



Recommendation ITU-R P.527-4
(06/2017)

**Electrical characteristics
of the surface of the Earth**

P Series
Radiowave propagation



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Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R P.527-4

Electrical characteristics of the surface of the Earth

(1978-1982-1992-2017)

Scope

This Recommendation gives methods to model the electrical characteristics of the surface of the Earth, including pure water, sea water, ice, soil and vegetation cover, for frequencies up to 1 000 GHz, in a systematic manner based on the evaluation of complex relative permittivity. In all cases conductivity can be calculated as a function of frequency and temperature from these evaluations. Previous information on electrical characteristics below 30 MHz in terms of permittivity and conductivity is retained in Appendix in view of its association with Recommendations ITU-R P.368 and ITU-R P.832. The new modelling method is fully compatible with this earlier information.

Keywords

Complex permittivity, conductivity, penetration depth, Earth's surface, water, vegetation, soil, ice

The ITU Radiocommunication Assembly,

considering

- a) that the electrical characteristics may be expressed by three parameters: magnetic permeability, μ , electrical permittivity, ϵ , and electrical conductivity, σ ;
- b) that the permeability of the Earth's surface, μ , can normally be regarded as equal to the permeability in a vacuum;
- c) that the electrical properties of the Earth's surface can be expressed by the complex permittivity or, equivalently, by the real part and imaginary part of the complex permittivity;
- d) that information on the variation of the penetration depth with frequency is needed;
- e) that knowledge of the electrical characteristics of the Earth's surface is needed for several purposes in propagation modelling, including ground-wave signal strength, ground reflection at a terrestrial terminal, interference between aeronautical and/or space borne stations due to reflections or scattering from the Earth's surface, and for Earth science applications;
- f) that Recommendation ITU-R P.368 contains ground-wave propagation curves from 1 MHz to 30 MHz for different ground conditions characterised by permittivity and electrical conductivity;
- g) that Recommendation ITU-R P.832 contains a world atlas of ground electrical conductivity for frequencies below 1 MHz,

recommends

that the information in Annex 1 be used to model the electrical characteristics of the surface of the Earth.

Annex 1

1 Introduction

This Annex provides prediction methods that predict the electrical characteristics of the following Earth's surfaces for frequencies up to 1 000 GHz:

- Water
- Sea (i.e. Saline) Water
- Dry and Wet Ice
- Dry and Wet Soil (combination of sand, clay, and silt)
- Vegetation (above and below freezing)

2 Complex permittivity

The characteristics of the Earth's surface can be characterized by three parameters:

- the magnetic permeability, μ ,
- the electrical permittivity, ϵ , and
- the electrical conductivity¹, σ .

Magnetic permeability is a measure of a material's ability to support the formation of a magnetic field within itself in response to an applied magnetic field; i.e. the magnetic flux density B divided by the magnetic field strength H . Electrical permittivity is a measure of a material's ability to oppose an electric field; i.e. the electrical flux density D divided by the electrical field strength E . Electrical conductivity is a measure of a material's ability to conduct an electric current; i.e. the ratio of the current density in the material to the electric field that causes the current flow.

Given an incident plane wave $\vec{E}(r, t) = \vec{E}_0 e^{j(\omega t - \vec{k} \cdot \vec{r})}$, with radial frequency ω , time t , magnetic permeability μ , electrical permittivity ϵ , and electrical conductivity σ , the propagation wave number vector $\vec{k}$, has a magnitude k given by

$$k = \sqrt{-j\omega\mu(\sigma + j\omega\epsilon)} \quad (1a)$$

The vacuum values of permittivity, permeability, and conductivity are:

- Vacuum Permittivity $\epsilon_0 = 8.854\,187\,817 \times 10^{-12}$ (F/m)
- Vacuum Permeability $\mu_0 = 4\pi \times 10^{-7}$ (N/A²)
- Vacuum Conductivity $\sigma_0 = 0.0$ (S/m)

It is convenient to define the relative permittivity, ϵ_r , and the relative permeability, μ_r , relative to their vacuum values as follows:

- Relative Permittivity $\epsilon_r = \frac{\epsilon}{\epsilon_0}$
- Relative Permeability $\mu_r = \frac{\mu}{\mu_0}$

where ϵ and μ are the associated permittivity and permeability of the medium. This Recommendation assumes $\mu = \mu_0$, in which case $\mu_r = 1$.

¹ It is called electrical conductivity to differentiate it from other conductivities such as thermal conductivity and hydraulic conductivity. It is called hereinafter as conductivity.

As shown in equation (1a) the wavenumber depends on both σ and ϵ , not either separately. Also formulations of other physical parameters describing various radio wave propagation mechanisms such as scattering cross section, reflection coefficients, and refraction angles, depend on values of this combination. Furthermore, the square root of this combination is equivalent to the refractive index formulation used in characterizing the troposphere and the ionosphere. The refractive index is also used in characterizing different materials at the millimetre wave and optical frequency bands. Accordingly, to simplify the formulations describing various propagation mechanisms and to standardize terminologies of electrical characteristics at different frequency bands, the combination $\epsilon - \frac{j\sigma}{\omega}$ is defined as the complex permittivity and used to describe the electrical characteristics of substances.

While permittivity refers to ϵ , relative permittivity refers to ϵ_r , and complex relative permittivity, defined as $\epsilon'_r - j \epsilon''_r$, refers to:

$$\epsilon'_r - j \epsilon''_r = \frac{\epsilon}{\epsilon_0} - j \frac{\sigma}{\omega \epsilon_0} \quad (1b)$$

where ϵ may be complex.

In equation (1b), ϵ'_r is the real part of the complex permittivity, and ϵ''_r is the imaginary part of the complex permittivity. The real part of the complex relative permittivity, ϵ'_r , is associated with the stored energy when the substance is exposed to an electromagnetic field. The imaginary part of the complex relative permittivity, ϵ''_r , influences energy absorption and is known as the loss factor. The minus sign in equation (1b) is associated with an electromagnetic field having time dependence of $e^{2j\pi f t}$ (f is frequency in Hz, and t is time in seconds). If the time dependence is $e^{-2j\pi f t}$, the minus (-) sign in equation (1b) is replaced by a plus (+) sign.

At frequencies up to 1 000 GHz, dissipation within the Earth's surface is attributed to either translational (conduction current) charge motion or vibrational (dipole vibration) charge motion, and the imaginary part of the complex relative permittivity, ϵ''_r can be decomposed into two terms:

$$\epsilon''_r = \epsilon''_d + \frac{\sigma}{2\pi f \epsilon_0} \quad (2)$$

where ϵ''_d represents the dissipation due to displacement current associated with dipole vibration, and $\frac{\sigma}{2\pi f \epsilon_0}$ represents the dissipation due to conduction current.

Conduction current consists of the bulk translation movement of free charges and is the only current at zero (i.e. dc) frequency. Conduction current is greater than displacement current at frequencies below the transition frequency, f_t , and the displacement current is greater than the conduction current at frequencies above the transition frequency, f_t . The transition frequency, f_t , defined as the frequency where the conduction and displacement currents are equal, is:

$$f_t = \frac{\sigma}{2\pi \epsilon_0 \epsilon''_d} \quad (3)$$

For non-conducting (lossless) dielectric substances $\sigma = 0$, and hence $\epsilon''_r = \epsilon''_d$. For some of those substances, such as dry soil and dry vegetation, $\epsilon''_d = 0$, and hence $\epsilon''_r = 0$ irrespective of the frequency, which is the case considered in § 2.1.2.3 of Recommendation ITU-R P.2040. On the other hand, for some other non-conducting substances, such as pure water and dry snow, $\epsilon''_d \neq 0$, and hence ϵ''_r , equal zero only at zero frequency. Accordingly, § 2.1.2.3 of Recommendation ITU-R P.2040 cannot be applied to those substances.

For conducting (lossy) dielectric substances, such as sea water and wet soil, the electrical conductivity σ has finite values different than zero. Accordingly, as the frequency tends to zero, the imaginary part of the complex relative permittivity of those substances tends to ∞ as it can be inferred from equation (3). In this case, it is easier to work with the conductivity σ instead of the imaginary part of

the complex relative permittivity which can be written from equation (2) after setting $\varepsilon_d'' = 0$ as follows:

$$\sigma = 2\pi\varepsilon_0 f \varepsilon_r'' = 0.05563 f_{\text{GHz}} \varepsilon_r'' \quad (3a)$$

with f_{GHz} is the frequency in GHz. Generalizing the above formulation to other frequencies, as done by equation (12) of Recommendation ITU-R P.2040, yields the sum of two terms: one term gives the electrical conductivity and the other term accounts for the power dissipation associated with the displacement current.

This Recommendation provides prediction methods for the real and imaginary parts of the complex relative permittivity, ε_r' and ε_r'' ; and the accompanying example figures show trends of the real and imaginary parts of the complex relative permittivity with frequency under different environmental conditions.

2.1 Layered ground

The models in § 5 apply to homogeneous sub-surface soil; however, the sub-surface is rarely homogeneous. Rather, it consists of multiple layers of different thicknesses and different electrical characteristics that must be taken into account by introducing the concept of effective parameters to represent the homogeneous soil. Effective parameters can be used with the homogeneous smooth Earth ground-wave propagation curves of Recommendation ITU-R P.368.

3 Penetration depth

The extent to which the lower strata influence the effective electrical characteristics of the Earth's surface depends upon the penetration depth of the radio energy, δ , which is defined as the depth at which the amplitude of the field strength of electromagnetic radiation inside a material falls to $1/e$ (about 37%) of its original value at (or more properly, just beneath) the surface. The penetration depth, δ , in a homogeneous medium of complex relative permittivity ε_r ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$) is given by:

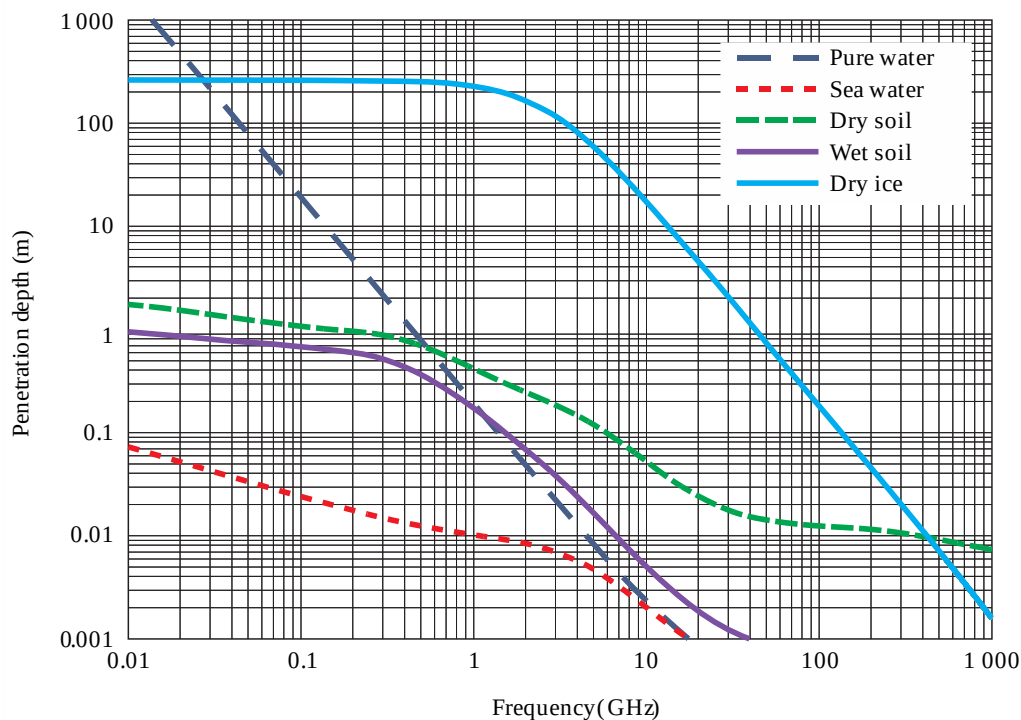
$$\delta = \frac{\lambda}{2\pi} \sqrt{\frac{2}{\sqrt{(\varepsilon_r')^2 + (\varepsilon_r'')^2} - \varepsilon_r'}} \quad (\text{m}) \quad (4)$$

where λ is the wavelength in metres. Note that as the imaginary part of the complex relative permittivity in equation (4) tends to zero, the penetration depth tends to infinity.

Figure 1 depicts typical values of penetration depth as a function of frequency for different types of Earth's surface components including pure water, sea water, dry soil, wet soil, and dry ice. The penetration depths for pure water and sea water are calculated at 20 °C, and the salinity of sea water is 35 g/kg. The penetration depths for dry soil and wet soil assume the volumetric water content is 0.07 and 0.5, respectively. Other soil parameters are the same as in Fig. 7. The penetration depth of dry ice is calculated at 0 °C.

FIGURE 1

Penetration depth of surface types as a function of frequency



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4 Factors determining the effective electrical characteristics of soil

The effective values of the electrical characteristics of the soil are determined by the nature of the soil, its moisture content, temperature, general geological structure, and the frequency of the incident electromagnetic radiation.

4.1 Nature of the soil

Although it has been established by numerous measurements that values of the electrical characteristics of soil vary with the nature of the soil, this variation may be due to its ability to absorb and retain moisture rather than the chemical composition of the soil. It has been shown that loam, which normally has a conductivity on the order of 10^{-2} S/m can, when dried, have a conductivity as low as 10^{-4} S/m, which is the same order as granite.

4.2 Moisture content

The moisture content of the ground is the major factor determining the permittivity and conductivity of the soil. Laboratory measurements have shown that as the moisture content of the ground increases from a low value, the permittivity and conductivity of the ground increase and reach their maximum values as the moisture content approaches the values normally found in such soils. At depths of one metre or more, the wetness of the soil at a particular site is typically constant. Although the wetness may increase during periods of rain, the wetness returns to its typical value after the rain has stopped due to drainage and surface evaporation.

The typical moisture content of a particular soil may vary considerably from one site to another due to differences in the general geological structure which provides different drainage.