

IEEE Guide for Radio Methods of Measuring Earth Conductivity

Feb 20, 1974

SH03566



THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, Inc.

IEEE Guide for Radio Methods of Measuring Earth Conductivity

**Sponsor
Wave Propagation Standards Committee
of the
IEEE Antennas and Propagation Group**

©Copyright 1974 by

The Institute of Electrical and Electronics Engineers, Inc.

*No part of this publication may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.*

Approved May 24, 1973
IEEE Standards Board

Robert D. Briskman, *Chairman*

Sava I. Sherr, *Secretary*

Stephen J. Angello
Saul Aronow
James E. Beehler
Richard Brereton
Warren H. Cook
Louis Costrell
Jay Forster

Joseph L. Koepfinger
William R. Kruesi
Benjamin J. Leon
Donald T. Michael
Voss A. Moore
J. David M. Phelps
Saul W. Rosenthal
Gustave Shapiro

Ralph M. Showers
Robert A. Soderman
Frederick G. Timmel
Leendert van Rooij
Robert V. Wachter
Bruno O. Weinschel
William T. Wintringham

Foreword

(This Foreword is not a part of IEEE Std 356-1974, Guide for Radio Methods of Measuring Earth Conductivity.)

This guide is the result of a survey of radio techniques employed for measuring the conductivity of the earth. Results are applicable to the design of communication channels that are influenced by the electrical characteristics of the earth. Emphasized are those techniques used at frequencies where the loss tangent is large.

The techniques are classed broadly into those which make use of drill holes into the earth and those which do not. Also, we distinguish between those methods that are passive and those that are active. In the latter case, the radio source is controlled.

Comments and critiques on the various techniques are included. The guide contains 68 references employed in the survey, plus appendixes which contain theoretical and practical details underlying some of the methods.

At the time it approved this standard, the Wave Propagation Standards Committee of the IEEE Antennas and Propagation Group had the following membership:

Kurt Toman, *Chairman*

George Millman, *Secretary*

B. R. Bean
H. H. Beverage
S. A. Bowhill
K. Bullington
C. R. Burrows
T. J. Carroll
R. C. Cohen
Herman V. Cottony

L. B. Craine
David Davidson
J. T. deBettencourt
F. H. Dickson
Harry Fine
Frank M. Greene
I. Katz
Martin Katzin
J. M. Kelso

Marcella L. Phillips
Phillip L. Rice
E. R. Schmerling
Ralph J. Slutz
Ernest K. Smith
Archie W. Straiton
Victor Twersky
James R. Wait

The guide was prepared by the Subcommittee on Earth Conductivity Measurements. Members of the Subcommittee were:

J. T. deBettencourt, *Chairman*

D. Davidson

J. R. Wait

Contents

SECTION	PAGE
1. Purpose and Scope.....	7
2. Surface-Measurement Techniques (Probes).....	7
2.1 Broad Area Coverage.....	8
2.2 Local-Area Methods.....	9
3. Measurements in Drill Holes.....	14
3.1 Core Samples.....	14
3.2 Depth Attenuation Measurement.....	17
3.3 Induction Logging.....	17
3.4 Antenna Input Impedance.....	18
3.5 Path Transmission Loss Measurements.....	18
4. References.....	20
 FIGURES	
Fig 1 Four-Electrode Equispaced Arrays for Surface Resistivity Measurements. (A) Wenner Array, (B) Eltran Array, (C) Right-Angle or Wait Array.....	10
Fig 2 Schematic Representation for Two-Layered Ground, Each Layer Anisotropic. (Sketch Shows Wenner-Type 4 Electrode Arrangement).....	12
Fig 3 Conductivity of Core Samples Versus Depth-Tubmen Road Drill Hole.....	15
Fig 4 A Depth-Attenuation Method for Obtaining Electrical Constants of Rock Media. Transmitter at A Separated a Distance R from a Receiving Dipole at B, with R varied. The Receiver is at C on Surface.....	16
Fig 5 Principle of Operation of Induction Log (Left) and Arrangement of Components of Sonde (Right).....	17
Fig 6 Electrically Short Linear Impedance Probes. (A) Bare Dipole Probe. (B) Insulated Dipole Probe.....	19
 APPENDIXES	
Appendix A: Mutual Impedance of Loops on the Ground.....	24
A.1 Purpose and Scope.....	24
A.2 Theory.....	24
A.3 Approximate Relations for Large Loss Tangents.....	25
A.4 A Measurement Scheme.....	28
A.5 Further Discussion.....	28
Appendix B: Transmission-Line Methods.....	29
B.1 Purpose and Scope.....	29
B.2 Theory.....	29
B.3 Method.....	29
B.4 Results and Discussion.....	31
Appendix C: List of Principal Symbols and Special Terminology.....	31
 APPENDIX FIGURES	
Fig A1 Complex Z_m/Z_o Plot for $\rho/\lambda_o = 0.1$	27
Fig B1 Electrical Characteristics of Drill Hole Water (Goffstown, N. H.), June 1961. Parallel-Wire Transmission Line Method.....	30

IEEE Guide for Radio Methods of Measuring Earth Conductivity

1. Purpose and Scope

The earth's surface and the material below it affect both the point-to-point radio-wave propagation above and below the earth's surface and the impedance of the antennas employed. For this reason the radio engineer is concerned with the macroscopic electrical properties of the earth. The properties of concern here are the conductivity and dielectric constant (or permittivity). We are also concerned with the horizontal stratification that may exist. However, we do not consider the effects of surface roughness in any detail.

In what follows, the magnetic permeability of the earth is taken to be that of free space $\mu_o = 4\pi \times 10^{-7}$ H/m. Exceptions, of course, occur in localized regions containing magnetic material for which the magnetic permeability μ differs from μ_o (for example magnetite).

The techniques for determining the electrical constants of the earth can be broadly divided into two categories:

(1) those where drill-hole access into the earth does not exist

(2) those where drill holes can be employed

Where a drill hole can be used, the methods for single drill holes give localized values of the constants in the vicinity of the hole. Propagation between two holes can be used to deduce bulk values of the electrical constants of the earth between. To characterize a broad area of the earth's surface would require data from an impractically large number of costly holes.

When interest is in the earth constants over a large area, such as coverage for broadcast stations, or where drill holes do not exist, techniques are employed which may be characterized as those which use *surface probes*.

The material in this guide is drawn from numerous articles and papers; most of it is available in the open literature. Useful summary texts are those of Keller and

Frischknecht, Ref [1] and Grant and West, Ref [2]. Theoretical background is found in the prolific writings of Wait, including his book, Ref [3]. These sources treat for the most part surface-probing techniques, although one chapter of Keller and Frischknecht, Ref [1] treats some well-logging methods. Additional material is reported below with pertinent references (Ref [4]).

In Section 2, we discuss techniques using surface probes and in Section 3 we discuss methods suitable for drill holes (including well logging) and, additionally, a few miscellaneous specialized cases. In what follows we exclude discussion of those arrangements which employ gamma, x-ray radiation, or similar sources of radiation.

SI units are employed throughout this guide.

2. Surface-Measurement Techniques (Probes)

The earth sometimes may be considered as a homogeneous (ideal) semi-infinite medium or, in practice, horizontally stratified. The loss tangent for such a conductive medium is

$$p = \tan \Psi = \sigma / \omega \epsilon_o \epsilon_r \quad (\text{Eq 1})$$

where

$$\epsilon_o \approx 10^{-9} / 36\pi \text{ F/m}$$

$$\omega = \text{the angular frequency}$$

$$= 2\pi f$$

$$f = \text{the wave frequency}$$

$$\epsilon_r = \text{the real relative dielectric constant of the earth (or permittivity relative to that for free space).}$$

For most cases of interest, the loss tangent is large.

As we have indicated, radio waves penetrate

into the earth. The wave field strength attenuates exponentially with depth, the field strength decreasing to e^{-1} at the skin depth δ . For highly conducting media

$$\delta = (2/\omega\mu_0\sigma)^{1/2} \quad (\text{Eq 2})$$

Actually most methods give an *apparent conductivity* σ_a since the theory is based on idealization of the model.

Surface measurements can be divided into two categories:

- (1) broad area coverage
- (2) local areas

In the broad area category, described below, ground-wave propagation is the usual method. Local area measurements are of several types, as discussed later.

2.1 Broad Area Coverage. The coverage diagram of a broadcast station is critically dependent upon soil constants. Characterizing coverage areas or states or a country such as the United States requires extensive measurements. The usual measurements are those of measuring the fields from a broadcast station at many points on the surface along radials from the station, or near the surface by airborne receivers.

2.1.1 Theoretical Calculations. The predicted variation of field strength with distance, frequency, soil constants, antenna types, and heights is due to the theoretical work of Norton, Ref [5] and amplified by others such as Wait, Refs [6], [3]. Theoretical curves of field strength versus distance at a given frequency are drawn for several pairs of values of σ and ϵ_r . The measured data are then compared with the theoretical curves. Generally, a range of paired values is obtained. Measurements repeated at other frequencies assist in isolating more correct values of ϵ_r and σ .

Recent theoretical calculations using digital computers have been given by Berry and Chrisman, Ref [7] and by Gerks, Ref [8], based on Bremmer's original equations. Propagation over a stratified earth has been treated theoretically by Wait, Refs [6], [3].

2.1.2 Large Area Maps (Estimated Constants). Estimates of ϵ_r and σ for various types of ground soil (and water) are given in Norton, Ref [5], CCIR, Ref [9], Jordan and Balmain, Ref [10], and FCC publications, Ref [11]. The FCC has published a map of conductivity for

the United States that is useful for broadcasters and for those concerned with radio point-to-point communication. A similar map is available for Canada. There are also standard field-strength curves published by the FCC and the U. S. Army Signal Corps.

These field-strength curves have been prepared for a spherical homogeneous earth. The constants deduced from a measurement are apparent or equivalent values in an actual case.

2.1.3 Wave-Tilt Method. One feature of ground-wave propagation, the *wave tilt*, can be used to deduce earth constants. Assuming for the moment a plane homogeneous earth, the ground-wave fields have two orthogonal electric components; one is the vertical field strength E_v and the other is a radial or longitudinal horizontal component E_h . The wave tilt, Ref [3], is the ratio

$$E_h/E_v \approx n^{-1} (1-n^{-2})^{1/2} \approx \frac{1}{n} \quad (\text{Eq 3})$$

where n is the (complex) refractive index of the earth relative to air given by

$$n = (\epsilon'_r)^{1/2} = (\epsilon_r)^{1/2} (1-jp)^{1/2} \quad (\text{Eq 4})$$

where

ϵ'_r = the complex relative dielectric constant

p = loss tangent given by Eq 1

ϵ_r = the real relative dielectric constant

Since n is complex, the resultant electric vector lies in the vertical plane and its end describes an ellipse tilted forward in the direction of propagation. A measure of the axial ratio and the tilt of the ellipse results in a measurement of n . For large loss tangents

$$n \approx (\sigma/\omega\epsilon_0)^{1/2} \exp(-j\pi/4) \quad (\text{Eq 5})$$

from which σ can then be deduced.

In the high-frequency band and for typical values of σ , n is still large and the elliptical properties are difficult to measure accurately.

An example of hf wave-tilt measurements in determining the electrical parameters of stratified earth is that of Eliassen, Ref [12].

2.1.4 Attenuation Method—Layered Earth Models. Maley, Ref [13], proposed a method to yield ϵ_r and σ for a two-layered earth from measurements of attenuation versus distance of the electric field from a vertical electric dipole. The theory is based upon that of Wait,

Ref [3]. The method is applicable for numerical distances from 0.1 to 10 units, for which values of both ϵ_r and σ result. The procedure for data analysis involves a least-squares process on the data from a large number of measurements. Localized irregularities would then not seriously affect results.

Stanley, Ref [14], published results of field strength versus distance measurements at Point Barrow. The results were matched to theoretical curves for a two-layer model to deduce the electrical constants of the two layers and thickness of the upper layer.

A related phenomenon in ground-wave propagation is that found for a mixed earth, for example, propagation across a land-sea boundary. Millington, Ref [15], evolved a quasi-analytical method for predicting the change in field strength, with results from simulated microwave model measurement. Pressey *et al*, Ref [16], have given quasi-empirical methods for variations of phase of importance to navigational aid devices such as Decca. Wait, Refs [17] and [3], and Wait and Walters, Ref [18], have given the theoretical basis for mixed path ground-wave in both amplitude and phase. The enhancement (or decrease) crossing a boundary depends upon conductivity contrast (for example, land to sea).

2.2 Local-Area Methods. Instead of distances of tens or hundreds of kilometers separating transmitting and receiving antennas, more localized measurements involve separations of the order of 1 km, depending upon the technique. Two major categories exist depending upon whether active or passive methods are used.

2.2.1 Passive Methods. Passive methods involve measurement of natural fields of the earth, for example, magneto-telluric or telluric current methods; currents flow in the earth caused by variations in the earth's magnetic field. Perturbations to the earth's field at frequencies about 1 Hz are attributed to sferics or lightning discharges and exclude man-made noise sources. (While not strictly *radio* methods, these are included here for completeness.) The theory of these methods may be found in the texts by Keller and Frischknecht, Ref [1], or Wait, Ref [3]. Other references include papers by Cagniard, Ref [19], Cantwell and Madden, Ref [20], Lahiri

and Price, Ref [21], Wait, Ref [22], Yungul, Ref [23], and Vozoff, Ref [24].

2.2.1.1 Magneto-Telluric (M-T) Method. In magneto-telluric methods the sources of the fields to be observed are natural telluric currents. The horizontal electric intensity E_h and the orthogonal magnetic intensity H_h are observed. At the earth's surface the apparent complex surface impedance of the earth looking downward is

$$\zeta_a = E_h / H_h \quad (\text{Eq 6})$$

assuming plane waves and uniform stratification. The observations are made at frequencies below 1 Hz at which the loss tangents of the media are large. Then

$$\zeta_a = (j \omega \mu_o / \sigma_a)^{1/2} \quad (\text{Eq 7})$$

for nonmagnetic media, where σ_a is the apparent conductivity of the earth. If the earth is assumed to be horizontally stratified, values of σ_a in Eq 7 may be used to determine the characteristics of those horizontal layers, depending upon the model assumed. Thus, for two-layer models (for example, an overburden of finite thickness above a semi-infinite rock medium) the equations and curves of Cagniard, Ref [19], Wait, Ref [6], and Wait and Conda, Ref [25] may be used for interpretation. For three-layer models, the relations of Cagniard, Ref [19], and the curves of Yungul, Ref [23] may be employed. Vozoff, Ref [24], shows how a generalized inversion technique can yield the stratification model.

E_h is readily observed by using a horizontal wire, usually fed at the center, with ends grounded via electrodes. The wire arms may be arranged in various dipole geometries. The magnetic field is more difficult to observe accurately. The simplest method makes use of the magnetic balance arrangement, with its bar magnet. A recent development is an optically pumped magnetometer (Ref [1], p 239).

2.2.1.2 Telluric-Current Method. In the telluric-current method only the horizontal electric field is measured, avoiding the troublesome measurement of the minute magnetic-field variations. In this method, measurements are made at a base station and at a remote site. Accurate timing is required and