REPORT 879-1

METHODS FOR ESTIMATING EFFECTIVE ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH

(Decision 3)

(1982-1986)

1. Introduction

This Report is concerned with the measurement of the effective electrical characteristics of the surface of the earth. A knowledge of these characteristics is especially important in MF and LF broadcast planning where the ground wave is the primary mode of propagation. The effective conductivity of the surface of the earth typically lies between 0.1 and 30 mS/m. From the curves found in Recommendation 368, it is seen that this range of conductivities results in a 44 dB difference in field-strength values for a 1 MHz signal at a distance of 100 km. Thus a knowledge of these characteristics is necessary both for accurate estimates of MF and LF broadcast coverage and for interference calculations.

2. Effective ground electrical characteristics

The term effective electrical characteristics is used in connection with ground-wave propagation to emphasize the fact that the values of conductivity, σ, and permittivity (dielectric constant), ε_r, which should be used for ground-wave field-strength calculations, may be different from those values which would be obtained from laboratory measurements. In many cases the values of the electrical characteristics at the surface must be modified because of the influence of terrain irregularities and sub-surface strata. At low frequencies and low surface conductivities, the ground-wave propagation loss may be determined by the value of the conductivity of the sub-surface strata.

2.1 *Relative importance of conductivity and permittivity*

For a homogeneous earth, the value of the permittivity, ε, has little influence on the MF and LF ground-wave transmission loss if $\varepsilon_r \ll 60\ \lambda\sigma$. In most cases it is sufficient to use the values of ε associated with the estimated conductivity ranges given in Recommendation 527. Alternatively, one can use the empirical relation found by Hanle [1966] $\varepsilon_r = 50\ \sigma^{1/5}$ where conductivity is expressed in units of S/m.

Over ground with horizontally stratified layers, however, the effective permittivity may become very large or even negative [Eliassen, 1957; Wait, 1970]. Thus, it is possible that the relation $\varepsilon_r \ll 60\ \sigma\lambda$ may not be satisfied for the effective electrical characteristics even though it may be satisfied for surface layer and the sub-surface layers. Wait [1970] has developed a theoretical relationship for the effective electrical characteristics over horizontally stratified ground. Report 716 discusses the necessity of using the total complex effective surface impedance when calculating the phase of the ground wave for precision radionavigation systems [Johler and Horowitz, 1974].

2.2 *Frequency dependence of the electrical characteristics*

The conductivity of soil samples shows a frequency dependence above 10 MHz as illustrated in Recommendation 527, Fig. 1. At lower frequencies, there is no inherent frequency dependence of the conductivity of the soil.

The effective electrical characteristics, however, will show a frequency dependence when the surface values are modified by sub-surface layers and irregular terrain. The frequency dependence of the effective electrical characteristics with underlying strata is a function of the ratio of top layer thickness to penetration depth. Thus the effective ground constants at LF may be significantly different from those at HF. The influence of terrain irregularities on the effective electrical characteristics is dependent on the ratio of terrain height variations to wavelength. Further information on this subject will be found in Report 1145.

2.3 *Penetration depth*

From the above discussion it can be seen that the effective electrical characteristics are determined by the extent to which the electromagnetic field penetrates the soil. This extent is characterized by the penetration depth which is shown in Fig. 2 of Recommendation 527. In the MF band, the penetration depth is typically 5 to 100 m. Consequently, any measurement method used to measure effective electrical characteristics should either use radio methods at the appropriate frequency or measure the soil to a depth equivalent to the penetration depth at the frequency of interest.

3. First order estimates of effective conductivity

Initial estimates of the effective conductivity in a region for the MF band can be obtained from a knowledge of the geological and lithological structure in the region. This method is based on the observed association between measured MF effective conductivities in the United States of America and Canada and the structural properties of the ground [Barghausen *et al.*, 1966]. Fig. 1 can be used to form these initial estimates. Similar associations between conductivity and structure have also been made for the Soviet Union [Yakupov *et al.*, 1969] and for Norway [Eliassen, 1957].

Since these initial conductivity estimates cover broad ranges, ground-wave field-strength estimates in the MF band using the mid-range conductivity values will have up to a ± 10 dB uncertainty at distances less than 100 km. These estimates, however, are useful for estimating broadcast coverage where measured data do not exist and for planning actual field measurements of the effective conductivity. The UNESCO-FAO *Soil Map of the World* is a useful source for geological and lithological data.

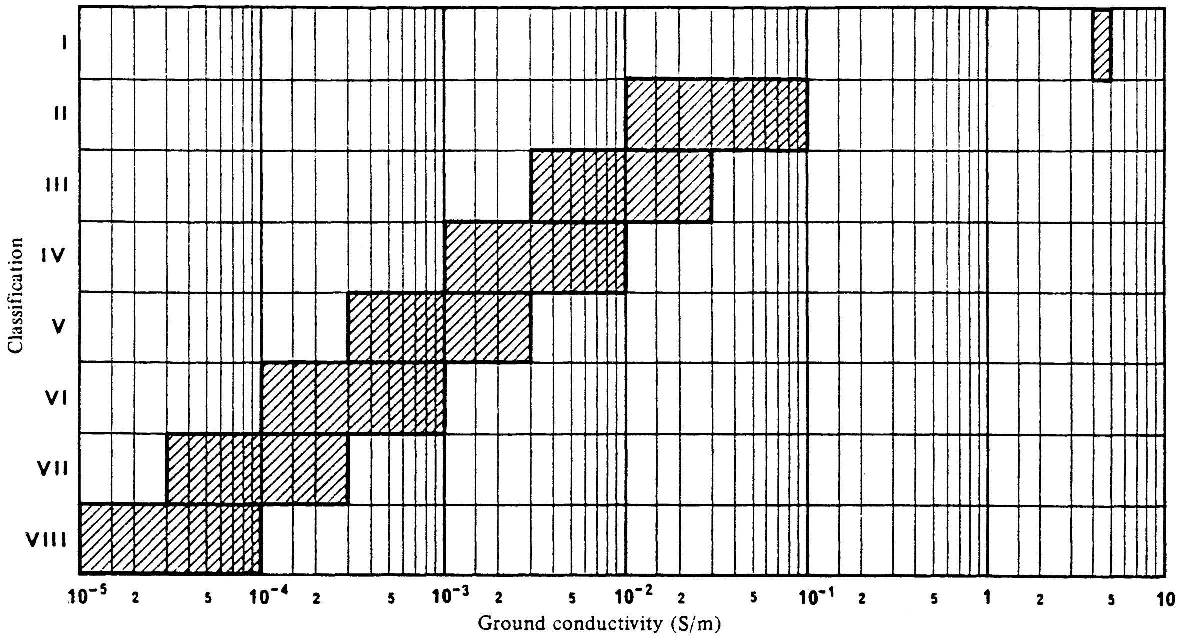


FIGURE 1 – *Expected ranges of effective ground conductivity*

Classification	*Terrain description*
I	Sea water*
II	Very moist soil; moist cultivated land
III	Marshes (fresh water); cultivated land
IV	Fresh water; sandy loam; hilly country in temperate climates
V	Medium dry ground; rocks; sand; medium-sized towns
VI	Dry ground; desert
VII	Very dry ground; granite mountains in cold regions; industrial areas
VIII	Dry glaciers in mountainous areas; permafrost; polar ice; high rocky mountains in temperate and cold climates

* In some particular areas, for instance the Baltic Sea, sea water conductivities can be much lower (see Report 229, § 5).

4. Field measurement of effective electrical characteristics

In the following sections the wave tilt method and the attenuation method of measuring electrical characteristics are discussed. These are the preferred methods for propagation applications since the results can be related directly to the effective values needed for ground-wave field-strength calculations.

Over homogeneous ground these methods can be used easily. The wave tilt method requires the measurement of three quantities at each field point but the electrical characteristics can be found directly from this data. The attenuation method, on the other hand, requires only a single field-strength measurement at each field point but the analysis of the data requires matching a series of field points to the theoretical ground-wave propagation curves.

In the case of inhomogeneous ground, however, the interpretation of measurement data can be very difficult. The problem arises from the sudden change in field strengths at a boundary between two regions of different conductivity. These transition effects associated with a boundary tend to damp out as one moves further from the transmitter. Thus care must be exercised to make measurements at a sufficient distance from the boundary so that the "steady state" conditions which are characteristic of the soil and not of the boundary have been established. Since the behaviour of electromagnetic fields over horizontally inhomogeneous ground is well understood (Recommendation 368), the attenuation method is preferred in these cases. In either case, it is very important to make measurements at a number of points along a radial path outward from the transmitter so that the transition to a region of different conductivity can be easily identified.

4.1 *Wave-tilt method*

4.1.1 *Measurement methods*

The wave tilt method has been reviewed with a bibliography covering a forty-year period by King [1976]. Eliassen [1957] provides detailed practical advice on measurement techniques. The method is based on the fact that, at a surface with finite conductivity, the electric field due to a vertically polarized source will have a small horizontal component in the direction of propagation. This causes the total electric field vector to be inclined or tilted from the local vertical as shown in Fig. 2. Since the vertical, E_z, and horizontal, E_x, components of the field are not in phase, the field traces out an ellipse in the plane defined by the vertical and the direction of propagation. A simple relationship exists between the electrical characteristics and the two field components:

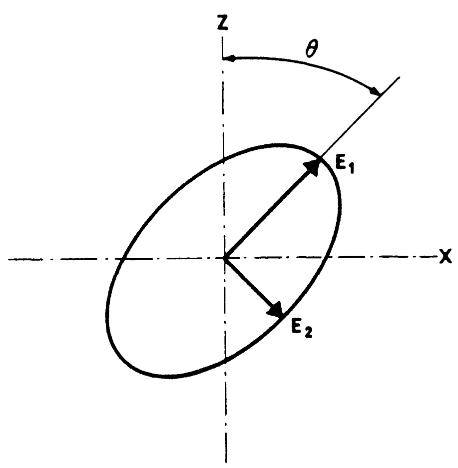
$$\varepsilon_r = |E_z/E_x|^2 \cos 2\varphi \tag{1a}$$

$$\sigma/f = |E_z/E_x|^2 (\sin 2\varphi)/18\,000 \tag{1b}$$

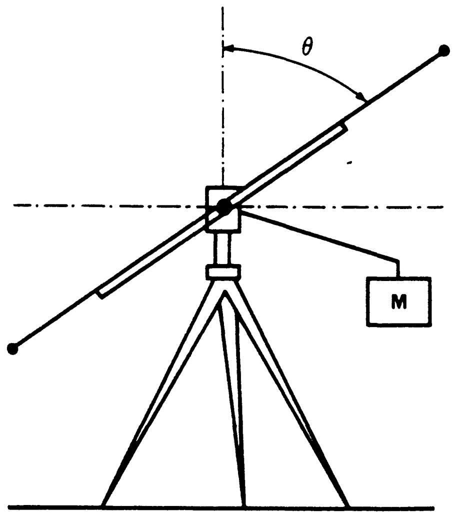
where φ is the electrical phase angle between the field components and f is the frequency of the ground wave in MHz.

In practice, however, it is very difficult to measure the horizontal component, E_x, of the field since it is generally much smaller than the vertical component E_z. A small misalignment of the measurement antenna introduces a large error component from E_z. In addition, the measurement of the phase angle, φ, requires expensive equipment.

A common method of making wave tilt measurements is to use a field strength meter (FSM) connected to a short dipole which can rotate about its centre on an axis normal to the field components. One then measures the maximum, E_1, and minimum, E_2, field strengths as the antenna is rotated and records their ratio $r = E_2/E_1$. In addition, the tilt angle θ, the angle between the vertical and the direction of E_1 is also recorded. Since only the ratio of the field-strength components, r, is required, this method has the advantage that a calibrated antenna and FSM need not be used.



(a) *Vertical electric field ellipse for propagation over lossy ground*



(b) *Rotatable dipole measurement apparatus and field strength meter (M)*

FIGURE 2

4.1.2 *Analysis of wave tilt data*

The variables of equation (1) are related to the measured quantities r and θ by the formula:

$$|E_x/E_z| = \sqrt{\frac{r^2 + \tan^2\theta}{1 + r^2\tan^2\theta}} \tag{2a}$$

$$\cos 2\varphi = \frac{(1 - r^2)\sin 2\theta - 4r^2}{(1 - r^2)\sin 2\theta + 4r^2} \tag{2b}$$

As an alternative to a numerical analysis of the data, the electrical characteristics can be obtained directly from r and θ by means of Fig. 3 [Eaton, 1976].

4.1.3 *Accuracy of wave tilt measurements*

The shaded rectangle A in Fig. 3 corresponds to a measurement error of ± 1° in the tilt angle and ± 1 dB in the axial ratio. From the figure it can be seen that accuracy of the effective conductivity depends mainly on the accuracy of the tilt angle measurement. Similarly, the accuracy of the effective permittivity is closely related to the accuracy of the axial ratio. For telecommunications purposes, the impact of this experimental error must be further assessed in terms of the uncertainty it introduces into field-strength calculations.

While the wave tilt method gives values for the electrical characteristics from a measurement at a single point, it is important that a survey of an area include a series of measurements along a radial line from the source of the field. This is required in order that transitions from a region with one set of electrical characteristics to another region with different electrical characteristics can be identified. Over homogeneous ground, the tilt angle and axial ratio will be independent of the distance from the source (this assumes the measurements are taken at a distance greater than several wave lengths). For inhomogeneous paths the tilt angle and axial ratio will change suddenly at a conductivity boundary. The values will then change slowly with radial distance until the final values are reached which are characteristic of the new region [Blomquist, 1975]. These distances can be very long. If a third conductivity region is encountered before the new equilibrium values have been established, the interpretation of wave tilt data can become very difficult [Stokke, 1978].

However, if these limitations are taken into account, the wave tilt method gives satisfactory results. Measurements in the Federal Republic of Germany show very good agreement between the measured values and the values calculated from Millington's method, when the wave tilt method was used to measure the ground conductivity [Damboldt, 1981].

4.2 *The attenuation method*

The attenuation method of measuring effective electrical characteristics consists of making field-strength measurements along a radial line from a vertically-polarized transmitting antenna and matching the experimental data to theoretical curves such as those found in Recommendation 368. If the curves match, the effective ground constants along the radial are the same as those used to calculate the theoretical curves.

4.2.1 *Measurement methods*

General methods of measuring field strengths are described in Report 227. It is important that field-strength measurements be made at a sufficient number of points along a radial so that a smooth experimental curve can be drawn and so that rapid changes in the slope of the curve will be recognized. This latter point is important in identifying the boundary between regions of different conductivity or inhomogeneous paths. A practical difficulty in using the attenuation method is finding a sufficient number of roads or other accesses to a number of points along a given radial path.

A modern approach to making attenuation method measurements has been successfully used in Finland [Laiho, 1976; Koskenniemi and Laiho, 1975]. The field-strength measurement apparatus is carried out on a small aircraft such as a light airplane or helicopter with the measurement antenna mounted externally on the aircraft. Field strength and navigation data can be recorded continuously as the aircraft flies along a radial by means of a strip chart recorder. Measurements of this kind tend to be very economical since a large area can be covered in only a few flight hours using only a pilot and a navigator/equipment operator.

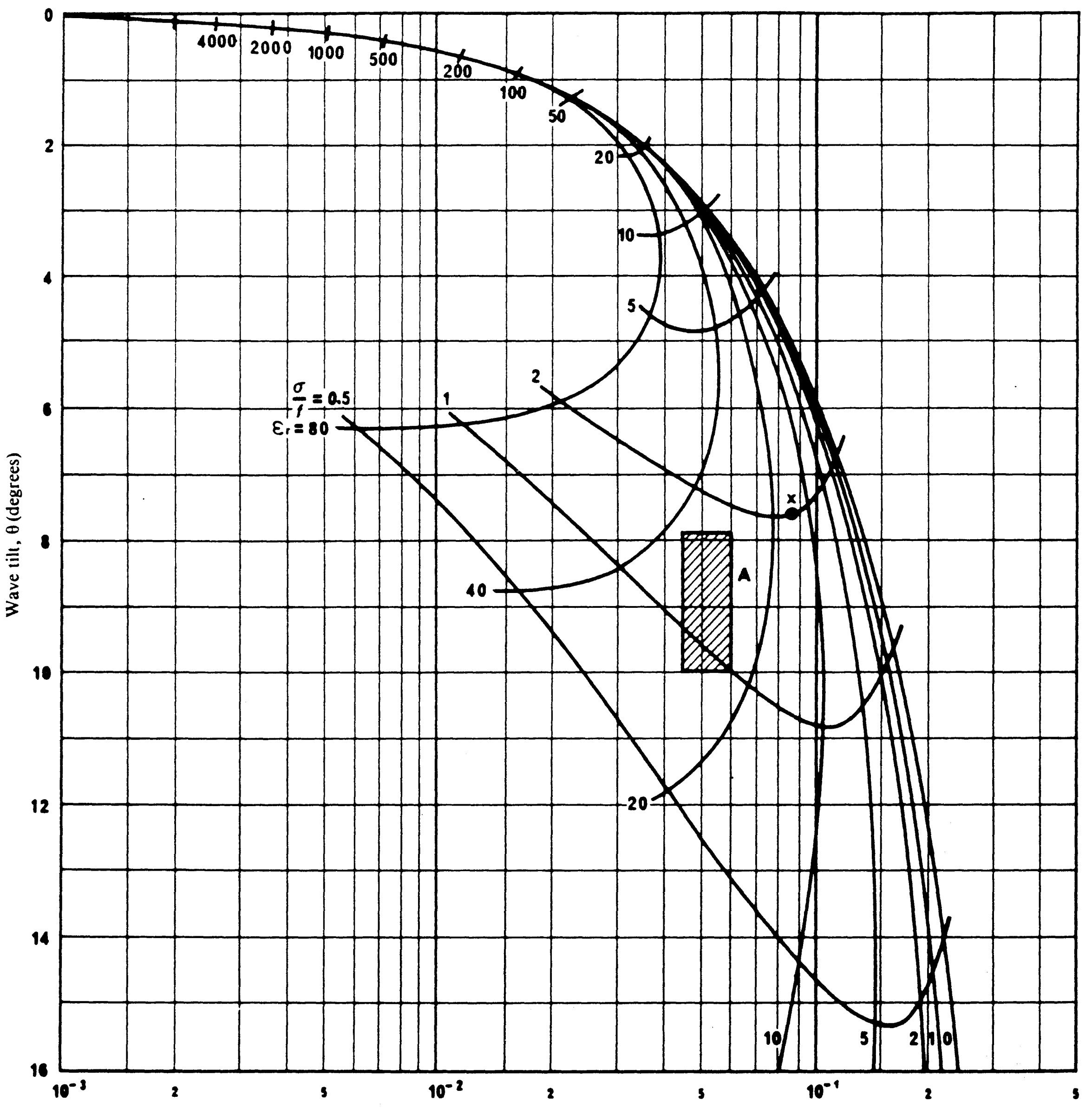


FIGURE 3 – *Relationship between wave tilt angle (θ), axial ratio of ellipse (r) and the ground parameters*

(The conductivity (σ) is in units of mS/m and *f* is the measurement frequency in MHz)

The altitude at which these aircraft measurements are taken is important because of height gain considerations. Most theoretical ground-wave curves are computed for both terminals on the surface. If the receiving terminal is elevated, the measured field will be higher than the surface value because of the height gain effect. Height gain corrections cannot be made to the measured data since this requires a knowledge of the ground constants. Laiho [1976] estimates, however, that the height gain is less than 1 dB for frequencies below 1400 kHz and heights below 100 m. This suggests that MF effective conductivity measurements with an aircraft should be made using the lowest frequency transmitter available and the lowest altitude consistent with flight safety.

4.2.2 *Analysis of attenuation method data*

The theoretical curves such as those found in Recommendation 368 are computed for an assumed reference radiated power. Thus, the measured data must be normalized to this reference. If the curves of Recommendation 368, which are based on a 1 kW effective monopole radiated power (e.m.r.p.) are used, a factor of 20 log p_{eff} must be added to the measured data in dB(μV/m) before analysis. p_{eff} is the e.m.r.p. of the transmitter used for the measurement. If this power is not known, it is suggested [Laiho, 1976; Gregorač and Budin, 1976] that the slope of the experimental curve be matched to the theoretical curves for distances close to the transmitter. Then, taking the measured field strengths, E_r, at n points along a radial path and the calculated values at the same distances, A_{sr}, which correspond to the conductivity curve whose slope matches the measured data, one can determine the effective radiated power from the relation,

$$p_{eff}^{1/2} = \left(\sum_{r=1}^{n} A_{sr} E_r \right) \Big/ \sum_{r=1}^{n} A_{sr}^2 \qquad (3)$$

and determine the average conductivity in the vicinity of the transmitter.

This method of data analysis can be used very easily over homogeneous paths. For inhomogeneous paths the analysis becomes very difficult for more than one change in conductivity along a radial. In the case of the measurements in Finland mentioned above [Laiho, 1976], the analysis was performed using a digital computer to make theoretical calculations over mixed paths using Millington's method (Recommendation 368) in a least-squares curve fitting procedure. A nearly identical procedure has been used in Yugoslavia [Gregorač and Budin, 1976]. More recently, an improved procedure has been developed [Grosskopf, 1981] which uses a special numerical optimization procedure to overcome these difficulties.

Figure 4 illustrates the difficulty in analyzing mixed path data. This figure is derived from the work of Stokke [1975] in developing a graphical method for calculating ground-wave transmission loss over mixed paths which is found in Annex II of Recommendation 368. The figure illustrates the simple case of the electric field over a path which has a change in conductivity at a distance d_1, from the transmitter.

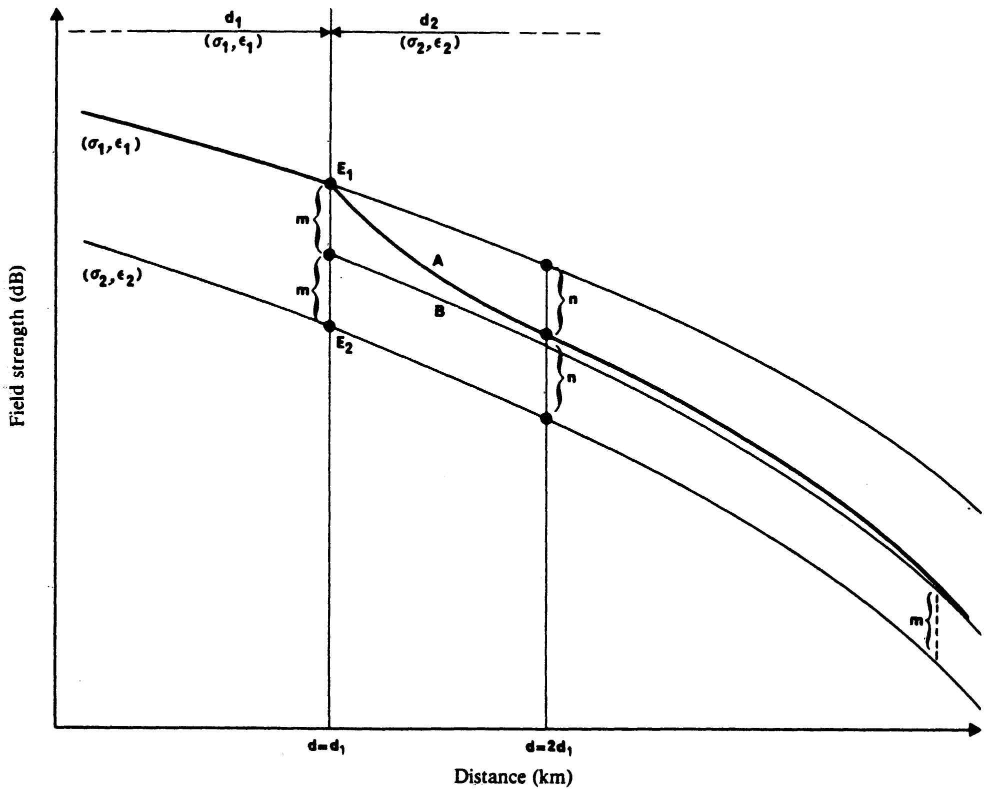


FIGURE 4 – *Electric field behaviour at a boundary between regions of different effective ground parameters*

When the conductivity changes from a value to a lower value, note that the field-strength curve goes through the mean between the two homogeneous earth curves at the distance $d = 2\ d_1$, and approaches a value which is parallel to the lower homogeneous earth curve. This asymptote is located above the lower homogeneous curve by a value equal to one-half the difference in dB between the two homogeneous curves at $d = d_1$.

Detailed descriptions of how existing field-strength measurements may be interpreted, especially when there are many changes in the conductivity, are given by Stokke [1978, 1984].

If the computational resources are not available or are not economical then a conductivity map should be made by using data from a series of transmitters. The data from each transmitter is used to define the boundaries of the homogeneous regions about each transmitter.

4.2.3 *Accuracy of the attenuation method*

Field-strength measurements in the MF band can generally be made to an accuracy of ± 2 dB. This implies an analysis error of ± 2 dB in the conductivity over homogeneous ground for the MF band as can be seen by reference to the figures of Recommendation 368. Additional errors will be introduced into the conductivity estimates on mixed paths for the reasons discussed above. Terrain irregularities will introduce more errors if the height of terrain features above the mean value along the path is much greater than a wavelength. Small terrain irregularities will result in a lower effective conductivity than would be measured for smooth terrain having the same soil structure [Barrick, 1971].

Moreover, the results will apply only to the particular path used, or to one very similar. The method is not suitable for detailed measurements of the electrical characteristics of earth over given small areas.

5. Other methods

Among other methods intended for telecommunication purposes one can identify the method of measuring the antenna input impedance. This method is based on the fact that the electrical characteristics of the earth can be deduced from measurements of the antenna input impedance. These measurements can be performed for antennas situated below, on, or just above the surface of the earth. Some laboratory measurements [Iizuka, 1964] and recent theoretical investigations [Popovič and Gavrilov, 1976] indicate the possibility of deducing the electrical characteristics of the ground from a cylindrical (or equivalent strip) antenna impedance measurement, the antennas being pressed on the air-ground interface. In the application of this method, particular attention should be paid to the alignment of the antenna axis exactly at the interface. The advantage is that immersing is no longer necessary.

Various other methods exist for measuring the conductivity or dielectric constant of the surface of the earth. Some of these are described in Report 229. General descriptions of these methods together with extensive bibliographies can be found in a review by Lytle [1974] and IEEE Standard 356 [IEEE, 1974].

These methods are usually not suitable for broadcast planning purposes. Many are designed for geophysical exploration and cannot be used economically for wide area mapping of ground constants. Other methods give values for the electrical ground constants which are difficult to relate to the effective values which should be used for ground-wave propagation loss calculations. For this reason, the attenuation or wave-tilt methods are preferred.

The probe methods, however, may be useful in planning antenna installations. A detailed knowledge of the ground conductivity about a proposed HF antenna site is useful in determining the requirements for a ground screen system to maximize antenna efficiency. When making these measurements, the probe separations should be adjusted so that the measurements result in an effective conductivity [Grant and West, 1965] of a layer equal in depth to the penetration depth at the frequency of interest.

6. Measurement results

Actual field measurement of effective electrical characteristics will have a significant variation in the results due to various factors which influence the effective values. The effective MF conductivity map for the United States of America [Fine, 1954] was constructed from attenuation method data. Data from over 7000 radial measurements using 621 MF broadcast stations were analyzed with manual methods. The effective conductivity shows at least a factor of two variations for different radials about each transmitter even over paths which are geographically similar. Computer aided data reduction with mixed path corrections [Laiho, 1976] in Finland gave a higher resolution map with less data. The overall results of this experience is to suggest that MF field-strength calculations using the homogeneous smooth earth calculations will have a 5 dB uncertainty associated with the errors in the ground conductivity data.

REFERENCES

BARGHAUSEN, A. F., FINNEY, J. W. and FISHER, R. M. [1966] Radio broadcasting on medium frequencies. NBS Rep. 9196, Accession No. PB 269533, National Technical Information Service, Springfield, Va. 22161, USA.

BARRICK, D. E. [1971] Theory of HF and VHF propagation across the rough sea. *Radio Sci.*, Vol. 6, **5**, 517-526.

BLOMQUIST, Å. [1975] Seasonal effects on ground-wave propagation in cold regions. *J. Glaciology*, Vol. 15, 73.

DAMBOLDT, T. [13-16 April, 1981] HF ground-wave field-strength measurements on mixed land-sea paths. IEE Second International Conference on Antennas and Propagation, Heslington, York, UK.

EATON, J. L. [1976] The wave-tilt method of measuring electrical ground constants in the LF and MF bands. BBC Rep. RD 1976/15, UDC 621.396.673.

ELIASSEN, K. E. [1957] A survey of ground conductivity and dielectric constant in Norway within the frequency range 0.2-10 Mc/s. *Geofysiske Publikasjoner*, Vol. 19, **11**.

FINE, H. [September, 1954] An effective ground conductivity map for the continental United States. *Proc. IRE*, Vol. 42, **9**, 1405-1408.

GRANT, F. S. and WEST, G. F. [1965] *Interpretation Theory in Applied Geophysics*. McGraw-Hill, New York, NY, USA.

GREGORAČ, L. and BUDIN, J. [June, 1976] Calculation of the efficiency of an MF transmitting aerial and of the average soil conductivity in its immediate vicinity. *EBU Rev. Tech.*, **157**.

GROSSKOPF, R. [1981] Eine verbesserte Methode zur Berechnung des Wirkungsgrades und der Leitfähigkeiten in der näheren Umgebung einer Mittelwellensendeantenna (An improved method for calculating the efficiency and the soil-conductivities in the immediate vicinity of an MF transmitting antenna). *Rundfunktechn. Mitt.*, Vol. 25, **2**.

HANLE, E. [1966] The complex impedance of the earth's surface at radio frequencies and its measurement. *NTZ-Comm. J.*, Vol. 3, 136-143.

IEEE [1974] *IEEE Guide for Radio Methods of Measuring Earth Conductivity*. IEEE Standard 356-1974.

IIZUKA, K. [January, 1964] An experimental investigation on the behaviour of the dipole antenna near the interface between the conducting medium and free space. *IEEE Trans. Ant. Prop.*, Vol. AP-12, 27-35.

JOHLER, J. R. and HOROWITZ, S. [1974] Propagation of a Loran pulse over irregular inhomogeneous ground. AGARD Conf. Proc. No. 144, 28-1 to 28-13, SHAPE Technical Centre, The Hague, Netherlands.

KING, R. J. [1976] Wave-tilt measurements. *IEEE Trans. Ant. Prop.*, Vol. AP-24, 115-119.

KOSKENNIEMI, O. and LAIHO, J. K. [October, 1975] Measurements of the effective ground conductivity at low and medium frequencies in Finland. *EBU Rev. Tech.*, **153**, 237-240.

LAIHO, J. K. [1976] Measurement of the effective ground conductivity in Finland. *SÄHKÖ* (Electricity in Finland), Vol. 49, 509-512.

LYTLE, R. J. [July, 1974] Measurement of earth medium electrical characteristics: techniques, results and applications. *IEEE Trans. Geosci. Electron.*, Vol. GE-12, **3**, 81-101.

POPOVIĆ, B. D. and GAVRILOV, T. [1976] A simple method for analysis of cylindrical antennae at the interface between two media. *Radio Electron. Engr.*, Vol. 46, 553-554.

STOKKE, K. N. [1975] Some graphical considerations on Millington's method for calculating field strength over inhomogeneous earth. *Telecomm. J.*, Vol. 42, **III**, 157-163.

STOKKE, K. N. [June, 1978] Problems concerning the measurement of ground conductivity. *EBU Rev. Tech.*, **169**, 106-111.

STOKKE, K. N. [November, 1984] Ground conductivity measurements. *Telecomm. J.*, Vol. 51, **XI**, 611-613.

WAIT, J. R. [1970] *Electromagnetic Waves in Stratified Media*, (2nd edition). Pergamon Press, MacMillan, New York, NY, USA.

YAKUPOV, U. S., BYALOBZKESKIY, S. G., GASSANOV, SH. SH., IZMAYLOV, L. I. and ALPSHIN, G. U. [1969] Maps of the electric conductivity of rocks in the permafrost zone of the northeastern part of the USSR, Acad. Sci. USSR, *Izvestia Phys.* (Solid Earth), **8**, 537.