Influence of the ground near transmitting and receiving aerals on the strength of medium-frequency sky waves


Abstract

The strength of the low-angle sky waves radiated by a medium-frequency aerial depends on the conductivity of the ground extending for many wavelengths in the direction of propagation. The field strength is greatest if the aerial radiates over open sea from the coast, and falls to a limiting value as the distance between the aerial and the sea increases. Measurements confirming the theoretical variation of field strength with distance from the sea are described, and the effects of ground and ionospheric irregularities are discussed.

1 Introduction

By day, the range of a medium-frequency (m.f.) transmitter is restricted to a few hundred kilometres because only the ground wave propagates efficiently. At night, however, propagation to very much greater distances is possible via the ionosphere, and interference with cochannel stations may occur. Broadcasting to distant areas is also feasible. Factors which govern the strength of sky-wave signals are therefore of vital importance in the planning of broadcasting services on an international basis.

A factor which has a greater effect on the propagation of sky-wave signals than is generally realised is the conductivity of the ground near the two terminals. It plays an important part in the transmission and reception of sky waves, because both the transmitted wave and the received signal are the vector sums of direct and ground-reflected waves. For the low-angle modes, which are important for long-distance propagation, it will be shown that the strength of the sky wave is influenced by the conductivity of the ground, not only near the aerials, but also many wavelengths from them in the direction of propagation.

Medium-frequency aerals, with very few exceptions, radiate vertically-polarised waves. Aerials intended for local ground-wave broadcasting are of necessity vertical, since only a vertically-polarised ground wave propagates efficiently. Aerials intended for sky-wave broadcasting are also mainly vertical, because horizontal aerals of practical heights do not radiate efficiently at low angles at m.f. For the same reason, listeners’ receiving aerials are insensitive at m.f. to the horizontal components of low-angle sky waves. Since we are concerned here with the transmission and reception of low-angle sky waves, horizontal polarisation will not be considered further.

For vertical polarisation, the vector sum of the direct and ground-reflected waves is greatest when the aerial is surrounded by the sea or is near the coast, because the reflection coefficient of sea water is approximately unity. For an aerial over land, however, the two component waves tend to cancel, and their resultant is much smaller, especially at very low angles. The reduction inland, relative to a coastal site, will be referred to as ’ground loss’. The ground loss is the same whether the aerial transmits or receives, even though ionospheric propagation is in general nonreciprocal. At m.f., the extraordinary wave suffers more attenuation than the ordinary. If the ordinary wave alone were present, propagation between vertical aerals or loops would be fully reciprocal. In the presence of a weak extraordinary wave, it is generally accepted that the average transmission loss remains independent of direction, because the two waves are randomly phased relative to each other.

Section 2 considers both the ground loss of an aerial well inland depends on the angle of incidence of the wave, the ground conductivity and the aerial height. Section 3.1 shows theoretically how the ground loss of an inland aerial is influenced by proximity to the sea, measurements confirming the theory being described in Section 3.2. The effect of sloping ground and Earth curvature is discussed in Section 4.

2 Ground loss for an aerial well inland

In this Section, the strength of a signal radiated (or received) by an aerial on flat ground of infinite extent and uniform conductivity is compared with that radiated by a similar aerial entirely surrounded by sea. Types of aerals considered are vertical conductors of various heights (mast aerals and wire receiving aerals) and vertical loops (ferrite-rod receiving aerals).

The vertical radiation pattern (v.r.p.) over flat uniform ground of a short vertical aerial is proportional to \( |1 + p(\theta)| \) \( \cos \psi \), where \( \psi \) is the radiation angle measured from the horizontal, and \( p(\theta) \) is the complex Fresnel plane-wave reflection coefficient for vertically-polarised waves. This expression disregards the surface wave, because the latter makes no significant contribution to the sky wave at the distances being considered.

Fig. 1a shows v.r.p.s, calculated at 1 MHz, for a short vertical aerial over flat ground of poor conductivity (10\(^{-3}\) S/m), good conductivity (10\(^{-2}\) S/m) and sea water (4 S/m): fresh water behaves like ground of good conductivity. The v.r.p. which would be obtained if the ground were a perfect conductor is also shown, for comparison. Fig. 1a shows that the finite conductivity of the ground causes the v.r.p. to fall to zero in the horizontal direction [\( p(0) = -1 \)]. The v.r.p. rises from zero most rapidly with sea water, which behaves like a perfect conductor except at angles very close to the horizon. Consequently, an aerial over the sea radiates or receives more efficiently than one over land, especially at angles near the horizon. The ratio between the v.r.p.s of aerals over land and sea is equal to the limiting ground loss for an aerial well inland, and is shown in Fig. 16. The large losses shown at very low angles are unlikely to be important, however, because of the presence of higher-angle multihop modes which have lower losses; this point is discussed in Section 5.

Although Fig. 1a was calculated for short vertical aerals, it is approximately correct for small loop aerals, provided that \( \psi \) is less than 15\(^\circ\), since the v.r.p. of a loop differs from that of a vertical aerial only by a factor of \( \cos \psi \). Fig. 1b applies to loop aerals without approximation, since it is independent of the \( \cos \psi \) factor. It also applies to tall vertical aerals, but is subject to a height-gain modification, discussed later in this Section. Fig. 1 is applicable only to a frequency of 1 MHz for the specified conductivities. Universal curves, which enable v.r.p.s and ground losses to be determined for a range of ground conductivities and frequencies, are shown in Fig. 2. The curves show the v.r.p. of a loop aerial as a function of the angle to the horizontal \( \psi \), and the complex relative

* The term ‘surface wave’ has here the same meaning as that ascribed to it by Norton; that is to say, a short-distance correction to the sum of the direct and reflected plane waves. The justification for the use of the Fresnel plane-wave approximation must be carefully examined, considering a reception rather than...
Vertica1 radiation patterns and ground loss for short vertical aerials

a. Vertical radiation patterns
b. Ground loss

Frequency = 1 MHz

The curves make use of a parameter $Q = (x)^{3/2} \sin \psi$ and Norton’s parameter $b = \tan^{-1}((e + 1)/x)$. They are restricted to the values of $\psi$ for which the approximation $\cos \psi \approx 1$ is valid ($\psi < 15^\circ$), and may therefore be used also for short vertical aerials, with little error.

In calculating the curves of Fig. 1, the aerial current was assumed to be the same for all conductivities; Fig. 16 therefore shows the ground loss for equal currents, not equal powers. Since the radiation resistance of an aerial depends on the conductivity of the ground below it, the true ground loss will differ from that shown in Fig. 16, if the radiation resistance of the aerial over land is significantly different from that over sea. Detailed investigations, such as that described in Reference 2, show that the difference is unimportant for all types of m.f. transmitting and receiving aerials. Thus, Fig. 16 is approximately correct for equal powers.

So far, only aerials small compared with the wavelength and close to the ground have been considered. Practical radiation at low angles. To determine the ground loss of a tall aerial, it is convenient to regard it as a receiving aerial, and to examine the variation with height above ground of the vertical component of the resultant electric field, due to a plane wave incident at angle $\psi$. This is given by

$$E_z = E \cos \psi \left( \frac{\beta \sin \psi}{\sqrt{(K_x \sin \psi)^2 + 1}} \right)$$

where $E$ is the strength of the downcoming wave, $z$ is the height above ground, $B = 2\pi/\lambda$ and $\lambda$ is the wavelength.

From eqn. 1, it can be shown that $E_z$ decreases initially and then increases, as $z$ increases from zero; this variation of $E_z$ with $z$ is frequently referred to as 'height gain'. The initial rate of decrease, at $z = 0$ is

$$\left( \frac{\partial E_z}{\partial z} \right)_{z=0} = j \beta \sin \psi \frac{1 - \rho(\psi)}{1 + \rho(\psi)}$$

where $E_z(0)$ is the field strength at ground level. Now, since

$$\rho(\psi) \approx \sqrt{(K_x \sin \psi)^2 + 1}$$

it follows that

$$\left( \frac{\partial E_z}{\partial z} \right)_{z=0} = \frac{j \beta}{\sqrt{K_x}}$$

This result, which is independent of $\psi$, is identical with eqn. 14 of Reference 2, which describes the height-gain variation of a ground wave. Thus tall aerials radiating sky waves are subject to the height-gain factors which apply for ground-wave propagation. The integrated effect of height gain for tall aerials has been discussed in Section 5.2.2 of Reference 2; this shows that, at 1 MHz, a 0.55 $\lambda$ base-fed aerial suffers losses of 0.7 dB and 1.2 dB with ground conductivities of $10^{-2}$ and $10^{-3}$ S/m, respectively, due to height gain. However, the height-gain reduction for a similar aerial surrounded by sea is negligible. Consequently a tall aerial well inland suffers an additional ground loss as a result of height gain.

3 Variation of ground loss with distance from the sea

The limiting ground loss discussed in Section 2 is modified by proximity to the sea and, similarly, radiation from an aerial surrounded by sea is modified by proximity to land. The situation which arises when an aerial near the coast radiates or receives sky waves which pass over the sea is considered in detail in this Section, and conclusions about aerials near the coast radiates...
3. Theoretical considerations

Fig. 3 shows a short vertical aerial distant \( r \) from a straight coastline which, initially, will be assumed to be normal to the plane of the paper. Because of the principle of reciprocity, it is immaterial whether the aerial transmits or receives; for convenience, it will be assumed to receive a plane sky wave incident at angle \( \psi \) from the horizontal. The variation in the vertical component of the electric field with distance from the coastline will then be examined.

This situation has been analysed by Andersen,3 using the compensation theorem: and an equivalent result has been derived by Clemmow5 using an integral equation method. The Andersen–Clemmow formula is not valid within half a wavelength of the land-sea boundary, but this region has been studied by Millar,6 using a Bessel-series expansion. If \( \psi \) is less than 15° and the sea is assumed to behave as a perfect conductor, the Andersen–Clemmow formula for the field strength \( E_x \) inland, relative to that over the sea \( E_x^{se} \), may be expressed in terms of Norton’s parameters \( p \) and \( b \), together with the parameter \( Q \) introduced in Section 2, as follows:

\[
\frac{E_x}{E_x^{se}} = \left[ 1 + \rho(\psi) \right] + \frac{1}{c-j} \left[ j\sqrt{2c} \left( e^{-j\frac{\pi}{4}} - F(r) \right) - \frac{e^{-j\theta}}{\sqrt{\sigma_0 \rho_0}} \left( 1 - G(p_0) \right) \right]
\]

where

\[
p_0 = \rho e^{-jb} \quad (\text{Norton’s numerical distance})
\]

\[
b = \tan^{-1} \left[ \left( \epsilon + 1 \right) \frac{1}{x} \right] \quad (\text{a Norton parameter})
\]

\[
r = \text{distance from the coast}
\]

\[
\epsilon - jx = \text{complex relative permittivity, defined in Section 2}
\]

\[
Q = \left( \frac{\gamma}{x^2} \right) \sin \psi \approx \psi \tan x
\]

\[
\rho(\psi) = \frac{\psi(\epsilon - jx)}{\psi(\epsilon - jx) + 1} \quad \text{the Fresnel plane-wave reflection coefficient, which can be expressed as a function of band } Q
\]

\[
c = Q^2(1 + j \tan b)
\]

\[
l = \rho Q^2 \cos b
\]

\[
F(r) = \frac{1}{\sqrt{2\pi}} \int_0^r e^{-j\theta} \, d\theta \quad (\text{the complex Fresnel integral})
\]

\[
G(p_0) = 1 - j\sqrt{\gamma \rho_0} e^{-j\theta} \text{erfc}(j\sqrt{\rho_0}) \quad (\text{Sommerfeld’s attenuation function})
\]

Eqn. 5 is essentially the same as eqn. 4 of Reference 3. The first term corresponds to the field strength well inland, and the remaining terms may be regarded as corrections accounting for the proximity of the sea. In eqn. 5, both the phase retardation factor \( e^{-j\theta} \cos \psi \) and the time factor \( e^{j\omega t} \) have been omitted. It should be noted that Andersen follows Norton in using the \( e^{-j\omega t} \) time factor, but the opposite convention is now more common and has therefore been used here.

Fig. 4 shows field strength as a function of distance from the coastline, calculated from eqn. 5, for three angles of arrival. Also shown is the attenuation of a ground wave arriving from over the sea; this may be obtained from eqn. 5 by setting \( \psi - 0 \). It will be seen that, at large distances from the coast, the field strength tends asymptotically to the value for ground of infinite extent, discussed in Section 2. The small discrepancy between the asymptotes of the \( \psi = 15^\circ \) curves and the corresponding values in Fig. 1a occurs because \( \cos 15^\circ \) is not quite unity. As the observer moves inland from the coast, the field strength due to a sky wave decreases almost as slowly as that due to the ground wave. Consequently.

![Fig. 3](image1.png)

**An aerial near a coastline**

![Fig. 4](image2.png)

**Variation of field strength with distance from the coast**

- Ground conductivity 10⁻³ S/m
- Frequency = 1 MHz
- Curves and the corresponding values in Fig. 1a occur because \( \cos 15^\circ \) is not quite unity. As the observer moves inland from the coast, the field strength due to a sky wave decreases almost as slowly as that due to the ground wave. Consequently.

- The transition from sea to land conditions may occupy many wavelengths, especially with low angles of arrival. The transition is virtually complete when the whole of the first Fresnel zone on the ground lies inland. This zone is a long narrow ellipse with its major axis lying in the direction of propagation. On sea, and on land of high conductivity, its extremity is approximately \( \lambda/\sqrt{2} \) from the aerial and its width is \( \lambda/\sqrt{2} \). Thus if \( \psi = 5^\circ \) (0.087 rad), the zone is 130 km long and 11.5 km wide. On poorly-conducting ground, however, the zone is somewhat smaller, and its dimensions are approximately halved at m.f. when the conductivity is 10⁻³ S/m. Contributions to the received signal from currents induced on the ground within the zone tend to add in phase, but contributions from outside the zone tend to cancel, and are therefore less important.

- Fig. 5 shows the first Fresnel zone on the ground, viewed from above, and a coastline passing through the point P. This illustration suggests that the coastline may be rotated through a large angle about P, without significantly affecting the field strength at the aerial. Although the curves of Fig. 4 were computed for normal incidence at the coastline, they are believed to be valid for directions within \( \pm 70^\circ \) of the normal, provided the distance from the coast is measured along the direction of propagation. Fig. 5 further suggests that the curves of Fig. 4 may also be applied to irregular coastlines, provided the distance from the sea is measured from the point at which the propagation path across the coast. The Fresnel-zone concept also suggests that the enhanced field strength near the coast will only be achieved if the outer extremity of the zone lies on the sea. Thus the ground loss at
the coast will be low only if open sea extends for many wavelengths in the direction of propagation.

To enable field strengths inland to be determined at medium frequencies, for a large range of ground constants, loss inland (relative to a coastal site) is slightly reduced, and a small correction must be applied to the curves when comparing inland and coastal sites.

The discussion so far has been restricted to the variation of the vertical electric field with distance from the coast. Since loop receiving aerials respond to the magnetic field, consideration must also be given to the way in which this varies.

The tangential magnetic field $H$ is related to the vertical component of the electric field $E_z$ by Maxwell's equation $\nabla \times H = j\omega \varepsilon E$. It therefore follows that

$$\frac{3H}{3r} = jwtE,$$

(6)

where $r$ denotes distance along the ground in the direction of propagation. Now $E_z$ may be expressed in the form

$$E_z(r) = E_{z,0} f(r) e^{-jk r},$$

(7)

where $E_{z,0}$ is the field strength over the sea, $f(r)$ is described by eqn. 5 and $k = \beta \cos \phi$. Substituting eqn. 7 into eqn. 6, and integrating by parts with respect to $r$, gives

$$H = -\frac{\omega \varepsilon E_{z,0}}{k} \left[ E_z(r) - E_{z,0} \int f'(r) e^{-jk r} dr \right] + A,$$

(8)

where $A$ is a constant, and $f'(r)$ is the derivative of $f(r)$ with respect to $r$. The computations based on eqn. 5 show that $f'(r)$ does not exceed $10^{-3}$ in the m.f. band, even when the ground is poorly conducting; it is therefore reasonable to neglect $f'(r)$ in eqn. 8. Further, $H$ cannot in general exist if

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universal curves of field strength as a function of numerical distance from the coast have been computed from eqn. 5, and are presented in Fig. 6. The curves for $b = 0$ correspond to ground which behaves predominantly as a conductor, while those for $b = 30^\circ$ are for ground which resembles a lossy dielectric. Values of $b$ outside this range are seldom found at m.f.* In calculating the curves of Figs. 4 and 6, the sea was assumed to behave as a perfect conductor. The finite conductivity of the sea does not significantly affect the field strength inland, but it does slightly reduce the field strength.
H is proportional to $E_z$, at the distances where eqn. 5 is valid. Thus Figs. 4 and 6 also apply to the magnetic field.

Eqn. 5 is not valid at the actual land–sea boundary, but the field strength at this point is of considerable interest because it is a convenient reference point for measurements. Millar has studied the variation of the magnetic field near the boundary, and has shown theoretically that the ground loss at the water's edge, for ground of good conductivity ($\sigma = 10^{-2}$ S/m), is about 1 dB at 10 MHz. At 1 MHz, the loss for $\sigma = 10^{-3}$ S/m would be similar, while the loss for $\sigma = 10^{-2}$ S/m would be less. Millar's theory applies to a sharp discontinuity between a perfect conductor and ground of arbitrary constants, but in practice the transition may be less abrupt (except at high tide), because the moisture retained in the beach will enhance its conductivity. The ground loss at the water's edge is therefore likely to be less than Millar's theory suggests, and for all practical purposes can be neglected. Millar also shows that the field strength, inland from the boundary, falls smoothly to the values given by the Andersen–Clemmow formula. Over the sea, it exhibits a small standing wave, caused by reflection from the coastline.

The situation which arises when a sky wave is received from over the land, rather than from over the sea, does not appear to have been studied in detail, although the relevant theory has been derived by Andersen and is given in eqn. 3 of Reference 2. The theory for the converse situation already discussed suggests that the full ground loss would apply for all inland sites. At sea, the ground loss would decrease gradually with increasing distance from the coast, the field strength increasing at a rate similar to the well known 'recovery' experienced by a ground wave. The ground loss would not approach zero until most of the first Fresnel zone lay on the sea. This trend has been demonstrated theoretically by Andersen, as a special case of a three-section ground (see the curve labelled $d = \infty$ in Fig. 6 of Reference 3). In passing, it should be noted that Andersen has produced solutions in closed form, together with a limited range of computed values, for the field strength at sea when a sky wave passes over a strip of land, and for the field strength inland when a sky wave passes over a strip of sea. In principle, there is no reason why his method should not be extended to a sky-wave passing over any type of mixed path.

### 3.2 Ground-loss measurement

There are two possible ways of measuring ground loss. In one method, sky-wave signals received at night from two distant transmitters, one near the sea and one inland, are recorded and compared. To minimise differences in propagation losses, both transmitters must radiate on similar frequencies and be situated in the same geographical area. They must also radiate on channels free from interference. As it is impossible to satisfy all these conditions simultaneously in Europe, the results obtained must be minimised by recording over long periods and applying semempirical corrections. Although this method has been attempted, the results obtained were inconclusive.

The alternative is to compare signals received simultaneously, at inland and coastal sites, from a single distant transmitter. Measurement is made by comparing the losses for ionospheric-reflection points are as close as possible; this, with the use of a common frequency, eliminates most of the uncertainty resulting from differences in propagation losses. The use of portable measuring equipment enables a detailed study of the variation of ground loss with location to be undertaken. This method was used for the measurements described here; it has also been used by Andersen at h.f.

The measurements described were made in Southern England, using the 845 kHz transmission from Rome. This transmission was chosen because it was so clear that the ionospheric-reflection points are as close as possible; this, with the use of a common frequency, eliminates most of the uncertainty resulting from differences in propagation losses. The use of portable measuring equipment enables a detailed study of the variation of ground loss with location to be undertaken. This method was used for the measurements described here; it has also been used by Andersen at h.f.

The measurements were then divided into three 1 hour periods, and the mean and the standard deviation of the field-strength ratio in decibels were computed for each period. The results of this computation are compared, in Table 1, with the corresponding values calculated for each half-minute unit, and the correlation coefficient computed for each displacement. No marked increase in correlation coefficient resulted. It was therefore concluded that no advantage was to be gained by displacing these two measurements in time.

The measurements were then divided into three 1 hour periods, and the mean and the standard deviation of the field-strength ratio in decibels were computed for each period. The results of this computation are compared, in Table 1, with the corresponding values calculated for the whole period.

The table shows small differences between the mean field-strength ratios. Significance tests, using the method described in Section 4.3 of Reference 11, showed that (c) the differences

![Fig. 7 Map of Southern England showing measuring sites](image-url)
Field strengths measured simultaneously at Gatwick and Pevensey on 23rd Jan. 1968

between the individual 1h measurements were not significant and (6) the difference between the 1h and 3h measurements was not significant. On the basis of this evidence, it was concluded that 1h recordings would suffice for all subsequent measurements of this type.

Table 1

<table>
<thead>
<tr>
<th>Period</th>
<th>Mean field-strength ratio (dB)</th>
<th>Standard deviation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3h period</td>
<td>5.72</td>
<td>5.74</td>
</tr>
<tr>
<td>First hour</td>
<td>5.51</td>
<td>6.00</td>
</tr>
<tr>
<td>Second hour</td>
<td>5.51</td>
<td>5.60</td>
</tr>
<tr>
<td>Third hour</td>
<td>6.20</td>
<td>5.54</td>
</tr>
</tbody>
</table>

One of the receivers was then taken in turn to each of the sites shown in Fig. 7, and operated inside a van with a glass-fibre body. 1h comparisons were made with the indoor site at Pevensey, or in the case of site K, with the indoor site at Gatwick. Comparisons were subsequently made at 15s intervals for 5min periods between the indoor site at Pevensey and sites on the beach, and between the receiver in the van and nearby open sites. In analysing the short-period comparisons, the two recordings were displaced in time for best correlation, and their differences in decibels treated as a variate as before. Care was taken to avoid choosing sites near overhead power lines and telephone wires, since these can cause errors, and, wherever possible, sites on level ground were selected. Measurements were made at two or three sites in each locality, and significance tests made between them. If the differences between sites were found to be significant, they were treated as separate sites; otherwise they were treated as one site and the data pooled. All the measurements were referred to the beach at Pevensey. In general, each measured field strength inland was derived from a 1h comparison, in conjunction with short-period comparisons at the two sites being compared. The overall error, resulting from finite observation periods, was assessed by calculating the standard error of the mean for each of the three recordings.

Result is thus the sum of the individual variances). Confidence limits were then ascribed to the final result.

Part of the reduction of field strength inland is due to the greater distance of the inland sites from Rome. A correction based on the EBU/CCIR propagation curves was therefore applied. The correction required for the site furthest from the coast was 2.5 dB; for all other sites it was less than 1.3 dB.

Fig. 9 shows the results of the measurements, corrected as described, together with their 95% confidence limits. Fig. 9 therefore shows how ground loss varies with distance from the sea at 845kHz, for an angle of arrival of about 4°. Also shown in Fig. 9 are theoretical curves for ground conductivities of $5 \times 10^{-1} S/m$ and $10^{-2} S/m$; these are believed to be the upper and lower conductivity limits for most of the area.

Part of the theoretical curve for $2 \times 10^{-2} S/m$ is also included, since the first 10km inland passes over a marshy area whose conductivity is known, from local ground-wave-attenuation measurements, to be of about this value. In computing these curves, the angle of arrival was assumed to be 4.3°. This figure corresponds to a virtual reflection height of 100km, and was derived from a ray-tracing computation, based on a night-time ionospheric profile which is believed to be...
The measurements show the same trend as the theoretical curves, and the agreement is considered to be satisfactory. Exact agreement would not be expected because the ground conductivity is not constant over the path, and, in some places, the terrain is hilly and rises to 180m above sea level. The large ground loss occurring well inland is, however, clearly demonstrated.

A few measurements were also made in a boat, at distances up to 1km from the beach. No significant increase in field strength, compared with the value on the beach, was observed. The theoretical increase is probably less than 0.5 dB.

4 Effect of Earth curvature and irregular terrain

Up to this point, the ground has been assumed to be perfectly flat. Ground loss is, however, modified where there are hills and cliffs, and may also be affected by Earth curvature. These factors are considered further in this Section.

4.1 Earth curvature

If the ground is assumed to be flat, the theory described in Section 2 suggests that the field strength due to a wave arriving at grazing incidence should be zero. However, a plane wave incident on a curved surface diffracts into the shadow region. Consequently, the field strength at the Earth's surface will be finite not only for grazing incidence, but also when the direction of arrival of the incident wave lies below the horizon.

The magnitude of the diffracted field on a cylindrical lossy surface has been studied theoretically, by Wait and Conda. Using a Bessel-series representation; their results are believed to apply with reasonable accuracy to a spherical surface of the same curvature. Fig. 10, which was derived from Wait and Conda's curves, shows how the field strength at the

![Figure 10](image)

**Theoretical vertical radiation patterns of short vertical aerials on the Earth's surface**

- v.r.p., assuming the Earth to be curved
- v.r.p., assuming the Earth to be flat

Earth's surface varies with the angle of arrival of a vertically-polarised 1 MHz plane wave; negative angles of arrival correspond to waves incident from below the horizontal. Curves for sea water and for ground of average conductivity ($5 \times 10^{-3} \text{S/m}$) are compared with those which would be obtained if the Earth were assumed to be flat, as in Section 2. By reciprocity, Fig. 10 also represents the v.r.p., at a great distance, of a short vertical aerial at the Earth's surface, and shows that the effect of Earth curvature on the v.r.p. of an aerial well inland is unimportant, but it is significant when the aerial is on or near the sea. The ground loss of an inland aerial is reduced by about 1dB at the angles which are important for long-distance propagation ($2^{-5}$), because of the effect of Earth curvature on the v.r.p. of the reference aerial near the sea. Fig. 10 also shows that an aerial surrounded by sea propagates efficiently to directions below the horizontal, but these very-low-angle modes are unlikely to be effective, unless the receiving aerial is also near the

4.2 Hills and cliffs

The v.r.p. of an aerial on a steep hill or cliff over looking level ground or sea is modified, because the difference between the direct and ground-reflected wave increased. It can be shown theoretically that the low-angle radiation from an aerial well inland may be greatly increased by raising it to a considerable height. Thus, an aerial on a mountain well inland will radiate as effectively, at some angles, as an aerial near the sea.

No further increase in sky-wave radiation is expected an aerial near the sea is raised, and at some angles of elevation the radiation may be considerably reduced. However, measurements of the magnetic-field strength due to Rome 845kHz, at the top of Beachy Head (a vertical cliff in south England 160m high), gave results 2-3 dB higher than was measured on a beach well away from the cliff. This enhanced field strength is believed to be a purely local effect, associated with the sharpness of the cliff edge; 200m from the edge, the measured increase was only 0.4 dB. These figures are consistent with the theoretical increases in the magnetic and electric fields which occur near the apex of a rectangular wedge illuminated by a plane wave. By reciprocity, an aerial situated in the region of enhanced field strength would give increased sky-wave radiation, but severe practical difficulties would attend the siting of an aerial so close to a cliff edge.

4.3 Sloping ground

Fig. 11a represents a wave incident at a point A on sloping ground, which may be either land or sea. Although a formal solution for this situation has not yet been attempted, the variation in the field strength at

![Figure 11](image)

An aerial on sloping ground

can be inferred from the theory which has already been discussed. Provided that the distance $AB$ is sufficiently great, the magnitude of the field strength at A will correspond to the effective angle of arrival $\theta + \alpha$, and will generally be greater than that corresponding to the angle $\theta$. Thus, the ground loss at A will be less than it would be if the ground were level. Because of the greater angle of arrival, the first Fresnel zone on the ground is considerably shorter. Consequently, the minimum distance $AB$ required for reduced ground loss to apply need not be very large.

If, instead, the slope is reversed, as shown in Fig. 11b, the effective angle of arrival will be less than $\theta$, and the field strength will be less than it would be if the ground were level. However, the distance $AB$ may have to become very great before the field strength falls completely to the value corresponding to the reduced angle of arrival, because the first Fresnel zone will be very long. Furthermore, the field strength will not be zero, even if the effective angle of arrival is negative, because the incident wave will diffract over the top of the hill.

5 Effect of the ionosphere on ground loss

In the preceding Sections, ground loss for inland aerials was calculated for a single, plane incident wave. However, several waves, incident at different angles, may be
may contain components distributed about a preferred direction, because of the roughness of the ionosphere. The way in which these factors modify the ground loss of an inland aerial is discussed in Sections 5.1 and 5.2.

5.1 Diffuse ionospheric reflection

The effect of ionospheric roughness on ground loss has been discussed by Andersen, assuming the power density of the incident wave to be normally distributed about a preferred direction $\psi_0$, with standard deviation $\theta_0$. The effective power-radiation pattern $B(\psi_0)$ of an aerial receiving the wave is then defined as

$$B(\psi_0) = \int P(\psi)(E(\psi))^2 d\psi$$

(9)

where $P(\psi)$ is the distribution function of the incident power, and $E(\psi)$ is the conventional plane-wave radiation pattern. Comparison of $B(\psi_0)$ for aerials over land and sea then gives the effective ground loss. Andersen showed that ionospheric roughness reduces ground loss slightly, at h.f.

Table 2

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<thead>
<tr>
<th>$\psi_0$, deg</th>
<th>Standard deviation of power distribution $\theta_0$, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>dB</td>
</tr>
<tr>
<td>5</td>
<td>5.8</td>
</tr>
<tr>
<td>10</td>
<td>3.4</td>
</tr>
<tr>
<td>15</td>
<td>2.3</td>
</tr>
</tbody>
</table>

at m.f. for $\psi = 32^\circ$, $\theta_0$ is unlikely to be so large at the lower propagation angles of interest here. It is therefore reasonable to conclude that the effect of diffuse ionosphere reflection on ground loss is relatively small at m.f., and need not be considered further.

5.2 Multihop propagation

If two or more waves with different angles of arrival are incident on a receiving aerial well inland, the ground loss will depend on the dominant wave. Thus, if a low-angle mode predominates, the ground loss will be greater than it would be if a high-angle mode were dominant. If both modes are of comparable strength, however, the ground loss will assume an intermediate value.

Fig. 12a shows the effective ground loss for an aerial well

![Figure 12a](image_url)

**Ground loss for multihop propagation**

(a) E-layer reflection (layer height 90km)
(b) F-layer reflection (layer height 250km)

The curves show the ground loss which occurs when sea water is replaced by ground of conductivity $5 \times 10^{-3}$ S/m at one end of the path. Numbers against the curves denote radiation angles. Frequency = 1 MHz

In the present investigation, the effective ground loss at 1 MHz was computed by numerical integration of eqn. 9, for $\theta_0$ up to $4^\circ$, assuming a ground conductivity of $5 \times 10^{-3}$ S/m. The results obtained are shown in Table 2.

It will be seen that the ground loss does not differ greatly from that which would be obtained with a plane wave.
assuming that reflection is from the E layer. For short distances, the effective ground loss is close to that for a single-hop mode, because the latter predominates, but at distances near the maximum range of the one-hop mode, the ground loss falls to the two-hop value. Curves for F-layer reflection are shown in Fig. 12b, since reflection from the F layer may occur in the late evening, at the higher frequencies in the m.f. band. Reflection from the E layer is, however, more important.

In deriving Figs. 12a and b, two short aerials surrounded by sea were taken as a reference. The relative strengths of all significant modes propagating between them was calculated, assuming the v.r.p. shown in Fig. 10, and taking ionospheric-absorption losses, polarisation-coupling losses and convergence gain into account. The effective strength of the received signal was assumed to be proportional to the r.m.s. sum of the modes, since they are randomly phased, and must be added on a power basis. The calculation was then repeated with one of the aerials well inland, and the r.m.s. sum compared with that for the reference condition, to obtain the effective ground loss shown in Fig. 12. Further calculations with both aerials well inland showed the total ground loss to be approximately doubled; thus Fig. 12 shows the effect of changing the conductivity at one end of the path regardless of the conductivity at the other terminal.

6 Conclusions

An m.f. transmitter will radiate sky waves most efficiently if it is situated on a coastline facing the service area. To obtain the maximum advantage, open sea must extend for at least 100 wavelengths in the direction of propagation. No additional advantage can be gained by placing the aerial out at sea. Some theoretical advantage can be gained by siting the aerial right at the edge of a vertical cliff overlooking the sea, but the great practical difficulties make this very unattractive.

An aerial at an inland site radiates less efficiently than one near the coast. As the distance from the coast increases, the radiated field falls to a limiting value when the aerial is so far inland that the sea has no influence. For low-angle sky-wave propagation, the ground loss does not reach its limiting value at m.f. until the aerial is at least 50 km from the coast. The field-strength reduction or ground loss, due to the siting of an aerial well inland, is increased by reduced ground conductivity, and is greatest for low-angle modes. An aerial well inland is also less effective than one near the coast, because it is further from the service area.

The initial increase in ground loss with distance from the coast is the same for all radiation angles, and depends on the ground conductivity. When the conductivity is high, aerials may be sited up to 5 km from the coast (measured in the direction of propagation), for a loss of less than 1° in areas of poor conductivity, however, aerials must be much nearer the coast.

The ground loss of an inland aerial can be reduced by siting it on ground sloping downhill in the direction of service area. The ground loss of an aerial on a mountain overlooking a plain is considerably reduced at some radiation angles, but may be greatly increased at others.

Ground loss applies equally to transmitting and receiving aerials. In analysing sky-wave field-strength recordings corrections should therefore be made for the terrain at terminals.

7 Acknowledgments

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8 References