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Summary of Methods for Measuring Electrical Properties of Geological Strata To Estimate Electromagnetic Shielding Effectiveness

by
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This report summarizes techniques for measuring electrical properties of the earth medium. Principal electrical properties of interest are the dielectric constant and conductivity (or resistivity). Representative measured results reported in the literature for various rock and soil types are included.

The measurement techniques considered are divided into three categories: (1) laboratory methods; (2) in situ measurements at the surface of the Earth; and (3) in situ drillhole measurement methods. Because many factors influence the electrical constants of the real earth, it is highly desirable, when practical, to perform measurements in situ rather than in the laboratory. Methods based on single drill holes provide localized values for the electrical constants in the vicinity of the hole. In contrast, propagation between two holes can be used to deduce bulk characteristics of earth-medium electrical constants between the two holes. Clearly, characterizing a broad area of the Earth's surface would require data from a large number of holes, and hence, this method can be quite expensive. When it becomes impractical to drill holes, in situ surface measurement methods can be substituted.

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The measurement techniques considered are divided into three categories: (1) laboratory methods; (2) *in situ* measurements at the surface of the Earth; and (3) *in situ* drill-hole measurement methods. Because many factors influence the electrical constants of the real earth, it is highly desirable, when practical, to perform measurements *in situ* rather than in the laboratory. Methods based on single drill holes provide

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FOREWORD

This investigation was performed for the Directorate of Engineering and Construction, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162731AT41, "Military Facilities Engineering Technology"; Work Unit CO-054, "Electromagnetic Pulse (EMP) Validation of Design Recommendations for C^3I Facilities." The HQUSACE Technical Monitor was Rodney Wells, CEEC-EE.

The study was done by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USA-CERL). The USA-CERL principal investigator was Ray G. McCormack. Much of the study was done by the University of Illinois at Urbana-Champaign, Electrical Engineering Department, under contract. Lawrence Epp performed that part of the study under the direction of Professor Raj Mittra at the university. Dana Finney, Information Management Office, was the USA-CERL technical editor.

Dr. Robert Quattrone is Chief of EM. COL N. C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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SUMMARY OF METHODS FOR MEASURING ELECTRICAL PROPERTIES OF GEOLOGICAL STRATA TO ESTIMATE ELECTROMAGNETIC SHIELDING EFFECTIVENESS

1 INTRODUCTION

Background

Most U.S. Government facilities that are critical to national defense use sensitive, complex communications/electronic (CE) systems that can be disrupted or damaged by incident electromagnetic energy. Further, electromagnetic energy generated by the CE systems can be radiated from the facility. If the information being handled by the CE system is sensitive in terms of protecting national defense, the radiated electromagnetic energy can compromise security.

The electrical conductivity, dielectric constant (or permittivity), and magnetic permeability of the Earth's surface and the material beneath it affect electromagnetic wave propagation both above and below the surface. The magnetic permeability for essentially all geological strata, however, is nearly equal to that of free space, making it possible to use a relative permeability of unity in calculating electromagnetic shielding. Hence, electrical conductivity and permittivity are the important parameters influencing the performance of electromagnetic systems that operate both on and under the Earth's surface. Transmission loss, phase shift, relative communication efficiency, and other system factors are affected by these parameters. These effects are important because many facilities supporting national defense are installed in the ground or underground and must be protected against nuclear electromagnetic pulse (EMP), electromagnetic interference (EMI), and/or compromising emanations.

For each situation requiring protection, it is desirable that earth, rock, or other geological strata provide electromagnetic shielding against incoming signals. This shielding is achieved through reflection of incoming incident electromagnetic energy combined with absorption of the energy propagating into the surrounding rock and soil. However, for most underground facilities, the rock and soil will provide only part of the necessary electromagnetic shielding so that other structures, such as metal buildings or shielded rooms, are required for additional shielding.

Many underground military facilities were constructed before sensitive CE equipment had widespread use and therefore were not hardened against EMP/EMI and compromising emanations. For structures that now support CE systems, it is essential to provide electromagnetic shielding. Retrofitting existing facilities can be expensive; therefore, it is important in terms of cost-effectiveness to assess the degree of shielding inherent in the surrounding soil and rock. In this way, retrofits can be designed at the least possible cost. In addition, this information would be important in planning new facilities, allowing designers to make intelligent decisions in establishing underground facility shielding levels. Also, in cases where siting is optional, designers can choose the location affording maximal protection against electromagnetic phenomena.

Besides showing the level of shielding possible, data on the electrical properties of soil and rock provide other critical information. The earth medium for several miles surrounding a fixed facility affects the magnitude and transient properties of the nuclear electromagnetic pulse energy incident upon the facility (i.e., the EMP threat to the facility); thus, many sets of data on rock and soil characteristics must be considered in calculating the EMP/EMI threat to a structure. Because of the large area involved, it is essential to be able to test these electrical parameters without the extensive, costly boring and excavation that would be required throughout the threat environment. For these reasons, an above-ground *in situ* measurement capability is needed.

Guidance is needed to help designers select appropriate methods for measuring the electrical properties of geological strata in determining the potential for electromagnetic shielding. Ideally, the measurements should be nondestructive to existing facilities, accurate, and low-cost and, if possible, should take advantage of any previous sitework (e.g., soil borings).

Objective

The objective of this work is to summarize the state of the art in methods for laboratory and field measurement of the dielectric constant and electrical conductivity of soil, rock, and other geological strata. This information will help provide military facilities designers with guidance in assessing the EMP hardness of underground construction.

Approach

The literature was reviewed and findings were consolidated. The various methods were classified as one of three types: (1) laboratory, (2) *in situ* measurement at the Earth's surface, and (3) *in situ* drill-hole measurement. Only methods considered to represent those in common use were evaluated. Some measured values for electrical parameters of soil and rock in different environments were then tabulated to provide examples.

Scope

The techniques described in this report for determining dielectric constant and electrical conductivity of soils and rock strata are for testing homogeneous materials. (In truth, the geological strata may be highly inhomogeneous with soil-filled cracks or other layers/zones of varying electrical parameters.) Further, the report is limited to test methods currently in use. Experimental methods that have not been proven are not included. Comprehensive reviews of methods for measuring electrical properties of the earth medium are available in the literature.[1]

Mode of Technology Transfer

It is recommended that information in this report be incorporated into Technical Manual 5-855-5, *Nuclear Electromagnetic Pulse (EMP) Protection.*

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[1] J. T. deBettencourt, D. Davidson, and J. R. Wait, "IEEE Guide for Radio Methods of Measuring Earth Conductivity," *Institute of Electrical and Electronic Engineers (IEEE) Trans. Antenna Propagat.*, Vol AP-22, No. 2 (March 1974), pp 373-400; R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 (July 1974), pp 81-101.

2 CONCEPT DEFINITIONS

To help explain the measurement techniques, this chapter briefly reviews the basic concepts defining the two electrical parameters under study--dielectric constant and conductivity.

Dielectric Constant

From Maxwell's equations in the MKS system, the definition of the complex dielectric constant (permittivity, ε^*) of a dielectric material can be written:

$$\varepsilon^* = \varepsilon - j\,\frac{\sigma}{\omega} \qquad \text{[Eq 1]}$$

Where ε is the real part of the complex dielectric constant, j is $\sqrt{-1}$, σ is the conductivity of the material, and ω is the angular frequency of the wave.

Equation 1 can also be defined as:

$$\varepsilon^* = \varepsilon_0\,(\varepsilon' - j\varepsilon'') \qquad \text{[Eq 2]}$$

Here, ε_0 is the dielectric constant of the vacuum and has a value of $(36\pi \times 10)^{9\ -1}$ F/m (MKS). ε' is associated with the ability of the dielectric material to store electric energy, and ε'', the loss factor, with the dielectric losses that occur in the material. The loss factor is also written:

$$\varepsilon'' = \frac{\sigma}{\omega\varepsilon_0} \qquad \text{[Eq 3]}$$

It is usually practical to use the relative (normalized) complex dielectric constant which is defined by:

$$\varepsilon_r = \frac{\varepsilon^*}{\varepsilon_o} = \varepsilon' - je'' \qquad \text{[Eq 4]}$$

or:

$$\varepsilon_r = \varepsilon'\,(1 - j\tan\Delta) \qquad \text{[Eq 5]}$$

The quantity tan Δ is commonly called the "loss tangent." It is proportional to the ratio of the power lost by means of dielectric loss to the energy stored per cycle and, therefore, is a good measure of the degree to which a dielectric material is lossy. The loss tangent can also be expressed using Equations 4 and 5:

$$\tan\Delta = \frac{\varepsilon''}{\varepsilon'} \qquad \text{[Eq 6]}$$

or:

$$\tan\Delta = \frac{\sigma}{\omega\varepsilon_0\varepsilon'}, \qquad \text{[Eq 7]}$$

The dielectric constant depends on many factors, including frequency, temperature, and water content of the dielectric material.

Magnetic Permeability

The notation and definitions of magnetic permeability can be written similar to those of the dielectric constant. However, in this report, the magnetic permeability of earth is taken to be that of a vacuum, $\mu_0 = 4\pi \times 10^{-7}$ H/m; therefore, the relative permeability is taken to be unity. Exceptions, of course, may occur in localized regions containing magnetic material.

As electromagnetic waves penetrate the earth, the wave field strength attenuates exponentially with depth. For highly conducting media, the skin depth δ is defined as:

$$\delta = \left(\frac{2}{\omega\mu_0\sigma}\right)^{\frac{1}{2}} \qquad \text{[Eq 8]}$$

The field strength decreases to e^{-1} at the skin depth.

Overburden is defined as the surface layers or regions of the earth that are water-bearing and subject to weathering. These layers mainly consist of sand, gravel, clays, and poorly consolidated rocks.[2]

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[2] J. T. deBettencourt, D. Davidson, and J. R. Wait.

3 LABORATORY MEASUREMENTS

Various laboratory methods are used to measure the dielectric constant of the earth medium. The choice of a particular method depends on the range of frequencies, properties of the material, and required level of precision.

For rock samples, bridge methods traditionally have been used at low frequencies, with resonance methods or standing wave methods employed at high frequencies. With the availability of sophisticated computers and automatic network analyzers, automatic measurement methods have now been reported. It is well known that bridge measurements have a high degree of accuracy, increasing the potential for accurate laboratory results. For ground soil samples, a shielded open-circuit coaxial transmission line method usually is used for measurements.

The laboratory methods typically determine electrical properties for small samples. *These samples must be taken during* drilling or excavation. Clearly, any given sample represents only a small volume of the medium; thus, to determine the degree of homogeneity, tests must be performed on numerous samples taken from selected regions in the medium of interest.

Precautions must be taken to prevent further drying or wetting of the soil or rock samples when they are collected for laboratory measurements. Rock samples sometimes may need to be cut into smaller pieces to fit dielectric holders. Since it is difficult to obtain a rock sample for which the original water content has not been altered, the sample can be resaturated for laboratory measurements using the water extracted from the drill hole from which the sample is obtained or other fluid that approximates the extracted water.

Chapter 6 contains samples of experimental data reported in the literature for rock and soil measurements done in the laboratory. More detailed reviews of laboratory methods are available elsewhere.[3]

Capacitive Cell Methods

A parallel-plate capacitor can be used as the test cell or sample holder for rock samples. Both the two-terminal-type holder (Figure 1) for roughly 10^{-1} to 10^{9} Hz, and a three-terminal type (Figure 2) for roughly less than 10^{5} Hz can be used at low

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[3] H. M. Altschuler, "Dielectric Constant," *Handbook of Microwave Measurement*, Vol 2, M. Sucher and J. Fox (Eds.) (Polytechnic Press, 1963), pp 495-548; H. E. Bussey, "Progress in Measurement of Electromagnetic Properties of Materials, 1963 to 1965," *Progress in Radio Science*, S. Silver (Ed.) (Space Science Laboratory, University of California, 1967); H. E. Bussey, "Measurement of RF Properties of Materials: A Survey," *Proc. IEEE*, Vol 55 (June 1967), pp 1046-1053; L. Hartshorn and J. A. Saxton, "The Dispersion and Absorption of Electromagnetic Waves," *Handbuch der Physik*, Vol 16, S. Flugge (Ed.) (Springer-Verlag, 1958), pp 640-725; V. P. Shestopalov and K. P. Yatsuk, "Methods of Measuring Dielectric Constants at Microwave Frequencies," *Soviet Uspekhi*, Vol 4, No. 4 (1962), pp 617-636; A. R. Von Hippel (Ed.), *Dielectric Materials and Applications* (John Wiley and Sons, 1954).

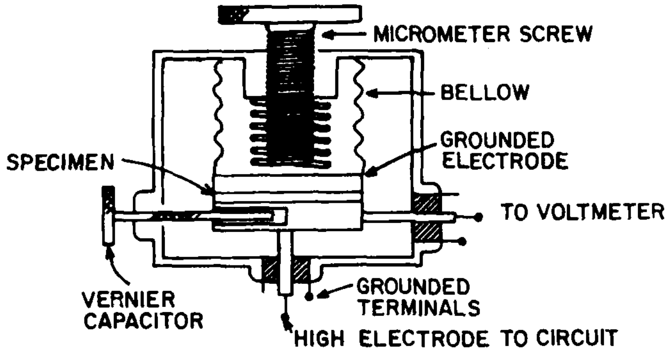

Figure 1. **Hartshorn-Ward capacitive holder.** (Source: A. R. Von Hippel [Ed.], *Dielectric Materials and Application* [John Wiley and Sons, 1954]. Used with permission.)

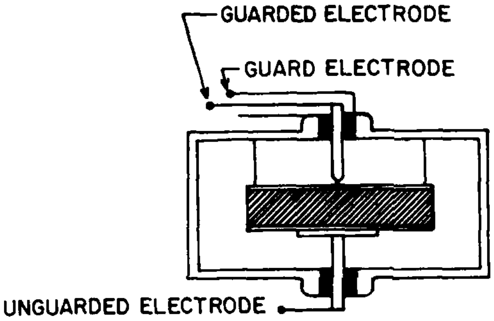

Figure 2. **Three-terminal electrode holder.** (Source: A. R. Von Hippel [Ed.], *Dielectric Materials and Application* [John Wiley and Sons, 1954]. Used with permission.)

frequencies. The three-terminal configuration may reduce the loss contribution due to the foreign-material conductance of the sample's edge.

The sample must be of a shape that allows its vacuum capacitance to be calculated. The preferable shape is a flat plate with plane and parallel surfaces, either circular or square. When micrometer electrodes are employed, the sample must be in the shape of a disk.

The Hartshorn-Ward capacitive holder (Figure 1) was developed to eliminate the errors caused by series inductance and resistance of the connecting leads and of the measuring capacitor at high frequencies. One disadvantage of the holder is that its capacitance calibration is not as accurate as that of a standard capacitor; also, it is not direct-reading. This drawback can be eliminated at low frequencies by connecting a standard capacitor in parallel with the system and measuring the change in total capacitance with the sample in and out in terms of this capacitor. A second problem with this device is that the edge capacitance of the electrode is slightly increased when the sample is inserted. This increase varies inversely with thickness. The problem can be mostly eliminated by making the diameter of the sample less than that of the electrodes by two times the sample's thickness.

The permittivity of a dielectric material is calculated from the measurement of (1) change in capacitance, as registered on the micrometer due to removing the sample, and (2) air capacitance in the holder for the geometrical volume of the specimen. The loss is obtained from the change in the circuit quality factor, Q, or conductance, respectively.

The Schering bridge (Figure 3) has been used for measurement over the frequency range 10 to 10^7 Hz, but other circuits, such as a Wheaton bridge, a voltmeter-ammeter circuit, an admittance meter, and a vector impedance meter, also can be used.[4] The admittance meter method has been used over the frequencies 1500 Hz to 500 MHz.[5] Substitution techniques with liquid immersion of the sample produce high accuracy for determining the loss tangent.[6]

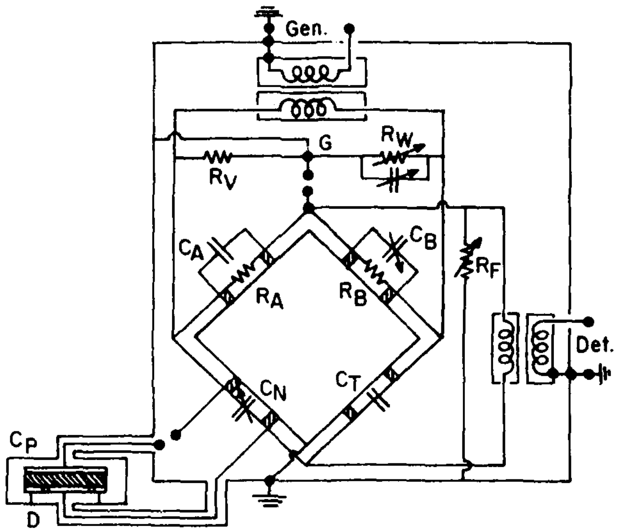

Figure 3. **Schering bridge with grounded guard terminal.** (Source: A. R. Von Hippel [Ed.], *Dielectric Materials and Application* [John Wiley and Sons, 1954]. Used with permission.)

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[4] J. R. Hanscomb and Y. Kaahwa, "A Digital Approach to Low-Frequency Dielectric Loss Measurement," *J. Physics*, Vol 11 (1978), pp 406-408; L. Hartshorn and J. A. Saxton; A. C. Lynch, "Unbalanced AC Bridges for the Measurement of Dielectric Loss," *Proc. Inst. Electr. Eng.*, Vol 124, No. 2 (1977), pp 188-189; E. I. Parkhomenko, *Electrical Properties of Rocks*, transl. by G. V. Keller (Plenum, 1967); D. J. Scheiber, "An Ultra Low Frequency Bridge for Dielectric Measurements," *J. Res. NBS (Engr. Instrum.)*, Vol 65C (1961), p 23; D. Wobschall, "A Frequency Shift Dielectric Soil Moisture Sensor," *IEEE Trans. Geosci. Electron.*, Vol GE-16, No. 2 (April 1978), pp 112-118.

[5] J. Poley, J. J. Nooteboom, and P. J. deWaal, "Use of VHF Dielectric Measurements for Borehole Formation Analysis," *The Log Analyst* (May-June 1978), pp 8-30.

[6] C. Cooke and J. E. Ford, "Accurate Measurement of the Dielectric Constant of Solids," *J. Physics*, Vol 14 (1981), pp 1285-1287.

Bridge methods are discussed in detail elsewhere in the literature.[7]

Standing Wave Method

The dielectric properties of rocks such as limestones and sandstones can be determined over a wide frequency range at ultrahigh frequencies (e.g., 300 MHz to 2400 MHz)[8] using the standing wave method. The dielectric specimen is inserted into a section of a waveguide--usually the coaxial line--ending in a short-circuited plate (Figures 4 and 5). By measuring the input impedance of the coaxial section, both when empty and when filled with the rock sample, the complex dielectric constant can be calculated. The input impedance is obtained by measuring the voltage-to-standing-wave ratio (VSWR = E_{max}/E_{min}) and the phase shift caused by the substance in the coaxial line; the phase shift is measured using the null indicator connected to the sonde diode. When low-loss dielectrics are measured, the VSWR of the coaxial line must also be taken into account.[9] Additional information about this method is available in the literature.[10]

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[7] R. Alvarez, "Complex Dielectric Permittivity in Rocks: A Method for Its Measurement and Analysis," *Geophysics*, Vol 38 (1973), pp 920-940; J. H. Beardsley, "A Variable Length Re-Entrant Cavity for Dielectric Measurements From 100 to 400 MC," *Rev. Sci. Instr.*, Vol 24, No. 2 (1953), pp 180-181; M. G. Broadhurst and A. J. Bur, "Two-Terminal Dielectric Measurements up to 6 x 10^8 Hz," *J. Res. NBS*, Vol 69C (July 1965), pp 165-172; H. E. Bussey (1967); H. E. Bussey (June 1967); J. C. Cook, "RF Electrical Properties of Bituminous Coal Samples," *Geophysics*, Vol 35, No. 6 (December 1970), pp 1079-1085; J. C. Cook, "Radar Transparencies of Mine and Tunnel Rocks," *Geophysics*, Vol 41 (December 1976), pp 1184-1206; C. Cooke and J. E. Ford; J. T. deBettencourt, D. Davidson, and J. R. Wait; J. R. Hanscomb and Y. Kaahwa; B. F. Howell, Jr., and P. H. Licastro, "Dielectric Behavior of Rocks and Minerals," *Am. Mineralogist*, Vol 46 (1961), p 269; A. S. Khalafalla and J. M. Viner, "Rock Dielectrometry at Mega- and Gigahertz Frequencies," presented at the 1973 Union Radio Scientifique Internationale (URSI) Meeting, Boulder, CO (August 1973); A. C. Lynch; R. J. Lytle, "The Yosemite Experiments: HF Propagation Through Rock," presented at the 1973 URSI Meeting, Boulder, CO (August 1973); R. J. Lytle (July 1974); A. G. Mungall and D. Morris, "Precision Capacitance-Conductance Bridge for Dielectric Measurements at Audio and Low Radio Frequencies," *Rev. Sci. Instr.*, Vol 34 (August 1963), pp 839-843; I. Ogawa and A. Kakimoto, "Improved Circuit for Impedance Measurement at Very High Frequency and Its Application in Testing Dielectric Properties of Insulating Materials," *Rev. Sci. Instr.*, Vol 49, No. 7 (July 1978), pp 936-939; E. I. Parkhomenko; J. V. Parry, "The Measurement of Permittivity and Power Factor of Dielectrics at Frequencies From 300 to 600 MHz," *Proc. Institution of Electrical Engineers (IEE) (London)*, Vol 98, Part 3 (July 1951), pp 303-311; J. Poley, J. J. Nooteboom, and P. J. deWaal; D. J. Scheiber; J. H. Scott, R. D. Carrolland, and D. R. Cunningham, "Dielectric Constant and Electrical Conductivity Measurements of Moist Rock: A New Laboratory Method," *J. Geophys. Res.*, Vol 72, No. 20 (1967), p 5101; A. R. von Hippel (Ed.); J. R. Wait (Ed.), *Electromagnetic Probing in Geophysics* (Golem Press, 1971); D. Wobschall.

[8] J. Poley, J. J. Nooteboom, and P. J. deWaal.

[9] J. Poley, J. J. Nooteboom, and P. J. deWaal.

[10] L. Hartshorn and J. A. Saxton; P. Hoekstra and A. Delaney, "The Dielectric Properties of Soils at UHF and Microwave Frequencies," presented at the 1973 URSI Meeting, Boulder, CO (August 1973); R. J. Lytle (July 1974); J. Poley, J. J. Nooteboom, and P. J. deWaal; V. P. Shestopalov and K. P. Yatsuk; A. R. Von Hippel (Ed.).

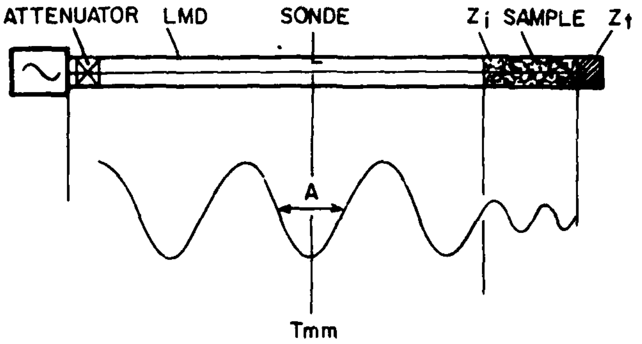

Figure 4. **Standing wave pattern.** (Source: J. Poley, J. J. Nooteboom, and P. J. deWaal, "Use of VHF Dielectric Measurements for Borehole Formation Analysis," *The Log Analyst* [May-June 1978]. Used with permission.)

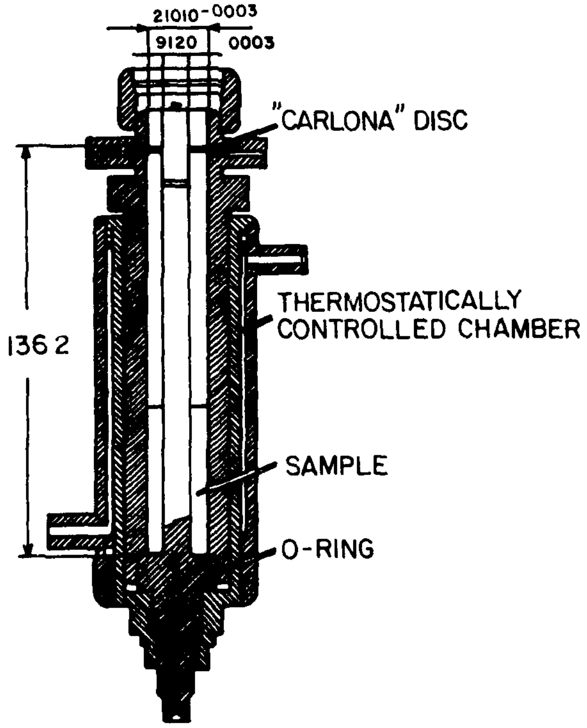

Figure 5. **Dielectric sample holder for the standing wave method.** (Source: J. Poley, J. J. Nooteboom, and P. J. deWaal, "Use of VHF Dielectric Measurements for Borehole Formation Analysis," *The Log Analyst* [May-June 1978]. Used with permission.)

Transmission Line Methods

Transmission line methods can be applied in both the frequency and time domains, and are suitable for broadband measurements at radio- and microwave frequencies. These methods can be divided into two types: total reflection and total transmission. In both cases, the sample's permittivity is expressed in terms of the measured values of the complex reflection and transmission coefficients, respectively. Although no analytical expression for permittivity is available, numerical methods can be used.

In a combined transmission-reflection method, permittivity of a sample is uniquely related to the reflection coefficient and the transmission coefficients. As mentioned above, measurements can be made in either the frequency or time domain. The combined method is explained further in many of the references.

An annular disk of dielectric sample is placed into a coaxial line (Figure 6) and can be viewed as a two-port network characterized by the scattering coefficients S_{11} and S_{21} (Figure 7). Coefficients are measured in the time domain by obtaining the reflected and transmitted responses of the component to an incident subnanosecond risetime pulse with a sampling oscilloscope, and then performing discrete Fourier transforms on the waveforms (Figure 8).

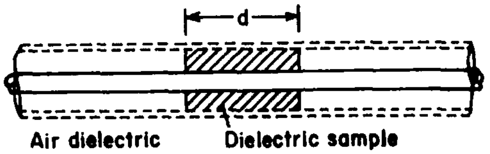

Figure 6. Transmission line method—dielectric sample in coaxial waveguide. (Source: M. Freeman, R. Nottenburg, and J. DuBow, "An Automated Frequency Domain Technique for Dielectric Spectroscopy of Materials," *J. Physics*, Vol 12 [1979]. Used with permission.)

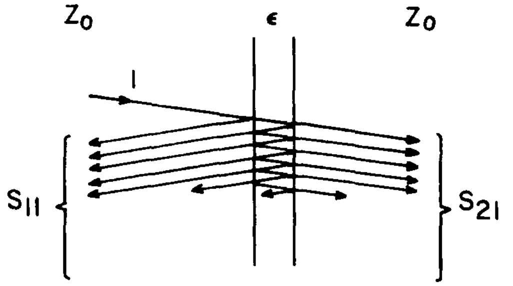

Figure 7. Transmission line method—configuration of dielectric sample. (Source: S. S. Stuchly and M. Matuszewski, "A Combined Total Reflection-Transmission Method in Application to Dielectric Spectroscopy," *Institute of Electrical and Electronic Engineers (IEEE) Trans. Instrum. Meas.*, Vol IM-27 [1978]. ©1978 IEEE. Used with permission.)

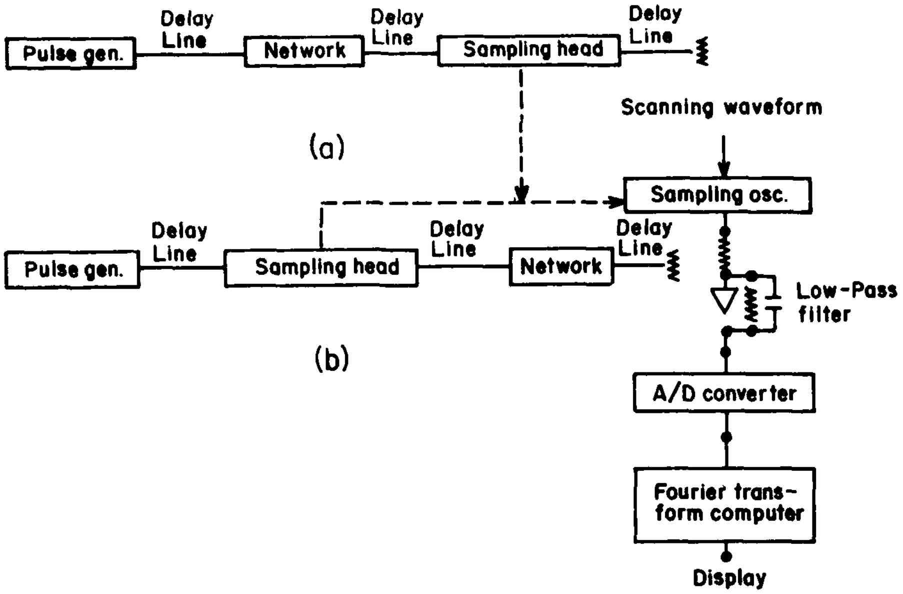

Figure 8. Transmission line method—block diagram of time domain measurements: (a) transmission and (b) reflection. (Source: A. Nicolson, "Broad-Band Microwave Transmission Characteristics From a Single Measurement of the Transient Response," *IEEE Trans. Instrum. Meas.*, Vol IM-17 [December 1968]. ©1968 IEEE. Used with permission.)

An inherent disadvantage with the time-domain techniques is the complexity in relating measured data to the actual dielectric parameters. This drawback is due to the necessity of using Fourier transform analysis and iterative computations. Another problem is that, for increasing spectral resolution, a Fourier transform must be performed on an increasing number of points. Even for a fast Fourier transform, the complexity of computations increases as N logN, where N is the number of data points. Finally, accurate time-domain measurements require complex instrumentation, demanding a great deal of skill and care in setting up an experiment.[11]

Better results can be obtained in the frequency domain. Using an automatic network analyzer, both the transmitted and reflected signals can be measured simultaneously (Figure 9). Use of both of these measured values permits simple closed-form solutions for the complex permittivity and permeability.[12]

Advantages of the automatic network analyzer are its ability to resolve very small frequency intervals (100 Hz at 1 GHz) and to measure many frequency points with only a linear increase in measurement and computation time. Also significant is the ability to use less than "perfect" sample holders that would introduce substantial errors with other techniques due to reflections and losses.[13]

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[11] M. Freeman, R. Nottenburg, and J. DuBow, "An Automated Frequency Domain Technique for Dielectric Spectroscopy of Materials," *J. Physics*, Vol 12 (1979), pp 899-903.

[12] M. Freeman, *R. Nottenburg, and J. DuBow; W. B. Weir*, "Automatic Measurement of Complex Dielectric Constant at Microwave Frequencies," *Proc. IEEE*, Vol 62 (1974), p 33.

[13] M. Freeman, R. Nottenburg, and J. DuBow.

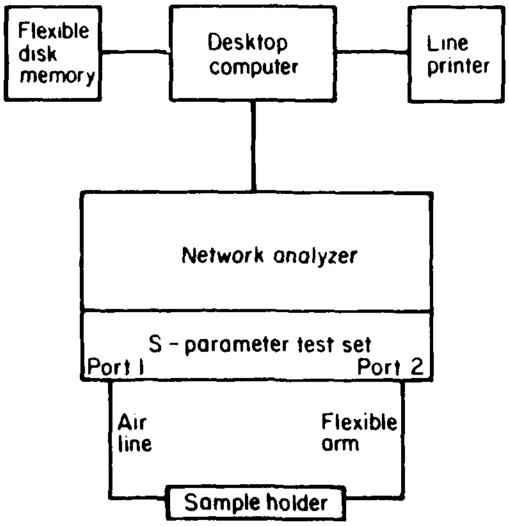

Figure 9. **Transmission line method—block diagram of frequency domain measurements.** (Source: M. Freeman, R. Nottenburg, and J. DuBow, "An Automated Frequency Domain Technique for Dielectric Spectroscopy of Materials," *J. Physics*, Vol 12 [1979]. Used with permission.)

A problem with the automatic network analyzer is nonlinearity. However, modifications that permit increased accuracy by taking into account errors arising from the nonlinearities have been reported.[14] The literature contains more comprehensive information on this method.[15]

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[14] M. Freeman, R. Nottenburg, and J. DuBow.

[15] W. J. Chudobiak, M. R. Beshir, and J. S. Wight, "An Open Transmission Line UHF CW Phase Technique for Thickness/Dielectric Constant Measurement," *IEEE Trans. Instrum. Meas.*, Vol IM-28 (March 1979), pp 18-25; W. J. Chudobiak, B. A. Syett, and H. M. Hafez, "Recent Advances in Broad-Band VHF and UHF Transmission Line Methods for Moisture Content and Dielectric Constant Measurement," *IEEE Trans. Instrum. Meas.*, Vol IM-28, No. 4 (December 1979), pp 284-289; M. Freeman, R. Nottenburg, and J. DuBow; W. L. Gans and J. R. Andrews, *Time Domain Automatic Network Analyzer for Measurement of RF and Microwave Components*, NBS Technical Note 672 (National Bureau of Standards, 1975); J. N. Lange, "Microwave Properties of Saturated Reservoirs," *Geophysics*, Vol 48, No. 3 (March 1983), pp 367-375; A. Nicolson, "Broad-Band Microwave Transmission Characteristics From a Single Measurement of the Transient Response," *IEEE Trans. Instrum. Meas.*, Vol IM-17 (December 1968), pp 395-402; A. Nicolson, "Measurement of the Intrinsic Properties of Materials by Time-Domain Techniques," *IEEE Trans. Instrum. Meas.*, Vol IM-19 (1970), pp 377-382; D. E. Palaith and S. K. Chang, "Improved Accuracy for Dielectric Data," *J. Physics*, Vol 16 (1983), pp 227-230; S. S. Stuchly and M. Matuszewski, "A Combined Total Reflection-Transmission Method in Application to Dielectric Spectroscopy," *IEEE Trans. Instrum. Meas.*, Vol IM-27 (1978), pp 285-288; M. J. C. van Germert, "High-Frequency Time-Domain Methods in Dielectric Spectroscopy," *Philips Res. Rep.*, Vol 28 (1973), pp 530-572; W. B. Weir; W. B. Westphal, *Techniques of Measuring the Permittivity and Permeability of Liquids and Solids in Frequency Range 3 Hz to 50 GHz*, Technical Report 36 (Massachusetts Institute of Technology, 1950).

Scattering and Transmission Methods

Complex permittivity can be computed by obtaining the complex refractive index from scattering of a spherical specimen or from transmission through a planar specimen (Figure 10). The real part of the permittivity is calculated from the phase difference between the waves propagating in free space and in the investigated dielectric specimen. The loss tangent is calculated by measuring power attenuation in the dielectric specimen and in free space.

Extensive theoretical results are available for these situations. Very accurate phase and amplitude measurements are required. The specimens should be penetrable so that the transmission loss through the sample can be measured. Nonunique solutions are possible if a single specimen is measured, but use of two differently sized samples can overcome this difficulty.[16] Details are available elsewhere.[17]

Cavity Resonator Method

A cavity resonator in the TE_{01} mode can be used for dielectric measurements of rock samples over the relative permittivity range of 1 to 100 or more and loss tangents

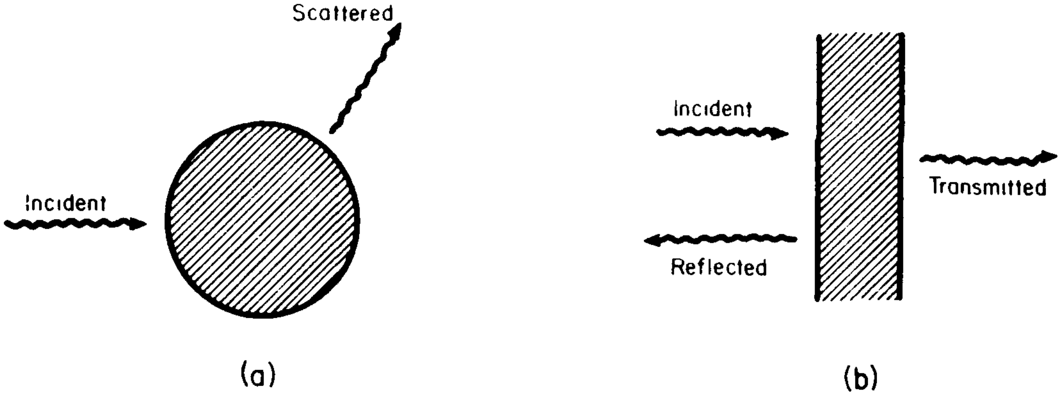

Figure 10. Transmission and scattering methods: (a) spherical and (b) planar samples. (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

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[16] R. J. Lytle (July 1974).

[17] R. Abbato, "Dielectric Constant Measurements Using RCS Data," *Proc. IEEE*, Vol 112 (1965), pp 1095-1097; H. M. Altschuler; D. C. Auth, W. G. Mayer, and W. J. Thaler, "A Light Diffraction Technique for Measuring Dielectric Constants at Microwave Frequencies," *Proc. IEEE* (1969), p 96; R. J. Lytle (July 1974); V. P. Shestopalov and K. P. Yatsuk; J. S. Yu and L. J. Peters, Jr., "Measurement of Constitutive Parameters Using the Mie Solution of Scattering Sphere," *Proc. IEEE*, Vol 117 (1970), p 876; J. S. Yu, P. C. Reardon, and P. C. Lysne, "Dielectric Logging With Downhole Invasion Effects," *IEEE Trans. Antennas Propagat.*, Vol AP-31, No 3 (May 1983), pp 397-412.

from 10^{-5} to 1.0. This method is used for VHF measurements in the national standard laboratories.[18]

Either a disk or a coaxial rod sample can be used (Figure 11). (A coaxial line resonator used for soil measurements is explained below under **Coaxial Line Resonator Method.**) The analysis is based on the impedance of the sample which is determined based on the cavity's Q value, dimensions, and/or transmission coefficient. A difficulty is that the method is time-consuming when applied over a broad range of frequencies since it is narrow-banded.

Advantages of this method are that loss tangents around 10^{-5} can be measured and that the fit error (due to either a gap around a disk sample or a top hole for inserting a rod sample) is small and easily calculated. Additional information about this method can be found in the literature.[19]

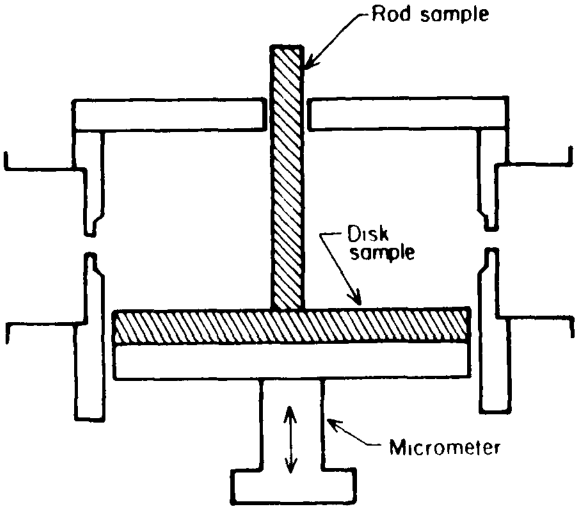

Figure 11. Tunable TE-mode cavity resonator. One of the two alternative sample forms is used. (Source: H. E. Bussey, "Measurement of RF Properties of Materials: A Survey," *Proc. IEEE*, Vol 55 [June 1967]. ©1967 IEEE. Used with permission.)

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[18] H. E. Bussey, D. Morris, and E. B. Zal'tsman, "International Comparison of Complex Permittivity Measurement at 9 GHz," *IEEE Trans. Instrum. Meas.*, Vol IM-23, No. 3 (September 1974), pp 235-239.

[19] H. E. Bussey and J. E. Gray, "Measurement and Standardization of Dielectric Samples," *IRE Trans. Instrum.*, Vol I-11 (December 1962), pp 162-165; H. E. Bussey, J. E. Gray, E. C. Bamberger, E. Rushton, G. Russell, B. W. Petley, and D. Morris, "International Comparison of Dielectric Measurements," *IEEE Trans. Instrum. Meas.*, Vol IM-13 (December 1964), pp 305-311; H. E. Bussey (June 1967); H. E. Bussey, "Dielectric Constant Measurements of the Earth," presented at the 1973 URSI Meeting, Boulder, CO (August 1973); H. E. Bussey, D. Morris, and E. B. Zal'tsman; H. E. Bussey, "Microwave Dielectric Measurements of Lunar Soil With Coaxial Line Resonator Method," *Proc. Tenth Lunar Planetary Science Conf., Houston, TX* (*Geochim. et Cosmochimica Acta*, Suppl. 11) (Pergamon Journals, March 1979), pp 2175-2182; R. J. Lytle (July 1974); V. P. Shestopalov and K. P. Yatsuk; A. R. Von Hippel (Ed.).

Cavity Perturbation Method

This method can be used for rock samples with low permittivities and moderate losses at microwave frequencies. A rectangular waveguide resonator in TE_{103} or TE_{105} mode is used widely.

Observed data are the volumes of the cavity and the small sample rod, and the frequency and Q with and without the sample. The complex permittivity is obtained from these measurements.

The cavity perturbation method often is simple, convenient, and reasonably accurate. For more details, consult the literature.[20]

Four-Electrode Method

The electrical parameters of rock samples can be determined over the frequency range 10^{-2} to 10^{4} Hz using the overvoltage or induced polarization phenomenon. This method usually is used for rock samples containing metallic or nonmetallic minerals.

A direct or alternating current is introduced into the sample by two current electrodes. The resulting voltage across two potential electrodes is then measured (Figure 12). From this measurement, the conductivity and dielectric constant of the sample are calculated.[21]

Shielded Open-Circuit Coaxial Transmission Line Method

A coaxial transmission line terminated by a shielded open circuit can be used to measure the dielectric constant (Figure 13). This method has provided measurements for lunar soil, various grains, and earth soil types.

The electromagnetic properties (dielectric constant and attenuation) of samples are obtained from the measured admittance. The admittance, in turn, is obtained by measuring the input reflection coefficient of the holder with its sample at the plane of

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[20] G. Birnbaum and J. Franeau, "Measurement of the Dielectric Constant and Loss of Solids and Liquids by a Cavity Perturbation Method," *J. Appl. Physics*, Vol 20 (1949), pp 817-818; H. E. Bussey (June 1967); L. Hartshorn and J. A. Saxton; R. J. Lytle (July 1974); A. Parkash, J. K. Vaid, and A. Mansigh, "Measurement of Dielectric Parameters at Microwave Frequencies by Cavity-Perturbation Technique," *IEEE Trans. Microwave Theory Tech.*, Vol MIT-27, No. 9 (September 1979), pp 791-795; S. Sen, P. K. Saha, and B. R. Nag, "New Cavity Perturbation Technique for Microwave Measurement of Dielectric Constant," *Rev Sci. Instrum.*, Vol 50, No. 12 (December 1979), pp 1594-1598; J. Verweel, "On the Determination of Microwave Permeability and Permittivity in Cylindrical Cavities," *Philips Res. Rep.*, Vol 20, No. 4 (August 1965), pp 404-414.

[21] B. D. Fuller and S. H. Ward, "Linear System Description of the Electrical Parameters of Rocks," *IEEE Trans. Geosci. Electron.*, Vol GE-8 (January 1970), pp 7-18; E. I. Parkhomenko; J. R. Wait (1959); J. R. Wait (Ed.) (1971).

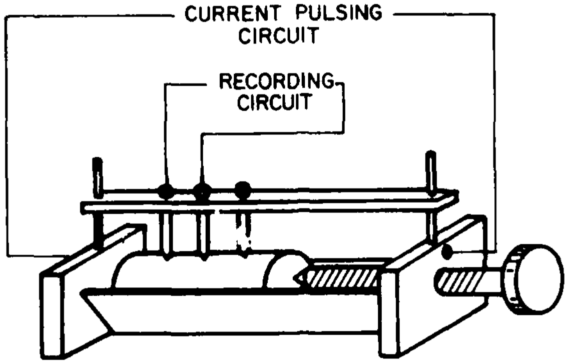

Figure 12. **Four-electrode method.** (Source: J. R. Wait [Ed.], *Electromagnetic Probing in Geophysics* [Golem Press, 1971]. Used with permission.)

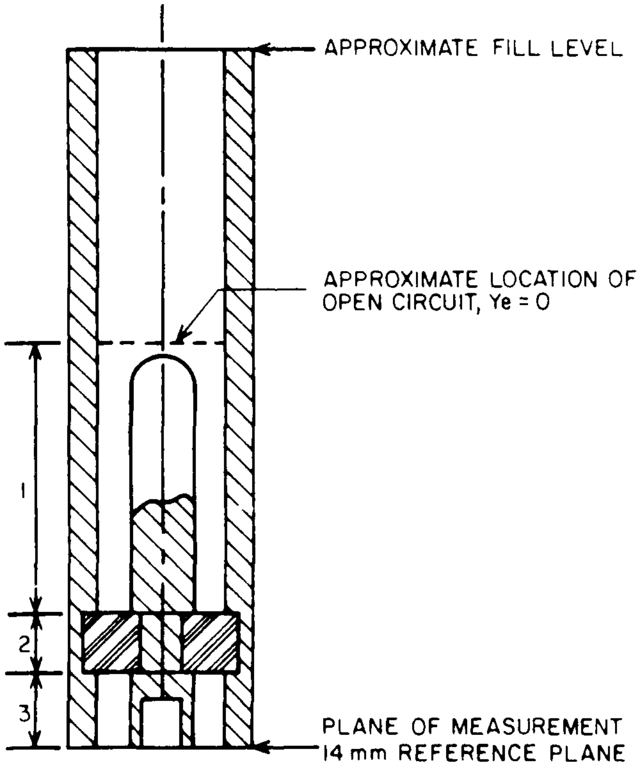

Figure 13. **Cross section of open-circuit sample holder.** (Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 [National Bureau of Standards, December 1978].)

the connector (input of section 3) by an automatic network analyzer (ANA).[22] Due to the low frequency limit of the ANA, most measurements reported have been made in the VHF or microwave frequency range, but theoretically, there is no low-frequency limit for this method.

This method has two main advantages: (1) the sample is easily inserted through the open end and (2) measurements can be made in a single sample holder for a wide range of frequencies. However, errors in measurements may arise due to an overcut/undercut support bead at low microwave frequencies.[23] More information is available elsewhere.[24]

Coaxial Line Resonator Method

The dielectric constant of soil also can be calculated at a series of microwave frequencies using a section of a coaxial transmission line that acts as a one-port cavity resonator (Figure 14). The cavity resonator begins to resonate when the electrical length

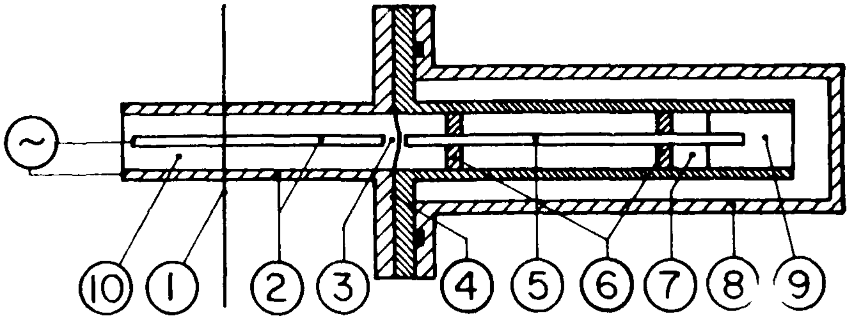

Figure 14. **Coaxial line resonator (14 mm diameter): (1) plane of 14-mm connector, (2) center conductor coupling rod and stainless steel outer conductor (for thermal isolation), (3) coupling gap, ~ 3.5 mm, (4) plastic film and indium wire vacuum seal, (5) open-circuited resonator bar, length 26 cm, (6) dielectric support beads for resonator bar and sample, (7) sample, (8) vacuum network analyzer (reflectometer) test port section, (9) open-circuit capacitance, C ≈ 0.163 pF, (10) automatic network analyzer (reflectometer) test port section.** (Source: H. E. Bussey, "Microwave Dielectric Measurements of Lunar Soil With Coaxial Line Resonator Method," *Proc. Tenth Lunar Planetary Science Conference*, Houston, TX [*Geochimica et Cosmochimica Acta*, Suppl. 11] [March 1979]. Copyright 1979, Pergamon Journals, Ltd. Used with permission.)

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[22] R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

[23] H. E. Bussey, "Dielectric Measurements in a Shielded Open Circuit Coaxial Line," *IEEE Trans. Instrum. Meas.*, Vol IM-29 (1980), pp 120-124.

[24] H. E. Bussey, "Dielectric Measurements of Lunar Soil," 1978 Lunar and Planetary Science IX Conference, Abstracts of Papers, Houston, TX (March 1978); H. E. Bussey (1980); R. L. Jesch.

of the center conductor (which is open-circuited at each end) equals 1, 2, ..., n half-wavelengths of the principal or transverse electromagnetic (TEM) mode. At a fixed resonant frequency, the real part of the permittivity is varied during the root-finding routine to satisfy terminating boundary conditions, which determines the real part of the permittivity. When the solution for the real part of the permittivity has been found, the electric and magnetic fields (E and H, respectively) are known throughout. The loss tangent of the sample is then obtained from the known fields and the Q value. The Q of a resonator is 2π times the energy stored divided by the energy dissipated per cycle.

The coaxial line resonator has been used for measurements of dry lunar soil within the frequency range 550 to 3300 MHz in six harmonics. Details are available in a paper by Bussey.[25]

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[25] H. E. Bussey (March 1979).

4 IN SITU SURFACE MEASUREMENTS

Since many factors influence the electrical parameters of the real earth, it is advisable to perform *in situ* measurements to obtain accurate data rather than relying on laboratory results. Factors affecting these properties include geological constituents, water content, frequency, weather, and local inhomogeneities.

In situ surface measurements have been made in both the time and frequency domains. Most current geophysical prospecting systems consist of a transmitting antenna and a receiving antenna placed some distance from the transmitter. The transmitted field induces eddy currents into the ground and the receiver measures the secondary fields from those induced currents. With the exception of transient field systems, the secondary field is observed in the presence of the much larger primary field. Some of these systems can be used for both surface and airborne measurements.

Recently developed systems show a trend toward (1) mergence of several systems such as those using resistivity, induced polarization, and electromagnetic methods; (2) microprocessor-controlled recording systems; and (3) computer modeling for interpretation. Combining data from several types of geophysical measurements makes it possible to obtain better resolution from the resulting joint data set than is feasible from data generated by only one system.

In-field microprocessor measurement can take advantage of several preprogrammed software applications including stacking, filtering, coherent harmonic detection, spectral storage, and spectral weighting. Computerized interpretation proceeds by establishing models of the earth, calculating or finding in a catalog the signatures of the models, selecting a model for which the signature best approximates that observed, and then assuming that this selected model is a reasonable representation of the real earth.

This report does not review all state-of-the-art airborne systems; the interested reader is referred to articles by Becker[26] and Ward[27] for a general review.

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[26] A. Becker, "Airborne Electromagnetic Methods," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1970), pp 33-43.

[27] S. H. Ward, "Airborne Electromagnetic Methods," *Mining and Ground Water Geophysics/1967*, L. W. Morley (Ed.), Economic Geology Report 26 (Geological Survey of Canada, 1970), pp 81-108.

Additional information can be found elsewhere in the literature.[28]

Resistivity Methods

Most resistivity methods use an array of four electrodes in contact with the ground. Two electrodes provide current to the ground while the other two are used to measure the voltage developed by this current. The mutual impedance (ratio of the measured voltage to the transmitted current) is then obtained to deduce the conductivity of the subsurface. The amount of current provided to the source must be great enough to provide easily detectable signals at the potential electrodes; often a heavy generator with a capacity ranging from 10 kW to several hundred kilowatts is used. For example, to investigate properties at 10,000 ft deep, a generator of 30 to 100 kW is needed. To obtain the high current levels required, it is also necessary to expend considerable effort in obtaining low-resistance ground contacts, particularly in areas where the ground resistivity is high. Either d.c. or a.c. of square or asymmetric square waveforms can be used as the source. In recent years, a.c. has been used more for the frequency range from 10^{-2} to 10^{2} Hz.

The electrode layout geometry controls the sensing area and depth of investigation for the measurements. Commonly used electrode configurations are shown in Figure 15. If in the Schlumberger array, the current electrodes are far apart and the potential electrodes are moved in-line between the current electrodes, then the gradient array is achieved.

Depth investigation of some collinear electrode arrays (Figure 15, a, c, e, f, and g) has been reported.[29] The dipole-dipole array has been used extensively to map two- and three-dimensional resistivity structures; this method has seen wide use due to its advantage in depth of exploration and flexibility in survey procedures.

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[28] J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 (January 1984), pp 80-87; G. V. Keller and F. C. Frischknecht, *Electrical Methods in Geophysical Prospecting* (Pergamon, 1966); R. J. Lytle, "Properties of the Ground Inferred From Electromagnetic Measurements," *IEEE Trans. Antenna Propagat.*, Vol AP-27, No. 6 (November 1979), pp 899-902; E. I. Parkhomenko; R. B. Rice, et al., "Developments in Exploration Geophysics," *Geophysics*, Vol 46, No. 8 (August 1981), pp 1088-1099; F. F. Segesman, "Well-Logging Method," *Geophysics*, Vol 45, No. 11 (November 1980), pp 1674-1684; H. O. Seigel, "An Overview of Mining Geophysics," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 7-23; J. S. Sumner, "The Induced-Polarization Exploration Method," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 123-133; J. R. Wait (Ed.) (1971); J. R. Wait, "Radio-Wave Propagation--Ground Structure and Topography," *Review of Radio Science 1972-1974*, S. A. Bowhill (Ed.) (Aeronomy Laboratory, University of Illinois at Urbana); S. H. Ward, "Electrical, Electromagnetic, and Magnetotelluric Methods," *Geophysics*, Vol 45, No. 11 (November 1980), pp 1659-1666.

[29] B. B. Bhattacharya and M. K. Sen, "Depth of Investigation of Collinear Electrode Arrays Over Homogeneous Anisotropic Half-Space in Direct Current Methods," *Geophysics*, Vol 46, No. 5 (May 1981), pp 768-780.

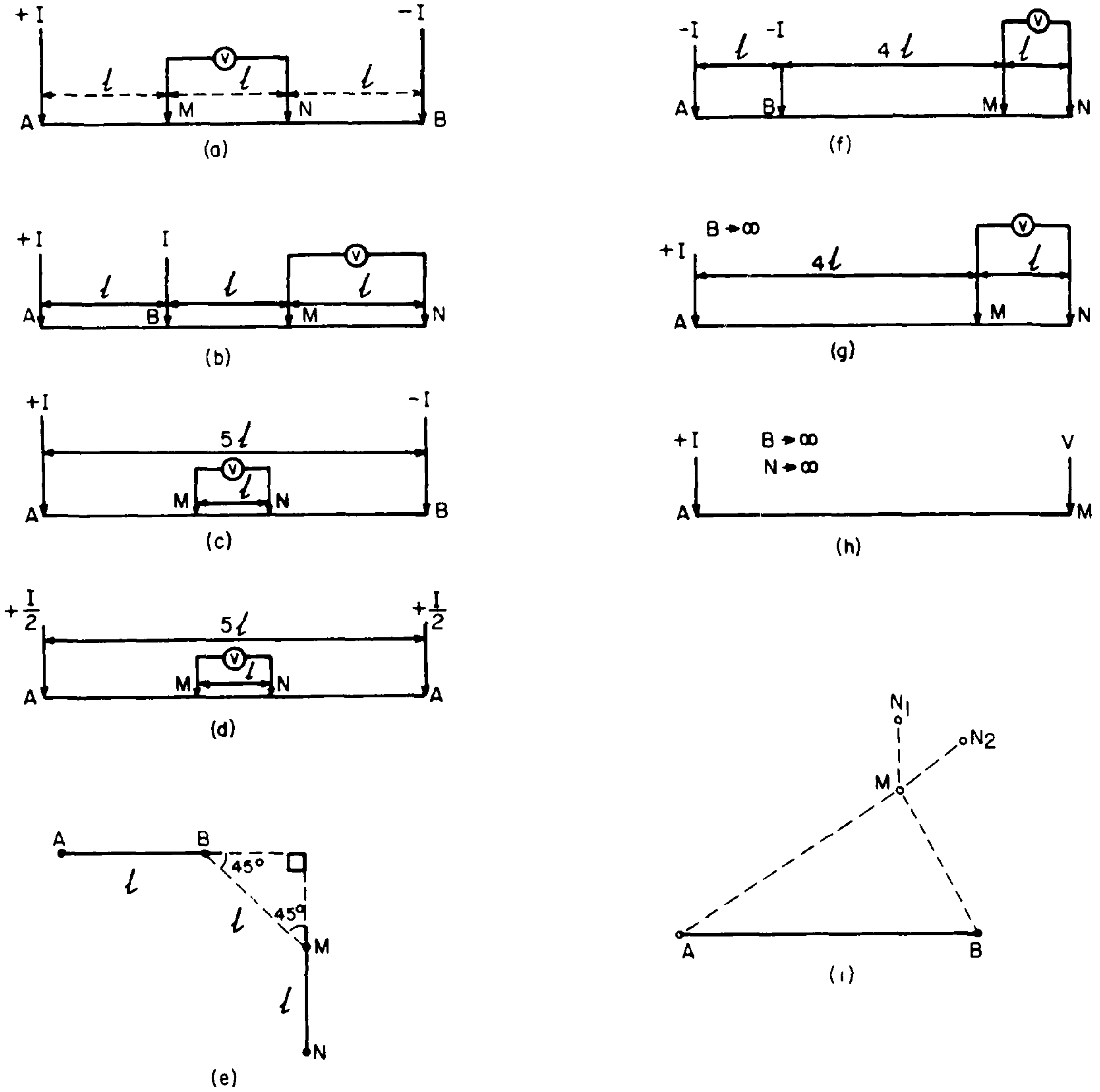

Figure 15. Various electrode arrays for resistivity methods: (a) Wenner, (b) Eltron, (c) Schlumberger, (d) unipole, (e) right-angle, (f) dipole-dipole, (g) pole-dipole, (h) two-electrode, (i) bipole-dipole.

Resistivity methods are treated extensively in the literature.[30]

Magnetometric Resistivity Method

The magnetometric resistivity (MMR) method uses a pair of current electrodes, as does the resistivity method. This method, however, differs from the other in that the potential electrodes are replaced by a sensitive coil or a magnetometer such that the component of the magnetic field due to the current flow is recorded. The magnetic field measurements are then used to deduce the resistivity and conductivity of the ground.

A major advantage of the MMR method over the resistivity method is that MMR can be used in a region of severe topography where the overburden is quite thick. In such a region, the electric field may be severely distorted, but the magnetic field--being an integral over a volume distribution of current--is not greatly affected by the local distortion of current in a surface layer. The MMR method also can be used for deeper exploration than the resistivity method.

The geometry of the electrodes and magnetometer can be arranged to control the sensing area, and the frequencies used are in the low range. For details, consult the literature.[31]

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[30] B. B. Bhattacharya and M. K. Sen; S. Coen and M. W. Yu, "The Inverse Problem of the Direct Current Conductivity Profile of a Layered Earth," *Geophysics*, Vol 46, No. 12 (December 1976), pp 1702-1713; J. T. deBettencourt, D. Davidson, and J. R. Wait; A. Dey, W. H. Meyer, H. F. Morrison, and W. M. Dolan, "Electric Field Response of Two-Dimensional Inhomogeneities to Unipolar and Bipolar Electrode Configurations," *Geophysics*, Vol 40, No. 4 (August 1975), pp 630-640; D. Doicin, "Quadripole-Quadripole Arrays for Dielectric Current Resistivity Measurements--Model Studies," *Geophysics*, Vol 41, No. 1 (February 1976), pp 79-95; M. El-Raey, "The Possibility of Remote Sounding of the Earth's Resistivity Profile," *Geophysics*, Vol 48, No. 5 (May 1983), pp 636-638; G. V. Keller and F. C. Frischknecht; G. V. Keller, "Recent Developments in the Use and Interpretation of Direct-Current Resistivity Surveys," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 63-75; R. J. Lytle (July 1974); R. J. Lytle and E. Laine, "A Computer Program for Four Probe Resistivity Measurements in a Horizontally Layered Earth," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 (October 1976), pp 232-235; R. J. Lytle (November 1979); T. R. Madden, "The Resolving Power of Geoelectric Measurements for Delineating Resistive Zones Within the Crust," *Geophys. Monograph*, Vol 14 (1971), pp 95-105; D. W. Oldenburg, "The Interpretation of Direct Current Resistivity Measurements," *Geophysics*, Vol 43, No. 3 (April 1978), pp 610-625; R. B. Rice, et al.; A. Roy, "Depth of Investigation in Wenner, Three-Electrode and Dipole-Dipole DC Resistivity Methods," *Geophys. Prospecting*, Vol 20 (1972), pp 329-340; A. Roy, "Resistivity Signal Partition in Layered Media," *Geophysics*, Vol 39, No. 2 (April 1974), pp 190-204; J. S. Sumner; J. R. Wait, *Geo-Electromagnetism* (Academic, 1982); J. R. Wait, "Mutual Coupling Between Ground Circuits and the Effect of a Thin Vertical Conductor in the Earth," *IEEE Trans. Antennas Propagat.*, Vol AP-31, No. 4 (1983), pp 640-644; S. H. Ward (November 1980); A. A. R. Zohdy, "Total Field Resistivity Mapping and Sounding Over Horizontal Layered Media," *Geophysics*, Vol 43, No. 4 (June 1978), pp 748-766.

[31] R. N. Edwards and E. C. Howell, "A Field Test of the Magnetometric Resistivity (MMR) Methods," *Geophysics*, Vol 41 (December 1976), pp 1170-1183; R. N. Edwards, H. Lee, and M. N. Nabighian, "On the Theory of Magnetometric Resistivity (MMR) Methods," *Geophysics*, Vol 43, No. 6 (October 1978), pp 1176-1203; H. O. Seigel, "The Magnetic Induced Polarization (MIP) Method," *Geophysics*, Vol 39 (1974), pp 321-339; H. O. Seigel, 1979.

Induced Polarization Method

This method is based on induced polarization effects and has been used extensively to explore base metal deposits in the time and frequency domains. This method usually involves the same equipment arrangements as those of the resistivity method to yield resistivity maps of the subsurface. Square waveforms are commonly used for the current source waveforms in the frequency range 10^{-2} to 10^{2} Hz.

Time-domain measurement techniques are similar to those of the resistivity methods. For frequency domain measurements, several different measurement techniques are possible. Traditionally, the percentage change of apparent resistivity with frequency has been measured. Recently, however, the phase shift between the measured voltage and primary current waveforms has been measured.[32] Another recent development is the measurement of complex resistivities and their changes with frequency.[33]

The relative advantages and disadvantages of commonly used induced polarization arrays are described in the references.[34]

Electromagnetic Sounding Methods

Electromagnetic sounding methods involve inductive coupling of electromagnetic energy into the subsurface. A transmitting coil carrying a.c. is placed on or above the Earth's surface, while a receiving induction coil, located at some distance from the transmitting coil, measures some parameter(s) of the resulting electromagnetic fields. These parameters are affected by the three-dimensional distributions of electrical conductivity, electrical permittivity, and magnetic permeability. At the receiver site, for example, the mutual impedance between transmitting and receiving loops is measured by mutual impedance methods; the tilt angle and ellipticity of the fields are measured using wave-tilt methods. Mutual impedance and wave-tilt methods are explained further in separate sections below. Components of the resulting magnetic field also have been measured. Frequencies used for these methods are in the extra low (ELF) or very low frequency (VLF) range.

Electromagnetic sounding methods can be divided into parametric, geometric, and combined sounding techniques. For the parametric soundings, measurements are made at several frequencies for one separation of the transmitter and receiver. With geometric soundings, measurements are taken at several separations for a single frequency. For the combined soundings, the measurements occur at several frequencies and at several distances. These sounding methods often use a horizontal loop source. This source is assumed to be small so that it can be approximated by a vertical magnetic dipole. Commercially available horizontal loop equipment is listed in Table 1. For the source, short or long grounded wire also can be used.

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[32] P. G. Hallof, "The IP Phase Measurement and Inductive Coupling," *Geophysics*, Vol 39 (1974), pp 650-665.

[33] K. L. Zonge and J. C. Wynn, "Recent Advances and Applications in Complex Resistivity Measurements," *Geophysics*, Vol 40 (1975), pp 851-864.

[34] P. G. Hallof; H. O. Seigel (1979); J. S. Sumner; J. R. Wait (1959); R. P. Wharton, "A Difference Potential Method for Induction Sondes, *IEEE Trans. Geosci. Electron.*, Vol GE-13, No. 2 (April 1975), p 87; R. J. Whitely, "Electrode Arrays in Resistivity and IP Prospecting: A Review," *Aust. Soc. Explor. Geophys. Bull.*, Vol 4, (1973), pp 1-29; K. L. Zonge and J. C. Wynn.

Table 1

Commercially Available Fixed Horizontal Loop Electromagnetic Equipment*

Domain	Manu-facturer	Model	Parameters Measured	Frequency Operation	Power Output (W)	Power Source**	Readout Device	Weight (kg)	Remarks
Time	Crone Geophysics	Pulse EM (PEM)	8 samples of secondary field; 1 sample of ramp voltage	Equiv. 18 to 1060 (Hz)	Max. 450	2 x 12 20 amp. hr Gel batt.	Meter	21	Moving Tx-loop system
	Geonics	UTEM	Vert. magnetic & horiz. electric fields	10 time slots -base freq. 7 to 90 Hz		1.5 kW MG	Meter or digital tape deck	60	Large loop
	Geoex.	SIROTEM	Vert. magnetic field	12 to 32 time slots 0.24 to 180 msec	Max. 176	22 V 10 amp. hr Nicads	Printer output	20	Single or double loop configuration moving loops choice of sizes
Frequency	Geoprobe	Maxi-probe EM 16	Vert. & hor. mag. field; hor. elec. fields	2^n(n=0 to 9),1k 2k,4.1k,8.2k, 16.4k,32.8k,41k	2100	6 HP MG	Meter	116	
	Scintrex	SE-77/ TSQ-2M (Turam)	Field strength ratio & phase diff.	35,105,315, 945 & 2835	500	3 HP MG	Automatic meter display	42	Reads harmonics of transmitted square wave
	Geotronics	EMR-1/ GT20A	32F	10 to 10, 000 Hz	20K	MG	Meter	810	Coherent super without carried reference

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*Source: S. H. Ward, "Ground Electromagnetic Methods and Base Metals," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 45-62. Reproduced with permission of the Minister of Supply & Services Canada.

**MG = motor generator.

Recently developed electromagnetic sounding systems use complex source waveforms that are repetitive but include several components of differing frequencies, often harmonically related. These components include the square wave, the saw-toothed waveform, and the pseudorandom waveform. Coherent detection is achieved using synchronized crystal clocks or radio links for time reference. Microprocessors also are used to control the receiver. With these systems, measurements can be made in terms of (1) the earth impedance versus frequency spectrum or (2) its step-function or impulse function response. The multichannel data usually are stored in digital form on magnetic tape cassettes. These data may be transformed, for greater ease of interpretation, from the frequency to time domain (or vice versa) by computer or even by programmable calculator.

One such product based on this concept is the EM-60 electromagnetic system by Lawrence Berkeley Laboratory. This system has a 100-m-diameter horizontal loop for exploring a depth of 2 km or more. Another example is the three-component magnetometer which has been used for measurements over the frequency range 10^{-3} to 10^{3} Hz.[35]

More information on these systems is available elsewhere.[36]

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[35] M. Wilt, N. E. Goldstein, M. Stark, J. R. Haught, and H. F. Morrison, "Experience With the EM-60 Electromagnetic System for Geothermal Exploration in Nevada," *Geophysics*, Vol 48, No. 8 (August 1983), pp 1090-1101.

[36] J. J. Daniels, G. V. Keller, and J. J. Jacobson, "Computer-Assisted Interpretation of Electromagnetic Soundings Over a Permafrost Section," *Geophysics*, Vol 41, No. 4 (August 1976), pp 752-765; P. M. Duncan, et al., "The Development and Applications of a Wide Band Electromagnetic Sounding System Using a Pseudo-Noise Source," *Geophysics*, Vol 45, No. 8 (August 1980), pp 1276-1296; D. B. Fleming, "Computation of the Vertical Component of the Magnetic Field of a Long Sinusoidally Varying Electric-Current Source at the Surface of a Layered Earth by Means of a Linear Digital Filter," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 (October 1976), pp 230-231; P. K. Fullagar and D. W. Oldenburg, "Inversion of Horizontal Loop Electromagnetic Frequency Soundings," *Geophysics*, Vol 49, No. 2 (February 1984), pp 150-164; W. E. Glenn and S. H. Ward, "Statistical Evaluation of Electrical Sounding Methods. Part I: Experimental Design," *Geophysics*, Vol 41, No. 6A (December 1976), pp 1207-1221; N. Harthill, "Time-Domain Electromagnetic Sounding," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 (October 1976), pp 256-260; H. O. Seigel, 1979; R. K. Verma and K. Mallick, "Detectability of Intermediate Conductive and Resistive Layers by Time-Domain Electromagnetic Sounding," *Geophysics*, Vol 44, No. 11 (November 1979), pp 1862-1878; S. H. Ward, D. F. Pridmore, L. Rijo, and W. E. Glenn, "Multispectral Electromagnetic Exploration for Sulfides," *Geophysics*, Vol 39, No. 5 (October 1974), pp 666-682; S. H. Ward, B. D. Smith, W. E. Glenn, L. Rijo, and J. R. Inman, Jr., "Statistical Evaluation of Electrical Sounding Method. Part II: Applied Electromagnetic Depth Sounding," *Geophysics*, Vol 41, No. 6A (December 1976), pp 1222-1235; S. H. Ward, "Ground Electromagnetic Methods and Base Metals," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 45-62; S. H. Ward (November 1980); M. Wilt and M. Stark, "A Simple Method for Calculating Apparent Resistivity From Electromagnetic Sounding Data," *Geophysics*, Vol 47, No. 7 (July 1982), pp 1100-1105; M. Wilt, et al. (August 1983).

Mutual Impedance Method

A small current-carrying loop of wire near the ground gives rise to several components of electric and magnetic fields at a distance along the ground. By measuring voltage proportional to the source current, the mutual impedance between the transmitting loop and receiving loop is obtained. The conductivity and permittivity of the subsurface are determined from this measurement.

The transmitting loop can be oriented with its axis vertical (called a "vertical magnetic dipole" or a "horizontal loop") or horizontal (called a "horizontal magnetic dipole" or a "vertical loop"). If a horizontal magnetic dipole is used, its axis can be pointed toward the receiver or positioned orthogonal to this direction. Three orthogonal transmitting loop orientations are thus possible, as are three orthogonal receiving coil orientations. From the nine possible combinations of transmitting and receiving loops, Figure 16 depicts the four loop configurations used most often. Table 2 lists commercially available equipment that uses these configurations. The mutual impedance method has been used in the ELF to high-frequency (HF) range for both surface and airborne measurements.

Data interpretation curves based on Sommerfield integrals have been plotted for homogeneous and vertically stratified grounds. Models include both conduction and displacement current effects. New techniques for data interpretation also have been reported.[37] For details, refer to the literature.[38]

Figure 16. Four loop-pair configurations for the mutual impedance method: (a) horizontal, (b) vertical coplanar, (c) vertical coaxial, (d) perpendicular. (Source: G. V. Keller and F. C. Frischknecht, *Electrical Methods in Geophysical Prospecting* [Pergamon, 1966]. Used with permission.)

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[37] R. K. Verma, "Detectability by Electromagnetic Sounding," *IEEE Trans. Geosci. Electron.*, Vol GE-15, No. 4 (October 1977), pp 232-251.

[38] J. T. deBettencourt, D. Davidson, and J. R. Wait; D. C. Fraser, "A New Multicoil Aerial Electromagnetic Prospecting System," *Geophysics*, Vol 37, No. 3 (June 1972), pp 518-537; D. C. Fraser, "The Multicoil II Airborne Electromagnetic System," *Geophysics*, Vol 44, No. 8 (August 1979), pp 1367-1394; G. V. Keller and F. C. Frischknecht; R. J. Lytle (July 1974); K. P. Sengpiel, "Resistivity/Depth Mapping With Airborne Electromagnetic Survey Data," *Geophysics*, Vol 48, No. 2 (February 1983), pp 181-196; K. P. Spies and J. R. Wait, "Determining Electrical Ground Constants From Mutual Impedance of Small Coplanar Loops," *IEEE Trans. Antennas Propagat.*, Vol AP-20 (1972), p 501; R. K. Verma; J. R. Wait (Ed.) (1971); J. R. Wait (1982); S. H. Ward (1979).

Table 2

Commercially Available Equipment for the Mutual Impedance Method*

Manufacturer	Model	Frequency of operation (Hz)	Coil separation (m)	Dipole Moment in amperemeters	Component Measured**	Readout Device	Range of Readings	Readability (%)	Weight (kg)	Power Source
ABEM (Sweden)	Demigun	880 & 2640	30,60,90, 150&180	50/880Hz 20/2640Hz	I/P & O/P	2 Dials	0-160%I/P ±80%O/P	±0.5	23.2	D or Ni-cad cells
Apex Parametrics (Canada)	Max Min II	222,444 888,1777 &3555	30,60,90 120,180, & 240	150/222 & 444Hz 75/888Hz 50/1777Hz	I/P & O/P	2 Dials & Tiltmeter	±100%I/P ±100%O/P	±0.5	--	3 x 6 V Cells
Geonics (Canada)	EM 17	1600	30,60,90 & 120	24/1600Hz	I/P & O/P	Meter (self-indicating)	±100%I/P	±0.5	12.61	C cells --Rx
	EM17L	817	50,100, 150 & 200	24(reduced) 48(normal)			±50%O/P	±0.25	13.4	D cells --Tx
McPhar (Canada)	VHEM	600 & 2400	30,60,90, or 40,80	60/600Hz 18/2400Hz	I/P & O/P	Dial & headset	±100%I/P ±100%O/P	±0.5	8.2	9V--Rx D cells --Tx
Scintrex (Canada)	SE-600	1600	60 or 90	27/1600Hz	I/P & O/P	Dial & headset	±100%I/P ±50%O/P	±0.5	15	6 & 13.5 V cells

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*Source: S. H. Ward, "Ground Electromagnetic Methods and Base Metals," *Geophysics and Geochemistry in the Search for Metallic Ores*, P. J. Hood (Ed.), Economic Geology Report 31 (Geological Survey of Canada, 1979), pp 45-62. Reproduced with permission of the Minister of Supply & Services Canada.

**I/P = in phase; O/P = out of phase.

Wave-Tilt Method

The tilt of an electromagnetic wave propagating along the Earth's surface is related to the electrical properties of the uppermost ground layers. The wave tilt at a particular location is defined by the ratio of horizontal and vertical fields that determines the tilt of the field loci, which are ellipses (Figure 17). For parallel or transverse magnetic (TM) polarization, the wave tilt is the ratio of electric fields ($W_e = E_h / E_v$), where E_h and E_v are the horizontal and vertical electric field components of the TM wave; for perpendicular or transverse electric (TE) polarization, it is the ratio of magnetic fields ($W_m = H_v / H_h$, where H_v and H_h are the vertical and horizontal magnetic field intensity components of the TE wave). Wave tilt is normally a complex quantity that has both amplitude and phase.

High-frequency E (>1 MHz) measurements can be made in high-conductivity regions such as the desert and permafrost areas. Low-frequency E (<1 MHz) measurements are used in regions of high conductivity.

Wave-tilt measurement techniques have been surveyed by King for both ground and airborne measurements.[39] All of these methods involve either very short electric dipoles or small loops (magnetic dipoles). In both cases, the dipoles and their associated feeders should be balanced perfectly, and the measurements should be made outside the induction region of the transmitter.

A major advantage of these methods is that the wave-tilt value does not depend on the absolute strength of the source. However, a disadvantage is that the methods may give erroneous results when local inhomogeneities are present in the ground. Additional information is available elsewhere.[40]

Transient Electromagnetic Method

This time-domain method consists of driving a current, I, into a transmitter loop and then switching it off abruptly (step function). The induced eddy currents decay with

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[39] R. J. King, "Wave Tilt Measurements," *IEEE Trans. Antennas Propagat.*, Vol AP-24 (January 1976), pp 115-119.

[40] S. A. Arcone, "Investigation of a VLF Airborne Resistivity Survey Conducted in Northern Maine," *Geophysics*, Vol 43, No. 7 (December 1978), pp 1399-1417; S. A. Arcone, "Resolution Studies in Airborne Resistivity Surveying at VLF," *Geophysics*, Vol 44, No. 5 (May 1979), pp 937-946; J. T. deBettencourt, D. Davidson, and J. R. Wait; R. J. King, "Crossed-Dipole Method of Measuring Wave Tilt," *Radio Sci.*, Vol 3 (1968), p 345; R. J. King (January 1976); R. J. Lytle (July 1974); R. J. Lytle, D. Lager, and E. Lain, "Subsurface Probing by High Frequency Measurements of the Wave Tilt of Electromagnetic Surface Waves," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 (October 1976), pp 244-249; R. P. Singh and T. Lal, "Wavetilt Characteristics of EM Waves Over a Homogeneous Earth Model," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-18, No. 4 (October 1980), pp 285-288; D. V. Thiel, K. S. Park, and R. J. King, "Wavetilt Fluctuations Near a Vertical Discontinuity in a Flat Ground Plane," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-20, No. 1 (January 1982), pp 131-134; J. R. Wait (Ed.) (1971); L. Warne, D. Evans, and C. Elachi, "Wave Tilt Sounding of a Linearly Inhomogeneous Layered Half Space," *IEEE Trans. Antennas Propagat.*, Vol AP-27, No. 3 (May 1979), pp 417-419.

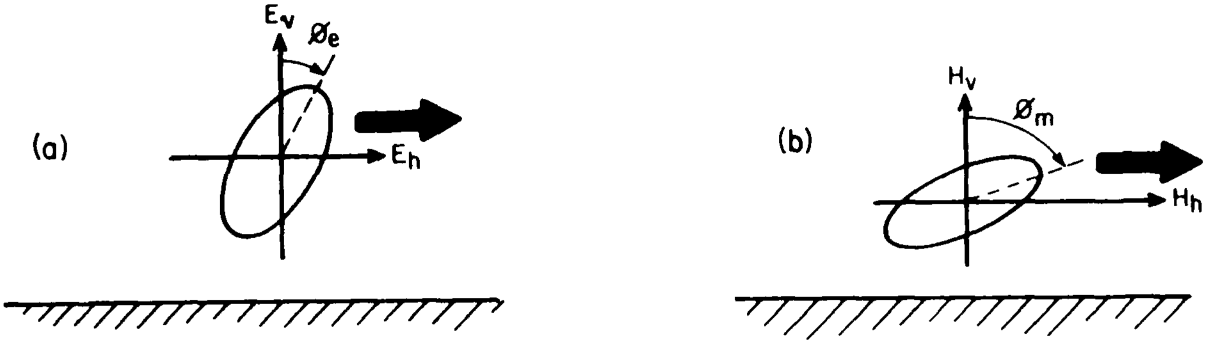

Figure 17. **Wave tilt method: geometry of the plane of incidence showing the locus of the resulting fields on the surface. (a) Incident wave is parallel polarized (TM polorization) and (b) incident wave is perpendicularly polarized (TE polarization).**

time, producing an electromotive force (emf), e(t), that can be measured in a receiver loop.* The conductivity and resistivity of the ground can then be estimated.

The transmitter is usually a horizontal rectangular loop (Figure 18) with a side dimension of hundreds or even thousands of meters. The measurements are made at a distance ranging from several hundreds to tens of kilometers from the transmitters. Results usually are presented in the form e(t)/I versus time, from which the conductivity of the subsurface is deduced. For transmitters, grounded wires also can be used (Figure 19). The length of the grounded wire transmitters is usually thousands of meters.

Disadvantages of the method are its requirements for high source power and long signal averaging times. Several other sources treat this method in greater depth.[41]

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*The expression e(t) relates to voltage as a function of time.

[41] D. D. Evans, "Mathematical Models for the Reflection Coefficients of Lossy Dielectric Half-Space With Application to Transient Response of Chirped Pulses," *IEEE Trans. Antennas Propagat.*, Vol AP-25, No. 4 (July 1977), pp 490-495; G. V. Keller and A. Rapolla, "A Comparison of Two Electrical Probing Techniques," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 (October 1976), p 250; B. R. Lienert, "Crustal Electrical Conductivities Along the Eastern Flank of the Sierra Nevadas," *Geophysics*, Vol 44, No. 11 (November 1979), pp 1830-1845; S. F. Mahmoud, A. Z. Botros, and J. R. Wait, "Transient Electromagnetic Fields at a Vertical Magnetic Dipole on a Two-Layer Earth," *Proc. IEEE*, Vol 67, No. 7 (July 1979), pp 1022-1029; A. P. Raiche and B. R. Spies, "Coincident Loop Transient Electromagnetic Master Curves for Interpretation of Two-Layered Earths," *Geophysics*, Vol 46, No. 1 (January 1981), pp 53-64; R. B. Rice, et al.; H. O. Siegel, 1979; B. R. Spies and A. P. Raiche, "Calculation of Apparent Conductivity for the Transient Electromagnetic (Coincident Loop) Method Using an HP-67 Calculator," *Geophysics*, Vol 45, No. 7 (July 1980), pp 1197-1204; J. R. Wait, L. Thrane, and R. J. King, "The Transient Electric Field Response of an Array of Parallel Wires on the Earth's Surfaces," *IEEE Trans. Antennas Propagat.*, Vol AP-23 (March 1975), pp 261-264; J. R. Wait (1982); S. H. Ward (1979).

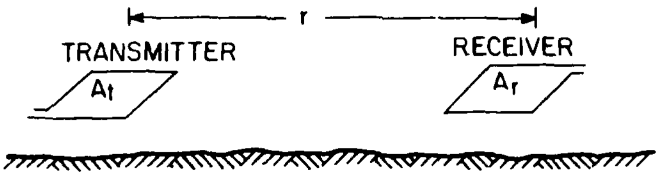

Figure 18. **Transient electromagnetic method—horizontal rectangular transmitter.** (Source: G. V. Keller and A. Rapolla, "A Comparison of Two Electrical Probing Techniques," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 [October 1976]. ©1976 IEEE. Used with permission.)

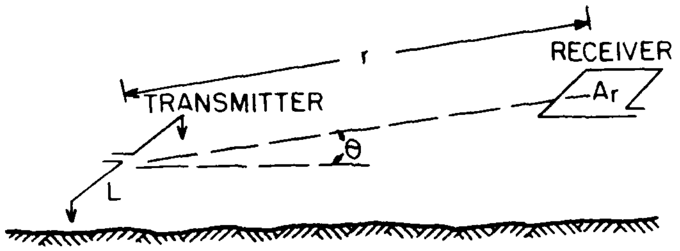

Figure 19. **Transient electromagnetic method—ground wire transmitter.** (Source: G. V. Keller and A. Rapolla, "A Comparison of Two Electrical Probing Techniques," *IEEE Trans. Geosci. Electron.*, Vol GE-14, No. 4 [October 1976]. ©1976 IEEE. Used with permission.)

Magnetotelluric Method

The magnetotelluric (MT) method uses electromagnetic principles to determine both lateral and vertical variations of the Earth's resistivity. The conductivity of the Earth can be estimated from knowledge of the resistivity. Naturally occurring magnetic and electrical fields are measured at the Earth's surface as a function of time; cryogenic and three-component magnetometers have been used recently to measure the magnetic fields. Data can be recorded at several locations simultaneously to improve the signal-to-noise ratio. In addition, an MT base station can be used with satellite telluric stations for better coverage at a reduced cost.

The frequencies used usually range from 10^{-3} to 10^{2} Hz, but for the audio-frequency MT method, frequencies in the kilohertz range are used. Because lower frequency electromagnetic fields penetrate farther into the Earth than higher frequency fields due to (the skin depth principle), the apparent resistivity curves can be viewed as an integrated resistivity versus a pseudo-depth profile of the Earth. The apparent resistivity curves are converted to true resistivity-depth curves by a number of interpretation schemes.

For a complete review of MT methods, the reader is directed to the literature.[42]

Telluric-Current Method

The telluric-current method is similar to the MT techniques except that only the horizontal electric fields can be measured simultaneously at the several locations. The advantage of this method over MT methods is that it avoids measurements of the minute magnetic field variations.

The telluric-current method can be used to study ratios of resistivities between locations, but cannot determine the absolute value of resistivity without auxiliary information.

A method that combines telluric-current and MT methods has been reported.[43] The method uses MT measurements at the base site, but only telluric measurements at remote sites. It thus combines the economy, simplicity, and speed of the telluric method with the quantitative advantages of the MT measurement. Details are contained in other published works.[44]

Input Impedance Methods

The input impedance of an antenna close to the Earth is sensitive to the electrical parameters of the ground. Horizontal linear antennas of nearly resonant length and within one-tenth wavelength of the ground have been shown to be effective for

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[42] F. Abramovici, "The Forward Magnetotelluric Problem for an Inhomogeneous and Anisotropic Structure," *Geophysics*, Vol 39, No. 1 (February 1974), pp 56-68; J. T. deBettencourt, D. Davidson, and J. R. Wait; V. Dmitriev and M. Berdichevsky," The Fundamental Model of Magnetotelluric Sounding," *Proc. IEEE*, Vol 67, No. 7 (July 1979), pp 1034-1044; T. D. Gamble, W. M. Goubau, and J. Clarke, "Magnetotellurics With a Remote Magnetic Reference," *Geophysics*, Vol 44, No. 1 (January 1979), pp 53-68; M.A. Goldstein and D.W. Strangway, "Audio-Frequency Magnetotellurics With a Grounded Electric Dipole Source," *Geophysics*, Vol 40, No. 4 (August 1975), pp 669-683; W. M. Goubau, T. D. Gamble, and J. Clarke, "Magnetotelluric Data Analysis: Removal of Bias," *Geophysics*, Vol 43, No. 6 (October 1978), pp 1157-1166; W. M. Goubau, P. M. Maxton, R. H. Koch, and J. Clarke, "Noise Correlation Lengths in Remote Reference Magnetotellurics," *Geopyhics*, Vol 49, No. 4 (April 1984), pp 433-438; G. V. Keller and F. C. Frischknecht; D. Loewenthal, "On the Phase Constraint of the Magnetotelluric Impedance," *Geophysics*, Vol 40, No. 2 (April 1975), pp 325-330; T. R. Madden; D. Patella, "Interpretation of Magnetotelluric Resistivity and Phase Soundings Over Horizontal Layers," *Geophysics*, Vol 41, No. 1 (February 1976), pp 96-105; D. Rankin and F. Pascal, "A Practical Method for the Inversion of Magnetotelluric Data for a Layered Earth," *Geophysics*, Vol 48, No. 6 (June 1983), pp 736-744; I. K. Reddy and D. Rankin, "Coherent Function for Magnetotelluric Analysis," *Geophysics*, Vol 39, No. 3 (June 1974), pp 312-320; R. B. Rice, et al.; J. R. Wait, *Wave Propagation Theory* (Pergamon, 1981); J. R. Wait (1982); S. H. Ward (November 1980).

[43] M. A. Goldstein and D. W. Strangway.

[44] J. T. deBettencourt, D. Davidson, and J. R. Wait; M.A. Goldstein and D. W. Strangway; J. F. Hermance and R. E. Thayer, "The Telluric-Magnetotelluric Method," *Geophysics*, Vol 40, No. 4 (August 1975), pp 664-668; G. V. Keller and F. C. Frischknecht.

determining the ground's conductivity and permittivity. However, it is advisable to perform measurements at several different frequencies or antenna lengths.

A recently developed technique uses a single superconducting coil. This airborne method can be used over the frequency range 10 to 2000 Hz. Changes in the transmitter input impedance are measured to provide maps of absolute ground conductivity.[45] See the literature for more details.[46]

Power Reflectivity Method

This method uses a transmitter and receiver located a substantial distance above the Earth--usually aboard an airplane. The transmitter is oriented toward the Earth and radiates plane waves (Figure 20). The receiver measures the reflected power or reflection coefficient phase and amplitude from the return signal, allowing the ground permittivity and conductivity to be determined. Time-of-arrival measurements are helpful in determining the thickness of the upper layer since time of arrival is effected by reflected signals at the earth-to-bedrock interface.

This method effectively averages the dielectric constant over a large area in only a short period of time, but for a small depth below the surface. Thus, surface roughness

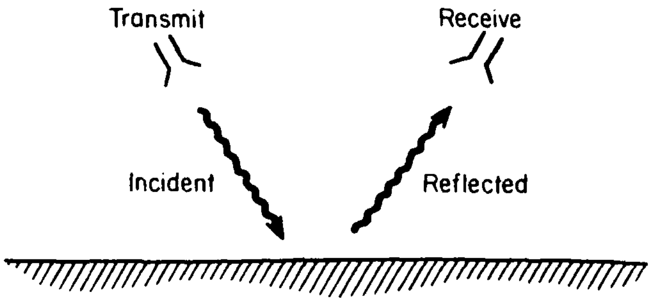

Figure 20. Power reflectivity method--ground reflection. (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

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[45] H. F. Morrison, W. Dolan, and A. Dey, "Earth Conductivity Determination Employing a Single Superconducting Coil," *Geophysics*, Vol 41, No. 6A (December 1976), pp 1184-1206.

[46] J. T. deBettencourt, D. Davidson, and J. R. Wait; R. J. Lytle (July 1974); H. F. Morrison, W. Dolan, and A. Dey.

can invalidate the results. Other considerations for this method are reviewed in several publications.[47]

Radiofrequency Interferometry Method

In this method, a transmitter and receiver are placed on the ground and separated continuously to record the standing-wave pattern resulting from interference between air- and ground-wave modes or between two or more ground-wave modes. Figure 21 shows four possible wave modes between the transmitter and receiver. In the figure, wavefronts A and B represent spherical waves propagating in air and ground, respectively. Wavefronts C and D are associated wavefronts that propagate in air and ground, respectively, to maintain continuity of the electric and magnetic fields of waves A and B across the air-ground interface. Wave C is an inhomogeneous wave that attenuates exponentially with height and propagates with the same horizontal phase velocity as B. The radiofrequency interferometry method uses the interference between C and A to compute the dielectric constant of the subsurface.

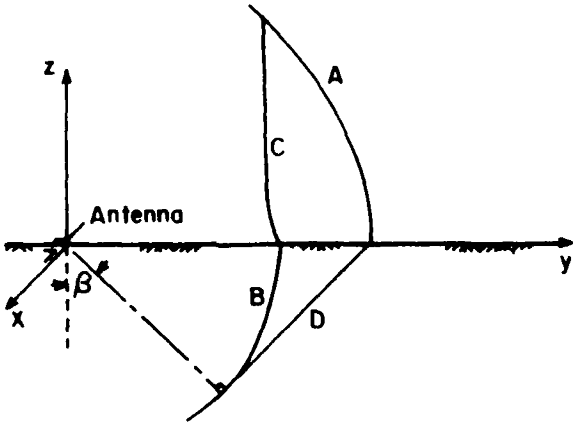

Figure 21. Radiofrequency interferometry method—radiation modes produced by a horizontal electric dipole on the ground surface. (Source: S. A. Arcone and A. J. Delaney, "Electrical Properties of Frozen Ground at VHF Near Point Barrow, Alaska," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-20, No. 4 [October 1982]. ©1982 IEEE. Used with permission.)

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[47] J. C. Bolomey, D. Lesselier, C. Pichot, and W. Tabbara, "Spectral and Time-Domain Approaches to Some Inverse Scattering Problems," *IEEE Trans. Antennas Propagat.*, Vol AP-29, No. 2 (March 1981), pp 206-212; J. C. Bolomey, D. Lesselier, and G. Peronnet, "Practical Problems in the Time-Domain Probing of Lossy Dielectric Media," *IEEE Trans. Antennas Propagat.*, Vol AP-30, No. 5 (September 1982), pp 993-998; S. Coen, K. K. Mei, and D. J. Angelakos, "Inverse Scattering Technique Applied to Remote Sensing of Layered Media," *IEEE Trans. Antennas Propagat*, Vol AP-29, No. 2 (March 1981), pp 298-306; S. Coen, "Inverse Scattering of a Layered and Dispersionless Dielectric Half-Space, Part I: Reflection Data From Plane Waves at Normal Incidence," *IEEE Trans. Antennas Propagat.*, Vol AP-29, No. 5 (September 1981), pp 726-732; D. D. Evans; R. J. Lytle (July 1974); J. R. Wait (1971); S. H. Ward, "Gross Estimates of the Conductivity, Dielectric Constant and Magnetic Permeability Distributions in the Moon," *Radio Sci.*, Vol 4 (1969), p 117.

The antennas used are electric dipoles placed on the ground in parallel. The electromagnetic field component of interest is the horizontal electric field E_x in the broadside direction. By measuring the field strength of E_x, the separation between interference minima of wavefronts A and C is determined. The dielectric constant and loss tangent are determined by trial-and-error modeling.[48]

This method has been used to measure the complex dielectric properties for the first few meters of permafrost in various soil types at frequencies between 30 and 300 MHz.[49] For other applications, consult the literature.[50]

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[48] S. A. Arcone and A. J. Delaney, "Electrical Properties of Frozen Ground at VHF Near Point Barrow, Alaska," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-20, No. 4 (October 1982), pp 485-492.

[49] S. A. Arcone and A. J. Delaney.

[50] A. P. Annan, "Radio Interferometry Depth Sounding: Part I--Theoretical Discussion," *Geophysics*, Vol 38, No. 3 (1973), pp 557-580; S. A. Arcone and A. J. Delaney; A. W. Biggs, "Terrain Influences on Effective Ground Conductivity," *IEEE Trans. Geosci. Electron.*, Vol GE-8 (1970), p 106; D. Cheng, J. A. Kong, and L. Tsang, "Geophysical Subsurface Probing of a Two-Layered Uniaxial Medium With a Horizontal Magnetic Dipole," *IEEE Trans. Antennas Propagat.*, Vol AP-25, No. 6 (November 1977), pp 766-769; J. T. deBettencourt, D. Davidson, and J. R. Wait; M. A. H. El-Said, "A New Method for the Measurement of the Average Dielectric Constant of the Underground Medium on Site," *IEEE Trans. Antennas Propagat.*, Vol AP-4 (1956), p 601; G. V. Keller and F. C. Frischknecht; J. A. Kong, L. Tsang, and G. Simmons, "Geophysical Subsurface Probing With Radio-Frequency Interferometry," *IEEE Trans. Antennas Propagat.*, Vol AP-22 (July 1974), pp 616-620; R. J. Lytle (July 1974); S. F. Mahmoud, E. A. Ibrahim, and M. A. H. El-Said, "On the Electromagnetic Interference Fringes Method in Geophysical Prospecting Applications," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-20, No. 2 (April 1982), pp 180-188; S. W. Maley, "A Method for the Measurement of the Parameters of a Two-Layer Stratified Earth," *IEEE Trans. Antennas Propagat.*, Vol AP-11 (1963), p 366; J. R. Rossiter, et al., "Radio Interferometry Depth Sounding: Part II--Experimental Results," *Geophysics*, Vol 38, No. 3 (1973), pp 581-599; J. R. Rossiter, et al., "Electromagnetic Sounding of Permafrost, N.W.T., Canada, in Summer and Winter," *Proc. Third International Conference on Permafrost* (National Research Council of Canada, 1978); J. R. Wait and L. C. Walters, "Curves for Ground Wave Propagation Over Mixed Land and Sea Paths," *IEEE Trans. Antennas Propagat.*, Vol AP-11 (1963), p 38; J. R. Wait (Ed.) (1971).

5 IN SITU DRILL-HOLE MEASUREMENTS

The methods reviewed in Chapters 3 and 4 measure electrical properties using antennas on the Earth's surface. If a site has existing drill holes (e.g., remaining from previous work), the antennas or conductors can be used inside these holes to deduce the electrical parameters and their variations with depth. The technology for measurement from a borehole is well advanced, due in part to legislation that requires each drilled oil well to have its electrical parameters measured and logged for the entire drill depth. Because of the large number of oil wells drilled, the petroleum industry has been seeking to develop accurate, low-cost measurement techniques.[51]

Typical drill holes are on the order of 7-3/4 to 15-3/4 in. in diameter and are filled with a corrosive drilling fluid. Depths can reach 33,000 ft through the layered earth. Typical bed thicknesses are on the order of 3 to 9 ft or more. The drilling fluid invades permeable formations, creating a flushed or invaded zone near the drill hole. Farther out from the drill hole, these formations are not affected by the drilling process. The electrical parameters of this uninvaded zone are of major concern for EMI/EMP analyses.

Resistivity Methods

The resistivity method is applicable for drill holes as well as for surface measurements. Potential theory can be used to determine the mutual impedance between current and potential probes. The mutual impedance depends on geometric factors and the ground conductivity.

Field transmitters (current) and receivers (voltage difference) can consist of simple d.c. devices manufactured commercially for conventional surface resistivity measurements. Lead or copper wire wrapped around an insulating cable is used for the downhole electrodes with these systems.

A variety of resistivity methods has been developed and tested for drill-hole applications. These methods can be classified based on the probes' mode of deployment with respect to the borehole (e.g., single-hole, hole-to-surface, hole-to-hole).

Single-hole resistivity systems (Figure 22) use a downhole current source located at a fixed distance from the downhole potential probes. The spacing between the downhole current and potential probes can be varied to provide variable-penetration profiles away from the drill hole; however, single-hole methods usually provide only a limited depth of investigation into the rock medium surrounding the hole.

Figure 23 shows an optimal source and receiver configuration for the hole-to-surface and surface-to-hole (Figure 24) methods. It consists of a pole in-hole current source and a surface dipole-potential receiver. The dipole measurement is approximately equal to the electric field component parallel to the direction of the dipole receiver. If the resistivity distribution within the surrounding earth is laterally homogeneous, then the only nonzero electric field component is directed radially away from the drill hole. However, when lateral inhomogeneities are present in the geoelectrical section, two

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[51] F. F. Segesman.

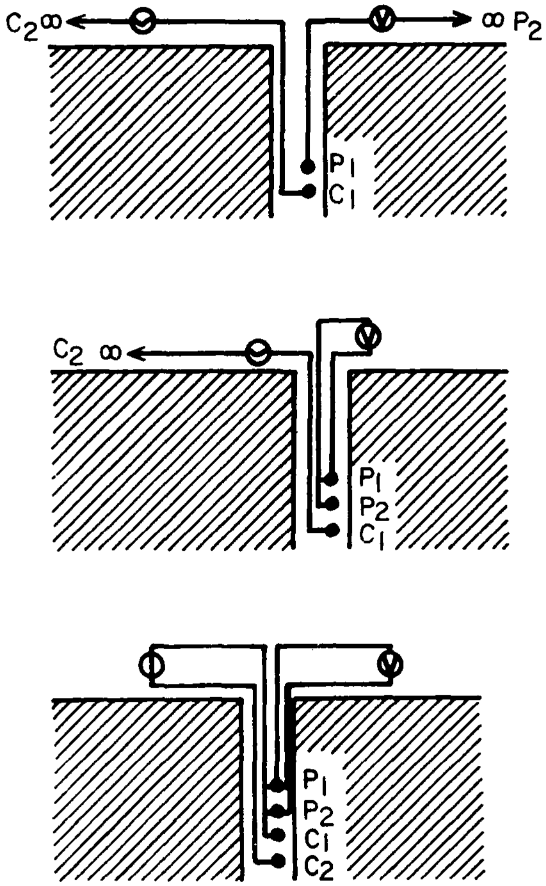

Figure 22. Single-hole resistivity methods: (a) pole-pole, or normal array, (b) pole-dipole, or lateral array, and (c) Wenner array. (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.)

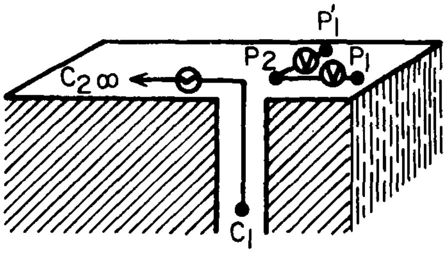

Figure 23. Hole-to-surface resistivity method--pole source and two-component dipole receiver. (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.)

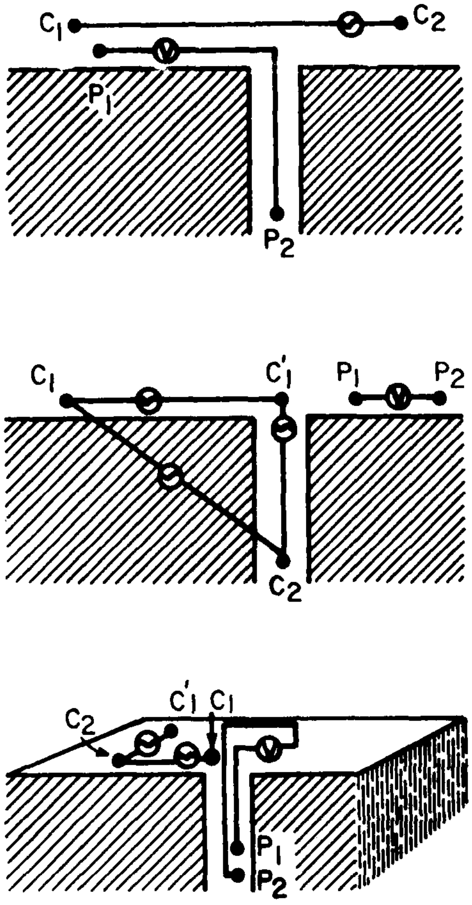

Figure 24. Surface-to-hole resistivity methods: (a) directional array, (b) downhole-radial array, and (c) two-component sonde, dipole receiver. (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.)

orthogonal components of the electrical field must be measured in order to define the electric field distribution.[52]

Hole-to-hole methods (Figure 25) provide the best resolution of all resistivity methods for obtaining electrical parameters of the earth medium between drill holes. In this method, current is injected at two separate points in one borehole and the resulting voltage is measured at two separate points in the other borehole. From these measured values, the resistivity is calculated.

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[52] J. J. Daniels and A. V. Dyck.

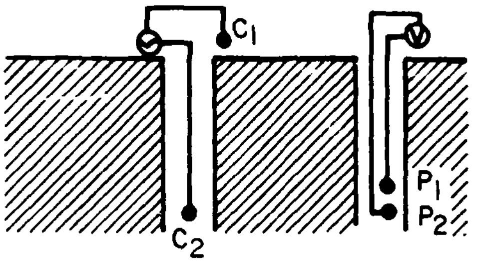

Figure 25. **Hole-to-hole resistivity methods—bipole source and dipole receiver.** (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.).

The layered earth models have been used as a fundamental interpretation aid for the resistivity methods. The models include a three-layered and n-layered earth for a buried current source and a buried/surface receiver. Numerical models of three-dimensional surface topography for buried electrodes also have been developed.[53] Additional information on resistivity methods is available elsewhere.[54]

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[53] J. J. Daniels and A. V. Dyck.

[54] L. Alfano, "Geoelectric Prospecting With Underground Electrodes," *Geophys. Prospecting*, Vol 10 (1962), pp 290-303; J. J. Daniels, "Three-Dimensional Resistivity and Induced Polarization Modeling Using Buried Electrodes," *Geophysics*, Vol 42, No. 5 (1977), pp 1006-1019; J. J. Daniels, "Interpretation of Buried Electrode Resistivity Data Using a Layered Earth Model," *Geophysics*, Vol 43, No. 5 (August 1978), pp 988-1001; J. J. Daniels, "Hole-to-Surface Resistivity Measurements," *Geophysics*, Vol 48, No. 1 (January 1983), pp 87-97; J. J. Daniels and A. V. Dyck; S. Gianzero and B. Anderson, "An Integral Transform Solution to the Fundamental Problem in Resistivity Logging," *Geophysics*, Vol 47, No. 6 (June 1982), pp 946-956; G. V. Keller and F. C. Frischknecht; R. J. Lytle (August 1973); R. J. Lytle, et al., *The Lisbourne Experiments: HF Propagation Through Permafrost Rock*, Report UCRL-51474 (Lawrence Livermore Laboratory, 1973); R. J. Lytle (July 1974); R. J. Lytle, "Resistivity and Induced-Polarization Probing in the Vicinity of a Spherical Anomaly," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-20, No. 4 (October 1982), pp 493-499; R. J. Lytle and J. M. Hanson, "Electrode Configuration Influence on Resistivity Measurements About a Spherical Anomaly," *Geophysics*, Vol 48, No. 8 (August 1983), pp 1113-1119; R. H. Merkel and S. S. Alexander, "Resistivity Analysis for Models of a Sphere in a Half-Space With Buried Current Sources," *Geophys. Prospecting*, Vol 19 (1971), pp 640-651; *Log Interpretation: Vol I—Principles* (Schlumberger Ltd., 1972); *Log Interpretation: Vol II—Applications* (Schlumberger Ltd., 1974); D. D. Snyder and R. M. Merkel, "Analytic Models for the Interpretation of Electrical Surveys Using Buried-Current Electrodes," *Geophysics*, Vol 38 (1973), pp 513-529; J. R. Wait (Ed.) (1971); W. J. Whan and J. J. Daniels, "Numerical Modeling of Three-Dimensional Surface Topography for Buried Electrode Resistivity Surveys," presented at the 52nd Annual Meeting of the Society of Exploration Geophysicists, Dallas, TX (October 1982); G. J. Zhang and L. C. Shen, "Response of a Normal Resistivity Tool in a Borehole Crossing a Bed Boundary," *Geophysics*, Vol 49, No. 2 (February 1984), pp 142-149.

Surface-to-Hole Electromagnetic Methods

The surface-to-hole electromagnetic method uses a transmitter on the surface and a receiver in a drill hole. A set of downhole measurements of the magnetic field resulting from a surface loop source provides data for deducing the conductivity and dielectric constant spatial variation over a large area around the hole. A commonly used source is a large transmitter of variable orientation.

Figure 26 shows a large transmitter loop. For time-domain measurements, the transmitter generates a repetitive step or triangular current waveforms. The induced eddy current caused by the source sets up a secondary magnetic field which is then measured with a mobile receiver coil as a function of time. For frequency-domain measurements, the transmitter generates a primary field at one or more frequencies. The receiver, a sensitive phase-locked amplifier, is driven by a coil that supplies reference amplitude and phase information to the receiver. The amplitude of the in-phase component of the total, primary, and secondary fields, normalized to the reference field strength, and the phase difference between the total field and the reference field are measured with the system. Thus, the field attenuation and phase shift between the transmitter and receiver are obtained to deduce the conductivity and dielectric constant of the earth medium. As an example of time-domain measurements, an 800 by 400 m transmitting loop has been used to investigate subsurface depths of several hundred meters using the source current range 50 to 100 A.[55]

Figure 27 shows a surface dipole transmitter configuration. The horizontal loop encircling the drill hole is excited by an a.c., and an alternating magnetic field is established in the ground. Components of the magnetic field are then measured within the hole to obtain the electrical parameters of the earth medium around the hole. The transmitter placed on one side of the hole's collar also can be used.

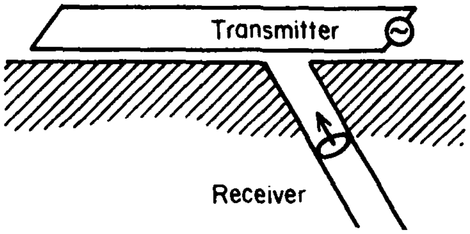

Figure 26. Surface-to-hole electromagnetic system—large-loop surface transmitter. (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.)

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[55] J. J. Daniels and A. V. Dyck.

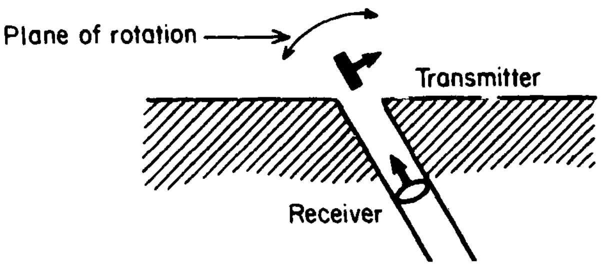

Figure 27. **Surface-to-hole electromagnetic system—small-loop surface transmitter.** (Source: J. J. Daniels and A. V. Dyck, "Borehole Resistivity and Electromagnetic Methods Applied to Mineral Exploration," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 [January 1984]. ©1984 IEEE. Used with permission.)

Several publications provide details on surface-to-hole electromagnetic measurement methods.[56]

Multiple Borehole Electromagnetic Methods

In the case of underground facilities, a unique situation usually exists for measuring the properties of the rock and soil above the volume that has been excavated. Boreholes often are required to provide a way to route electric wiring, antenna cables, and control cables; they also may be needed to provide ventilation for bringing in air or for passing engine exhaust from the facility to the outside environment.

The boreholes may or may not have metallic liners. In either case, the holes provide a means for establishing a parallel conductor transmission line from the aboveground area all the way into the facility. If metallic liners are used in the boreholes, the

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[56] C. T. Barnett, M. J. Davidson, G. H. McLaughlin, and M. N. Nabighian, "Exploration With the Newmont EMP System," *Geophys. Prospecting*, Vol 26 (1978), p 686; J. J. Daniels and A. V. Dyck; J. T. deBettencourt, D. Davidson, and J. R. Wait; "The Structure and Physical Properties of the Earth's Crust," *Geophysics Monograph*, Vol 14, J. G. Heacock (Ed.) (Am. Geophys. Union, 1971); G. W. Hohmann, G. D. van Voorhis, and P. H. Nelson, "A Vector EM System and Its Field Application," *Geophysics*, Vol 43, No. 7 (1978), pp 1418-1440; J. E. Noakes, *An Electromagnetic Method of Geophysical Prospecting for Application to Drill Holes*, Ph.D. Dissertation (University of Toronto, 1951); M. L. Oristaglio and M. H. Worthington, "Inversion of Surface and Borehole Electromagnetic Data for Two-Dimensional Electrical Conductivity Models," *Geophysics. Prospecting*, Vol 28 (1980), pp 633-657; D. J. Salt, "Tests of Drill-Hole Methods of Geophysical Prospecting on the Property of Lake Dufault Mines Limited, Duffresony Township, Quebec," *Mining Geophys.*, Vol 1 (1966); J. R. Wait, *Electromagnetic Waves in Stratified Media*, 2nd ed. (Pergamon, 1970); J. R. Wait (Ed.) (1971); S. H. Ward and H. A. Harvey, "Electromagnetic Surveying of Diamond Drill Holes," *Canadian Mining Manual* (National Business Publications, 1954), pp 19-30; M. H. Worthington, A. Kuckes, and M. Oristaglio, "A Borehole Induction Procedure for Investigating Electrical Conductivity Structure Within the Broad Vicinity of a Hole," *Geophysics*, Vol 46, No. 1 (January 1981), pp 65-67.

liners themselves can be used as the transmission line conductors. If no liners are used, electrical conductors can be temporarily routed through the boreholes for testing, or other in-place conductors can be used.

Several techniques can be used to measure the parallel transmission line electrical parameters and, from these measurements, estimate with relative accuracy the average resistivity and permittivity of the soil and rock overburden. However, the measurement is complicated by several factors. Ideally the transmission line conductors (liners) would be in close contact with the borehole walls for the entire length of the holes. In practice, this arrangement is difficult to achieve because of the clearance required for inserting the liners into the borehole.

In past experience with these measurements, the degree of liner contact with the borehole walls is an unknown. Some soil, debris, and water usually flow between the liner and borehole wall causing a buildup of deposits spaced somewhat randomly. The electrical parameters and size of these deposits are not known, and thus, their effect on the transmission line characteristics' measurement is a loss of accuracy.

If insulated conductors (such as wires) within the boreholes are used as the transmission line conductors, the equivalent circuit of the transmission line will contain an extra capacitance due to that existing between the conductor and the borehole walls. This capacitance depends on the system geometry, frequency, wire insulation permittivity, and possibly metal conductivity. This capacitance term must be taken into account when calculating resistivity and permittivity of the overburden.

Another complicating factor is the degree of homogeneity of the overburden. Normally, the soil on top will have much lower resistivity than the underlying rock. Further, there may be layers of water-bearing strata, and the water can have varying levels of salt or mineral content that produce significant localized differences in the resistivity and permittivity. If the strata parameters vary greatly between adjacent layers, the propagation of electromagnetic energy through the strata will be influenced significantly at the boundaries between high- and low-resistivity volumes. Usually, the transmission line parameters are measured assuming homogeneous media in the strata. This assumption generally results in a conservative estimate of the electromagnetic shielding obtainable because the reflections are not considered. If, however, a highly conductive vein is present and its extremities are close to the excavated underground cavity, this vein may act as a conducting and reradiating element, resulting in transmission line measurements that yield overly optimistic electromagnetic shielding predictions.

Another factor to consider is the discontinuities in media at the upper and lower ends of the transmission line. Typically, transmission line measurements are simple only if the media between and well beyond the ends of the transmission line are homogeneous. In the approach described here, boundary reflections must be taken into account if accurate parameter estimates are to be obtained.[57]

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[57] R. A. Falls, A. A. Cuneo, and H. F. Knauf, *Electromagnetic Soil Properties in the VHF/UHF Range*, USAMERDC-2030 (Army Mobility Equipment Research and Development Center, May 1972).

Open-Circuit Impedance Method

A technique for determining the overburden parameters when there is no access to the underground cavity involves measurement of the transmission line open-circuited input impedance. Measurements are taken with conductors inserted into the boreholes as shown in Figure 28. Two different conductor lengths are used, usually with the second length being twice that used in the first measurement. From the measured data, the characteristic impedance and propagation constant can be derived. By taking these measurements at varying frequencies, the values for attenuation and phase constants can be obtained and used further to deduce values for the conductivity and permittivity of the medium.[58]

Open-Circuit/Short-Circuit Impedance Method

When the load end of the transmission line is accessible (as with underground facilities in an excavated volume), the input impedance is measured with the source end both open- and short-circuited (Figure 29). From these values, the attenuation and phase factors can be determined and related to resistivity and permittivity.

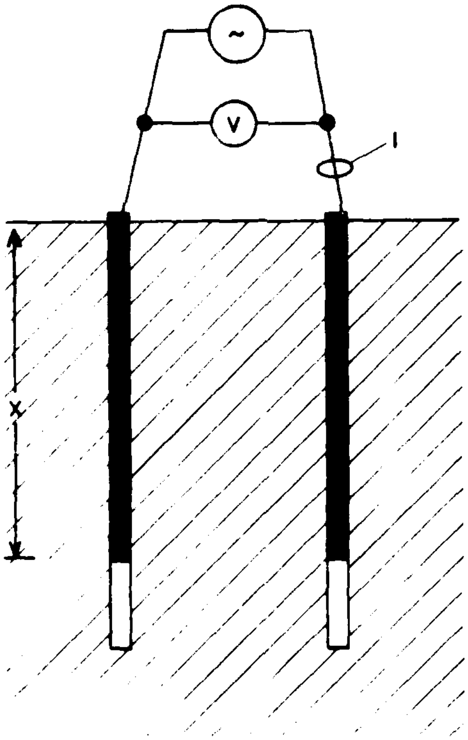

Figure 28. Open-circuit measurement method. (Source: [S] H. A. Roberts, T. J. Bock, and J. E. B. Tuttle, *Mesurements of Electrical Properties of Raven Rock Mountain*, HDL-TR-2015 [U] [U.S. Army Research and Development Command, Harry Diamond Labs, October 1983].)

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[58] E. J. Kirscether, "Ground Constant Measurements Using a Section of Balanced Two-Wire Transmission Line," *IEEE Trans. Antennas Propagat.*, Vol AP-8 (1960), p 307.

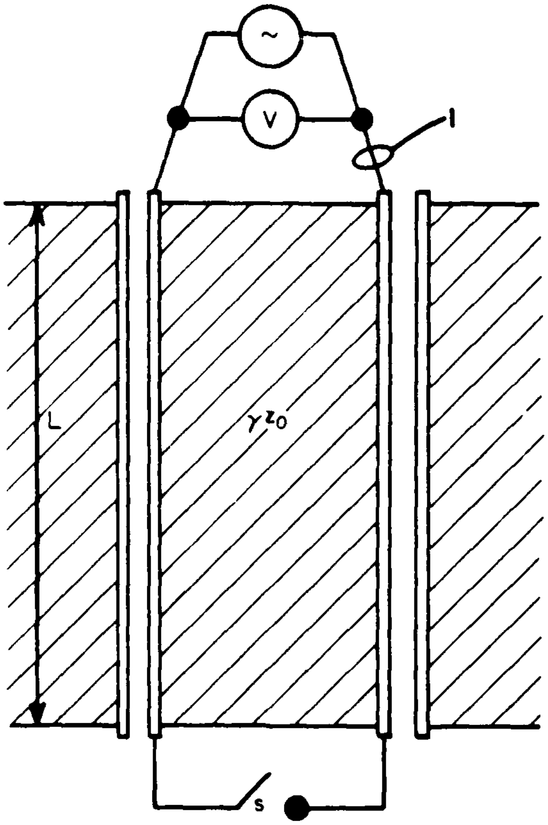

Figure 29. **Open-circuit impedance measurements for determining line constants.** (Source: [S] H. A. Roberts, T. J. Bock, and J. E. B. Tuttle, *Mesurements of Electrical Properties of Raven Rock Mountain*, HDL-TR-2015 [U] [U.S. Army Research and Development Command, Harry Diamond Labs, October 1983].)

Attenuation Method

When the load end of the transmission line is accessible, an attenuation method also can be used to determine the line and media parameters. In this method, the transmission line is short-circuited; the short-circuit current in the termination and the line input current are measured in a frequency range at which the wavelength is greater than a skin depth. (Skin depth defines a phenomenon in which current flows on a surface because of the fields present. The depth of penetration is defined by $\gamma = \frac{2}{\omega\mu\sigma}$, where $\omega = 2\pi$ [frequency], μ = magnetic permeability, and σ = conductivity.) From these data, the attenuation constant can be calculated directly and related to resistivity and permittivity.[59]

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[59] (S) H. A. Roberts, T. J. Bock, and J. E. B. Tuttle, *Measurements of Electrical Properties of Raven Rock Mountain*, HDL-TR-2015 (U) (U.S. Army Research and Development Command, Harry Diamond Labs, October 1983).

Hole-to-Surface Electromagnetic Methods

This method uses a transmitter in a drill hole and a receiver on the surface (Figure 30). The field attenuation and phase shift between the transmitter and receiver are measured, from which the conductivity and dielectric constant of the ground are deduced.

Known values for the geometry of the situation, the pattern and impedances of the transmitter and receiver, and the input power level are used to estimate the electrical parameters for the medium through which the signal is passed. Subsurface anomalies, particularly near the surface, have a decided effect on the data quality.[60]

Consult the literature for more information on hole-to-surface electromagnetic methods.[61]

Cross-Borehole Electromagnetic Methods

The conductivity and dielectric constant of earth medium can be determined using two or three drill holes. With two drill holes, a transmitter is placed in one drill hole with a receiver in a second hole; when three drill holes are used, the first two holes have the same conditions as for the two-hole method, plus a second receiver is placed in the third drill hole.

For the two-hole situation (Figure 31), the absolute attenuation and phase shift for continuous wave signals, or the arrival times for pulse signals, are measured. For the three-hole method (Figure 32), the differential phase shift and differential attenuation between two receivers are measured. When the subsurface region of interest is

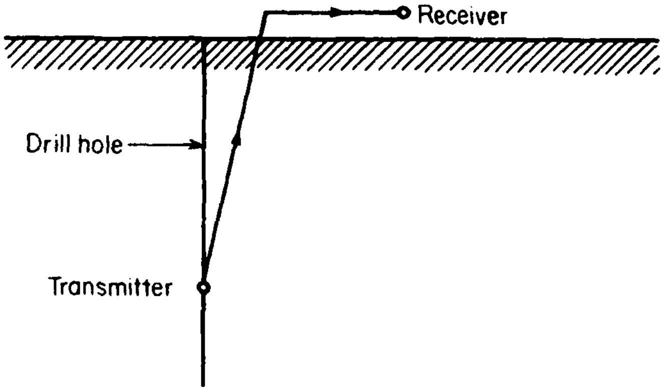

Figure 30. Hole to surface electromagnetic system. (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

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[60] R. J. Lytle (July 1974).

[61] R. N. Grubb and J. R. Wait, "In Situ Measurements on the Complex Propagation Constant in Rocks for Frequencies From 1 to 10 MHz," *Electron Lett.*, Vol 7 (1971), p 506; G. W. Hohmann, G. D. van Voorhis, and P. H. Nelson; R. J. Lytle (July 1974).

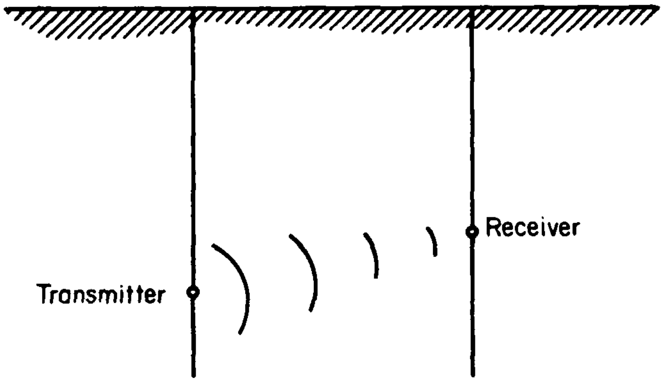

Figure 31. **Cross-borehole electromagnetic method: two-hole situation.** (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

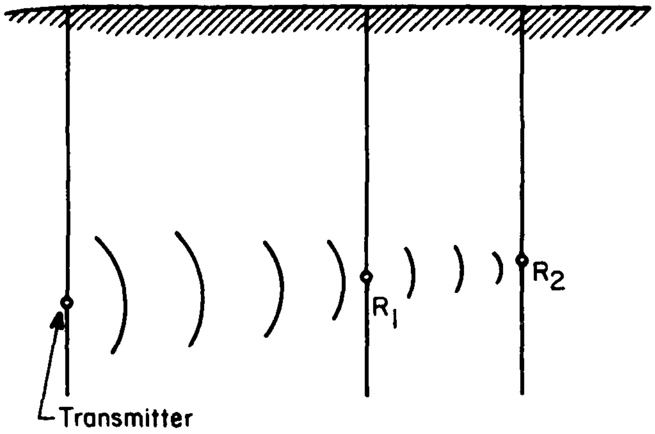

Figure 32. **Cross-borehole electromagnetic method: three-hole situation.** (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

homogeneous enough, is not very lossy, and has a small electrical contrast between the surrounding medium and the anomalous structure, the dominant physical mechanism of propagation from the transmitter and receiver through the medium is described adequately by straight-line ray optics. Then the electrical parameters of the subsurface medium are calculated directly from the measurements.

However, when there is a large electrical contrast between the drill holes, propagation of the signals may not always be governed by straight-line ray optics. Possible modes of propagation include direct, reflected, up-over-down, and subsurface reflected paths (Figure 33). Depending on the relative level of the different modes,

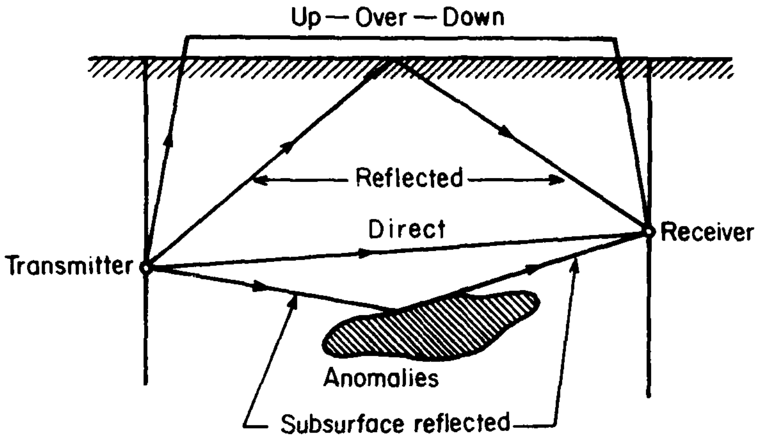

Figure 33. **Cross-borehole electromagnetic method: interference modes.** (Source: R. J. Lytle, "Measurement of Earth Medium Electrical Characteristics: Techniques, Results, and Application," *IEEE Trans. Geosci. Electron.*, Vol GE-12, No. 3 [July 1974]. ©1974 IEEE. Used with permission.)

various interference phenomena are feasible. If only two modes are competitive (e.g., the direct and reflected modes), then ray optic procedures can be used with the differential path differences to predict the notching (in-phase and out-of-phase) behavior of the received signal with frequency variation. For pulse excitation, time of arrival can be used to separate the various modes and their attenuation.[62]

Hole separations should be greater than a wavelength and less than many skin depths. Depending on hole separations, frequencies used range from 10^2 to 10^7 Hz. For example, transmitting frequencies of about 10^7 Hz have been used for hole separations of a few tens of meters.[63] Vertical linear and vertical dipole antennas served as transmitters.

A major advantage of this method is that the measurements can be made over a wide range of frequencies. This method also is useful in areas where complex geology may render other measurement methods such as the surface resistivity technique grossly ineffective in evaluating underground electrical properties.

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[62] R. J. Lytle (July 1974).

[63] R. J. Lytle, E. F. Laine, D. L. Lager, and D. T. Davis, "Cross-Borehole Electromagnetic Probing to Locate High-Contrast Anomalies," *Geophysics*, Vol 44, No. 10 (October 1971), pp 1667-1676.

Cross-borehole electromagnetic methods are described in detail elsewhere.[64]

Induction Log Method

Induction logging makes use of several transmitting and receiving coils wound on an insulating mandrel. The coils are arranged to be coaxial along the structure for lowering into a drill hole as a probe (Figure 34). The transmitter coils are energized by a constant-amplitude fixed-frequency current. The frequency typically is chosen in the kilohertz range since the losses due to skin effect are minimal, thereby ensuring appreciable penetration of the signal into the formation. The oscillating magnetic field produced results in the induction of Foucault (or eddy) currents in the earth formation. The eddy currents are nearly proportional to the apparent conductivity of the formation. These currents, in turn, contribute to the voltage induced in the receiver coils. By selecting only the voltage component that is in phase with the transmitter current, a signal is obtained which is approximately proportional to the formation conductivity, and the conductivity and relative dielectric constant can be determined.

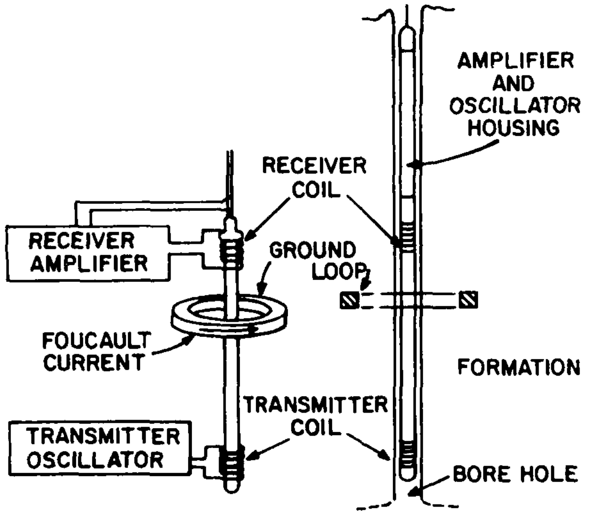

Figure 34. Induction log method. (Source: *Log Interpretation: Volume I—Principles* [Schlumberger, Ltd., 1972]. Used with permission.)

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[64] J. Carolan, Jr., and J. T. deBettencourt, "Radio Waves in Rock Near Overburden-Rock Interference," *IEEE Trans. Antennas Propagat.*, Vol AP-11 (1963), p 336; J. T. deBettencourt, D. Davidson, and J. R. Wait; D. L. Lager and R. J. Lytle, "Determining a Substance Electromagnetic Profile From High Frequency Measurements by Applying Reconstruction Technique Algorithms," *Radio Sci.*, Vol 12, No. 2 (March-April 1977), pp 249-260; R. J. Lytle (August 1973); R. J. Lytle (1973); R. J. Lytle (July 1974); R. J. Lytle, E. F. Laine, D. L. Lager, and D. T. Davis; R. D. Radcliff and C. A. Balanis, "Electromagnetic Geophysical Imaging Incorporating Refraction and Reflection," *IEEE Trans. Antennas Propagat.*, Vol AP-29, No. 2 (March 1981), pp 288-292; C. K. H. Tsao and J. T. deBettencourt, "Measurement of the Phase Constant for Rock-Propagated Radio Signals," *IEEE Trans. Commun. Technol.*, Vol COM-15 (1967), p 592; C. K. H. Tsao and J. T. deBettencourt, "Subsurface Radio Propagation Experiments," *Radio Sci.*, Vol 3 (1968), p 1039; J. R. Wait and J. A. Fuller, "On Radio Propagation Through Earth," *IEEE Antennas Propagat.*, Vol AP-19 (1971), p 796.

The induction log method is useful for measuring high conductivity (e.g., $\sigma > 2 \times 10$ S/m), although it also can provide measurements at reduced accuracy for conductivities of 5×10 S/m or lower. This method has an advantage in that no electrical contact with the wall of the drill hole is needed. Thus, the method can be used in drill holes filled with air, gas, oil-based muds, or water-based muds. A more complete discussion of this technique's advantages and drawbacks can be found in the literature.[65]

Electromagnetic Propagation Tool Method

The dielectric constant and conductivity of earth can be determined by using the electromagnetic propagation tool (EPT) at an operating frequency of 1.1 GHz (Figure 35). The antennas used both for transmission and reception are the cavity-backed slot type. Four antennas comprise an array that provides for transmission on either side of a pair of receivers. The two transmitters are energized alternately to launch plane waves, and their signal levels and relative phases are measured between the pair of receivers. These measurements are then transformed into attenuation and phase shifts, which are used to compute the dielectric constant and conductivity of the formation.

The main disadvantage of this method is that, due to the high frequency of operation, the measurement has a shallow penetration depth--on the order of 3 to 5 cm. Since the area surrounding the formation is disturbed by the process of drilling the hole, values obtained for the parameters do not describe this zone accurately.

A more thorough review of the EPT method is available in other publications.[66]

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[65] J. T. deBettencourt, D. Davidson, and J. R. Wait; W. C. Duesterhoeft, Jr., "Propagation Effects in Induction Logging," *Geophysics*, Vol 26, No. 2 (April 1961), pp 192-204; W. C. Duesterhoeft, Jr., and H. W. Smith, "Propagation Effects on Radial Response in Induction Logging," *Geophysics*, Vol 27, No. 4 (August 1962), pp 463-469; H. Edmundson (Ed.), *The Technical Review* (Schlumberger Ltd., 1983); S. Gianzero and B. Anderson; G. V. Keller and F. C. Frischknecht; J. H. Moran and K. S. Kunz, "Basic Theory of Induction Logging and Application to Study of Two-Coil Sondes," *Geophysics*, Vol 27, No. 6 (1962), pp 829-858; E. A. Nosal, "Statistical Determination of Geophysical Well Log Response Function," *Geophysics*, Vol 48, No. 11 (November 1983), pp 1525-1535; A. Roy and R. L. Dhar, "Relative Contribution to Signal by Ground Elements in Two-Coil Induction Logging System," *Geophys. Prospecting*, Vol 18 (1970), pp 389-404; *Log Interpretation: Vol I—Principles* and *Vol II—Applications*; F. F. Segesman; J. R. Wait (Ed.) (1971); J. R. Wait, "General Formation of the Induction Logging Problem for Concentric Layers About the Borehole," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-22, No. 1 (January 1984), pp 34-42; R. P. Wharton.

[66] T. J. Calvert, R. N. Rau, and L. E. Wells, "Electromagnetic Propagation--A New Dimension in Logging," paper 6542, presented at the 47th Annual California Regional SPE Meeting, AIME, Bakersfield (April 1977); W. C. Chew, C. Gianzero, and K. J. Kaplin, "Transient Response of an Induction Logging Tool in a Borehole," *Geophysics*, Vol 46, No. 9 (September 1981), pp 1291-1300; R. Freedman and J. P. Vogiatzis, "Theory of Microwave Dielectric Constant Logging Using the Electromagnetic Wave Propagation Method," *Geophysics*, Vol 44, No. 5 (May 1979), pp 969-986; G. Huchital, "The Use of High Frequency Electromagnetic Radiation to Probe for Economically Producible Hydrocarbon" (available from Schlumberger-Doll Research, Ridgefield, CT 06877); R. B. Rice, et al.; *Log Interpretation: Vol I—Principles* and *Vol II—Applications*; F. F. Segesman.

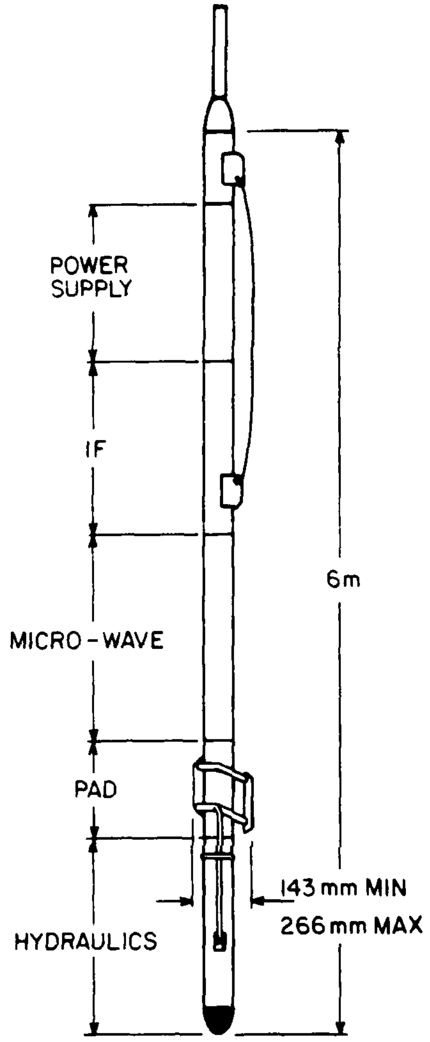

Figure 35. **Electromagnetic propagation tool: outline.** (Source: G. Huchital, "The Use of High-Frequency Electromagnetic Radiation to Probe for Economically Producible Hydrocarbons," [Schlumberger Doll Research, Ridgefield, CT 06877]. Used with permission.)

Deep Propagation Tool Method

The basic theory for the deep propagation tool (DPT) is the same as described above for the induction logging tool. The operating frequency of the DPT is midway between that of standard induction tools (20 KHz) and the EPT (1.1 GHz).

Figure 36 shows the DPT sonde. The sensors are loop antennas mounted on a mandrel, and the tool is run as a mandrel device like an induction logging tool. The sonde section contains one transmitting antenna and four identical receivers (Figure 37). The transmitting loop antenna is modeled as a vertical magnetic dipole. Attenuation is measured by the pair of receivers closest to the transmitter and the phase difference is measured by the pair of receivers farthest from the transmitter. From these measurements, the resistivity and dielectric constant are determined.

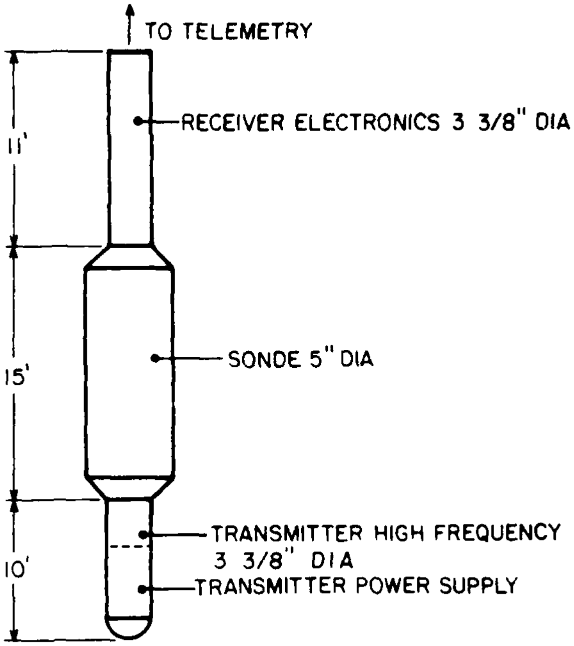

Figure 36. **Deep propagation tool.** (Source: G. Huchital, R. Hutin, Y. Thoraval, and B. Clark, "The Deep Propagation Tool: A New Electromagnetic Logging Tool," paper SPE 10988, presented at the Annual Fall Technical Conference and Exhibition [September 1982]. ©1982 SPE AIME. Used with permission.)

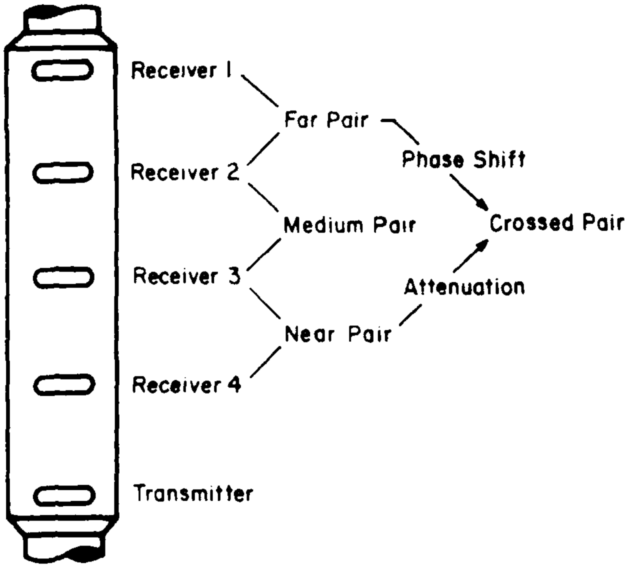

Figure 37. **Deep propagation tool: antennas.** (Source: Schlumberger, Ltd., 1983. Used with permission.)

An advantage of the DPT over the EPT is that the DPT can determine electrical parameters of the uninvaded formation adjacent to the drill hole. The DPT method is covered in detail elsewhere.[67]

Depth Attenuation Method

In this method, the depth attenuation rate of the field is measured between transmitting and receiving antennas as their separation distance is varied in a drill hole (Figure 38). The exponential decay of the signal with skin depth is used to deduce the skin depth and the conductivity of the earth medium. Conductivity is determined when the dielectric constant is known. The analysis is simplified if the distance between the transmitting and receiving antennas is greater than one wavelength in the medium. This assumption limits the lowest frequency for useful observations in drill holes, which have limited penetration depths into the rock. Thus, this method is used for probing the medium within one skin depth of the drill hole.

Measurements have been reported with small, vertically polarized antennas located in the lower rock portions of 1000-ft drill holes at frequencies near 150 MHz; antenna separation distances up to 500 ft were used.[68]

Other experiments with this technique are reported in the literature.[69]

Antenna Input Impedance Method

Linear wire radiators can be used in drill holes to determine electrical properties of a medium from the measured input impedance. This method has been used to obtain the conductivity and dielectric constant of the medium within one skin depth of the drill hole. The various types of linear antennas include electrically short linear impedance probes, electrically long insulated antennas, and near-resonant-length antennas.

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[67] W. C. Chew, "Response of a Current Loop Antenna in an Invaded Borehole," *Geophysics*, Vol 49, No. 1 (January 1984), pp 81-91; G. Huchital, "The Use of High Frequency Electromagnetic Radiation to Probe for Economically Producible Hydrocarbon"; G. Huchital, *Apparatus and Method for Determination of Subsurface Permittivity and Conductivity*, U.S. Patent No. 4,209,747 (June 24, 1980); G. Huchital, R. Hutin, Y. Thoraval, and B. Clark, "The Deep Propagation Tool," paper SPE 10988, presented at the SPE AIME Meeting (September 1982); R. B. Rice, et al.; F. F. Segesman; J. S. Yu, "Self-Consistent Evaluation of Complex Constitutive Parameters," *IEEE Trans. Antennas Propagat.* Vol AP-29, No. 2 (March 1981), pp 408-412; J. S. Yu, P. C. Reardon, and P. C. Lysne.

[68] J. T. DeBettencourt and J. W. Frazier, "Rock Electrical Characteristics Deduced From Depth Attenuation Rates (in Drill Holes)," *IEEE Trans. Antennas Propagat.*, Vol AP-11 (1963), p 358.

[69] J. T. deBettencourt and J. W. Frazier; J. T. deBettencourt, D. Davidson, and J. R. Wait; J. A. Fuller and J. R. Wait, "EM Coupling of Co-Axial and Co-Planar Loops in Uniform Dissipative Media," *Proc. IEEE*, Vol 60 (1972), p 993; J. A. Fuller and J. R. Wait, "Mutual Electromagnetic Coupling of Coaxial Loops in a Borehole," *Radio Sci.*, Vol 8, No. 5 (May 1973), pp 453-457; R. J. Lytle, E. F. Laine, D. L. Lager, and J. T. Okada; R. J. Lytle (July 1974).

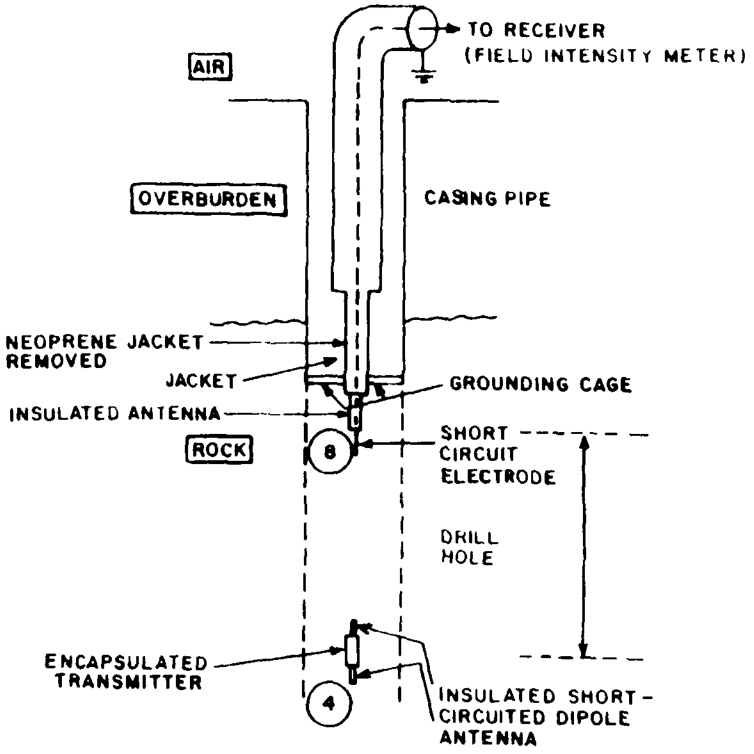

Figure 38. **Depth attenuation method.** (Source: J. T. deBettencourt and J. W. Frazier, "Rock Electrical Characteristics Deduced From Depth Attenuation Rates [in Drill Holes], "*IEEE Trans. Antennas Propagat.*, Vol AP-11 [1963]. ©1963 IEEE. Used with permission.)

Figure 39 shows electrically short linear impedance probes. These probes are useful when there is a conductive fluid, such as water, present in the drill hole to serve as contact between the dipole electrodes and the surrounding medium. The direct effect of water on the measurement results can be considered negligible if the thickness of the water layer is small compared with the dipole length. Experimental difficulties include those associated with obtaining a balanced center-fed arrangement with a feeder to the surface where the impedance measurements are made. Measurements have been reported for the frequency range 150 Hz to 20 kHz to depths of 400 ft using these probes.[70]

Electrically long insulated wire antennas also can be used. As long as the loss tangent of the medium is large, a useful approximation is possible by considering the immersed insulated wire to be a coaxial metallic outer conductor. A sinusoidal current distribution is valid and the input impedance shows characteristics of a coaxial

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[70] C. K. H. Tsao and J.T. deBettencourt, "Conductivity Measurements in Dissipative Media With Electrically Short Probes," *IEEE Trans. Instrum. Meas.*, Vol IM-16 (1967), p 242.

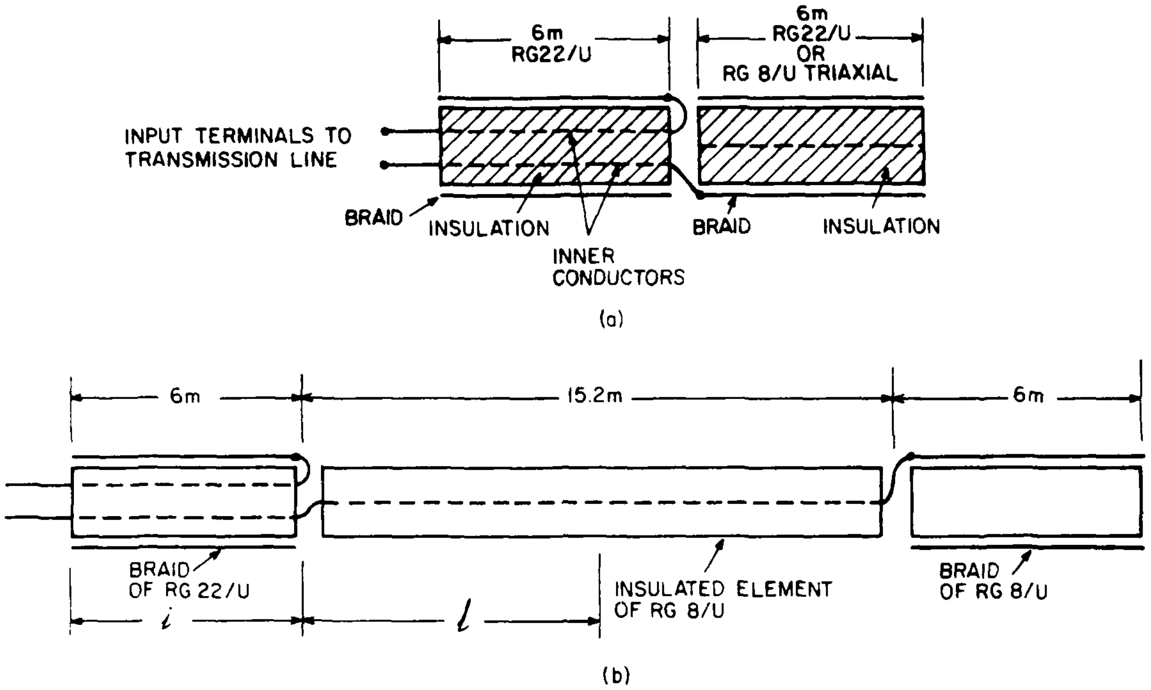

Figure 39. **Antenna input impedance method: electrically short linear impedance probes. (a) Bare dipole probe and (b) insulated dipole probe.** (Source: J. T. deBettencourt, D. Davidson, and J. R. Wait, "IEEE Guide for Radio Methods of Measuring Earth Conductivity," *IEEE Trans. Antennas Propagat.*, Vol AP-22, No. 2 [March 1974]. ©1974 IEEE. Used with permission.)

transmission line. The quarter-wave resonance conductivities of the rock surround the antennas. To review this method, see the literature.[71]

Transmission Line Methods

Transmission line methods have practical use in field measurements of ground soil. These methods use unshielded balanced parallel wire transmission lines, coaxial transmission lines, or a single-conductor transmission line. The time domain reflectometry (TDR) method using two parallel transmission lines is included in this category. Most of these techniques are used in short drill holes that usually are less than a few meters deep.

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[71] J. T. deBettencourt and R. A. Sutcliffe, "Studies in Deep Strata Communication," *Communications and Data Processing Operation*, AD407840 (U.S. Air Force Cambridge Research Lab, October 1962); J. T. deBettencourt, D. Davidson, and J. R. Wait; R. J. Lytle, E. F. Laine, D. L. Lager, and J. T. Okada; R. J. Lytle (July 1974); J. C. Rogers and I. C. Peden, "The VLF Permittivity of Deep Antarctic Ice Measured In-Situ With an Electrically Short Dipole Probe," presented at the 1973 URSI Meeting, Boulder, CO (August 1973); C. K. H. Tsao and J. T. deBettencourt; C. K. H. Tsao and J. T. deBettencourt, "Impedance of a Finite Length Insulated Dipole in Dissipative Media," *Conference Proceedings on Environmental Effects on Antennas Performance*, Boulder, CO, Vol I (July 1969), pp 72-76.

For the unshielded balanced parallel wire transmission lines inserted into a drill hole, standard open- and short-circuit procedures can be used to determine the characteristic impedance and propagation constant of the transmission line. These quantities can then be used to estimate the conductivity and dielectric constant of the ground soil. Measurements have been reported for the frequency range 0.6 to 400 MHz; the wires were 3 mm in diameter spaced 22.2 mm center to center.[72]

Figure 40 shows a single-conductor transmission line. Wide-band pulses are launched up the line from a transmitter at the tip, and a computer is used to Fourier-transform the pulses received at the surface and compute the frequency-dependent conductivity and dielectric constant. If computer use is inconvenient, single-value measurements can be made directly from the pulses received. Measurements have been reported for the frequency range 25 to 100 MHz.[73]

For the TDR method, two 1-m rods are inserted into the ground in parallel and attached to the leads of a portable cable tester. A step pulse travels the length of the rods and is reflected at the ends. The time of travel is used to measure the dielectric constant of the lossy soil. The accuracy of this measurement is sensitive to any air layer that may exist between each rod and the soil; therefore, an effort should be made to insert the rods tightly into the ground.[74]

More information on transmission line methods is available in the literature.[75]

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[72] E. J. Kirscether.

[73] P. K. Hayes, "A Single-Probe On-Site Method of Measuring the Dielectric Constant and Conductivity of Soft Earth Media Over a 1-GHz Bandwidth," *IEEE Trans Geosci. Remote Sensing*, Vol GE-20, No. 4 (October 1982), pp 504-510.

[74] A. P. Annan, "Time-Domain Reflectometry--Air Gap Problem for Parallel Wire Transmission Lines," *Geol. Surv. Can.*, Paper 77-1B (1977), pp 59-62.

[75] A. P. Annan, 1977; J. L. Davis and W. J. Chudobiak, "In-Situ Meter for Measuring Relative Permittivity of Soils," *Geol. Surv. Can.*, Paper 75-1A (1975), pp 75-79; J. T. deBettencourt, D. Davidson, and J. R. Wait; P. K. Hayes; E. J. Kirscether; R. J. Lytle (July 1974); G. C. Topp, "Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines," *Water Resources Res.*, Vol 16, No. 3 (1980), pp 574-582.

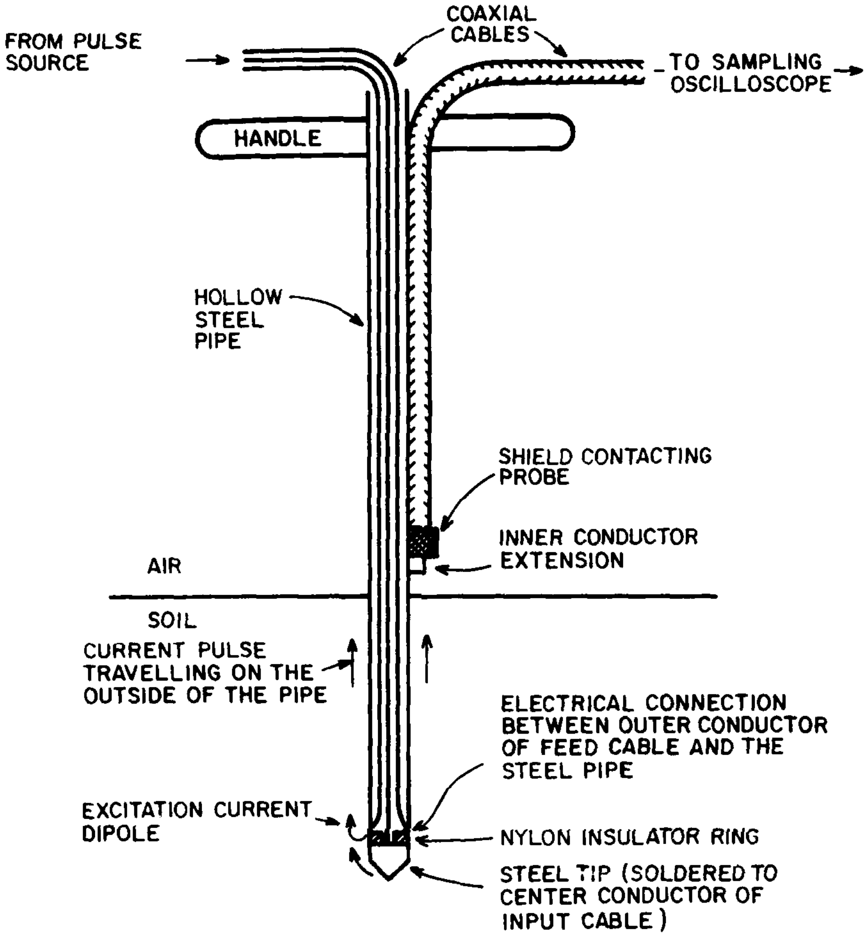

Figure 40. **Transmission line method: single conductor transmission lines.** (Source: P. K. Hayes, "A Single-Probe On-Site Method of Measuring the Dielectric Constant and Conductivity of Soft Earth Media Over a 1-GHz Bandwidth," *IEEE Trans. Geosci Remote Sensing*, Vol GE-20, No. 4 [October 1982]. ©1982 IEEE. Used with permission.)

6 EXAMPLES OF MEASURED DATA

A great amount of data have been reported from both experimental and *in situ* measurements of electrical parameters.[76] Examples of these data are reported in this chapter to help designers estimate electromagnetic shielding effectiveness for generic strata types. Table 3 lists representative values for the dielectric constant and conductivity of various earth media.

The data show that the dielectric constant of a soil sample is dependent on frequency, water content, and other soil properties. At low frequencies, the dielectric constant is very dependent on conductivity. At higher frequencies, however, the dielectric constant approaches a limit which is primarily a function of water volume fraction and only slightly dependent on soil type. Studies on modeling soil types have been reported.[77] Experimental results have been reported by Jesch for five different test frequencies ranging from 300 to 9300 MHz.[78] The soil textural types include sand sandy loam, silt loam, clay loam, and clay (Tables 4 through 8).

For rock samples, as was true for the soil samples, factors having the most effect on the electrical parameters are frequency, water content, and geological constituents. Typical values of various rocks are listed in Table 9 for the (real) relative dielectric constant and in Table 10 for resistivity.

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[76] J. C. Cook, 1976; B. D. Fuller and S. H. Ward; P. Hoekstra and A. Delaney; R. L. Jesch; G. V. Keller and F. C. Frischknecht; C. L. Longmire and K. S. Smith, *A Universal Impedance for Soils*, DNA001-75-C-0094 (Defense Nuclear Agency, October 1975); R. J. Lytle (August 1973); R. J. Lytle, E. F. Laine, D. L. Lager, and J. T. Okada; R. J. Lytle, D. Lager, and E. Laine; R. J. Lytle (November 1979); J. H. Scott, "Electrical and Magnetic Properties of Rock and Soils," *Electromagnetic Pulse Theoretical Notes*, Note 18, AFWL EMP 2-1 (U.S. Air Force Weapons Laboratory, April 1971); *U.S. Geological Survey Technical Letter*, Special Project 16 (26 May 1966); J. R. Wait (Ed.) (1971).

[77] J. R. Wang and T. J. Schmugge, "An Empirical Model for the Complex Dielectric Permittivity of Soils as a Function of Water Content," *IEEE Trans. Geosci. Remote Sensing*, Vol GE-18, No. 4 (October 1980), pp 288-295; D. Wobschall, "A Theory of the Complex Dielectric Permittivity of Soil Containing Water: The Semidisperse Model," *IEEE Trans. Geosci. Electron.*, Vol GE-15, No. 1 (January 1977), pp 49-58.

[78] R. L. Jesch.

Table 3

Typical Terrain Constants*

Terrain Type	Wavelength							
	3 m		10 cm		3 cm		1 cm	
	ε'	σ	ε'	σ	ε'	σ	ε'	σ
Seawater	80	1-5	69	6.5	65	0.16	22	50
Fresh water	80	0.001-0.1	--					
Humid soil, clay	30	0.01-0.02	24	0.6				
Fertile cultivated soil	15	0.005	--					
Grass, meadow, race courses, sports grounds	--	--	3.6	0.05-0.11				
Rocky ground	7	0.001	--	--				
Urban areas, large towns	5	0.001	--	--				
Dry soil	4	0.01	--	--		≈0.007		
Very dry soil	4	0.001-0.0001	2	0.03	3	-0.1		

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* ε' = relative dielectric constant; σ = conductivity in S/m. Source: D. C. Auth, W. G. Mayer, and W. J. Thaler, "A Light Diffraction Technique for Measuring Dielectric Constants at Microwave Frequencies," *Proc. IEEE* (1969). ©1969 IEEE. Used with permission.

Table 4

Experimental Results of Sand Texture for Varied Moisture Levels*

Sand - 0% Moisture

(Mean density = 1.540; SD = 0.022 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	2.702	0.0486	-0.00372	0.0002
500	2.694	0.0492	-0.00206	0.00006
1000	2.693	0.0515	0.00161	0.0004
2000	2.695	0.0515	0.00833	0.0003
4000	2.656	0.0419	0.0836	0.004
9300	2.737	0.0660	0.240	0.02

Sand - 1% Moisture

(Mean density = 1.614; SD = 0.014 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.227	0.0352	0.0503	0.001
500	3.131	0.0299	0.0680	0.002
1000	3.062	0.0182	0.0968	0.0006
2000	3.015	0.0112	0.136	0.001
4000	2.914	0.0068	0.304	0.002
9300	3.037	0.0132	0.640	0.05

Sand - 2% Moisture

(Mean Density = 1.455; SD = 0.015 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.072	0.043	0.0705	0.002
500	2.977	0.032	0.0892	0.003
1000	2.930	0.036	0.113	0.003
2000	2.915	0.079	0.139	0.009
4000	2.891	0.083	0.340	0.02
9300	2.905	0.038	0.789	0.03

*Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

Table 4 (Cont'd)

Sand - 4% Moisture
(Mean density = 1.583; SD = 0.020 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	4.225	0.168	0.173	0.01
500	4.079	0.162	0.197	0.01
1000	4.019	0.165	0.231	0.01
2000	3.940	0.142	0.287	0.03
4000	3.946	0.148	0.607	0.02
9300	3.373	0.198	1.38	0.32

Sand - 8% Moisture
(Mean density = 1.732; SD = 0.016 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	6.957	0.235	0.249	0.007
500	6.792	0.249	0.278	0.01
1000	6.708	0.300	0.335	0.02
2000	6.533	0.128	0.535	0.02
4000	6.425	0.196	1.27	0.07
9300	5.854	0.231	2.86	0.18

Sand - 14%
(Mean density = 1.732; SD = 0.015 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	10.458	0.413	0.251	0.01
500	10,641	0.415	0.296	0.01
1000	11.179	0.349	0.429	0.04
2000	9.951	0.334	0.693	0.05
4000	10.544	0.441	1.80	0.24
9300	10.179	1.14	3.38	1.0

Table 5

Experimental Results of Sandy Loam Texture for Varied Moisture Levels*

Sandy Loam - 0% Moisture
(Mean density = 1.435; SD = 0.008 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	2.650	0.040	-0.00195	0.00008
500	2.642	0.047	0.00081	0.0001
1000	2.660	0.079	0.00762	0.0004
2000	2.680	0.102	0.00820	0.002
4000	2.691	0.125	0.102	0.01
9300	2.663	0.027	0.166	0.09

Sandy Loam - 1.5% Moisture
(Mean density = 1.410; SD = 0.004 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.791	0.008	0.124	0.001
500	3.548	0.010	0.177	0.001
1000	3.341	0.020	0.277	0.004
2000	3.243	0.020	0.393	0.002
4000	3.023	0.034	0.743	0.02
9300	3.236	0.065	1.58	0.06

Sandy Loam - 3% Moisture
(Mean density = 1.402; SD = 0.022 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.954	0.067	0.135	0.004
500	3.690	0.053	0.194	0.004
1000	3.464	0.052	0.308	0.006
2000	3.278	0.039	0.412	0.02
4000	3.174	0.106	0.798	0.02
9300	3.190	0.045	1.65	0.08

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*Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

**Erroneous data.

Table 5 (Cont'd)

Sandy Loam - 6% Moisture
(Mean density = 1.547; SD = 0.012 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	5.967	0.076	0.406	0.005
500	5.407	0.062	0.520	0.004
1000	4.909	0.028	0.723	0.01
2000	4.408	0.035	0.913	0.04
4000	4.301	0.019	1.43	0.06
9300	3.813	0.084	3.42	0.36

Sandy Loam - 12% Moisture
(Mean density = 1.650; SD = 0.044 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	10.063	0.534	0.985	0.01
500	9.164	0.681	1.16	0.1
1000	7.759	0.699	1.40	0.2
2000	8.148	0.555	2.33	0.2
4000	7.551	1.294	3.14	0.1
9300**	--	--	--	--

Sandy Loam - 24% Moisture
(Mean density = 1.928; SD = 0.024 cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	24.527	0.326	1.88	0.002
500	24.328	0.185	2.11	0.002
1000	22.705	0.625	2.7	10.04
2000	21.156	1.072	3.51	0.56
4000	16.549	1.56	4.27	0.91
9300	9.884	2.4	9.57	2.5

Table 6

Experimental Results of Silt Loam Texture for Varied Moisture Levels*

Silt Loam - 0% Moisture
(Mean density = 1.106; SD = 0.037 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	2.340	0.049	0.00325	0.0002
500	2.321	0.051	0.00771	0.0004
1000	2.318	0.059	0.0188	0.0009
2000	2.343	0.085	0.0351	0.003
4000	2.325	0.044	0.103	0.004
9300	2.408	0.094	0.188	0.019

Silt Loam - 2.5% Moisture
(Mean density = 1.133; SD = 0.043 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.137	0.029	0.102	0.002
500	2.959	0.025	0.140	0.002
1000	2.812	0.018	0.205	0.001
2000	2.728	0.016	0.270	0.005
4000	2.646	0.018	0.519	0.02
9300	2.660	0.052	0.958	0.04

Silt Loam - 10% Moisture
(Mean density = 1.435; SD = 0.010 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	9.151	0.186	0.675	0.02
500	8.083	0.182	0.903	0.04
1000	7.458	0.343	1.25	0.07
2000	5.573	0.157	1.82	0.10
4000	5.275	0.048	2.45	0.50
9300	4.065	0.268	6.83	1.3

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*Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

Table 6 (Cont'd)

Silt Loam - 5% Moisture
(Mean density = 1.267; SD = 0.017 g*/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	4.453	0.097	0.214	0.007
500	4.038	0.083	0.301	0.009
1000	3.692	0.078	0.467	0.03
2000	3.391	0.080	0.589	0.02
4000	3.319	0.108	1.17	0.10
9300	3.170	0.092	2.30	0.12

Table 7

Experimental Results of Clay Loam Texture for Varied Moisture Levels*

Clay Loam - 0% Moisture
(Mean density = 1.266; SD = 0.035 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	2.775	0.024	0.00229	0.00007
500	2.760	0.027	0.00625	0.00006
1000	2.773	0.037	0.0167	0.0002
2000	2.771	0.051	0.0289	0.007
4000	2.758	0.048	0.185	0.04
9300	2.708	0.076	0.404	0.21

Clay Loam - 1% Moisture
(Mean density = 1.311; SD = 0.010 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.265	0.050	0.074	0.001
500	3.131	0.048	0.101	0.001
1000	3.045	0.041	0.144	0.001
2000	3.008	0.037	0.197	0.009
4000	2.915	0.064	0.472	0.04
9300	2.989	0.141	0.732	0.03

Clay Loam - 3% Moisture
(Mean density = 1.235; SD = 0.022 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.402	0.061	0.123	0.004
500	3.175	0.056	0.169	0.005
1000	2.962	0.066	0.248	0.01
2000	2.824	0.100	0.344	0.02
4000	2.759	0.055	0.708	0.06
9300	2.784	0.048	1.29	0.07

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*Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

Table 7 (Cont'd)

Clay Loam - 6% Moisture
(Mean density = 1.436; SD = 0.035 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	5.667	0.047	0.283	0.007
500	5.108	0.023	0.387	0.007
1000	4.649	0.101	0.568	0.003
2000	4.151	0.065	0.761	0.06
4000	4.024	0.156	1.14	0.10
9300	3.826	0.122	2.31	0.73

Clay Loam - 12% Moisture
(Mean density = 1.468; SD = 0.018 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	8.719	0.183	0.689	0.02
500	7.734	0.138	0.926	0.03
1000	7.363	0.223	1.43	0.13
2000	5.702	0.018	1.66	0.08
4000	5.682	0.005	2.26	0.02
9300	4.657	0.418	3.85	0.68

Clay Loam - 24% Moisture
(Mean density = 1.920; SD = 0.021 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
9300	14.283	0.324	15.46	2.32

Clay Loam - 48% Moisture
(Density = 1.641 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant	Attenuation (dB/cm)
9300	9.75	38.95

Table 8

Experimental Results of Clay Texture for Varied Moisture Levels

Clay - 0% Moisture
(Mean density = 1.174; SD = 0.040 g/cm^3

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	2.717	0.052	0.00455	0.0003
500	2.703	0.053	0.00933	0.0004
1000	2.721	0.065	0.0213	0.0005
2000	2.721	0.068	0.0346	0.008
4000	2.732	0.105	0.180	0.02
9300	2.677	0.052	0.271	0.03

Clay - 1% Moisture
(Mean density = 1.173; SD = 0.016 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.038	0.022	0.0782	0.001
500	2.902	0.023	0.106	0.002
1000	2.806	0.032	0.154	0.006
2000	2.745	0.049	0.211	0.009
4000	2.652	0.034	0.443	0.05
9300	2.728	0.185	0.830	0.09

Clay - 3.5% Moisture
(Mean density = 1.233; SD = 0.096 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	3.877	0.061	0.158	0.004
500	3.612	0.050	0.216	0.005
1000	3.444	0.034	0.326	0.007
2000	3.276	0.039	0.385	0.02
4000	3.149	0.059	0.844	0.05
9300	3.077	0.179	1.32	0.27

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*Source: R. L. Jesch, *Dielectric Measurements of Five Different Soil Textural Types as Functions of Frequency and Moisture Content*, NBSIR 78-879 (National Bureau of Standards, December 1978).

Table 8 (Cont'd)

Clay Loam - 7% Moisture
(Mean density = 1.376; SD = 0.007 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	6.030	0.034	0.344	0.005
500	5.399	0.015	0.459	0.005
1000	4.952	0.058	0.702	0.004
2000	4.187	0.005	0.813	0.03
4000	4.289	0.085	1.38	0.20
9300	3.754	0.053	2.41	0.43

Clay - 14% Moisture
(Mean density = 1.444; SD = 0.024 g/cm^3)

Frequency (MHz)	Relative Dielectric Constant		Attenuation (dB/cm)	
	Mean	SD	Mean	SD
300	10.676	0.204	0.766	0.04
500	9.402	0.186	1.08	0.06
1000	9.871	0.807	1.44	0.05
2000	6.294	0.124	2.00	0.08
4000	5.642	0.823	3.83	1.2
9300	5.185	0.950	7.72	2.5

Table 9

Dielectric Constants of Rocks*

Rock	Source, Mineral Composition (%)	ε'	Frequency (Hz)	Water Content (%)
Sedimentary rocks				
Anhydrite with gypsum	Anhydrite, 92 Gypsum, 8	6.3	--	Dry
"Chuneski" shale, bentonitic		10-45.0	10^2-10^6	10
"Chuneski" shale, bentonitic		4-7.0	10^2-10^6	Dry
"Gumbrin" shale, bentonitic		9.5-10	10^2-10^6	Dry
Dolomite		8.0-8.6	10^3-10^7	Dry
Limestone	Georgian SSR	7.3	--	Dry
Limestone		8.0-12.0	--	--
Arkosic sandstone	Quartz, 23	--	--	--
	Feldspar, 75	--	--	--
	Mica, 2	4.9	--	Dry
Quartz-feldspar sandstone	Quartz, 40	--	--	--
	Feldspar, 45	--	--	--
	Other, 15	5.1	--	Dry
Sandstone	Garm	4.66	5 x 10^5	Dry
	Zubovskoe	3.96	5 x 10^5	Dry
Variegated sandstone		9.0-11.0	--	--
Shaly sandstone		5.33	--	Dry
Shaly sandstone		7.17	--	0.2
Metamorphic rocks				
Amphibolite		7.9-8.9	10^5-10^7	Dry
Gneiss		8.0-15.0	--	--
Granite gneiss		8.0-9.0	$5\text{x}10^2$-$5\text{x}10^7$	--

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*Source: R. J. Lytle, "Properties of the Ground Inferred From Electromagnetic Measurements," *IEEE Trans. Antenna Propagat.*, Vol AP-27, No. 6 (November 1979). ©1979 IEEE. Used with permission.

Table 9 (Cont'd)

Quartzite	Shokshinskoe	4.36	5×10^5	Dry
Quartzite	Ridderskoe	4.85	5×10^5	Dry
Quartzite		6.6	--	--
Quartzite		7.0	--	--
Marble		8.22	--	Dry
Marble		8.37	--	0.002
Marble		8.9-9.0	10^3-10^7	Dry
Talc slate		7.5-34.0	5x10-5x10^7	Dry
Micaceous slate		9.0-10.0	5x10-5x10^7	Dry
Roofing slate	Georgian SSR	6.71	--	Dry
Roofing slate	Georgian SSR	7.74	--	0.1
Phyllite		13.0	--	--
Igneous rocks, acid				
Biotite-granite aplite	Quartz, 40	--	--	--
	Microline, 32	--	--	--
	Plagioclase, 20	4.8	--	Dry
	Other, 8	--	--	--
Granite	Altai	5.42	5×10^5	Dry
Granite	Leznikovskoe	4.74	5×10^5	Dry
Granite	Garm	5.06	5×10^5	Dry
Granite	Valaamskoe	4.5	5×10^5	Dry
Granite		7.0-9.0	--	Combined moisture
Volcanic tuff		3.8-4.5	--	Dry
Ingenous rocks, intermediate				
Diorite	Kola Peninsula	5.9-6.3	10^5-10^7	Dry
Diorite		8.5-11.5	10^4-10^7	Dry
Dacite		6.8-8.16	3×10^6	--
Igneous rocks, basic				
Augite porphyry	Kola Peninsula	9.5-12.6	10^5-10^7	Dry
Basalt	Berestovetskoe	15.6	5×10^5	Dry
Basalt	Kutai	10.3	5×10^5	Dry

Table 9 (Cont'd)

Gabbro		8.8-10.0	10^4-10^7	Dry
Gabbro	Southern Urals (3.26% ore content)	12.8	--	Dry
Diabase	Oneshsk	11.6	5×10^5	Dry
Diabase		9.0-13	10^4-10^7	Dry
Labradorite	Ukrainian SSR	7.82	--	--
Igneous rocks, ultrabasic				
Peridotite (Plagioclase)	Kola Peninsula	15.7-18.8	10^5-10^7	Dry
Peridotite	Olivene, 70	12.1	5×10^5	Dry
	Augite, 25	--	--	
	Mica, 5	8.6	--	Dry
Olivene pyroxenite	Kola Peninsula	8.4-9.5	10^5-10^7	Dry
Igneous rocks, alkaline				
Syenite		6.83	5×10^5	Dry
Syenite		13.0-14.0	--	Dry
Aegerine-phyllite nepheline syenite	Kola Peninsula	6.93	--	Dry
Mica nepheline syenite with aegerine	Kola Peninsula	8.47	--	Dry
Microcrystalline nepheline syenite	Kola Peninsula	9.55	--	Dry
Aegerine nepheline syenite		9.56	--	Dry
Fayalite	Near Mariupol	8.32	--	Dry
Luyavrite	Kola Peninsula	9.7-11.4	10^5-10^7	Dry
Urtite	Kola Peninsula	7.3-8.5	10^5-10^7	Dry
Felspathic urtite	Kooshva	11.9	--	Dry

Table 10

Resistivity of Rocks*

Rock Type	Source	Resistivity (ohm-cm)	
		Wet	Dry
Sedimentary rocks			
Dolomite	Armenian SSR	3.5×10^4-5.0×10^5	--
Limestone**	Kazakhstan SSR	4.2×10^7	1.2×10^9
Limestone**	Georgian SSR	2.1×10^7	2.3×10^9
Limestone marl***	Georgian SSR	8.4×10^8	--
Sandstone+	Donbas	1.41×10^7	6.4×10^{10}
Sandstone	Kara-Shishak	3.5×10^6	3.1×10^7
Arkosic sandstone	Jezkazgan	6.8×10^4	1.0×10^8
Quartzitic sandstone	Dashkesan	2.3×10^4-3.3×10^4	--
Tuffaceous sandstone	Dashkesan	10^5-1.0×10^7	--
Metamorphic rocks			
Clay slate++	Georgian SSR	6.4×10^6	1.6×10^7
Clay slate	Georgian	1.1×10^6	1.6×10^9
Clay slate	Nerchinsk	1.0×10^5	1.0×10^8
Clay slate+++	Georgian SSR	4.0×10^5	6.0×10^8
Quartz-sericite slate	Ziryanskii Mine	5.0×10^6	3.6×10^9
Quartz-chlorite slate		5.0×10^5	2.0×10^8
Calcareous quartzite	Altai	4.0×10^5	2.0×10^{10}
Quartzite	Georgian SSR	4.7×10^8	
Metamorphosed tuff	Altai	2.0×10^5	1.0×10^7
Gneiss	Kugrasin	6.8×10^6	3.2×10^8
Marble	Nerchinsk	1.4×10^6	2.5×10^{10}
Marble		7.06×10^{11}	1.8×10^{20}
Hornfels	Kugrasin	6.0×10^7	6.0×10^8
Hornfels	Trans-Caucasus	8.1×10^5	6.0×10^9
Skarn	Armenian SSR	2.5×10^4	--

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*Source: R. J. Lytle, "Properties of the Ground Inferred From Electromagnetic Measurements," *IEEE Trans. Antenna Propagat.*, Vol AP-27, No. 6 (November 1979). ©1979 IEEE. Used with permission.

**Dolomitzed form

***Fine-grained rocks

+Water content, 0.37%

++Strongly quartzitic

+++Shaly

Table 10 (Cont'd)

Igneous rocks,			
acidic			
Granite	Azerbaidjan	3.0×10^{7}	--
Granite	Ubinskoe	0.36×10^{9}	3.2×10^{18}
Granite	Kola Peninsula	0.16×10^{9}	0.3×10^{16}
Granite porphyry		4.5×10^{5}	1.3×10^{8}
Granite porphyry	Urals	7.0×10^{5}	1.0×10^{7}
Quartz vein	Komsomol'skoe	0.6×10^{10}	1.0×10^{18}
Quartz porphyry	Georgian SSR	9.2×10^{7}	--
Feldspar porphyry	Australia	4.0×10^{5}	--
Leucophyre (albite)	Georgian SSR	2.9×10^{4}	0.4×10^{9}
Leucophyre (albite)	Urals	4.5×10^{5}	--
Intermediate			
Porphyrite	Georgian SSR	10^{3}	3.3×10^{5}
Porphyrite	Azerbaidjan SSR	6.7×10^{4}	
Porphyrite	Dashkesan	5×10^{6}	--
Diorite porphyry	Caucasus	1.9×10^{5}	2.8×10^{6}
Carbonitized porphyry	Armenian SSR	2.5×10^{5}	5.9×10^{6}
Diorite	Urals	2.8×10^{6}	--
Quartz diorite	Azerbaidjan SSR	2.0×10^{6}	1.8×10^{7}
Quartz diorite	Georgian SSR	2.0×10^{8}	--
Dacite	Georgian SSR	2.1×10^{6}	--
Andesite	Georgian SSR	4.5×10^{6}	1.7×10^{4}
Basic and ultrabasic			
Diabase porphyry	Trans-Caucasus	9.6×10^{4}	1.7×10^{7}
Diabase	Karelaia	3.0×10^{6}	2.2×10^{11}
Diabase	Georgian SSR	3.8×10^{4}	3.3×10^{7}
Diabase	Georgian SSR	2.9×10^{4}	0.8×10^{9}
Diabase	Sibaevskoe	4.57×10^{9}	--
Diabase	Blyavinskoe	1.18×10^{7}	1.0×10^{12}
Diabase	Khibini	0.16×10^{8}	0.17×10^{13}
Olivine norite		$3 \times 10^{6}-6 \times 10^{6}$	--
Olivine norite		$10^{5}-6 \times 10^{5}$	--
Basalt	Armenian SSR	1.6×10^{5}	--
Basalt	Berestovetskoe	2.3×10^{6}	1.3×10^{9}
Peridotite		3.0×10^{5}	6.5×10^{5}

7 CONCLUSIONS

State-of-the-art technology for measuring electrical properties of earth media in the laboratory and *in situ* has been reviewed for potential application to military facilities. The measurement techniques were divided into three categories: (1) laboratory, (2) *in situ* measurement at the Earth's surface, and (3) *in situ* drill-hole measurement.

Laboratory measurements are relatively inexpensive to perform and are accurate, but have some disadvantages; for example, these methods require that drilling or excavating be done in advance. Also, characteristics may change due to variable water content. Since each sample represents only a localized area in the stratum, inhomogeneities cannot be detected easily.

In situ measurements at the Earth's surface usually require that results from several methods be combined to improve data resolution and overall accuracy. These methods therefore represent a somewhat time-consuming, costly approach. However, they have the distinct advantage of requiring no drilling or excavating and thus are highly useful for underground facilities. Much current research is seeking to improve techniques for measuring electrical properties at the surface.

The technology for *in situ* drill-hole measurements is well developed, partly as a result of the petroleum industry's R&D into oil well strata logging. Methods using more than one drill hole also are established and can provide useful information regarding strata parameter homogeneity.

Examples of measured data have been provided to demonstrate the type of data to be expected using these methods. In addition, these data can help facilities designers in determining the amount of electromagnetic shielding provided by strata of general types.

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