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A Three Component
Drillhole EM
Receiver Probe

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A THREE COMPONENT
DRILLHOLE EM
RECEIVER PROBE

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Abstract

Most downhole EM receiver probes currently in use measure only the component of the magnetic field vector parallel to the borehole. This is mainly due to the difficulties of fitting coils of sufficient sensitivity and bandwidth sideways within a probe. While the so-called axial component data is very useful, it does not allow direct determination of the direction to the conductor from the drillhole, an important parameter. An EM probe which measures the transverse components of the magnetic field as well as the axial component would, however, give an indication of the direction to the conductor, provided that the orientation of the probe can be determined. The object of this thesis project was to develop such a probe.

The difficulties inherent in the design of a transverse sensor were overcome by using an assemblage of ferrite slabs as a magnetic flux collector. The collector serves to funnel the magnetic flux from a wide area through the coil at its center, greatly increasing the coil's effective area. The sensors developed in this research are only 30 cm long, yet have an effective area of 63 m². The axial sensor is also somewhat unusual in that it uses larger blocks of ferrite at its ends to act as flux collectors. These greatly increase the sensitivity over what a single narrow rod the same length would have. The axial sensor is about 21 cm long but has an effective area of 250 m² and a bandwidth around 10 kHz. All three sensors plus batteries and electronics were fitted into a probe 41 mm in diameter and about 2 m long.

The probe was tested at the Gertrude West test site near Sudbury Ont. After processing of the data to correct for the rotation of the probe as it was lowered down the drillhole, profiles showing the vertical, the east and the north components of the field were produced. These showed that a conductive body dipping towards the north passed just south of the drillholes tested, an interpretation in agreement with the geology as known from previous drilling. Whereas the data from a single-component probe would only give an idea of the distance, size, shape etc. of the conductor, that of the three-component probe was able to give a good estimate of the direction to the conductor as well.
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I would like to thank Dr. A.V. Dyck and others at the Geological Survey of Canada for their assistance in the final field testing of the probe. It was through Dr. Dyck that I became interested in drillhole EM work, and indeed it was he who suggested the topic for this thesis. I also wish to thank Mr. Krause and others at the exploration division of INCO Limited for allowing access to the Gertrude West property for the field test.

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Chapter 1

Introduction

Geophysical prospecting methods are becoming increasingly important in the search for mineral resources. Many of the older mining camps occur in regions where there is little overburden and were found by traditional prospecting methods. As these areas are exploited the search must turn to regions with heavier overburden and few outcrops, where prospecting by geology alone is difficult or impossible. In such regions, various geophysical methods have become indispensable in the locating of areas of particular interest and in their subsequent study. This growing need, plus the advances in computers and electronics in the past two decades have resulted in great innovations in geophysical instrumentation and data interpretation.

One of the branches of applied geophysics to experience the greatest advances in the past years is electromagnetic (EM) prospecting, wherein the interaction of natural or manmade EM waves with underground structures of varying conductivity is used to map those structures. EM prospecting is itself a broad subject, ranging from the detection of horizontal strata in sedimentary basins to the mapping of steeply dipping conductors and contacts in areas of heavy overburden. Of interest here is its use in the detection and study of conductive orebodies (or sometimes conductive zones associated with orebodies) occurring within a more resistive country rock. Typically, a large wire loop carrying a time-varying current (the transmitter) is used to create the primary magnetic field. Where this time-varying field intersects conductive bodies, eddy currents are induced which in turn produce secondary magnetic fields which are then detected by receiver sensors (usually coils). The vari-
ation of this secondary field with the position of the receiver is used, along with available geologic data, to estimate the location, size and shape of the conductive body. The advances in EM prospecting technology in recent years have included the replacement of simple frequency-domain systems with wide-band time-domain systems, better noise rejection techniques, much higher power transmitters, digital data recording and processing, and multi-component receivers. These developments all increase the amount of information available to the user, making interpretation potentially more detailed and accurate, though perhaps more involved.

An additional development has been the gradual increase in the use of EM sensors designed to be lowered down exploration drillholes to measure the magnetic field beneath the surface of the earth. The measurement of the fields at the surface (or from the air), though more than adequate for reconnaissance surveys, still gives only a limited idea of the nature of deeper conductors. The fields from deep targets are often obscured by the effects of conductors near the EM system such as a layer of moderately conductive overburden, widespread background conductivity of the host rock, or other conductors nearer to the surface. There are also difficulties with the inversion of a limited set of field data to give a unique conductivity structure for the ground, due in part to the complex interaction of multiple conductors and the fundamental limitations of using data taken on one two-dimensional plane to describe a three-dimensional environment. Some of these problems can be overcome to a certain extent if the target has already been drilled and EM measurements can be made along the drillholes. Such measurements should allow better interpretation since they are conducted nearer to the target and further away from the effects of overburden, and, in a sense, give a different view of the target.

The idea that drillhole EM data has the potential to improve the accuracy
of interpretation is supported by a study by Oristaglio and Worthington (1980) involving a 2D numerical inversion routine using the finite element method. They found in a test on synthetic data that the inversion routine modelled their original cross section much more accurately when provided with data such as would be recorded along a drillhole in addition to surface data. Such inversion routines are not yet practical for a 3D earth, but there is little doubt that drillhole EM data should increase the resolving power of other interpretation methods as well.

Naturally, borehole EM work presupposes the existence of drillholes in the area of interest, and thus it can not be used for initial reconnaissance work. Situations where it could be used include the studying of new prospects where only one or two holes have been drilled which may or may not have intersected the body of interest, and in established mining areas where the search is on for deeper, more elusive orebodies that may have been missed by earlier searches. In either situation, the searchers will have clues or at least hopes that an economically exploitable orebody is 'down there', based on the results of surface surveys or small ore pockets found in the drillholes as well as geological intuition. The alternative to using borehole EM work would probably be to drill more boreholes, a procedure vastly more expensive than an EM survey, and which may or may not give fruitful results.

Borehole EM methods appear to be gaining acceptance in the geophysical community, as evidenced by the number of commercial EM systems incorporating borehole probes. Two such systems are described in papers by Hohmann et al. (1978) and Boyd and Wiles (1984). Another is the Crone PEM system used to test the probe built for this thesis (Dyck, 1981, Ogilvy, 1983). Similar equipment is also available for Geonics EM37, SIROTEM and UTEM time domain EM systems, and probably many others. Less work has been published dealing solely with the in-
interpretation of borehole EM data, and how this may differ from the interpretation of surface EM data. A major work dealing primarily with the interpretation of borehole EM data is that of Dyck (1981, summarized in 1984).

Figure 1.1 shows schematically a typical downhole EM system. A large, fixed
transmitter loop 200 to 1000 m across is used. The transmitter loops are usually rectangular to facilitate layout, and are sized according to the depth of the drillhole or expected targets. The loop may be centered around the drillhole, but often it is offset somewhat to increase the coupling with possible targets. Sometimes more than one transmitter loop is used in the survey in order to vary the coupling with any conductors; this aids in the locating of targets. As well, the survey can be performed along more than one drillhole, and thus further increase the amount of information available for interpretation.

Most EM sensors designed to work down boreholes measure only that vector component of the magnetic field along the axis of the drillhole probe (hereafter called the axial field). Surveys using such sensors, while very useful for estimating the approximate depth, size, shape and radial distance of conductors, are less helpful in judging the direction to the conductor from the borehole (a rather important parameter). While data taken using more than one transmitter loop can sometimes give clues to the direction to the target, often the indications of direction are minor and ambiguous (see the data in chapter 6, for example). A solution to this problem is to develop a borehole EM sensor which measures the magnetic field at right angles to the probe (the transverse field) as well as the axial field. Provided that the orientation of the probe is known, transverse-field data can usually give the direction to the conductor, as well as aid in the determination of other parameters such as conductor size and shape.

Limited use has been made of multi-component EM receivers, even in surface work. This is probably due not only to the greater expense and complexity of multi-component equipment, but also to the greater time and trouble involved in recording and interpreting a much increased quantity of manually recorded data.
The problem is lessened, however, with the advent of computerized data recording and processing. The difficulties facing the development of three-component borehole probes are much more serious. Sensor coils for boreholes are typically elongated in the direction of the field that they detect, and there are severe technical difficulties involved in fitting sensors of sufficient sensitivity and bandwidth transversely within the small diameter of the borehole probe casing. In addition, there is the problem of determining what direction the probe is facing as it is lowered down the drillhole. Without some means of determining the orientation of the probe, all that can be determined from the transverse sensors is the total horizontal field, which will provide some helpful information but not the direction to the target body (which was the main reason for adding the transverse sensors).

Due to the technical difficulties, little work seems to have been done on developing three-component borehole EM probes. Worthington et al. (1981) describe a two-component probe (two transverse sensors, no axial sensor) which used mumetal frames to draw magnetic flux from a wide area through coils in the center. Their sensor was used with a simple frequency-domain EM system and with the transmitter loop centered about the drillhole, the theory being that in the absence of lateral variation in conductivity, the transverse sensors should have zero output. The probe apparently had no means of orientation, so only the total horizontal field was recorded. No axial sensor was provided, since the axial field would be dominated by the primary field. Such considerations are meaningless for time-domain systems, where time separation is used to record the secondary field in the absence of the primary field.

This thesis describes the development and subsequent testing of a wide-band three-component borehole EM receiver probe suitable for use with time-domain EM
systems. The problems involved in designing a transverse sensor were overcome by using an assemblage of ferrite slabs to collect and channel magnetic flux through a small coil. An attempt was made, with some success, to use the primary EM field as measured through the two transverse sensors to estimate the probe's orientation. Other methods of orientation, such as using the earth's steady magnetic field, gravity devices or gyroscopic devices, all have their shortcomings, and would greatly increase the complexity of the probe (Dyck, 1981).

Chapter 2 describes the theory and complications involved in the design of EM sensor coils. In chapter 3, more practical aspects of sensor design are discussed, along with details of the sensors built for this project. Chapter 4 describes field tests conducted to verify that the probe functioned as designed and that it could indeed be useful in pinpointing conductive targets. The various computer programs necessary to turn the recorded field data into useable profiles are described in chapter 5. Chapter 6 deals with the interpretation of the field data. Finally, chapter 7 concludes the thesis with a discussion of what has been accomplished in this project, and what remains to be done in the future.
Chapter 2

Sensor Theory

Electromagnetic prospecting systems usually measure the magnetic field by measuring the emf induced in a coil. Coils function according to the Faraday induction law which relates the line integral of the electric field around a closed loop to the magnetic flux linking that loop as follows;

\[ \oint \mathbf{E} \cdot d\mathbf{l} = -\frac{d\phi}{dt}, \]

where \( \phi \) is the flux. For a single turn conductive loop, this can be rewritten as

\[ V = -\frac{d}{dt} \int \mathbf{B} \cdot d\mathbf{a}, \quad (2.1) \]

where \( V \) is the total voltage induced around the loop and \( \mathbf{B} \) is the magnetic flux density. For air-cored receiver coils, \( \mathbf{B} = \mu_0 \mathbf{H}_o \) (\( \mu_0 \) is the permeability of free space and \( \mathbf{H}_o \) is the ambient magnetic field). Assuming \( \mathbf{H}_o \) to be spatially constant across the coil, the voltage output will be

\[ V_o = -\mu_0 n A \frac{dH_o}{dt}, \]

where \( n \) is the number of turns in the coil, \( A \) is its cross sectional area, and \( H_o \) is the magnitude of the vector component of \( \mathbf{H}_o \) parallel to the coil axis. By transforming this equation to the complex frequency (Laplace Transform) domain, we can immediately write down the sensitivity of an air-cored coil as

\[ S_o = \frac{\tilde{V}_o}{\tilde{H}_o} = -\mu_0 n A s, \quad (2.2) \]
where \( s = j\omega + \sigma \) is the complex frequency.

Although air-cored receiver coils are used in some types of EM work, they must be large to achieve sufficient sensitivity and are thus not suitable for borehole receiver probes. The usual method of increasing sensitivity while maintaining reasonable sensor size is to insert a core of some highly permeable magnetic material. The net effect of the core is to increase the magnetic flux linking the coil and thus the output voltage. Suitable core materials are classed as ferromagnetic, and have their magnetic structure subdivided into domains in which all of the atomic or molecular magnetic moments are aligned. The moments of the various domains within a piece of magnetic material are normally randomly oriented, so that there is no net magnetic moment. However, in the presence of an ambient magnetic field \( H_0 \), the domains with moments approximately parallel with the ambient field will grow at the expense of domains with moments pointing in other directions. This results in a net magnetic moment per unit volume, \( M \), which will contribute to the flux density within the material according to the relation

\[
B = \mu_0 (H + M). \tag{2.3}
\]

If the ambient field is not too strong and the material is magnetically soft, \( M \) will be proportional to \( H \) and in the same direction, so that

\[
M = \kappa H, \tag{2.4}
\]

where \( \kappa \) is the magnetic susceptibility. Furthermore, equations 2.3 and 2.4 can be combined to give

\[
B = \mu_0 (1 + \kappa) H = \mu_0 \mu_r H, \tag{2.5}
\]

where \( \mu_r \) is the relative permeability. An additional complication is that the \( H \) of equations 2.3 to 2.5 is not the ambient field but is rather the internal field of the
core, i.e., the sum of the ambient field with the internal demagnetization field;

\[ H = H_0 + H_d. \]  \hspace{1cm} (2.6)

The demagnetization field represents the reduction of the magnetic field within a body due to magnetization and is given by

\[ H_d = -NM, \]  \hspace{1cm} (2.7)

where \( N \) is the demagnetization factor. In certain specific geometries (ellipsoids and infinite plates and rods in a uniform field), \( N \) is a constant whose magnitude depends on the shape of the magnetic body and on the direction of the ambient field. \( N \) varies from 0 for infinite cylinders magnetized along their length to 1 for infinite plates magnetized transversely. Combining equations 2.6, 2.7 and 2.4, we find

\[ H = \frac{1}{1 + N\kappa}H_0 \]

and

\[ M = \frac{\kappa}{1 + N\kappa}H_0 \]

and finally

\[ B = \mu_0 \left( \frac{1 + \kappa}{1 + N\kappa} \right)H_0 = \mu_0 \mu_{app} H_0, \]  \hspace{1cm} (2.8)

where

\[ \mu_{app} = \frac{1 + \kappa}{1 + N\kappa} \]  \hspace{1cm} (2.9)

is the apparent (relative) permeability. Thus we can rewrite equation 2.2 to give the sensitivity of a coil with a core of magnetic material of apparent permeability \( \mu_{app} \);

\[ S_c = -\mu_0 \mu_{app} nA \]

or

\[ S_c = -\mu_0 A_{eff} s, \]  \hspace{1cm} (2.10)

where \( A_{eff} = \mu_{app} nA \) is the effective area of the sensor. The term effective area reflects one way of understanding the overall effect of a magnetic core; that is, to
consider it as a means of focussing the magnetic flux lines through the coil. The flux which in the absence of magnetic material would flow across a wide area is instead channelled through the core and thus the coil. \( \mu_{\text{app}} \) is the ratio of that area to the core cross section \( A \). \( A_{\text{eff}} \), then, is the area of a single-turn wire loop in freespace which would have sensitivity equal to the cored coil.

In order to find the sensitivity \( S_o \), we still must know \( N \). For ellipsoidal bodies it is possible to find \( N \) analytically (Maxwell, 1881). The formula for \( N \) for prolate (elongated) ellipsoids magnetized along their long axis is

\[
N = \frac{1}{m^2 - 1} \left( \frac{m}{\sqrt{m^2 - 1}} \ln(m + \sqrt{m^2 - 1}) - 1 \right),
\]

where \( m \) is the ratio of the long axis of the ellipsoid to the short axis. Using equations 2.9 and 2.11, figure 2.1 was plotted showing the relation of \( \mu_{\text{app}} \) to \( m \) for ellipsoids of various \( \mu_r \).

It is unlikely, though, that ellipsoidal cores would ever be used in coils; most often cylindrical cores are used. It is not possible to find \( N \) for cylinders by the same analytical means as for ellipsoids. In fact \( N \) varies with position within the cylinder as well with the permeability of the material, whereas \( N \) is constant for an ellipsoid of a given shape. Empirical relations for \( N \) in cylinders have been found, however. For example, Warmuth (1954) gives the relation for \( N \) at the center of a cylinder magnetized along its length as

\[
N = N_0 \frac{2.26 \ln(1 + 0.156m) + 1}{2.15 \ln(1 + 0.326m) + 1},
\]

where \( m \) is the ratio of length to diameter and \( N_0 \) is the demagnetization factor of an ellipsoid of equal length to diameter ratio. Using equations 2.12, 2.11, and 2.9 one can estimate \( \mu_{\text{app}} \) at the center of a cylinder and from there use equation 2.10
Chapter 2: Sensor Theory

Figure 2.1: Apparent permeability of prolate ellipsoidal magnetic bodies as a function of the ratio of major axis length to minor axis length, for various material permeabilities.

to estimate the sensitivity of a cylinder cored coil. It turns out that $\mu_{app}$ is greater for cylinders than for ellipsoids of equivalent length/diameter, as one might expect from the greater amount of material present at the ends of a cylinder. Although the $\mu_{app}$ calculated using these equations is valid only at the center of the cylinders, it can still be used to calculate the sensitivity with reasonable accuracy as long as the coil is short and is centred on the cylinder. For coils distributed over much of the length of the cylinder a correction factor of between 0.7 to 1 must be applied to the sensitivity to account for the decrease in flux density toward the end of the cylinder.

There exist in the literature (e.g., Snelling, 1969, DeMaw, 1981) plots of $\mu_{app}$
of cylinders as a function of \( m \), based on empirical data, and these are quite similar to figure 2.1. Plots such as these are useful in selecting the proper core size and permeability to be used for a sensor. Naturally, since \( \mu_{\text{app}} < \mu_r \), one might choose a material with as high a permeability as possible in order to maximize the sensitivity. However, the more permeable metals tend to be highly conductive, and if the conductivity of the core is too great, the band width of the sensor will be limited by eddy currents induced in the core. In order to reduce this effect, it is necessary to either settle on non-conductive materials of moderate permeability, such as ferrites, or use cores built up out of thin strips or wires of high permeability material such as mumetal.

It is evident from figure 2.1 that permeable cores can easily increase coil sensitivity by a factor of 100 or more, and this is of great benefit to the design of compact sensors. However, the use of permeable cores introduces some problems too. While the sensitivity of air-cored coils has little temperature dependence, improperly designed permeable-cored sensors can have rather large temperature coefficients; since permeability is a temperature-sensitive parameter. This can be important to EM systems which attempt to normalize the data with respect to receiver sensitivity and transmitter current. Also, in some frequency domain systems, the receiver sensors are tuned to resonate at a certain frequency. Since the resonant frequency is dependant on coil inductance which in turn varies as \( \mu_{\text{app}} \), such systems can be extremely temperature dependent.

The largest relative variations of sensitivity with temperature will occur in coils with magnetically long cores, that is, cores with length to diameter ratio \( m \) large enough such that \( \mu_{\text{app}} \approx \mu_r \). Such cores would be found near the lower right part of figure 2.1. Obviously a 10% change in the cores permeability over a range
of temperature (not an unreasonable variation) would result in a 10% change in the sensitivity. On the other hand, cores with moderate \( m \) and high \( \mu_r \) have a much lower temperature coefficient. For example, \( \mu_{app} \) of a core with \( m = 12 \) and \( \mu_r = 1000 \) will change less than 1% with a 10% change in \( \mu_r \).

As well as increasing the temperature coefficient of the coil, a permeable core can introduce other possible problems. The core can be a source of noise independent of the electronic noise of the sensor amplifier. The magnetization noise relates to the effect of thermal agitation on domain boundaries and the stop-and-go movement of domain boundaries as they meet and overcome crystal lattice defects. Also slight nonlinearity in the relation between \( B \) and \( H_c \) can lead to signal distortion and slight variations in sensitivity as the earth’s static magnetic field biases the core. These effects are usually minor, however, and are thus neglected.

We saw earlier an estimate of the sensitivity of a coil (equation 2.10) based only on Faraday’s law and the effective area of the coil. Real coils have winding resistance, inductance and capacitance which alter the signal seen at the amplifier input from that given by equation 2.10. Figure 2.2 shows a circuit of discrete components and a signal source intended to approximate the properties of a sensor coil. The signal source, \( R_w \), \( L \), and \( C \) replace the infinite network of small signal sources, \( R \)’s, \( L \)’s, and \( C \)’s of the coil. \( C \) also includes the input capacitance of the amplifier. \( R_d \), a damping resistor, is often necessary to reduce the enormous amplification at the resonant frequency which would otherwise saturate the amplifier and lead to ringing in the time domain. The diagram shows one end of the coil tied to ground as was done for the sensors constructed for this project; it is also possible to place the coil across a differential amplifier and tie the center of the coil to ground. This offers certain advantages, including lower effective capacitance of the coil, but
Figure 2.2: Equivalent circuit diagram for a coil, showing signal source $V_o$, winding resistance $R_w$, inductance $L$, capacitance $C$, damping resistor $R_d$ and the preamplifier.

adds to circuit complexity.

By applying standard circuit analysis techniques, the network function of the equivalent circuit (i.e. the complex ratio of output signal to input signal) works out to be

$$T(s) = \frac{1}{LCs^2 + (CR_w + L/R_d)s + (1 + R_w/R_d)}.$$  \hspace{1cm} (2.13)

Since $R_w \ll R_d$, and $CR_w \ll L/R_d$, this simplifies to

$$T(s) \approx \frac{1}{LCs^2 + (L/R_d)s + 1}.$$  

In the frequency domain ($s = j\omega$),

$$T(\omega) = \frac{(\omega'_o)^2}{(\omega'^2 - \omega^2) + 2j\omega\alpha},$$  \hspace{1cm} (2.14)

where $\omega'_o = \frac{1}{\sqrt{LC}}$ is the undamped resonant frequency, $\omega_o = \omega'_o(1 + R_w/R_d)$ is the resonant frequency, and $\alpha = \frac{1}{2}\left(\frac{R_w}{L} + \frac{1}{CR_d}\right)$. This network function is that of a two-pole lowpass filter. Figure 2.3 shows its theoretical amplitude response with
Figure 2.3: Amplitude response curves for the transverse coils of the probe for various amounts of damping. These were calculated from measured parameters \((R_w, L, F_c)\) assuming the equivalent circuit. The curves are normalized with respect to initial coil sensitivity \(S_0\).

Various amounts of damping. Figure 2.4a shows the calculated step response of the circuit, also for various \(R_d\). The parameters used in calculating figures 2.3 and 2.4 correspond to those of the actual transverse coils of the EM probe.

Using equations 2.10 and 2.13 the overall sensor sensitivity can now be written as

\[
S(s) = S_0(s)T(s)G = -\mu_0\mu_\text{app} n A s T(s) G, \tag{2.15}
\]

where \(G\) is the gain of the amplifiers packaged with the sensor (as opposed to any additional variable gain in the receiver unit itself).

The impedance of the coil is an important parameter since it determines the
Figure 2.4a: Calculated step response of the transverse coils of the probe for various amounts of damping. Curves a, b, and c are underdamped, curve d is critically damped and curve e is overdamped. Curve c corresponds to the damping resistance actually used. These responses do not include the effect of the initial differentiation of the coil.

Figure 2.4b: Estimated time delay vs. frequency for the transverse coils for various amounts of damping. Curve c has the flattest response and corresponds to curve c above.
bandwidth of the sensor (along with the capacitance) and can be responsible for much of the noise. For coils with cylindrical cores, the impedance is given approximately by (Snelling, 1969)

\[ L = c\mu_0\mu_{app}\frac{n^2A}{l}, \]  

(2.16)

where \( l \) and \( A \) are the length and cross sectional area of the core, and \( c \) is a factor which depends on the ratio of coil length to core length; it is about 1 for fully wound cores and increases up to about 3 for short coils on long cores. As we saw earlier, the resonant frequency is given approximately by \( 1/\sqrt{LC} \), and the useful bandwidth of the sensor will be somewhat less than this, so it is obviously desirable to minimize \( L \). Equation 2.16 implies that as much of the gain as possible should be realized by increased \( \mu_{app} \) rather than by making the coil larger, and that long narrow cores are better in this regard.

The capacitance, \( C \), should likewise be minimized. However, it is a much more elusive quantity than the inductance. It depends not so much on coil size as on such factors as coil shape and winding technique. This capacitance includes not only the interwinding capacitance, but also the winding-to-core capacitance and the amplifier input capacitance. There are a number of tricks to reducing the capacitance, but these all relate to the principle that the total capacitance of several capacitors in series is a fraction of the individual capacitance. Thus the effective capacitance of the coil is reduced by keeping sections at significantly different potentials apart. Therefore tall and narrow coils are better than low and wide ones, several coils in series are better than one big coil, and layer wound coils are better than haphazard ones. With these tricks the capacitance can be reduced to a few tens of picofarads, and this level is necessary since the inductance is large and cannot be reduced much without sacrificing sensitivity. At such low capacitances, merely changing the model
of amplifier or rearranging the coil leads or sensor shielding can alter the resonant frequency significantly.

The winding resistance $R_w$ is a less important parameter than the inductance, though it does set the minimum source impedance of the coil at low frequencies. $R_w$ will vary approximately with the number of turns in the coil, $n$, or with $n^2$ if the wire diameter is sized to take full advantage of a given winding volume for any specified $n$.

The damping resistance $R_d$ is a parameter which can be adjusted to give the coil the best response. However, it is not obvious what criteria should be used in deciding which transfer response is best. Analysis of the frequency domain amplitude response of the coil (figure 2.3) shows that there will be a maximum sensitivity at frequency

$$\omega_m = \sqrt{\omega_0^2 - 2\alpha^2}$$

whenever $\alpha < \frac{1}{\sqrt{2}}\omega_0$. When $\alpha > \frac{1}{\sqrt{2}}\omega_0$ the maximum is at zero frequency. Thus the flattest amplitude response will occur when $\alpha = \frac{1}{\sqrt{2}}\omega_0$. Substituting for $\alpha$ and $\omega_0$ and solving for the damping resistance we find that

$$R_{d-f} \simeq \frac{1}{\sqrt{2}}\sqrt{L/C}$$

will give the flattest response for a coil of given $L$ and $C$. (This corresponds to curve c of figure 2.3.) This choice of damping may be appropriate for a frequency-domain EM system. Less damping should be used if minimum phase distortion is more important than a flat amplitude response, since the phase delay below resonant frequency increases with the amount of damping.

It is also possible to select $R_d$ based on the time domain step response (figure 2.4a). Solution of the differential equations of the equivalent circuit show that
the circuit will be critically damped when \( R_d \) is given approximately by

\[
R_{d-c} \approx \frac{1}{2} \sqrt{L/C}.
\]

When damping is less than critical (larger \( R_d \)), the step response will show an overshoot; however, this overshoot will be slight with damping still well below critical. Thus the best time domain response will be from a slightly underdamped circuit, with \( R_d \) selected to minimize the rise time while maintaining acceptable overshoot. This is in fact how the damping was selected for the coils designed for this project. Another way of comparing the time-domain performance of filters is to look at the time delay vs. frequency characteristics (figure 2.4b). The time delay is simply the phase response divided by frequency. Filters with maximally flat time delay curves have the least signal distortion. Curve c of figure 2.4b has the most constant time delay and corresponds to the best step response of figure 2.4a (also curve c).

One factor which should be considered when designing an EM sensor is noise. Although most EM systems use some type of filtering or stacking procedure to improve the signal-to-noise ratio, it is still necessary to reduce the sensor noise as much as possible; preferably to a level below that of the natural electromagnetic field noise. Since the various noise sources are uncorrelated, we can estimate the total noise spectrum of the sensor-preamp system by summing their squares;

\[
V_n^2(f) = G^2 \left\{ \left( A_{eff} 2\pi f B_n(f) \right)^2 + 4KT(R_p + \Re(Z_s(f))) 
+ i_n^2(f)\left( R_p^2 + |Z_s(f)|^2 \right) + e_n^2(f) \right\}.
\] (2.17)

The first term is due to the noise in the magnetic field, \( B_n(f) \), whether from natural sources such as distant thunderstorms (sferics) or manmade sources such as power
lines or VLF navigation stations. Since this noise is amplified just as the signal is, not much can be done about it at the sensor/preamp stage unless the coil is tuned to a certain frequency or the preamp has bandpass/reject characteristics built into it. However EM noise should not be forgotten, since it may set a limit on the amount of amplification of the sensor. Moreover, there is no point in trying to reduce electronic noise much beyond the levels of natural EM noise. This does not apply, of course, to magnetotelluric sensors for which the natural EM noise is the signal.

The second term of equation 2.17 is the thermal resistor or Johnson noise at temperature $T$ of the real part of the coil's source impedance

$$\Re(Z_s) = \frac{(\omega_o')^2 (R_w (\omega_o^2 - \omega^2) + 2\alpha \omega^2 L )}{(\omega_o^2 - \omega^2) + 4\omega^2 \alpha^2}$$

(2.18)

and the source resistance of the amplifier feedback network, $R_p$ (For the usual, non-inverting op-amp configuration using resistors $R_1$ and $R_2$, $R_p = \frac{R_1 R_2}{R_1 + R_2}$). The third term is the noise due to the amplifier input current noise $i_n$ interacting with the source impedances of the coil and the feedback network. The source impedance of the coil is given by

$$|Z_s|^2 = \Re^2(Z_s) + \Im^2(Z_s),$$

(2.19)

where

$$\Im(Z_s) = \frac{(\omega_o')^2 (\omega L (\omega_o^2 - \omega^2) - 2R_w \omega \alpha )}{(\omega_o^2 - \omega^2) + 4\omega^2 \alpha^2}. $$

(2.20)

The final term of equation 2.17 is the amplifier input voltage noise $e_n$.

It is useful to consider the EM sensor as having three stages of amplification. These include the amplification of the magnetic flux density by the permeable core (by $\mu_{app}$), amplification by the coil (by $-j\mu_o n A \omega$) and finally the actual electronic amplification ($G$). The overall gain (sensitivity) required of the sensor and preamplifier will be determined by the parameters of the EM system as a whole (e.g.
transmitter current, minimum transmitter-sensor separation, receiver gain etc.) but the three components of sensor gain can be adjusted according to other considerations such as the required sensor bandwidth, sensor dimensional limitations and noise. For example, a magnetotelluric sensor has little size restriction and a low bandwidth but requires high gain and very low electronic noise and therefore the sensor should be designed to maximize the gain by using a large core and coil and so minimize the necessary electronic amplification. On the other hand, the sensors built for this project were very dimensionally restricted and required high bandwidth and so it was necessary to achieve proportionately more of the amplification by electronic means.

As mentioned previously, as much of the gain as possible should be realized through increased $\mu_{\text{app}}$, given the size limitations of the sensor. This is because increasing $\mu_{\text{app}}$ contributes less to the coil inductance (which controls bandwidth and noise) than increasing coil size $n$ does. Once $\mu_{\text{app}}$ has been maximized in the available space, there is left the task of deciding how to apportion the remaining necessary sensor gain between amplification by increased coil size and amplifier gain. This decision should be based on consideration of overall sensor noise and bandwidth.

Figure 2.5 shows the estimated total electronic noise density (after amplification) of the axial and transverse sensors designed for this project, as well as the various noise components contributing to the axial sensor noise. These were calculated using equations 2.17 through 2.20. At higher frequencies, most of the noise is due to the input current noise interacting with the increasing source impedance of the coil and, to a lesser extent, the Johnson noise of the source resistance. At lower frequencies, the input voltage noise and the Johnson noise of the amplifier feedback
network become more important. Figure 2.5 appears to show that the noise is worse at higher frequencies. However, the sensitivity of a coil also rises with frequency, and thus the signal to noise ratio, which is a more important factor in sensor design that the actual noise level, will be lowest (poorest) at lower frequencies (though this also depends on the spectrum of the signal waveform).

The noise spectrum of the transverse sensor is much greater than that of the axial sensor. This is the result of the more severe dimensional limitations placed on the transverse sensor, resulting in a much lower \( \mu_{\text{app}} \). Due to the shape of the
core of the transverse sensor, the coil inductance $L$ for a given number of turns was much greater than the axial coil inductance (by a ratio of about 3.6), and thus the transverse coils had to be made smaller or else bandwidth would have been decreased further. With lower core and coil amplification, the amplifier gain $G$ of the transverse sensor had to be made 3.5 times larger than that of the axial sensor. The noise spectrum, while similar in level to that of the axial sensor at the amplifier input, was therefore also amplified to four times that of the axial sensor.

To further illustrate the effects of tradeoffs between coil gain and amplifier gain, consider two imaginary coils; coil $a$ with $n$ turns, and coil $b$ with $n/2$ turns, used with the same core. By equation 2.16, the inductance of coil $b$ will be $1/4$ that of coil $a$, as will be the winding resistance $R_w$. The bandwidth of coil $b$ will be twice that of coil $a$ (assuming that the capacitance can be reduced to similar levels in both cases), and the required damping resistance $R_d$ will be halved. Since the sensitivity of coil $b$ is reduced to half, twice the amplifier gain $G$ is required. At higher frequencies, the sensor output noise will likely be lower for coil $b$, since the input noise, due primarily to $L$, will be decreased more with respect to coil $a$ than the gain is increased. At low frequencies, the sensor output noise of coil $b$ may be higher or lower than that of coil $a$, depending on which noise components dominate at the amplifier input. If the noise due to the coil’s source impedance still dominates at low frequencies, then the output noise will be reduced, but if coil size is such that the amplifier input voltage noise dominates, then the output noise for coil $b$ will be almost double that of coil $a$.

Since it is more important to minimize noise at the lower frequencies, it is ultimately the amplifier input voltage noise that limits how much of the total sensor gain can be taken over by the amplifier, as most of the other noise sources are
reduced by decreasing the coil size. The best low-noise, precision bipolar-type operational amplifiers that are currently available have an input voltage noise equivalent to the Johnson noise of a resistor of 550 to 1200 ohms. (Precision FET input op-amps are also available. These have almost negligible input current noise, but input voltage noise an order of magnitude larger than that of precision bipolar types, and are thus mainly suitable for sensors of extremely high source impedance.) If op-amps of still lower voltage noise become available, it may be possible to further increase the electronic gain, though eventually the Johnson noise of the amplifier feedback network will be the limiting factor, since the feedback resistances can only be reduced so far.

Considering this, when designing an EM sensor one should increase the coil size $n$ until either the bandwidth starts to become limited or else the noise due to the coil source impedance begins to overtake the input voltage noise at lower frequencies. When this is done, the output signal to noise ratio should be optimum.

While references have been made to cylindrical cored sensors, most of what has been said in this chapter will apply to permeable-cored EM sensors of any shape, although the actual expressions given for $N$, $\mu_{\text{app}}$, and $L$ will no longer apply. There are other types of sensors that have not been discussed, such as those using air cores with transformers to step up the signal level. Even these sensors may be governed by principles similar to those given above.

In this chapter we have seen that the theory of sensor coil design, while an initially simple concept, is, upon closer scrutiny an array of competing factors which must be considered carefully in view of the design goals and limitations in order to optimize performance. The next chapter will consider the practical application of this theory towards the design of the three-component EM probe.
Chapter 3

Probe Construction

We now turn to some of the more practical aspects of the design of the sensors for the three-component EM probe. The goal was to build a three-component sensor of given sensitivity and of as large bandwidth and as low noise and signal distortion as possible. The bandwidth of a time-domain sensor should be in the range of a few kHz to a few tens of kHz, and electronic noise should be kept less than the natural EM field noise. The main limitation on the design is, of course, space; everything from the sensors themselves to the batteries must be fitted into a narrow tube. Other considerations include the fact that the probe must be able to withstand the fluid pressures several hundred metres down a borehole and must be able to operate under battery power for a day or so.

The entire EM probe, including sensors, electronics and couplings, is about 2 m long. The upper third of the probe is of stainless steel tubing, and contains most of the probe's electronics as well as the batteries. This section of the probe (but not the electronics it contains) as well as the connecting cable and winch assembly was constructed for an earlier project, but was reused for this project to avoid needless duplication of effort and expense. The actual sensors and their preamplifiers are situated in the lower two thirds of the probe. This section of the probe is enclosed in an epoxy fiberglass tube. A non-metallic casing is required around the sensors, since the eddy currents induced in a metal casing would restrict the sensors to low frequencies. The fiberglass tube has an outer diameter of 41.3 mm (1.625 in) and an inner diameter of 31.8 mm (1.25 in). Such a tube should easily withstand the
fluid pressures at up to 1 km depth (fluid pressure: 10 MPa, bursting pressure of tube as estimated from dimensions and material properties: 120 MPa).

The probe is designed to fit a size 'A' (47 mm) drillhole with adequate clearance. Although some borehole probes will fit size 'E' (36 mm) drillholes, it was judged that it would be difficult to design a three-component probe to fit that size hole. After allowing for hole clearance and sufficient wall thickness, the fiberglass tube around the sensors of such a probe would have an inner diameter of only 22 to 25 mm (7/8 to 1 in), leaving little room for the transverse sensors.

Although the difficult part of the project was the development of the transverse-field sensors, we will discuss the design of the axial-field sensor first, as an introduction.

It was concluded in the last chapter that as much as possible of the sensor's total amplification should be realized by core design rather than by increased coil size or electronic amplification. Using various approximations (which assume an ellipsoidal core, high permeability and high length/diameter ratio), it is possible to rewrite equation 2.10 to show the dependance of effective area on core length \( l \) and diameter \( d \) as follows;

\[
A_{\text{eff}} \approx \frac{\pi}{4} \frac{l^2 n \omega}{\ln(2l/ed)},
\]  

(3.1)

where \( n \) is the number of turns in the coil and \( \ln(e) = 1 \). Obviously, the sensor core should be made as long as size limitations permit. Increasing the diameter also increases the sensitivity, but to a lesser extent.

In single-coil EM borehole probes, the sensor itself often takes up the better part of a meter of the length of the probe. In three-component probes, however, the combined length of all three sensors should be not much more than a meter if the entire probe, including electronics, batteries and couplings, is to be of manageable
length. This restricts the length of the axial-field sensor as well as the transverse-field sensors.

For this reason, the axial-field sensor designed for this project is not of the standard cylinder-cored coil design as described in the previous chapter, but is of somewhat novel design itself. Figure 3.1 is a simplified schematic of this sensor. The main core is a ferrite rod, about 1.27 cm (1/2 in) in diameter and 15.4 cm (6.1 in) long. What is unusual is the addition of larger diameter (actually octagonal) blocks to the ends of the rod, increasing its total length to 20.8 cm (8.2 in). It was found from tests that the addition of these blocks increased the sensors sensitivity by two and one half times, while increasing the length by only 35%. According to the equations of chapter 2, the sensitivity of the rod with the end blocks is about equivalent to the sensitivity that would be expected from a single rod of total length and diameter equal to that of the end blocks. Thus this sensor has the sensitivity (and the inductance) of a large diameter rod with the winding diameter of a thin rod. It was estimated that a single, thin rod would have to be about 28.6 cm (11.25 in) long in order to have the same sensitivity as the shorter rod with end blocks.

As shown in figure 3.1, the entire sensor is surrounded by a layer of brass foil. This foil is grounded and serves as a shield to prevent the coil from responding to the electric field (that is, acting as an electric field antenna). The overlapping edges of the foil are not in electrical contact in order that there be no closed circuit around the sensor axis, since otherwise eddy currents would be induced around the coil which would limit the sensor's bandwidth. The ferrite rod and end blocks are held together by plastic strapping placed under tension. While it might have been simpler to glue the core together, a layer of glue could reduce the permeance
Figure 3.1: Simplified exploded view of the axial-field sensor. Details not shown include the wiring between coils and to the preamp, the signal guarding scheme, and the means of holding the ferrite blocks together.
and thus the effective area of the sensor. Also a glued joint could eventually work loose, since ferrite is not the most readily glued of materials and the probe might be subjected to shock, vibration or temperature extremes in the field.

The axial sensor coil contains 10,000 turns of wire, wound in five sections along the narrow rod. The inductance of the sensor is 16.5 H and the resonant frequency is about 10.4 kHz, which implies that the equivalent capacitance is about 14 pF. The capacitance was reduced to this level through the use of five coils in series rather than a single large coil and through the technique of signal guarding. Theoretically, by splitting the coil into five sections, the net interwinding capacitance is reduced by a factor of 25, since each section will have one-fifth the capacitance of a single, large coil and the capacitances of the five sections add in series.

When interwinding capacitance has been reduced by breaking the coils into sections, other sources of stray capacitances begin to dominate. These include the preamplifier input capacitance and capacitances between the winding and the shield and between the winding and the core. The latter sources can be reduced by signal guarding. This technique involves the use of strips of foil around the inside and outside of the coils and around the coil leads. These strips are maintained at potentials close to those of the adjacent sections of coil by means of a resistor voltage divider network powered by the output of the preamplifier. With low potential difference between coil and surroundings, the capacitive attenuation at higher frequencies will be much reduced. Use of this technique was found to nearly double the bandwidth of the axial-field sensor, which implies that the effective capacitance was reduced by a factor of four. Though useful, the technique must be used with caution since it can introduce positive feedback and instabilities at higher frequencies.

The preamplifier of the axial-field sensor is a simple single-input, noninverting
amplifier built using a precision low noise operational amplifier (AD OP-27G produced by Analog Devices). The electronic noise of the sensor (figure 2.5) is about the same order of magnitude as the natural EM noise, judging by published charts of typical EM noise density (e.g., Macnae et al., 1984).

While the design of the axial-field sensor was more or less straight-forward, that of the transverse-field sensors was much more difficult. Though considerably more effort was spent on their development, and they take up a third more room in the probe, the final transverse-field sensors have only one quarter the sensitivity (before amplification) of the axial-field sensor, and half the bandwidth. This is mainly due to the lower efficiency of the transverse sensor design.

Figure 3.2 shows a simplified diagram of the transverse-field sensor construction. The permeable core of the sensor is in the shape of an elongated 'H' when viewed from the side, with the magnetic flux being drawn into and along the sides of the 'H' and through the crossbar in the middle. The coil surrounds the crossbar, and is connected to a miniature preamplifier circuit board immediately adjacent to the crossbar. The entire assembly of ferrite slabs and glass spacer blocks is held together by plastic strapping as was the axial sensor.

The 'H'-core is similar to the axial-field sensor in that both have wider sections which funnel the flux through a narrower section around which the coils are placed. Most of what has been said thus far in this and the previous chapter regarding sensor design still applies to the transverse-field sensors, except that new methods must be used to estimate the degree of magnetic flux concentration ($A\mu_{app}$) achieved by the new core design.

One method of making a preliminary estimate of the total possible flux capture of an 'H'-core is to calculate the flux drawn through an elongated ellipsoid placed
Figure 3.2: Simplified exploded view of the transverse-field sensor.
with its long axis at right angles to the field. If the ellipsoid is sufficiently elongated, then the demagnetization factor, \( N_\perp \approx \frac{1}{2} \) (since \( N_\parallel \approx 0 \)). If the permeability is large, it follows from equation 2.9 that

\[
\mu_{\text{app}} \approx \frac{1}{N_\perp} \approx 2.
\]

Thus the effective area for a coil wound around the long axis of an ellipsoid of length \( l \) and diameter \( d \) will be

\[
A_{\text{eff}} = nA\mu_{\text{app}} \approx \frac{\pi}{2} nld.
\]  \hspace{1cm} (3.2)

Comparing equation 3.2 with 3.1, we find that for identical ellipsoids

\[
\frac{A_{\parallel}}{A_\perp} \approx \frac{1}{2} \frac{l/d}{\ln(2l/ed)}.
\]  \hspace{1cm} (3.3)

Since it has been assumed that \( l \gg d \), it is apparent that the transverse-field sensor is, by nature, less sensitive than the axial-field sensor, for a given \( n, l \) and \( d \). For the dimensions of the final transverse sensor design, \( A_{\parallel}/A_\perp = 2.8 \).

The estimate of effective area given by equation 3.2 is not very accurate, however, since the permeance of the 'H'-core will be less than that of an ellipsoid. Also, not all of the flux will be drawn through the crossbar (and hence the coil), but rather some will leak across the gap between the arms, thus further reducing \( A_{\text{eff}} \).

To get a better idea of how \( A_{\text{eff}} \) varies with sensor shape, it is necessary to use a numerical method to estimate the magnetic fields in and around the sensor core. One such technique is the finite element method, in which the field is estimated at numerous discrete points at the nodes of a grid by the principle of minimization of energy (Coggon, 1971). Although it can be applied to three-dimensional problems, these are difficult to set up and are computationally expensive (Pridmore et al.,
Figure 3.3: Flux capture of transverse-field sensor as a function of sensor length for various material permeabilities. Flux is expressed in terms of effective length.

Thus 2D models were used in the study of 'H' core design. While they do not directly give quantitative estimates of the $A_{eff}$ of the actual core, they give some idea of how sensitivity varies with shape.

Figure 3.3 shows how the amount of flux capture varies with sensor length, for various material permeabilities. Flux capture is expressed in terms of effective length, $L_{eff}$, which is the 2D equivalent of $A_{eff}$. This plot is somewhat analogous to figure 2.1, which showed $\mu_{app}$ vs. $m$ for axial-field sensors. Even if limitations of space are neglected, figure 3.3 shows that there are diminishing returns from increasing the length/width ratio beyond 12 or so. (Width here is the sensor dimension in the direction of the measured field.)
One of the conclusions reached by the numeric modelling study was that the amount of flux captured was not very dependent on the cross-section of the crossbar. Thus the crossbar diameter could be made considerably smaller than the overall sensor diameter and so allow more winding space for the coil. A study was also made of how the flux through the cross bar varied with the size of the air gap between the arms of the 'H'-core. It was found that it was greatest when the air gap was half the total width of the sensor, though it was not much reduced if the air gap was increased to 2/3 of the total width (again, allowing more room for the coil).

It seems, then, that within certain limits, it is the overall dimensions of the transverse-field core that determines the amount of flux captured rather than the dimensions of the crossbar or the width of the air gap. These latter factors do have an important effect on the sensor inductance, however. For instance, it was found experimentally that increasing the crossbar length (and thus the airgap) while keeping the sensor length and arm width constant increased the sensor's effective area while decreasing its inductance.

It was demonstrated earlier that the transverse sensor necessarily has a lower sensitivity for a given sensor volume than the axial sensor. The transverse sensor design also suffers from other problems. For one thing, it has a much greater inductance for a given sensitivity than does the axial sensor. The ratio of the inductance of the transverse sensor to that of the axial sensor used in the probe, when normalized with respect to winding size \((n^2)\) and sensitivity, was 14. This larger inductance of the 'H'-core limits the size of the coil which can be used without restricting the sensor's bandwidth or increasing electronic noise. The 'H'-core design leaves little room for the coil anyway, and thus it is also more difficult to implement
the techniques used to reduce coil capacitance. The sectionalizing of coils to reduce capacitance does not work well unless there is sufficient space left between the sections, so it is difficult to reduce interwinding capacitance by this method. The winding-core capacitance will tend to be greater for the 'H'-core design since the coil is against the core at its sides as well as along its inner radius. In conclusion, the transverse sensors have lower sensitivity, increased inductance and capacitance, less winding space and are more difficult to construct than axial sensors.

The coils used for the transverse sensors were wound in two sections with plastic washers between the sections, and had about 6700 turns total. It was found that splitting the coil into two sections increased the bandwidth considerably, but little further benefit was derived from splitting the coil in three. In order to conserve valuable space, the coils were wound without bobbins. The inductance of the sensors was 27 H and the resonant frequency about 5.2 kHz, indicating an equivalent capacitance of 35 pF. The gain of the transverse sensor preamplifiers is such that the overall sensitivity is similar to that of the axial sensor. As shown by figure 2.5, the electronic noise of the transverse-field sensors is much greater than that of the axial-field sensor. However this may not be important, as natural EM field noise also tends to be much greater in the horizontal direction.

Since the three-component probe was intended to be used with available EM equipment, including the upper portion of the probe, the cable-winch assembly, and the receiver, all of which can handle only one EM signal at a time, it was necessary to devise a method of controlling which of the three signals should be sent up the cable to the receiver at a given time. The method eventually used relies on timed pulses sent down the cable to control the probe. These pulses are generated at a control/interface box connected between the winch and the receiver. The cable
shielding is used to transmit these pulses, since the cable contains only a single twisted-pair, which is required for signal transmission up the cable. To select one of the three EM field components the operator pushes one of three buttons which causes a pulse of duration .1, .2 or .3 s to be sent down the cable to the probe. The electronics in the upper section of the probe then connects one of the signals from the three sensor preamplifiers to the probe output amplifier, based on the length of the pulse. The control/interface box, besides containing control circuitry, contains amplifiers and attenuators in order that the signal from the probe can be raised or lowered to whatever level is required by the receiver.

This concludes the discussion of the probe construction. It would appear that the goals of the project have been met fairly well by the final design. While the transverse-field sensor has a substantially lower rise time (or lower bandwidth) and greater noise than the axial-field sensor, it should be remembered that the purpose of the transverse data is to aid in characterizing and locating conductors, while the axial-field data will remain the primary interest. The next chapter will review the field trials of the probe.
Chapter 4

The Field Tests

A total of four field tests of the three-component drillhole receiver probe were made to demonstrate its field worthiness, its ability to interface with existing field equipment and, most importantly, its usefulness in aiding the identification and locating of geophysical targets.

The first two of the field tests were conducted just north of Luther lake, about fifty miles north-west of Toronto. These were surface tests made primarily to ensure that the probe would function properly away from the laboratory environment and to track down any problems that might exist prior to later and more important borehole tests. They also provided a better estimate of the probe's sensitivity and bandwidth than could be made in an electromagnetically noisy downtown laboratory and showed that the probe could work with existing EM equipment.

The Luther tests were made in conjunction with Scott Holladay's field testing of his EM system. This system uses a grounded wire source and multiple electric and magnetic field sensors to obtain the earth's frequency response. To test the drillhole receiver probe, it was merely connected in lieu of the usual coil during part of a calibration run. The probe was connected via the same cable-winch assembly and the same channel selector/adapter box as was used in later downhole tests. Although the EM system was of a different sort than that for which the probe was intended to work with, suited more for the investigation of sedimentary basins than for hardrock mineral exploration, it still allowed a good field test of the entire receiver probe-cable-adapter box assembly and helped give a good estimate of the
probe's sensitivity.

The geology of the Luther site consists of flat sedimentary deposits overlain by glacial deposits. The site was chosen for its simple and known geology and its lack of cultural noise (i.e. power lines, fences and the like). The nature of the site plus the proximity of the receiver to the transmitter wire during the calibration run meant that the resulting frequency responses were influenced little by the geology and closely approximated the frequency responses of the probe in freespace.

The probe and associated electronics functioned well for these tests despite the fact that they were conducted in part after dark in late winter in near-blizzard conditions. The main problem in using the probe proved to be the need to assemble and disassemble the probe before and after use in order to save the probe batteries. Before extensive use of the probe, a way should be found to switch the power on and off without disassembly. The assembly-disassembly process is both time-consuming and tricky, and each time it is done there is risk of damaging the electronics, or worse, damaging the seal that keeps out water. Aside from this problem, however, there were no difficulties with the equipment.

Figure 4.1 shows one set of the data collected. For this example the axis of the probe was parallel to the transmitter wire so that the two transverse coils shared the total field. Due to the proximity of the receiver probe to the transmitter wire during the test, the magnetic field was not very dependent on the geology, so that by modelling the earth with a halfspace with a resistivity of 50 $\Omega m$, and using the program BIPOLE written by Dave Boerner, it was possible to estimate the field at the probe. Then, knowing the total field and using the resultant of the two transverse coils in the equation $|V| = \omega \mu_0 A_{\text{eff}} G |H|$, where $G$ is the gain, the average effective area of the transverse coils ($A_{\text{eff}}$) was found to be about $A_{\text{eff}} = 62.5$ m$^2$ or
Figure 4.1: Example of probe data from the Luther Lake test site. The data has been normalized with respect to frequency and transmitter current. The curves are dominated by the frequency response of the probe coils, but include slight filtering due to the various amplifiers, one kilometer of cable and the earth itself.

$1.88 \times 10^4 \text{ m}^2$ if the probe amplifier gains are included. Another set of data collected with the axial coil of the probe oriented vertically enabled the sensitivity of that coil to be similarly estimated at $A_{\text{eff}} = 252 \text{ m}^2$ or $2.12 \times 10^4 \text{ m}^2$ including amplifier gain. These estimates of the coil sensitivities agree fairly well with those made using a Helmholtz coil in the laboratory. The response curves also show that the axial coil's frequency response was flat almost to 10 kHz while those of the transverse coils were flat only to about 3 kHz.

Once these two initial field tests were completed, the receiver probe was ready
Figure 4.2: Crone Pulse EM waveform and derivative. The beginnings of the steps are exponential with a time constant of about 1 ms while the ends of the steps are quarter-sinusoids about 0.7 ms long. Sampling of the secondary field takes place after the final cut-offs of current when the primary field is zero. The entire cycle shown here is 43.5 ms long (repetition rate: 23 Hz).

to be tested in the environment for which it was designed, that is, down a drillhole with a few hundred metres of water over it. The final two field tests were conducted in association with Dr. A.V. Dyck and the Geological Survey of Canada using Crone Pulse EM (PEM) equipment. This system, which is more of the type for which the receiver probe was designed to work with than the EM system used for the first two tests, uses a large rectangular loop of a few hundred metres to a side as the source. As shown in figure 4.2, the transmitted waveform consists of alternating steps so that the system waveform, as seen by a differentiating coil receiver or conductors in the earth, is pulse-like. The actual turn-off pulses, though, are quarter sinusoids about 700 μs long, which is rather long compared to the rise time of the coils. Thus the rise time of the coils has little effect on the primary voltage pulse except at its beginning and end, which appears much like a simple off-step to the coils. The damping of the coils was intended to be just sufficient to eliminate the apparent
Figure 4.3: The Crone PEM coil response as input to the receiver, showing the primary field pulse, the secondary field decay curve, and the nine sampling windows of the receiver. Sampling for channel 1 begins 100 μs after the end of the primary pulse.

ringing after a step-off function, and is thus appropriate for this EM system.

For these field tests, the three-component receiver probe with its cable, winch and adapter/control box replaced the probe-cable-winch assembly usually used with the system. The Crone receiver stacks the waveforms and integrates the signal over a total of nine windows, as shown in figure 4.3. The first of these windows coincides with the tail end of the primary field pulse, and is thus usually dominated by its effect, at least when the primary field is roughly aligned with the sensor coil, as it usually is for the single, axial-coil probe normally used with the PEM equipment. Under such circumstances, with the probe in a vertically oriented drillhole under a large, flat transmitter loop, the primary field will usually be 5 to 50 times the strength of the secondary fields, and so this Primary-Pulse (PP) channel is considered to give a good representation of the primary field. In fact, the data from the
remaining windows, channels 1 to 8, is often displayed normalized with respect to the primary field as determined by the PP channel in order that the target responses are less influenced by depth or distance from the transmitter loop.

For the transverse coils of the three-component receiver probe, though, it is less likely that the PP channel will be dominated by the primary field since these coils will usually be closer to being perpendicular to the primary field. In fact, the primary field component can be almost zero for these coils. This is not desirable, however, since the probe relies on the primary field as sensed by the transverse coils to determine its orientation. In order to assure a measureable component of the primary field across the drillhole, the transmitter loops were placed with one side closer to the drillholes instead of being centered around them.

The first of the two final field tests was conducted at a test site near Bell's Corners just outside of Ottawa. This test, like the first two, was preliminary in nature, and was made primarily to ensure that all of the equipment functioned properly prior to embarking on the final field trial. In particular, the test would show if the probe could withstand the high pressures down a drillhole and if the electronics were compatible with the Crone PEM system. After some initial problems (traced to a loose wire in the probe), the probe and its channel (field component) switching device appeared to function well, and reasonable looking data were obtained. As the geology of this test site is not remarkable, the data were not analyzed in detail.

The final and most important field test of the probe was conducted at the Gertrude West property of INCO Limited just west of Sudbury, Ontario. The site lies on the southern edge of the Sudbury basin, an area noted for its unusual geology and economic importance. This basin is characterized by the Sudbury Nickel Irruptive, an intrusive body exposed on the present surface as an elliptical
ring about 60 km long and half as wide. It is located on the border between the Superior and Southern provinces of the shield and is just north of the Grenville Front. The rocks of the Irruptive range from gabbroic rocks termed ‘norite’ along its outer-lower edge, to granophyric rocks termed ‘micropengmatite’ along its inside edge. Surrounding the irruptive are the older rocks which it intruded into; the Archean granitic gneisses of the Superior Province along the north and the highly metamorphosed Huronian volcanic and sedimentary rocks of the Southern Province along the south. The contact between the irruptive and these older rocks is known as the norite contact, and dips towards the center of the basin at angles between 30 and 90 degrees. It is near this contact, at the base of the magma intrusion, that most of the rich sulphide ores of the region are found. The sulphide bodies, consisting mainly of pyrrhotite, pentlandite, and chalcopyrite, are quite conductive and are thus suited to EM prospecting techniques.

At the Gertrude West site, the norite contact strikes east-west and dips towards the north. As shown in figure 4.4, extensive drilling, completed decades ago, has outlined two sulphide bodies roughly parallel to the contact. The larger, upper one outcrops and dips towards the north at an angle of about 45° and extends downwards for about 200 m. The second body is smaller and lies about 30 m below the lower end of the larger deposit. The bodies are more or less sheet-like in shape, although the lower end of the upper deposit is perhaps more bulbous in nature.

Two drillholes were surveyed for this field test. Figure 4.4 shows their location and the positioning of the two transmitter loops, named the East and North loops. The drillholes do not intersect appreciable sulphides and pass just north of the main sulphide zones. As mentioned earlier, the loops were offset from the drillholes in order to increase the horizontal component of the primary field across them, which
Figure 4.4: The Gertrude West test site, showing the estimated extent of the sulphide bodies, the drillholes in the area and the transmitter loops. Drillholes 23090 and 29303 were the ones surveyed in this field test.
in turn enabled the orientation of the probe to be determined. The use of two transmitter loops meant that two independent estimates of the orientation could be made, and these compared to give some idea of the precision of the method. The two loops would also have slightly different couplings with the conductors and thus lead to differences in the data which might aid later analysis. Comparison of the axial sensor data for different transmitter loop locations is the standard method of determining the direction of conductors from the borehole, when only an axial sensor is available.

Figure 4.5 shows a block diagram of the equipment setup for the field test. For each depth at which measurements were made, the readings for each of the nine channels of the receiver were taken for each of the three coils of the probe and for both transmitter loops. The recording of this considerable amount of information
Figure 4.6: An example of the raw data as initially recorded. The plots for all three coils are shown for drillhole GW-29303 using the north loop. In these plots, and in similar ones in later chapters, the data from the eight PEM channels (sampling windows) is displayed as parts per thousand of the axial PP channel on a linear-logarithmic scale as a function of depth.
was facilitated by the use of a digital voltmeter hooked up to the receiver which was in turn controlled and read by an HP-85 computer. The data was stored on magnetic tape and later transferred to other computers for data correction and analysis.

Once the setup of the equipment was completed (which took a couple of days), the drillhole surveys proceeded relatively smoothly. Due to continual rotation of the probe as if was lowered down the drillholes, the data from the transverse coils was not immediately readable, and little could be said of the data at the time of the survey except that it seemed 'reasonable looking'. The data from the axial coil, though, was immediately readable and was found to compare favourably with data from the same drillholes recorded previously by A. Dyck using the single-coil probe (Dyck, 1981).

Figure 4.6 shows the raw data from borehole GW-29303 using the North transmitter loop. The amplitude of the eight sampling windows is displayed as parts per thousand of the primary pulse (PP) channel on a linear-logarithmic scale (that is, linear between −10 to +10 ppk and logarithmic elsewhere) as a function of depth. In these plots, channel 1 (the earliest) normally has the greatest amplitude, though due to the higher gain applied by the PEM receiver to the later channels, this may not be true of slowly decaying responses from large or highly conductive bodies.

It is clear from these plots that there is a strong transverse-field response of magnitude similar to the axial-field response, though it has been broken up by the erratic rotation of the probe. In the next chapter we will see how the transverse coil data was manipulated to get it into a more useful form.
Chapter 5

Data Processing

It was shown in the last chapter that while the axial coil data could be plotted and used directly using the standard normalization schemes, the transverse coil data was initially unreadable due to the frequent and apparently random rotation of the probe as it was lowered down the drillhole. In this chapter we will see the procedures used to process the data and the resulting cleaner curves.

As mentioned earlier, it was intended that the primary field data of the transverse coils would serve to determine the orientation of the probe at each stop down the drillhole. The main advantages of this method are that no additional equipment either in the probe itself or on the surface is required and there are no extra data recording procedures involved. This saved on development time and expense as well as on the time required in the field. This method, however, is not without its problems. The transverse components of the primary field will be relatively weak for a probe in a near-vertical hole under a large horizontal loop, even when the loop is offset somewhat from the hole, and the primary field window of the receiver can be strongly influenced by secondary fields. Thus it may become necessary to attempt to remove the influence of the secondary field before using the primary window data in the orientation algorithm.

There are other methods which could be used to determine the orientation of the probe. One could devise some sort of electronic compass using two static magnetic sensors at right angles, but this technique too would have its problems if the drillhole was close to being parallel with the earth’s magnetic field or if the
probe was situated close to mineral bodies with induced or remanent magnetization. Other possible methods include miniature gravity sensing devices and gyroscopes, but these would be expensive and/or tricky to use.

A computer program (PEM-FIX) was used to correct the transverse coil data for probe orientation. At the start of this program, the primary field at the probe is estimated for each location along the drillhole where data was taken. The algorithm calculates the field using the Biot-Savart law which relates the magnetic field at some point in space to the current flowing in a short straight element of conductor at some other point as follows:

\[ d\mathbf{H} = \frac{i\, ds \times \mathbf{r}}{4\pi r^2}, \]

where \( d\mathbf{H} \) is the magnetic field at the point of observation, \( ds \) is the conductor element, \( i \) is the current in that element, \( \mathbf{r} \) is the distance between the element and the point of observation and \( \mathbf{r} \) is the unit vector pointing from the element towards the point of observation. This can be integrated to give the magnetic field due to a segment of wire:

\[ H = \frac{i}{4\pi d} \left( \cos \theta_1 + \cos \theta_2 \right), \]

where \( d \) is the length of the perpendicular between the point of observation and the wire segment and \( \theta_1 \) and \( \theta_2 \) are the angles at the point of observation between this perpendicular and the endpoints of the wire. The field is oriented perpendicular to the plane containing the wire and the point of observation. By summing the effects of four such wire segments, the axial and transverse components of the magnetic field due to the square transmitter loops were estimated, and from these the azimuth of the horizontal field was obtained.

Once the primary fields have been computed, these can be compared to the fields as recorded by the 'Primary-Pulse' or PP channel of the Crone PEM receiver.
to give an estimate of the probe's orientation. The process was simplified for the Gertrude-West field data since the drillholes were assumed to be vertical and thus only the horizontal field components are involved. First the horizontal angle of the primary field counter-clockwise from coil 2 of the probe (i.e., the x direction in the probe's coordinates) was found using the arctangent of the ratio of the PP channels for the two transverse coils. Then this angle was subtracted from the actual horizontal angle of the field from east to yield the orientation of coil 2 of the probe counter-clockwise from east.

This estimation of the probe's orientation was actually done twice for each location of the probe down the drillhole at which data was taken. Since data was taken using two different transmitter loops, one offset towards the north and one offset towards the east, it was possible to make two independent estimates of the orientation and then compare these to give some idea of the precision of the method. Initially, the average difference between these two estimates was rather large, about 27° for the data from one drillhole and about 34° for the other. This was an indication that the PP channel data was not giving a good estimate of the primary field, but was contaminated with secondary fields. Thus it became necessary to attempt to remove this influence from the PP data.

To remove the secondary field component from the PP channel, a method was needed to estimate the secondary field during the PP window from the secondary field data contained in channels 1 to 8. The procedure eventually used in effect utilized the data from channels 1 to 8 to estimate the earth's impulse response. The impulse response was in turn used to estimate the secondary field during the PP channel window. In practice, a vector was calculated which when multiplied by the observed intensities in channels 1 to 8 in any set of data would yield a correction
factor which would then be subtracted from the initial PP reading for that data set.

The initial assumption on which the correction scheme was based is that the earth’s impulse response can be represented as an infinite sum of the impulse responses of individual current filament-loops as follows:

\[
I(t) = \sum_{i=1}^{\infty} a_i(\delta(t) - b_iu(t)e^{-b_it}),
\]

(5.1)

where \(I(t)\) is the time domain response to an impulse at \(t = 0\), the \(a_i\) are weighting coefficients and the \(b_i\) are inverse time constants. The \(a_i\) and \(b_i\) are real and will depend on the transmitter-conductor-receiver geometry and the properties of the conductors. Referring to figure 4.2, and taking \(t = 0\) to be the start of the exponential on-step, the derivative of the transmitter current waveform can be approximated by

\[
P(t) = \begin{cases} 
\frac{2\Delta T}{\pi \tau_{on}} e^{-t/\tau_{on}}, & \text{for } 0 \leq t < T/2; \\
-\sin \frac{\pi}{2\Delta T} (t - T/2), & \text{for } T/2 \leq t \leq T/2 + \Delta T; \\
0, & \text{otherwise.}
\end{cases}
\]

where \(\tau_{on}\) is the time constant of the exponential turn on, \(\Delta T\) is the quarter period of the sinusoidal turn off and \(T\) is half of the full transmitter waveform cycle shown in figure 4.2. To find the earth’s response to this waveform, it is necessary to perform a convolution. We assume for now that we are measuring only after the turn off so that we can neglect the \(u(t)\) and the \(\delta(t)\) term in the impulse response. Performing
the convolution on one term $I_i$ of the summation (5.1), we obtain

$$P(t) * I_i(t) = -b_i \left\{ \frac{2\Delta T}{\pi \tau_{on}} e^{-b_i t} \int_0^{T/2} e^{\frac{(s-T)}{2\Delta T}} e^{\frac{s}{2\Delta T}} ds \right\}$$

$$- e^{-b_i t} \int_{T/2}^{T+2\Delta T} \sin \frac{\pi}{2\Delta T}(s-T/2) e^{b_i s} ds \}$$

$$= -b_i \left\{ e^{-b_i t'} \left[ \frac{2\Delta T}{\pi \tau_{on}} \left( e^{T/2} - e^{-b_i T/2} \right) e^{-b_i \Delta T} \right] \right.$$

$$\left. - \left( b_i + \pi e^{-b_i \Delta T} / 2\Delta T \right) \right\}$$

where $t'$ is 0 at the end of the sinusoidal turn off. Now, integrating over the $j$'th window of the receiver;

$$C_{j,i} = 10^{i-1} \frac{(e^{-b_i t_j'} - e^{-b_i t_j})}{(t_{j+1}' - t_j')} \left( \frac{1}{(1 + e^{-b_i T})} \right) \left\{ \frac{2\Delta T}{\pi \tau_{on}} \left( e^{-T/2} - e^{-b_i T/2} \right) e^{-b_i \Delta T} \right.$$ 

$$\left. - \left( \pi e^{-b_i \Delta T} / 2\Delta T + b_i \right) \right\}$$

where $C_{j,i}$ is the $j$'th channel response to the $i$'th component of the earth's impulse response, the power of 10 is the extra receiver gain automatically applied by the Crone PEM receiver for that channel, and the $1/(1 + e^{-b_i T})$ term is to account for the effects of previous cycles of alternating polarity and period $T$. After selecting suitable inverse time constants to represent the earth's impulse response, a matrix was formed from the $C_{j,i}$ coefficients which would map the amplitudes of the impulse response terms (the $a_i$) to the eight receiver channel readings. This matrix was then inverted using singular value decomposition methods (with no damping), so that given the receiver outputs, the impulse response amplitudes could be estimated.

In a method similar to that which yielded equation 5.2 above, but no longer neglecting the $\delta(t)$ term in the impulse response, an equation was obtained for
the terms relating the amplitudes of the impulse response to the secondary field component of the PP channel. A vector was formed from these terms, using the same time constants as were used to form the matrix above. Finally, when this vector was multiplied by the inverted matrix, a vector was obtained which when multiplied by the eight receiver channel outputs would give an estimate of the total secondary field contribution to the PP channel. This secondary field contribution was then subtracted from the PP data and the corrected PP data used in the determination of probe orientation as outlined above. For uniformity, the PP correction was also applied to the axial sensor data. This will alter the axial field profiles slightly when the data is normalized with respect to the PP data.

Different selections of time constants for the discretization of the earth's impulse response led to different correction vectors. Several of these were tested on the drillhole data in order to find out which would reduce the average difference between the two probe orientation estimates the most. The set eventually chosen reduced the average angle difference from about 34° and 27° for drillholes GW-29303 and 23090 to about 12° for both. (This set included four inverse time constants; 100, 320, 1000 and 3200 s$^{-1}$.) The actual angle used to adjust each data set for probe orientation was the average of the two orientation estimates. After the adjustment, data equivalent to an east and a north coil were obtained.

Figure 5.1 shows the two sets of estimates of probe orientation for drillhole GW-29303. They agree fairly well except in the section between 110 and 160 metres. Of course the agreement of the orientation estimates does not guarantee their accuracy, for systematic errors are possible. As well as relying on the receiver data, the orientation estimates depend on the accuracy of the calculated primary fields which, in turn, depend on how well the transmitter loop-drillhole geometry is known.
Figure 5.1: Probe orientation estimates for drillhole GW-29303. Those angles estimated from the north transmitter loop data are marked with an 'o', and those from the east loop with an 'x'.

Aside from the correction to the PP data, other corrections were made to the transverse data. To attempt to compensate for the slower response of the transverse coils, a fraction of the PP channel reading was subtracted from that of channel 1. Since the correction to channel 1 relied on the value of the PP channel, and the correction to the PP data relied (in part) on the value of channel 1, an iterative procedure had to be used. The effect of this correction was minor. Finally, the transverse data was scaled by a factor of 1.128 in order to compensate for the slightly lower sensitivity of the transverse sensors.

Figure 5.2 compares the primary fields of GW-29303 as calculated from loop-drillhole geometry to those actually measured (with all corrections applied). As can
Figure 5.2a: Vertical, east and north components of the primary field for drillhole GW-29303 with the north transmitter loop, as calculated using loop-drillhole geometry.

Figure 5.2b: The primary field components as actually measured for the same drillhole and transmitter loop as above.
Figure 5.3: Horizontal field data for drillhole GW-29303 using the north loop. The first two plots show the data from the two transverse coils now rotated to be equivalent to east and north respectively. The final plot shows the total horizontal field.
be seen, there is reasonable agreement. That there is much east field at all in the measured data is the result of the average of the two probe orientation estimated being used.

Figure 5.3 shows the same data as was shown in figure 4.6 (GW-29303 with the north transmitter loop) but now corrected for probe orientation. The axial data is not shown here, for it is altered only slightly. The transverse data, though much improved is still not as smooth looking as the axial data. Channel 1 (the earliest) and, to a lesser extent, channel 2 are obscured by considerable noise. As can be seen from comparison of figures 5.1 and 5.3, the noise peaks in the data appear to be correlated with the probe orientation. Inaccurate estimates of the probe orientation may be partly to blame, despite the agreement of the two sets of orientation estimates. Another factor may be the contamination of the early channels by the primary field, as a result of the longer rise time of the transverse sensor coils. However, since the plot showing the total horizontal field is also somewhat rough there must be other factors as well. It is known that natural and man-made EM noise is usually much greater in the horizontal direction. Also, the transverse sensors have a much higher level of electronic noise than the axial sensor. However, these types of noise should be much reduced by the stacking procedure used in the receiver. A more likely explanation of this remaining noise is that the geometry of the system makes the transverse field sensors more susceptible to small conductors near to the drillhole.
Chapter 6

Data Interpretation

In this chapter we will interpret the borehole EM data from the Gertrude West site, and show how the transverse-component data aids in that interpretation. While much can be learned from the axial data alone, it can be difficult in the absence of supporting geological data to determine with any certainty the direction of the conductor, even when multiple transmitter loops are used to observe the effects of varying transmitter-conductor coupling. With the addition of the transverse data, however, it is usually possible to determine the direction to the conductor with certainty, and at the same time reinforce other conclusions based on the axial data.

For the Gertrude West survey, much was already known of the conductor from extensive drilling, including its overall shape, size, position and orientation. (The geology of the site was described in chapter 4 -see figure 4.4 for map.) In a true exploration situation, it is likely that much less geological information would be available. For example, in an area of heavy overburden, the only direct geological data might be the core logs of the drillholes being surveyed. In such instances, it is up to the interpreter to use the EM data together with geological clues to estimate the size, shape and whereabouts of any conductors present. Thus to demonstrate the potential of the three-component data, we will attempt to show that even without the aid of the available geological information, a reasonable estimate of the conductor's size and location could be made based on the EM data.

A major work concerning the interpretation of drillhole EM data is that of Dyck (1981, 1984). Dyck interpreted drillhole EM responses mainly by trial and
error fitting using computer models of simple three-dimensional conductor shapes in freespace. The shapes he used for the modelling were the thin plate and the two layer sphere. These two shapes give responses which represent two extremes of the types of response one might expect from a real conductor, and together they can mimic many of the features found in anomalies.

In a plate-like body, the induced currents are confined to the plane of the plate no matter what the direction of the primary field, and thus the net magnetic moment of the plate will be perpendicular to it. The rectangular plate is useful in modelling sheet-like conductors where dip, azimuth and shape might be of importance. In the sphere on the other hand, the induced currents are not confined, so that the net magnetic moment of the sphere will be parallel to the primary field. The sphere is useful in modelling compact conductors or the effect of the nearest edge of thick tabular bodies. The anomalies due to most real conductors would likely not be fitted too closely by either of these two models, but would require some combination of their characteristics.

The effects of the currents induced in these models (or any model) on the observed EM profiles can be put into two categories; static effects and dynamic or time-dependent effects. Static effects are basically those dependent only on the transmitter-conductor-receiver geometry, while dynamic effects depend on the electrical properties of the conductor as well. Both static and dynamic effects are important to interpretation. We will study these effects as they apply to the plate model, since that model appears more appropriate to the interpretation of the Gertrude West data.

We will consider first the static effects of the plate model. Since the induced moment must be perpendicular to the plane, the relative positioning and angle between
the transmitter and the plate do not have much influence on the anomaly shape, although the coupling certainly influences the anomaly amplitude greatly and, in fact, the amplitude can be negative from the usual sense for plates displaced far from the transmitter or dipping steeply away from it. Very poor coupling between plate and transmitter can influence anomaly shape slightly, for instance making it narrower if the closer half of the plate is coupled better than the more distant half. A much greater effect on anomaly shape is due to the relative angle between the plate and the receiver, since this directly determines which lobes of the secondary field the receiver passes through. This domination of the anomaly by relative plate-receiver orientation may facilitate interpretation somewhat, but there are still many parameters which can be varied, and thus many ambiguities can arise.

In order to understand the dynamic effects of the plate model, it is necessary to think of the currents induced in the plate as being the sum of many non-interacting current systems or eigencurrents (this is in fact how the models are computed). Generally, the higher the order of the eigencurrent, the greater the geometric complexity of the current system will be, the faster its decay with time and the greater the geometric attenuation will be. The decay of some current components faster than others leads to apparent shifts in the total current -the phenomenon of eddy current migration.

Since the higher order (and more rapidly decaying) current components are concentrated towards the edges of the plate, as time progresses the currents appear to collapse towards the centre of the plate. For a plate roughly perpendicular to the drillhole, with one edge fairly close, this will mean that the current vortex will draw away from the drillhole, resulting in a wider anomaly profile at later times. If the plate dips upwards or downwards from the drillhole, the anomaly peak, influenced
more by the nearest edge of the current vortex, will appear to migrate upwards or downwards. It should be mentioned that all of these migration effects will be noticeable only when the body is relatively close to the drillhole, since the effects of the higher order current components decay faster with distance than the overall response which is usually dominated by lower order components. The most distant conductors, whether plate-like or not, should have more or less the effect of a simple dipole, with little migration.

We can now apply some of these ideas to the actual interpretation of the Gertrude West data. Figures 6.1a to 6.1d show all of the pulse EM data collected at the site. For completeness, the data from both boreholes and using both transmitter loops are presented. Although the four data sets are quite similar, the differences still provide valuable clues to aid in interpretation. As in chapters 4 and 5, the data are plotted as parts per thousand of the axial primary field on a linear-logarithmic scale. Since the channel 1 (the earliest) data of the horizontal components are particularly noisy, they are not shown in these plots in order that the remaining channels not be obscured.

All four data sets show a single, strong negative anomaly in the vertical field data, peaking at a depth of about 180 m. Plainly, there is a good conductor not far off-hole. This vertical field anomaly appears to both widen and move upwards as we progress from the early channels to the late. From this we can surmise that the eddy currents are migrating upwards and away from the drillhole, towards the central, more conductive regions of the body. We thus have evidence of a dipping conductive body with its lower extremities nearer to the drillhole. This is good reason to attempt to use the plate model to fit the data rather than the sphere model, since migration in the anomaly of a sphere tends to be downwards, away
Figure 6.1a: Crone PEM field data from borehole GW-29303 with the north transmitter loop. The data is displayed as parts per thousand of the axial primary field. The early channels are labeled ‘E’ and the late ‘L’.
Figure 6.1b: Data from borehole GW-29303 with the east transmitter loop.
Figure 6.1c: Data from borehole GW-23090 with the north transmitter loop.
Figure 6.1d: Data from borehole GW-23090 with the east transmitter loop.
from the transmitter.

The vertical field anomaly of drillhole GW-23090 is much stronger and narrower than that of GW-29303. This probably indicates that GW-23090 passes much closer to edge of the conductor than does the other drillhole. There is also a slight difference in the responses from the two transmitter loops. The north loop responses seem slightly stronger and sharper than do those of the east loop, perhaps indicating a slightly better coupling of the conductor with the north loop. It is not likely, though, that such differences could allow reliable determination of the direction to the conductor from the boreholes, even if south and west loop data were also available. In previous surveys by Dyck (1981, pg. 44), the north and west transmitter loops gave the strongest responses at Gertrude West, while at the nearby Gertrude site, those loops gave the smallest response, even though at both sites the conductors lie mainly to the south of the boreholes.

If the vertical (axial) field data were all that were available, not much more could be inferred, though computer modelling could be used to give quantitative estimates of distance to the body, its size, and so on. However by using the horizontal field data, some idea of the direction of the conductor can be gained. While only a minor response is visible in the east field data, there is a strong crossover in the north field response, present in all four data sets at about 180 m., corresponding to the peak in the vertical-component data. The lack of substantial east-field response compared to a strong north-field response shows that the conductor is placed more or less symmetrically about the north-south axis of the drillholes, and can not lie to the east or west. With careful consideration of signs, it can be definitely concluded from the polarity of the north field crossover that the conductive body lies to the south of the borehole, which is in agreement with the geological evidence.
Figure 6.2: Cross section of earth showing the primary field of the north transmitter loop and how it intersects the sheetlike conductor at the Gertrude West site. The length of the arrows is proportional to the logarithm of the field amplitude. The view is facing west.

The curves of both the vertical and the horizontal field data are bunched closely together, indicating that the time constant of the body is rather large. The time constant depends on both the conductivity of the body and its dimensions. If we have some idea of the length and width of the conductor, we can use this feature to estimate its conductivity-thickness product, $\sigma t$ (assuming that it is plate-like).

Figure 6.2 shows, in a cross-sectional view facing west, the primary field due to the transmitter loop, and how it would intersect the plate-like conductor at Gertrude West. The strongest coupling of the primary field with the plate occurs along its bottom half, while the top half is weakly coupled or coupled in the opposite direction. Thus the strongest eddy currents will be induced in the lower end of the plate, and so most of the secondary field will stem from that end as well. The result is a field much like that a smaller plate situated at the lower end of the big plate
Figure 6.3a: Data from plate model, for drillhole GW-23090 with the north transmitter loop. Compare this with figure 6.1c.
Figure 6.3b: Data from plate model, for drillhole GW-23090 with the east transmitter loop. Compare this with figure 6.1d.
would produce. This explains, in part, how an extensive conductor can produce a narrow anomaly, as that seen in GW-23090. Additionally there is geological evidence that the lower end of the body is thicker, which would also tend to increase the amplitude and sharpness of the anomaly.

Dyck's PLATE program (Dyck et al, 1981) was used to attempt to fit the data from GW-23090 as closely as possible. The resulting plots are shown in figure 6.3. The final model used a square plate only 100 m in extent but with a conductivity-thickness product of 225 S. This model was found to fit the data better than a larger plate of lower conductivity, probably due to the reasons given above, or to the limitations of the PLATE program in estimating the field at a distance from the plate small in relation to the plate dimensions. The plate used in the model dipped at an angle of 45° towards the north to a depth of 180 m only 5 m south of the drillhole. The plate was shifted 25 m to the east to produce the slight east anomaly. Rotating the plate eastwards about the axis of the drillhole would have had a similar effect. As can be seen from comparing figures 6.1 and 6.3, the model reproduces the overall shape of the observed anomaly fairly well.

Figure 6.4 compares the field data (GW-23090, north loop) to the responses of plates of various orientations. Plate 'A' is the plate of best fit, as described above. Plates B to D are the same as plate A except for their position and dip. Even without geological data to support our interpretation, it would be possible to reject plates B, C and D as possible interpretations of the data. Plates C and D can be dismissed readily by noting that the north field crossover is opposite in sign to that observed. Plate B can be rejected as well since a) due to poor coupling with the transmitter, the response of plate B is very low in amplitude and narrow compared to the observed response (moving the plate closer would increase the amplitude, but
Figure 6.4: Comparison of field data from GW-23090 with theoretical responses of plates of various orientation and position but identical size, shape and conductivity. The vertical and north field components are shown for each plate. The sketch shows the transmitter loop, drillhole and plate positioning, viewed facing west.
not the width), b) plate B has downward migration while the observed data shows upward migration, c) the vertical response of plate B has no positive shoulder above the negative peak as does the observed data, and d) the lower (negative) peak in the north field profile is much larger than the upper for plate B whereas they are about equal in the observed data. Since it was shown earlier that the conductor could not be predominantly east or west of the drillhole, we can conclude that only a conductor of location and dip similar to that of plate A could produce the observed response.

In this chapter, we have seen how the addition of the transverse-component data can do much to aid the interpretation of drillhole EM data. In particular, the transverse field data has, in this instance at least, permitted an accurate estimate of the direction to the conductor. In other situations, interpretation might not be so easy, but the extra information provided by the transverse sensors would still be of benefit.
Chapter 7

Conclusions

This thesis has traced the development and subsequent testing of a three-component borehole EM receiver probe. It has been shown that the two main difficulties involved in the design of a three-component probe, namely the construction of transverse sensors compact enough to fit within the probe and the problem of orienting the probe, can be overcome without major difficulties. The resulting three-component data offers advantages to interpretation over single-component data. In particular, it allows direct determination of the overall direction of the conductive body from the drillhole, whereas this parameter cannot be determined from single-component data without the aid of multiple transmitter loops or geological data.

The transverse sensors designed for this project used ferrite slabs to collect the magnetic flux and funnel it through a coil in the center. These sensors were about 30 cm long, had a sensitivity (before amplification) of 62 m² and a bandwidth of about 5 kHz. The axial sensor was even shorter, yet it had a sensitivity of 250 m² and twice the bandwidth of the transverse sensors. The entire probe, including batteries and electronics, was about 2 m in length and 41 mm in diameter. Although they have less bandwidth and signal to noise ratio than the axial sensor, the transverse sensors still provide much valuable information not available to single-component borehole surveys.

For the transverse-component data to be useful in helping to determine the direction of conductors from the drillhole, a method of determining the orientation
of the probe must be found. The probe designed for this project contained no special direction sensing devices. Instead, measurements of the transverse primary field were used to determine the orientation of the probe. Computer processing of the primary field data was necessary in order to remove the effects of the secondary field. This method of orientation was found to work fairly well for the data from the Gertrude West test site, but this does not mean that it would work as well at other sites. At sites where there is conductive overburden or where large conductors are situated between the transmitter and the receiver, the transverse primary field may be more strongly contaminated with secondary components, making orientation even less precise. Also, the geometry of the hole(s) and the available transmitter loop locations may be such that there is not enough transverse primary field to work with. It would certainly be helpful for any future three-component probe design to incorporate some alternate method of orientation, such as dip meters and/or a magnetic field compass, despite the greater expense and complexity involved.

After processing of the data from the Gertrude West site, plots were produced showing the vertical, east and north field data at various time delays as a function of depth down the drillhole. The vertical (axial) field profiles were similar in quality to those of previous surveys using a single-component probe with the same transmitter and receiver equipment. The horizontal field profiles were somewhat noisier, particularly in the earlier channels. The noise appeared to be the result of inaccurate estimates of the probe orientation and contamination of the early channels by the primary field because of the longer rise time of the transverse coils. Perhaps also, the transverse sensors have a greater susceptibility to small conductors intersected by or near to the hole. Some of the noise could also be due to the greater intensity of natural or man-made EM noise in the horizontal plane or to the greater electronic
noise of the transverse sensors.

Though the quality of the east and north field profiles was not equal to that of the vertical field, they still showed features very valuable to interpretation. The axial field data suggested the presence of a dipping conductive body with its lower extremities nearer to the drillhole. However, only by using the horizontal field data could some idea be gained of the direction to this conductor. While the east field data showed only a minor response, there was a strong positive to negative crossover in the north field at a depth corresponding to the peak in the vertical field data. It was obvious from this that the conductive body lies mainly to the south of the borehole, an interpretation in agreement with the available geological data.

On consideration of the field tests, some possible improvements to the probe and associated equipment come to mind. As previously mentioned, inclusion of some additional means of determining the orientation of the probe could do much to reduce the errors associated with uncertainty in orientation. A second improvement might be to increase the degree of computer control of the data recording process. A computer was used at the Gertrude West site to record the data, but the transmitter loop, field component and receiver channel all had to be selected manually. Greater computer control would reduce the tedium and the possibility of human error.

Despite the technical problems involved in the construction of a three-component EM probe, the rewards appear to be well worth the effort. Much can be learned from single-component drillhole data, but determination of the direction to the conductor is not possible without geological data or the use of multiple transmitter loops; and even then uncertainties can arise. The addition of transverse field data, however, should in most instances directly give a reasonable estimate of the direction to the conductor, and at the same time confirm other interpretations.
based on the axial data.
References


Oristaglio, M.L. and Worthington, M.H. (1980). Inversion of surface and bore-


Appendix

Probe Construction Details

Probe Casing

Overall probe length: 2.0 m

Maximum diameter: 41.3 mm (Will fit size ‘A’ (47 mm) drillhole.)

The sensors are contained in an epoxy fiberglass (G10) tube 122 cm (48 in) in length, with outer diameter 41.3 mm (1.625 in) and inner diameter 31.8 mm (1.25 in).

Transverse sensor

Coil sensitivity: \( A_{\text{eff}} = 62.5 \text{ m}^2 \)

Inductance: 26.5 H

Resonant frequency (at peak amplitude, without damping): 5.2 kHz

Coil resistance (DC): 1.47 k\(\Omega\)

Damping resistance: 499 k\(\Omega\)

Amplification: \( \times 301.2 \) (preamplification: 60.0, final: 5.02)

The transverse-field sensor coils were wound in two sections using 40 gauge wire. The coils contained a total of about 6700 turns. The two coil sections were separated by a plastic washer. To save space, no bobbins were used for the coils.

Figure 3.2 showed the transverse sensor construction. The diagram shows the ferrite sides of the ‘H’ as being solid. Actually, they were made up of three slabs, each about 5 \( \times \) 25 \( \times \) 100 mm (with the outside edges trimmed), placed end to end. The slabs were cut from 25 \( \times \) 25 \( \times \) 100 mm blocks (Philips ‘I’ core 1B5, material 3C5,
initial permeability: $\geq 3000$) using a diamond saw. The ends of the blocks were smoothed by grinding. Figure A.1 shows the mechanism used to hold the entire assembly of ferrite and glass spacer slabs together. The plastic strapping is placed under tension by adjusting the screw at the end. The entire sensor is surrounded by a layer of plastic and a layer of brass foil (0.0254 mm thickness) to prevent the coil from responding to the electric field. (The foil is connected by copper wire to signal ground.) A final layer of plastic surrounds the foil. The sensor is held firmly within the fiberglass tube by friction fit.

**Axial sensor**

Coil sensitivity: $A_{\text{eff}} = 252 \, \text{m}^2$

Inductance: 16.5 H

Resonant frequency: 10.4 kHz

Coil resistance: 823Ω
Damping resistance: 604 kΩ
Amplification: ×84.3 (preamplification: 16.8, final: 5.02)

Figure 3.1 showed the axial sensor construction. The central ferrite rod (1.27 cm diameter × 15.4 cm length) and the octagonal end blocks are held together by the same method as the transverse sensor components. The end blocks were cut from the same ferrite blocks used for the transverse sensor slabs. The axial sensor coil contains 10,000 turns of 36 gauge wire wound in five sections. Each section was wound on a bobbin (Philips pot core coil former 3019-F1D). Figure A.2 is a detailed cross-section through the axis of the sensor, showing the coils and the signal guarding scheme (not shown in figure 3.2). Thin strips of brass foil (0.0254 mm thickness) around the inside and outside of the coils are maintained at potentials close to those of the adjacent sections of coil by means of a resistor voltage divider network powered by the output of the preamplifier. Like the transverse sensor, the axial sensor is surrounded by a layer of plastic and a layer of brass foil in order to shield the sensor from the electric field. The overlapping edges of the foil are not in electrical contact.

Electronics

Figures A.3 to A.7 show the electronics of the three-component probe system. Most details are shown, with the exceptions of the various power supplies (batteries) and the interconnections between probe and cable, winch and buffer box etc. Figure A.3 gives an overview of the probe and surface electronics. The probe electronics includes the three preamplifiers (contained in the lower section of the probe along with the sensors), the control circuitry which selects which of the three signals is sent to the surface, and the final buffer amplifier. At the surface, the cable
Figure A.2: Cross section of the central section of the axial-field sensor, showing the hookup of the five coils and the signal guarding scheme.

(or rather the winch at the end of the cable) is connected to the control/buffer box which is in turn connected to the receiver. The control/buffer box contains the control board which sends the pulses to the probe that select which of the signals is sent to the surface, and the buffer board which buffers the incoming signals and can either amplify or attenuate them to the level required by whatever receiver is being used.

The preamplifiers of the sensors (figure A.4) are simple single-input, noninverting amplifiers built using precision low noise opererational amplifiers (AD OP-27G produced by Analog Devices). The axial and transverse amplifiers differ only in the degree of amplification and damping. The axial preamplifier also provides the voltage used in the signal guarding of the axial coils.

The probe control circuitry (figure A.5) selects the signal to be directed to the surface based on the length of pulses sent from the control/buffer box at the surface
Figure A.3: Overview of probe and surface electronics.
**Figure A.4a:** Transverse-field sensor preamplifier.

**Figure A.4b:** Axial-field sensor preamplifier.
Figure A.5: Schematic of probe control and output board.
along the shield of the cable. The cable shield is connected to ground at the probe through a resistor and capacitor in parallel. Any pulse of sufficient amplitude and duration will trigger the circuitry and select the signal by means of a CMOS analog switch. Not shown are the two sets of batteries; one set for the control circuitry, and another with regulators for the preamplifiers. The batteries are standard 9 V transistor batteries. The preamps draw about 7.7 mA and the control circuitry and buffer amplifier draw about 3 mA (at low signal levels with no load). Each set of batteries should be good for at least two days use.

Figure A.6 shows the control board of the control-buffer box. Pushing switches 1 to 3 momentarily connects the full 9 V battery voltage between the cable shield (guard) and the ground wire for a duration of 0.1, 0.2 or 0.3 s. The LED provides visual confirmation that a switch was successfully pressed. Power for the control board is a single 9 V battery.

Finally, figure A.7 shows the buffer board of the control-buffer box. The input section is simply the standard instrumentation amplifier configuration with a selectable gain of ×1 or ×10. Following this is an attenuator, used for receivers requiring low signal levels. The circuit also includes a meter for monitoring the peak amplitude of the signal. Output to the receiver can be single or double sided. The circuit is powered by two 9 V batteries, and draws about 17 mA of current.

Mention should be made of the various grounds in the system. Each preamplifier in the probe has a signal ground and a power ground. The three power grounds are connected to the preamp regulators (not shown) and then to ground mecca near the batteries. The three signal grounds join at the probe’s control(buffer board. Ground is connected to the metal case of the probe and thus to the local ground at the borehole. The probe ground is isolated from ground of the surface control(buffer
Figure A.6: Schematic of the control board of the surface control/buffer box.

Appendix: Probe Construction Details

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Figure A.7: Buffer board schematic. All amplifiers are TL084IJ's. All resistors are precision 1% resistors.
box (using the instrumentation amplifier), though a switch is provided to connect probe and surface ground if desired. For the downhole tests reported in this thesis, the grounds were left unconnected and the buffer board was set to attenuate the signal by a power of ten.