REPORT 229-6

ELECTRICAL CHARACTERISTICS OF THE SURFACE OF THE EARTH

(Question 1/5)

(1959-1963-1970-1974-1978-1982-1986-1990)

1. Introduction

This Report discusses the physical factors upon which the electrical characteristics of the surface of the Earth depend. The methods for estimating and determining the values of the electrical characteristics in connection with the calculation of radio propagation are discussed in Report 879.

2. The characteristics of the ground

The electrical characteristics of any medium may be expressed by three parameters: the permeability μ, the permittivity ε and the conductivity σ. They jointly influence wave propagation in accordance with the following expression for the propagation coefficient k:

$$k = \sqrt{j\omega\mu\,(\sigma + j\omega\varepsilon)} = j\omega \sqrt{\mu \left(\varepsilon - j \frac{\sigma}{\omega} \right)} \quad (1)$$

where a time dependence of the form exp $(j\omega t)$ is assumed.

The permeability of the ground, μ, can normally be regarded as equal to the free-space permeability so that in most propagation problems we are concerned only with permittivity, ε and the conductivity, σ. When referred to the ground, the propagation coefficient may be written:

$$k = j \frac{2\pi}{\lambda} \sqrt{\varepsilon_r - j60\,\sigma\lambda} \quad (2)$$

where ε_r is the relative permittivity, σ is in S/m, and λ is the free-space wavelength in metres.

It may be noted that the displacement and the conduction current densities are in the ratio of ε_r to 60 $\sigma\lambda$, from which their relative importance can be judged. It is seen that at frequencies above 100 MHz account must be taken of the variation of permittivity and conductivity with frequency (dipolar and ionic) [Saxton and Lane, 1952]. Furthermore, it should be noted that a value of 80 has often been used for the relative permittivity of sea water at low temperatures and frequencies below about 1 GHz. The actual value, even at low frequencies, depends on the temperature and composition of the sea water.

Typical values of conductivity and permittivity for different types of ground, as a function of frequency, are given in Recommendation 527. These values, frequently referred to as intrinsic values, refer to homogeneous sub-surface soil structures and can be determined by laboratory measurements of soil samples. They normally coincide with the values obtained with other surface impedance measurements in the case of homogeneous sub-surface structures.

However, the sub-surface structure is rarely homogeneous, but rather consists of two or more layers of different thickness and different conductivities and permittivities. This fact must be taken into account and this could be done by introducing the concept of effective parameters. This concept of effective parameters allows the use of the homogeneous smooth earth ground-wave propagation curves of Recommendation 368, the inhomogeneous sub-surface soil being replaced by an equivalent homogeneous structure whose parameters are the effective conductivity and effective permittivity. These parameters can be determined if the values of the parameters of each layer are known. These values coincide with the results obtained by surface impedance or antenna impedance measurements.

In some frequency bands, in which attention should be paid to other factors influencing the ground-wave propagation, such as terrain irregularities, vegetation cover, surface objects, etc., this concept can be extended by further modification of that effective value. Such values are obtained by application of the ground-wave attenuation method, or by analytical means.

3. Factors determining the effective electrical characteristics

The effective values of the constants of the ground are determined, not only by the nature of the soil, but also by its moisture content and temperature, by the frequency, by the general geological structure of the ground and by the effective depth of penetration and lateral spread of the waves.

3.1 *Nature of the soil*

Although it has been established by numerous measurements that the values of the electrical characteristics vary with the nature of the soil, it seems probable that this variation may be due not so much to the chemical composition of the soil as to its ability to absorb and retain moisture. It has been shown that loam, which normally has a conductivity of the order of 10^{-2} S/m can, when dried, have a conductivity as low as 10^{-4} S/m, which is of the same order as that of granite.

3.2 *Moisture content*

The moisture content of the ground is probably the major factor determining its electrical constants. Laboratory measurements have shown that, as the moisture content is increased from a low value, the values increase, rapidly reaching their maximum as the moisture content approaches the values normally found in such soils on site. At depths of one metre or more, the wetness of the soil at a particular site seems to be substantially constant all the year round and, although it may increase during rain, the drainage of the soil and surface evaporation soon reduces it to its normal value after the rain has stopped.

The moisture content of a particular soil may, however, vary considerably from one site to another, due to differences in the general geological formation which provide better drainage in one case than another.

3.3 *Temperature*

Laboratory measurements of the electrical characteristics of soil have shown that, at low frequencies, the temperature coefficient of conductivity is of the order of 3% per degree Celsius, while that of the permittivity is negligible. At freezing point, there is generally a large decrease in both permittivity and conductivity. Although these changes are appreciable, it must be borne in mind that the range of temperature variation during the year decreases rapidly with depth, so that temperature effects are likely to be important only at high frequencies where the penetration of the waves is small (see § 3.6), or when the ground is frozen to a considerable depth.

Figure 1 illustrates the dependence of the conductivity [Albrecht, 1963] and relative permittivity [Blomquist, 1968] on the water content and temperature of the soil. It should be emphasized that such variations will only occur in the intrinsic electrical characteristics. Changes in the effective electrical characteristics will depend on the extent to which changes in water content and temperature penetrate the surface.

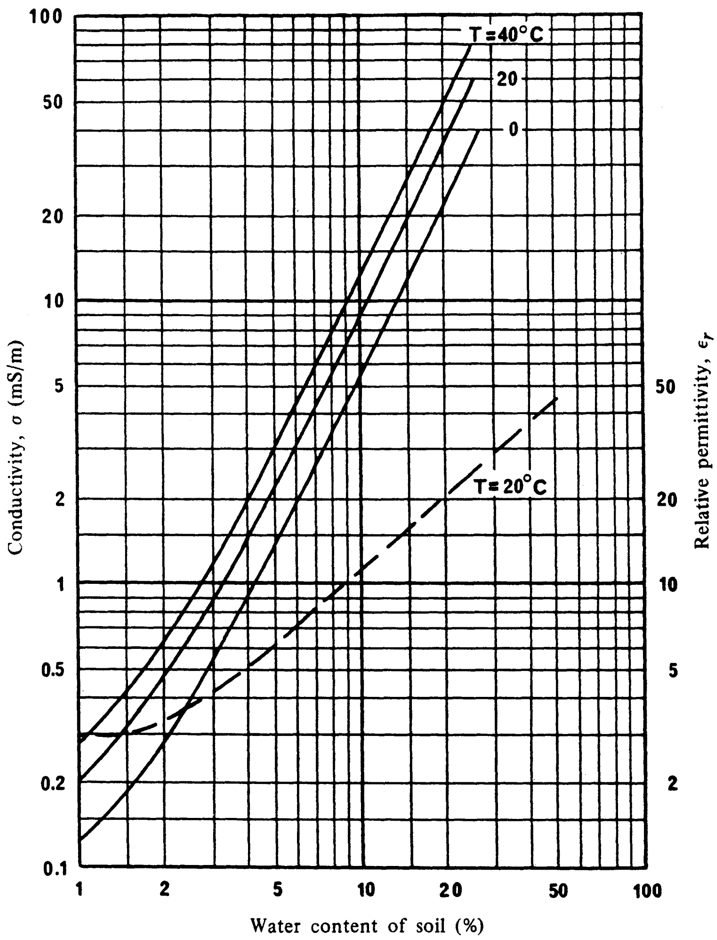

FIGURE 1 – *The intrinsic conductivity and relative permittivity of soil as a function of water content*

——— Conductivity, σ

– – – Relative permittivity, ϵ_r

3.4 *Seasonal variation*

The effect of seasonal variation on ground-wave propagation loss depends upon the ratio of the depth of the soil exhibiting seasonal changes to the penetration depth. Any such seasonal effects will be frequency dependent. Very small seasonal variations, observed in Loran-C phase measurements [Doherty and Johler, 1975] at 100 kHz, have been interpreted as entirely caused by refractive index changes. Measurements at medium frequencies carried out in India have shown almost no variations in field strengths in the rainy monsoon season when compared with those recorded during the dry season. Temperature zone MF measurements in Finland [Koskenniemi and Laiho, 1975] have shown only a 1 to 2 dB change in field strength between summer and winter.

Actual measurements by radio amateurs [Sevick, 1978] of the conductivity of the first one-half metre of soil in the USA show a seasonal cyclic variation of a factor of two in the surface conductivity. These conductivity values seem to be a function of mean soil temperature with small fluctuations associated with measured rainfall.

3.5 *Frequency*

Laboratory measurements on soil samples show that there is a variation of the permittivity and conductivity with frequency which depends markedly on the moisture content. The values for fresh water and sea water can be calculated for any frequency from the data given [Saxton and Lane, 1952].

3.6 *General geological structure*

The ground involved in overland propagation is not usually homogeneous, so that the effective electrical characteristics are determined by several different types of soil. It is, therefore, of great importance to have a complete knowledge of the general geological structure of the region concerned. The effective electrical characteristics over an area or along a path are determined, not only by the nature of the surface soils, but also by that of the underlying strata. These lower strata may form part of the medium through which the waves travel or they may have an indirect effect by determining the water level in the upper strata.

3.7 *Energy absorption by surface objects*

Although surface objects have no direct influence on the electrical characteristics of the ground itself, they can contribute appreciably to the attenuation of ground waves, and the effects of such energy losses may be taken into account by using appropriately modified values of the electrical characteristics in propagation calculations.

Particularly high attenuation rates are associated with transmission loss in wooded terrain at frequencies above about 30 MHz [Blomquist, 1958; Rice, 1971; Saxton and Lane, 1955; Tamir, 1967]. Such attenuation may increase even more when the trees are covered with wet snow, and under conditions of rain when the trees are in leaf. A more detailed treatment of this subject is given in Report 1150.

4. Penetration and spread of waves

4.1 The extent to which the lower strata influence the effective electrical characteristics depends upon the depth of penetration of the radio energy, δ, which is defined as that depth at which the wave has been attenuated to $1/e$ (or 37%) of its value at the surface. The penetration depth as a function of frequency is shown in Recommendation 527 for different types of ground and water.

4.2 If the penetration depth, δ, is less than the thickness of the layer, the underlying strata have little influence. If δ is much greater than the top layer thickness, propagation is determined by the electrical characteristics of the lower strata. In intermediate cases, the effective electrical characteristics can be determined by a theoretical relationship [Wait, 1970] and an appropriate model of the sub-surface structure.

4.3 The radio energy received at a point does not travel solely by the direct path from the transmitter, but also by a large number of indirect paths distributed on either side of it. It is necessary, therefore, to consider electrical characteristics not only along the path itself, but also over the area covered by the lateral spread of the wave paths. No definite limits can be put on this area, but it has been suggested that it is effectively the first Fresnel half-wave zone, i.e. the ellipse having the transmitter and receiver positions as its foci and axes of $(D + \lambda/2)$ and $\sqrt{D\lambda}$ respectively, where D is the length of the direct path and λ is the wavelength.

5. Sea water

The electrical conductivity of sea water is a function of the salt content (salinity) and temperature. At frequencies below 1 GHz its value is given by the expression:

$$\sigma = 0.18\, C^{0.93}\, [1 + 0.02\, (T - 20)] \qquad \text{S/m} \qquad (3)$$

where C is the salt content in parts per thousand and T is the temperature in degrees Celsius.

At 20 °C a value of 5 S/m is used as a world-wide average. In some areas of the Baltic Sea values of less than 1 S/m have been observed. In the Red Sea the conductivity may exceed 6 S/m.

The permittivity of sea water is also a function of salinity and temperature. A value of 80 has often been used for the relative permittivity of sea water at 20 °C although the actual low frequency value is about 70. However, at frequencies below about 100 MHz, ε_r is much less than 60 $\lambda\sigma$, and either value may be used to calculate ground-wave propagation factors over the sea with no measurable differences in the results.

6. Ice and snow

6.1 Sea ice

Sea ice is a complex substance whose electrical characteristics vary over a large range as a function of the temperature and age of the ice. There is good agreement between theoretical physical models of sea ice [Luchininov, 1968] and measured electrical characteristics [Wentworth and Cohn, 1964]. The range of values of these electrical characteristics is shown in Fig. 2 for frequencies between 0.1 and 30 MHz. Above about 30 MHz the electrical characteristics of sea ice asymptotically approach those of fresh water ice (Recommendation 527).

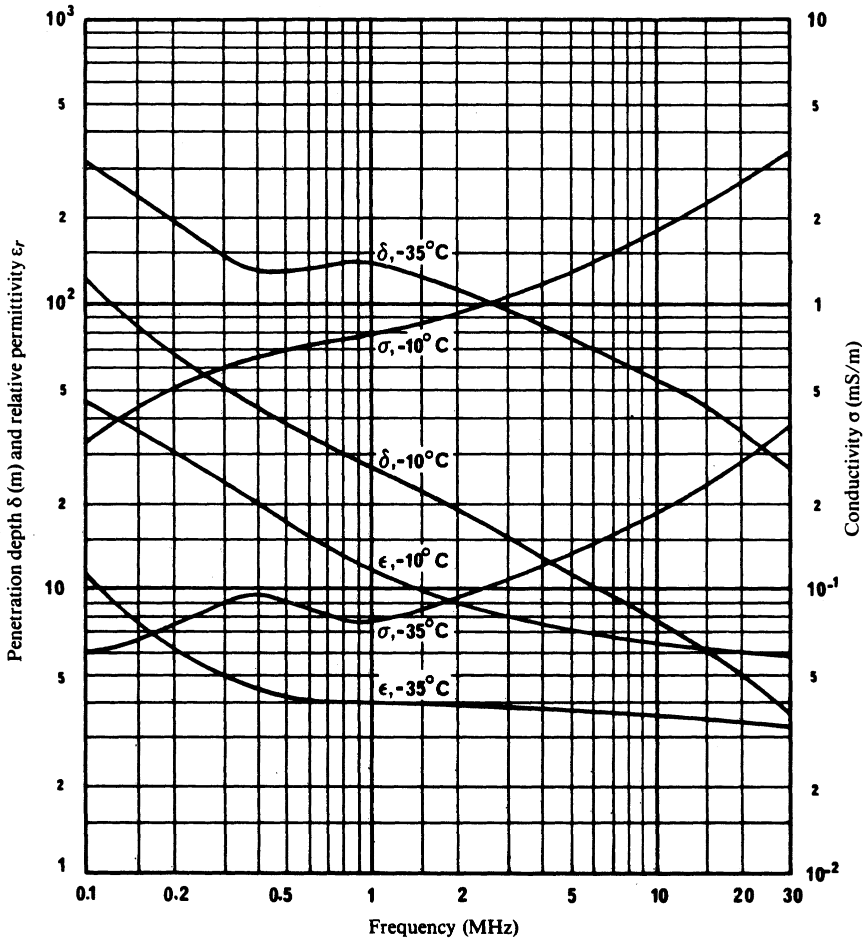

FIGURE 2 – *Range of values of the penetration depth (δ), relative permittivity (εr), and conductivity (σ) of sea ice* [Wentworth and Cohn, 1964]

(These extreme values occur for new ice at −10° C with an age of less than one month and old ice at −35° C with an age greater than one year).

Propagation over sea ice is anomalous [Bourne *et al.*, 1970]. The presence of a low conductivity ice layer over high conductivity sea water gives rise to a trapped surface wave or "Elliott" mode. This mode dominates at distances close to the transmitter where the field may exceed the free space value. At intermediate distances the surface wave mode interferes with the normal ground wave mode and the field oscillates with distance. At large distances the field exhibits normal ground wave behaviour. The ice layer also has a strong influence on the height gain terms. A theoretical analysis of propagation over sea ice [Hill and Wait, 1981] has provided a consistent explanation of the observed phenomena and led to the suggestion that this anomalous behaviour can be used for airborne remote sensing of sea ice fields.

The range of penetration depths in sea ice is also shown in Fig. 2 for frequencies between 0.1 to 30 MHz. The effective values of conductivity and permittivity of an ice layer over the ocean can be determined from the relationship discussed above in § 4.2 if the thickness of the ice layer is known.

Changes in ground-wave propagation over sea ice will also occur if a film of water forms on the ice due to rain or melting of the surface.

6.2 Antarctic ice

The continent of Antarctica is covered by a sheet of ice with an average thickness of 2.2 km. Measurements at 30 MHz made as a part of the International Antarctic Project [Jiracek and Bentley, 1971] indicate that this ice has a relative permittivity between 2.8 and 3.2 and an effective conductivity between 5 x 10^{-5} and 10^{-6} S/m. The relative permittivity varies linearly with the density of the ice.

Radio waves can easily penetrate the Antarctic ice and be reflected by the underlying bedrock. This has led to anomalous results in vertical ionospheric soundings and disastrous aircraft incidents related to false radar altimeter indications.

6.3 Snow

The electrical characteristics of snow are dynamic. The characteristics change as the snow alternately melts and freezes. It is useful to distinguish between dry snow and wet snow. Wet snow contains inclusions of liquid water.

The relative permittivity of dry snow is linearly proportional to the density of the snow [Hallikainen et al, 1986]. For densities less than 0.5 g/cm^3 the relative permittivity is given by the expression:

$$\varepsilon_r = 1 + 1.9\rho$$

where ρ is the density of the snow in g/cm^3. The relative permittivity of dry snow is generally independent of temperature and frequency in the microwave region of 1 to 37 GHz. The corresponding loss term of the permittivity of dry snow is negligible for frequencies below about 15 GHz. A typical value for the complex relative permittivity of dry snow is 1.6 - j10^{-3}.

Wet snow is a complex mixture of air, ice and liquid water. The measured electrical characteristics can be fitted to a modified Debye model. Even a small amount of liquid water can cause a large change in the properties of dry snow. Wet snow is dispersive with the largest change in electrical characteristics occurring between 3 and 18 GHz. A typical value of the complex relative permittivity of wet snow at 10 GHz is 2 - j0.4.

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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.