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IEEE Guide for Measurements of Electromagnetic Properties of Earth Media

IEEE Antennas & Propagation Society

Sponsored by the
Wave Propagation Standards Committee



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**Wave Propagation Standards Committee
of the
IEEE Antennas & Propagation Society**

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Abstract: The electromagnetic properties of the earth play an important role in the design and implementation of radio communications systems, geophysical prospecting instruments, and subsurface mapping techniques. Measurement techniques include dc resistivity, surface impedance, propagation studies, wave tilt methods, probe impedance methods, mutual impedance methods, transient methods, time domain reflectometry, ground probing radar, laboratory-based techniques, and free-space reflection measurements. The separation distance between the probes and the wavelength of the radiation both affect the volume of earth material measured. This guide provides a summary of current measurement techniques and, where appropriate, inversion methods for determining the conductivity and the relative permittivity of the volume under investigation.

Keywords: dc resistivity, earth permittivity measurements, electromagnetic geophysics, ground conductivity measurements, ice, inversion, radio communications, radio reflection, surface impedance, time domain reflectometry

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Introduction

(This introduction is not part of IEEE Std 356-2001, IEEE Guide for Measurements of Electromagnetic Properties of Earth Media.)

This IEEE guide represents a total rewrite of IEEE Std 356-1974 [B1.7]^a, which had been prepared by J. T. deBettencourt, D. Davidson, and J. R. Wait. Prior attempts to revise this standard by committees led by John Cavanaugh and George Hagn were merged into the effort just completed. It has been prepared by a subcommittee of the Wave Propagation Standards Committee (WPSC) of the IEEE Antennas & Propagation Society, chaired by David Thiel of the Radio Science Laboratory, Griffith University. The individuals with primary responsibility for this version, as well as those who contributed or made useful comments, are acknowledged. 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 via email to d.thiel@me.gu.edu.au.

The current guide covers the theory, field methodology/measurement techniques, 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 provides guidance rather than listing requirements. We hope it will 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.

Participants

This guide was prepared by the Subcommittee on the Measurements of Earth Constants, of the WPSC, which had the following members:

David V. Thiel, *Chair*

John F. Cavanaugh

George H. Hagn
James R. Wait

Glenn S. Smith

It was indeed sad that during the preparation of this guide, James R. Wait died suddenly. Professor Wait had been a major force in this field for the past 45 years, as well as a major contributor to the WPSC. The subcommittee dedicates this guide to his contributions to the field.

During the preparation of this guide, a major contribution was made by:

Ben K. Sternberg

Useful comments were made by:

Gary S. Brown

Walter A. Flood

Wolfhard J. Vogel

^aThe numbers in brackets correspond to those of the bibliography in Annex B.

At the time of approval of this guide, the IEEE Antennas & Propagation Society (AP-S) Wave Propagation Standards Committee (WPSC), which balloted and approved this guide for submission to the IEEE Standards Board, had the following membership:

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The subcommittee, the WPSC, and the AP-S appreciate the assistance of all those who contributed to this guide.

The following members of the balloting group voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

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IEEE Guide for Measurements of Electromagnetic Properties of Earth Media

1. Overview

The electromagnetic properties of the earth (conductivity σ in S/m, permittivity ε in F/m, and magnetic permeability μ in H/m) can have a major effect on 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 & Propagation Society to replace IEEE Std 356-1974, IEEE Guide for Radio Methods of Measuring Earth Conductivity [B1.7],¹ which was also published as a paper by deBettencourt et al. [B1.5]. In 1974 Lytle published a comprehensive review paper [B1.14].

The International Telecommunication Union (ITU) has published world surface conductivity maps for a number of frequency bands [B1.9], although these are no longer being updated. The curves of conductivity and relative permittivity in ITU-R Recommendation 527-3 [B1.8] exhibit no dispersion in the band 3–30 MHz, whereas measured values show significant dispersion in this band for which surface soils typically can show characteristics from lossy conductors to lossy dielectrics [B1.11]. 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

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

is described by the Kramers–Kronig relations [B1.11]. Therefore, the ITU values for the HF band are inconsistent with the results of complex variable theory and are in error.

1.1 Scope

The purpose of this guide is to describe the measurement principles of the electrical properties of naturally occurring solid materials, although it will also serve as a guide for the measurement of any solid material. These properties are the conductivity σ (in S/m) and the permittivity (or dielectric constant) ε (in F/m). The magnetic permeability μ (in H/m) will not be 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 $\varepsilon_0 = 8.854 \times 10^{-12}$ 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 A) passing through a block of the material (length l in m and cross-section A in m²) is related to the voltage V applied to plate electrodes covering two parallel faces of the cube, as given by Equation (1):

$$I = \frac{V}{R} \quad (1)$$

where R is the resistance in ohms. The conductivity σ can be determined using Equation (2):

$$R = \frac{l}{\sigma A} \quad (2)$$

Similarly, the permittivity of the 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) by the capacitance C (in F/m), as shown by Equation (3) and Equation (4):

$$C = \frac{Q}{V} \quad (3)$$

and

$$C = \frac{\varepsilon A}{l} \quad (4)$$

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, by using Equation (5), one can write [B1.3]:

$$RC = \frac{\varepsilon}{\sigma} \quad (5)$$

When the material has conduction and displacement currents, the relationship between the applied voltage and the current can be written as shown in Equation (6):

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

where $e^{j\omega t}$ notation has been used for a time-harmonic signal.

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 shown in Equation (7):

$$\varepsilon_r = \varepsilon'_r - j\varepsilon''_r \quad (7)$$

where ε'_r is the real part (also called the *effective relative permittivity*) and ε''_r 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 [B1.1, B1.2]. For example, 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 [B1.11].

It is well known that the physical and electromagnetic properties of the earth are highly nonuniform. Consequently, the use of parameters σ and ϵ to describe the earth has to take into account the fact that they will be a function of spatial dimensions or will represent a composite value, which is directly affected by the nonuniformity of the sample. In rock mechanics, these differences are described by the terms “rock mass” to represent the nonuniform composite structure, and “rock material” to represent the uniform material. 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 guide does not cover electrical or electromagnetic geophysical methods [B1.10] 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, and many airborne and satellite remote sensing techniques. The guide does include the methods used to provide “ground truth” for these mapping methods.

The frequency of measurement, the water content of the sample, the temperature of the sample, the pressure on the sample, and the degree of fracture of the sample will all affect measurements [B1.1]. 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 [B1.10].

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) [B1.19].

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 shall be 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 [B1.18]. 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 shall be made to numerical methods for forward modeling and data inversion for two- and three-dimensional structures.

1.2 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).

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 very generalized surface coverage diagram for in-situ measurements is given in Figure 1.

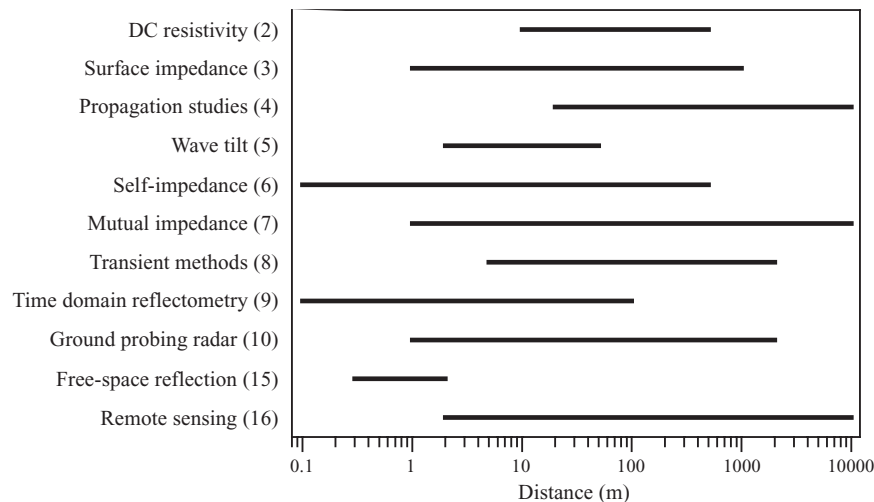


Figure 1—Approximate coverage area (linear traverse)

NOTE—The numbers in parentheses refer to the relevant clauses.

1.3 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 shall be discussed separately. The divisions used in this guide 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. Each technique is discussed in turn, with bibliography given in Annex B, as well as suggested further reading.

Table 1—Measurement method categories

In-situ 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)	

NOTE—The numbers in parentheses refer to the relevant clauses.

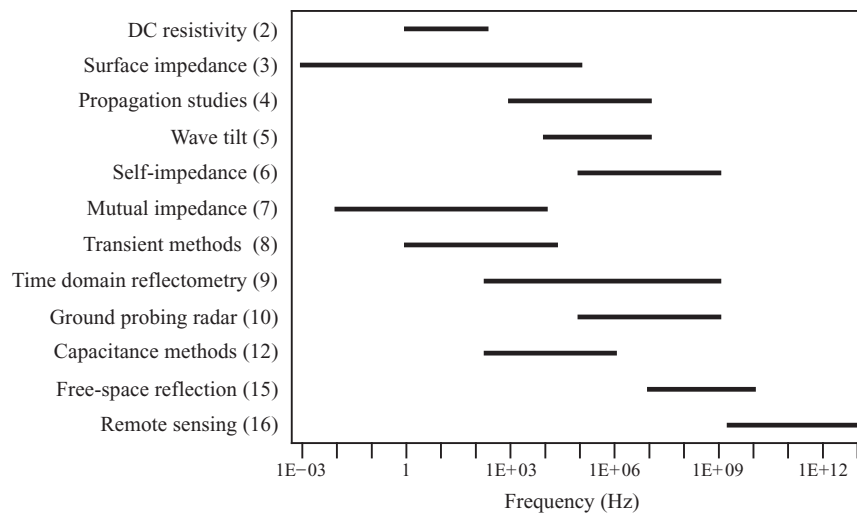


Figure 2—Frequency ranges of field methods

NOTE—The numbers in parentheses refer to the relevant clauses.

1.4 Notation

Throughout this guide, a set of standard definitions shall be used. The complex propagation constant γ for an electromagnetic wave propagating through any material is defined by Equation (8) [B1.3]:

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

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 is the square root of -1 .

The resistivity ρ of the medium is given by Equation (9):

$$\rho = \frac{1}{\sigma} \quad (9)$$

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) [B1.6] 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. Thus, in Equation (10) one can write:

$$\delta = \frac{1}{\alpha} \quad (10)$$

When the conduction current is much larger than the displacement current (i.e., $\sigma \gg \omega\varepsilon$), we can write an approximate expression [Equation (11)] 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 $\sigma \approx \omega\varepsilon$, 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 Equation (12):

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

If the conduction current dominates the displacement current in the earth, then, by using Equation (13), 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 is given by Equation (14):

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

The reflection coefficient for a plane wave in Medium 1, incident at an angle θ_i , is polarization dependent and is given by Fresnel's equations [B1.3]. Note that θ_i is measured with respect to the surface normal (Figure 3a). One can use Snell's Law [Equation (15)] to calculate the angle θ_t of the lines of constant phase in Medium 2:

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

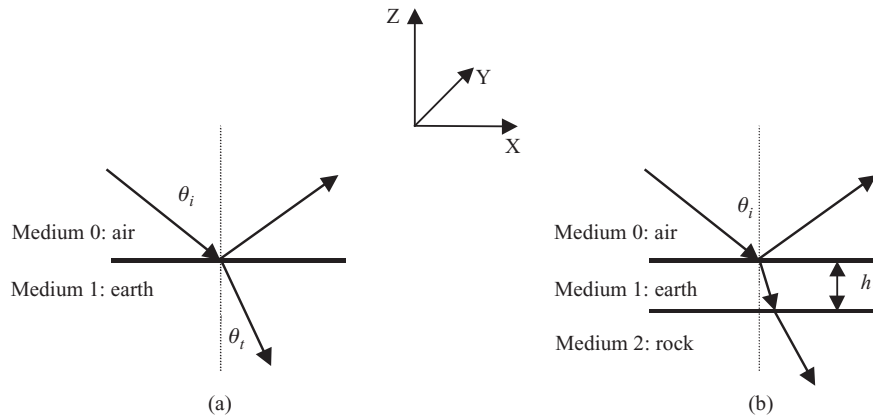


Figure 3—Schematic diagrams for electromagnetic radiation incident on the earth's surface:
(a) uniform, infinitely deep earth; (b) single layer above a uniform, infinitely deep earth

In a lossy medium, ϵ_r is complex [Equation (7)], so θ_c will 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 $\Gamma_{||}$ is given by Equation (16):

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

and for perpendicular (TE) polarization when the electric field is perpendicular to the plane of incidence, the reflection coefficient $\Gamma_{\perp}$ is given by Equation (17):

$$\Gamma_{\perp} = \frac{(Z_1 \cos \theta_i - Z_0 \cos \theta_t)}{(Z_1 \cos \theta_i + Z_0 \cos \theta_t)} \quad (17)$$

Note that, for any horizontally layered medium having n layers, the intrinsic impedance Z_n is given by Equation (12), i.e., Equation (18):

$$Z_n = \sqrt{\frac{j\omega\mu_n}{\sigma_n + j\epsilon_n\omega}} \quad (18)$$

where $n = 0, 1$, and 2 are the layer numbers.

If the medium is nonuniform, it is common to assign a single parameter, the effective surface impedance, to describe interactions on the surface. Geophysicists often use apparent resistivity ρ_a to quantify the total loss measured in the medium. Thus, many geophysical techniques will yield contour maps of ρ_a and not attempt to interpret the underlying structure. In this guide, reference will be made to effective surface impedance and apparent conductivity, which are directly related to ρ_a through Equation (9), assuming that the earth is uniform and infinitely deep.

The effective impedance concept can be used to describe the reflection of electromagnetic waves from the plane surface of a nonuniform material. For example, if the earth plane is horizontally layered, it is possible to calculate the effective surface impedance for a plane wave incident from the air.

Two separate cases must be considered, TM and TE. In the general case for an angle of incidence θ_i it is convenient to define the effective impedance $\hat{Z}$ [B1.25] by Equation (19):

$$\hat{Z}_1 = Z_1 \sqrt{1 - \frac{\gamma_0^2 \cos^2 \theta_i}{\gamma_1^2}} \quad (19)$$

where Z_1 is the intrinsic impedance of the earth defined in Equation (18), and the angle of incidence θ_i is as shown in Figure 3a.

For a uniform earth that is infinitely deep (Medium 1) the surface impedance is given by Equation (20):

$$Z_S = \hat{Z}_1 \quad (20)$$

In the TM case, for a single earth layer of depth h_1 overlying an infinite half-space (see Figure 3b), the resultant surface impedance Z'_S is given by Equation (21) [B1.25]:

$$Z'_S = Q_1 Z_S \quad (21)$$

where Z_S is the surface impedance of an infinitely deep earth of Medium 1 given by Equation (21), and Q_1 is given by Equation (22):

$$Q_1 = \frac{\hat{Z}_1 + \hat{Z}_2 \tanh(u_1 h_S)}{\hat{Z}_2 + \hat{Z}_1 \tanh(u_1 h_1)} \quad (22)$$

Here, $u_1 = \gamma_1 \cos \theta_i = \sqrt{\gamma_1^2 - \gamma_0^2 \sin^2 \theta_i}$, γ_0 is the complex propagation constant for free space, and γ_1 is the complex propagation constant for Medium 1; $\hat{Z}_2$ is given by Equation (19), using the electrical properties of Medium 2.

For a multilayered earth plane, one can calculate the surface impedance by calculating the intrinsic impedance of the lowest layer (i.e., assuming no reflection from a lower boundary), and use Equation (21) and Equation (22) iteratively until the upper surface of the top layer is determined. This calculation is identical to the expression used to calculate the input impedance of a multicomponent transmission line [B1.25].

In the simplest case of normal incidence, $\theta_i = 0$, the reflection coefficient $\Gamma_{||}$ is given by Equation (23):

$$\Gamma_{||} = \frac{Z_0 - Z_S}{Z_0 + Z_S} \quad (23)$$

In the TE case, the surface admittance, Y_S is given by Equation (24):

$$Y_S = Q' \hat{Y}_1 \quad (24)$$

where $\hat{Y}_1 = u_1 / j\gamma_1 \omega$ and

$$Q' = \frac{\hat{Y}_2 + \hat{Y}_1 \tanh(u_1 h_1)}{\hat{Y}_1 + \hat{Y}_2 \tanh(u_1 h_1)} \quad (25)$$

When the earth electrical properties vary continuously as a function of depth (e.g., when the moisture content is varying exponentially), analytical expressions for the surface impedance and surface admittance can be derived [B1.10]. In general, the vertical gradient down to approximately one skin depth for the frequency in use has to be considered.

If the earth is anisotropic, it is possible to rotate the resistivity tensor to the direction of interest and calculate the effective surface impedance [B1.16]. This is true both for horizontally oriented anisotropy and tilted (i.e., dipping) structures [B1.22]. When the earth has a dipping, layered structure (i.e., nonhorizontal, parallel stratifications), a more complex solution is required [B1.26].

There are analytical formulas for the permittivity of materials consisting of mixtures of dielectric materials [B1.21]. Similarly, in composite materials, artificial dielectric theory can be applied to conductive particles embedded in a lossy matrix [B1.2, B1.23, B1.24]. At most frequencies, the

complex permittivities of earth materials are dominated by the water content [B1.11–B1.13, B1.27]. The water distribution is often highly variable, particularly in the vertical direction. A lumped impedance RC network model, such as the Longmire–Smith (L-S) model [B1.13], allows a description of the relationship between the real and imaginary part of the permittivity. A plot of the imaginary part ε_r'' versus the real part ε_r' of the relative permittivity ε_r is referred to as a Cole–Cole plot [B1.4, B1.11]. Only recently has dispersion been incorporated into numerical methods [B1.11, B1.17, B1.20].

2. DC resistivity

2.1 Theory

DC resistivity measurements represent the most fundamental approach to determining the conductivity of in-situ materials from a surface. Two electrodes are used to make electrical contact with the surface to inject current, and the potential distribution is measured in the vicinity of the current electrodes. Despite the name, low-frequency alternating voltages and currents are used. Table 2 summarizes the common electrode arrangements and the expressions used to calculate the apparent conductivity. Note that I is the injected current, V is the voltage detected, a is the standard electrode spacing, and n is an integer. The geometry for these different electrode arrangements is illustrated in Figure 4.

Table 2—Common resistivity electrode configurations [B2.3]

Electrode arrangement	Apparent conductivity, σ_a
Wenner array	$I/2\pi Va$
Schlumberger array	$I/\pi Vna(n+1)$
Three-electrode array (pole–dipole) (Eltran array when $n = 1$)	$I/2\pi Vna(n+1)$
Dipole–dipole array	$I/\pi Vna(n+1)(n+2)$
Right-angle array (Wait array)	$0.05305 \times (I/V)/a$

NOTE — I is the current, V is the voltage detected, a is the standard electrode spacing, and n is an integer.

For measurements on a semi-infinite uniform half-space (conductivity σ) using hemispherical electrodes with radius r , the resistance between one electrode R_E and a point an infinite distance away is given by Equation (26) [B2.16]:

$$R_E = \frac{1}{2\pi r\sigma} \quad (26)$$

As there can be significant difficulties in ensuring adequate contact between the electrodes and the ground, the effect of the contact is minimized by using a set of voltage electrodes and a different set of current electrodes located in the vicinity; this constitutes a four-point electrode system, and is used to map the conductivity profile of the upper parts of the earth's surface. DC current is injected into the ground at one electrode and extracted at another (the current electrodes), and two other spaced electrodes (the voltage electrodes) are used to determine the voltage for a given electrode spacing at the surface in the local area. This process usually is repeated for different electrode spacings to check for layering. Data commonly are plotted as contours of apparent resistivity covering the area surveyed [B2.3]. The right-angle array technique (or Wait array) is described in more detail in [B2.3, B2.18].

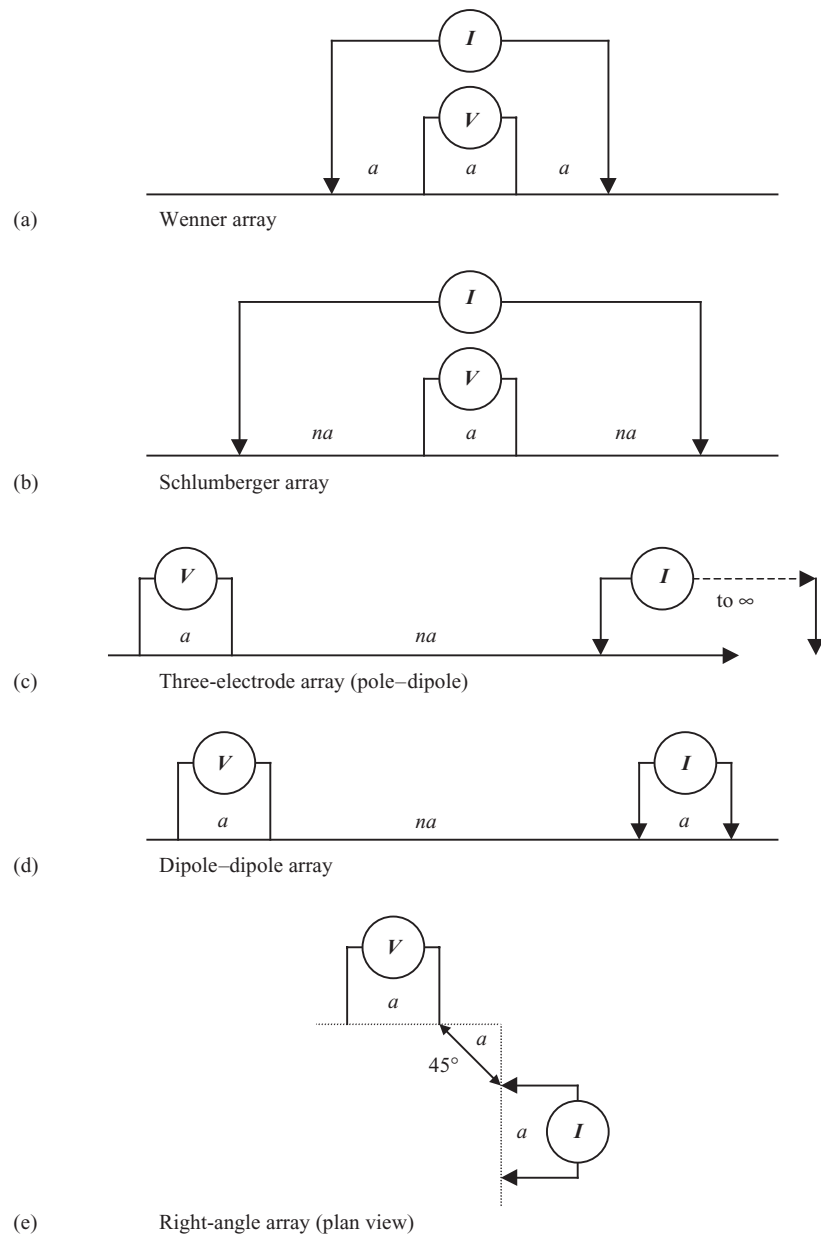


Figure 4—Common apparent resistivity arrays [B2.3, B2.5, B2.14–B2.16, B2.18]

The forward modeling problem requires the solution of Laplace's equation for the potential distribution found on the surface.

When the earth is inhomogeneous, the potential distribution is distorted. For example, current in Medium 1 flowing to Medium 2 changes direction if the conductivity is different [B2.14]. The surface potential due to horizontal bedding layers can be calculated using the method of images [B2.14] or using effective resistance calculations in an integral equation [B2.16]. Other variations in conductivity can be solved analytically. These include buried spheres, anisotropic earth materials, vertical dikes, exponentially varying conductivity, wedge-shaped anomalies, and borehole configurations [B2.3, B2.5, B2.14–B2.16, B2.18]. Numerical modeling techniques include the finite difference method [B2.9], the finite element method [B2.11], and the conjugate gradient method [B2.19].

While measurements are clearly influenced by subsurface variations in conductivity, rugged topography has a similar effect since the current tends to follow the surface. Shallow conductive layers also can result in misleading potential variations [B2.14].

When the earth is horizontally layered, the results become a function of the electrode spacing, a . Information about the conductivities of the two layers and the depth of the upper layer can be determined by multiple measurements using different spacings.

Automated inversion techniques for field survey results based on these models have been under investigation [B2.7, B2.8, B2.13, B2.19]. For example, least squared error minimization techniques combined with a forward modeling numerical technique have been investigated [B2.8, B2.11, B2.19]. For in-field use, a simple calculator-based method is available [B2.7].

2.2 Field methodology

Both dc and extremely low frequency (ELF) ac (less than 60 Hz) current sources are used [B2.14]. If the source is dc, the polarity must be reversed periodically to reduce the effect of electrolytic polarization [B2.13]. This reversal is implemented a number of times each second. While a dc source clearly yields dc resistivity, the spontaneous potentials (SP) in the earth (the basis of another method of geophysical mapping) can significantly alter the results. This bias effect can be minimized by simply noting the potential before the current source is applied, and subtracting this value from the measured results. The ac technique eliminates the SP effect, and allows the use of narrow-band amplifiers tuned to the source frequency to improve the signal-to-noise ratio. The measured resistivity is usually lower than the true dc value, and there can be interference through inductive coupling from the current supply leads.

The ac electrodes can be metallic conductors (steel, brass, aluminum, stainless steel, etc.). For dc currents, porous-pot electrodes filled with electrolyte are used [B2.5, B2.6]. The electrodes have to penetrate the ground by at least 10 cm to ensure adequate contact. The feed cables for both the current source and the potential measurements shall be insulated from the ground.

Figure 4 represents a number of the common configurations used for resistivity mapping. The larger the spacing between the electrodes, the deeper the effective area of measurement. The expressions given in Table 1 for the apparent conductivity σ_a assume a uniform earth half-space, where I and V are the injected current and measured voltage, respectively. It is clear from these expressions that the spacing between the electrodes, a , is the most important parameter in determining the volume of earth to be associated with a resulting apparent resistivity datum.

The probe resistance can cause significant problems. While the four-electrode array is independent of the probe resistance, if this is too high, then insufficient current is injected into the earth. This results in poor quality voltage measurements and an associated loss in the maximum probing depth. It is possible to model the contact points as hemispherical electrodes coated with a layer of insulation to investigate the influence of contact resistance analytically [B2.16].

In highly resistive earth, the technique can still be used effectively. In the Antarctic [B2.1], the current was provided by a 810 V voltage source and the voltmeter used had an input impedance of $10^{14} \Omega$.

Marine resistivity surveys have been successful in determining the resistivity of the sea floor and the layered structure beneath [B2.12]. In one example, a dipole-dipole array of nine electrodes is floated in a regularly spaced line behind a vessel. The first two inject current, and the following seven are nonpolarizing potential difference electrodes. Six voltage measurements are made, and the apparent conductivity for the n^{th} channel (σ_{an}) is calculated. These data are then inverted to give a horizontally layered interpretation that includes the resistivity of each layer and its depth.