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CULTURAL NOISE IN EM PROSPECTING FOR GEOTHERMAL RESOURCES

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ABSTRACT

Numerical analysis tools are used to characterize the fields reradiated by cultural scatterers like powerlines, pipelines and fences. These fields are then compared to the returns expected from deeply buried targets and suggestions are made for methods to identify and remove cultural noise from survey data.

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F	Magnetic Vector Potential
j	Square Root of -1
w	Frequency in Radians
I	Current in the Source
A	Area of Source Loop
L	Length of Line Source
HED	Horizontal Electric Dipole
VMD	Vertical Magnetic Dipole
u_i	$(\lambda^2 + \gamma_i^2)^{1/2}$
γ_i	$(j\sigma_i\mu_0 w - \epsilon_i\mu_0 w^2)^{1/2}$
μ_0	Permeability of Free Space
ϵ_i	Relative Permittivity of i^{th} Layer
ϵ_0	Permittivity of Free Space
σ_i	Conductivity of the i^{th} Layer
ρ	Radial Distance Between Source and Receiver
ρ_1	Distance from Source to Receiver
ρ_2	Distance from Cultural Conductor to Receiver
d	Depth of Complex Image Plane = $\delta(1-i)Q$
z	Height of Receiver
h	Height of Source
a	Radius of a Conductor
A_{eq}	Equivalent Radius of a Multiconductor System
δ	Skin Depth $\sqrt{\frac{2}{w\mu_0\sigma}}$
λ	Dummy Variable of Integration

$$R_0 \sqrt{\rho^2 + (z-h)^2}$$

$$R_1 \sqrt{\rho^2 + (z+h)^2}$$

$$R_2 \sqrt{\rho^2 + (d+z+h)^2}$$

INDEX OF SYMBOLS USED (CON'T)

- Q Complex Factor Which Accounts for Layering of Earth Model
- $\vec{E}$ $\vec{E} = E_x \vec{a}_x + E_y \vec{a}_y + E_z \vec{a}_z$ Electric Field in V/M
- $\vec{H}$ $\vec{H} = H_x \vec{a}_x + H_y \vec{a}_y + H_z \vec{a}_z$ Magnetic Field in A/M
- $\vec{J}$ Source Current Density in A/M²

SECTION I

INTRODUCTION

To search for deeply buried, geothermal resources by electromagnetic (EM) methods, interest must be directed to the very low frequency part of the survey data and surveys must be conducted over larger areas. Small signal amplitudes are to be expected and significant interference from noise sources can be anticipated. The sources of noise that one must consider are:

1. Natural atmospheric noise due to:
 - ▶ distant lightning transients propagated in the earth/ionosphere wave guide;
 - ▶ local thunderstorm activity;
 - ▶ very low frequency (VLF) and extremely low frequency (ELF) emissions from the ionosphere, or deep space.
2. Man made noise due to:
 - ▶ radio transmissions;
 - ▶ power line radiation of 60 cycle noise (and harmonics).
3. Geological noise due to:
 - ▶ surface anomalies-ground water effects, etc.;
4. Cultural noise due to:
 - ▶ reradiation from pipelines, powerlines, fences, etc.

In this work we are concentrating our attention on the characterization of cultural noise and the methods by which it could be identified and removed from data taken in active EM surveys.

To serve as a basis for comparison of cultural noise to expected signals, the EM-60 [1] and the TDEM [2] surveying techniques were selected.

These two systems are logical choices for searching for deeply buried targets and they provide a contrast of frequency domain and time domain interpretation of survey data.

The cultural noise sources that were selected for detailed consideration are pipelines, overhead power lines, and fences. These are all horizontal scatterers which are most likely to cause problems in EM-60 and TDEM surveys.

The approach used here to characterize cultural noise involved the use of a two layer model for the surface of the earth. The first step taken in the analysis was to calculate the field expected on the surface of the earth including the reflection from a more conductive lower layer which represented the geothermal resource target.

The second step involved the introduction of the cultural scatterer into the problem and the calculation of the currents that would flow on the cultural scatterer using the fields obtained in step one.

In the third step, the cultural noise fields reradiated by one cultural scatterer are computed and added to the original fields to obtain the total field expected at an observer location.

In the final step, the total fields obtained with the cultural scatterer present are compared to the fields expected when there is no cultural scatterer present. In this final step we can identify how the presence of the cultural noise might be confused with the reflection from the target.

In the material to follow we 1) describe the models used in this analysis, 2) describe the data obtained by applying these models to reasonable survey conditions, and 3) suggest ways in which the cultural noise may be removed from the data.

SECTION II

MODELS FOR TRANSMITTING ANTENNAS

Two popular types of transmitting antennas used in electromagnetic survey systems are the horizontal loop and the grounded horizontal wire antenna. Each of these radiators have certain inherent advantages and disadvantages depending upon the purpose of the survey, survey technique, and field conditions. [1-5] The primary advantage of the loop antenna is that it couples inductively to the earth and does not require a ground contact. This is of particular importance in regions of high surface resistivity where good ground contacts are difficult to make. A disadvantage of the loop is that the field strength falls off much more rapidly with distance than does the grounded horizontal wire source. Depending on size, the logistics of deploying a loop antenna in the field can also be more difficult than a straight grounded dipole.

In the field, a loop antenna consists of one or more turns of wire laid out as a circle or rectangle of variable size. A variable current, usually in the form of a step, ramp or square wave is applied to the coil in order to generate an electromagnetic field. The horizontal wire antenna consists of a length of wire grounded at each end and driven by a varying current source. If the dimensions of the transmitting antennas are small with respect to the dimensions of the survey or with respect to the freespace wavelength, then the horizontal loop can be approximated by a vertical magnetic dipole (VMD), while a ground horizontal wire can be approximated by a horizontal electric dipole (HED). The VMD, HED, and their associated coordinate systems are given in Figure 1. Both antennas generate primarily a vertical magnetic field component and a horizontal electric field component at the surface of the earth. The receiving antenna for EM survey systems is often a horizontal loop antenna or a horizontal wire. Therefore, the major fields of interest are the vertical magnetic field component and the horizontal electric field component.

VMD Vertical Magnetic Dipole

HED Horizontal Electric Dipole

Figure 1. Antenna Models

The electromagnetic fields generated by elementary dipole sources in the presence of conducting media has been investigated by numerous authors, beginning with Sommerfeld.^[6] More recent treatments by Banos^[7], and Wait^[8,9] provide solutions for sources in the presence of a stratified, conducting earth. However, the more exact analytical expressions are in the form of complex integrals which are difficult to apply directly. Simplified expressions have been developed by Bannister^[10] using Quasi-static image theory.

Physically, the essence of Bannister's image theory technique is to replace the finitely conducting earth with a perfectly conducting earth located at a complex depth $d/2$ where $d = 2/\gamma_1 = \delta(1-i)$. If the physical antenna is located at a height, h , above the surface of the earth, then the image is located at the depth $h + d$ below the earth surface. For a layered earth, the complex depth parameter is $d = \delta(1-i)Q$, where Q is the layered earth correction factor developed by Wait.^[8] (See Appendix A for further details on this approximation).

Formulas for the Quasi-static fields of a small horizontal loop (vertical magnetic dipole) and a horizontal electric dipole are given in Figures 2 and 3.

$$\gamma_0 = i\omega(\mu_0\epsilon_0)^{1/2} \sim 0 \text{ (air)}$$

$$\gamma_1 \sim (i\omega\mu_0\sigma_1)^{1/2} \text{ (earth)}$$

$$d = 2/\gamma_1 = \delta(1 - i).$$

$$\delta \sim \sqrt{2/\omega\mu_0\sigma_1}$$

$$E_\phi \approx -\frac{i\omega\mu_0 IA}{4\pi\rho^2} \left[1 - \frac{\rho^3}{(\rho^2 + d^2)^{3/2}} \right]$$

$$H_z \approx -\frac{IA}{4\pi\rho^3} \left\{ 1 - \frac{\rho^3}{(\rho^2 + d^2)^{3/2}} \left[1 - \frac{3d^2}{(\rho^2 + d^2)} \right] \right\}.$$

$$H_\rho \approx -\frac{3IA}{2\pi\gamma_1\rho^4} \text{ valid only for } \rho \gg \delta$$

Figure 2. Quasi-static Fields of a Vertical Magnetic Dipole on the Earth Surface for an Observer on the Earth's Surface. (From ref. 10).

$$\gamma_0 = i\omega(\mu_0\epsilon_0)^{1/2} \sim 0 \text{ (air)}$$

$$\gamma_1 \sim (i\omega\mu_0\sigma_1)^{1/2} \text{ (earth)}$$

$$d = 2/\gamma_1 = \delta(1 - i)$$

$$\delta \sim \sqrt{2/\omega\mu_0\sigma_1}$$

$$E_x \approx -\frac{i\omega\mu_0 I}{4\pi} \left\{ \ln \left[\frac{R'_{11} - (x + L/2)}{R'_{12} - (x - L/2)} \right] - \ln \left[\frac{R'_{21} - (x + L/2)}{R'_{22} - (x - L/2)} \right] + \frac{d^2}{2} \left[\frac{(x + L/2)}{(R'_{21})^3} - \frac{(x - L/2)}{(R'_{22})^3} \right] \right\}$$

$$E_y \approx -\frac{Iy}{2\pi\sigma} \left[\frac{1}{(R'_{21})^3} - \frac{1}{(R'_{22})^3} \right]$$

$$E_z \approx \frac{i\omega\mu_0 I}{4\pi} \left\{ \ln \left[\frac{R'_{11} - (d + h)}{R'_{12} - (d + h)} \right] - \ln \left[\frac{R'_{21} - h}{R'_{22} - h} \right] + \frac{2h}{\gamma_0^2} \left[\frac{1}{(R'_{21})^3} - \frac{1}{(R'_{22})^3} \right] \right\}$$

$$H_x \approx \frac{Iy}{4\pi} \left\{ \frac{1}{[(x - L/2)^2 + y^2]} \left[\frac{(d + h)}{R'_{12}} - \frac{h}{R'_{22}} \right] - \frac{1}{[(x + L/2)^2 + y^2]} \left[\frac{(d + h)}{R'_{11}} - \frac{h}{R'_{21}} \right] \right\}$$

$$H_y \approx \frac{I}{4\pi} \left\{ \frac{(d + h)}{[y^2 + (d + h)^2]} \left[\frac{(x + L/2)}{R'_{11}} - \frac{(x - L/2)}{R'_{12}} \right] + \frac{h}{(y^2 + h^2)} \left[\frac{(x + L/2)}{R'_{21}} - \frac{(x - L/2)}{R'_{22}} \right] + \frac{(x + L/2)}{[y^2 + (x + L/2)^2]} \left[\frac{(d + h)}{R'_{11}} - \frac{h}{R'_{21}} \right] - \frac{(x - L/2)}{[y^2 + (x - L/2)^2]} \left[\frac{(d + h)}{R'_{12}} - \frac{h}{R'_{22}} \right] \right\}$$

$$H_z \approx -\frac{Iy}{4\pi} \left\{ \frac{1}{[y^2 + (d + h)^2]} \left[\frac{(x + L/2)}{R'_{11}} - \frac{(x - L/2)}{R'_{12}} \right] - \frac{1}{(y^2 + h^2)} \left[\frac{(x + L/2)}{R'_{21}} - \frac{(x - L/2)}{R'_{22}} \right] \right\}$$

where

$$R'_{11} = [(x + L/2)^2 + y^2 + (d + h)^2]^{1/2}$$

$$R'_{12} = [(x - L/2)^2 + y^2 + (d + h)^2]^{1/2}$$

$$R'_{21} = [(x + L/2)^2 + y^2 + h^2]^{1/2}$$

$$R'_{22} = [(x - L/2)^2 + y^2 + h^2]^{1/2}$$

Figure 3. Quasi-static Fields from an Elevated Horizontal Electric Dipole of Finite Length for an Observer on the Earth's Surface (From Ref 10).

SECTION III

MODELS FOR CULTURAL SCATTERERS

The cultural scatterers considered here all fall within the general classification of a long horizontal axial conductor near the earth's surface. Specifically, this report deals with powerlines, fences, and pipelines.

For the purposes of this report, the scatterers considered are taken to be much longer than the dimensions normally encountered during a geophysical survey. Under these conditions, the scatterers can be modelled reasonably well as infinitely long transmission lines.

The generalized transmission line model for an incremental length of a horizontal conductor parallel to the earth is depicted in Figure 4.

Figure 4. Horizontal Conductor Parallel to the Earth

Here, the incremental line parameters

R_c, L_c are associated with the conductor;

R_e, L_e are associated with the earth or "external" circuit;
and

C_s, G_s are the total shunt capacitance and shunt conductance.

The currents and voltages observed at any point along the line will satisfy the "Telegraphers Equations".

$$\frac{\partial \hat{V}}{\partial x} = E_x^{inc}(x) - \hat{Z}\hat{I}$$

$$\frac{\partial \hat{I}}{\partial x} = -\hat{Y}\hat{V},$$

which can be combined into a single wave equation,

$$\frac{\partial^2 \hat{I}}{\partial x^2} = -\hat{Y} \frac{\partial \hat{V}}{\partial x} = \hat{Y}\hat{Z}\hat{I} - \hat{Y}E_x^{inc}(x),$$

or

$$\frac{\partial^2 \hat{I}}{\partial x^2} - \hat{Y}\hat{Z}\hat{I} = -\hat{Y}E_x^{inc}(x).$$

For an infinitely long line, this equation has the solution

$$I(x) = \frac{1}{2\hat{Z}_0} \int_{-\infty}^{\infty} E_x^{inc}(x') e^{-\gamma|x-x'|} dx'.$$

Here γ denotes the complex propagation constant, $\gamma = \sqrt{\hat{Z}\hat{Y}}$. The characteristic impedance, $\hat{Z}_0$, is defined by

$$Z_0 = \sqrt{\frac{\hat{Z}}{\hat{Y}}}.$$

The currents on pipelines, powerlines, and fences can all be determined using this final integral equation. Of course, the value of the characteristic impedance and propagation constant depend upon the incremental line parameters that depend upon the configuration of the scatterer and its contact with the surrounding media. In the section to follow, we present the approximate formulas for these line parameters.

POWERLINE MODEL

Although a power line will have several conductors, we can use a single conductor model for the line because it is the "algebraic sum" of the currents on each wire (the common mode current) that engenders the most significant external radiation.

To use a single conductor model for a power line, we require an effective radius for that conductor. Figure 5 shows several common powerline configurations and their equivalent radii (from reference 11).

For the calculations to be made here, we have selected a high voltage transmission line (Figure 6) for detailed consideration. The most significant feature of this type of powerline is the two guard wires that run above the phase conductors for lightning protection. Since these conductors are grounded at every tower, they are the principal source of the cultural noise.

Arrangement	Equivalent Radius
$a_e = \sqrt{aD}$
$a_e = \sqrt[3]{1.59 aD^2}$
$a_e = \sqrt[3]{aD^2}$
$a_e = \sqrt[4]{1.4 aD^3}$

$$L_c = \frac{\mu_0}{2\pi} \ln \frac{2h}{a_e}, \quad C_s = \frac{1}{L_c (3 \times 10^8)^2}$$

Figure 5. Equivalent Single Wire Radii of Multiwire Configurations (From Reference 11, page 25).

Figure 6. High Voltage Transmission Line and Equivalent Circuit.

Our single conductor model of the powerline includes only these two conductors grounded at each tower. Assuming the wire radius is 1.5cm and separated by 3 meters, the equivalent radii is $a_e = \sqrt{aD} = \sqrt{.015 \times 3} = 0.2$ meters.

The average span between towers is about 180 meters and the height is about 18 meters for this type of transmission line.^[12]

The grounding of the wires at each tower is included in the model by "smearing" this discrete conductance over the entire span to provide an effective shunt conductance, $G_s = \frac{G_{\text{tower}}}{\text{span}}$. To compute the discrete ground conductance at each tower, it was assumed that four ground stakes of 5cm radius (with 5 meter separation) were driven into the ground to a depth of 3 meters in a rectangular pattern. Using Figure 5, we see that this grounding scheme is the equivalent of one 1.72m radius ground stake driven 3 meters into the ground. The resistance of a ground stake is given by Sunde^[13] to be:

$$R = \frac{1}{2\pi\sigma\ell} \left[\log \frac{4\ell}{a_{\text{eq}}} - 1 \right],$$

where ℓ = length of ground stake below the earth's surface. If we assume an additional ohmic impedance of 10 ohms to allow for contact resistance, then

$$G_{\text{tower}} = \frac{1}{10 + \frac{0.05}{\sigma_1}} \text{ mhos},$$

$$G_s = \frac{G_{\text{tower}}}{\text{span}} = \frac{1}{1800 + 9/\sigma_1} \text{ mhos/meter}.$$

The line inductance and capacity are computed from the formulas given in Figure 5. The ohmic resistance of the line was taken to be $1. \times 10^{-5}$ ohms/meter.

The soil impedance at low frequencies was obtained from curve fits [14] to numerical solutions of Carson's integral [15]:

$$Z_{\text{soil}} = A \frac{w \sqrt{w_r}}{\sqrt{w + w_r}} + iB \frac{w \sqrt{w_I}}{\sqrt{w + w_I}},$$

where

$$A = \mu_0/8, w_r = 1.29 \times 10^6/h^2\sigma_1$$

and

$$B = 7.5 \times A, w_I = w_r/56.25.$$

For the frequency range of interest here, $R_{\text{soil}} \approx \frac{w\mu_0}{8}$, which is the value derived by Wait. [16]

With these parameters, the definition of the transmission line model for the powerline is complete.

The characteristic impedance, Z_0 , and propagation constant, γ , of the powerline are then given by:

$$Z_0 = \sqrt{\frac{(R_{\text{wire}} + R_{\text{soil}}) + iw(L_{\text{wire}} + L_{\text{soil}})}{G_s + iwC_s}} ;$$

$$\gamma = \sqrt{((R_{\text{wire}} + R_{\text{soil}}) + iw(L_{\text{wire}} + L_{\text{soil}})) \times (G_s + iwC_s)}.$$

These formulas are used in computing the expected responses in Sections 4 and 5 to follow.

FENCE MODELS

As in the powerline model, we seek a single conductor model of the multiconductor fence. Unlike the powerline, the separation between conductors is not much smaller than the average height of the conductors. Consequently, formulas for equivalent radii and incremental line capacitance are not as easily obtained. The determination of the total incremental capacity of fence conductors involves the solution of a system of simultaneous equations. As an example of how this is done, consider the three wire fence with the first wire located at height $z = h$ above the ground and the second and third wires located at $z = 2h$ and $z = 3h$, respectively. By definition the total capacity is the total charge on the 3 wires when all are held at a one volt potential with respect to the earth, $Q = CV$.

Since the potential everywhere in space is the superposition of the potential due to the charge on each line and its image, a set of simultaneous equations for the charge on the individual wires is obtained.

$$V(z=h) = 1 = \frac{1}{2\pi\epsilon_0} \left[Q_1 \ln \frac{2h}{a} + Q_2 \ln \frac{3h}{h} + Q_3 \ln \frac{4h}{h} \right] .$$

$$V(z=2h) = 1 = \frac{1}{2\pi\epsilon_0} \left[Q_1 \ln \frac{3h}{h} + Q_2 \ln \frac{4h}{a} + Q_3 \ln \frac{5h}{h} \right] .$$

$$V(z=3h) = 1 = \frac{1}{2\pi\epsilon_0} \left[Q_1 \ln \frac{4h}{h} + Q_2 \ln \frac{5h}{h} + Q_3 \ln \frac{6h}{a} \right] .$$

Here, "a" is the radius of the individual wire and $V = \frac{-Q}{2\pi\epsilon_0} \ln r$ is the potential due to an individual line charge of Q coulombs/meter.

The total capacity is obtained by solving the above system of equations for the individual charges and then adding the results. Extension to 4 or 5 wire systems is evident. In the numerical calculations to be considered in Section 4, we have assumed that the 3rd wire was about 1.5 meters high and the wire radius was 0.001 meters to obtain a value of $C_s = 20$ pfd/meter. As before, $L_{\text{wire}} = \frac{1}{c^2 C_s} = .55 \mu\text{henries/meter}$.

When the fence wire is connected to metal posts, a ground exists at each post which increases the cultural noise generated by the scatterer. The effect of this periodic grounding on induced polarization (IP) measurements has been previously considered by Nelson.^[17] Here we are concerned with higher frequencies where currents on the fence itself produce unwanted cultural noise. Nelson measured the impedance of individual fence stakes at several sites. He found that there was considerable stake-to-stake variation in the impedance obtained even at a given site. Generally the impedance fell in the range of 200 to 2000 ohms magnitude, with a lagging phase angle between 100 and 300 milliradians at 1Hz excitation. For the numerical calculation in Section 4, we used Sunde's formula for stake impedance.

$$R = \frac{1}{2\pi\sigma_{\text{soil}} \ell} \left[\ln \frac{4\ell}{a} - 1 \right] ,$$

with $\ell = 0.5$ meters, $a = 0.03$ meters. This yields $R = \frac{1}{\sigma_{\text{soil}}}$ which is in the center of the range observed by Nelson.^[17] As in the powerline model, the discrete shunt conductance at a stake can be smeared over the distance between stakes:

$$G_s = \frac{G_{\text{stake}}}{\text{separation}} .$$

The characteristic impedance and propagation constant are computed using the same formulas used for the powerlines.

PIPELINE MODEL

The transmission line properties of buried conductors have received considerable attention for both insulated conductors^[18,19,10] and uninsulated conductors.^[12,13,21,22] The model used in this work follows that of Vance,^[12] where the external impedance of a buried conductor is given as:

$$Z_{\text{ext}} = \frac{w\mu_0}{8} + iw \frac{\mu_0}{2\pi} \ln \frac{.794\delta}{a} .$$

The radius "a" of the pipe was assumed to be 0.1m. We also assumed an ohmic impedance R_{pipe} of 1×10^{-5} ohm/m. This gives

$$Z_e = \left(\frac{w\mu_0}{8} + 1. \times 10^{-5} \right) + iw \frac{\mu_0}{2\pi} \ln \frac{.794\delta}{.1} .$$

The admittance per unit length of a buried conductor is:

$$Y_e = \frac{2\pi\sigma}{\ln \left(\frac{0.794\delta}{a} \right)} .$$

The characteristic impedance, z_o , and propagation constant, γ , of the pipe are then given by:

$$z_o = \sqrt{\frac{Z_e}{Y_e}} \quad \gamma = \sqrt{Z_e \times Y_e} .$$

To analyze the response of an insulated buried pipe, it is sufficient to use the same formulas above except for placing the capacity of the insulation in series with the soil admittance. [22]

$$1/Y_{\text{insulated}} = \frac{1}{i\omega 2\pi\epsilon} \ln \left(\frac{b}{a} \right) + \frac{\ln \left(\frac{0.794\delta}{b} \right)}{2\pi\sigma} .$$

Bannister [20] also gives the external impedance of a long buried insulated wire as

$$Z_e = \frac{i\omega\mu_0}{2\pi} \left[\ln \left(\frac{1.123}{\gamma a} \right) + \frac{e^{-2\gamma h}}{2} \right] ,$$

where h is the depth of burial and $\gamma^2 \sim i\omega\mu_0\sigma$.

If the propagation constant along the buried pipe is taken to be that of the surrounding medium, the admittance can be calculated as

$$Y = \gamma^2/Z_e \quad .$$

Numerical results calculated with Bannister's equations for insulated wires do not differ significantly from those calculated with Vance's formulas as modified for insulated wires for parameters within the range considered in this report.

SECTION IV

CURRENTS INDUCED ON CULTURAL SCATTERERS

In Section III it was noted that the electrical properties of powerlines, fences, and pipelines could all be approximated by transmission line parameters and that the currents flowing on these scatterers could be determined from the integral.

$$I(x) = \int_{-\infty}^{\infty} \frac{E_x^{\text{inc}}(x') e^{-\gamma|x-x'|} dx'}{2z_0}$$

In this section we examine results of this integration and how the currents on the cultural scatterers depend upon frequency, distance down the line, and the separation of the transmitting antenna and the scatterer. Both vertical magnetic dipole (VMD) and horizontal electric dipoles (HED) are considered in separate subsections. In each case, numerical integration of the integral above was used to obtain the response data.

VERTICAL MAGNETIC DIPOLE EXCITATION

When a cultural scatterer is present in the vicinity of a vertical magnetic dipole, there exists an incident E-field which is parallel to the scatterer at the midpoint (see geometry, Figure 7). This incident field produces a current on the scatterer which in turn produces scattered E and H fields.

In Figures 8, 9 and 10 are shown the magnitude of the AC current that would be observed at the center of an uninsulated pipeline, a periodically grounded powerline, and a fence with metal stakes when excited by a vertical magnetic dipole (VMD) located 100 meters from the line.

Figure 7. Loop to Receiver Geometry with Scattering Body Present

Figure 8. Current Observed at the Midpoint of a Pipeline Located 100 Meters from a Vertical Magnetic Dipole, Over a Homogeneous Earth.

Figure 9. Current Observed at the Midpoint of a Powerline with Periodic Grounding Located 100 Meters from a Vertical Magnetic Dipole Over a Homogeneous Earth.

Figure 10. Current Observed at the Midpoint of a Fence on Metal Stakes Located 100 Meters from a Vertical Magnetic Dipole Over a Homogeneous Earth.

In all cases, the exciting source was assumed to have time dependence $e^{+j\omega t}$ and the conductivity of a uniform earth below the antenna was varied as a parameter.

The frequency dependence of the current is similar in all cases. However, the highest currents are induced on the pipe; therefore, we would expect the pipe to be the worst case scatterer. For most of the numerical work to follow only the buried pipe model was analyzed.

The currents induced by a VMD at various points along a pipe are shown in Figures 11, 12 and 13. These are currents caused by a current loop 100, 1000 and 2000 meters (ρ_1) away from the pipe over a homogeneous earth ($\sigma = .001$).

We can see from the figures that the current falls off away from the midpoint along the line. This is because the E_{inc} field is parallel to the pipe only at the midpoint and the fields fall off as $1/\rho^3$ away from the VMD. This allows us to integrate the incident field over finite limits when determining the current at a point on the line. The rate of fall off of current on the pipe is inversely proportional to the pipe-source distance. Therefore, the integration limits must increase as ρ_1 increases. In our current calculations, the incident E-field was integrated from $-100\rho_1$ to $+100\rho_1$ along the scattering line.

The total current induced on a scatterer is also inversely proportional to the source-scatterer separation. The current induced at the midpoint of pipe at different source-scatterer separations is shown in Figure 14.

As the conductivity of the earth's upper surface changes, the spectral response of the current also changes. A factor of 10 increase in conductivity causes the frequency response of the current to be shifted down a factor of 10. Figure 15 shows the spectral response of current magnitudes on a pipe for various upper earth conductivities.

Figure 11. Current Induced at Points Along a Pipe 100 Meters Away from a VMD Over a Homogeneous Earth, $\sigma = .001$.

Figure 12. Current Induced at Points Along a Pipe 1000 Meters Away From a VMD Over a Homogeneous Earth, $\sigma = .001$.

Figure 13. Current Induced at Points Along a Pipe 2000 Meters Away From a VMD Over a Homogeneous Earth, $\sigma = .001$.

Figure 14. Current Induced on Midpoint of Pipe at Various Distances Away From VMD Over Homogeneous Earth, $\sigma = .001$.

Figure 15. Current Induced on Midpoint of Pipe 1000 Meters Away From VMD Over Homogeneous Earth for Different Conductivities.

HORIZONTAL ELECTRIC DIPOLE EXCITATION

In all cases considered in this report, it was assumed that the transmitting electric dipole antenna was 1000 meters long and positioned parallel to a buried pipeline with the transmission line equivalent discussed in Section III. The parameters that were varied in determining the current on the pipeline were the frequency, the conductivity of the uniform media under the pipeline, and the separation between the transmitting antenna and the scatterer. The electric field produced by a horizontal electric dipole is constant at low frequencies (Figure 3) rather than being directly proportional to frequency as they are for a VMD (Figure 2). Consequently, the currents on the scatterer are also constant at low frequencies (Figure 16).

The dependence of the current on the distance down the line with HED excitation (Figure 17) is more irregular than the spatial dependence with VMD excitation (Figure 14), possibly due to interference effects attributed to the finite line length. This interference effect is also probably responsible for the small irregularities observed at the center of the line (Figure 18) where the small dependence of line current on earth conductivity is indicated (on an expanded scale).

RERADIATED FIELDS

When the cultural scatterer is excited by a vertical magnetic dipole, the current on the scatterer is a smooth function of distance down the line (Figure 13). For this reason, the fields near the scatterer can be approximated by the fields due to a line source. As given by Bannister, ^[10] these are:

Figure 16. Magnitude of Induced Current at Center of Buried Pipe Due to 1 Ampere HED of Length 1000 m at Distance of 100 m, 1000 m, 2000 m, 5000 m, and 10,000 m. Homogeneous Earth of Conductivity .001 mhos/meter.

Figure 17. Magnitude of Induced Current in a Buried Pipe at Distances of 0 m, 1000 m, 2000 m, and 5000 m from the Center. Uniform Earth of Conductivity .001. Source is 1 Ampere HED of Length 1000 m at a Distance of 100 m from Pipe.

Figure 18. Magnitude of Induced Current at Center of Buried Pipe Over a Uniform Earth of Conductivity .001 and .01. Source is 1 Ampere HED of Length 1000 m Located at a Distance of 100 m.

$$E_x \doteq \frac{-i\omega\mu_0 I}{2\pi} \ln \sqrt{\frac{y^2 + (d+z+h)^2}{y^2 + (z-h)^2}},$$

$$H_z \doteq \frac{-I}{2\pi} \left(\frac{1}{y^2 + (d+z+h)^2} - \frac{1}{y^2 + (z-h)^2} \right).$$

The current, I , is not constant along the line. However, if the distance to the receiver is relatively small ($\rho_2 \leq 10\rho_1$), we can assume that the current is almost constant for the purpose of calculating the scattered fields.

When the cultural scatterer is excited by the horizontal electric dipole, the current is not as nearly uniform along the line. To account for this difference, it was decided to break the scatterer into a number of segments and to evaluate the total reradiated field by summing the fields contributed by each segment (Figure 3). Since the current driving each segment is calculated from the transmission line equations, this approach has the potential of being more accurate than the assumed line source approximation, and the restriction that the receiver must be close to the scatterer can be removed.

SECTION V

CHARACTERIZATION OF CULTURAL NOISE AS OBSERVED WITH A VERTICAL MAGNETIC DIPOLE SOURCE

To characterize how cultural noise might appear in an active EM survey, it was decided to calculate fields that would exist over a two layer earth due to VMD excitation. The scatterer is then introduced and the cultural noise is added to the signal to illustrate how the cultural noise might be misinterpreted as a buried target.

Figure 19 shows a block diagram of the EM-60 EM prospecting system which is one type of equipment that can be used for deep prospecting. [1] The transmitter truck will deliver a repetitive square wave into a loop antenna of about 100 meters in diameter. The fundamental frequency of this signal can be varied from .001 to 1000 Hz and the amplitude of the source current can be varied up to about 400 amperes depending upon the resistance of the loop. The receiving system measures the amplitude and phase of the fundamental and 10 harmonics of up to five channels of input data.

The phase can be referenced to the transmitter current (through the telemetry link) or relative phase measurements can be made (for example, the phase of E_x can be measured relative to H_z). The accuracy of these phase measurements is better than 0.05 degrees. This equipment could also be used to measure transient data if so desired.

Here we shall examine the characteristics of cultural noise in both CW and transient data.

"NOISE FREE" CW FIELDS PRODUCED BY VMD EXCITATION

In this section we illustrate what the two layered earth fields look like without the cultural scatterer present. These calculated fields

A low frequency electromagnetic prospecting system

Figure 19. A Low Frequency Electromagnetic Prospecting System (from reference 1, page 26).

are produced using the equations of Figure 2 with the layered earth factor Q included in the calculation of the complex image location (See Appendix A). The data have all been normalized to the fields that would occur without the earth present. (On the site this is equivalent to referencing the phase to that of the transmitter current).

In Figures 20 and 21, the primary fields 1000 and 2000 meters away from a current loop over a homogeneous earth are shown. As expected the magnitude of the fields is approximately that of free space for very low frequencies and becomes increasingly attenuated at high frequencies. It can be seen in these figures that the break frequency of the magnitude is proportional to the resistivity of the top layer. Also comparing Figure 20 to 21, we see that break frequency is inversely proportional to the source-receiver distance squared. To a first order approximation,

$$f_{\text{break } E_{\phi}} \approx \frac{8 \times 10^5}{\sigma \rho^2}$$

$$f_{\text{break } H_z} \approx \frac{2.2 \times 10^6}{\sigma \rho^2} .$$

The presence of a lower layer has little effect on the magnitude of the fields. As can be seen in Figures 22 and 23, there is only a small difference in magnitude for a homogeneous earth ($\sigma = .01$) and that of a 2-layer earth with a lower layer conductivity of 100 mho/m, upper layer .01 mho/m. There is no effect on the break frequency.

The presence of a lower layer is best determined from the phase of the fields. In Figures 24 and 25, we show phase information (in radians) for the E_{ϕ} and H_z fields from a VMD over a stratified earth

Figure 20. Normalized Field Magnitudes Over a Homogeneous Earth, 1000 Meters Distant From VMD Source.

Figure 21. Normalized Field Magnitudes Over a Homogeneous Earth, 2000 Meters Distant From VMD Source.

Figure 22. Normalized Field Magnitudes With an Upper Conductivity of .01 mhos/m and a Depth of 1000 Meters, 1000 Meters Distant From VMD.

Figure 23. Normalized Field Magnitudes With Upper Conductivity of .01 mho/m, 1000 Meters Depth, 2000 Meters From VMD Source.

Figure 24. Normalized Field Phases With an Upper Conductivity of .001 mho/m, 1000 Meters Depth, 1000 Meters to VMD Source. Dashed lines indicate negative functional value.

Figure 25. Normalized Field Phases With an Upper Conductivity of .01 mho/m, 1000 Meters Depth, 1000 Meters to VMD Source. Dashed lines indicate negative functional value.

with the lower layer at 1000 meters. It can be seen that at very low frequencies the phase is determined by the conductivity of the lower layer, while at high frequencies the phase is determined by the conductivity of the upper layer.

When the fields are observed at a point 2000 meters from the loop (Figure 26) the presence of the lower layer is more easily detectable since the phase changes observed are larger. From these figures, we see that the presence of the lower layer can be detected more readily as the distance between the source and receiver is increased. It is often suggested that the distance between source and receiver should be at least twice the depth to target. [23]

Figure 27 shows that an overburden, which is more highly conductive than the target layer, causes a cross-over in the phase data.

CULTURAL NOISE CW FIELDS PRODUCED BY VMD EXCITATION

Scattered fields from the periodically grounded power line, fence, and an uninsulated pipeline are shown in Figures 28 and 29. These fields are computed for $\rho_1 = 100$ meters and $\rho_2 = 900$ meters as defined in Figure 7. All scattered fields are normalized by dividing by the free space fields from a vertical magnetic dipole. Also shown here are the normalized "noise free" fields levels which exist when there is no scattering body present.

As evident in these figures, the magnitude of the cultural noise is much lower than the noise-free signal at very low frequencies. This suggests that very low frequency data (or late time data) should be relatively immune to the effects of cultural noise.

As expected, all these scatterers behave basically the same way. The uninsulated pipe is the worst case and the periodically

Figure 26. Normalized Field Phases With Upper Conductivity of .01 mho/m, 1000 Meters Depth, 2000 Meters from VMD Source. The dashed lines indicate that the functions are negative in value.

Figure 27. Normalized Field Phases With Upper Conductivity of 1.0 mho/m, 1000 Meters Depth, 1000 Meters to VMD Source. Dashed lines indicate negative functional value.

Figure 28. Cultural Noise and Noise Free Field Magnitudes Over a Homogeneous Earth With $\sigma = .01$, $\rho_1 = 100$ m, $\rho_2 = 900$ m.

Figure 29. Cultural Noise and Noise Free Field Magnitudes Over a Homogeneous Earth With $\sigma = .1$, $\rho_1 = 100$ m, $\rho_2 = 900$ m.

grounded powerline and fence are somewhat less important. The scattered field from an ungrounded powerline was also computed. The magnitude of the scattered field produced was more than a factor of 100 less than the "noise-free" field even at its peak value. We concluded, therefore, that the ungrounded powerline and the fence on wooden posts are probably not significant noise sources. In the remaining calculations attention was concentrated on predicting the response of the pipeline since it was the most significant scatterer.

TOTAL FIELDS IN A CW (VMD) SURVEY

In actuality, the fields seen in an EM survey will include effects of both targets and noise sources. In this section, we will present results obtained by combining the noise free fields and cultural noise.

Even at low frequencies the presence of cultural conductors near an EM survey may seriously impede the search for geothermal targets. Figures 30 through 33 show the total fields resulting over a stratified earth, with a pipe located 100 m from the source. It can be clearly seen in these figures that the pipe over a homogeneous earth may be easily mistaken for a highly conductive layer of earth at some depth (compare phase data in Figures 30 and 31).

CULTURAL NOISE IN TIME DOMAIN (VMD) SURVEY DATA

When the fields from a vertical magnetic dipole are measured in the time domain, the major field of interest is the H_z field. If our receiver is a loop, the voltage induced in the receiver is proportional to the time derivative of the vertical magnetic field (H_z).

Figure 30. Normalized Total E-Fields With Upper Conductivity of .01 mho/m With and Without Pipe Present, 1000 Meter Depth, 1000 Meters to VMD Source.

Figure 31. Normalized Total H_z Fields With Upper Conductivity of .01 mho/m, With and Without Pipe, 1000 Meters Depth, 1000 Meters to VMD Source.

Figure 32. Normalized Total E_ϕ Fields With Upper Conductivity of .01 mho/m, With and Without Pipe, 1000 Meters Depth, 2000 Meters to VMD Source.

Figure 33. Normalized Total H_z Fields With Upper Conductivity of .01 mho/m, With and Without Pipe, 1000 Meters Depth, 2000 Meters to VMD Source.

Using the formulas given in Figure 2, we have calculated the H_z and H_z derivative fields observed at 10,000 meters from a vertical magnetic dipole driven by an approximation to a unit step of current. The earth was assumed to be stratified with a more conducting layer located at a depth of 500m. Noise-free results are shown in Figures 34 through 37.

At early times the conductivity of the upper surface may be determined by: [4]

$$\sigma_1 = \frac{9.0}{2\pi\mu_0\rho^5\dot{H}_z}$$

where H_z is $\frac{\dot{H}_z}{t}$.

In Figure 35, if we use the value of H_z at .002 seconds, we get an upper conductivity indication of .0011 mho/m. Figure 36 at .004 seconds indicates an upper conductivity of .0103 mho/m. These are both very close to the actual conductivities of .001 and .01 respectively. The conductivity of the lower layer becomes apparent at late times. Comparing Figures 35 and 36, we can see that the layered earth responses are approximately the same from 5 to 100 seconds. This is caused by a highly conductive lower layer ($\sigma_2 = 1.0$ mho/m) at 5000 meters depth.

Figures 38 and 39 show the time domain cultural noise from a pipe 9900 meters from a VMD source and 100 meters to the receiver. As can be seen, the scattered field falls off very rapidly in the time domain. This suggests that cultural noise removal may be easier in time domain data than it is in the frequency domain.

Figure 34. Time Domain H_z Field 10,000 Meters Away From VMD Over Stratified Earth, Depth = 5000 m, $\sigma_1 = .001$ mho/m.

Figure 35. Time Domain $\dot{H}_z$ Field 10,000 Meters Away From VMD Over a Two-Layer Stratified Earth for Two Different Bottom Layer Conductivities (σ_2). Depth = 5000 m, $\sigma_1 = .001$ mho/m. Negative and positive functional values are denoted by dashed and solid lines, respectively.

Figure 36. Time Domain $\dot{H}_z$ Field 10,000 Meters Away From VMD Over a Two-Layered Stratified Earth for Two Different Bottom Layer Conductivities (σ_2). Depth = 5000 m, $\sigma_1 = .01$ mho/m. Negative and positive functional values are denoted by dashed and solid lines, respectively.

Figure 37. Time Domain $\dot{H}_z$ Field 10,000 Meters Away From VMD Over Homogeneous Earth, $\sigma = 1.0$. Negative and positive functional values are denoted by dashed and solid lines, respectively.

Figure 38. Scattered H_z Field From Pipe Located 9900 Meters From VMD Source, 100 Meters to Receiver, Homogeneous Earth, $\sigma = .001$. Dashed line indicates negative functional values.

Figure 39. Scattered $\dot{H}_z$ Field From Pipe Located 9900 Meters From Source, 100 Meters to Receiver, Homogeneous Earth, $\sigma = .001$. Dashed line indicates negative functional values.

SECTION VI

CHARACTERIZATION OF CULTURAL NOISE AS OBSERVED WITH A HORIZONTAL ELECTRIC DIPOLE SOURCE

Horizontal electric dipole sources are extensively used in EM surveying for both frequency domain and time domain surveys for deeply buried targets. In this section, the cultural noise obtained in these surveys is to be quantified. As in the prior section, the noise-free fields observed over a 2 layer earth are computed, then the cultural conductor is introduced and the cultural noise reradiated by the scatterer is added to the signal to illustrate how the cultural noise might be misinterpreted as a return from a buried target.

For the frequency domain analysis we shall concentrate attention on the compensator system or the TURAM system. For the time domain system, we shall address the TDEM approach.

"NOISE-FREE" CW FIELDS PRODUCED BY FINITE LENGTH HORIZONTAL ELECTRIC DIPOLE EXCITATION

The typical layout of an EM survey using a horizontal electric dipole is shown in Figure 40. The exciting source is the same for both TURAM or Compensator (Sundberg) methods.^[3] The antenna consists of a long insulated conductor grounded on each end and driven by a high power transmitter. Measurements are made along traverses perpendicular to the antenna. In the compensator method the amplitude and phase of the vertical component of the magnetic field (or other components) is measured. As in the EM-60 application previously considered, a hardwire or telemetry link to the transmitting antenna is required to accurately establish the phase of the observed signal. As in the VMD excitation, the phase data have the most information.

Figure 40. Compensator or TURAM Layout from Reference 3, Page 539.

In the TURAM method the receiving unit consists of two identical horizontal loops spaced 50-200 ft. apart which are joined by a cable. The voltage difference between the two is a measure of the gradient of the vertical magnetic field. Unlike the Sundberg method, no phase reference link to the transmitter current is required since the phase difference between the voltages induced in the two loops is a direct indication of conductivity of the earth below.

The frequency of excitation and the length of the antennas and traverses should be governed by the depth that one wishes to penetrate in the survey. For deeply buried targets, traverses out to 10 or 20 km would be appropriate. However, it was considered unlikely that very long antennas would be used in these surveys. Therefore, for the numerical work here we restricted our attention to a 1 km antenna. The "noise-free" fields were computed using Bannister's formulas (Figure 3) assuming that the antenna carries one ampere of current with time dependance $e^{+i\omega t}$. Figure 41 depicts the geometry used in the field calculations. The source is taken to be a horizontal antenna of length 1000 meters centered at the origin of a Cartesian coordinate system and aligned with the x-axis. The field is observed at points along the y-axis.

Presented here are the H_z and E_x components of the field which are the most sensitive to the layered earth. It should be noted that $\frac{\partial H_z}{\partial y} = +i\omega\epsilon_0 E_x$, so that the E_x component recorded here is proportional to the data obtained in the TURAM method.

In Figures 42 and 43, we show the effect of source to receiver separation on the primary fields above a homogeneous earth of 10^{-3} mhos/meter conductivity. As expected, the field magnitudes decrease as an approximate function of distance to the third power. The magnetic field magnitude remains relatively constant at low frequencies until a particular "break" frequency is reached.

Figure 41. Geometry of Source and Receiver for the Horizontal Electric Dipole.

Figure 42 & 43. Magnitude of Primaries E_x and H_z Over a Homogeneous Earth of Conductivity .001 for a Source to Receiver Separation of 1000 m, 5000 m, and 10,000 m. Source is HED of Length 1000 m Carrying One Ampere.

The corresponding phase functions for E_x and H_z show that the break frequency for the H_z is the same frequency at which a transition in the asymptotic behavior of the phase occurs (Figures 44 and 45). This break frequency is also inversely proportional to the earth conductivity for the upper layer just as it is with VMD excitation. In fact,

$$f_{\text{break}} \approx \frac{8 \times 10^5}{\sigma y^2}$$

fits all the data.

When a layered media is introduced the phase behaves much as it did for the VMD excitation. At low frequencies the phase is that expected for a homogeneous media with the conductivity of the lower media. At higher frequencies the phase follows the behavior expected with a uniform media of the conductivity of the upper layer. The transition of the phase behavior from one media to the other depends upon the thickness of the layer. It appears that if the surface layer is thick, the two break frequencies which determine the transition between the two homogeneous results are the frequencies where the layer thickness is about 1/2 skin depth thick ($h \approx \frac{1}{2} \delta$) in a uniform media of conductivity σ_1 and σ_2 , respectively (Figure 46-47) $f = \frac{1}{\pi \mu \sigma (4h)^2}$. For a thin layer the upper break frequency may exceed the break associated with distance from the transmitter. That is,

$$\frac{1}{\pi \mu \sigma_1 (4h)^2} > \frac{8 \times 10^5}{\sigma_1 y^2},$$

then the distinction between the second and third break frequencies is not apparent (Figures 48 and 49).

Figure 44. Phase of E_x Over a Homogeneous Earth of Conductivity .001 for a Source-to-Receiver Separation of 1000 m, 5,000 m, and 10,000 m. Source is HED of Length 1000 m.

Figure 45. Phase H_z Over a Homogeneous Earth of Conductivity .001 for Source-to-Receiver Distance of 1000 m, 5000 m, and 10,000 m. Source is HED Length 1000 m.

Figure 46. Phase of Noise Free H_z Over a Two-Layer Earth
For Lower Layer Conductivities of .1, and
1.0. Overburden Conductivity = .001, Thickness =
5000m. Source to Receiver Separation of 10000m.

Figure 47. Phase of Noise-Free H_z Over a Two Layer Earth For Lower Layer Conductivities of .01, .1, and 1.0. Overburden Conductivity = .01, Thickness = 5000m. Source to Receiver Separation of 10000m.

Figure 48. Phase of Noise Free H_z Over a Two-Layer Earth
 For Lower Conductivities of .01, .1 and 10.
 Overburden Conductivity = .001, Thickness = 1000m.
 Source to Receiver Separation of 10000m.

Figure 49. Phase of Noise Free H_z Over a Two-Layer Earth For Lower Layer Conductivities of .01, .1, and 1.0. Overburden Conductivity = .01, Thickness = 1000m. Source to Receiver Separation of 10000m.

TOTAL FIELDS DUE TO A HORIZONTAL ELECTRIC DIPOLE IN THE PRESENCE OF A CULTURAL SCATTERER

As an example of the cultural noise that might be observed in a HED survey, the field reradiated by a horizontal pipe interposed between the source and receiver was computed. The pipe was assumed to be parallel to the transmitting antenna and positioned 100 meters away from the source antenna. The receiving antenna was assumed to be 10km from the source and the target depth was either 1000 meters or 5000 meters, as in the cases considered while computing "noise-free" fields.

In this symmetrical case, the magnitude of the cultural noise is always much less than the magnitude of the noise-free field and, consequently, the magnitude of the total H_z field is not much diminished by the presence of the cultural scatterer whether the earth is homogeneous or layered (Figure 50).

The perturbation in the phase is more significant although not calamitous. Errors in the prediction of the depth of the lower layer can be expected as well as errors in the estimate of the lower layer conductivity (Figures 51 and 52).

TIME-DOMAIN RESULTS FOR HED SOURCES

Most time-domain survey systems utilize horizontal loop receivers or SQUID devices which detect the H_z -field, or the time-derivative of H_z . Figures 53 through 56 provide time domain responses of the vertical magnetic field and its time derivative for the case of an HED source of length 1000m over a conducting earth in the presence of a buried pipe scatterer. The configuration is again depicted by Figure 41. The source current is a unit of 1 millisecond step function which has been modified to give a finite rise time. The source-receiver separation is again taken to be 10000m, and the layered earth case consists of an overburden of conductivity .001, 5000m thickness, over a halfspace of conductivity 1.0.

Figure 50. Magnitude of the Noise-Free H_z and Total H_z Over A Homogeneous Earth of Conductivity .01, and Over A Layered Earth of $\sigma_1 = .01$, $\sigma_2 = 1.0$ with Overburden Thickness 5000 M. Source is HED of Length 1000 M at Distance of 10000 M. Buried Pipe Scattered 100 M From Source.

Figure 51. Phase of the Noise Free and Total H_z Field Over a Two Layer Earth for Lower Layer Conductivities of 0.01, 0.1 and 1.0 mhos/meter with an Overburden Conductivity of 0.01 mhos/meter, Thickness is 1000 meters. Source to Receiver Separation is 10 km and Interposed Buried Pipelines is 100m from the Source.

Figure 52. Phase of Noise-Free and Total H_z Field Over a Two Layer Earth for Lower Layer Conductivities of 0.01, 0.1 and 1.0 mhos/meter with an Overburden Conductivity of 0.01 mhos/meter, Thickness is 1000 Meters. Source to Receiver Separation is 10 km and Interposed Buried Pipeline is 100m from the Source.

Figure 53. Time Domain Display of Noise Free H_z , Scattered H_z , and Total H_z Over a Homogeneous Earth of Conductivity .001. Source is HED of Length 1000 m at Distance of 10,000 m. Scatterer is Buried Pipe 100 m From Source. Source Current is Modified Step Function. Dashed lines indicate negative functional values.

Figure 54. Time Derivative of Noise Free H_z , Scattered H_z , and Total H_z Over a Homogeneous Earth of Conductivity .001. Source is HED of Length 1000 m at a Distance of 10,000 m. Scatterer is Buried Pipe 100 m From Source. Source Current is Modified Step Function. Negative and positive functional values are denoted by dashed and solid lines, respectively.

Figure 55. Time Domain Display of Noise Free H_z , Scattered H_z , and Total H_z Over Two-Layer Earth. Upper Layer Thickness is 5000 m. $\sigma_1 = .001$, $\sigma_2 = 1.0$. Source is HED of Length 1000 m at Distance of 10,000 m. Scatterer is Buried Pipe 100 m From Source. Source Current is Modified Step Function. Dashed lines indicate negative functional values.

Figure 56. Time Derivative of Noise Free H_z , Scattered H_z , and Total H_z Over Two-Layer Earth. Upper Layer Thickness is 5000 m, $\sigma_1 = .001$, $\sigma_2 = 1.0$. Source is HED of Length 1000 m at Distance of 10,000 m. Scatterer is Buried Pipe 100 m from Source. Source Current is Modified Step Function. Dashed lines indicate negative functional values.

Using the apparent resistivity calculation discussed by Keller and Rapolla,^[4] we can obtain the surface conductivity (high frequency response) from the early time behavior of H_z :

$$\sigma_1 \sim \frac{3L \cos \theta}{2\pi \mu_0 \gamma^4 H_z(t)} \quad t \sim 0$$

where L is the length of the source HED, γ is the distance of source to receiver, and θ is the angle which measures the receiver offset relative to a line normal to the source dipole. For our configuration, $L = 1000\text{m}$, $\theta = 0$, and $\gamma = 10000\text{m}$.

We then have

$$\sigma_1 \sim \frac{3.8 \times 10^{-9}}{H_z(t)} \quad t \sim 0$$

From Figures 55 and 56, we use the field values at time $t \sim .002$ seconds to avoid the time period in which the pulse is still rising. This yields a primary field value of

$$\dot{H}_z^p \sim 3.6 \times 10^{-5} ,$$

which gives

$$\sigma_1 \sim .0011 .$$

This is very nearly the earth model value of $\sigma_1 = .001$. Note that for the same times, the presence of the scatterer causes a reduction in the total field to a value of

$$\dot{H}_Z^t \sim 1.2 \times 10^{-5} ,$$

which gives

$$\sigma_1 \sim .0032 .$$

Hence, we see that the presence of the scattered field has manifest itself as a higher apparent conductivity near the surface.

The behavior of the late time response is governed by the conductivity at depth, with a slower decline in $\dot{H}_Z$ with higher subsurface conductivity. The presence of cultural scatterer does not affect the late time response.

SECTION VII

SUGGESTED METHODS OF CULTURAL NOISE REMOVAL

In the numerical work performed here, only a 2 layer earth model was used to predict the target return in a noise-free environment and an environment contaminated by cultural noise. Consequently, the noise effects observed here are limited by the simplicity of the geology assumed and the simplicity of the data inversion routine that is appropriate for these models. Nevertheless, several observations are appropriate:

- 1) The principal effects of the cultural scatterers are to introduce noise in the higher frequency portion of the spectrum or the early time data in time domain surveys;
- 2) The cultural noise can cause misinterpretation of some data yielding overestimates of the near surface conductivity and erroneous depth predictions;
- 3) Cultural noise can preclude data interpretation if the observed signals do not fit plausible geological explanations.

The most seriously affected data was that associated with small source receiver separations and shallow targets (Figures 30-33). Under these conditions, the phase changes of interest occur at the frequency range of 0.1 to 10 Hz, which happens to be the same frequency range where the currents induced on the pipe are most significant. When searching for deeper targets at greater distances, the frequency range of interest is lower (.001 to 1 Hz in Figure 52) and so the effects of the cultural noise are not as significant.

Perhaps the most serious consequence of the presence of cultural

noise is the possibility that the data would be rejected as implausible when it did not conform to the variation expected. For example, the slope of the phase function at low frequencies in Figures 31-33 or 51 and 52 does not conform to the $\theta = kf^{3/2}$ function expected for the two layer media present. An analyst may reject the data containing cultural noise as being implausible.

Based upon these observations, we have considered the possibility of cultural noise removal by measurements alone and by data analysis alone. Three approaches were found useful. Each of these approaches is described below.

CULTURAL NOISE REMOVAL BY MEASUREMENT ALONE

Figure 57 shows one scheme for the elimination of cultural noise by cross polarization of the source antenna and a horizontal cultural conductor. If the earth below the antenna was only a layered media, there would be no excitation of the cultural conductor at all due to symmetry. We are assured, then, that the excitation will only be due to asymmetric caused by lateral variations in the earth. This excitation should be much smaller than that predicted for the cases considered here.

CULTURAL NOISE REMOVAL BY SYMMETRICAL MEASUREMENTS

This approach makes use of the fact that current on a horizontal conductor produces an H_z component of the field that is of opposite polarity on the opposite side of the scatterer (Figure 58). If ρ_1 is large compared with ρ_2 , the H_z phase of the noise-free field is nearly

Figure 57. Removal of Cultural Noise by Cross Polarization of the Source Antenna and Horizontal Cultural Conductor.

Figure 58. Elimination of Cultural Noise by Recording the Fields on Opposite Sides of Cultural Noise Source.

Figure 59. Total H_z Field 100 Meters Either Side of Pipe 10,000 Meters from VMD Source Over Stratified Earth, $\sigma_1 = .01$, $\sigma_2 = 1.0$, $d = 5000$. Dashed line indicates negative functional values.

Figure 60. Comparison of Primary H_z Field With Summation of Total Fields on Opposite Sides of a Pipe, $\rho = 10,000$ m, $\sigma_1 = .001$, $\sigma_2 = 1.0$, VMD Source.

constant on either side of the cultural scatterer. Therefore, if we add the total fields at symmetric points on each side of the scatterer, the scattered fields will cancel, leaving only twice the noise-free fields. Dividing by two will give approximately the noise-free field which would be seen if there were no scatterer present.

We have calculated the total fields on both sides of a pipe 10000 meters away from a VMD source. The fields were computed 100 meters away on either side of the pipe and are shown in Figure 59. The fields were added together and then divided by two. Results are shown in Figure 60. The noise-free field is shown for comparison. This is the field from a VMD over a stratified earth with $\sigma_1 = .001$, $\sigma_2 = 1.0$, and a layer depth of 5000 meters. As can be seen, the summed total fields are very close to the noise-free field. The effect of the pipe is very much minimized, and the target layer is quite apparent.

NOISE REMOVAL BY DATA INVERSION TECHNIQUES

In this report, we use the term data inversion to mean "that process by which one decides on the structure of the earth based upon measurements of electric and magnetic fields at the surface of the earth".

Generally one is trying to identify the depth, size and conductivity of the more conducting regions that are expected to be geothermal resources or metallic ore bodies. Since the location, size, and conductivity of the cultural conductors are already known, it would appear that solving for noise currents would be a minor perturbation to the process of data inversion. How that perturbation occurs in the numerical solution is easily derived as shown in the following paragraphs.

Conceptually, we can contemplate that anywhere in space the EM field can be decomposed into three components. These are:

1. The primary field, due to the transmitting antenna over a homogeneous earth, $\vec{E}^p$ and $\vec{H}^p$;
2. The cultural noise primary field due to currents flowing on cultural conductors over a uniform earth, $\vec{E}^n$ and $\vec{H}^n$;
3. The secondary fields due to currents flowing in the inhomogeneous regions of the earth, $\vec{E}^s$ and $\vec{H}^s$.

Following the procedures used by Ting and Hohmann,^[24] we assume that the total field satisfies Maxwell's equations everywhere in space:

$$\nabla \times \vec{E} + j\omega\mu\vec{H} = 0,$$

$$\nabla \times \vec{H} - (j\omega\epsilon(\vec{r}) + \sigma(\vec{r})) \vec{E} = \vec{J}(\vec{r});$$

where $\vec{J}$ is the source current density, $\epsilon = \epsilon_0$ and $\sigma = 0$, if the observation point $\vec{r}$ is above the surface of the earth.

The component fields have been chosen so that each component satisfies a simpler set of Maxwell's equations.

$$\nabla \times \vec{E}^p + j\omega\mu\vec{H}^p = 0,$$

$$\nabla \times \vec{H}^p - (j\omega\epsilon_1 + \sigma_1) \vec{E}^p = \vec{J}^p;$$

$$\nabla \times \vec{E}^n + j\omega\mu\vec{H}^n = 0,$$

$$\nabla \times \vec{H}^n - (j\omega\epsilon_1 + \sigma_1) \vec{E}^n = \vec{J}^n;$$

and

$$\nabla \times \vec{E}^s + j\omega\mu\vec{H}^s = 0,$$

$$\nabla \times \vec{H}^s - (j\omega\epsilon_1 + \sigma_1) \vec{E}^s = \vec{J}^s.$$

Here: $\epsilon_1 = \epsilon_0$ and $\sigma_1 = 0$ if the observation point is above the earth's surface and ϵ_1 and σ_1 are the values of the permittivity and conductivity in the earth, here assumed to be uniform throughout the half space.

$\vec{J}^p$ is the volume current density for the transmitting source that engenders the primary field $\vec{E}^p$ and $\vec{H}^p$. For a HED source,

$$\vec{J}^p = I^p \delta(y) \delta(z) \vec{a}_x - \frac{L}{2} \leq x \leq + \frac{L}{2} = 0; \text{ elsewhere}$$

$\vec{J}^n$ is the cultural noise volume current density on the cultural conductor or conductors.

Usually, $\vec{J}^n = I^n(\vec{r}') \vec{a}_\rho$, where $\vec{a}_\rho$ is along the conductor. Finally, we identify the secondary fields E^s and H^s that are caused by secondary source current:

$$\vec{J}^S = (\sigma_2(\vec{r}') - \sigma_1) (\vec{E}^P + \vec{E}^n + \vec{E}^S),$$

where $\sigma_2(\vec{r})$ is the conductivity of the media in regions that are not homogeneous.

It is to be noted that all three sets of Maxwell's equations involve the calculation of fields above and within a homogeneous media, given a source current density. This is a problem with a known solution in the form

$$\vec{E} = \int_{Vol} \vec{K}(\vec{r}, \vec{r}') \cdot \vec{J}(\vec{r}, \vec{r}') dV',$$

where $\vec{K}$ is the required dyadic Green's function [25] and $\vec{J}$ is the source current density of interest, $\vec{J}^P$, $\vec{J}^n$ or $\vec{J}^S$. Using this equation, three integral equations are developed that must be solved simultaneously for $\vec{J}^n$ and $\vec{J}^S$.

(at observation points)

$$\vec{E}(\vec{r}) = \vec{E}^P + \int_{Vol_2} \vec{K}(\vec{r}, \vec{r}') \cdot \vec{J}^S(\vec{r}') dV' + \int_{Vol} \vec{K}(\vec{r}, \vec{r}') \cdot \vec{J}^n(\vec{r}') dV'$$

(at points in the target region, i.e. $\vec{r} \in Vol_2$)

$$\vec{E}^S(\vec{r}) = \int_{Vol_2} \vec{K}(\vec{r}, \vec{r}') \cdot \vec{J}^S(\vec{r}') dV'$$

and

$$\vec{J}^S(\vec{r}') = (\sigma_2(\vec{r}') - \sigma_1) (\vec{E}^S(\vec{r}') + \vec{E}^P(\vec{r}') + \vec{E}^n(\vec{r}'))$$

(at points along the cultural conductor $\vec{r} \in \text{Vol}_{cc}$)

$$\vec{E}^n(\vec{r}) = \int_{\text{Vol}_{cc}} \vec{K}(\vec{r}, \vec{r}') \cdot \vec{J}^n(\vec{r}') dV,$$

and

$$\vec{J}^n(\vec{r}') = (\sigma_{\text{conductor}} - \sigma_1) (\vec{E}^S(\vec{r}') + \vec{E}^P(\vec{r}') + \vec{E}^n(\vec{r}')).$$

In this form it is apparent that there is no fundamental problem with calculating the currents on the cultural conductor and in identifying the component of the observed field which is cultural noise. In fact, since the location and conduction of the cultural conductor are known, only a small increase in numerical work would be needed to add the cultural conductor to the problem.

Presently, however, the data inversion is not accomplished by solving a set of simultaneous equations. This is due partly because there are some fundamental numerical analysis problems associated with the direct solution of this system and partly because, even if the numerical problems were solved, the computer resource requirements would be expensive utilizing the high speed main frame computers available today.

Most currently available data inversion techniques rely on matching the data measured in the field to predicted performance curves. These predicted performance curves may be of several types.

1. Prediction of secondary fields from a horizontally layered earth (one dimension model (1D));
2. Predicted responses of infinite cylinders in a homogeneous media (2D);
3. Predicted responses of infinite half sheets or strips in an otherwise homogeneous media (2D);

4. Predicted responses of spheres or prolate spheroids in a homogeneous media (3D-Analytical);
5. Predicted responses of arbitrary shapes and profiles (3D-Numerical);
6. Scale model measurements of reasonable profile (2D or 3D).

In all these cases, the location of the source with respect to the target region has to be assumed. Thus, the presence of a cultural conductor that acts as a second transmitting antenna would not be easily included without adding another dimension to the book of master curves now available. It seems to this writer that this approach would not be fruitful.

However, we would recommend that if the cultural noise cannot be eliminated by cross-polarizing the transmitting antenna and the cultural conductor, the current on the cultural conductor should be measured. This could be done by measuring the Horizontal H field over a fence, pipeline or railroad track (or below the power line). With this measurement, one could identify the "primary field" component of the cultural noise and remove it from the data. Then one could analyze the secondary field observed, neglecting the fact that part of that return from the target is due to excitation by cultural noise currents. Once an underground conductivity profile is established, one could then recalculate the secondary field due to the cultural noise current for this profile. If this secondary cultural noise is small, then the profile is probably accurate. If it is not small, the error expected is known.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

Based upon the numerical prediction we have made here, it appears that cultural noise has its biggest effect on the high frequency or early time data, causing errors in predicting the conductivity and depth of the overburden. At very low frequencies, 0.01 Hz and below, the effect of cultural noise was not as severe.

In surveys involving simple cultural conductors like a long power line or pipeline, it appears that cross-polarizing the transmitting antenna and the cultural conductor is a simple way to remove or minimize the noise problem. Averaging symmetrical measurements on each side of the cultural conductor appears to be an effective way of removing cultural noise from the data, provided the principal interest is in the data at a reasonably large depth below the cultural conductor.

Based upon these conclusions, we would recommend that further work be performed in three areas.

1. Scale model studies of cultural noise problems should be performed to provide further insight into the adequacy of the models used in the analysis presented here.
2. More careful consideration of the antenna characteristics of long horizontal antennas is warranted. In this work, numerical integration was used to predict both the response and the reradiated fields. This numerical approach observes the nature of the response function.
3. Work should begin on direct inversion techniques that can incorporate cultural conductors in the data reduction algorithms. Costs for computer resources will drop dramatically in the next few years now that 32 bit micro-processing chips are being introduced into the market. Accordingly, the analyst should be ready to use these new tools as they become available.

APPENDIX A

COMPARISON OF THE IMAGE THEORY APPROXIMATION TO THE EXACT SOLUTION

The field equations for a vertical magnetic dipole and a horizontal electric dipole over a stratified earth have been developed by Wait.^[8] These equations have the form of complex integrals, but may be reduced to more straight forward computations by the use of image theory (Bannister^[10]). The image theory results are approximately correct for low frequencies. We will show this through example, using the E_ϕ and H_z fields of a vertical magnetic dipole over a homogeneous earth.

The basic concept of the image theory technique is to replace the finitely conducting earth with a perfectly conducting earth located at a complex depth, $d/2$, where $d = 2/\gamma_1 = \delta (1-i)$. The image theory geometry is shown in Figure A-1.

When a two-layer earth model is used, the depth of the image plane is given by $d = \delta(1-i)Q$. Q is the correction factor given by Wait^[8] to account for the presence of the lower layer.

$$Q = \frac{(\gamma_1/\gamma_2) + \tanh \gamma_1 h_1}{1 + (\gamma_1/\gamma_2) \tanh \gamma_1 h_1} ,$$

where h_1 = depth to the lower layer. For a homogeneous earth, $Q = 1$.

The exact solution of the vertical magnetic dipole over a homogeneous earth is given by Wait.^[9] At the surface, the magnetic vector potential is

$$\bar{F} = \frac{i\mu_0 w I d A}{2\pi} \int_0^\infty \frac{\lambda}{\lambda + u} J_0(\lambda \rho) d\lambda .$$

FigureA-1. Image Theory Geometry

The solution of the integral gives

$$\bar{F} = \frac{i\mu_0 w I d A}{2\pi} \left[\frac{1 - (1+\gamma\rho)e^{-\gamma\rho}}{\gamma^2 \rho^3} \right] .$$

The $\bar{E}$ and $\bar{H}$ fields can be derived from

$$\bar{E} = -\text{curl } \bar{F}$$

$$\bar{H} = \frac{-\gamma^2 \bar{F}}{i\mu_0 w} + \frac{1}{i\mu_0 w} \text{grad div } \bar{F} .$$

Solving for E_ϕ and H_z , we get

$$E_\phi = \frac{I d A}{2\pi\sigma\rho^4} \left[3 - (3+3\gamma\rho + \gamma^2\rho^2)e^{-\gamma\rho} \right] ,$$

$$H_z = \frac{I d A}{i w \mu_0 2\pi\sigma\rho^5} \left[(9 + 9\gamma\rho + 4\gamma^2\rho^2 + \gamma^3\rho^3)e^{-\gamma\rho} - 9 \right] .$$

If we use the approximation $e^{-\gamma\rho} = 1 - \gamma\rho + \frac{\gamma^2\rho^2}{2}$ and neglect the higher order terms, the E_ϕ and H_z field solutions reduce to

$$E_\phi \approx \frac{i\mu_0 w I d A \rho}{4\pi} \left(\frac{1}{\rho^3} - \frac{\gamma}{\rho^2} \right)$$

$$H_z \approx - \frac{I d A}{4\pi} \left[1 - 3\gamma\rho \right] .$$

We now compare this solution with that given by image theory. The E_ϕ and H_z fields derived by use of image theory for a vertical magnetic dipole over a homogeneous earth are

$$E_\phi = \frac{-i\omega\mu_0 IA\rho}{4\pi} \left(\frac{1}{\rho^3} - \frac{1}{(\rho^2+d^2)^{3/2}} \right) ,$$

$$H_z = -\frac{IA}{4\pi} \left[\frac{1}{\rho^3} - \frac{1}{(\rho^2+d^2)^{3/2}} \left(1 - \frac{3d^2}{(\rho^2+d^2)^{3/2}} \right) \right] .$$

As $d = 2/\gamma$ we see that the image theory results have the same form as the first order approximation to the exact solution and are approximately equal at low frequencies.

A numerical analysis was also done to compare the exact solution to that derived by image theory. The ratio of exact solution to image theory approximation is shown in Figures A-2 and A-3. We can see that the image theory approximation is very precise up to about 10Hz and actually gives acceptably good results up to about 1000Hz.

Figure A-2. Exact Solution Divided by Image Theory Approximation.

Figure A-3. Exact Solution Divided by Image Theory Approximation.

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