The Effect of Electrode Contact Resistance On Electric Field Measurements

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ABSTRACT

A simple equivalent circuit model and field measurements show that dipolar electric field measurements can be changed by up to 50% due to the effects of electrode contact resistance (R_C). The equivalent circuit model shows that a high R_C enhances the effective wire-to-ground capacitive coupling, leading to a complex dependence of received voltage on frequency, electrode contact resistance, wire length, and wire capacitance. The model shows that measured electric field voltages will fall between a perfectly grounded asymptote ($R_C \rightarrow 0$) and an ungrounded asymptote ($R_C \rightarrow \infty$). Field tests were made of this model using the controlled source audio-frequency magnetotelluric (CSAMT) technique. By varying the effective R_C and the signal frequency, the behavior predicted by the model was confirmed. The tests indicate that electrode contact resistance or ECR effects cannot be ignored in CSAMT data, and that they may influence complex resistivity measurements in certain conditions.

A simple, workable solution to the ECR problem was devised by inserting a high-impedance amplifier in series with the electrodes and by shielding the lead wires, grounding the shield to a common-mode reference pot. Measurements using this configuration show that ECR effects virtually can be eliminated even at high R_C values.

INTRODUCTION

Electric field measurements at the surface of the earth are made by measuring the potential difference between two grounded electrodes as a function of signal frequency or elapsed time. In many techniques such as induced polarization (IP) or magnetotellurics (MT), the required spectral range is less than 100 Hz or so, and the effects of electrode contact resistance, input characteristics of the measuring device, and inductive air-wave pickup can be ignored in most applications. However, the past decade or so has witnessed a trend toward higher frequency measurements. Both IP and MT have been used experimentally up to the kilohertz range to extend their capabilities, and there has been an increased use of kilohertz-range electric-field techniques such as audio-frequency magnetotellurics (AMT) and controlled source AMT (CSAMT). These developments take the measurements out of the realm where electrode contact resistance and other effects can be ignored.

The problem of electrode contact resistance apparently has not been addressed specifically in the literature. Zonge, Ostrander, and Emer (1980) presented some CSAMT data which showed that electric field measurements can be affected quite dramatically by electrode contact resistance, but no detailed study of this effect has been published. This paper is designed to fill this gap by providing empirical and theoretical considerations necessary to understand electrode contact resistance (ECR) effects and to develop a workable solution to the problem.

ORIGIN OF THE ECR PROBLEM

The response of the earth to an impressed coherent signal of frequency ***f*** can be described by an equivalent circuit, which includes the nature of the measurement system and its interaction with the earth. For a differential-input, dipolar system grounded to the surface of a conductive, homogeneous half-space, the equivalent circuit of Figure 1 provides a good first approximation to half the dipole response, with

V_R = Received voltage
V_1 = Voltage detected at the electrode
V_2 = Average potential difference between the electrode and the reference Electrode (or ground)
R_C = Contact resistance of the electrode plus internal resistance of the electrode
C_W = Distributed capacitance between the wire and ground

R_W = Distributed resistance of the wire
L_W = Distributed inductance of the wire
R_I = Equivalent input resistance of the measuring device
C_I = Equivalent input capacitance of the measuring device
L = Length of the wire

For frequencies considered in this discussion, the resistance and inductance of the wire and the input impedance and capacitance of the measurement device can be ignored, although they should be taken into account as signals in the 10 kHz or higher range are considered.

The capacitive reactance of the coupling between the wire and the earth is

$$jX_C = \frac{j}{2\pi f L C_W} \tag{1}$$

and the received voltage will be

$$V_R = \frac{jX_C V_1}{R_C + jX_C} + \frac{R_C V_2}{R_C + jX_C} \tag{2}$$

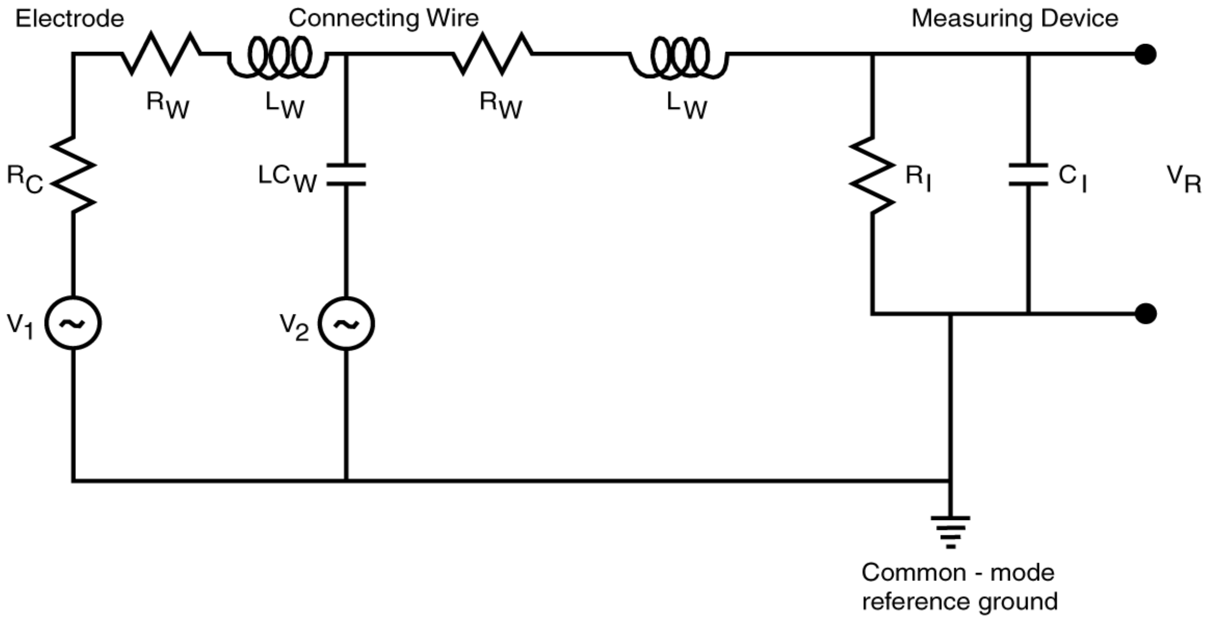

Figure 1. Simplified equivalent-circuit model of one-half of a differential-input grounded dipole. Symbols are explained in the text.

For a homogeneous earth far from current sources the potential gradient across the wire will be constant, and the average potential difference V_2 between the wire and the ground will be half the electrode potential ($V_2 = \frac{1}{2}V_1$). This simplifies equation (2) to

$$V_R = \frac{jX_C V_1}{R_C + jX_C} + \frac{\frac{1}{2} R_C V_1}{R_C + jX_C} \tag{3}$$

which can be rewritten to contain all the important terms explicitly as

$$V_R = \left(\frac{1}{1 - j2\pi f L C_W R_C} - \frac{j\pi f L C_W R_C}{1 - j2\pi f L C_W R_C} \right) V_1 \tag{4}$$

Testing the lemma of this equation proves to be useful. For zero contact resistance ($R_C \to 0$), which is the normal assumption in geophysical work, the second term drops out and $V_R = V_1$. In other words the capacitive effect of the wire is shorted out and the measurement consists only of the ground potential at the electrode, which is the desired measurement. On the other hand, as the contact resistance goes to infinity ($R_C \to \infty$), the first term drops out and we have $V_R = \frac{1}{2}V_1$. In this case the wire is effectively ungrounded and capacitive effects dominate. Between these two lemma the voltage is frequency-dependent. For low frequencies ($f \to 0$), the limit $V_R = V_1$ is approached, as before; for high frequencies ($f \to \infty$), the limit $V_R = \frac{1}{2}V$ is approached. Hence, the received voltage is dependent upon electrode contact resistance, and the magnitude of the effect is a function of signal frequency. We call this behavior the “electrode contact resistance” or “ECR” effect.

One way of visualizing the ECR effect is that the limits $R \to 0$ and $R \to \infty$ are the asymptotic bounds of an envelope inside of which all finite-value voltage curves will fall, with both contact resistance and frequency determining the shapes of the voltage curves within this envelope. An example is provided in the calculated electric field values of Figure 2, in which we have taken L=152 meters, C_W = 23 pf/m, and a frequency range of 4 to 4096 Hz, all typical values for CSAMT survey work. Note the dispersion of voltage values for high frequencies at contact resistances as low as 3 kΩ, which are not uncommon in field survey work. This suggests that the

ECR effects are of great importance in CSAMT, and could be important in IP work when long arrays and high frequencies are used.

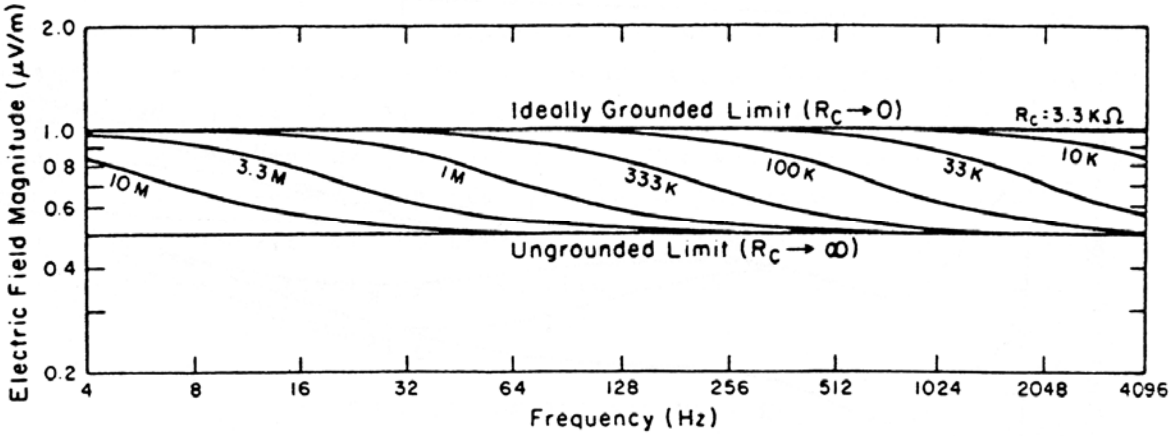

Figure 2. Calculated ECR effect for a homogeneous earth for various contact resistances. Values are referenced to an electric field magnitude of 1.0 V/m. A dipole length of 152m and a wire capacitance of 23 pf/m were assumed.

ILLUSTRATION OF THE ECR PROBLEM

In order to illustrate the ECR effect, a series of CSAMT field experiments were conducted. The work was done at a standard test site in Avra Valley, west of Tucson, Arizona. This site involves a horizontally layered alluvial cover overlying a granitic basement. Maximum resistivities are nearly 50 Ωm near the surface and around 10 Ωm in the lower part of the alluvial cover. A dipolar transmitter source, 1200 meters in length and located 4.5 km east of the receiver site was used for the measurements. The horizontal electric field parallel to the transmitter source and the horizontal magnetic field perpendicular to the source were measured simultaneously using a two-channel digital receiver. The electric field was sensed by a 150 meter dipole, using differential input, terminated by standard porous ceramic electrodes (“pots”) filled with a saturated copper sulfate solution. The contact resistance of the pots was 300 ohms. The magnetic field was sensed by a high-gain, ferrite-core, dB/dt antenna. Data precision is better than 1% for all measurements.

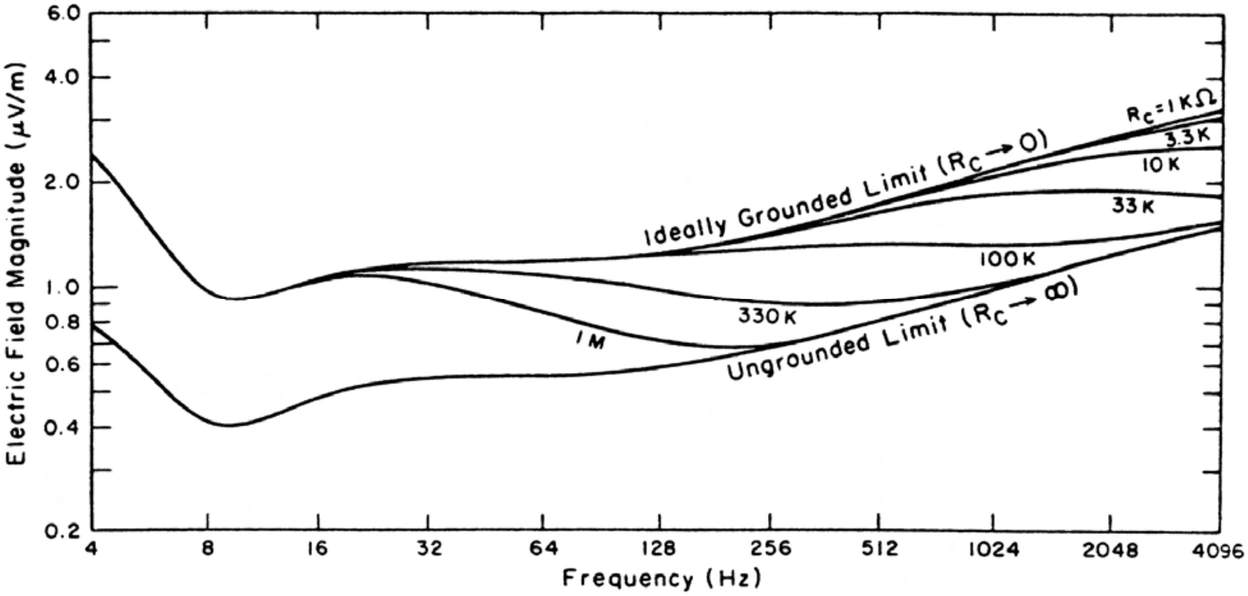

Figure 3. CSAMT field measurements of the ECR effect with various contact resistances. Note the similarity to Figure 2.

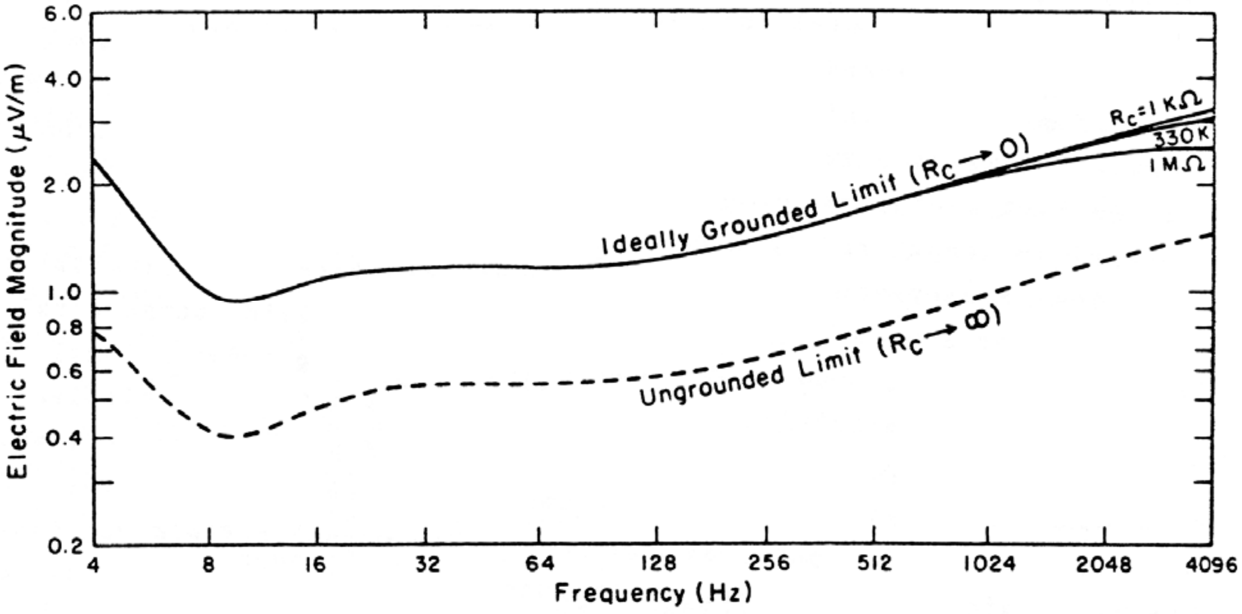

Figure 4. CSAMT field measurements of the ECR effect with an active-pot, shielded-wire system. This new configuration virtually eliminates the ECR problem except at exceedingly high contact resistance.

The ECR effect was simulated in the field by introducing resistors in series with the end electrodes in order to simulate variations in pot resistance. Resistor values of 1K, 3.3K, 10K, 33K, 100K, 330K, and 1.0M ohms were used. The results are shown in Figure 3. The curves measured in the field show the same asymptotic behavior as the theoretical curves in Figures 2, superimposed on the high-over-low resistivity layering at the test site. The envelope limits ($R_{\mathbf{C}} \rightarrow 0$ and $R_{\mathbf{C}} \rightarrow \infty$) are separated by the predicted $\Delta V_{\mathbf{R}} = ½V_{\mathbf{1}}$ criteria, and intermediate curves fall between these two limits according to contact resistance and frequency, as predicted by the model.

SOLUTION OF THE ECR PROBLEM

The data indicate that two problems must be solved. The first problem is to reduce the effective electrode contact resistance seen by the measuring system. The second problem is to reduce as much as possible the wire-to-ground capacitance in the system. Both problems must be solved by changes in the survey design, since they are essentially site-dependent.

A possible solution can be found by introducing what we call “active pots”. A high-impedance amplifier is inserted in series between the pots and the receiver as close to the pots as possible. This minimizes the importance of Rc by virtue of the high impedance of the amplifier. The capacitive coupling problem can be solved by shielding the lead wires between the pot amplifier and the receiver.

A series of field tests were run to test the new configuration. A field preamplifier normally used for complex resistivity (CR) application was used as a makeshift amplifier. A shielded, twisted-pair was used for the electric field dipole, with shield and ground conductor grounded to the common-mode electrode in the center of the array.

The results (Figure 4) show a marked decrease in the ECR effect of about two orders of magnitude. Even at 1MΩ the ECR effect influences only the data above 1kHz. This effect can be reduced further by designing amplifiers specifically for this application.

SOME IMPLICATIONS OF THE ECR EFFECT

The results of this study indicate that a shielded-wire, active-pot system is essential for AMT and CSAMT measurements in many typical field environments. As a rule of thumb, when the product of the wire length (km), the frequency (kHz), and the electrode contact resistance (kΩ) exceeds 2.0 the ECR effect can be appreciable. Since the electric field magnitude is squared to calculate the AMT apparent resistivity, even small ECR effects are greatly magnified in field results. Failure to avoid or at least correct for these effects could drastically influence depth/resistivity inversions and would make the solution of influences such as static offset virtually impossible.

In addition, complex resistivity surveys also can be affected by ECR effects if the arrays are sufficiently large, according to the $LfR_C > 2.0$ criterion. Magnetotelluric work, which normally utilizes arrays 100 meters in length and frequencies no higher than 400 Hz, should be unaffected except for R_C values in excess of 50 kΩ.

REFERENCES

Zonge, K.L., Ostrander, A.G., and Emer, D.F., 1980, Controlled Source Audio-frequency Magnetotellurics Measurements: Technical papers, 50th Annual SEG Meeting, 5, 2491-2521. Abstract: Geophysics, 46, 460.