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Special Technical Report 30

THREE TECHNIQUES FOR MEASUREMENT OF GROUND CONSTANTS IN THE PRESENCE OF VEGETATION

By: N. E. GOLDSTEIN   H. W. PARKER   G. H. HAGN

Prepared for:

U.S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY 07703

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STANFORD RESEARCH INSTITUTE

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March 1967

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SRI Project 4240

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ABSTRACT

Foliage degrades the usefulness of conventional wave tilt and propagation loss techniques for estimating in situ the RF ground constants in forested regions. therefore, an investigation was made of three other techniques that should provide more accurate input data for modeling, mathematically, radio antenna performance in forests.

Two of these techniques are RF methods providing complementary information: the open-wire transmission-line probe method gives independent measurements of the near-surface conductivity and the dielectric constant; the dipole feed-resistance (measured as a function of height) method allows a coarse estimate of the effective conductivity to the skin depth. The latter technique, however, requires theoretical refinement before it can be applied singly. At present there is no mathematical basis for evaluating numerically the dipole feed-resistance over a stratified earth.

The third technique, the dc geophysical resistivity method, yields a measure of the earth conductivity stratification beneath the vegetation. The dc resistivity method is supplementary to the RF methods, but its usefulness may be limited to estimation of stratification since the accuracy with which conductivity can be extrapolated from dc to RF is not known. Available literature indicates that the conductivity will be highly dependent on physical-chemical properties (especially moisture content) of the soil and near-surface rocks.

This special technical report describes the three techniques, giving the theory, instrumentation, and methods of interpretation for each. Results of the tests conducted during this investigation are analyzed briefly.

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ACKNOWLEDGMENTS

The authors are indebted to the following colleagues who obtained most of the field measurements used in this report: Withan Makarabhiromya of the Military Research and Development Center Electronics Laboratory in Bangkok; G. M. Roemers of the SRI Communication Laboratory in Menlo Park, and J. D. Hice and Narong Yoothanom, both formerly of the SRI Communication Laboratory.

The authors also wish to thank J. R. Wait of ESSA, Boulder, and L. J. Mueller of USAECOM, Fort Monmouth, for their helpful comments on a draft of this report.

I INTRODUCTION

Because of a need to know the electrical constants of earth beneath forest vegetation in order to determine the directivity pattern, efficiency, and impedance of antennas surrounded by forest,[1*] Stanford Research Institute has applied a combination of tools and developed techniques for obtaining such information. This effort has been in support of the SEACORE program of Project AGILE, under Contract DA 36-039 AMC-00040(E) monitored by the U.S. Army Electronics Command (USAECOM) for the Advanced Research Projects Agency (ARPA).

We have selected for study several convenient methods of obtaining radio-frequency ground-constant estimates in terrains where the application of techniques conventionally used by radio engineers will be invalidated by the presence of foliage. The wave-tilt method, for example, was ruled out because of wave scatter from the trees.[2] The technique of curve-fitting path-loss data to model calculations requires that the model include trees, and it also was ruled out because present models for forest radio wave propagation incorporate ground constants as only a second-order effect.[3,4] Indeed, simple forest-slab models that neglect the presence of the ground entirely have been used successfully to describe wave propagation over forested terrain.[5]

Many methods for obtaining ground constants have been studied and used under the current contract,[6] but apparently only three of these are suited to measurement in the presence of vegetation. These are:

(1) Open-wire transmission line (OWL)[7]

(2) Direct-current resistivity sounding[8]

(3) Dipole feed resistance, $R(H,\lambda)$.

In this technical report we refer to electrical conductivity, dielectric constant, and magnetic permeability as ground constants.

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*References are given at the end of this report.

The word "constant" is inexact, however, since all three parameters will vary (even for a given frequency) with location because of differences in climate, physiography, and geology. Furthermore, at any site, the electrical conductivity and dielectric constant might show a seasonal variation in response to the varying moisture content of the near-surface soil and rocks. In regions of the world with pronounced wet and dry seasons, the near-surface conductivity and dielectric constant can change by factors of 10 and 5, respectively, over the course of a year.

In order to realize fully the usefulness of ground-constant measurements as a means for evaluating electromagnetic-wave propagation over an area, a fairly complete knowledge of the specific environment is necessary. In addition to knowing the ground constants, ideally we should also know the following:

(1) Pedagogical description of the soil, including

  (a) Soil particle size distribution

  (b) Soil mineralogy

  (c) Percentage of interstitial water by volume at times of maximum and minimum water saturation

  (d) pH (Hydrogen ion concentration)

  (e) Water salinity

  (f) Underlying geology

(2) Variety and density of local vegetation

(3) Local topography

(4) Altitude of the site

(5) Yearly rainfall pattern of the region

(6) Yearly temperature variation.

With this information we can attempt to estimate the seasonal variation of the ground constants. We can also interpolate or extrapolate, with greater confidence, ground-constant information taken at widely separated sites.

Clearly, then, the determination of ground constants and the intelligent use of this information require an appreciation of geology and geophysics. However, the field engineer, unskilled in analyzing the natural environment, will in most cases require only a few simple field methods by which he can evaluate the performance of his antennas and radio systems. It is for him that this special technical report is oriented.

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II SUMMARY

The open-wire transmission line (OWL) is a balanced, two-conductor earth probe, whose input impedance (when inserted into the ground) is used to calculate the relative dielectric permittivity, conductivity, and magnetic permeability of ground near the probe. Since only a small volume is sampled, the technique has a disadvantage in that a statistically acceptable number of samples must be taken in order to estimate the ground constants of any large region. A further consequence of this limited sampling feature is that only surface constants can be obtained without digging or drilling holes, making this type of probe more valuable at VHF (where the skin depth is relatively small).

The advantages of the OWL technique are its simplicity and ease of operation, and its adaptability to calibration in the laboratory using samples with known properties or to calibration in the field with air as the standard.

Futhermore, measurements with the OWL are fairly accurate (±10 percent in most soils) as well as reproducible, and they can be made at the frequencies of interest. For most soils the technique will give a satisfactory estimate of relative permittivity even when only moderate care is exercised in performing the measurements. However, greater care must be taken if a reliable conductivity estimate is desired (i.e., one must consider the type of soil and probe dimensions and strive for the greatest measurement accuracy). The technique has the advantage of providing magnetic permeability estimates. This feature is not important for most soils, since they have permeability very nearly that of free space, but the permeability value can serve as a check on the reliability of the other constants calculated from the measured data.

Direct-current resistivity sounding supplements the OWL method as an earth-penetration technique.* Current is introduced into the ground by means of two current electrodes, and the resulting potential difference between two other electrodes at the earth surface is measured. Several schemes for arranging these electrodes are commonly used,[9] and the result is a determination of the apparent earth resistivity (ρ_A) as a function of current-electrode separation. As this separation is increased, the depth of current penetration into the earth increases, and the resulting apparent resistivities reflect the conductive characteristics of the ground at progressively greater depths. These ρ_A data are compared with theoretical curves of earth-model apparent resistivity to estimate effective conductivities and layer thicknesses for the area studied.

Prior knowledge of the geology of a region is helpful in these interpretations but not essential if the electrode separations are made sufficiently large so that gross features of the earth stratification become apparent. A common rule is that depth of penetration will be about one-half the current-electrode spacing; and spacings of 170 to 600 meters are common in geophysical prospecting. For radio-propagation applications, spacings out to about 70 meters should suffice, since the skin depth rarely is greater than 30 meters at HF and above. Usually, the linear arrays are set up in two orthogonal directions, in sequence, as a check on homogeneity. Thus gross vertical and horizontal earth electrical profiles can be inferred, in addition to the magnitude of earth conductivity at dc. However, *a priori* knowledge of the frequency dependence of conductivity for the type of ground measured is required in order to extrapolate the dc values to radio frequencies, and such

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*The use of audio frequencies may be better than dc because the audio frequencies are low enough to effect penetration but some of the problems of coupling to the earth (e.g., polarization of the ground near the electrodes) are avoided.

knowledge is not usually available.* Therefore, the primary value of dc sounding in radio work is in determining whether earth electrical properties at radio frequency can be expected to change within one skin depth of the surface.

Another technique, developed entirely by SRI, involves the use of a theoretical model for antenna impedance in conjunction with measured feed-point resistances [$R(H,\lambda)$] obtained for a half-wave horizontal electric dipole antenna at several heights H above earth. The feed-point resistances are measured as functions of antenna height and frequency with standard impedance bridges, usually not transformed to balanced feed connection.† The measured values are compared to theoretical curves for a "best fit" estimation of the effective conductivity of the underlying earth.

In its present state of development this method is not particularly useful unless used in conjunction with the other techniques. The method does not give reliable information on the dielectric permittivity; therefore, an inaccurate value of conductivity will result unless a separate means, such as the OWL method, is used to determine the dielectric permittivity. Moreover, the dipole feed-point resistance method currently is limited by an inadequate theoretical analysis. The interpretation curves generated for the technique assume a homogeneous earth, whereas the real ground often is better approximated by a sequence of horizontal layers, each with different conductivity and dielectric permittivity. This is because the near-surface earth usually is vertically inhomogeneous. For this reason the method should be used with the dc-resistivity

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*J. R. Wait (private communication) thinks one could extrapolate with some confidence (there is still an accuracy problem) from ρ_A soundings made at audio frequencies, and he recommends using right-angular or dipolar arrays as well as the Wenner array. The dipolar array has several advantages (see pp. 97-100, Ref. 10) and using audio frequency as high as possible makes sense.

†Maintaining a balanced feed is relatively unimportant when the antenna is operated in the half-wave resonant mode.

method so that the probable effect of electrical-property layering can be surmised. To make the dipole $R(H,\lambda)$ technique more powerful, attention must be given to solving the theoretical problem of the feed-point resistance of a horizontal electric dipole over an arbitrarily layered earth.

Despite its shortcomings, the dipole $R(H,\lambda)$ technique is useful if we desire a rough estimate of the effective ground conductivity to the skin depth at the frequency of excitation, and it can be used in most forests because the horizontal antenna elements do not couple efficiently to the predominantly vertical stems of the vegetation, provided the antenna is located at $\lambda/10$ above ground or less, the frequency is below about 15 MHz, and foliage is not allowed to touch the antenna. This technique would, of course, be most exact for a dipole over open, flat homogeneous terrain.

One other technique, not considered by us, which has potential application to the measurement of RF electrical constants in forested (or any variegated) terrain, involves using the inductive coupling between an oscillating magnetic dipole transmitter and a receiver oriented to minimize vegetation coupling effects.[10] However, calculations from theory[11,12] for this and similar techniques have neglected displacement currents, so that their use has been restricted to the lower frequencies. Because of the high measurement accuracy and/or refinement of the instrumentation required, we have not tried to adapt induction techniques to radio field engineering, but they may well provide a basis for obtaining efficient estimates of electrical terrain properties for very large regions--especially at frequencies low enough that displacement currents may safely be neglected.

The conventional techniques--such as wave-tilt methods and path-loss curve fitting--have been used by SRI to document ground constants in open terrain,[6] but the three techniques discussed above show more promise for vegetative terrain--and they can be used in open terrain as well.

III TRANSMISSION-LINE METHOD

A. Theoretical Considerations

A balanced, two-conductor transmission-line probe can be used to measure the electrical parameters of earth, as suggested by Kirkscether in 1900.[7] The technique depends on measurement of the input impedances of a transmission line inserted vertically into earth, and on the assumption that earth in the vicinity of the two-conductor probe is not so highly conductive that the use of simple transmission-line theory is precluded. If the input end of the line is at the earth's surface, and input impedances Z_1 and Z_2 are measured for two probe lengths L and 2L respectively, then the characteristic impedance Z_o of the line in earth can be computed:

$$Z_o = \left[Z_1\left(2Z_2 - Z_1\right)\right]^{1/2} \quad , \tag{1}$$

where the Z's are complex. From Eq. (1) the complex propagation constant Γ for TEM waves on the line in earth may be found:

$$\Gamma = \frac{1}{L} \operatorname{arctanh} \frac{Z_o}{Z_1} \quad . \tag{2}$$

If the impedance measurements are repeated in air for the same spacing between conductors, we can estimate the ground constants relative to a "calibration" in air. Using primes to denote air-related symbols,* we then have

$$\epsilon_r = \frac{\omega'}{\omega} \mathrm{Im}\left\{\frac{\Gamma}{Z_o}\right\} \div \mathrm{Im}\left\{\frac{\Gamma'}{Z_o'}\right\} \tag{3}$$

---

*In practice, the same nominal frequency is used for both air and ground measurements, but often a slightly different frequency is required to balance the system (slightly different ambient temperature, etc.) and the ω'/ω ratio provides the required correction.

$$\delta = \cot \left[\text{ARG} \frac{\Gamma}{Z_o} \right] \tag{4}$$

$$\mu_r = \frac{\omega'}{\omega} \, \text{Im} \left\{ Z_o \Gamma \right\} \div \text{Im} \left\{ Z_o' \Gamma' \right\} \quad , \tag{5}$$

where

ϵ_r = relative dielectric permittivity of earth

μ_r = relative magnetic permeability of earth

δ = loss tangent of earth

ω = radian wave frequency (radians/meter)

Im = imaginary part of the complex variable

ARG = phase angle of the complex variable.

The other parameters of the medium in the vicinity of the line follow from those above:

$$\text{conductivity } \sigma = \omega \, \epsilon_o \, \epsilon_r \, \delta \quad , \tag{6}$$

$$\epsilon_o = 8.854 \times 10^{-12} \text{ farad/meter} \quad , \tag{7}$$

$$\text{attenuation rate } \alpha = \frac{\omega}{c} \left[\frac{\mu_r \epsilon_r}{2} \left(-1 + \sqrt{1 + \delta^2} \right) \right]^{1/2} \quad , \tag{8}$$

$$\text{phase constant } \beta = \frac{\omega}{c} \left[\frac{\mu_r \epsilon_r}{2} \left(1 + \sqrt{1 \div \delta^2} \right) \right]^{1/2} \quad , \tag{9}$$

Usually the permeability μ_r, which is computed as an accuracy check, can be assumed equal to one.

When $\Gamma L \ll 1$ (at low frequency and/or short probe length), the line acts as a capacitor and we can write simple approximations to the above expressions.* Assuming $\mu_r = 1$, we find that if $\Gamma L \ll 1$ we need only measure Z_1 and Z_1' to estimate the ground constants:

$$\epsilon_r \approx \frac{\omega'}{\omega} \frac{\mathrm{Im}\{Z_1'\}}{\mathrm{Im}\{Z_1\}} \quad , \tag{10}$$

$$\delta \approx - \cot \left[\mathrm{ARG}\ Z_1 \right] \quad . \tag{11}$$

The remaining constants may be found from Eqs. (6) through (9). This approximate technique is clearly the simplest for field work and, for radio engineering purposes, can probably be applied with confidence in any soil at frequencies below at least 3 MHz.

If ω is in radians/second, Z in ohms, and L in meters, the equations in this chapter produce σ in mhos/meter, α in nepers/meter, and β in radians/meter.

B. Measurement Technique

In all measurements of impedance using standard bridges we have transformed the impedance through some length of coaxial line or balun to obtain the true input impedance of the transmission-line probe. The transmission-line probe itself is made of two brass rods, in sets 10- and 20-cm long, with a 2.5-cm dielectric spacer at the input to each set. Holes are made in the earth to accept the rods at a leveled spot where punching or drilling can be kept parallel.

In obtaining measurements by the OWL technique, Kirkscether[7] sacrificed some accuracy by using an unbalanced connection to a General Radio 916-A RF bridge at frequencies up to 10 MHz. The error introduced in this way is probably not serious if the approximate solution can be used

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*Using the probe as if it were a capacitor also allows measuring under conditions of high loss where strict transmission-line theory may not apply. One could also use capacitor probes of other geometries.

for computing the ground constants (i.e., assuming that the line acts like a capacitor); but the approximation may not be applicable in the general case at frequencies as high as 10 MHz. We have used an unbalanced General Radio 1606-A RF bridge at low HF and a General Radio 1602-B Admittance meter and Boonton 250-A RX meter with coaxial transmission-line balun at higher frequencies (Fig. 1).

FIG. 1 GROUND-CONSTANT MEASUREMENTS WITH VHF OWL PROBE

C. Preliminary Results

The transmission line was used in this configuration to measure earth constants at a field site in the vicinity of Ban Mun Chit, Cholburi Province, southeastern Thailand, where the soil had the appearance of brown, sandy loam. The results are presented in Fig. 2. Mean values of ϵ_r and σ are plotted as functions of frequency. The dashed curves indicate the observed general trends, which are in agreement with previous observations.[13,14] In sandy soil, moisture content has the dominant influence on electrical constants. The average natural moisture content of the soil within one meter of the surface at Ban Mun Chit site was estimated at only about 10 percent by weight, with extreme variations between 6 and 18 percent.*

We have also successfully used a larger ground probe (essentially similar to the one described above, scaled up to a spacing of about 10 cm) consisting only of 3-cm diameter brass rods inserted in carefully spaced holes punched in the earth. This configuration, tested at Coyote Hills, California, near Fremont, was adequate for measurement by the approximate method.

The Coyote Hills site, a flat low land about 1 kilometer from San Francisco Bay, was covered with dry grass. The area was dry on the surface during the August 1966 test period, but there is often flooding during the winter rainy season (see Fig. 3). The water table in the area rarely drops more than a few feet below the surface. After reading radio handbook discussions one would probably term the soil "good" ground.[15]

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*Private communication from Environmental Research Division, Military Research and Development Center, Bangkok. This was based on laboratory measurements using core samples from the near-surface soil, which was classified as brown sand by the soil specialists.

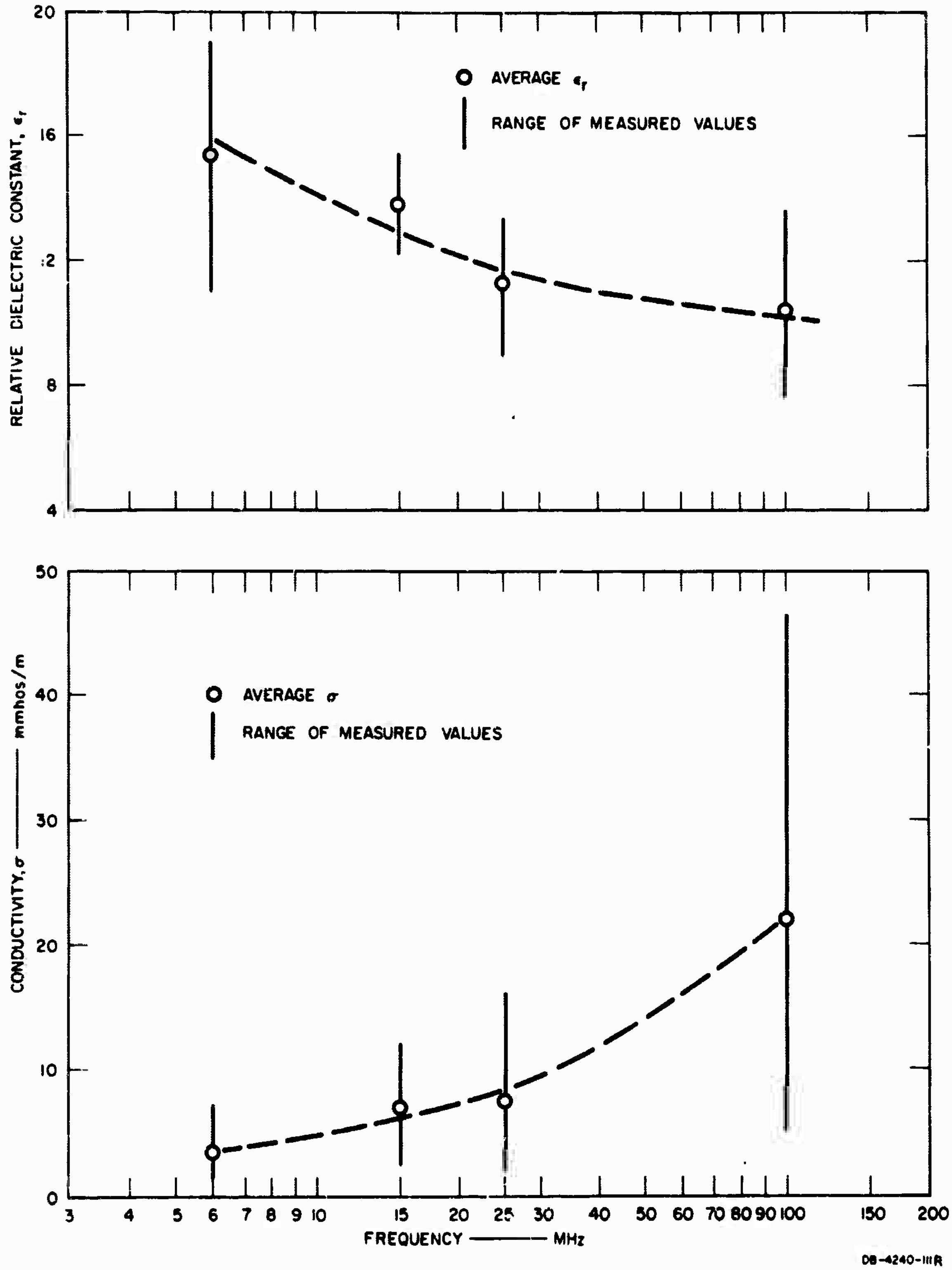

FIG. 2 GROUND CONSTANTS AT BAN MUN CHIT FROM OWL METHOD

FIG. 3 COYOTE HILLS TEST SITE

From the approximate measurements at 6 MHz with the transmission-line probe at that site, we calculated that $\epsilon_r \approx 21$ and $\sigma \approx 0.01$ mho/meter for the surface layer of earth down to about one-half meter. (A loss tangent of 3 was calculated from the measured values.)

IV DC RESISTIVITY SOUNDING*

A. Introduction

The open-wire transmission-line technique (OWL) of Sec. II can be employed to obtain radio-frequency (RF) values of ground constants beneath living vegetation for use in slab-type mathematical models, but some assurance is required that the values obtained at the surface with the OWL will apply to sufficient depth to permit the use of only one ground layer in the model. Direct-current sounding, as used in electrical prospecting and ground water problems, provides a way to estimate the change in electrical properties of the earth as a function of depth.

A dc vertical-resistivity profile can be obtained from a succession of apparent resistivity measurements (defined below) made with an array of electrodes inserted only a small distance into the earth's surface. Direct (or commutated direct) current is delivered to the ground through one pair of electrodes (A and B) in a four-electrode array, and the resulting potential gradient is measured by means of the second pair of electrodes (M and N)- see Fig. 4. The resistivity of homogeneous earth is given by

$$\rho = 2\pi \frac{\Delta V}{I} \cdot \frac{1}{G} \quad , \qquad (12)$$

where

ΔV = the potential difference measured between the potential electrodes

I = the current applied to the ground

G = a geometrical factor which depends on configuration of the four-terminal electrode array.

---

*The sounding arrays described in this section can also be used at audio frequencies where the accuracy may be somewhat improved because of improved coupling to the earth.

In general, G is expressed as

$$G = \frac{1}{\overline{AM}} - \frac{1}{\overline{BM}} - \frac{1}{\overline{AN}} + \frac{1}{\overline{BN}} \quad , \tag{13}$$

where $\overline{AM}$ is the distance between current electrode A and potential electrode M, etc.

If the earth is not uniform, and it is often unwise to assume the contrary, Eq. (12) yields a value that may be unlike any true resistivity or even average resistivity of the earth. In this case, Eq. (12) defines a quantity called the apparent resistivity ρ_A, which can have a wide

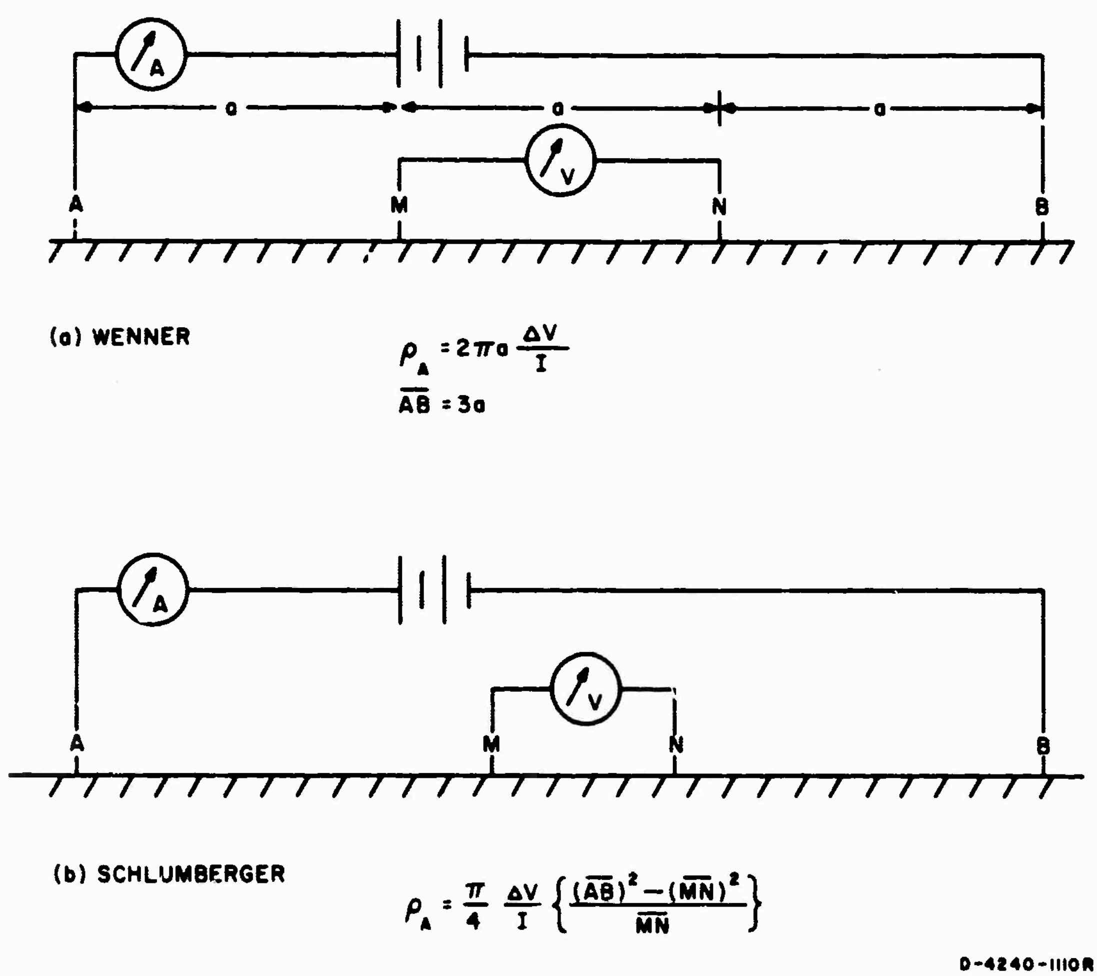

FIG. 4 SCHEMATIC DIAGRAMS OF WENNER AND SCHLUMBERGER dc RESISTIVITY METHODS

range of values depending on the rock-resistivity variation within the earth and the locations of the electrodes in the array.

As the spacing $\overline{AB}$ between current electrodes is increased, the variation in apparent resistivity will be due primarily to the effect of increased current pentration into the earth--provided that the resistivity of the soil surrounding the electrodes does not vary appreciably as the electrodes are moved to various positions in the area being sampled. A quantitative interpretation of the observed surface difference of potential, in terms of electrode spacing and applied current, can be made by comparing the observed data with a prepared set of theoretical curves for various stratified-earth resistivity-profile models.*

Suggested field practices for applying the dc sounding method are given in Appendix A.

B. Technique and Analysis

The most common electrode configuration used are those in which the electrodes are colinear and arrayed symmetrically about a point, such as the Wenner and Schlumberger configurations† shown in Fig. 4. The Schlumberger electrode configuration has two advantages: (1) it requires only infrequent increases of potential electrode separation as the current electrodes are moved apart; and (2) it yields good definition of local inhomogeneities close to the potential electrodes. In the Schlumberger configuration the distance $\overline{MN}$ is in principle infinitely small so that the actual potential gradient is measured. However, in practice $\overline{MN}$ can only be kept as small as is commensurate with the

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*A more exact model fit can be obtained by trial and error if a computer is available.

†Watt, et al., in Ref. 9 recommend using the Eltran or dipole arrays when spacings up to a skin depth are employed. At frequencies and spacings where mutual coupling becomes a problem, the right-angle array described by Wait and Conda[16] is probably least subject to errors.

sensitivity of the measuring instruments and the amount of current driven into the earth. The Wenner array has all four electrodes equally spaced, the distance a between adjacent electrodes (called the electrode spacing) being as large as is desired. This avoids the accuracy problem of the Schlumberger array but at the expense of more setups per site.

The Wenner configuration is generally preferred over the Schlumberger for the following reasons. First, measurements of ρ_A are more precise because $\overline{MN}$, hence ΔV, is larger. Second, measurements of ρ_A are less affected by local inhomogeneities that might occur in the earth near the potential electrodes.

Since the primary purpose of the dc sounding under consideration is to obtain stratification information to depths pertinent to radio frequencies, we must estimate the depth at which the RF currents become--in the context of our mathematical radio propagation models--negligible. One way of accomplishing this is outlined as follows:

(1) Use the OWL technique to estimate σ and ϵ_r at the surface.

(2) Use these data to compute skin depth of the soil at the lowest frequency of interest.*

(3) Assuming that the ground is nearly homogeneous, choose a maximum electrode spacing $\overline{AB}$ at least twice that of the skin depth.

(4) Examine the change in ρ_A with current electrode spacing. If this function varies slowly or not at all, the OWL values can be used with confidence.

If ρ_A changes markedly with electrode spacing, the σ, and probably ϵ_r, are varying with depth, and the OWL measurements at the surface must be supplemented by further work.

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*If $\sigma \gg \omega\epsilon$, we can approximate skin depth by $\delta s \approx (\sigma\omega\mu/2)^{-1/2}$ (Ref. 17). Otherwise, $\delta_s = \{[(\omega^4\mu^2\epsilon^2)/4 + (\sigma^2\mu^2\omega^2)/4]^{1/2} - (\omega^2\mu\epsilon)/2\}^{-1/2}$.

We can either repeat the OWL measurements at various depths or attempt to estimate from the dc resistivity data the σ and ϵ_r at the radio frequencies of interest. Of these two methods, the latter is the easier to apply, but how well dc ground constant data can be extrapolated to radio frequencies has not been studied adequately. We do know that the influence of soil water must be taken into account. An indication of the probable range of error arising from neglect of moisture content when extrapolating earth conductivities from 1 kHz to 1-10 MHz may be inferred from Fig. 5. The limits of the shaded areas are based on the measurements reported in Ref. 14, pages 14 through 19. This figure shows that inaccurate knowledge of the soil water content can lead to as much as an order-of-magnitude error in conductivity when conductivities measured at 1 kHz are extrapoled to the 1- to 10-MHz range.

In electrical sounding work, at sites where little is known about the geology, it is advisable to conduct two orthogonal soundings to determine whether the ground has an apparent anisotropy that would influence the interpretation of the ground constant data. We use the words "apparent anisotropy" because the "crossed-array" measurements do not permit a distinction between a true anisotropy of the soil and/or rocks and a subsurface inhomogeneity near one of the electrodes. To obtain a better idea of whether anisotropy or inhomogeneity exists in the near-surface soil and rock, we could rotate the entire crossed array by 30° or 45° and repeat the measurements. If anisotropy were present, the four ρ_A's measured for a given electrode spacing would all be different but fairly close in value. If inhomogeneity were present, three of the four ρ_A's measured for a given electrode spacing would be roughly the same magnitude, but the fourth would be much larger or smaller than the others.

Some apparent anisotropy is to be expected in the data from orthogonal depth soundings. The coefficient of anisotropy is given by

$$C = \left[\frac{\rho_A^p(a)}{\rho_A^q(a)}\right]^{1/2} ,$$

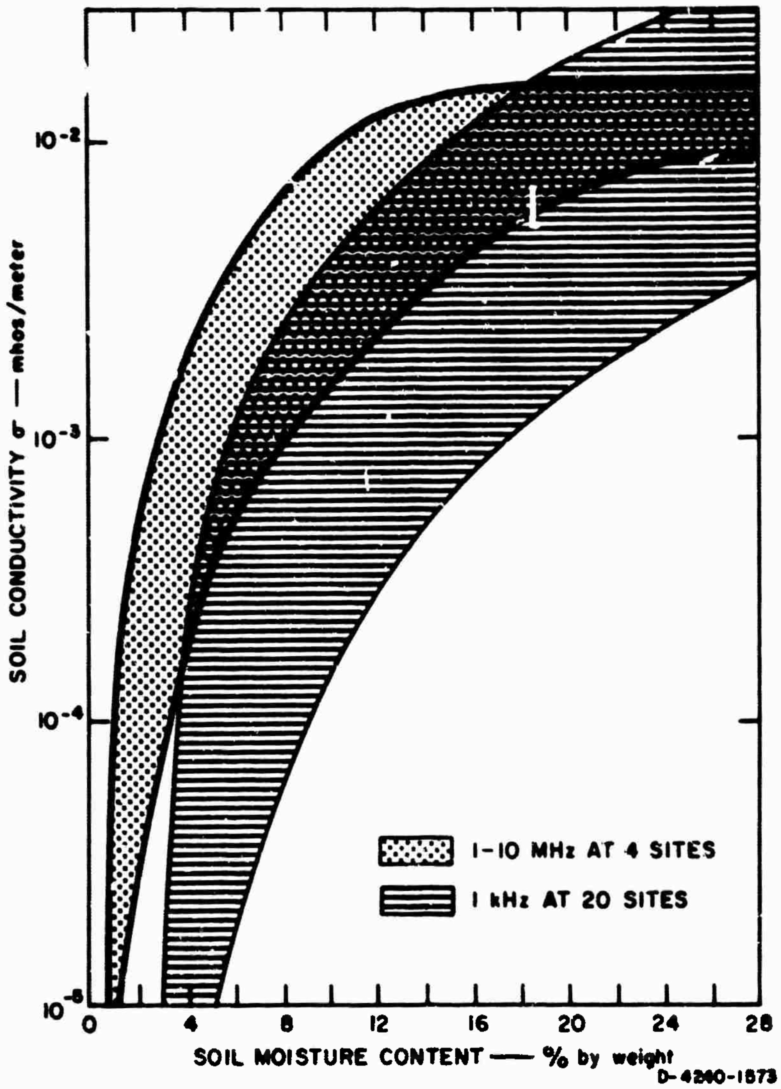

FIG. 5 TYPICAL RANGES OF VARIATION OF SOIL CONDUCTIVITY (in England) WITH MOISTURE CONTENT FOR FREQUENCIES BETWEEN 1 AND 10 MHz AND AT 1 kHz (after Ref. 14)

where $\rho_A^p(a)$ and $\rho_A^q(a)$ are the apparent resistivities measured in the orthogonal directions p and q for an electrode separation a. Often $C \approx 1$; and, when this is the case, we are fairly safe in ignoring apparent anisotropy. However, it is wise practice to calculate C as the measurements are being made in the field to decide whether soundings should be made in other directions. If the apparent anisotropy is great, the interpretation of (and use of) the results becomes rather complicated.

To facilitate analysis, the results of electric soundings are usually plotted on full-logarithmic graphs, with the electrode spacing plotted on the abscissa. A standard presentation is shown in Fig. 6.[18] In this figure three different stratified-earth models are shown, but the ratios of the resistivities and the ratios of the layer thicknesses are constant for all three models. Use of the logarithmic scale results in identical curve shapes regardless of the actual magnitudes of the variables. That is, all three curves would superimpose with simple translations of the coordinate axes. This allows simple comparison of the field curves with theoretical curves prepared in advance for a variety of stratified-earth models.[19]

C. Examples of Direct-Current Resistivity Measurements

1. Coyote Hills, California

Background: A resistivity survey was made at the Coyote Hills site (near Fremont, California)[*] on 24 August 1966 by members of the SRI Communications Laboratory. The instrument used was the ABEM "Terrameter," manufactured by the ABEM Company in Stockholm, Sweden. This device is designed for use with a Wenner electrode configuration (Fig. 4).

Discussion of the Data: For the interpretation of resistivity depth-sounding data, measurements by means of the Wenner configuration permit the use of theoretical curves prepared by Mooney and Wetzel.[19] These curves are given for a wide range of stratified two-, three-, and four-layer earth models. The procedure for interpreting these curves is purely mechanical except perhaps for noting whether the earth model derived is consistent with known or inferred geology.

Values of apparent resistivity were calculated and plotted against electrode spacing a. Matching the observed values in Fig. 7 to the Mooney curves gives the following interpretation:

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[*] Described on page 13.

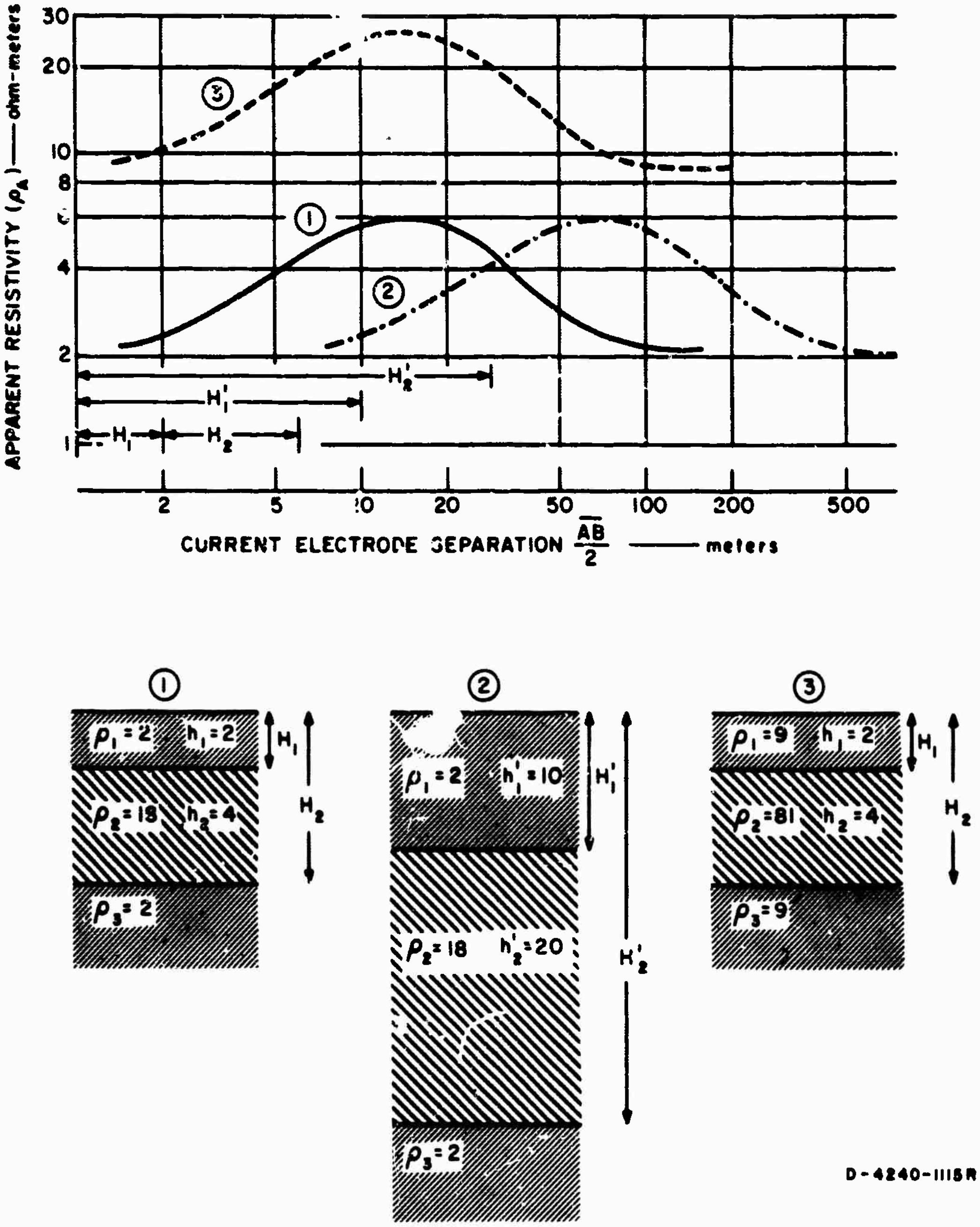

FIG. 6 STANDARD PRESENTATION OF APPARENT-RESISTIVITY DATA FOR THREE EARTH MODELS

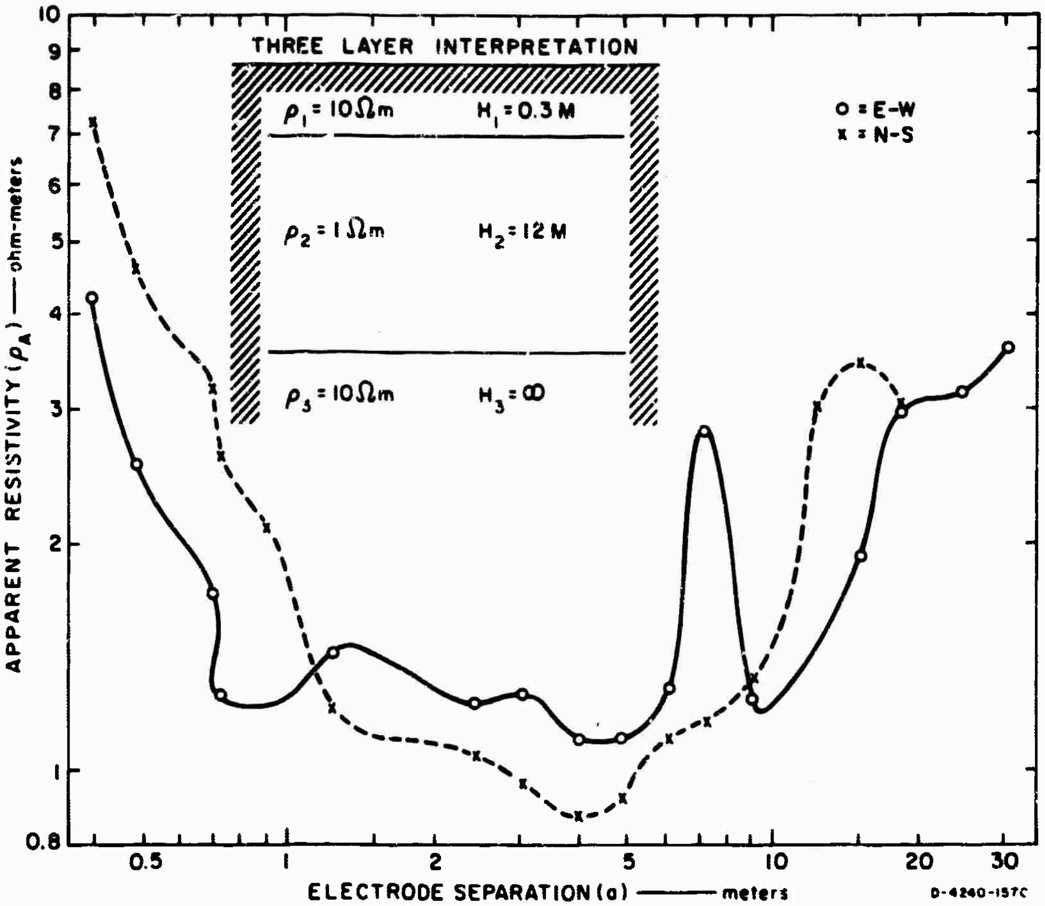

FIG. 7 APPARENT RESISTIVITIES AND THEIR INTERPRETATION — COYOTE HILLS SITE

(1) A thin surface layer, approximately 30 cm thick, exists for which the resistivity is about 10 ohm-meters.

(2) There is an intermediate conducting layer, ex-extending to about 7.5 meters beneath the surface, with a resistivity of only about 1 ohm-meter.

(3) A lower layer (of undetermined depth and extent) exists in which the dc resistivity is again about 10 ohm-meters.

The maximum electrode separation was only 30.5 meters and thus nothing can be inferred regarding earth resistivities below about 15 meters (50 feet). There is a slight indication of a fourth layer because of a change in slope in ρ_A at a $\approx$ 15 meters on the North-South electrode array. However, as a similar feature was not measured on the East-West line, a four-layer interpretation does not seem to be warranted. The measured data are basically identical for the soundings in the two orthogonal directions. Hence, no significant anisotropy is apparent. The earth model derived is consistent with a geological environment of water-bearing sands and shales fairly recent* in deposition.

2. Ban Mun Chit, Thailand

Background: On 7 June 1966 an earth-resistivity survey was made on a forest trail at Ban Mun Chit, Thailand by SRI Communications Laboratory personnel. The Schlumberger electrode configuration was used: two potential electrodes remaind fixed and two current electrodes were moved progressively farther apart (Fig. 4). The four electrodes were colinear and symmetric about the midpoint between the potential electrodes. The apparatus used in this survey (a standard power supply, voltmeter, and ammeter) was assembled from available laboratory equipment.

Analysis of Data: Apparent resistivity was calculated for the various electrode separations at which readings of voltage potential and current insertion were made. The apparent resistivity is given by the following equation:

$$\rho_A = \frac{\Delta V}{I} G^{-1}$$

$$G^{-1} = \frac{\pi}{b}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{b}{2}\right)^2\right]$$

$$G^{-1} \cong \frac{\pi L^2}{4b} \qquad \text{if } L \geq 5\,b \quad . \tag{14}$$

Here, b is the distance $\overline{MN}$ of Fig. 4. Because Eq. (14) is exact for any ratio L/b, we used it in the calculations (Table I), which were carried out by slide rule.

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*Quaternary or Tertiary in geological terminology.

Table I

DIRECT-CURRENT RESISTIVITY SURVEY--BAN MUN CHIT, 7 JUNE 1966

	(meters)									
	L/2	b/2	ΔV(x)	I(a)	ΔV/I	G_1^{-1} *	G_2^{-1} †	ρ_A (Ωm)	P§	Δ C**
N-S	1.22	0.61	16.5	0.13	128.0	12.6	9.4	360	50.0	1.22
	1.83		8.9	0.14	63.5	28.2	25.2	480	18.0	1.09
	2.44		3.7	0.10	37.0	50.0	47.2	523	11.0	1.05
	3.05		2.25	0.105	21.5	78.0	75.2	487	35.0	1.16
	3.66		1.85	0.130	14.2	112.0	110.0	500	43.0	1.19
	4.28		0.86	0.120	7.2	151.0	151.0	324	17.0	1.08
	4.88		0.60	0.115	5.2	209.0	198.0	310	38.0	1.17
	5.50		0.46	0.120	3.8	253.0	251.0	295	73.0	1.31
	6.10		0.35	0.122	2.9	315.0	312.0	262	95.0	1.39
	6.70		0.254	0.115	2.2	383.0	377.0	253	284.0	1.68
	7.92		0.145	0.120	1.2	530.0	529.0	190	810.0	2.84
E-W	1.22	0.61	20.0	0.110	182		9.4	542		
	1.83		9.4	0.125	75		25.2	570		
	2.44		4.0	0.120	33.5		47.2	470		
	3.05		1.6	0.100	16.0		75.2	360		
	3.66		1.05	0.100	10.5		110.0	350		
	4.28		0.64	0.105	6.2		151.0	276		
	4.88		0.45	0.120	3.8		198.0	224		
	5.50		0.27	0.120	2.3		251.0	170		
	6.10		0.23	0.160	1.4		312.0	134		
	6.70		0.06	0.145	0.4		529.0	66		
	7.92		0.02	0.190	0.1		705.0	21		

* $G_1^{-1} = \frac{\pi L^2}{4b}$

† $G_2^{-1} = \frac{\pi}{b}\left[\left(\frac{L}{2}\right)^2 - \left(\frac{b}{2}\right)^2\right]$

§ P = percent anisotropy = $\left[1 - \frac{\rho_A(N\text{-}S)}{\rho_A(E\text{-}W)}\right] \times 100$

** Δ C = coefficient of anisotropy = $\left[\rho_A\,(N\text{-}S)/\rho_A\,(E\text{-}W)\right]^{1/2}$

In Fig. 8 we show the apparent resistivities (ρ_A) plotted against $\overline{AB}/2$ ($\overline{AB}$ = L) for the line of electrodes in two orthogonal directions, north-south (N-S) and east-west (E-W). For measurement made in the E-W direction, Fig. 8 shows that ρ_A decreased almost monotonically with increasing $\overline{AB}/2$. Our interpretation of this curve is that a layer several feet in thickness exists at the surface. This layer has a resistivity, roughly 600 ohm-meters, that is extremely high for soil, being comparable to that reported in the literature for young granite deposits. An exact description of the soil at this site--which appeared to be brown, sandy loam--will be given in Ref. 20.

Below the near-surface region the rocks appear to become more conductive. The E-W curve in Fig. 8 may be interpreted as showing that a resistivity of less than 10 ohm-meters occurs at a depth of about 3.3 meters. However, a reliable estimate of resistivity as a function of depth cannot be made from the data because the current electrode separation was not increased sufficiently and because a significant anisotropy is indicated by the difference between the E-W and N-S curves (the rocks seem to be much more conductive in the E-W direction than in the N-S direction.)

Coefficients of anisotropy were calculated (see Table I) and found to range between 1.05 and 2.84. These coefficients increase with depth, and an order-of-magnitude difference in resistivity occurs for $\overline{AB}/2$ equal to 8 meters. Because the Schlumberger technique is highly sensitive to local inhomogeneities near the potential electrodes, we suspect that the pronounced differences in resistivity are either (1) a consequence of nonuniform rock weathering, or (2) a result of the presence of tree roots near the potential electrodes, since the array was placed among large trees.

<u>Conclusion</u>: In this survey the electrode separation was not large enough to provide a good estimation of near-surface earth resistivities. All we can say about the Ban Mun Chit site is that a layer approximately 3 meters thick lies at the surface with a resistivity of

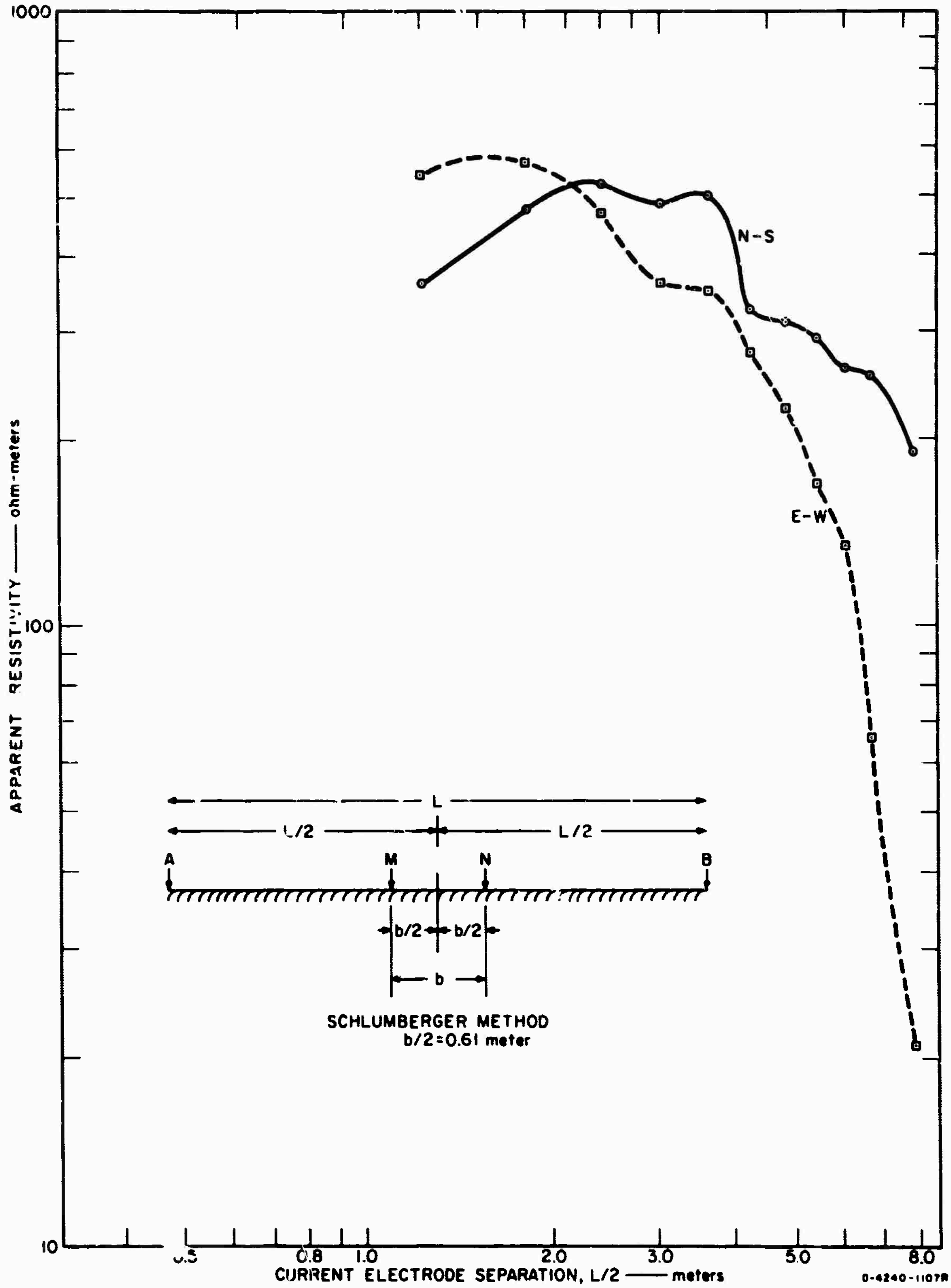


FIG. 8 APPARENT RESISTIVITY AT BAN MUN CHIT SITE

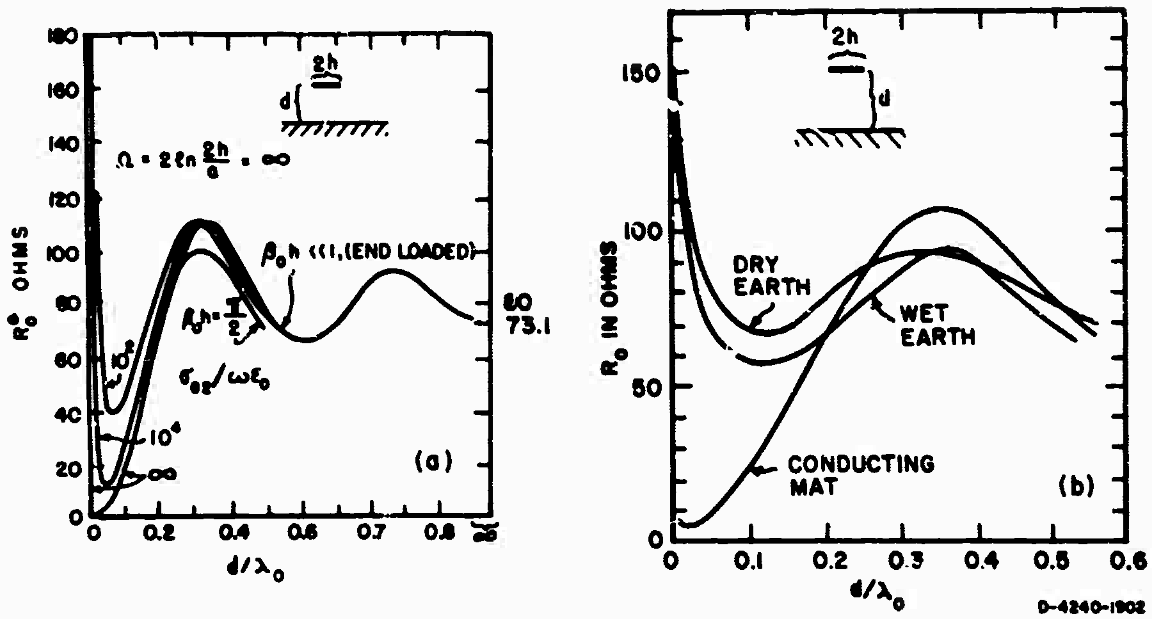
300 to 600 ohm-meters.* Beneath the surface layer the resistivity decreases to, perhaps, less than 10 ohm-meters. The pronounced local anisotropy and the limited electrode separation make it difficult to guess what the bulk resistivity of the underlying rocks might be.[21]

*Conductivity at dc of 1.7 to 3.4 millimhos/meter.

V DIPOLE FEED-RESISTANCE METHOD

A. Discussion of R(H) Method

The problem of determining the losses of horizontal dipole antennas located over imperfectly conducting earth has been considered for many years. An excellent bibliography of early references is given by King,[22] who points out that "an analysis of the impedance of an antenna of length h and small radius a at a height d > h over a plane earth with arbitrary conducting and dielectric properties is an intricate problem still awaiting solution." The first major contribution to this problem was made by Sommerfeld[23] almost sixty years ago, and since that time much attention has been given to the solution of his integral equations. An excellent summary of recent work is given in Ref. 24. An approximate solution for the driving-point resistance of a short, end-loaded dipole parallel to a lossy conducting plane was obtained by Sommerfeld and Renner,[25] and several example calculations of resistance vs height were plotted by King in Fig. 27.1 of Ref. 22. For comparison, King plotted the resistance of a half-wave horizontal dipole as a function of height (in wavelengths) over a perfectly conducting plane and concluded that for $d/\lambda_o \leq 0.25$ the values for a short, end-loaded antenna are approximately correct for a thin half-wave dipole. It was apparent to one of the authors (Hagn) from these curves (reproduced here as Fig. 9a), and from measured data obtained at VHF by Proctor[26] (reproduced here as Fig. 9b), that measured values of dipole feed-point resistance vs height obtained in the height range $0 \leq d/\lambda_o \leq 0.25$ might (at least in theory) be used to estimate the modulus of the effective complex dielectric constant of the earth from the surface to one skin depth in the immediate vicinity of the antenna. The technique would be to use a mathematical model (such as Sommerfeld and Renner's) to generate a set of solutions for R vs height that are parameteric in σ and ϵ_r for a given frequency. Measured values of R vs height obtained at the site of interest could then be plotted on these parametric curves and the best fit would then give an estimate of the



(a) Radiation resistance of horizontal dipole over conducting earth (Sommerfeld and Renner)

(b) Measured resistance of horizontal resonant antenna over conducting earth (Proctor)

FIG. 9 THEORETICAL AND MEASURED CURVES OF HORIZONTAL DIPOLE RESISTANCE vs. HEIGHT (after King, Ref. 22, p. 806)

σ value. One also could consider the antenna height producing the minimum resistance as well as the value of the minimum. All that is necessary to put this method into practice (in open terrain) is to generate the parametric curves. The technique could also be used in forested terrain if an appropriate forest modification factor could be derived or if the effect of the forest is negligibly small.* Unfortunately, the theoretical problem is yet unsolved, even for the case of open terrain, although several additional approximate solutions have been developed. Aikens, Tucker and Chapman,[27] using the formulation of Carson[28] as modified by Wise,[29,30,31] have developed approximate equations for the driving-point resistance of a half-wave horizontal dipole over finitely conducting, homogeneous ground:

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*One might expect the coupling from the horizontal antenna elements to the vertical tree trunks to be rather small, and so use a simple modification of $R_{\text{trees}} \approx R_{\text{no trees}} \times \text{Re}(n)$, where n is the refractive index of the forest considered as a lossy dielectric slab.

$$R = 72 + 30 \left\{ - 2Ci\left(4\pi H/\lambda_o\right) + Ci\left[\sqrt{1 + \left(4\pi H/\lambda_o\right)^2} - 1\right] + Ci\left[\sqrt{1 + \left(4\pi H/\lambda_o\right)^2} + 1\right]\right\} + R' \quad ,$$

$$\text{where } R' = \frac{\sqrt{30\lambda_o}}{4H\sqrt{\sigma}}\left[\cos\eta + \sin\left(\eta\sqrt{\cos 2\eta}\right)\right] \quad ,$$

$$\tan 2\eta = \frac{\epsilon_r - 1}{60\lambda_o\sigma}$$

$$Ci(x) = -\int_x^{\infty} \frac{\cos u}{u}\, du \quad ,$$

where

H = antenna feedpoint height (meters)

σ = earth conductivity (mhos/meter)

ϵ_r = relative dielectric permittivity of earth

λ_o = free-space wavelength (meters).

From these relationships, the data for the example curves of Fig. 10 were generated on a computer for 6 MHz. Notice that the resistance vs height above a perfectly conducting ground plane ($\sigma = \infty$) has been plotted for comparison. Figure 11 presents these same curves, but with an expanded ordinate. The dashed curves show the regions where the approximate solution to the equation becomes less accurate. According to Aikens, et al, the approximation is strictly applicable only for low antenna height or low conductivity; and the dashed curves are for antenna heights such that $\delta_B \geq 90° - \gamma_B$, where $\tan \delta_B = \frac{4H}{\lambda_o}$ and $\cos \gamma_B = [\epsilon_r^2 + (60\sigma\lambda_o)^2]^{-1/4}$. The angle γ_o is the pseudo-Brewster angle. But we should not expect this approach to work at very low antenna heights because the assumption that current distribution on the wire is approximated by a sinusoid begins to break down. Aikens et al, indicate they used this formula down to a height of about 1 meter. Wait* has indicated to the authors that the approach of images should not be expected to work well when the horizontal dipole is closer to the earth than one skin depth. The antenna heights corresponding approximately to one skin depth have been plotted on Fig. 11. Observe that only the dashed lines fall at heights above the skin depth. This indicates that the only applicable region of the chart is that where Aikens, et al., indicate their approximate expression is not too good.

B. Results with R(H) Method

In order to test the effectiveness of this technique in forested terrain, we first established that R at 6 MHz was not significantly affected by the presence of vegetation near the antenna when the antenna was less than $0.1\lambda_o$ above the earth. The data of Fig. 12 were obtained in a conifer forest in California, where the pine trees were 50 to 100 feet tall and were spaced about 10 feet apart. We expected that the horizontal dipole would couple strongly to the earth below a height of about $0.1\lambda_o$. At this low height the effect of the vegetation should be negligible in comparison to the effect of earth since the earth usually has electrical parameters at least ten times greater than those of the vegetation.[32] Furthermore, antenna-to-forest coupling was not expected to be very important at any antenna height since the dominant vertical growth pattern of the vegetation is orthogonal to the active elements of the antenna.† The usual effect of the forest is a slight increase in R, as in Fig. 12.

The length of the dipole above an imperfectly conducting ground for which the antenna is resonant (feed-point impedance is purely resistive) is itself a function of dipole height above ground.[26] The

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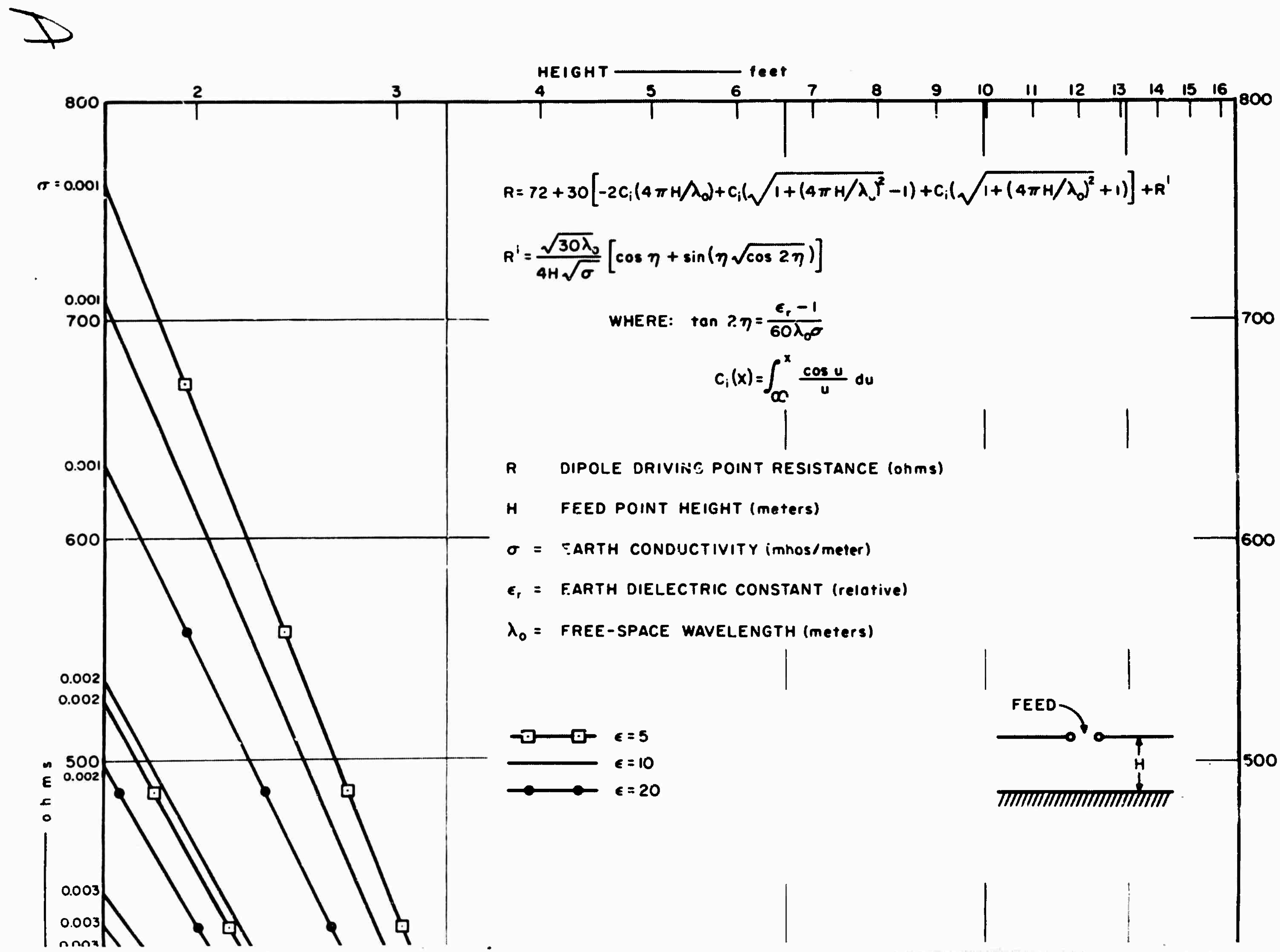
*Private communication, 1967.

†The antenna elements should be visibly free of vegetation: the assumption that there is little coupling to vegetation requires that the antenna be free of entangling stems, which may easily be as highly conducting as the earth.[32]


HEIGHT —— feet
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
800 700 600 500
ohms
σ = 0.001
0.001
0.001
0.002
0.002
0.002
0.003
0.003
R = 72 + 30[-2Ci(4πH/λ0) + Ci(√(1+(4πH/λ0)²) - 1) + Ci(√(1+(4πH/λ0)²) + 1)] + R'
R' = √(30λ0)/(4H√σ) [cos η + sin(η √(cos 2η))]
WHERE: tan 2η = (εr - 1)/(60λ0σ)
Ci(x) = ∫∞^x (cos u/u) du
R DIPOLE DRIVING POINT RESISTANCE (ohms)
H FEED POINT HEIGHT (meters)
σ = EARTH CONDUCTIVITY (mhos/meter)
εr = EARTH DIELECTRIC CONSTANT (relative)
λ0 = FREE-SPACE WAVELENGTH (meters)
ε = 5
ε = 10
ε = 20
FEED
H

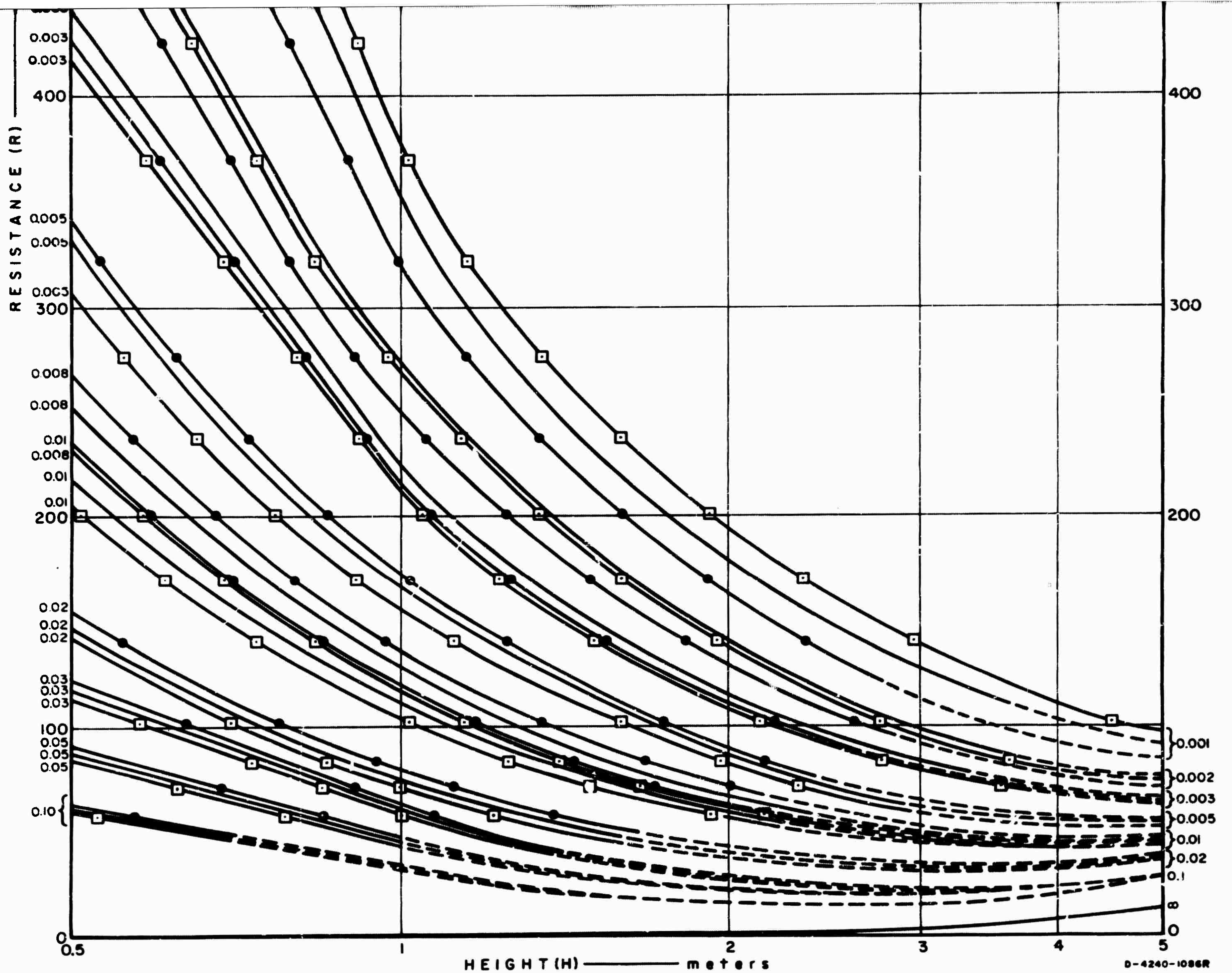


FIG. 10 CALCULATED 6-MHz HALF-WAVE HORIZONTAL DIPOLE, FEED RESISTANCE vs. HEIGHT ABOVE GROUND

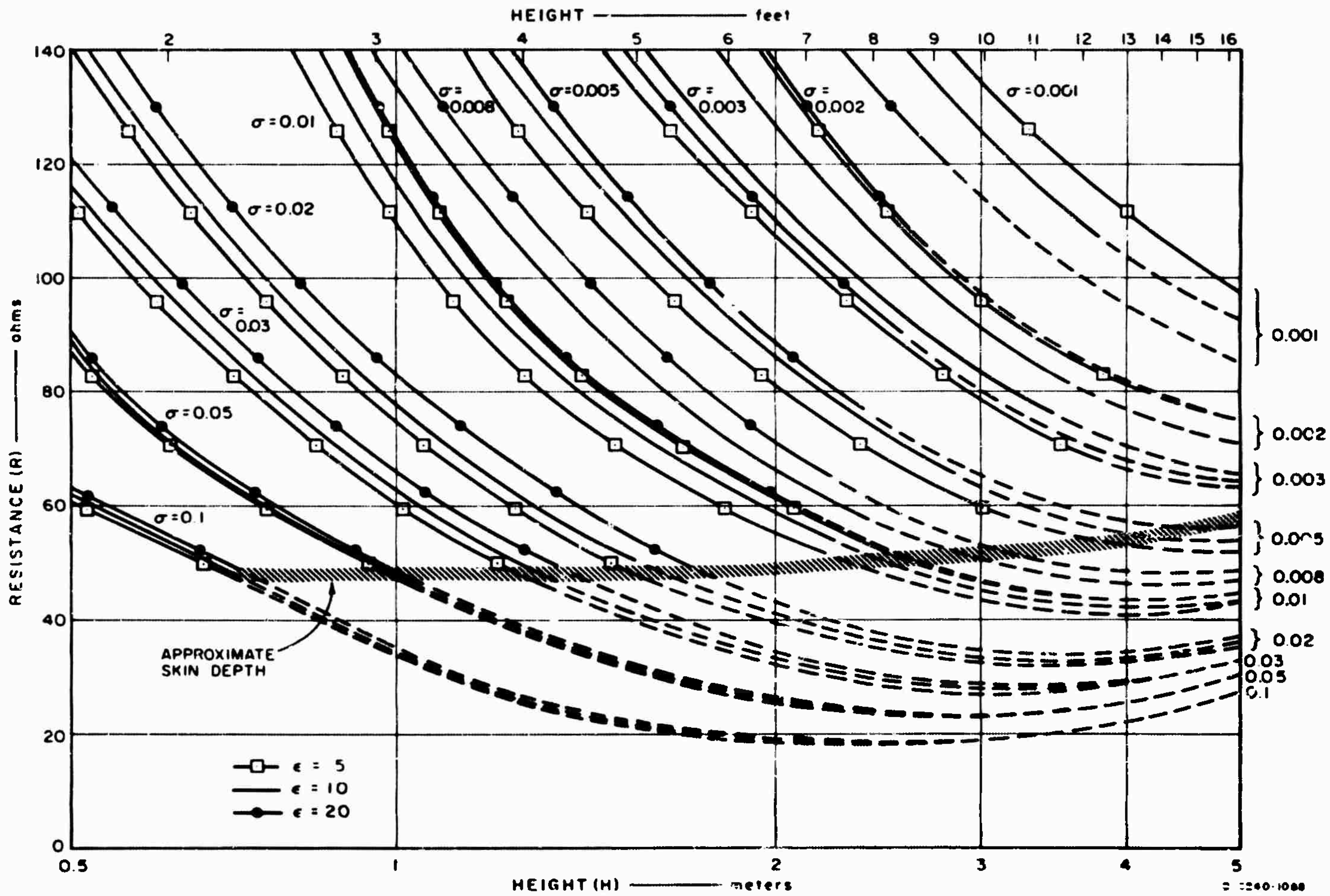


FIG. 11 CALCULATED 6-MHz HALF-WAVE HORIZONTAL DIPOLE, FEED RESISTANCE vs. HEIGHT ABOVE GROUND

(Expanded resistance scale)

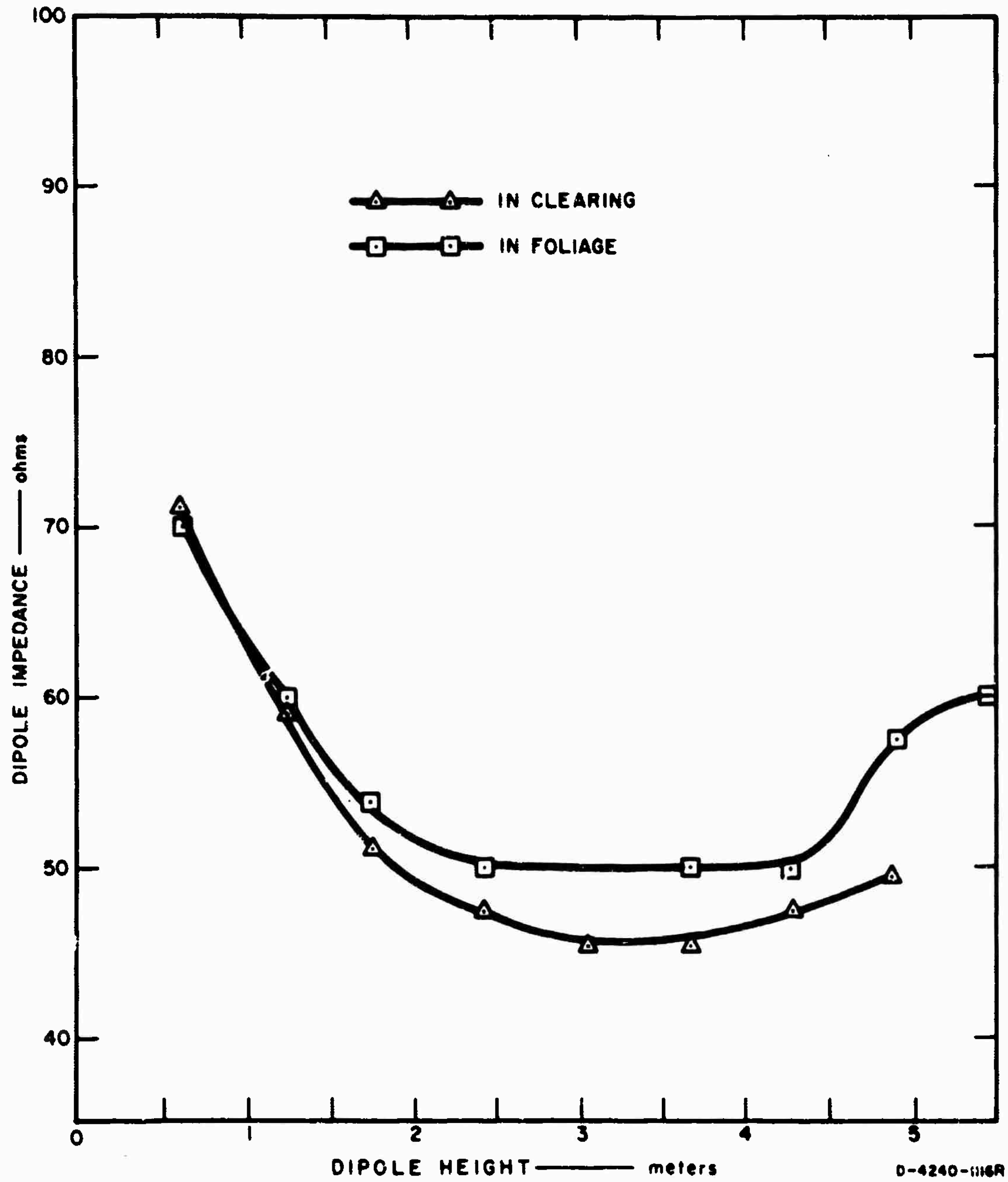


FIG. 12 6-MHz HALF-WAVE HORIZONTAL DIPOLE FEED RESISTANCE vs. HEIGHT ABOVE GROUND question then arises: does one re-resonate the antenna at each height before recording the feed-point resistance; or, if only one antenna length is used, at what height is the antenna length adjusted for resonance? Theoretically, the antenna should be resonated at each measurement height, but in practice the error in using one length is negligible if the antenna is originally resonated at $H \approx 0.2\lambda_o$.

Table II shows how the dipole estimates of σ obtained from the curves of Fig. 11 compared with the OWL probe estimates for several areas investigated during the course of the work.

Table II

COMPARISON OF 6-MHz EARTH-CONDUCTIVITY ESTIMATES AT SEVERAL SITES

Site	Conductivity (mhos/m)	
	OWL	Dipole R(H,λ)
Coyote Hills, California	0.01	0.05 ± 0.02
Bangkok Rice Paddy*	0.14	>0.1
Chumphon, Thailand		
Forest	0.08	0.03 ± 0.02
Clearing	0.06	0.05 ± 0.02

*Since dipole resistance curves had not been yet generated for $\sigma > 0.1$, these data, obtained in a rice paddy, provided only an estimate.

The discrepancy in these conductivity data arises primarily, we think, from the simplified theoretical analysis of the dipole R(h, problem we employed. The numerical evaluation for the dipole feed-resistance variation was based on homogeneous earth approximated by a lossy plane at the air-earth interface. Thus, the fit of the measured to the modeled curves can never yield exact values of conductivity if

the earth is stratified above the skin depth for the dipole frequency.*
Unfortunately, stratification is the situation usually encountered; thus we would not expect conductivities measured by the two techniques [R(H) and OWL] to be the same. The degree to which the conductivities differ is proportional to the degree of vertical inhomogeneity present. To enhance the usefulness of the R(H) technique, the theory must be expanded to include earth stratification, an extension of the work done by Wait[11] for a magnetic dipole.

Figures 10 and 11 show that the conductivity estimate depends increasingly on independent knowledge of ϵ_r for lower and lower values of σ. For this reason the R(H,λ) and the OWL techniques complement each other nicely, the latter providing the necessary measure of ϵ_r.

C. Discussion of R(λ) Method

In theory the R(H) technique can also yield ϵ_r if we let both frequency and dipole height vary inversely in such a way that the dipole height is maintained a constant fraction of a wavelength above gound (e.g., as we double the frequency we halve the height). Let us call this the R(λ) method. Figure 13 gives a set of curves parametric in σ for different ϵ_r but constant dipole height in wavelengths, with frequency the dependent variable. Assuming that σ and ϵ_r vary slowly over the HF band from 4 to 16 MHz, curves such as those in Fig. 13 theoretically could be used to estimate both σ and ϵ_r. Unfortunately, in many soils either ϵ_r varies fairly rapidly with frequency in this range and σ is nearly constant (high water content), or σ varies (as in Fig. 5) and ϵ_r does not (low water content).†[13,14] Thus, ideally it is in

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*The effect of stratification on results obtained using the wave-tilt method in open terrain has been analyzed by Eliassen.[33]

†For this latter case ($\epsilon_r \leq 10$) it might be possible to estimate ϵ_r from the water content by the relationship given by Josephson and Blomquist.[34] $\epsilon_r = 0.78W + 2.5$, or by Albrecht:[35] $\epsilon_r = kW + 2.0$, where W is the water content in percent by weight and k depends on the type of soil, equalling 0.5 for sand, 1.0 for average fertile soil, and 1.5 for clay. Once the value for ϵ_r had been determined, σ vs frequency could be scaled off Fig. 12 after plotting the R(H,λ) data.

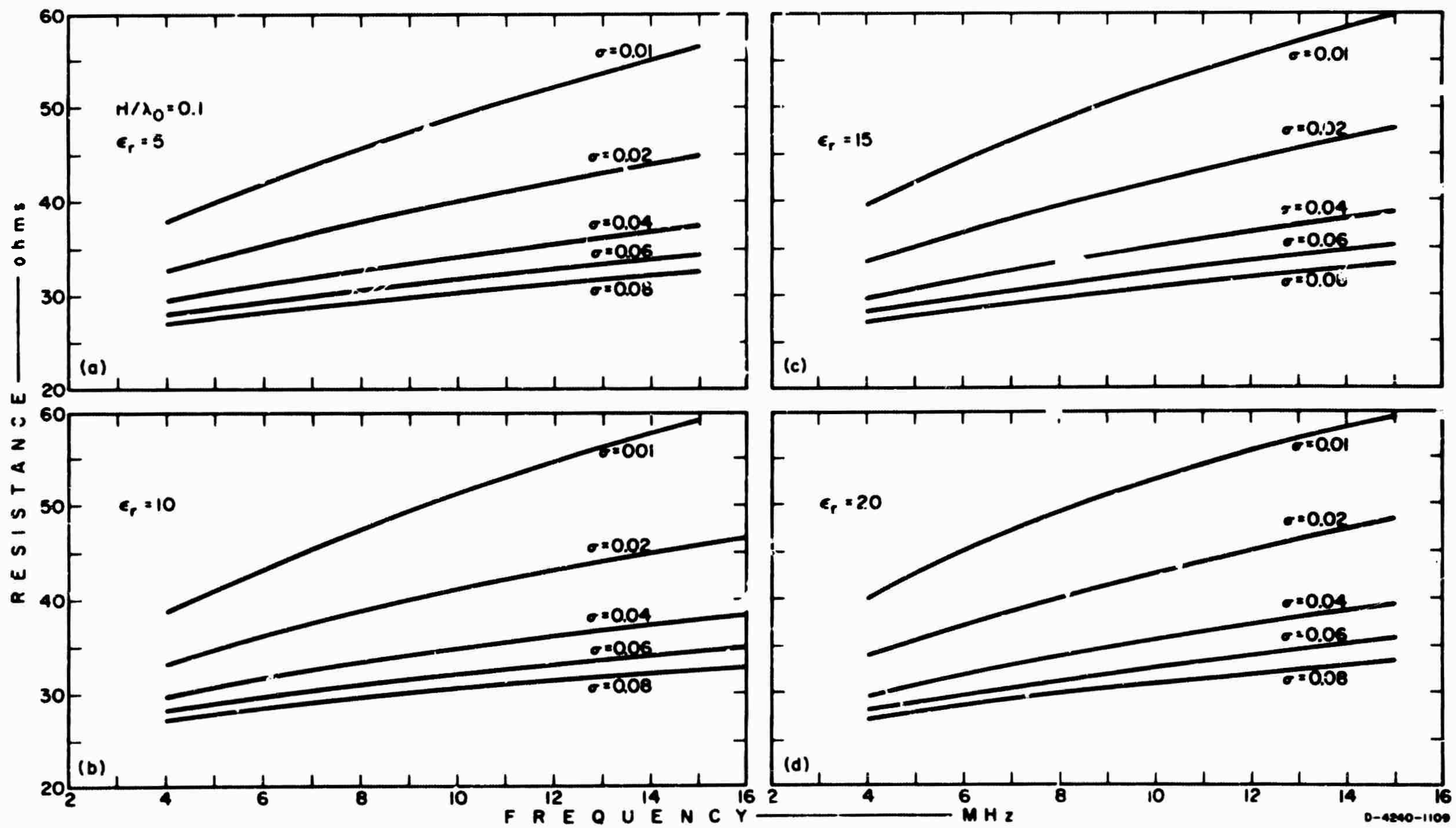

FIG. 13 HALF-WAVE DIPOLE FEED RESISTANCE AT $0.1\lambda_0$ ABOVE GROUND vs. FREQUENCY AND ELECTRICAL CONSTANTS

general necessary (1) to measure soil water content and its salinity, and (2) to include in the theoretical calculations an empirical law, as yet undefined, relating σ and ϵ_r to frequency and soil water characteristics. (This would be in addition to refining the theory to include earth stratification.) Albrecht, in Ref. 35, gives an expression relating ϵ_r and σ (in mho/m) good for $W \geq 3$ percent which involves the temperature of the ground, t (in degrees Centigrade) and a constant K (which relates σ to frequency as Kf^m):

$$\epsilon_r \cong 80K\sigma^{1/2}e^{-0.01t} ,$$

but this expression is independent of frequency. We have solved this equation for K using, for σ and ϵ_r, the data of Fig. 2 (Ban Mun Chit, where $6 \leq W \leq 18$), and assuming $t = 22°C$. The results are given in Table III.

Table III

K AS A FUNCTION OF FREQUENCY FOR BAN MUN CHIT RESULTS

Frequency (MHz)	ϵ_r	σ (mho/m)	K
6	15.5	0.0035	1.82
15	13.9	0.0070	1.15
25	11.5	0.0075	0.92
100	10.4	0.022	0.49

Evidently, the "constant" K is a function of frequency for the Ban Mun Chit results, and this functional relationship must be known in the general case before Albrecht's formula can be applied. It might be pointed out that if the relationship is known, then water content (W) can be used to estimate ϵ_r, and by assuming a reasonable value of t, Albrecht's formula can be used to estimate σ. The feasibility of this approach also depends on our having a physical-chemical description of the soil, a topic that was stressed in the Introduction. Thus, we did not pursue the constant-height (in wavelengths) approach in our investigation, and we prefer to use the OWL method to obtain ϵ_r.

D. Other Similar Approaches

The main problem in using the R(H) method is in obtaining reasonably accurate parameteric curves of R vs height and ground constants. In the absence of a solid theoretical approach one could always develop these curves empirically for several frequencies in the band of interest. To do this, sites with different ground constants would be selected on the basis of homogeneity and lack of stratification using the dc or audio probing techniques described in Sec. IV. These sites would then be calibrated at the frequencies of interest using OWL probes. R(H) data would then be taken; and, by doing this at sites with ground ranging from "poor" to "good" the required curves could be constructed. The approach could also be used at forested sites, where the electrical properties of the vegetation could be cataloged using OWL probes designed for that purpose.[32]

Vogler and Noble[36] have cataloged the required values for electrically short dipoles, and possibly these values could be used along with measured impedance data obtained with short dipoles. Measurement accuracy probably would be increased by putting capacitive loading on the ends of the dipole (e.g., like the Yo Yo antenna[37]) and using resistance values four times those given by Vogler and Noble. The use of a $\lambda/2$ dipole is probably preferable to the use of a short dipole, (when the appropriate parametric curves are available) especially in forests, since--because of its lower Q--it would probably be less affected by nearby objects other than the ground (i.e., tree trunks, etc.).

In open terrain, vertical antennas also could be used to estimate the electrical properties of the earth;[25] however, nearby tree trunks could have a greater relative effect than the earth on antenna impedance for vertical antennas located in forests.[38] Nevertheless, the analysis of Wait of a vertical monopole with circular ground screen of finite dimensions placed in the open over homogeneous earth may provide a technique for estimates of ground constants in an open terrain.

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VI CONCLUSIONS AND RECOMMENDATIONS

The open-wire transmission-line (OWL) and dipole $R(H,\lambda)$ techniques, together with dc resistivity soundings, should prove useful for the estimation of ground electrical constants and earth stratification in the presence of vegetation. The same techniques are suited to ground-constant measurement in open terrain and are recommended* in combination for a description of the earth environment in the vicinity of antennas or at field sites where knowledge of earth constants and structure is desired over a moderately confined area. The versatility of these tools and techniques would support their inclusion in the study of forested areas, and the data from them should prove useful in the mathematical models describing antenna patterns and efficiency, radio propagation, etc.

The OWL measurements provide data on the ground constants at radio frequencies in the immediate vicinity of the probe. Although any single result of the OWL measurements is confined to a small volume, this technique may be used easily to obtain ground constants at any frequency from MF through VHF. Areas of moderate size can be covered reasonably well by repetitive sampling, but the technique is best applied to describing the immediate vicinity of an antenna structure. The OWL technique gives an estimate of all the electrical constants, although the relative dielectric constant estimate is likely to be the most accurate of the three. It is the only technique that provides a good estimate of earth permittivity at an arbitrarily chosen radio frequency of interest for the ground beneath living vegetation. The measurement of magnetic permeability (known to be essentially unity for

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*The recommendation is contingent on refinement of the dipole theory [to obtain a more accurate solution to the equation for $R(H, \lambda, \sigma,$ and $\epsilon_r)$, to include effect of forest earth stratification, etc.]. The curves in Figs. 10 and 11 should not be used for more than coarse estimation of effective earth conductivity below a horizontal dipole.

practically all soils) provides redundancy and hence a check on the accuracy of the other constants. It is recommended that other probe configurations be investigated with a view toward increasing the size of the area that can be measured during one equipment set up.

The dc/audio resistivity soundings are valuable primarily for defining earth stratification. In this role they indicate whether surface values for ground constants obtained with the OWL technique can be extrapolated with confidence to the skin depth at the lowest radio frequency of interest. The dipole array, used at audio frequencies, is recommended for this application.[9] The Wenner, Eltran, and L electrode arrays are useful for dc sounding work. The Schlumberger method is not recommended. The dc conductivity data also can be extrapolated to a wide range of radio frequencies if we can be reasonably sure of the frequency variation of conductivity for the soil and rock at the site of the soundings. That research area has not been explored thoroughly enough to justify its recomendation at this time, although the use of audio frequencies may be far superior to dc when the actual conductivity value is sought with a view toward extrapolation to radio frequencies.

The dipole $R(H,\lambda)$ measurements allow easy estimates of ground conductivity in the HF band over moderate areas comparable to the size of antenna farms, and they also reflect the influence of earth to the skin depth at the frequency of interest. However, this technique does not (at the current state of the art) provide reliable data on the effective dielectric constant or on the conductivity of the stratified earth. Furthermore, the exact modification required to account for the forest effect, though small, has not been worked out. These handicaps probably can be overcome by refinement of the model in the latter instances, and by both refinement and empirical investigation of the frequency dependence of ground constants on soil water characteristics in the former. The model may be extended, based on the work of Wait,[11,12] to include two earth strata; therefore, we recommend that the necessary theoretical modifications be carried out so that more accurate conductivity estimates may be made for two or three earth layers, which occur most often. This should be done for both magnetic* and electric dipoles. The most promising present use of this technique is a check on the order of magnitude of conductivity values obtained with the OWL technique, particularly in the lower half of the HF band, where the technique is reasonably good for identifying soils with relatively high conductivity. The dipole impedance measurements, apart from their use in estimating ground constants, are inherently valuable for obtaining ground-proximity loss data[1,39,40] as well as tree-proximity effect[38,41] and should be used to study the relationship of ground and tree-proximity losses to forests.

*It may be possible to design a magnetic dipole earth sensor that is easier to use and that couples less strongly to vertical vegetation than the half-wave horizontal electric dipole.

Appendix

SUGGESTED FIELD PRACTICES FOR THE DC RESISTIVITY METHOD

Appendix

SUGGESTED FIELD PRACTICES FOR THE DC RESISTIVITY METHOD

1. Potential Electrodes

If the field data are erratic with changing electrode separation and are not easily reproduced, the cause could be contact potentials set up between the potential electrode and the electrolytic solutions in the earth. This would not be a problem if identical conditions existed at both potential electrodes in the Wenner or Schlumberger arrays, but in fact the conditions may be sufficiently different to be troublesome. To overcome this problem, two precautions may be taken: (1) a metal electrode may be used for which the electromotive force from the metal to a solution of its salt is small, such as iron or lead; or (2) a "nonpolarizing" electrode may be used instead of a metal stake. In the latter, the cables are connected to a rod, usually copper, immersed in a saturated solution of a salt of the metal (e.g., copper sulfate), contained in an unglazed porcelain pot. Electrical contact between the copper rod and the earth is made as the solution diffuses through the porcelain into the ground. To eliminate thermoelectric and diffusion-rate effects, it has been found that the electrolyte solution should be gelled by adding ordinary gelatin.

Metal stakes, driven into the ground to serve as potential electrodes, do not measure the potential difference between two points; but because of their finite length of immersion into the ground, the potential difference measured is an averaged value. However, if the electrodes have the same burial depth and are not buried so deep that they cross resistivity discontinuities, the point-electrode approximation (upon which the mathematical models for interpretation of results are based) is valid. A better approximation to the point electrode can be achieved by insulating all but a small portion of the metal stake or porcelain pot.

2. Current Electrodes

The theory for the interpretation of resistivity data is based on a point source and sink of current.[20] However, a metal stake is commonly driven into the ground for a current electrode, just as for the potential electrodes, hence, a point source is not used in practice. In homogeneous earth this means that, instead of having hemispherical equipotential surfaces about the electrode, we have equipotential surfaces that are closer to prolate ellipsoids of revolution. Therefore, we would expect a different potential gradient at the surface for a stake current source. It has been found that the potential gradient at the surface from a stake does not approach that from a point source except at horizontal distances from the stake of 10 times it burial depth. This means that some caution should be taken during field measurements when the electrode separations are small, e.g., when the distance a in the Wenner configuration is less than 10 feet.

When the electrode spacing becomes large, we may neglect the length of the stake and concentrate our efforts on putting enough current into the ground to make the necessary measurements. In this regard an attempt should be made to lower the contact resistance between the current stakes and the earth. For example, the stakes should be driven deep enough to reach a region where the earth is moist. In arid regions the contact resistance must be lowered by increasing the effective area of the electrode (e.g., using several stakes or a metal sheet) or by wetting the ground with an electrolyte.

A common practice is to put an ohmmeter across the current electrodes to check whether the combined contact and ground resistances seem to be low enough, say about 500 to 1500 ohms.

It may be that the contact and ground resistances are so low that more current than necessary or desirable will be drawn from the power source, thus shortening the life of batteries or blowing fuses in a power supply. If this happens, either the applied voltage should be lowered or the contact resistance should be increased by reducing the electrode contact area.

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13. ABSTRACT

Foliage degrades the usefulness of conventional wave tilt and propagation loss techniques for estimating in situ the RF ground constants in forested regions; therefore, an investigation was made of three other techniques that should provide more accurate input data for modeling, mathematically, radio antenna performance in forests.

Two of these techniques are RF methods providing complementary information: the open-wire transmission-line probe method gives independent measurements of the near-surface conductivity and the dielectric constant; the dipole feed-resistance (measured as a function of height) method allows a coarse estimate of the effective conductivity to the skin depth. The latter technique, however, requires theoretical refinement before it can be applied singly. At present there is no mathematical basis for evaluating numerically the dipole feed-resistance over a stratified earth.

The third technique, the dc geophysical resistivity method, yields a measure of the earth conductivity stratification beneath the vegetation. The dc resistivity method is supplementary to the RF methods, but its usefulness may be limited to estimation of stratification since the accuracy with which conductivity can be extrapolated from dc to RF is not known. Available literature indicates that the conductivity will be highly dependent on physical-chemical properties (especially moisture content) of the soil and near-surface rocks.

This special technical report describes the three techniques, giving the theory, instrumentation, and methods of interpretation for each. Results of the tests conducted during this investigation are analyzed briefly.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
HF ground constants						
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Dipole impedance near earth surface						
Direct-current earth resistivity sounding						
Skin depth						
Effect of vegetation						
Dipole impedance in vegetation						
SEACORE						