INFLUENCE OF GEOLOGIC NOISE
ON
INDUCTIVE MINING PROSPECTING METHODS

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Electromagnetic prospecting methods are limited by their sensitivity to geologic noise relative to target conductors. As the number of undiscovered, easily detectable orebodies decreases, the need to distinguish targets in complicated geologic settings creates greater interest in evaluating and reducing the influence of geologic noise. The physical scale modeling approach is used to calculate the slingram response of three geologic models:

1) A target beneath the edge of an overburden sheet.
2) A target beneath inhomogeneous overburden.
3) A relatively deep, wide target near a shallow body.

Analysis of measurements for the horizontal coplanar, perpendicular, vertical coplanar and vertical coaxial coil configurations, indicates that some existing simple interpretation methods can be effective even when the target response is severely distorted by geologic noise. Target identification and evaluation is enhanced when measurements are made over a wide range of frequencies. In addition, the use of more than one coil configuration may improve interpretation by producing complementary responses.

Meaningful interpretation can in some cases be achieved by analysis of the shoulders of anomalies, indicating the
need to use closely-spaced stations along survey lines in order to accurately measure these lesser anomaly features.

Application of frequency differencing to the data gives mixed results, depending on the specific model. For the models investigated, frequency differencing is best suited for qualitative interpretations of profile shape.
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<td>b</td>
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<td>C&lt;sub&gt;n&lt;/sub&gt;, D&lt;sub&gt;n&lt;/sub&gt;</td>
<td>Geometric coefficients of series expansions.</td>
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<tr>
<td>f</td>
<td>Frequency (Hertz).</td>
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<td>H&lt;sub&gt;o&lt;/sub&gt;, H&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Primary, secondary magnetic field vector.</td>
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<td>I&lt;sub&gt;1&lt;/sub&gt;, I&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Successive samples of inphase component.</td>
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<tr>
<td>K</td>
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<tr>
<td>L</td>
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<td>P&lt;sub&gt;1&lt;/sub&gt;, P&lt;sub&gt;2&lt;/sub&gt;</td>
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<td>Q&lt;sub&gt;1&lt;/sub&gt;, Q&lt;sub&gt;2&lt;/sub&gt;</td>
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<td>ΔQ</td>
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<td>δ</td>
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<td>ε</td>
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<td>σ</td>
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<td>Internal, external conductivity.</td>
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<td>σ&lt;sub&gt;t&lt;/sub&gt;</td>
<td>Conductivity-thickness product (Conductance).</td>
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<td>μ</td>
<td>Magnetic permeability (Henry/M).</td>
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<td>ω</td>
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ACKNOWLEDGEMENTS

I am deeply indebted to The United States Geologic Survey for providing employment and facilities during the course of this project, in particular Dr. Frank Frischknecht who suggested the topic of investigation and placed his own knowledge and experiences in scale modeling at my disposal. I am also very grateful to Julius Likler for fabricating coil mounts, and Tom Grover for assistance with the fiber optics. Thanks are also given to Dr. Cathy Skokan for her service as thesis advisor, and to Drs. Alexander Kaufman and Guy Towle for their comments and service as members of my committee. I have no thanks for the army of mice and rabbits who continually strive to invade the modeling laboratory at the Denver Federal Center.

It is with deep sorrow that I note the untimely death of Dr. Frischknecht in a helicopter accident on August 12, 1987. A great source of Elan Vital has been extinguished.
INTRODUCTION

The limit of depth of exploration for electromagnetic methods is often determined by the sensitivity of the system to geologic noise which occurs in the form of conductive overburden, clay lenses, uneconomic mineral deposits and other features. System sensitivity may sometimes be evaluated using computer modeling programs to produce the appropriate response of an ideal environment. For models more complex than a "single target in a conductive half-space with infinite layer of homogeneous overburden" there are few working computer programs and the cost of available computer resources make such simulations impractical. For these situations, physical scale-modeling provides a means of rapidly determining the response for a large number of complex geologic settings. The continued investigation of geologic noise influence is very important to the continued success of electromagnetic prospecting methods. Most of the "obvious" orebodies which are close to the surface or not obscured by substantial geologic noise, have already been located in areas where exploration has taken place. The attention of explorationists must now be directed towards the detection of deeper orebodies, or shallow ones which are masked by noise. Success in this endeavor requires understanding of the behavior of the
different components which are measured. Consideration of these factors has led to a number of schemes for increasing the signal-to-noise ratio and discriminating between bodies with differing conductivities.

The main objective of this study is to present the results of scale model studies of three different types of geologic noise: the edge effect of overburden, the effect of inhomogeneous overburden, and the effect of a shallow confined noise source. A second objective is to evaluate the effectiveness of simple interpretation methods for each case. The results provide a detailed set of measurements which can be used for further analysis of geologic noise, and a comparison of the degree of target detectability exhibited by each model.

Types of Noise

Sources of noise in an electromagnetic system can be divided into several categories (Ward, 1967). A distinction is commonly made between internal noise generated by the various circuits and components of the system itself, and external noise contributed by sources in the surrounding environment. External sources are often further classified into three types: electromagnetic interference, cultural noise, and geologic noise. Electromagnetic interference
includes powerline coupling, radio-frequency and atmospheric interference; cultural noise is caused by man-made structures including buried pipelines, fences, grounded powerlines, etc. Geologic noise may be defined as "The aggregate of the responses of undesirable geologic conductors" (Bosschart, 1968).

The effect of internal noise is to limit the accuracy of measurement. This type of noise is reduced by proper design and construction of measuring devices.

The effect of external noise is to limit the "depth of investigation" of an EM system (Kaufman, 1978b). This term should not be confused with "depth of penetration", as they represent different concepts. The penetration limit of any EM system is determined by the amount of attenuation imposed on the fields by the surrounding medium; while the depth of investigation is determined by the ability of the system to distinguish individual responses contributed by sources within the depth of penetration.

Geological Noise

The external noise contributed by conductive earth materials and geologic structure can be studied by modeling. Definition of what constitutes a source of geological noise will vary, depending on the specific goals
of a field survey. Figure 1 shows an imaginary geologic cross-section, each element of which can be either a target or a source of unwanted signal. A mining geophysicist (Paterson, 1967) might consider the sulphide orebody as the target; the groundwater geophysicist (Palacky et al., 1981) might be interested in the location of the fault or the variations in overburden thickness; the engineering geophysicist (Culley, 1973) might seek to locate the clay pod. Typical mining targets (Paterson, 1967) are confined bodies with much greater conductivity than the surrounding medium. Two common sources of noise are layers of surface material and buried confined bodies that may be closer to

FIGURE 1. Imaginary geologic setting.
the surface than the target, or whose conductivity may be different (Brock, 1973). The geological noise models investigated in this thesis can be illustrated with three examples of common environments which might be encountered during a field survey.

In one environment (Figure 2), regional faulting has produced a broad flat valley which is covered with conductive alluvium. Attempts to explore the fault zone for mineralization (as shown), or for a water-producing section, encounter difficulties with the anomaly produced by the edge of the overburden. The "Basin and Range" province of the western United States is one environment where this situation could easily exist. Investigations by Betz (1977)

FIGURE 2. Target near edge of conductive overburden.
and Gaucher & St-Amant (1970) show that a very small gap in a layer of overburden can produce a substantial anomaly. Figure 3 illustrates a basement orebody overlain by a thick layer of glacial deposits, as might be encountered in the Great Lakes region. The response of the target is obscured to some extent by the variable response of the overburden (Villegas-Garcia & West, 1983).

The final illustration (Figure 4) shows a relatively deep target masked by the response of a smaller, near-surface body. This situation may be encountered in any type of geologic setting, since the process by which an economic

---

**FIGURE 3.** Target beneath inhomogeneous overburden.
orebody occurs often results in nearby occurrences of lower-grade mineralization and alteration of the surrounding rock (Brock, 1973).

In Figures 2 and 3, the orebody is the only conductor present within the "basement" of the model. When testing a suspected target with a drillhole, one might encounter some conductive overburden material which could account for the presence of the anomaly (Scott, 1973). The risk of falsely concluding that the overburden is the sole source of the anomaly is avoided simply by a determination to continue drilling until "bedrock" conditions have been examined. In Figure 4, encountering the undesirable bedrock conductor might be taken as justification to abandon the drillhole at
that point. In a reconnaissance survey where large blocks of mining claims may be deleted based upon the recommendations of the geophysicist, this possibility is an immediate concern. It is certainly less embarrassing to predict an economic conductor where none exists, than to proclaim an area to be barren which subsequently yields a world-class orebody.

The Need For Scale Model Data

The analytical approach to investigating the behavior of electromagnetic fields requires the solution of Maxwell's equations subject to the boundary conditions of the particular model. For simplified models such as a layered earth (Sinha, 1975; Kaufman, 1979), or idealized shapes such as spheres and long cylinders (Best & Shammas, 1979), separation of variables is fairly straightforward and results in a solution expressed using tabulated functions such as Bessel functions or Legendre polynomials. As the complexity of the model increases (West & Edwards, 1985), the boundary-value problem and its solutions become correspondingly more difficult. At present, the use of integral equation and finite-element or finite difference methods allows numerical field solutions for a thin sheet or a three-dimensional body in a conductive host medium covered
by a layer of homogeneous conductive overburden with infinite lateral extent (Hanneson, 1981). Although the solution of multi-body models is under investigation, available computer models are inadequate to describe the field behavior for the geologic settings presented in the previous section.

The primary need for physical scale-modeling in geophysical research is to investigate models which are too complex for computer methods. Once a scale-model system has been built and tested properly, a model of any complexity can be examined so long as scaling is valid. Historically, the scale model usually precedes the computer model, and serves as a final check on the validity of the numerical method. As computer methods advance to include the increased complexity of these models, the application of physical modeling should then turn to even more complicated geological settings. However, the development of a computer program for a given model does not always exclude the need for an equivalent physical model. The obvious advantages of using a computer are the speed with which results can be generated, and the ability to vary the model parameters over a wide, continuous range. Some disadvantages can also be present: the program might require expensive amounts of processing time on a large computer system, ranging from a
scale of hours for detailed studies using thin-sheet programs, to extreme cases of one week or more for some three-dimensional models. Some programs also encounter computational difficulties over certain ranges of model parameters. The expense must be compared with that of producing the equivalent physical model; if the necessary materials and facilities are readily available, physical modeling may be more cost-effective. Negi (1973) illustrates a thought algorithm for establishing scale model goals and evaluating the validity of physical modeling systems. The time required to collect data from a physical model is usually significantly greater than the computer time requirement, although computer-controlled data acquisition can make physical modeling comparably rapid.

In some respects, the results from a physical model give a realistic picture of the accuracies to expect in the field, since the model system suffers from some of the same operational problems which are seen in a field survey and which are not reflected in any computer model. The scale model shows the same problems of accuracy resulting from signal strength, primary field cancellation, coil alignment, distance from source to receiver, azimuth accuracy, etc.
Review of Model Studies

Frischknecht (1987) and Negi (1973) chronicle the development of physical scale model methods from theoretical investigations of electromagnetic similitude (Stratton, 1941 & Sinclair, 1948). During the early 1950's, instrumentation problems were examined and studies performed for plates and spheres in free space and in a brine host. The current-gathering effect of elongated conductive bodies in a conducting host was demonstrated during this period. Airborne EM studies appeared in the late 1950's for models in air (Hedstram & Parasnis, 1958), and in the 1960's for conductive brine host (Gaur, 1963).

Scale Modeling of Ground Methods

Studies by Lowrie & West (1965) demonstrated the influence of a conductive layer above the target for insulating host media. Phasor diagrams of the free-space response of dipping plates were presented by Strangway (1966), Ketola & Puranen (1967), Nair (1968), and others. Beginning in the early 1970's, a large body of measurements were made of the slingram response of various types of targets in a conductive brine or HCl host. The influence of the host is examined in several papers: Roy (1970); Gaur Et. Al. (1972, 1973); and Verma (1975) made measurements with
and without an insulating cover on the target in order to examine the influence of galvanic currents which flow between the host and target. Olm (1981) performed a series of measurements to evaluate the effectiveness of the frequency-differencing method for a variety of geologic noise models in air. Current areas of interest in physical modeling are investigations of new types of conductive materials available for model construction (Frischknecht, 1987) and improvement of data-handling and interpretation by use of computers.
REVIEW OF THEORY

The following sections examine some theoretical developments in geologic noise analysis. The large body of experimental, numerical and field studies summarised by Negi (1973) and Frischknecht (1971,1987) permits many different comparisons of relative resolving power. Limitations on the ability to distinguish between desirable and undesirable conductors is an immediate concern to field operators (Scott, 1973).

Relative Resolution

Investigations of the resolving capabilities of airborne inductive methods (Ward, 1967) and ground methods (Bosschart, 1968; Paterson, 1967) discuss the sensitivity of the inphase and quadrature components of the secondary magnetic field. Theoretical developments by Kaufman and Keller (1985a, 1985b), establish a form of "rating scale" for the changing sensitivity observed by measuring both the quadrature and inphase components of the total field over a broad range of frequencies. As a starting point, assign the resolution of direct current methods as the "worst case". The sensitivity of a DC method, where the electric field is measured at the earth's surface, depends on the contrast coefficient "K". For a spheroid:
where $\sigma_e$ is the conductivity of the host medium, and $\sigma_i$ is the conductivity of the spheroid. Examining the behavior of $K$ shows that it's value is relatively unchanged by a large variation in conductivity contrast (Figure 5). $K$ also has significant magnitude for resistive as well as conductive bodies; a consequence of the fact that the sources of the secondary DC electric field are charges which arise at interfaces where conductivity changes.

$$K = \frac{\sigma_i / \sigma_e - 1}{\sigma_i / \sigma_e + 2}$$

FIGURE 5. Behavior of parameter "K".
**Similarity of High Frequencies to DC Case**

Expressing the secondary magnetic field of induced currents in a confined conductor for the high-frequency portion of the spectrum in asymptotic form (Kaufman & Keller, 1985, p. 345):

\[ \tilde{H}_s = \tilde{H}_o \left[ A - \frac{B}{\sqrt{\sigma_i \mu \omega b}} \right] \]  
\[ \tilde{H}_q = \tilde{H}_o \frac{C}{\sqrt{\sigma_i \mu \omega b}} \]  

Where \( A, B, \) and \( C \) are geometric factors which depend only on the dimensions and locations of the conductor and of the source and receiver, \( \tilde{H}_o \) is the primary magnetic field, and \( b \) is some characteristic dimension of the conductor. The constant \( \mu \) is the magnetic permeability of free space, and \( \omega \) is radian frequency. The quadrature component tends to zero with increasing frequency, conductivity, or dimensions of the body, and so becomes difficult to measure accurately. At high frequencies the inphase component dominates, however it tends to the asymptotic limit "\( A \)" with increasing frequency and so becomes insensitive to changes in conductivity. In this respect, measurements in the high frequency portion of the spectrum yield no improvement of resolution over DC methods.
Resolution at Low Frequencies

The condition \( \sqrt{\sigma \mu \omega b} < 1 \) defines the "small parameter" region of the spectrum. In terms of commonly used induction numbers (Ward, 1967) this can be written as \( \sigma \mu \omega L^2 < 1 \) for a half-space, and \( \sigma \mu \omega L < 1 \) for a thin plate ("L" is coil separation and "t" is the plate thickness). In the small parameter region, the secondary magnetic field due to currents in a confined conductor is a Maclaurin series (Kaufman & Keller, 1985):

\[
\text{Inphase } \vec{H}_s = \vec{H}_0 \left[ -\frac{C_2}{a^2}\omega^2 + \frac{C_4}{a^4}\omega^4 - \frac{C_6}{a^6}\omega^6 + \cdots \right] \quad (3)
\]

\[
\text{Quadrature } \vec{H}_s = \vec{H}_0 \left[ \frac{C_1}{a}\omega - \frac{C_3}{a^3}\omega^3 + \frac{C_5}{a^5}\omega^5 - \cdots \right]
\]

where \( C_1, C_2, \text{ etc. are geometric factors and } a = 1/([\sigma \mu b^2]). \)

In the small parameter region, the quadrature component dominates over the inphase. The value of both components is defined mainly by the leading term of their series, so that when the frequency is sufficiently low:

\[
\text{Inphase } \vec{H}_s \approx -\vec{H}_0 \frac{C_2}{a^2}\omega^2 \quad \text{Quadrature } \vec{H}_s \approx \vec{H}_0 \frac{C_1}{a}\omega \quad (4)
\]
Comparing these expressions with those for the high frequency limit, there is an obvious improvement in the ability to resolve conductivity using either component. The quadrature value changes in direct proportion to conductivity. The inphase component, which is smaller, is more difficult to measure but depends on a higher power of conductivity and thereby has greater resolving power than the quadrature component in the small parameter region. In the presence of geologic noise, the ratio of the target contribution to the noise contribution is (Kaufman, 1978b):

$$\text{In} = \frac{C_T^T \sigma_N^2}{C_N^2 \sigma_T^2} = \frac{C_T^T \sigma_N^2 b_T^4}{C_N^2 \sigma_N^2 b_N^4} \quad \text{Quad} = \frac{C_T^T \sigma_N^2}{C_N^2 \sigma_T^2} = \frac{C_T^T \sigma_T b_T^2}{C_N^2 \sigma_N b_N^2}$$

Where index "T" denotes target parameters and "N" denotes noise parameters. This signal-to-noise ratio depends upon the conductivities, characteristic dimensions, and geometric factors of the two bodies. For many cases the conductivity of the target is greater than that of the noise source; however the dimensions and/or geometric factor of the noise source may tend to offset the differences in conductivity. If $\sigma_T$ equals $\sigma_N$, the ratio becomes dependent upon the geometric factors and the ability to discriminate between
the target and noise response is similar to the DC method. When \( a_T \) is greater than \( a_N \), resolution becomes increasingly worse. The influence of the second term of the Maclaurin series may decrease the target response more than it does the noise, so that the signal-to-noise ratio may be very small. If the second term is negligible in the noise quadrature response but significant in the target:

\[
\text{Target Quadrature} = \overline{H}_o \left[ \frac{C_T}{a_T} \omega - \frac{C_T^2}{a_T^3} \omega^3 \right]
\]

\( \text{(6)} \)

\[
\text{Noise Quadrature} = \overline{H}_o \frac{C_N}{a_N} \omega
\]

The signal-to-noise ratio can be improved by decreasing frequency so that the second term of the target response is also negligible, but once the point is reached where both target and noise response are completely defined by the first term of their series, no further improvement of the resolving power is possible with continued decrease of frequency. In fact, since the amplitude of the measured field diminishes with frequency, a point may be reached where the measured signal is comparable in amplitude with the operational or internal noise level (Ward, 1967).
Resolution of Higher-Order Terms

Kaufman (1978b) observed that if measurements are made at more than one frequency, the leading term of the Maclaurin series can be removed by use of frequency differencing. For example, the difference function for the quadrature component measured at two frequencies is:

\[ \Delta Q = \left[ Q(\omega_1) - \frac{\omega_1}{\omega_2} Q(\omega_2) \right] \]  \hspace{1cm} (7)

The leading term of the quadrature difference depends on \( a^3 \) \( (a^3b^6) \). In general, the magnitude of the geometric factor \( C_n \) (Equation 6), decreases as index "n" increases (Kaufman & Keller, 1985) and successive terms of the series have increasing sensitivity to the parameter \( a \). Removing the leading terms of the series from the response increases resolving power by measuring only terms which depend on higher powers of \( a \). Olm (1981) applied this method in a model study of geologic noise using an insulating host medium. Measuring higher terms without limit theoretically increases the relative contribution of the target response to any desired value if \( a_T < a_N \). The obvious limitation of this approach depends on the small contribution from these higher-order terms to the total response. In order
to measure the higher terms, the total response must be measured with corresponding accuracy.

The preceeding comparison of resolution can be summarized with a relative scale (Figure 6). Direct current and high frequency measurements have comparable resolution. Increased sensitivity to the target is obtained by measuring at low frequencies when $\alpha_N$ is greater than $\alpha_T$, with the inphase component having greater sensitivity than the quadrature component. If $\alpha_N$ equals $\alpha_T$, resolution depends only on geometric factors. Both quadrature and inphase sensitivity can be improved by measuring the contribution from the higher terms of their series. If $\alpha_T$ is greater than $\alpha_N$, sensitivity to the target becomes worse at low frequencies and when sensing higher-order terms.

**Effect of Current in the Host Medium**

In large proportions of model studies and in the development of interpretational aids, it was assumed that the host medium is an insulator. Although this is a valid approximation in many cases, finite host conductivity can exert a strong influence on target response when galvanic current is directed through the target from the host. A general set of equations describing the field of a buried spheroid for small parameters is found in Kaufman & Keller.
<table>
<thead>
<tr>
<th>DC and High frequencies</th>
<th>Low frequency Quadrature</th>
<th>Low frequency Inphase</th>
<th>Higher-order terms</th>
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</thead>
<tbody>
<tr>
<td>Increasing sensitivity when $a_T &lt; a_N$</td>
<td></td>
<td></td>
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<tr>
<td>Decreasing sensitivity when $a_T &gt; a_N$</td>
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</table>

FIGURE 6. Comparison of relative sensitivity.

(1985, p. 522-523); which express the total field as a sum of two terms: an inductive component and a galvanic component which includes the influence of surface charges and currents which close through host and target. The inductive term is proportional to the parameter $D_1$, where:

\[
\text{Inphase } D_1 \approx - \frac{2|\sigma_i \mu \omega b^2|^2}{315}
\]

\[
\text{Quadrature } D_1 \approx - \frac{\sigma_i \mu \omega b^2}{15}
\]

The galvanic term is proportional to the parameter "K" presented earlier (Equation 1). In the small parameter region, the influence of galvanic current is generally greater than the influence of inductive coupling between host
and target currents. The effect of galvanic current is
typically to increase both inphase and quadrature values to
a varying degree. This is clearly shown in model studies by
Gaur (1972), which used a conductive brine host and targets
covered with an insulating sleeve to block the flow of
galvanic current into the target from the host. Comparison
with measurements made without the insulating cover and in
free space showed that the insulated conductor response was
nearly identical to the free space response; whereas
electrical contact with the host produced dramatic
alteration of anomaly shape and amplitude.

Summary of Features of the Frequency Spectrum

Figure 7 illustrates a division of the frequency
spectrum into regions where different factors influence the
observed magnetic field. For a highly conductive target in
a moderately conductive host, one might consider the
following divisions:

Region 1) Induced currents in the target dominate,
host currents are negligible.

Region 2) Galvanic currents flowing through target from
the host become significant compared to
induced target currents, producing a small
biasing effect on observed anomaly.
FIGURE 7. Summary of frequency spectrum.
Region 3) Galvanic currents have the same order of magnitude as induced currents, current interaction between host and target has significant influence, host response is substantial with or without the presence of the target.

Region 4) Upper portions of the medium begin to dominate response.

Region 5) Skin depth in target becomes smaller than target thickness (location of region depends on thickness).

Region 6) Displacement currents become significant.

The relative contributions of the target and host are illustrated by a rough scale, also the equivalence of the regions to the commonly used divisions of the transient response into "early" and "late" times.

System Focus

In a comparison of the signal from a target and geologic noise, Bosschart (1968) observed:

"the two can be distinguished when the causative bodies have measureably contrasting conductivities or when their dimensions or geometry relative to the prospecting configuration show characteristic differences."
For a steeply dipping tabular body beneath relatively resistive overburden, several types of measuring system could have equal resolving power:

1) A system which favors the response of vertically oriented conductors over horizontal.

2) A system sensitive to finite dimensions of sources.

3) A system which separates responses based on conductivity range.

Bosschart illustrates the last system in a manner which demonstrates the concept of resolving power at low frequencies (Figure 8). When properly focused the system has negligible response to the low-conductivity host and overburden; the sensitivity of the response to changes in the target conductivity is at a maximum for both components. The concept of "system focus" is also implemented by use of wideband measuring systems such as the 128-frequency MAXIPROBE EMR-16 (Sinha, 1979). Other approaches include the filtering process of threshold stacking (Bosschart and Seigel, 1974), and geometric adjustments for turam surveys (Duckworth and Bays, 1984). The model study contained in this thesis provides material for evaluation of the use of wideband systems in the presence of geological noise.
FIGURE 8. Concept of system focus (reproduced from Bosschart, 1968).
Method For Determining Apparent Conductivity-Thickness

Several of the concepts reviewed in the preceding sections are incorporated in simple interpretational methods which translate theory into a useful field tool. Interpretation is improved in many cases when measurements are made in the small-parameter region, inasmuch as the contribution of geologic noise is reduced relative to that of the target under proper conditions. Furthermore, the behavior of the Maclaurin series which describes the small-parameter response leads to a simple interpretation scheme which can be applied to a wide variety of conductor shapes and geometry.

Noting that the odd-power terms of the Maclaurin series define the quadrature component while the even terms define the inphase component (Equation 3), it is apparent that when both components are defined mainly by their leading term, the ratio of the inphase to quadrature component is proportional to the quantity $\frac{\alpha \mu \omega b^2}{\sigma t \mu \omega L}$. For a thin plate, the appropriate induction number is $\frac{\sigma \mu \omega L}{\sigma t \mu \omega L}$.

Interpretation methods for thin plates have been developed from widely-used model results such as those of Ketola and Puranen (1967). The work of Betz (1977) represents an example of an approach to interpretation in the small-parameter region. Using the slingram results of
Ketola and Puranen, Betz plotted the inphase/quadrature ratio versus the induction number \( \sigma f L \) where "f" is frequency in Hertz. On a log-log scale, the linear relation of the inphase/quadrature ratio to frequency produces a straight line in the small-parameter region (Figure 9). Departure from this straight line occurs as frequency increases. Betz obtained a slope of about 0.73 for the straight line. A similar slope is obtained from studies by Nair (1968). Theoretical considerations predict that this slope should equal 1.0 in the small-parameter region. Investigation of the apparent disagreement is beyond the scope of this thesis; the important point is that Betz’s results illustrate the simple relation which can be established between measured response and the apparent conductance of a body.

Use of a simple straight-line relation to convert measured field values into apparent conductivity-thickness presumest a number of conditions which are not always met in a field survey. The small-parameter condition has already been discussed, a further assumption is that the conductor is "inductively thin"; meaning that the skin depth in the conductor is larger than the characteristic dimension (in the case of a plate, this dimension is thickness). Additionally, the method assumes that the influence of host
currents is negligible. A detailed analysis of the influence of these factors is beyond the scope of this thesis. Examination of the influence of such effects on interpretation can be found in references such as Palacky and Sena (1979), Lajoie and West (1977), and Parasnis (1971).
Scaling Equation for Model Parameters

It can be shown that any system which obeys Maxwell's equations may be scaled in a linear manner (Frischknecht, 1987). For measurement of normalized amplitudes of the magnetic field components, sufficient scaling conditions are:

1) The value of the induction number in the model must equal the induction number in the full-scale system, by appropriate scaling of the conductivity, frequency, and length parameters.

2) The magnetic permeability of the model materials must equal the permeability of the full-scale material.

3) The electric permittivity of the model may assume any value as long as displacement currents can be neglected over the range of model frequencies used.

Neglect of displacement currents is a common feature of model studies where frequencies do not exceed a few megahertz. In particular, at the highest model frequency used (500 Kilohertz), assuming a conductivity of 20 Siemens/M and a dielectric constant ten times greater than the free-space value.
\[
\frac{\text{Displacement current}}{\text{Conduction current}} = \frac{\omega \varepsilon}{\sigma} = 1.4 \times 10^{-5}
\]

(9)

The displacement currents are nearly five orders of magnitude smaller than conduction currents. There are some cases (Sinha, 1976) where displacement currents are significant in the full-scale system. Equality of magnetic permeability can be assumed for most non-magnetic materials. The remaining condition of equality of induction numbers is satisfied by the relation

\[
\left( \frac{l_W}{l_M} \right)^2 = \frac{\omega_M \sigma_M}{\omega_W \sigma_W} \quad \text{or,} \quad L^2 = F \cdot C
\]

(10)

where "L" is the length scaling factor, "C" represents the conductivity scaling factor, and "F" is the frequency scaling factor.

Dimension Scaling and Probe Equivalence

Instruments currently used for slingram surveys (such as the improved version of the trademark "MAXMIN" system) might typically operate at frequencies between 100 Hertz and 15 Kilohertz, with coil separations varying from 20 meters to 400 meters. This study uses a length-scaling factor of 1000 to simulate a 200 meter field separation using a 20
centimeter coil separation in the model. This scaling factor is also convenient in terms of the size and weight of the model materials. The coil dimensions are limited by the need to retain the dipole behavior of the source and receiver in the model. For a pair of thin coils, this condition is satisfied for many cases when the separation of the coils is much greater than the coil diameter (Keller & Frischknecht, 1977); however this may not be sufficient when one or both coils is very near a concentration of current, such as the corner of a large body (Frischknecht, 1987). A diameter of 2 cm was chosen for both coils, so that the separation is ten times greater than the diameter.

Model Materials, Conductivity and Frequency Scaling

Using a length-scaling factor of 1000, the model frequencies and conductivities must satisfy

\[
\frac{\omega_M \sigma_M}{\omega_W \sigma_W} = 10^6
\]

The possible combinations of scale factors are somewhat limited by the availability of suitable model materials with the desired conductivity, and by the operational frequency range of the equipment. Scale models of three-dimensional bodies with relatively high conductivities often use carbon
or graphite in the form of blocks or epoxy-fiber sheets, with conductivity values between 13,000 and 120,000 S/M. Inhomogeneous materials and lower conductivities are produced by mixing epoxy casting resin with flake graphite or carbon. These materials are fairly easy to shape, and allow modeling of fairly large bodies without exceeding 100 pounds of weight, given the length-scaling factor above. Conductive host rock is often simulated with a saturated NaCl solution, which has a conductivity around 20 S/M at room temperature (Frischknecht, 1987). Higher conductivities can be obtained by using other solutions such as NaOH (27 S/M) or HCl (72 S/M); but the toxic properties of these chemicals makes protection of personnel and equipment difficult when large volumes must be handled.

This study uses combinations of carbon, graphite and brine as model materials. Knowing this, it remains to determine the conductivity scaling factor which relates them to the real world. Given that the useful frequency range of the model measuring system is between 1000 Hertz and 500 kilohertz, the frequency scaling factor is approximately 100 for the range of real-world frequencies given previously. Therefore, a value of 10,000 is used for conductivity scaling. The scaling requirements are thus completely satisfied by:
\[ l_W = l_M \times 10^3 \]
\[ \omega_W = \omega_M \times 10^{-2} \]
\[ \sigma_W = \sigma_M \times 10^{-4} \]  \hspace{1cm} (12)

The choice of length and frequency scaling was influenced by technical practicality; that is, these values are somewhat pre-determined by available technology and instruments. Similarly, the choice of model materials was influenced by practical considerations. The continued development of conductive plastics and foams; or the use of semi-permeable membranes for separating fluids of different conductivity while allowing electrical contact might increase the available range of conductivities for model material. This allows a greater variety of geologic models to be investigated with a single measuring system.

Validity of the Scale Models

Consider the validity of representing a conductive half-space with a finite volume of brine. Frischknecht (1987) notes studies demonstrating that the effect of the walls of the brine container are small when they are at distances greater than about one skin depth from the transmitting and receiving coils. Furthermore, the
influence of boundaries that are more than one or two coil spacings from the center of the configuration is negligible for ordinary slingram systems, regardless of the skin depth. For a brine with a conductivity of 20 S/M and magnetic permeability equal to free space, the skin depth at 1000 Hertz is

\[ \delta = \sqrt{\frac{2}{\sigma \mu \omega}} = 3.6 \text{m} \quad (13) \]

The container used in this study is a concrete tank with dimensions 3.65 X 2.75 X 1.5 meters, filled to an approximate depth of 1.3 meters with fluid containing roughly 10,000 pounds of dissolved salt. At frequencies below about 10 Kilohertz the skin depth begins to exceed the distance to the tank walls. However, since the smallest tank dimension is about six times greater than the coil separation, the signal from the walls of the tank is negligible with respect to measurement accuracy and target response. This might not be the case for a system with very high sensitivity.

Applying the conductivity scale factor of 10,000 gives an equivalent real-world host conductivity of 0.002 S/M, or a resistivity of 500 Ohm-meters. In absolute terms, this
represents an average value for a variety of rock types (Paterson, 1971; Keller & Frischknecht, 1977), particularly tertiary volcanics (up to 200 ohm-meter) or granites and older volcanics (approx. 1000 ohm-meters). In terms of the goals of the model study, the objective was to construct a model which reflected the influence of host currents, particularly near the frequency range where their effect is first seen. Refering back to figure 7, the combination of model frequency and brine conductivity covers a broad range of host influence, from "negligible" to "appreciable". Dilution of the brine would simulate the influence of more highly resistive host material up to extreme cases such as the very old rocks of the Canadian shield (10,000 ohm-meters), where the contribution of host currents becomes negligible over the range of frequencies commonly used in exploration.

The dimensions, conductivities, and other parameters of the model materials used to simulate targets and geologic noise are listed in Table 1. The scaled conductivity values could be representative of some sulphide ores (Keller & Frischknecht, 1977), but this quantity alone has little meaning in characterising an orebody. The conductivity-thickness product (conductance) is a more meaningful quantity; statistical studies by Strangway
### Table 1
PARAMETERS OF MODEL MATERIALS

**MODEL COMPONENT:**

<table>
<thead>
<tr>
<th>MATERIAL:</th>
<th>BRINE</th>
<th>GRAPHITE SLAB</th>
<th>GRAPHITE SLAB</th>
<th>CARBON FIBER</th>
<th>GRAPH/ EPOXY</th>
<th>CARBON SLAB</th>
</tr>
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<tbody>
<tr>
<td>HOST</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TARGET 1</td>
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<tr>
<td>TARGET 2</td>
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<td></td>
</tr>
<tr>
<td>NOISE 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOISE 2</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
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**DIMENSIONS (cm):**

<table>
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<th>59.8</th>
<th>150.0</th>
<th>122.0</th>
<th>15.0</th>
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<tbody>
<tr>
<td>WIDTH</td>
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<td>10.2</td>
<td>150.0</td>
<td>76.0</td>
<td>15.0</td>
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<td>THICKNESS</td>
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<td>5.0</td>
<td>0.71</td>
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**MODEL CONDUCTIVITY (S/M):**

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<th></th>
<th>20</th>
<th>1.24e5</th>
<th>1.47e5</th>
<th>1.31e4</th>
<th>150.0</th>
<th>1.61e4</th>
</tr>
</thead>
</table>

**MODEL CONDUCTANCE (S):**

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<th>1448</th>
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<th>93</th>
<th>2.7</th>
<th>193</th>
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</table>

**SCALED CONDUCTIVITY (S/M):**

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<th>0.002</th>
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<th>14.7</th>
<th>1.31</th>
<th>0.015</th>
<th>1.61</th>
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</thead>
</table>

**SCALED CONDUCTANCE (S):**

<table>
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<th></th>
<th>144.8</th>
<th>735</th>
<th>9.3</th>
<th>0.27</th>
<th>19.3</th>
</tr>
</thead>
</table>

**INDUCTION NUMBER:**

<table>
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<tr>
<th>Frequency</th>
<th>1.25 KHz</th>
<th>0.008</th>
<th>2.85</th>
<th>14.5</th>
<th>0.38</th>
<th>0.006</th>
<th>0.184</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500 KHz</td>
<td>3.16</td>
<td>1143</td>
<td>5803</td>
<td>152</td>
<td>2.37</td>
<td>73.4</td>
</tr>
</tbody>
</table>
(1966) and others have shown that the conductivity-thickness of many producing orebodies falls within a range of 1 to 300 Siemens. Typical values for layers of conductive overburden range from near zero to approximately 10 Siemens or more for brine-saturated clays or sands. The targets are therefore suitable to model the midrange and higher conductance orebodies. The carbon overburden models are well suited to represent a wide range of overburden types, particularly when the skin depth in the material exceeds the thickness of the sheet. In this event, the sheet can represent layers with different thickness and conductivity so long as the product remains constant. The small carbon plate is similarly suitable to model a range of low-conductance noise sources.

**Measurement and Data Collection Method**

The modeling facility of the U.S. Geological Survey at the Denver Federal Center has been used for several previous studies (Frischknecht, 1987), the more recent (Olmo, 1981; Miles, 1985) have included improvements in data-gathering efficiency by incorporating computer control of the process wherever possible. The author has modified the data collection system to take advantage of partial computer control available in the upgraded instrumentation used for
this study. During 1985 and 1986 the author made a series of improvements such that the usable frequency range extends from 1000 Hertz to a theoretical maximum of around 5 Megahertz. It was determined while testing the system that the noise contribution from the AM radio band makes measurements at frequencies much higher than 500 Kilohertz subject to increasing error.

A block diagram of the system (Figure 10) shows the connection of the components. The setup is visualized as consisting of four sections:

1) Circuits for recording position of the two coils.
2) Signal generation and driver circuits for the transmitter coil.
3) Signal preamplification and measurement circuits.
4) Computer interfacing for data acquisition.

Position sensing. Without repeating the mechanical descriptions of the draw-works which position the coil assembly (Frischknecht 1971, 1987), the position sensing is performed by 2 multi-turn precision potentiometers which are mechanically linked to the draw-works. The shaft of the horizontal sensor is connected to a capstan on the horizontal draw-works; the vertical sensor shaft is driven by a pinion gear and a rack mounted on the vertically-moving
FIGURE 10. Block diagram of system.
portion of the carriage. Vertical position sensing was not required for this study. The potentiometers are connected to voltage dividers, the horizontal sensor is calibrated to read zero at the center of the tank, and ±1.0 volt at approximately ±65 cm from the center. After correcting for non-linearity of the potentiometers, the horizontal (and vertical) change in position can be measured accurately to within 0.5 millimeter.

**Low frequency transmitter.** Two different circuits are used depending on frequency; one for frequencies below 10 Kilohertz, and one for frequencies from 10 KHz to 500 KHz (Figure 11). A Hewlett-Packard 3325A function synthesizer is used to drive both circuits. For the low frequencies, the output of the 3325A is connected to an HP 467A power amplifier; the amplified signal then passes through a coupling transformer with a center-tapped secondary. A shielded, twisted-pair cable approximately 8 feet long connects the transmitter coil to the transformer. The cable shield is connected to the center-tap of both. Using twisted-pair cable in this manner reduces common-mode noise picked up by the long connection path.
A. Low frequency measurements (1KHz to 10KHz).

B. High frequency measurements (10KHz to 500KHz).

FIGURE 11. Transmitter portion of system.
High frequency transmitter. For high frequency measurements, the circuit is modified as shown in the figure. The output of the HP 3325A is connected directly to the coupling transformer and 8 foot twisted-pair cable. A hand-wound toroidal inductor is inserted in the cable to provide additional common-mode noise reduction (Frischknecht 1971, 1987). The toroids present a relatively large impedance to the common-mode signal (25,000 to 100,000 ohms depending on frequency) compared to the impedance seen by the differential-mode signal (Approximately 5 ohms). The need for such improvements in common-mode rejection is that, although the instruments and circuits used in this study have very high common-mode rejection; slight differences between the resistance and physical paths of the long signal wires will result in some portion of the common-mode signal being converted to differential-mode. This unwanted signal will then pass through the inputs of instruments, etc. unaffected by common-mode rejection. The only way to reduce this problem is to suppress common-mode signal in the cable itself. The toroids are not used in the low frequency circuit since the coupling between parts of the system (and hence, common-mode pickup) becomes small.

Power amplification is provided using OEI (Optical Electronics Inc.) brand 9911 voltage followers capable of
delivering 500 milliamperes to a 20 ohm load at frequencies up to 100 Megahertz (Figure 12). A 20 ohm current-limiting resistor is included in the output circuit to avoid the effects of accidentally short-circuiting the follower. The circuit fits in an aluminum box with dimensions of 3X3X5 inches, continuous shielding is maintained at the input and output.

FIGURE 12. High frequency transmitter amplifier circuit.
Coils. The coils are wound on forms 0.5 cm in height and 2 cm in diameter (Figure 13). The coils are composed of two solenoidal sections (Becker, 1967), center-tapped and provided with faraday shields (Frischknecht, 1987), sealed with low-loss "Q-dope" and coated with clear acrylic nail polish to prevent electrical contact with the brine. The transmitter coil has 28 turns of #30 magnet wire in each section (56 turns total), the receiver coil has a total of

![Coil forms diagram](image)

A. Form.  
B. Completed coil with Faraday shield.

FIGURE 13. Coil forms.
120 turns of #34 wire. The coil sections are wound in opposite directions; the outside wires are joined to form the center-tap. The faraday shields are made of thin brass foil, the shield center is connected to the center-tap. The resonant frequency of both coils, including connection cables, is well above the operational frequency range of the system. Using a coil separation of 20 cm, the receiver coil produces signal voltages between 10 and 25 microvolts. The author designed a plexiglass coil mount which was fabricated with excellent precision in the USGS model shop. The mount (not shown) includes fine-leveling adjustment and allows a single coil pair to serve for all coil configurations.

Low frequency receiver. The receiver portion of the system is shown in Figure 14. For low frequencies (less than 10 KHz), a shielded twisted-pair cable directly connects the receiver coil to the differential inputs of a PAR (Princeton Applied Research) 125A phase-locked amplifier, the cable shield connecting the coil center-tap to the common ground of the PAR input. As in the transmitter circuits, the use of twisted-pair cable and differential configuration reduces common-mode noise.
A. Low frequency measurements (1KHz to 10KHz).

B. High frequency measurements (10KHz to 500KHz).

FIGURE 14. Receiver portion of system.


**High frequency receiver.** The use of a direct connection for the receiver coil was not feasible for the higher frequencies, due to problems of coil resonance and stray signal pickup created by the long cable. Therefore, measurements made above 10 KHz use a greatly modified receiver circuit (Figure 14b). The coil is connected by a shorter (3 foot) length of cable to a preamplifier. The preamplifier circuit uses an OEI 9914 wideband operational amplifier in the inverting configuration with a closed-loop gain of 40Db (Figure 15). Each side of the differential amplifier is capable of delivering a 5-volt output at 50 milliamperes to the load, at frequencies up to 50 Megahertz. The circuit is laid out symmetrically inside a 2X2X3 inch aluminum box which is machined so that there are no gaps when closed, shielded connectors are used at the input and output. It was originally planned to use the 9914 in the non-inverting configuration (increased input impedance), however it was found that the 9914 requires a 51 ohm input biasing resistor. Since this input resistor destroys the high input impedance advantage of the non-inverting configuration, and since the 9914 appeared least susceptible to "lock-up" in the inverting configuration, the circuit shown was chosen. The DC offset of the amplifier is small enough that it was unnecessary to
compensate the circuit. A reference such as Hoenig and Payne (1973) is extremely helpful in avoiding the numerous pitfalls of small-signal amplification using highly sensitive wideband op-amps. The output of the preamplifier is connected to a wideband isolation transformer, the

FIGURE 15. Receiver preamplifier circuit.
capacitance is minimized by using the shortest practical cable length (about 6 inches). To avoid stray signal pickup, a fiber-optic signal link is used to make the 8 foot connection from the isolation transformer to the instruments. The isolation transformer connects to a MATH Associates "Fiberlink" brand transmitter (model XA-1000). A fiber-optic cable then connects this to a model RA-1000 receiver, and the signal finally reaches the input of either the PAR 125A described previously, or a PAR 5202 for frequencies above 100 KHz.

**Inphase and quadrature measurement.** The PAR phase-locked amplifiers are operated to provide an analog output of inphase and quadrature measurements as normalized percentages with respect to a reference signal taken from the HP 3325A signal generator. This is equivalent to the mutual coupling ratio normally measured with slingram systems. Observations of the noise level of the output showed that the system is capable of measurements to an accuracy of 0.1 percent or better under good conditions. The system was found to be sensitive to nearby vehicle traffic, this problem was effectively solved by making all measurements late at night.
Data collection method. There are four channels of information to record at any "station" of a profile: the horizontal position, vertical position, inphase value and quadrature value. If the coil assembly does not change height, the number of channels is reduced to three. The output voltages of the position sensors and the PAR amplifiers are connected to four channels of a Hewlett-Packard 3495A scanner which connects any desired channel to the input of an HP 3437A system voltmeter. The digital output of the system voltmeter is passed to an HP 9825A computer for processing and storage. Data files are recorded on HP data cassettes and then transferred to a VAX-780 mainframe computer using a modem-equipped HP-85A computer as a transfer link. The 9825 collects data using an input program developed by the author wherein the frequency selection and inphase adjustment are performed automatically; the only function served by the operator is to manually zero the quadrature reading and throw the switch which controls carriage movement.

A typical profile length is around 1 meter. The reading process is triggered automatically by presetting a desired starting voltage to compare with the horizontal sensor. The 9825A computer acquires a set of 500 inphase
and quadrature readings along this distance. For a total distance of 1 meter, this translates to a data density of one reading for each 2 millimeter of carriage travel. One additional feature of the data collection program is automatic data smoothing during input. The system is able to perform real-time data stacking by using a high-speed subroutine to achieve a fast reading speed from the scanner and voltmeter. Each of the 500 values for position, inphase and quadrature is generated in a high speed "burst" of 14 staggered readings of the three channels. A total of 6 position readings, 4 inphase and 4 quadrature are averaged to produce one data sample (Figure 16). Upon completion of a profile, the 500 samples are smoothed with a running 5-point filter. The number of samples is then reduced by sorting the sample positions into 1 cm intervals. For example, data samples with positions that lie between +0.5 cm and +1.5 cm are averaged to a single value whose average position is very close to +1.0 cm. The final data density, with respect to coil spacing, is 20 data points to 1 coil spacing.
"Read burst" for one station (carriage travel ≈ 2 mm)

<table>
<thead>
<tr>
<th>Position samples</th>
<th>Inphase</th>
<th>Quad</th>
<th>Inphase</th>
<th>Quad</th>
<th>Position samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>P2</td>
<td>P3</td>
<td>I1</td>
<td>I2</td>
<td>Q1</td>
</tr>
</tbody>
</table>

FIGURE 16. Scanning sequence for one data sample.

System Tests

The response of the system to the brine host is a valid test of measurement accuracy. The host response was recorded for nearly every profile appearing in this study, a sample comparison of measured response versus calculated response for horizontal coplanar coils is shown in Figure 17; results for other coil configurations are not shown. The response of all configurations agrees closely with the calculated curves. Some scatter due to RF interference from the AM radio band appears at the highest frequencies.
FIGURE 17. Comparison of measured and calculated host response for horizontal coplanar coils.

Calculated response = solid line
Measured inphase = circle
Measured quadrature = square
SCALE MODEL RESULTS

Description of Models and Data Presentation

Diagrams showing cross-sections for each of the three models investigated are found in Figures 18, 19, and 20. The dimensions and depths are drawn to scale. The centerline of each target is located at station 00. All profiles are perpendicular to the strike of the targets and noise bodies (in the case of overburden sheets, the profile is perpendicular to the edge). The coil separation is 20 cm in all cases; the coils were partially submerged so that the coil centers are at the brine surface. The dimensions, type of material, and conductivity for each component are listed in Table 1.

Data Profiles. The modeling portion of this study measures standard slingram quantities at 14 different frequencies between 1250 Hertz and 500 Kilohertz using a moving two-loop coil system. The measurements were repeated for four of the commonly used coil configurations: horizontal coplanar, perpendicular, vertical coplanar and vertical coaxial. Stacked measurements were recorded at intervals of 0.5 cm. Profiles of measured inphase and quadrature components of the secondary magnetic field are
FIGURE 18. Cross-section of Model 1.
FIGURE 19. Cross-section of Model 2.
FIGURE 20. Cross-section of Model 3.
expressed normalized to the primary field strength at the receiver. Except where specifically stated (Model 2), the response of the brine half-space has been subtracted from the response. It must be kept in mind that, obviously, this does NOT mean that host currents no longer affect the response of the model. All profiles discussed in the following sections are included in Appendix "A". The horizontal axis indicates the location of the midpoint between the coils, expressed as a fraction of the coil separation. Positive and negative positions denote stations to the right and left of station 00. To avoid over-crowding, only 7 of the 14 frequencies are shown on each profile.

Phasor Diagrams

A common method of presenting and interpreting slingram and other types of electromagnetic data is to construct what are often referred to as "phasor diagrams". An advantage of this method is that it allows presentation of a large amount of data (measurements at many different frequencies and coil separations), in a manner suitable for simple, straightforward interpretation of both conductance and depth to a target. Figure 21 shows some typical values that are measured from field profiles. Since the model data from
FIGURE 21. Typical quantities measured from profiles.
this study is presented in part through phasor diagrams, a brief description of their use is appropriate. A typical phasor diagram constructed from measured (or computed) profiles is illustrated in Figure 22a. A commonly plotted value is the maximum anomaly, either positive or negative. In some instances, values of the anomaly shoulders are used (particularly for interpretations of conductor dip). By plotting a number of inphase and quadrature pairs for several different values of induction number and ratio of depth/coil separation it is possible to characterise the target response for a given coil configuration and target shape. As illustrated in Figure 22b, interpretation is carried out by plotting measured inphase and quadrature response on a "master curve" appropriate for the type of suspected target. Measurement at a single frequency and coil separation is sufficient to estimate conductance and depth, however it is desirable to perform measurements at several frequencies and separations. This is especially true when the measured response is affected by geologic noise, since the departure of the data from "expected" behavior often alerts the interpreter to the presence of such noise. Parasnis (1971) and Palacky & Sena (1979) give field examples and a number of cautionary observations on interpretation using phasor diagrams.
FIGURE 22a. Typical phasor diagram (reproduced from Nair et al., 1968, p. 220).

FIGURE 22b. Interpretation example using a phasor diagram (from Palacky & Sena, 1979, p. 1957).
Calculation of Apparent Conductance

The idea of relating the ratio of the inphase and quadrature components to an apparent value of conductance has been discussed previously. For the conductor thicknesses listed in Table 1, it can be stated that the condition of "inductive thinness" will rarely exist over the frequency range used in this study. Interpretive curves similar to Figure 9 were constructed from inphase and quadrature values calculated using a proprietary USGS computer program called "SHEETT". A detailed description of the method of computation used by such programs can be found in Hanneson (1981). The model parameters used were those of the host brine and the targets for model 1 and model 3 (see Table 1). The program would not operate using the physically small dimensions and relatively high frequencies of the model system, so the scaled real-world values for dimensions, conductance, frequency and host conductivity were used. For purposes of interpretation the straight-line portion of the curve is assumed to extend to the highest frequencies of the system, as shown in the figure. Obviously, the assumption of straight-line behavior for all frequencies can have a drastic effect on interpreted conductance values.
Model 1: Edge Effect of Overburden

Comparison of Profiles. A complete description of the model and parameters are found in Figure 18 and Table 1. The data profiles appear in Appendix "A", Figures A.1 and A.2 indicate the frequency for each trace. This first model represents a "worst case" from the viewpoint of identifying a discernible target response in the profile data. An examination of the response of all four coil configurations (Figures A.3 through A.14), shows that the target response is almost completely obscured by the edge anomaly of the overburden. A close comparison of the overburden and total response reveals some subtle alteration of the anomaly shape by the presence of the target, most visible in the left-hand shoulder and, at low frequencies, in the shape of the negative maximum. The inphase component is, as expected, most sensitive to the target response at the lowest frequencies; showing a noticeable broadening and increase of magnitude when the target is present. The effect is most prominent in the total perpendicular response (Figure A.8), the vertical coplanar (Figure A.11), and the vertical coaxial (Figure A.14). The best chances of identifying the presence of the target appear to be through the vertical coplanar or vertical coaxial response, in that the target
causes the appearance of an unexpected left shoulder in the total response at low frequencies. Target visibility is less in the shape of the horizontal coplanar and perpendicular profiles, inasmuch as the presence of the target serves to distort features of the anomaly which are already present in the overburden response, such as the negative excursion and left shoulder of the horizontal coplanar. The change in sign of the target high-frequency quadrature response does not significantly alter the total response for this model.

Frequency-Differenced Profiles. The noise reduction brought about by frequency differencing offers minimal improvement over the "raw" profiles for this model. This result is predictable since the induction number for the overburden is relatively large at the lowest frequency (Table 1) and the amplitude of the target response is greatly diminished with respect to the overburden. Profiles of the frequency-differenced responses are shown in Figures A.15 through A.26. The influence of the target is slightly enhanced at the lower frequencies in the total response (Figure A.17, A.20, A.23 and A.26), but the overall visual effect of differencing at the higher frequencies is to produce a diminished-looking edge anomaly.
Comparison of Phasor Diagrams. The small index numbers which appear on the phasor diagrams refer to the "frequency number" of the plotted values; that is, index number "1" refers to the lowest frequency while number "7" refers to the highest frequency. Except where necessary to avoid confusion, only one point on each curve is indexed. Figure 23 shows the response at station 00 where the target has its maximum anomaly. The total inphase component is very nearly equal to the target value at the lowest frequency (2 KHz); at the second frequency (5 KHz) it differs by a factor of nearly 1.5 from the target inphase. The total quadrature at the low frequencies is very nearly equal to the sum of the target and overburden values. The overburden quickly dominates the total response with increasing frequency.

The influence of the overburden is less for the perpendicular configuration at the maximum positive anomaly (Figure 24). Here the total response at the lower frequencies approaches more closely to the response of the target alone for both inphase and quadrature components, being nearly identical at the lowest frequency.

Similar convergence of the total response with the target response is seen for the vertical coplanar and vertical coaxial configurations (Figure 25 and Figure 26). The vertical coaxial results in particular show excellent
FIGURE 23. Model 1, horizontal coplanar response at station 00.

Target response = diamond
Overburden response = circle
Total response = square
FIGURE 24. Model 1, maximum positive anomaly for perpendicular coils.
FIGURE 25. Model 1, vertical coplanar response at station 00.

Target response = diamond
Overburden response = circle
Total response = square
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 26. Model 1, vertical coaxial response at left anomaly shoulder.
agreement at the two lowest frequencies. The vertical coaxial total response also exhibits an interesting "loop" shape over the first five frequencies as the overburden influence becomes greater than that of the target; this is due simply to the particular manner in which the target and overburden response behave at station 00.

**Horizontal Coplanar Shoulder Response.** A noticeable increase of target influence on the horizontal coplanar response relative to the response at station 00 is apparent in the left-side positive shoulder of the anomaly (Figure 27). One reason for this improvement might be that neither of the coils is directly above the overburden at this position (the entire array is located over the brine half-space). In this case, the relative influence of the target should be greater than when one or both coils are very close to the overburden. The total response is still markedly influenced by the overburden, but follows the target response much more closely at higher frequencies than the response at station 00.
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 27. Model 1, horizontal coplanar response at left anomaly shoulder.
**Interpretation of Apparent Conductance.** Figures 28 through 32 show results of calculating apparent conductance using the method described previously. The inphase and quadrature values used for computation are taken from the phasor diagrams. The highest frequency (500 KHz) was not used for interpretation here. For all four coil configurations, the apparent conductance of the target shows an asymptotic approach to the true value of 1448 Siemens as frequency decreases. The apparent conductance of the overburden is much lower, but does not approach the true value of 93 Siemens. This is not surprising since the interpretation scheme is based on a "thin confined plate" model rather than the edge anomaly of a semi-infinite sheet.

The horizontal coplanar coil configuration shows excellent convergence of the apparent conductance for the total response at both station 00 (Figure 28) and the left anomaly shoulder (Figure 29). The perpendicular configuration (Figure 30) comes slightly closer to the true value. The interpretation method is not as effective for the vertical coplanar and vertical coaxial configurations (Figures 31 and 32) due to the existence of zero-crossings in both the inphase and quadrature components in the low frequency range. The overburden response is omitted in the vertical coaxial plot for this reason. However, the total
FIGURE 28. Model 1, interpreted conductance: horizontal coplanar coils, station 00.

Target response = diamond
Overburden response = circle
Total response = square
FIGURE 29. Model 1, interpreted conductance: horizontal coplanar coils, left anomaly shoulder.

Target response = diamond
Overburden response = circle
Total response = square
FIGURE 30. Model 1, interpreted conductance: perpendicular coils, maximum positive anomaly.
FIGURE 31. Model 1, interpreted conductance: vertical coplanar coils at station 00.

Target response = diamond
Overburden response = circle
Total response = square
FIGURE 32. Model 1, interpreted conductance: vertical coaxial coils, left anomaly shoulder.
response for both configurations agrees with the target response at the lowest frequency.

In conclusion, an outstanding feature seen in this model is the fact that, although the magnitude of the total response is strongly dominated by the geologic noise, to the extent that one is hard-pressed to discern the target at all but the lowest frequencies, the ratio of the inphase and quadrature components, and changes in this ratio as frequency varies, are strongly dominated by the target. This result would be most valuable in a situation where there is a known unmineralized section along the edge of an overburden sheet: establishing a "background" conductance value for the barren zone gives a reference for the interpreted conductance at other points along the edge. Any dramatic increase of this value might serve as an indicator that further investigation is warranted. Success of this approach requires that the overburden conductance be determined at locations away from the edge to maximize the accuracy of the interpretation. It must be pointed out that such an approach is by no means a "complete" interpretation process since it does not include determinations of conductor depth and dip, and does not address the problem of estimating separate values of thickness and conductivity.
Model 2: Inhomogeneous Overburden

This model uses the same target as model 1, beneath a continuous layer of inhomogeneous overburden with a conductivity much less than that of the target (Figure 19). A list of the parameters for each model component appears in Table 1. The target profiles are the same as those for model 1. The profiles for the overburden response and total response of this model are plotted without subtracting the response of the brine host since, in a real-world setting, the host response would be difficult to determine in the presence of extensive variable overburden.

Comparison of Profiles. Figures A.27 through A.34 show the overburden and total response for the horizontal coplanar, perpendicular, vertical coplanar and vertical coaxial coil configurations. At sufficiently low frequencies, the effect of the overburden is to linearly shift the target anomaly, and to slightly change the amplitude of the target response. The overburden influence is greater on the quadrature component than on the inphase component at low frequencies. At high frequencies, the quadrature response of the target is significantly enhanced by the presence of the overburden. In part, this is expected because of the additional phase rotation introduced
when a portion of the overlying host is replaced by a more highly conductive overburden.

A significant alteration of the "average" overburden response is seen when the target is present. Consider the response near the ends of the profile (I.E. near station -1.5). The horizontal coplanar response of the overburden (Figure A.27) is not noticeably changed by the presence of the target (Figure A.28). However, a comparison of the perpendicular profiles (Figures A.29 and A.30) shows a dramatic decrease in the overburden quadrature response at high frequency. In particular, at the highest frequency the quadrature response of the overburden alone is about 1.07, while the response when the target is present decreases to about 0.6. The perpendicular inphase response is affected to a much smaller degree; changing from about 0.86 to 0.9 when the target is present. The effect is significant in both the high frequency inphase and quadrature components for the vertical coplanar response (Figures A.31 and A.32) and vertical coaxial response (Figures A.33 and A.34).

Frequency-Differenced Profiles. Figures A.35 through A.38 show the result of frequency differencing. It can be seen that differencing effectively reduces the contribution of the overburden (and host) when it has relatively low
induction numbers. This allows a more meaningful interpretation than when overburden influence is "removed" by simply subtracting some average background value from the data. However, it should be kept in mind that the anomaly produced by the differencing operation is reduced in amplitude with respect to the original, and that the frequency characteristics are altered. The interpreter should consider the possible errors and uncertainty when using such techniques, particularly if the altered data is used for quantitative interpretation.

**Comparison of Phasor Diagrams.** For this model, in which the geologic noise has induction numbers which are much smaller than the target, the increasing dominance of the target response at low frequencies is quite apparent. On most of the diagrams, the total response at low frequencies can be approximated by taking the sum of the individual responses. The horizontal coplanar response at station 00 (Figure 33) shows negligible influence of the overburden on the total measured inphase and quadrature at the two lowest frequencies. With increasing frequency, the total response shows a clockwise rotation; the effect on interpretation would be similar to that noted by Lowrie & West (1965), in that the target appears to be deeper and
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 33. Model 2, horizontal coplanar response at station 00.
more highly conductive when overburden is present. As the overburden influence increases, the total response folds back upon itself to form a "loop" shape. Inasmuch as the negative maximum anomaly of the target is easily discerned in the profiles, and by itself provides sufficient information for interpretation of conductance values, little additional information is gained by analysis of the shoulders of the horizontal coplanar anomaly. This does not mean that there is no useful information at all contained in the anomaly shoulders; only that, for this particular model, shoulder analysis would only provide confirmation of conductance values obtained using the maximum negative anomaly. For a different model, poor quality data, or widely-spaced observation points, the situation might be different.

The maximum positive anomaly of the perpendicular configuration (Figure 34) also shows negligible overburden influence at low frequencies. The inphase component of the total response for this configuration matches the target response more closely than does the horizontal coplanar configuration. Similar behavior is seen in the vertical coplanar response (Figure 35) and vertical coaxial response (Figure 36).
FIGURE 34. Model 2. maximum positive anomaly for perpendicular coils.
FIGURE 35. Model 2, vertical coplanar response at station 00.
FIGURE 36. Model 2, vertical coaxial response at left anomaly shoulder.
Frequency-Differenced Phasor Diagrams. Figures 37 and 38 show the effect of frequency differencing on the horizontal coplanar and perpendicular phasor diagrams. The overburden contribution to the total response is noticeably reduced at low frequencies, especially for perpendicular coils. Both configurations show negligible effect of the overburden at the three lowest frequencies, compared with negligible effect at only the two lowest frequencies for the "raw" data. The "loop" shape seen in the original horizontal coplanar data (Figure 33) is also removed.

Interpretation of Apparent Conductance. Results for this model are similar to those for model 1, with significant improvement in most cases. The horizontal coplanar configuration (Fig 39) shows negligible influence of the overburden on estimated conductance values at low frequencies. The apparent overburden conductance, as in model 1, is much higher than the true value of approximately 2 Siemens. The lowest frequency is discarded for the overburden response, as the inphase and quadrature values are so small that measurement error has a large effect on their ratio. Conductance estimates for the perpendicular configuration (Figure 40), vertical coplanar (Figure 41) and vertical coaxial configurations (Figure 42) show a greater
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 37. Model 2, frequency-differenced response, horizontal coplanar coils at station 00.
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 38. Model 2, frequency-differenced response, perpendicular coils, positive maximum.
Target response = diamond
Overburden response = circle
Total response = square

FIGURE 39. Model 2, interpreted conductance: horizontal coplanar coils at station 00.
FIGURE 40. Model 2, interpreted conductance: perpendicular coils, maximum positive anomaly.
FIGURE 41. Model 2, interpreted conductance: vertical coplanar coils at station 00.
FIGURE 42. Model 2, interpreted conductance: vertical coaxial coils, left anomaly shoulder.
degree of overburden influence than the horizontal coplanar. However, it is worthwhile to note that the perpendicular and vertical coaxial configurations yield conductance estimates which are smaller than the true target values, while the horizontal coplanar and vertical coplanar estimates are larger than the true value. It might therefore be desirable to choose a coil configuration in which error is "on the side of caution".

Overall, the relative sensitivity to the target and overburden is compatible with field examples described by Betz (1977).

Figure 43 shows estimates of conductance using the frequency differenced data for horizontal coplanar coils. The convergence of the total response and target response is noticeably improved over the middle frequencies. The overburden response shows increasing error at low frequencies; this is due to the inherent error in the extremely small magnitude of the differenced inphase and quadrature values.

In summary, results for this model illustrate the success of simple interpretational schemes (under favorable conditions) in reducing the influence of noise contributed by moderately conductive overburden. Enhancement by the overburden of the high-frequency quadrature response of the
FIGURE 43. Model 2, interpreted conductance: horizontal coplanar coils, frequency-differenced data.
target actually improves detectability of the target for this particular model. The success which can be achieved through simple means relies upon good field procedure, particularly careful surveying of profile grids to minimize operational noise. The measuring system used in this study represents such a case, since many of the conditions which create operational noise in the field (uneven terrain, improper coil alignment, etc.) are either not an issue or can be largely eliminated in laboratory measurements.
Model 3: Deep Target, Shallow Noise Source

This model simulates a relatively deep, wide, high-conductance target whose response is obscured by that of a shallow, confined body with a much smaller conductance. Figure 20 shows the geometry of the model components, physical parameters are listed in Table 1. The vertical coplanar response is not included in the results for this model.

Comparison of Profiles. Figures A.39 through A.47 show the target response, noise body response, and total response for this model. The total response for all three coil configurations (Figures A.41, A.44, and A.47) clearly shows the dominance of the target at low frequencies for both the inphase and quadrature components. At the lowest frequency, the inphase contribution of the noise body is nearly zero and the total inphase is a near-perfect match of the target response alone. As frequency increases, the inphase response of the noise body alters the anomaly shape; however the presence of the target continues to have a noticeable effect on the profiles over the full frequency range. The quadrature component of the noise response has a greater influence on the total response. At high frequencies, the noise body exerts a strong influence on both the total
inphase and quadrature response; however, the high-frequency quadrature enhancement seen in the horizontal coplanar and perpendicular target response (Figure A.39 and A.42) is still obvious in the total response.

The asymmetric geometry of the target and noise with respect to the coil configuration results in a different shape at high frequencies for each shoulder of the horizontal coplanar and vertical coaxial total response. The right shoulder of the horizontal coplanar response is diminished and broadened with respect to the left, creating the illusion of a dipping conductor. The effect is reversed in the quadrature component of the vertical coaxial response (Figure A.47); the left shoulder being diminished with respect to the right shoulder.

In summary, the enhancement of the quadrature component of the target response at high frequencies is encouraging as an indicator of the presence of a deep source of current, particularly for horizontal coplanar and perpendicular coils. When interpreting field data, if one observes a significant change in the amplitude of the quadrature anomaly at high frequencies, accompanied by a broadening and smoothing of the anomaly shape, part of the effect might be attributed to phase rotation of the response of a deep conductor. Noting the almost negligible contribution of the
noise body to the inphase component at low frequencies, for this particular model it can be assumed that the inphase response at the lowest frequencies represents the inphase response of the deep target alone.

An optimum interpretation scheme for a field reconnaissance survey might proceed as follows: one should first examine the low frequency inphase response of all coil configurations for possible conductors. The behavior of the quadrature component at higher frequencies would then serve as a "red flag" to indicate a possible deep source. Finally, for those features with an accompanying "red flag", the inphase response at the lowest frequencies would be used as a first approximation of the true inphase response of a relatively deep, large target. This type of approach could be applied blindly, but would work best where there is some knowledge of host conductivity (and overburden if present) near the anomaly.

**Frequency-Differenced Profiles.** The character of this model, where the geologic noise is caused by a relatively small confined body, might lead one to expect that frequency differencing could significantly improve the appearance of the profiles when small-parameter conditions are met. Figures A.48, A.49, and A.50 show the result of frequency
differencing the total response of each configuration. The operation removes some of the "false dip" caused by the asymmetric geometry of the model. After differencing, the inphase contribution of the noise body is substantially reduced, most noticeably in the vertical coaxial response (Figure A.50); however the quadrature component shows little visual improvement. In particular, the high-frequency quadrature enhancement seen in the "raw" horizontal coplanar and perpendicular profiles is not present in the differenced data for these configurations (Figures A.48 and A.49).

Comparison of Phasor Diagrams. Figures 44 and 45 show the horizontal coplanar response at station 00 and the maximum positive response of the perpendicular configuration. The total response for both configurations converges with the target response as frequency decreases, the major effect of the noise body is seen in the quadrature component. The noise influence on interpretation here would be opposite of that seen in model 2; the target would appear to be shallower and less conductive rather than than deeper and more conductive.

The tendency of the total response to converge with the target response at low frequencies illustrates the equivalence of the low frequency range with the late-stage
FIGURE 44. Model 3, horizontal coplanar response at station 00.
FIGURE 45. Model 3, maximum positive anomaly for perpendicular coils.
response of transient methods, wherein the body with highest conductivity tends to dominate regardless of its location (Kaufman & Keller, 1985).

Comparison of Anomaly Shoulders. Due to the symmetry of the individual anomalies, the shoulder responses of the target alone or the noise body alone are identical for the horizontal coplanar and vertical coaxial anomalies. As a result of the geometry of this particular model, the left shoulder of the total anomaly nearly coincides with the left shoulder of the noise anomaly and is relatively far from the target, while the right shoulder of the total anomaly nearly coincides with the shoulder of the target anomaly and is relatively far from the noise body. Figures 46 and 47 show the horizontal coplanar response for the left and right shoulders respectively. The influence of the target is clearly greater in the right shoulder than in the left, inasmuch as the total response more closely follows the target response at all frequencies in the right shoulder. This behavior is not as pronounced for the vertical coaxial configuration, the total response being only slightly shifted towards the target response between the left (Figure 48) and right shoulder (Figure 49).
Target response = diamond
Noise response = circle
Total response = square

FIGURE 46. Model 3, horizontal coplanar response at left anomaly shoulder.
FIGURE 47. Model 3, horizontal coplanar response at right anomaly shoulder.

Target response = diamond
Noise response = circle
Total response = square
Target response = diamond  
Noise response = circle  
Total response = square

FIGURE 48. Model 3, vertical coaxial response at left anomaly shoulder.
Target response = diamond
Noise response = circle
Total response = square

FIGURE 49. Model 3, vertical coaxial response at right anomaly shoulder.
Interpretation of Apparent Conductance. The interpretive curve used to calculate conductance for this model was generated using program "SHEETT" in the same manner as for the target of the previous models. Figure 50 shows apparent conductance values for horizontal coplanar coils at station 00. The target response converges to about 4000 Siemens at low frequencies, this is considerably less than the true value of 7350 Siemens. This might be due to the fact that the "SHEETT" program assumes a vanishingly thin plate, while the actual target has substantial thickness. The noise body response comes much closer to the true value of 193 Siemens. Excellent convergence of the total response with the target response is seen at low frequencies, similar behavior is seen for the maximum positive anomaly of the perpendicular configuration (Figure 51). The increase of apparent conductance of the noise body at the two lowest frequencies is probably due to error in measuring the extremely small magnitudes of the inphase and quadrature components. Figure 52 shows the anomaly shoulder response for horizontal coplanar coils. The right shoulder is slightly closer to the target value at low frequencies. In the vertical coaxial results (Figure 53), the target conductance at low frequency is very close to the average of the shoulder values.
FIGURE 50. Model 3, interpreted conductance: horizontal coplanar coils at station 00.
FIGURE 51. Model 3, interpreted conductance: perpendicular coils, maximum positive anomaly.
FIGURE 52. Model 3, interpreted conductance: horizontal coplanar coils at anomaly shoulders.
FIGURE 53. Model 3, interpreted conductance: vertical coaxial coils at anomaly shoulders.
CONCLUSIONS

In summary, the following conclusions are drawn from the analysis of the model results:

1) For model 1, the distortion of anomaly shape due to the overburden edge can so obscure the target response that there seems little chance of confidently identifying a target from examination of field profile shapes for scaled frequencies such as those used in this study.

2) This situation, as expected, can be improved to a certain degree by application of noise-reduction techniques as described by Betz, Bosschart, and others, and presented in theoretical detail by Kaufman & Keller (1985).

3) These techniques become ineffective when the conductivity contrast between noise and target is small, again an expected result. Additionally, full implementation of noise reduction techniques requires that measurements be made in or near the small-parameter region of the spectrum. When this condition is not satisfied, most techniques (and the theories upon which they are based) begin to break down.

4) In situations represented by model 1 and model 3, advantage can be taken of the fact that the coil array is some distance away from the overburden (or noise body) when one of the anomaly shoulders is measured. Although there is still a fairly high-amplitude contribution to the shoulder
from the geologic noise, the relative sensitivity to the target versus the noise is greater than for measurements made closer to the noise source. In this event, more complete information is obtained by examining the edges of the anomaly in addition to the maximum anomaly.

5) Results from all three of the models emphasize the desirability of performing measurements with different coil configurations. In particular, the commonly-used horizontal coplanar configuration was in several cases "outperformed" by the perpendicular configuration in terms of reproducing the response of the target in phasor diagrams and estimating target conductance. The best use of the vertical coplanar and vertical coaxial configurations seems to be for an overburden edge, as the response of these configurations to the edge is smaller and much smoother than that of the others tested in this study. Obviously, the more quantities one can measure which respond in a different way to the geologic model in question, the more meaningful the analysis which can be made.

6) The change in sign of the high-frequency quadrature response of the targets shows strongly in the total response, being considerably amplified when the geologic noise is a continuous layer as in model 2. Although the effect is obscured in model 1, it can serve as an indicator
of deeper sources of current if it is attributable to phase rotation by overlying host or overburden. This clearly shows the desirability of performing measurements over a broad range of frequencies, rather than restricting attention to a single, limited range of the spectrum.

7) Finally, for the models investigated, there appears to be little difficulty in making a fairly accurate estimate of the apparent target conductance in the presence of geologic noise, even when the target response appears to be completely lost in the profiles. These results are highly promising, since the existence of computer programs such as SHEET allows generation of a variety of interpretive curves for a wide range of host and target conductivities. Selection of the proper curve for interpretation would require knowledge of host and overburden conditions near the anomaly, the necessary data being provided by extending survey lines beyond the anomaly to a distance equal to two or three coil spacings. Combinations of existing inversion routines for layered-earth soundings and stored sets of interpretive curves could form the basis for an interactive computer interpretation program. Noting the recent interest in applications of computer "expert systems" to geophysics, endeavors along this line would certainly be worthwhile.
Recommendations

Obviously, the interpretive analysis in this study is quite limited considering the number of possible approaches. The discussion of the profile data is from the viewpoint of the geophysicist performing a "first pass" reconnaissance survey, where the primary need is to quickly identify the presence of a target by visual inspection of field data. A detailed examination of subtle alterations of profile shape was not attempted. Further analysis of such features might yield additional information for quantifying the influence of geologic noise and enhancing target visibility in the profiles. One potentially useful investigation would be to combine the horizontal coplanar and perpendicular responses to compute wavetilt and ellipticity values (Smith and Ward, 1974). Further scale-model investigations might test coil configurations not investigated in this study, such as the various "broadside" types or the "null" vertical configuration. The influence of galvanic currents between the host, noise, and target could be analysed by performing measurements with and without insulating covers on the model components. Results of such investigations would certainly enhance the ability of electrical geophysical methods to estimate geologic cross-sections along profiles or, eventually, in three dimensions.
REFERENCES


Betz, J. E., 1975, Test program report with additional comments on the MAXMIN II electromagnetic system of Apex Parametrics Ltd.: memo, Toronto.

1976, Considerations behind the making of a well rounded electromagnetic exploration system: memo, Toronto.

1977, Poster presentation: Prospectors and Developers Association Convention, Toronto.


1974, The TRIDEM three frequency airborne electromagnetic system:  
Canadian Mining Journal, April, 1974, p. 68-69.

Brock, J. S., 1973, Geophysical exploration leading to the discovery of the Faro deposit:  

Caven, R. J., 1976, Geophysical surveying at the Umex Thierry deposit: Canadian Mining Journal, October, 1976, p. 34-42.


Nair, M.R., Biswas, S.K., & Mazumdar, K., 1968,
Experimental studies in the electromagnetic response of tilted conducting half-planes to a horizontal-loop prospecting system: Geoexploration, Vol. 6, p. 207-244.


Palacky, G.J., Ritsema, I.L, De Jong, S.J., 1981,


FIGURE A.1. Legend for "raw" data profiles.
FIGURE A.2. Legend for frequency-differenced profiles.
FIGURE A.4. Model 1, overburden response, horizontal coplanar coils.
FIGURE A.5. Model 1, total response, horizontal coplanar coils.
FIGURE A.7. Model 1, overburden response, perpendicular coils.
FIGURE A.8. Model 1, total response, perpendicular coils.
FIGURE A.10. Model 1, overburden response, vertical coplanar coils.
FIGURE A.11. Model 1, total response, vertical coplanar coils.
FIGURE A.13. Model 1, overburden response, vertical coaxial coils.
FIGURE A.14. Model 1, total response, vertical coaxial coils.
FIGURE A.15. Models 1 and 2, frequency-differenced target response, horizontal coplanar coils.
FIGURE A.16. Model 1, frequency-differenced overburden response, horizontal coplanar coils.
FIGURE A.17. Model 1, frequency-differenced total response, horizontal coplanar coils.
FIGURE A.19. Model 1, frequency-differenced overburden response, perpendicular coils.
FIGURE A.20. Model 1, frequency-differenced total response, perpendicular coils.
FIGURE A.22. Model 1, frequency-differenced overburden response, vertical coplanar coils.
FIGURE A.23. Model 1, frequency-differenced total response, vertical coplanar coils.
FIGURE A.24. Models 1 and 2, frequency-differenced target response, vertical coaxial coils.
FIGURE A.25. Model 1, frequency-differenced overburden response, vertical coaxial coils.
FIGURE A.26. Model 1, frequency-differenced total response, vertical coaxial coils.
FIGURE A.27. Model 2, overburden response, horizontal coplanar coils.
FIGURE A.28. Model 2, total response, horizontal coplanar coils.
FIGURE A.29. Model 2, overburden response, perpendicular coils.
FIGURE A.30. Model 2, total response, perpendicular coils.
FIGURE A.31. Model 2, overburden response, vertical coplanar coils.
FIGURE A.32. Model 2, total response, vertical coplanar coils.
FIGURE A.33. Model 2, overburden response, vertical coaxial coils.
FIGURE A.34. Model 2, total response, vertical coaxial coils.
FIGURE A.35. Model 2, frequency-differenced total response, horizontal coplanar coils.
FIGURE A.36. Model 2, frequency-differenced total response, perpendicular coils.
FIGURE A.37. Model 2, frequency-differenced total response, vertical coplanar coils.
FIGURE A.38. Model 2, frequency-differenced total response, vertical coaxial coils.
FIGURE A.40. Model 3, noise body response, horizontal coplanar coils.
FIGURE A.41. Model 3, total response, horizontal coplanar coils.
FIGURE A.42. Model 3, target response, perpendicular coils.
FIGURE A.43. Model 3, noise body response, perpendicular coils.
FIGURE A.44. Model 3, total response, perpendicular coils.
FIGURE A.45. Model 3, target response, vertical coaxial coils.
FIGURE A.46. Model 3, noise body response, vertical coaxial coils.
FIGURE A.47. Model 3, total response, vertical coaxial coils.
FIGURE A.48. Model 3, frequency-differenced total response, horizontal coplanar coils.
FIGURE A.49. Model 3, frequency-differenced total response, perpendicular coils.
FIGURE A.50. Model 3, frequency-differenced total response, vertical coaxial coils.