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THE INFLUENCE OF A CONDUCTOR WITH MULTIPLE GROUNDS ON INDUCED POLARIZATION SURVEYS[1]

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ABSTRACT

The effect of multiply grounded conductors such as power lines and fence lines on induced-polarization (IP) measurements on the earth's surface is of interest in geophysical exploration. A relatively simple and computationally efficient method of analysis is presented to determine the induced-polarization error that is caused by the effects of electrically interconnected grounds over a homogeneous earth. The ground electrodes may have arbitrary separation, number and impedance, although this paper presents calculated results only for ground electrodes with a linear alignment, fixed impedances and separation. The ground electrodes are taken to be buried hemispheres with an arbitrary interface impedance. Interactions between the ground electrodes and the measurement array are described by a matrix equation, and the ground-electrode current magnitudes and phases are found by performing a matrix inversion. The potential at a field point due to the ground-electrode currents and the measurement-array current sources is then found and compared to the undisturbed field-point voltage to produce normalized IP profiles. Results are presented for the pole-pole and the Schlumberger arrays. In general, the effect of structures such as long fence lines and power lines is to produce effects of only a few milliradians on traverses parallel and normal to the structure when reasonable distances are maintained between the array and any individual grounds of the conductor.

INTRODUCTION

Electrical surveys made to determine induced-polarization (IP) profiles are often influenced by man-made conducting structures in contact with the earth. These structures can have a wide variety of forms such as well casings (Wait, 1983; Holladay and West, 1984; Trofimenkoff et al., 1986; Johnston et al., 1986, 1987), buried pipelines, grounded power lines and fences (Wynn and Zonge, 1975; Nelson, 1977; Wait, 1984). In this paper, structures that have discrete ground connections to the earth and are interconnected by a conductor that is insulated from the earth are considered. Power lines, grounded fence lines, insulated pipelines and telephone circuits are all structures that fall into this general classification, and this analysis provides the geophysicist with a tool to assist in the interpretation of surveys in locations that have cultural contamination consisting of a conductor with discrete ground electrodes.

The problem is formulated and solved in a manner very similar to that used by Trofimenkoff et al. (1986) and Johnston et al. (1986, 1987) to treat the case of apparent resistivity in the presence of a vertically embedded conductor. To simplify the problem, the ground electrodes are treated as buried hemispheres with the diameter coincident with the ground surface and are interconnected with conductors of either zero or arbitrary impedance. The ground electrodes are replaced by point current sources which produce the same hemispherical equipotentials. Interactions between the ground electrodes and the measurement array are described by a matrix equation and the ground-point currents are then found by a matrix inversion. The normalized IP response is then found by comparing the potential at the field point in the presence of the interconnected ground electrodes to the potential in the presence of the measurement-array primary current source over a purely resistive earth.

PROBLEM DEFINITION

The problem involves the determination of the voltage at an arbitrary location on the surface of an assumed homogeneous earth in response to a unit point current source on the surface of the earth in the presence of a conductor with multiple grounds at arbitrary locations, as shown in Figure 1. The multiply grounded conductor is assumed to have discrete connections to the earth that can be modelled by half-buried spheres insofar as practical array dimensions and positions are concerned. The analysis is initially carried out for the general case of a completely arbitrary multiple-ground electrode geometry with arbitrary grounding impedances and electrode spacing and is then applied to a multiply grounded conductor with a linear array of equispaced, equal-impedance ground electrodes with equal interconnecting impedances.

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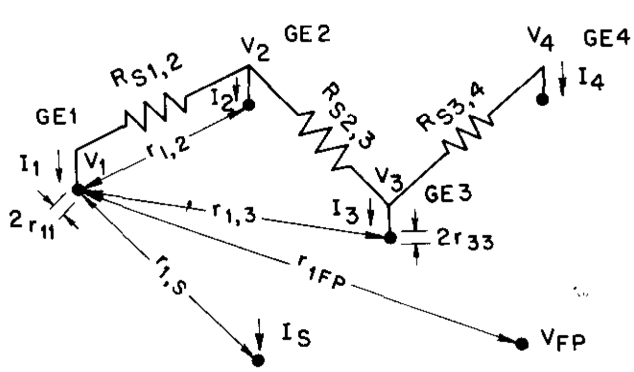

Fig. 1. Connected ground electrodes in the presence of a pole-pole array.

It is useful to visualize the effect of the ground electrodes in developing the analysis. Current is fed into a homogeneous earth at the measurement-array current-injection point and will establish spherical, constant-potential surfaces in the absence of the multiply grounded conductor. Note that for the time-varying case, these equipotentials are influenced by the propagation attenuation and delay of the wave travelling through the earth (Wait, 1982). In this analysis, the current will be assumed to be injected into the ground by a vertical wire of infinite length, as shown in Figure 2. Wait (1982) has shown that for this case the potential that is produced at other points on the ground surface is described by

$$V_{FP} = \frac{\rho I}{2\pi r} e^{-\gamma r},$$

where

$$\rho = \frac{1}{\sigma},$$

and the subsurface propagation constant is

$$\gamma = (j\sigma\mu_o\omega)^{1/2} .$$

Potentials (V) and currents (I) will be treated as phasors without any special notation. The assumption that only vertical wires are used to inject current into the ground essentially means that the electromagnetic (EM) coupling, due to coupling between horizontal conductors laid on the surface of the earth, is not included in the analysis. Efforts to include the inductive coupling into this analysis have not as yet been successful.

In survey geometries in which the survey arrays are perpendicular to the ground-electrode conductor, the EM coupling between the array and the ground conductor is minimized. With the grounded conductor in place, the ground electrodes nearest the array current injection point act as current sinks and the ground electrodes farthest from the array current injection point feed currents into the earth. The sum of all the ground-electrode currents is zero as no other current sinks or sources are connected to the ground structure. These ground-electrode currents distort the shape of the spherical constant-potential surface established by the measurement-array point current source.

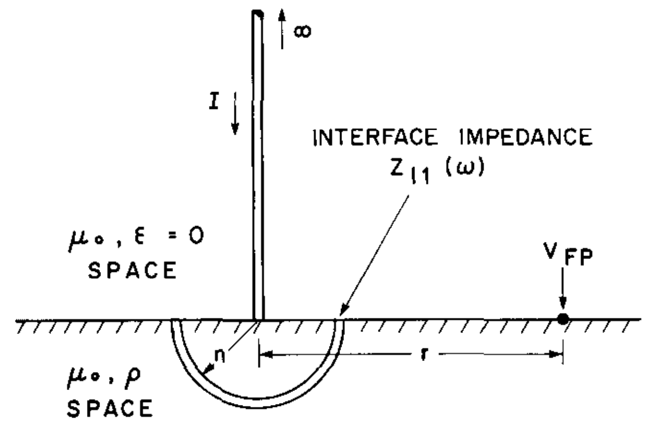

Fig. 2. Configuration for current injection into the ground and detail of ground electrode with interface impedance.

The multiply grounded conductor with zero conductor *impedance will assume some constant potential* V_{gc} *such* that the sum of all the ground-electrode currents will be zero. The current flow into or out of a particular ground electrode will be a function of V_{gc}, radial distance to the primary current source (I_s), and the impedance of the ground electrode to infinity.

In a manner analogous to the substitution theorem in electrical circuit analysis, the multiply grounded conductor may be removed and replaced by point current sources on the surface. For the case when the interconnecting impedance is zero, the magnitude of each point current source is adjusted so the potential of the corresponding ground electrode achieves a value of V_{gc}. Each of these point current sources produces the same effect as the corresponding ground electrode when it is in place.

MATHEMATICAL FORMULATION

The circuit model shown in Figure 1 is initially investigated assuming that the interconnecting conductors have zero resistance. Each ground electrode is assumed to be hemispherical and is assigned a specific number, and the potential at the surface of each electrode is then calculated. For example, the surface potential of ground electrode number one is

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + Z_{13}I_3 \ldots + Z_{1S}I_S \tag{1}$$

where Z_{11} is the self-impedance of hemispherical ground electrode 1 to infinity, Z_{1n} is the transfer impedance from ground electrode n to ground electrode 1, and Z_{1s} is the transfer impedance from the primary current source to ground electrode 1. All impedance terms are complex quantities. In general

$$Z_{mn} = \frac{\rho}{2\pi r_{mn}} e^{-\gamma r_{mn}}, \tag{2}$$

where r_{mn} is the surface radial distance between ground electrode m and ground electrode n,

$$Z_{nn} = \frac{\rho}{2\pi\, r_n} + Z_{In}\ (\omega)\,, \qquad (3)$$

where r_n is the equivalent hemisphere radius of a buried ground electrode of an arbitrary shape, and $Z_{In}\ (\omega)$ is the interface impedance of the ground electrode to the ground, as shown in Figure 2. Nelson (1977) has presented the results of measurements on power line tower grounds, wooden pole power grounds and metal fence line stakes. He has lumped the two impedance components together and has presented the impedance magnitude and the phase shift in milliradians. He found that different types of grounds give phase shifts that vary over a wide range (20 to 600 mrad from 0.1 to 1.0 Hz). His convention will be used, that is, the self ground resistance and the interface impedance will be combined to give Z_{nn}.

The transfer impedance from the primary current source to a particular ground electrode is given by

$$Z_{ns} = \frac{\rho}{2\pi\, r_{ns}}\, e^{-\gamma r_{ns}}\,, \qquad (4)$$

where r_{ns} is the radial surface distance separating the primary current source point (I_s) and the ground electrode n.

The potentials and currents of all ground electrodes may be related in an impedance matrix. In the following matrix equations, four (N) ground electrodes will be assumed, which is large enough in indicating general matrix forms without requiring excessively cumbersome arrays to be written.

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & \cdot\cdot & \cdot\cdot \\ Z_{31} & \cdot\cdot & Z_{33} & \cdot\cdot \\ Z_{41} & \cdot\cdot & \cdot\cdot & Z_{44} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} + \begin{bmatrix} Z_{1S} \\ Z_{2S} \\ Z_{3S} \\ Z_{4S} \end{bmatrix} I_s \qquad (5)$$

If the interconnecting ground-electrode conductor has zero impedance, the electrode voltages assume the same value V_{gc} while the individual point current sources have a wide range of values. The ground-electrode currents are the unknowns in the above equation. It is useful to rewrite equation (5) so that these values are shown explicitly. One thus obtains

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & \cdot\cdot & \cdot\cdot \\ Z_{31} & \cdot\cdot & Z_{33} & \cdot\cdot \\ Z_{41} & \cdot\cdot & \cdot\cdot & Z_{44} \end{bmatrix}^{-1} \times \begin{bmatrix} V_{gc} - Z_{1s}\ I_s \\ V_{gc} - Z_{2s}\ I_s \\ V_{gc} - Z_{3s}\ I_s \\ V_{gc} - Z_{4s}\ I_s \end{bmatrix}. \qquad (6)$$

This impedance matrix can be inverted to produce an admittance matrix,

$$[Y] = [Z]^{-1} \qquad (7)$$

where elements of the admittance matrix are designated as Y_{mn}.

The exact grounding conductor potential V_{gc} is still unknown, but it may be found by applying the condition that the sum of the ground-electrode currents is zero. To obtain zero for the sum of the ground-electrode currents, let

$$V_{gc} \sum_{m=1}^{N} \sum_{n=1}^{N} Y_{mn} = I_s \sum_{n=1}^{N} Z_{ns} \sum_{m=1}^{N} Y_{mn}\,. \qquad (8)$$

Thus,

$$V_{gc} = I_s \frac{\sum_{n=1}^{N} Z_{sn} \sum_{m=1}^{N} Y_{mn}}{\sum_{m=1}^{N} \sum_{n=1}^{N} Y_{mn}}\,. \qquad (9)$$

After substituting V_{gc} into equation (6), the ground point currents may be determined.

Finite Conductor Impedance

The conductor interconnecting the ground electrodes generally has a significant impedance that should be taken into account. The ground electrodes can be connected together in different topologies; however, only a linear conductor connection is treated here.

The linear conductor connection

The term "linear conductor connection" designates the connection of the ground electrodes to the grounding conductor, as shown in Figure 1. The ground electrodes may be placed in the earth in random locations. It is convenient to take the potential of ground electrode 1 as the reference and to measure the other potentials with respect to it.

$$V_2 = V_1 + Z_{S12}\, I_1$$

$$V_3 = V_1 + (Z_{S12} + Z_{S23}) I_1 + Z_{S23}\, I_2$$

$$V_4 = V_1 + (Z_{S12} + Z_{S23} + Z_{S34})\, I_1 + (Z_{S23} + Z_{S34})\, I_2 + Z_{S34}\, I_3\ etc. \qquad (10)$$

where Z_{Smn} is the conductor impedance between ground electrodes m and n.

These terms may be introduced into equation (5) to give the result

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} - Z_{S12} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} - Z_{S12} - Z_{S23} & \cdot\cdot & Z_{33} & Z_{34} \\ Z_{41} - Z_{S12} - Z_{S23} - Z_{S34} & Z_{42} - Z_{S23} - Z_{S34} & \cdot\cdot & Z_{44} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} + \begin{bmatrix} Z_{1S} \\ Z_{2S} \\ Z_{3S} \\ Z_{4S} \end{bmatrix} I_s\,. \qquad (11)$$

The generating function for the terms in the impedance matrix is

$$Z_{mn} = \begin{cases} Z_{mn} - \sum_{k=n}^{m-1} Z_{Skl} \text{ for } m > n \\ Z_{mn} \text{ for } m \leq n \end{cases} \tag{12}$$

where $l = k+1$.

Equation (11) is then processed in the same way as was equation (5) to find the ground-electrode currents.

Induced-Polarization Profiles

The effect of linear, multiply grounded conductors on an IP survey can be examined by taking an array and performing an analytical traverse past the conductor and its grounds. The calculated potential is normalized to the potential that would be measured by the same array over a resistive earth in the absence of the grounded structure. In the examples that follow, f = 1 Hz and ρ = 50 Ω m. The number of ground electrodes is called N and the separation of the ground electrodes is d.

Examples of profiles will be given based on two structures that might be encountered in field surveys. The first structure is a fence with 51 (N) steel posts separated by 5 (d) m and interconnected with a steel wire with a total length of 250 m. Nelson (1977) has given measurement data on the impedance to ground of this type of post and has found that it has a large resistance to ground with a large reactive component. Wide ranges of values are given by Nelson (1977) and a median value, $Z_{ge} = 300/\underline{0.30\text{rad}}\Omega$, will be used here. In the present example, the interconnecting impedance of the wires on the fence is taken to be very small due to the close spacing of the posts and hence $Z_{ser} = 0$.

The other structure of interest is a high-voltage power line with a length of 2700 m with 10 (N) towers separated by 300 m (d). It is assumed to have one overhead ground wire with a diameter of 0.80 cm. This steel wire is taken to have a relative permeability (μ_r) of 200. The inductance of this wire with its return path in the ground becomes difficult to evaluate precisely. By making opposing extreme assumptions regarding the return path (the current return is taken to occur at infinity in one case and at the ground surface in the other case), we find that the inductance of the wire is determined mainly by its internal inductance, and the external inductance which is affected by the current return path is only about 20 percent of the total. A useful expression that will overestimate the inductance by a few percent is (Giacoletto, 1977):

$$L = \frac{\mu d}{2\pi} \left[\ln \left(\frac{2d}{r_c} \right) - 1 + \frac{\mu_c}{4\mu} \right] \tag{13}$$

where d is the separation of the grounds, r_c is the radius of the single ground conductor, and μ and μ_c are the permeability of free space and the conductor, respectively.

Skin effect on this conductor at 1 Hz is found to be negligible and R and L retain their low-frequency values. The impedance of the ground wire on the high-voltage transmission system is found to be

$$Z_{ser} = 1.20 + j\,0.0229\ \Omega. \tag{14}$$

Nelson (1977) has measured the IP response of large power line grounds and has found that the IP phase shifts range from 7 to 20 mrad over a frequency range of 0.1 to 1.0 Hz. The worst case phase shift of 20 mrad will be used here. Power line grounds are designed in Alberta to have a resistance to the earth of about 4.0 Ω. Incorporating the resistance and phase shift into the ground-electrode impedance one obtains

$$Z_{ge} = 4.0 - j\,0.080\ \Omega\,. \tag{15}$$

The pole-pole array

The simplest array to consider is the pole-pole array. This consists of a current source I_s with the current return at infinity and a voltage pickup point with the reference potential taken at infinity. Figure 3 shows the plan view of this array on (a) parallel and (b) normal traverse to a straight, grounded conductor. The distance between the array centre to the grounded conductor (normal to the grounded conductor) is denoted $lh1$. A normal traverse is achieved by stepping $lh1$ to different values. The distance from the array center to ground electrode No. 1 (parallel to the grounded conductor) is called $lh2$. A parallel traverse is achieved by stepping $lh2$ over a range of values. The voltage that is measured at the field point using the pole-pole array on an undisturbed ground with a uniform resistivity (Sumner, 1976) is

$$V_{PP} = \frac{\rho I_s}{2\pi a}\,. \tag{16}$$

where a is the separation between the current injection point and the voltage pickup point.

The potential change caused at the field point by the ground electrode currents is

$$V_{PP_\Delta} = \sum_{n=1}^{N} \frac{\rho I_n}{2\pi\, r_{nFP}}\, e^{-\gamma r_{nFP}}\,, \tag{17}$$

where I_n is the electrode current for a particular location of the array primary current and r_{nFP} is the distance from the ground electrode (number n) to the field point at which the ground voltage is measured relative to infinity. The complete phasor potential normalized to the resistive earth potential measured by the array is

$$Z_{an} = \frac{Z_a}{\rho} = 1 + \frac{V_{PP_\Delta}}{V_{PP}} \tag{18}$$

$$Z_{an} = 1 + \frac{a \sum_{n=1}^{N} [I_n\, (r_{nFP})^{-1}\, e^{-\gamma r_{nFP}}]}{I_s}\,, \tag{19}$$

where Z_{an} is a normalized apparent impedance.

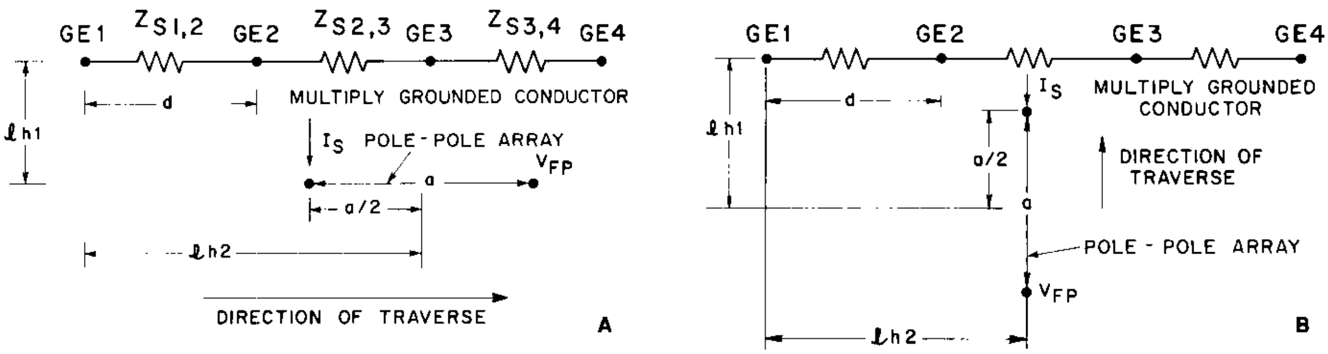

Fig. 3. A pole-pole array on a traverse past a grounded conductor: (a) parallel traverse; (b) normal traverse.

The induced polarization response is usually measured in terms of the phase shift of the measured potential using the primary current as the phase reference. The phase shift may be presented in units of milliradians and is given by

$$P_I = 1000 \tan^{-1}\left[\frac{\mathrm{Im}\,(Z_{an})}{\mathrm{Re}\,(Z_{an})}\right]. \tag{20}$$

For cases where the IP response is small this can be simplified because the real part of Z_{an} is approximately unity, thus giving

$$P_I \approx 1000\,\mathrm{Im}\,(Z_{an}). \tag{21}$$

The induced polarization caused by a grounded fence line of a pole-pole array on a parallel traverse is shown in Figure 4. The measurement array is allowed to come within 5 m of the fence line. Even at this close proximity the fence line causes an IP response of only 15 mrad. Figure 5 shows the IP response of a parallel traverse past a power line. The IP response is small and is less than 2 mrad even when the traverse closely approaches the power line. For the power line, three effects can contribute to the total IP response. Figure 6 shows each effect in isolation. Figure 7 shows the IP response of this array on a traverse past the end of a grounded fence line and a traverse through the fence line. It is to be noted that the response is less than 2.0 mrad. Similarly, Figure 8 shows that the IP response due to a large power line (240 kV) is less than 0.4 mrad. This traverse passes through the midpoint of a 10-tower power line on a line normal to the power line.

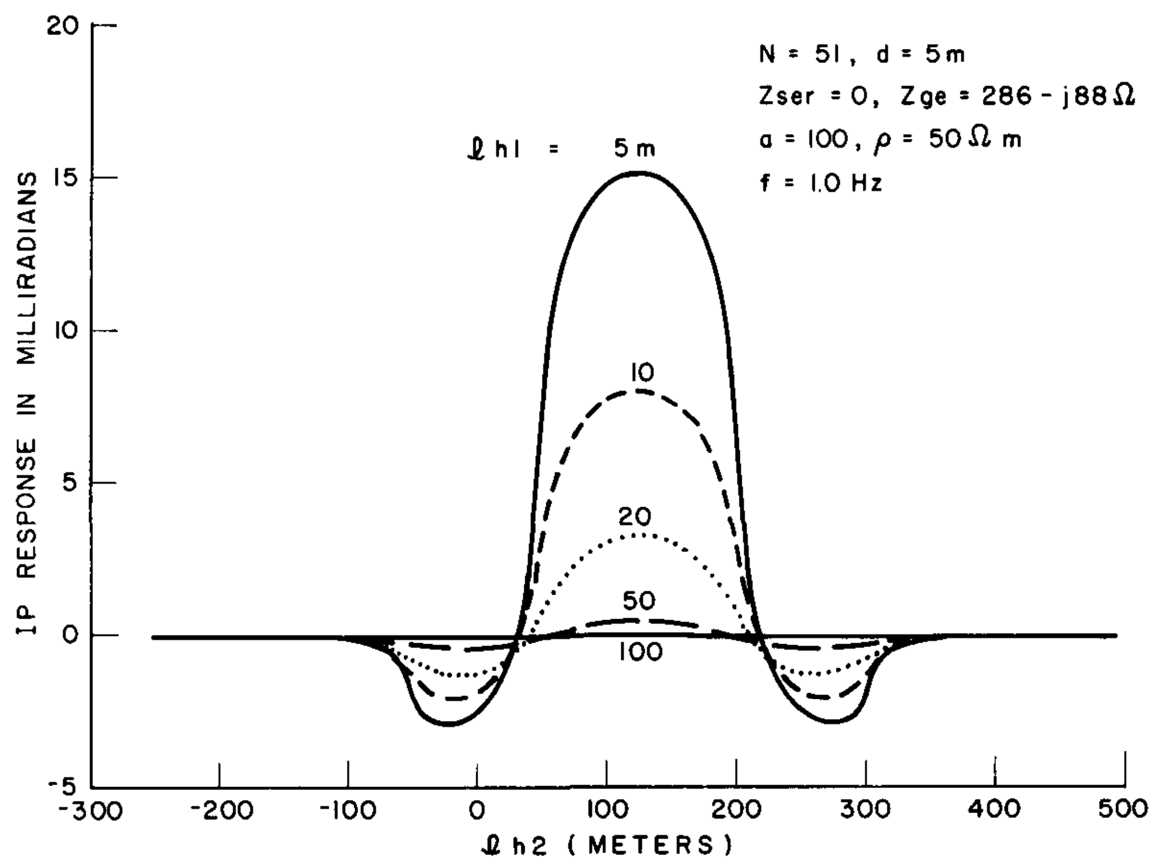

Fig. 4. IP response of a pole-pole array on a parallel traverse past a fence line.

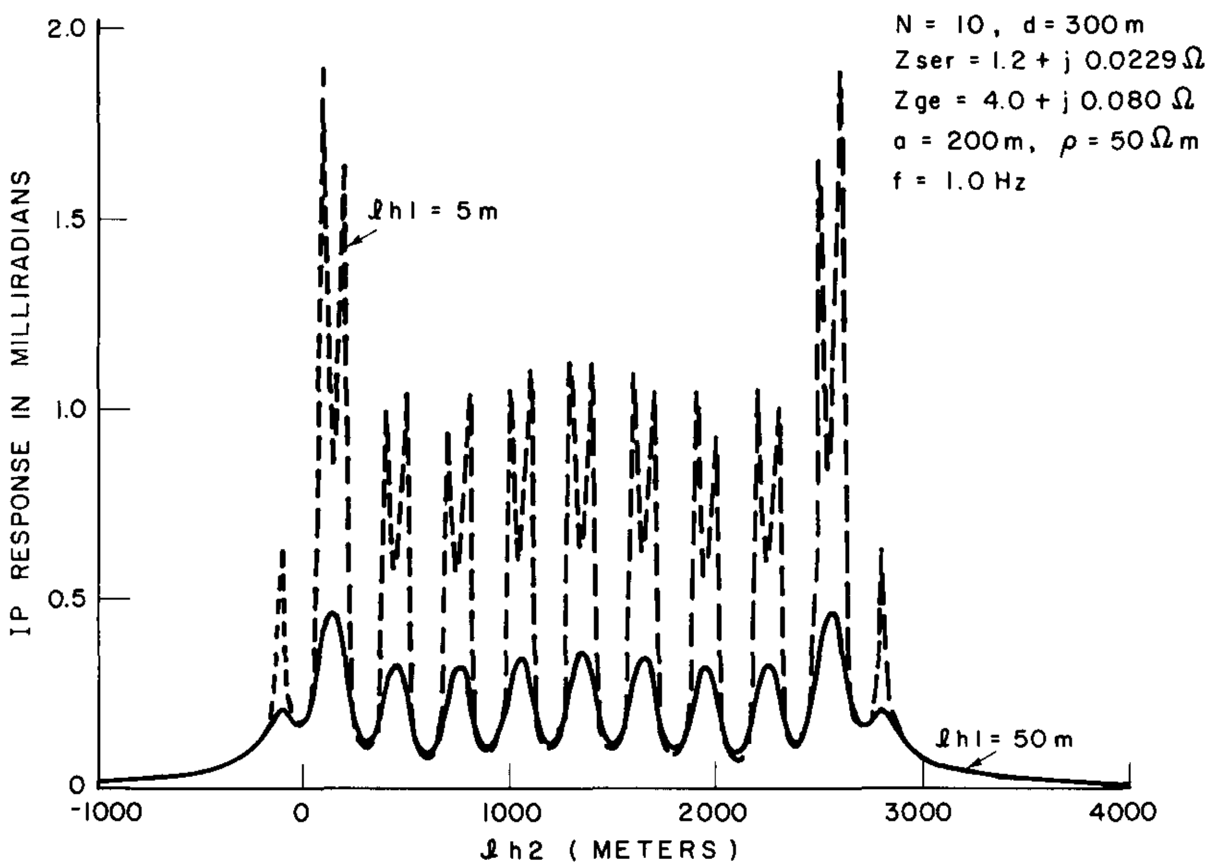

Fig. 5. IP response of a pole-pole array on a parallel traverse past a power line.

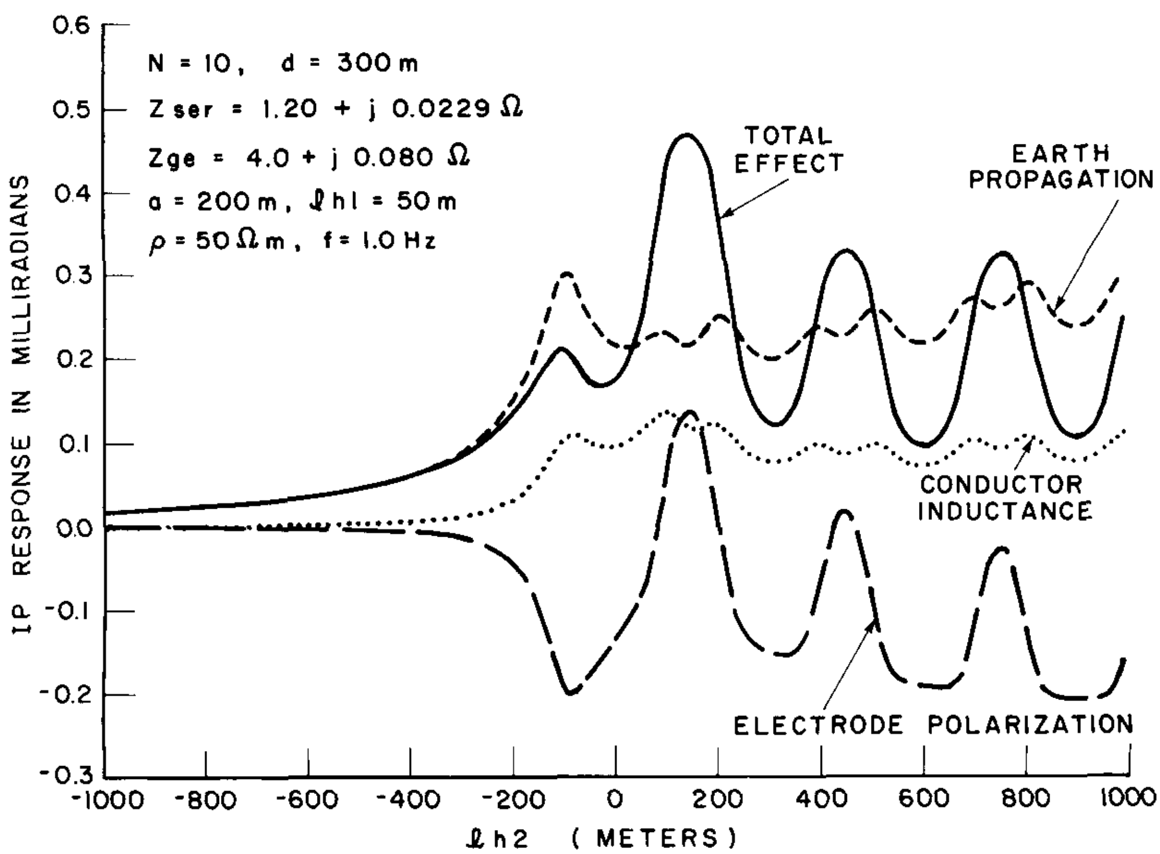

Fig. 6. A pole-pole array on a parallel traverse past a power line. The effects of earth propagation, conductor inductance and the electrode polarization are shown.

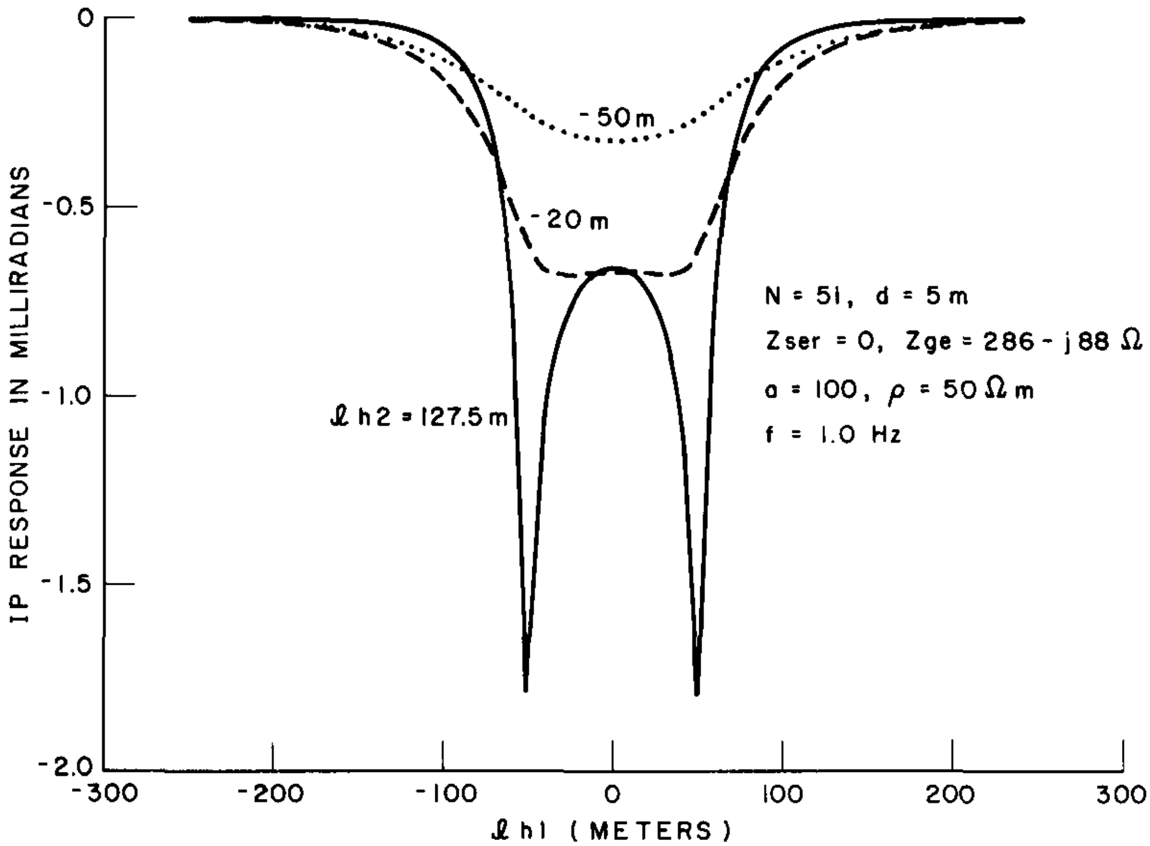

Fig. 7. IP response of a pole-pole array on a normal traverse past a fence line.

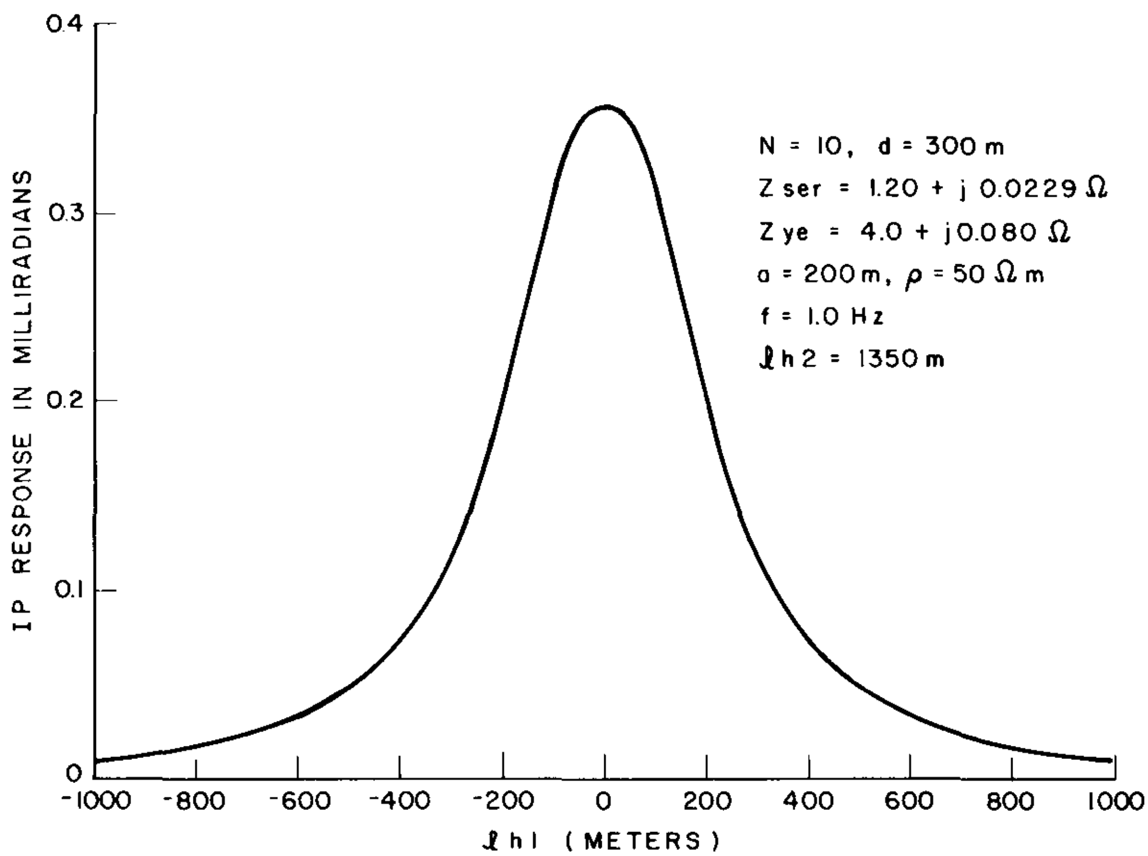

Fig. 8. IP response of a pole-pole array on a normal traverse through a power line, midway between two towers.

The Schlumberger array

A more widely used array than the pole-pole array is called the Schlumberger array and consists of a current-driving pair of electrodes separated by $2a + b$ m with an inside pair of voltage pickup electrodes separated by b m. Figures 9a and 9b show this array on traverses parallel and normal to the linear multiply grounded conductor.

The voltage observed at the pickup array in this configuration over a uniform earth (Sumner, 1976) is

$$V_{SCH} = \frac{\rho I}{\pi a(\frac{a}{b} + 1)} \quad . \tag{22}$$

The change in the voltage at the pickup probes is

$$V_{SCH_\Delta} = \frac{\rho}{2\pi} \sum_{n=1}^{N} \left[\frac{I_{1n}\, e^{-\gamma r_{3n}}}{r_{3n}} - \frac{I_{1n}\, e^{-\gamma r_{1n}}}{r_{4n}} - \frac{I_{2n}\, e^{-\gamma r_{2n}}}{r_{3n}} + \frac{I_{2n}\, e^{-\gamma r_{4n}}}{r_{4n}} \right] , \tag{23}$$

where I_{1n} represents the current induced in the positive ground electrodes due to the positive ground current from the array and I_{2n} is due to the negative ground current of the array. The distances r_{3n} and r_{4n} are the radial distances between each of the voltage pickup points to each of the ground electrodes:

$$Z_{an} = 1 + \frac{V_{SCH_\Delta}}{V_{SCH}} \quad . \tag{24}$$

The calculated results for parallel IP traverses past a fence line are shown in Figure 10 with distances of 5, 10, 20, 50 and 100 m separating the fence line from the array. Figure 11 shows an IP survey on a parallel traverse past a power line. Figures 12 and 13 show the IP survey on a normal traverse past a fence line and a power line respectively.

It is to be noted that on parallel traverses larger IP responses occur due to the likelihood of a current-injection electrode and a voltage pickup point simultaneously being near the electrodes of the grounded structure. This circumstance does not occur on a normal traverse and the IP responses are much smaller.

Conclusions

An efficient numerical method is presented for determining the induced polarization effects of electrically connected ground electrodes on the surface of a uniform-resistivity earth. The method is quite general and treats any number of ground electrodes with arbitrary locations, grounding impedances and interconnecting impedances.

Analytical traverses made past two sample grounded structures with the pole-pole and Schlumberger arrays show that the arrays in general have a small response to the structures. It appears that one should be able to avoid problems with grounded structures by maintaining a reasonable distance from them or, in other cases, by ensuring that the ground electrodes lie on an equipotential. The IP response seems to occur in fairly equal measure to earth propagation effects, interconnecting inductances between ground electrodes and reactive interface impedances in the power line case. All three effects can be expected to occur in the general case. Situations that enhance the IP response of a grounded structure occur when a primary source electrode is in close proximity of a ground electrode while a potential pickup electrode is simultaneously close to another ground electrode. Such occurrences depend on the geometries and the dimensions of the array and the grounded structure. Thus, a given array may perform well with one grounded structure and badly with one with slightly different ground spacings. It is necessary to look at the detailed geometry of a given array and a given ground structure to determine if good or poor performance will result. Even in the extreme case where the array is in close proximity to the grounded structure examined here, the grounded structure caused effects of less than 10 to 15 mrad. In the cases where the array is somewhat further away from the grounded structure, the effects are less than one mrad. The normal traverses generally had a lower response because

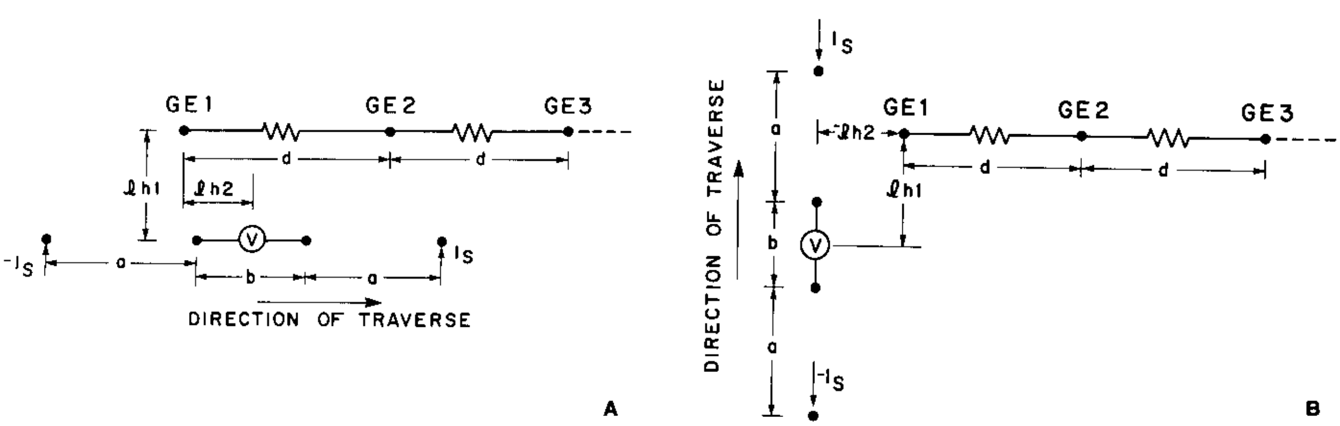

Fig. 9. A Schlumberger array in the presence of a grounded conductor: (a) parallel traverse; (b) normal traverse.

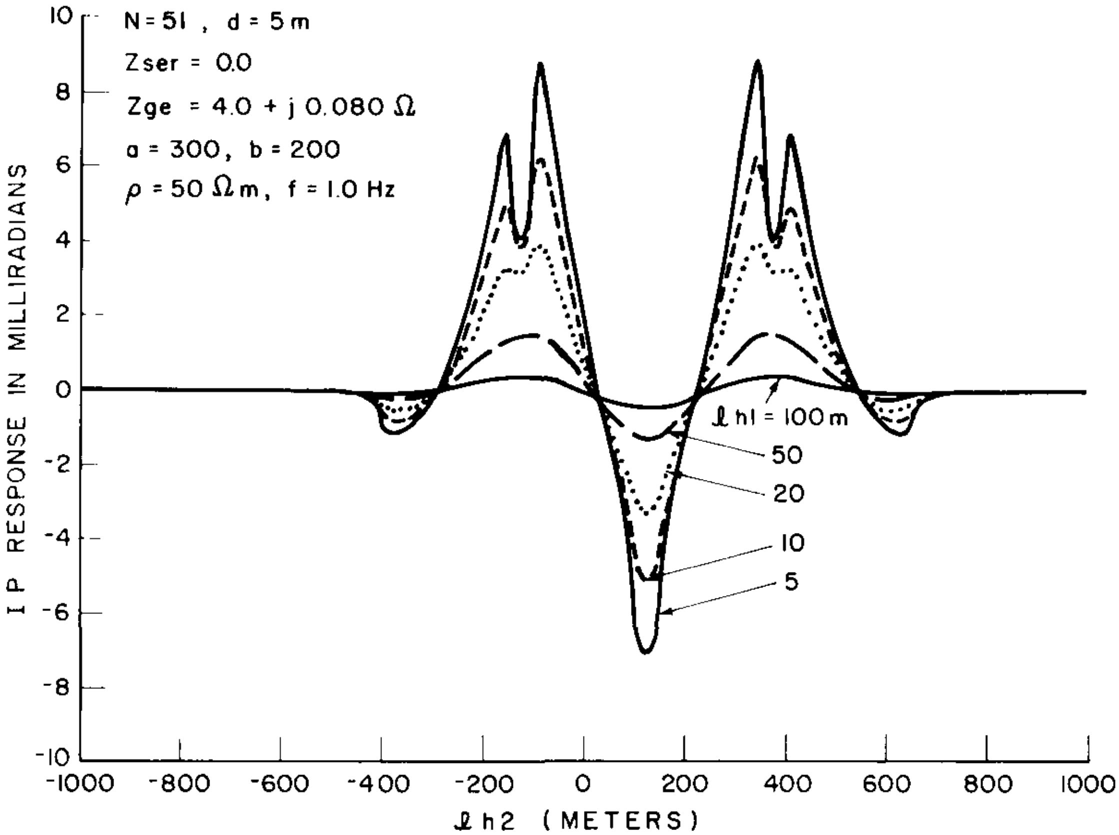

Fig. 10. IP response of a Schlumberger array on a parallel traverse past a fence line.

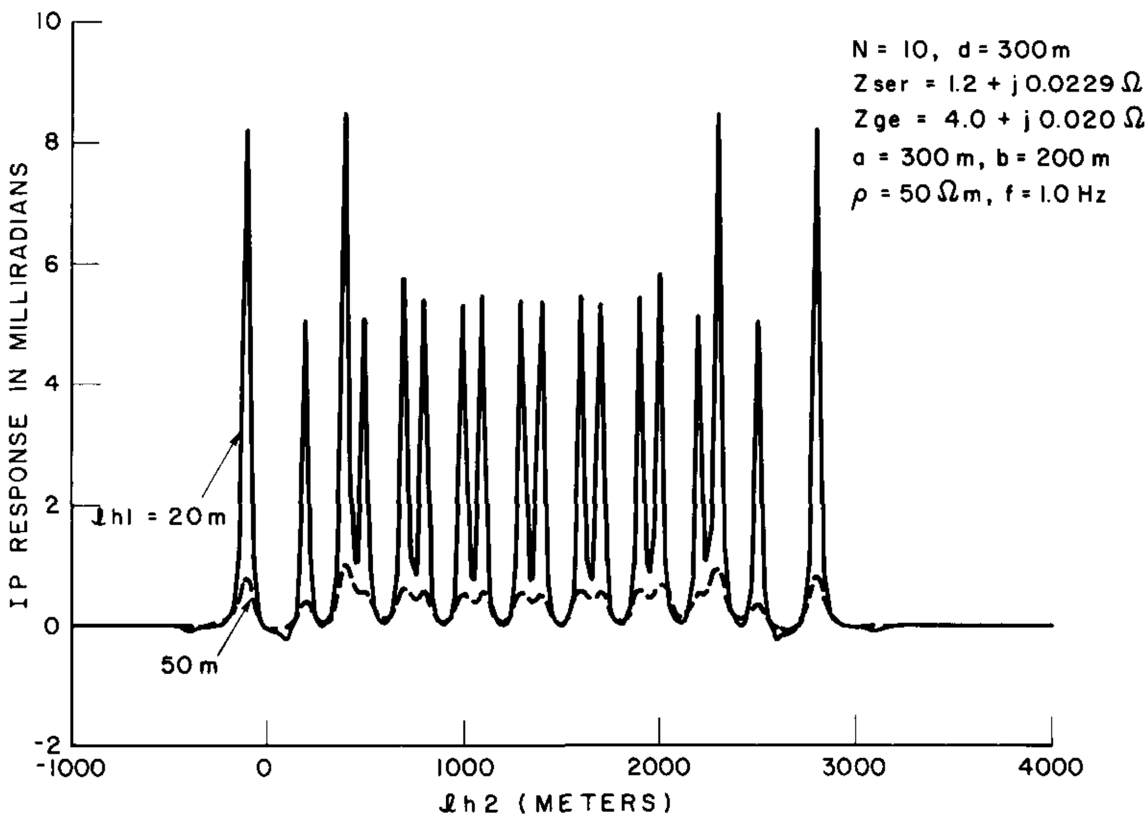

Fig. 11. IP response of a Schlumberger array on a parallel traverse past a power line.

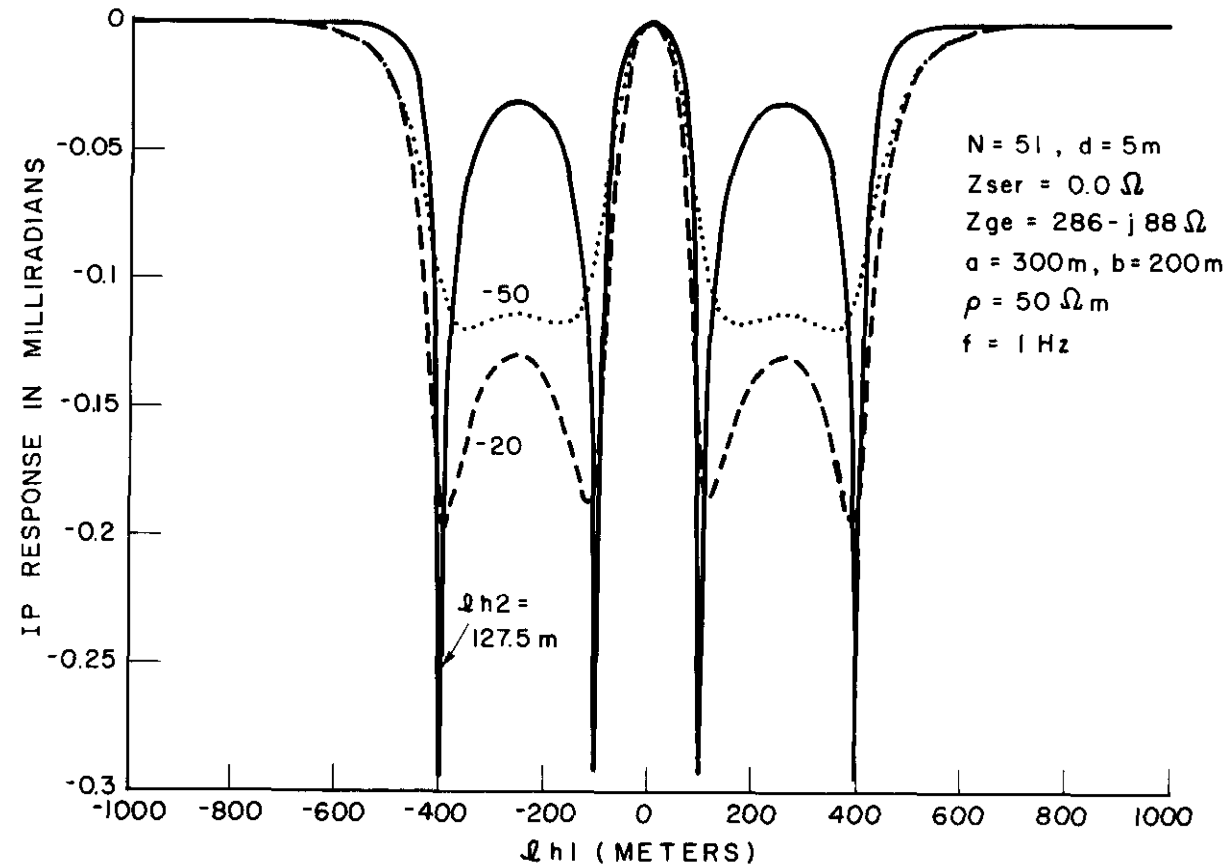

Fig. 12. IP response of a Schlumberger array on a normal traverse past a fence line.

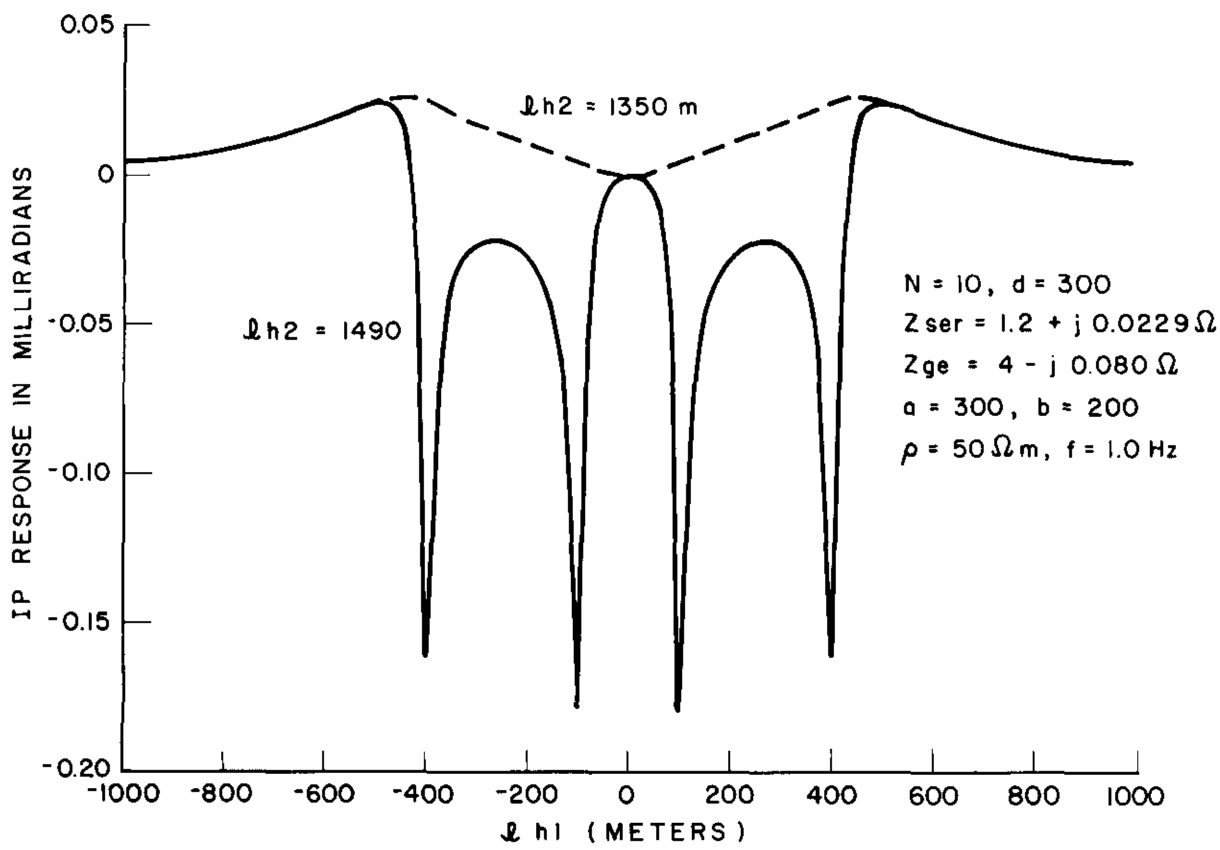

Fig. 13. IP response of a Schlumberger array on a normal traverse past a power line. The solid line shows a traverse within 10 m of the nearest tower, while the dashed line is midway between two towers.

one array electrode only could be near the structure at any given location. Even the fence, with the close proximity (2.5 m) of an array electrode to a ground electrode, gave IP responses of less than 5 mrad.

This analysis provides the geophysicist with a method of determining how closely surveys may be made to a multiply grounded structure without serious problems or, if a grounded structure must be closely approached, how to compensate for the effects of the grounded structure. Analytical survey data on a dipole-dipole array are available from the authors (Johnston et al., 1989).

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