can be used to supplement ground waves at night, using a separate transmission on a different frequency, or they may be used to serve areas which are much larger than can be covered by ground waves. Sky waves can propagate to considerable distances. For example, European broadcasting transmitters have been regularly observed in southern Africa and in both North and South America.

5. Conclusions

Ground-wave propagation curves, such as those published by the CCIR, apply to land which is smooth and of uniform conductivity, but this condition is rarely satisfied in practice. The ground may be of variable conductivity and sections of the propagation path may be over sea water, which has a much greater conductivity than dry land. However the semi-empirical method for calculating field strengths along mixed land–sea paths which has been described gives reliable results and its use is recommended. It has been shown that propagation through cities and built-up areas can be explained by assuming that the ground behaves as an inductively-loaded surface.

Sky-wave propagation at frequencies between 300 and 3000 kHz is influenced by the transition between E-layer reflection and propagation via the F layer which occurs within this frequency band. At the lowest frequencies in the band, waves are reflected from the lower side of the E layer with relatively little loss, because they do not penetrate

very deeply into the layer. At higher frequencies, sky-waves may traverse the E layer and be reflected from the F layer; their propagation then has more in common with the type of propagation observed at h.f. An interesting feature of sky-wave propagation arises because the Earth's gyromagnetic frequency lies within the m.f. band. As a consequence, the extraordinary wave of the magnetic-ionic theory is greatly attenuated and only the ordinary wave propagates efficiently. This leads to polarisation coupling loss, which may be quite large in tropical regions. The attenuation of the extraordinary wave also has a significant effect on the coupling loss which occurs between hops on multi-hop paths.

Sky wave signals are strongest at night but vary considerably from night to night, and during short periods of an hour or less. Thus a 100 kW m.f. broadcast transmitter may adequately serve an area of radius up to 200 km during the day but this radius of good quality reception will be considerably reduced at night because of sky-wave interference.

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