

IEEE Guide for Measurements of Electromagnetic Properties of Earth Media

IEEE Antennas and Propagation Society

Sponsored by the
Wave Propagation Standards Committee

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IEEE Guide for Measurements of Electromagnetic Properties of Earth Media

Sponsor

Wave Propagation Standards Committee
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IEEE Antennas and Propagation Society

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Abstract: Measurements of the electrical properties of naturally occurring solids are covered in the scope of this project. Not covered are methods that rely on mapping earth structure anomalies unless directly related to electrical properties. Coverage of numerical methods for forward/inverse modeling is limited.

Keywords: conductivity, earth materials, electromagnetic measurement techniques, IEEE 356, permittivity, resistivity

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Introduction

This introduction is not part of IEEE Std 356-2010, IEEE Guide for Measurements of Electromagnetic Properties of Earth Media.

This guide represents a total rewrite of IEEE Std 356-1974, IEEE Guide for Radio Methods of Measuring Earth Conductivity, which had been prepared by J. T. deBettencourt, D. Davidson, and J. R. Wait. Prior attempts to revise this guide by committees led by Dr. John Cavanaugh and Mr. George Hagn were merged into IEEE Std 356-2001. This latest version was prepared by a subcommittee of the Wave Propagation Standards Committee (WPSC) of the IEEE Antennas and Propagation Society, chaired by Prof. David Thiel of the Centre for Wireless Monitoring and Applications, Griffith University. The individuals with primary responsibility for this version as well as those who contributed or made useful comments are acknowledged in the participants section. An invitation is extended to users of the guide to contribute to the next revision whenever they see deficiencies or have ideas for an improvement by communicating with the WPSC Chair via email to d.thiel@griffith.edu.au.

The current guide covers the theory, field methodology/measurement techniques, suggestions for further reading, and a list of references for each of the several field and laboratory techniques covered. The frequency range of applicability and the geographical extent of applicability are indicated.

The current version of this standard retains the same number, IEEE Std 356, and it is a guide that describes recommended practices rather than a standard in the strict sense of the word. It is designed to be of use to those who plan and/or make laboratory and/or field measurements of the macroscopic electromagnetic parameters (i.e., the effective conductivity σ in S/m, and the effective relative permittivity ϵ_r) of earth media including surface soil, rocks, and ice.

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1. Overview

1.1 Scope

The scope of the project is to cover measurements of the electrical properties of naturally occurring solids. Not covered are methods that rely on mapping earth structure anomalies unless directly related to electrical properties. There is limited coverage of numerical methods for forward/inverse modeling.

1.2 Background

The electromagnetic properties of earth [conductivity σ in siemens/meter (S/m), permittivity ϵ in farads/meter (F/m), and magnetic permeability μ in henries/meter (H/m)] can have a major effect upon the performance of electrical and electromagnetic systems. Examples of these systems include both communications systems and remote sensing systems. For example, the electrical properties of the earth beneath an antenna can influence the antenna efficiency (and the need for a metallic ground plane) and radiation pattern, and these properties also can limit the effective depth of ground-penetrating radar. Many different methods and techniques have evolved for the measurement of the electrical properties of the earth at and near the surface at radio frequencies, and other methods using lower frequencies were developed for measuring the conductivity deeper into the earth for geophysical prospecting and other applications.

This guide is intended to describe these methods (both the theory and field methodology) and provide references for further reading for each method. The descriptions represent the recommended practice of these techniques. There is a further attempt to provide guidance on the limits of applicability of the methods (e.g., in frequency or in geographical context).

This guide has been prepared by the Wave Propagation Standards Committee of the IEEE Antennas and Propagation Society to replace the document, IEEE Std 356-1974, IEEE Guide for Radio Methods of Measuring Earth Conductivity [B1.7], which was also published by de Bettencourt et al. [B1.6].¹ In 1974, Lytle also published a comprehensive review paper [B1.15].

The International Telecommunication Union (ITU) has published world surface conductivity maps for a number of frequency bands [B1.9], although these maps are no longer being updated. The curves of conductivity and relative permittivity in ITU-R Recommendation 527-3 [B1.10] exhibit no dispersion in the band 3 MHz to 30 MHz; whereas measured values show significant dispersion in this band for which surface soils typically can show characteristics from good conductors to lossy dielectrics (King and Smith [B1.12]). The real and imaginary parts of the complex relative permittivity form a Hilbert transform pair. As a result, the conductivity and relative permittivity are not independent variables. Their mutual coupling is described by the Kramers–Kronig relations (King and Smith [B1.12]). Therefore, the ITU values for the high-frequency (HF) band are inconsistent with the results of complex variable theory and are in error.

1.3 Intention

The intent of this guide is to describe the measurement principles used to determine the electrical properties of naturally occurring solid materials, although it should also serve as a guide for the measurement of any solid material. These properties are the conductivity σ (in S/m) and the permittivity ϵ (in F/m). The magnetic permeability μ (in H/m) is not considered except where it impacts on the interpretation. This is because $\mu \cong \mu_0$ (to within less than 5%) for most naturally occurring materials. Even dry, pure magnetite sand only increases μ_r to 1.09. In free space (vacuum), the permittivity is $\epsilon_0 = 8.854 \times 10^{-12}$ F/m and the magnetic permeability is $\mu_0 = 4\pi \times 10^{-7}$ H/m.

The conductivity of a material is defined by Ohm's Law, i.e., the current I [in amperes (A)] passing through a block of the material (length l in meters (m) and cross-section A in m²) is related to the voltage V applied to plate electrodes covering two parallel faces of the cube by Equation (1):

$$I = V/R \quad (1)$$

where R is the resistance in ohms (Ω).

The conductivity σ can be determined since

$$R = l/\sigma A \quad (2)$$

Similarly, the permittivity of material can be determined by the same physical arrangement of a block (area A and length l) between two parallel electrodes by measuring the voltage V between the plates and the charge stored on the plates Q [in coulombs (C)] by the capacitance C (in F/m):

$$C = Q/V \quad (3)$$

and

$$C = \epsilon A/l \quad (4)$$

where the effects of fringing fields have been ignored. The similarity between the measurements of R and C , and consequently ϵ and σ , result in very similar methods being used to determine the two parameters.

In particular, using Equation (2) and Equation (4), one can write (from Cheng [B1.4]):

$$RC = \epsilon/\sigma \quad (5)$$

¹ The numbers in brackets correspond to those of the bibliography in Annex B.

When the material has conduction and displacement currents, the relationship between the applied voltage V varying with angular frequency ω and the current I can be written as:

$$V = \frac{1}{\sigma + j\omega\epsilon} \times I \times \frac{l}{A} \quad (6)$$

where

$e^{j\omega t}$ notation used for a time-harmonic signal
 t is the time
 $j = \sqrt{-1}$

Dividing the permittivity by the permittivity of free space ϵ_0 provides the relative permittivity ϵ_r . The complex relative permittivity for a linear, isotropic medium can be written as:

$$\epsilon_r = \epsilon'_r - j\epsilon''_r \quad (7)$$

where

ϵ'_r is the real part (also called the effective relative permittivity)
 ϵ''_r is the imaginary part that accounts for losses

The conductivity σ can range in value from 10^{-6} S/m for very dry sand, rock, or fresh water ice to 10 S/m for highly saline soils. The effective relative permittivity ϵ'_r can range from 3 to 100 for isotropic materials, but the effective relative permittivity can assume much larger values (or even be negative) in the case of mixed and/or anisotropic media (Cheng [B1.4], Ahrens [B1.1]). For example, King and Smith [B1.12] reported that a clay-loam soil with 10% water content was found to vary continuously from $\sigma = 10^{-2}$ S/m and $\epsilon'_r = 10^4$ at 100 Hz to $\sigma = 5$ S/m and $\epsilon'_r = 10$ at 10^{10} Hz. For a uniform anisotropic earth, the electrical characteristics can be represented by a 3×3 tensor. Angle rotation of the resistivity tensor has been shown to predict the response of the earth in all possible orientations in dip and strike (Wilson and Thiel [B1.29]).

It is well known that the physical and electromagnetic properties of the earth are highly non-uniform. Consequently the use of parameters σ and ϵ to describe the earth should take into account the fact that they can be a function of spatial dimensions or can represent a composite value, which is directly affected by the non-uniformity of the sample. In rock mechanics, these differences are described by the terms “rock mass” to represent the non-uniform composite structure, and “rock material” to represent the uniform material (Brady and Brown [B1.2]). This distinction can also be made by differentiating between those methods of measurements that are made in-situ and those that are made on rock samples in the laboratory. This distinction is also directly related to the wavelength of the radiation in the material under consideration and the size and separation of the contact electrodes used in the measurement.

This document does not cover electrical or electromagnetic geophysical methods reported by Keller and Frischknecht [B1.11] that rely on mapping anomalies in the earth’s structure, unless such information is directly related to determining the electrical properties of such materials. These geophysical techniques include magnetic tilt methods, magnetic surveys, most types of ground probing radar (GPR) and many airborne and satellite remote sensing techniques. The document does include the methods used to provide “ground truth” for these mapping methods.

The frequency of measurement, porosity of rock, water content, temperature, pressure, and the degree of fracture of the sample can affect measurement. Porosity is defined as the percentage of pore space in a unit volume of rock. Pores in a rock are often filled with fluids that give rise to finite resistance. While measuring the conductivity, there can be significant problems with probe contacts, both for in-situ measurements (probe impedance, conductive layers, etc.) and sample measurements (surface preparation, air gaps, etc.). In addition, these materials can be highly inhomogeneous, anisotropic, layered, and fractured so that the orientation of the electrodes should play a significant part in determining the results obtained

(Keller and Frischknecht [B1.11]). Anisotropic of a rock sample is scale-dependent. Consequently, electrode orientation as well as the separation of electrodes can influence the anisotropy measurement.

The measurements on soil samples are particularly difficult as the removal of a sample can strongly affect soil compaction and water content (particularly the water concentration profile as a function of depth) (Sternberg and Levitskaya [B1.20]).

In-situ measurements are commonly made from or above the earth's surface, e.g., with inserted probes, from an airborne platform or from boreholes. In-situ measurements, where properly implemented, can avoid the problems resulting from changes in compaction and soil moisture content. An attempt was made to cover all of these techniques.

Given the inhomogeneous and anisotropic nature of earth mass, the derivation of reliable data from field and laboratory measurements is difficult. It is possible to find analytical solutions to certain idealized earth structures. The calculation of field results using analytical or numerical methods from a postulated earth structure is called forward modeling. Thus one can derive characteristic curves to deduce ground constants. More commonly, however, automated data inversion techniques are not available as the number of unknown parameters (including their spatial distribution) is so large that least squared error minimization techniques do not converge to the correct answer (Oldenburg [B1.19]). The mathematical techniques of numerical modeling for solving the forward problem (i.e., assuming a particular earth profile to calculate expected measurement results), and stimulated annealing and artificial neural networks for the inverse problem (i.e., determining the electrical properties of the earth from the measurements) require considerable computation time and effort. Therefore, only passing mention is made to numerical methods for forward modeling and data inversion for two and three-dimensional structures.

1.4 Applications

The measurement of the electromagnetic properties of soil and rock, commonly called “ground constants,” are important for a wide variety of reasons including:

- a) Ground plane assessment for the location of antennas, and assessment of the characteristics of installed antennas
- b) Estimation of the coverage area of transmitters
- c) Mapping of conductive and resistive formations to obtain geological information and locating buried objects
- d) Assessment of ore-grade quality, moisture content, salinity, etc.
- e) Propagation studies for communications links above the surface and through-rock communications systems
- f) Assessment of aquifer activity for water search, assessment of nuclear waste disposal sites, the location of dams and rock drilling for tunnels and storage sites
- g) Measurement of surface parameters to calibrate antenna sites and remote sensing systems (including surface soil moisture content, soil salinity, aquifer location etc.)
- h) Estimation of oil and gas reserve and their producibility

The area of coverage of these techniques is not only frequency-dependent but also relates to the ease of use of the technique and whether it is possible to perform the measurements from an airborne platform. A generalized surface coverage diagram for *in-situ* measurements is given in Figure 1.

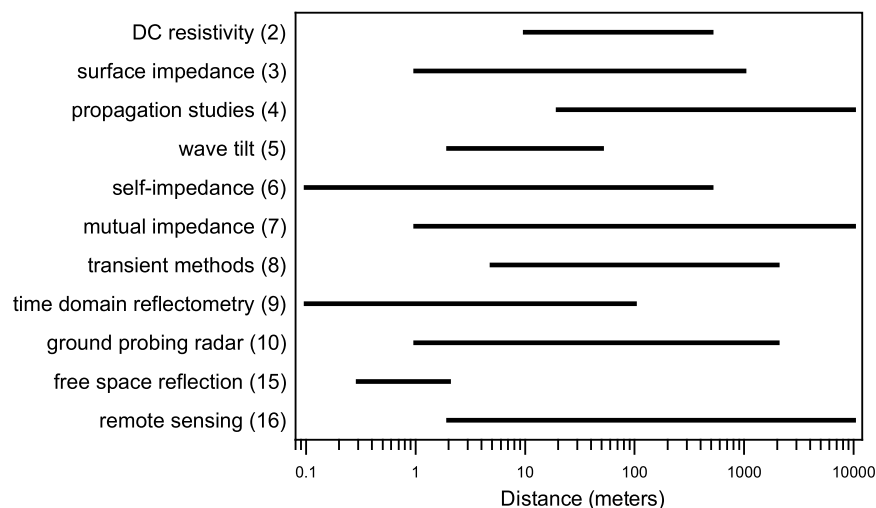


Figure 1—Approximate coverage area (linear traverse)

1.5 Document organization

The distinction between methods of measurement is quite blurred in many cases. However, in the interests of clarity, each different generic measurement technique is discussed separately. The divisions used in this document are listed in Table 1.

As the effect of frequency is very important, not only because of the depth of electromagnetic wave penetration, but also because the electrical parameters can differ dramatically over the frequency range, Figure 2 has been included to categorize the different measurement techniques in terms of their typical frequencies of operation.

Table 1—Measurement method categories

<i>In-situ</i> measurements	Laboratory measurements
Resistivity methods (2)	Time-domain reflectometry (9)
Surface impedance methods (3)	Resistivity methods (11)
Propagation studies (4)	Capacitance methods (12)
Wave tilt methods (5)	Transmission line methods (13)
Probe self-impedance (6)	Waveguide and cavity methods (14)
Mutual Impedance (7)	
Transient electromagnetic methods (8)	
Time-domain reflectometry (9)	
Ground probing radar (10)	
Transmission line methods (13)	
Free-space reflection (15)	
Microwave and millimeter-wave remote sensing (16)	

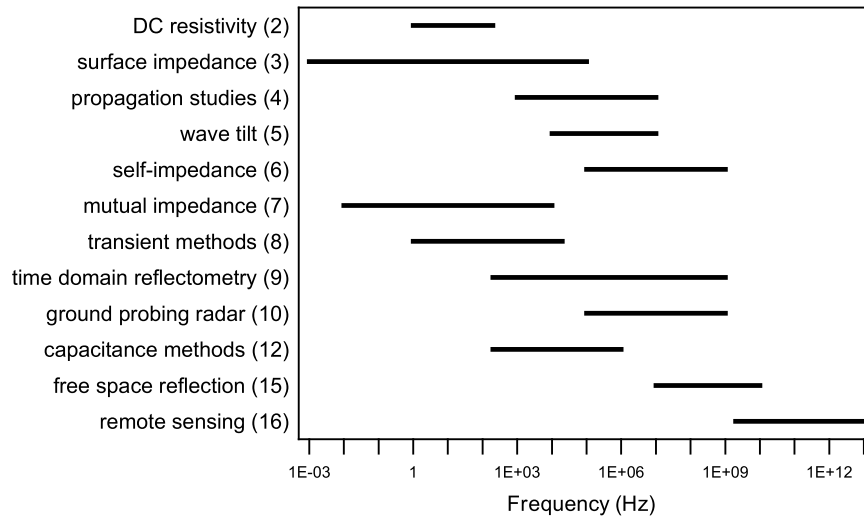


Figure 2—Frequency ranges of field methods

1.6 Notation

Throughout this guide, a set of standard definitions are used. The complex propagation constant γ for an electromagnetic wave propagating through any material is defined by Equation (8) (from Cheng [B1.4]):

$$\gamma = \alpha + j\beta = j\omega\sqrt{\mu(\epsilon + \sigma/j\omega)} \quad (8)$$

where

- α is the attenuation constant
- β is the phase constant
- ω is the angular frequency
- μ is the magnetic permeability of the medium
- ϵ is the permittivity of the medium
- σ is the conductivity of the medium
- $j = \sqrt{-1}$

The resistivity ρ of the medium is given by

$$\rho = 1/\sigma \quad (9)$$

As there are losses associated with the propagation, one can attribute a finite value to the conductivity of the medium. If the medium is uniform, then the field strength of the propagating wave attenuates exponentially. The separation distance between two points along a line in the direction of propagation is designated the penetration depth (or skin depth, δ) (IEEE Std 211™-1997 [B1.8]) if the field at one point is $1/e$ less than the field at the other. This can be defined as the reciprocal of the attenuation constant. This can be written as

$$\delta = 1/\alpha \quad (10)$$

When the conduction current is much larger than the displacement current (i.e., $\sigma \gg \omega\epsilon$), one can write an approximate expression for δ as

$$\delta \cong \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (11)$$

where f is the frequency of the radiation ($f = \omega/2\pi$).

When $\sigma \approx \omega\epsilon$, it is necessary to use the full expression for the skin depth δ derived from Equation (8) and Equation (10).

The intrinsic impedance of the Medium Z , is given by

$$Z = \sqrt{\frac{j\omega\mu}{\sigma + j\epsilon\omega}} \quad (12)$$

If the conduction current dominates the displacement current in the earth (i.e., $\sigma \ll \omega\epsilon$), then one can write

$$Z \cong \sqrt{j\omega\mu\rho} \quad (13)$$

The normalized impedance Δ is the ratio of the intrinsic impedance Z divided by the impedance of free space Z_0 , that is

$$\Delta = \frac{Z}{Z_0} \cong \frac{Z}{120 \pi \Omega} \quad (14)$$

The reflection coefficient for a plane wave in Medium 0, incident at an angle θ_i on Medium 1, is polarization dependent and is given by Fresnel's equations [B1.4]. Note that θ_i is measured with respect to the surface normal [see Figure 3(a)]. One can use Snell's Law to calculate the transmission angle θ_t of the lines of constant phase in Medium 2:

$$\sin \theta_t = \sqrt{\frac{\epsilon_{r0}}{\epsilon_{r1}}} \sin \theta_i \quad (15)$$

where

ϵ_{r0} is the relative permittivity of Medium 0
 ϵ_{r1} is the relative permittivity of Medium 1

In a lossy medium, ϵ_r is complex [Equation (7)], so θ can be a complex angle. From this angle, one can calculate the equation for the planes of constant amplitude and constant phase. For parallel (TM) polarization when the magnetic field vector is perpendicular to the plane of incidence, the reflection coefficient $\Gamma_{\parallel}$ is given by the expression:

$$\Gamma_{\parallel} = \frac{(Z_0 \cos \theta_i - Z_1 \cos \theta_t)}{(Z_0 \cos \theta_i + Z_1 \cos \theta_t)} \quad (16)$$

where

Z_0 is the intrinsic impedance of Medium 0
 Z_1 is the intrinsic impedance of Medium 1