



**Recommendation ITU-R P.2040-1**  
(07/2015)

**Effects of building materials and structures  
on radiowave propagation above  
about 100 MHz**

**P Series**  
**Radiowave propagation**



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## Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

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| Series     | Title                                                                                |
|------------|--------------------------------------------------------------------------------------|
| <b>BO</b>  | Satellite delivery                                                                   |
| <b>BR</b>  | Recording for production, archival and play-out; film for television                 |
| <b>BS</b>  | Broadcasting service (sound)                                                         |
| <b>BT</b>  | Broadcasting service (television)                                                    |
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| <b>P</b>   | <b>Radiowave propagation</b>                                                         |
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| <b>SF</b>  | Frequency sharing and coordination between fixed-satellite and fixed service systems |
| <b>SM</b>  | Spectrum management                                                                  |
| <b>SNG</b> | Satellite news gathering                                                             |
| <b>TF</b>  | Time signals and frequency standards emissions                                       |
| <b>V</b>   | Vocabulary and related subjects                                                      |

**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.2040-1

**Effects of building materials and structures on radiowave propagation above about 100 MHz**

(Question ITU-R 211/3)

(2013-2015)

**Scope**

This Recommendation provides guidance on the effects of building materials and structures on radio-wave propagation.

The ITU Radiocommunication Assembly,

*considering*

- a) that electrical properties of materials and their structures strongly affect radiowave propagation;
- b) that it is necessary to understand the losses of radiowaves caused by building materials and structures;
- c) that there is a need to give guidance to engineers to avoid interference from outdoor to indoor and indoor to outdoor systems;
- d) that there is a need to provide users with a unified source for computing effects of building materials and structures,

*noting*

- a) that Recommendation ITU-R P.526 provides guidance on diffraction effects, including those due to building materials and structures;
- b) that Recommendation ITU-R P.527 provides information on the electrical properties of the surface of the Earth;
- c) that Recommendation ITU-R P.679 provides guidance on planning broadcasting-satellite systems;
- d) that Recommendation ITU-R P.1238 provides guidance on indoor propagation over the frequency range 900 MHz to 100 GHz;
- e) that Recommendation ITU-R P.1406 provides information on various aspects of propagation relating to terrestrial land mobile and broadcasting services in the VHF and UHF bands;
- f) that Recommendation ITU-R P.1407 provides information on various aspects of multi-path propagation;
- g) that Recommendation ITU-R P.1411 provides propagation methods for short paths in outdoor situations, in the frequency range from about 300 MHz to 100 GHz;
- h) that Recommendation ITU-R P.1812 provides a propagation prediction method for terrestrial point-to-area services in the frequency range 30 MHz to 3 GHz,

*recommends*

that the information and methods in Annex 1 and Annex 2 should be used as a guide for the assessment of the effects of building material properties and structures on radiowave propagation, and in developing deterministic models of propagation involving the built environment.

Annex 1 describes basic principles, and provides expressions to evaluate reflection from and transmission through building materials and structures. It also includes a model for electrical properties as a function of frequency, and a table of parameters for relevant materials.

Annex 2 gives definitions for various types of propagation loss associated with buildings, and provides guidance on measuring building entry losses.

Examples of building-entry loss measurements may be found in Report ITU-R P.[BEL\_MEASUREMENT].

## **Annex 1**

### **1 Introduction**

This Annex provides guidance on the effects of building material electrical properties and structures on radio-wave propagation.

Section 2 describes fundamental principles concerning the interaction of radio waves with building materials, defines various parameters in use for these purposes, and gives basic expressions for reflection from and transmission through single material interfaces and single and multiple layer slabs, typical of building construction.

Section 3 defines a model for electrical properties, and a table of parameters for various building materials.

### **2 Basic principles and theory**

Radio waves that interact with a building will produce losses that depend on the electrical properties of the building materials and material structure. In this section, theoretical effects of material electrical properties and structure on radio-wave propagation will be discussed.

#### **2.1 Theory of material electrical properties**

##### **2.1.1 Introduction**

This section describes the development of simple frequency-dependent formulae for the permittivity and conductivity of common building materials. The formulae are based on curve fitting to a number of published measurement results, mainly in the frequency range 1-100 GHz. The aim is to find a simple parameterization for use in indoor-outdoor ray trace modelling.

The characterization of the electrical properties of materials is presented in a number of different ways in the literature. These are described in § 2.1.2 in order that the measured data can be reduced to a common format.

## 2.1.2 Method

### 2.1.2.1 Definitions of electrical constants

The following treatment deals only with non-ionized, non-magnetic materials, and throughout we therefore set the free charge density,  $\rho_f$ , to zero and the permeability of the material,  $\mu$ , to the permeability of free space  $\mu_0$ .

The fundamental quantities of interest are the electrical permittivity,  $\epsilon$ , and the conductivity,  $\sigma$ . There are many ways of quantifying these parameters in the literature, so we first make explicit these different representations and the relations between them.

### 2.1.2.2 Derivation

The starting point is the wave equation derived from Maxwell's equations. Under the above assumptions, the wave equation for the electric field  $\vec{E}$  is:

$$\nabla^2 \vec{E} - \epsilon \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \frac{\partial \vec{J}_f}{\partial t} \quad (1)$$

where:

$\vec{E}$  : (vector) electric field intensity (V/m)

$J_f$  : current density of free charges (A/m<sup>2</sup>)

$\epsilon$  : dielectric permittivity (F/m)

$\mu_0$  : permeability of free space (N/A<sup>2</sup>) =  $4\pi \times 10^{-7}$  by definition.

In a conductor,  $\vec{J}_f$  is related to  $\vec{E}$  through Ohm's Law by:

$$\vec{J}_f = \sigma \vec{E} \quad (2)$$

where:

$\sigma$  : conductivity (S/m).

Combining equations (1) and (2) gives:

$$\nabla^2 \vec{E} - \epsilon \mu_0 \frac{\partial^2 \vec{E}}{\partial t^2} = \mu_0 \sigma \frac{\partial \vec{E}}{\partial t} \quad (3)$$

Writing  $\vec{E}$  in exponential notation:

$$\vec{E} = \vec{E}_0 e^{j(\omega t - \vec{k} \cdot \vec{r})} \quad (4)$$

where:

$\vec{E}_0$  : value of  $\vec{E}$  for  $t = \vec{r} = 0$  (V/m)

$\vec{k}$  : (vector) wave number (m<sup>-1</sup>) magnitude =  $2\pi/\lambda$  where  $\lambda$  is the wavelength in m

$\omega$  : angular frequency (s<sup>-1</sup>) =  $2\pi f$  where  $f$  is the frequency in s<sup>-1</sup>

$\vec{r}$  : (vector) spatial distance (m).

and substituting in equation (3) gives

$$k^2 - \epsilon \mu_0 \omega^2 + j \omega \mu_0 \sigma = 0 \quad (5)$$

where  $k$  is the magnitude of  $\vec{k}$ .

Equation (5) shows that the electric field intensity propagates as an attenuated sinusoidal wave.

### 2.1.2.3 Non-conducting dielectric

In a non-conducting dielectric ( $\sigma = 0$ ) the field is unattenuated and from equation (5) the velocity of propagation,  $v$  ( $= \omega/k$ ), is:

$$v = \frac{1}{\sqrt{\epsilon \mu_0}} \quad (6)$$

$\epsilon$  is conventionally written in terms of the relative permittivity and the permittivity of free space:

$$\epsilon = \eta \epsilon_0 \quad (7)$$

where

$\eta$ : relative dielectric permittivity of the medium concerned

$\epsilon_0$ : dielectric permittivity of free space  $= 8.854 \times 10^{-12}$  (F/m).

Thus the velocity of propagation in a medium of relative permittivity  $\eta$  can be written:

$$v = \frac{c}{\sqrt{\eta}} \quad (8)$$

where  $c$  is the velocity of light in free space ( $= 1/\sqrt{\epsilon_0 \mu_0}$ ). In other words,  $\sqrt{\eta}$  is the refractive index of the dielectric medium.

### 2.1.2.4 Conducting dielectric

When  $\sigma \neq 0$ , the wave attenuates as it propagates. It is convenient in this case to define a complex relative permittivity which may be derived as follows. Equation (5) can be rearranged, with the substitution  $c^2 = 1/(\epsilon_0 \mu_0)$ , to give:

$$\frac{c^2}{v^2} = \eta - j \frac{\sigma}{\epsilon_0 \omega} \quad (9a)$$

Since equation (8) gives  $\frac{c^2}{v^2} = \eta$ , this can be interpreted as a complex relative permittivity given by

$$\eta = \eta' - j \frac{\sigma}{\epsilon_0 \omega} \quad (9b)$$

This shows that the relative permittivity defined for a pure dielectric, becomes the real part  $\eta'$  of the more general, complex relative permittivity  $\eta$  defined for a conducting dielectric.

There are no universally accepted symbols for these terms. In this Recommendation, relative permittivity is written in the form:

$$\eta = \eta' - j\eta'' \quad (10)$$

where  $\eta'$  and  $\eta''$  are the real and imaginary parts. Using equation (9b), the imaginary part is given by:

$$\eta'' = \frac{\sigma}{\varepsilon_0 \omega} \quad (11)$$

Note that the sign of the imaginary part of  $\eta$  is arbitrary, and reflects the sign convention in equation (4). In practical units, equation (11) gives a conversion from  $\eta''$  to  $\sigma$ :

$$\sigma = 0.05563 \eta'' f_{\text{GHz}} \quad (12)$$

Another formulation of the imaginary part of  $\eta$  is in terms of the *loss tangent*, defined as:

$$\tan \delta = \frac{\eta''}{\eta'} \quad (13)$$

and so:

$$\tan \delta = \frac{\sigma}{\varepsilon \omega} \quad (14)$$

From equation (10) this gives:

$$\eta = \eta' (1 - j \tan \delta) \quad (15)$$

and in practical units:

$$\sigma = 0.05563 \eta' \tan \delta f_{\text{GHz}} \quad (16)$$

Another term sometimes encountered is the  $Q$  of the medium. This is defined as:

$$Q = \frac{\varepsilon \omega}{\sigma} \quad (17)$$

and is the ratio of the displacement current density  $\partial D / \partial t$  to the conduction current density  $J_f$ . For non-conductors,  $Q \rightarrow \infty$ . From equation (14):

$$Q = 1 / \tan \delta \quad (18)$$

Yet another term encountered is the complex refractive index  $n$  which is defined to be  $\sqrt{\eta}$ . Writing  $n$  in terms of its real and imaginary parts:

$$n = n' - j n'' = \sqrt{\eta} \quad (19)$$

$\eta'$ ,  $\eta''$  and  $\sigma$  are given from equations (10) and (12) by:

$$\begin{aligned}\eta' &= (n')^2 - (n'')^2 \\ \eta'' &= 2n'n'' \\ \sigma &= 0.1113n'n'' f_{\text{GHz}}\end{aligned}\quad (20)$$

### 2.1.2.5 Attenuation rate

A conducting dielectric will attenuate electromagnetic waves as they propagate. To quantify this, substitute equation (5) in equation (4) and simplify using equation (14):

$$\vec{E} = \vec{E}_0 \exp \left\{ j \left( \omega t - \sqrt{\eta'(1 - j \tan \delta)} \vec{k}_0 \cdot \vec{r} \right) \right\} \quad (21)$$

where:

$\vec{k}_0$  : (vector) wave number ( $\text{m}^{-1}$ ) in free space.

The imaginary part under the square root sign leads to an exponential decrease of the electric field with distance:

$$\vec{E} \propto \vec{E}_0 \exp(-|\vec{r}|/\Delta) \quad (22)$$

In a practical calculation using complex variables, the attenuation distance,  $\Delta$ , at which the field amplitude falls by  $1/e$ , can be evaluated as:

$$\Delta = \frac{-1}{\text{Im}(k_0 \sqrt{\eta})} \quad (23a)$$

where the function “Im” returns the imaginary part of its argument. Analytically it can be shown that:

$$\Delta = \frac{1}{k_0 \sqrt{\eta'}} \sqrt{\frac{2 \cos \delta}{1 - \cos \delta}} \quad (23b)$$

which can be evaluated by calculating  $\tan \delta$  from  $\eta'$  and  $\sigma$  and inverting to obtain  $\cos \delta$ . More direct evaluation is possible in the two limits of  $\sigma \rightarrow 0$  (dielectric limit) and  $\sigma \rightarrow \infty$  (good conductor limit). By choosing the appropriate approximation of the term under the square root sign in equation (21) these limits are:

$$\Delta_{\text{dielectric}} = \frac{1}{k_0 \sqrt{\eta'}} \frac{2}{\tan \delta} \quad (24)$$

and:

$$\Delta_{\text{conductor}} = \frac{1}{k_0 \sqrt{\eta'}} \sqrt{\frac{2}{\tan \delta}} \quad (25)$$

Equations (24) and (25) are accurate to about 3% for  $\tan \delta < 0.5$  (dielectric)  $\tan \delta > 15$  (conductor).  $\Delta_{\text{conductor}}$  is usually referred to as the “skin depth”.

For practical purposes the attenuation rate is a more useful quantity than the attenuation distance, and is related to it simply by

$$A = \frac{20 \log_{10} e}{\Delta} = 8.686 / \Delta \quad (26)$$

where:

$A$ : attenuation rate in dB/m (with  $\Delta$  in m).

Substituting equations (24) and (25) in equation (26) and converting to practical units gives:

$$A_{\text{dielectric}} = 1636 \frac{\sigma}{\sqrt{\eta'}} \quad (27a)$$

$$A_{\text{conductor}} = 545.8 \sqrt{\sigma f_{\text{GHz}}} \quad (27b)$$

### 2.1.3 Frequency dependence of material properties

In the literature, the real part of the dielectric constant,  $\eta'$ , is always given, but often the frequency is not specified. In practice for many materials, the value of  $\eta'$  is constant from DC up to around 5-10 GHz after which it begins to fall with frequency.

The value of  $\sigma$  is usually a strong function of frequency in the band of interest, increasing with frequency. This may be one reason why the imaginary part of the dielectric constant, or the loss tangent, is often specified in the literature: equations (12) and (16) show that these terms remove a linear frequency dependence compared to the frequency dependence of  $\sigma$ .

For each material a simple regression model for the frequency dependence of  $\sigma$  can be obtained by fitting to measured values of  $\sigma$  at a number of frequencies.

### 2.1.4 Models of material properties frequency dependence

In order to derive the frequency dependence of material properties, the values of the electrical constants of the materials can be characterized in terms of the measurement frequency, real part ( $\eta'$ ) and imaginary part ( $\eta''$ ) of the relative permittivity, loss tangent ( $\tan \delta$ ) and conductivity ( $\sigma$ ). Expressions in § 2.1.2.4 permit conversions between these quantities.

For the conductivity, there is usually statistically significant evidence for an increase with frequency. In this case the trend has been modelled using:

$$\sigma = c f_{\text{GHz}}^d \quad (28)$$

where  $c$  and  $d$  are constants characterizing the material. This is a straight line on a  $\log(\sigma)$ – $\log(f)$  graph. The trend line is the best fit to all available data.

For the relative permittivity one can assume similar frequency dependency:

$$\eta' = a f_{\text{GHz}}^b \quad (29)$$

where  $a$  and  $b$  are constants characterizing the material. However in almost all cases there is no evidence of a trend of relative permittivity with frequency. In these cases a constant value can be used at all frequencies. The constant value is the mean of all the values plotted. Some examples are given in Table 3.

## 2.2 Effects of material structure on radiowave propagation

### 2.2.1 Plane wave reflection and transmission at a single planar interface

This section considers a plane wave incident upon a planar interface between two homogeneous and isotropic media of differing electric properties. The media extend sufficiently far from the interface such that the effect of any other interface is negligible. This may not be the case with typical building geometries. For example, propagation losses due to a wall may be influenced by multiple internal reflections. Methods for calculating reflection and transmission coefficients of single-layer and multi-layer slabs are given in § 2.2.2.

A plane wave is useful for analysis purposes, but the concept is largely theoretical. In practice a wave may approximate but not be exactly planar. The point is important here because a truly plane wave does not experience free-space (spreading) loss. The following methods take no account of free-space losses, only the effect of the media interface.

#### 2.2.1.1 Oblique incidence on a plane media interface

Figure 1 illustrates a sinusoidal plane wave incident obliquely to a plane interface separating two uniform non-magnetic dielectric media having relative permittivities  $\eta_1$  and  $\eta_2$ . Values for  $\eta$  can be calculated from the real part of the permittivity,  $\eta'$ , and conductivity,  $\sigma$ , using equations (10) and (11). Table 3 provides parameters from which these can be calculated as functions of frequency.

There are three important theorems for this case that follow from geometrical considerations.

- 1) The vector wave numbers of the reflected and transmitted (refracted) waves lie in the plane of incidence, i.e. the plane defined by wave number  $k_i$  of the incident wave and the normal to the interface. This is taken to be the x-z plane in Fig. 1.
- 2) The angles of incidence and reflection are equal (both  $\theta_1$  in Fig. 1).
- 3) The angle of refraction,  $\theta_2$ , is related to the angle of incidence by Snell's law.

$$\frac{1}{c_1} \sin \theta_1 = \frac{1}{c_2} \sin \theta_2 \quad (30)$$

where  $c_1 = c/\sqrt{\eta_1}$  and  $c_2 = c/\sqrt{\eta_2}$  are the respective wave speeds in the two media, and  $\eta_1$  and  $\eta_2$  represent the complex relative permittivities of the two media.

These theorems ensure that the exponential space-time factors,  $\exp\{j(\omega t - k \cdot r)\}$ , for the three waves ( $k \rightarrow k_1, k_1', k_2$ , respectively) are identical at all points in the interface.