INTERPRETATION OF AIRBORNE EM MEASUREMENTS
BASED ON
THIN SHEET MODELS

BY

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ABSTRACT

An airborne electromagnetic (AEM) prospecting system is used as a very rapid means of economically searching large geologically potential areas for sulphide ore bodies within the top few hundred feet of the earth's surface. This is possible because massive sulphide ores are usually much more electrically conductive than most host rocks. The system usually consists of a transmitting coil and a receiving coil flown by an aircraft. The transmitting coil generates a time-varying magnetic field in the low audio-frequency range (100-4000 Hz). Any small perturbations of a component of the field are then recorded continuously as the aircraft flies along flight lines. The record over a conducting body is called an anomaly profile.

The magnitude of an anomaly depends on conductivity, size and shape of the conducting body causing it, and the flight direction and height of the AEM system. Interpretation is based on a qualitative or quantitative comparison of the observed response (anomaly) with the responses that would be observed by the system over simple idealized conductors. Many geological conductors are somewhat sheet-like in form and dip into the earth at an appreciable angle. The extent of the sheet is often large compared to the region sensed by the system. Both for airborne and ground EM measurements the single most important model has been the (thin) half-plane. For the multitude of AEM systems actually in use even this simple model has not been fully explored. The only available data are the peak amplitudes of the vertical half-plane for 'small-scale' systems (inaccurate) and the Lockwood quadrature system, and some profiles over perfectly
conducting half-planes for a variety of systems plus a few random model profiles for a few systems.

The thesis contains systematic studies with several AEM systems over vertical and dipping half-planes, vertical and flat ribbons, strike limited sheets, vertical half-plane under a thin flat overburden and two parallel half-planes. Studies have been restricted to thin conductors because of modelling convenience, and to keep the number of parameters under control. While thick bodies are interesting, the simpler thin case must obviously be done first.

Field and model data have been compared in a number of cases, and it is found that most of the field data is explicable without further elaboration of the models. However, certain discrepancies are found even in these selected cases which indicate that additional features of the conductors may have to be taken into account (and cast suspicion on the quality of altimetry). In the cases examined, it did not seem that the conductivity of host rocks was having much influence.

The study indicates that it is often possible to discriminate flat-lying conductors from dipping conductors with the present systems. Other effects such as finite extent, influence of overburden, and fringe conductors are difficult to identify from a single flight with a current AEM system.
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I. INTRODUCTION

I.1 What is an AEM System?

An airborne electromagnetic (AEM) prospecting system is used for the detection of subsurface bodies which are electrically conducting. It consists usually of a transmitting coil and a receiving coil flown by an aircraft. A controlled time-varying magnetic field is produced by the transmitter. Most often the frequency of the transmitting current is in the range 100-4000 Hz. A component of the field is then recorded at a point separated from the source, by measuring the $emf$ induced in the receiving coil.

The transmitter can be thought of as having a dipole type alternating magnetic field. If a conducting zone is in the vicinity, the source field will cut it, and induced or eddy currents will flow inside the conductor in closed loops more or less normal to the direction of the magnetic field. These eddy currents, in turn, will generate their own magnetic field. Thus at any point, the total magnetic field is composed of a primary field due to the source, and a secondary field due to the eddy currents induced in the conducting zone. This secondary field lags behind the primary field. Its amplitude is dependent upon the frequency of the source current and the conductivity distribution of the body. Since the secondary field is
extremely small compared to the primary field, the primary field at the receiver must be separated out somehow and only the secondary field measured. Measurements made using simple alternating fields are known as 'frequency-domain' measurements; where a complex waveform or transient time-variation is employed the measurements are said to be made in the 'time-domain'.

1.2 Actual AEM Systems:

In several actual 'frequency domain' AEM systems, the inphase (P) and quadrature (Q) components of the secondary field are measured with respect to the primary field. These quantities are recorded continuously as the aircraft flies along survey lines. They are referred to as inphase (P) and quadrature (Q) responses or anomalies, respectively. We obtain the spatial distribution of these anomalies along the flight line. Magnitudes of these anomalies are usually expressed in parts per million (ppm) of the primary field which, by definition, is totally inphase.

1.2.1 'Rigid-Boom' Systems:-

The most straightforward method of separating the secondary and primary field strengths is to have the transmitter and the receiver coils rigidly coupled so that
3.

the primary field is stable. These systems are known as the 'rigid-boom' systems. A change in the coil-separation of one part in a hundred thousand causes a change of 30 ppm in the inphase response. Presently, a sensitivity of a few parts per million has been achieved in these systems.

'Rigid-boom' systems are of three kinds depending on how the transmitter and receiver coils are mounted. In the most common kind of the 'rigid-boom' systems the coils are separated by a distance of 20-30 feet and are housed in a large bird which is towed by a helicopter by means of a long cable (Fig. 1.2.1a). The coils are vertical* and coaxially oriented, the axis being directed along the line of flight. This is known as the helicopter system (HEM). The helicopter flies at a normal height of 200 feet, and the bird trails at a height of about 100 feet. The distance between the transmitter and receiver coils is very small compared to the flight height of the bird. Because of the small dimensions of the coil-separation and the bird-height these systems are, in a rather loose term, known as 'small-scale' systems.

*Coil configurations are usually described by stating the orientation of the plane in which the winding lies, although this is more ambiguous than describing the orientation of the axes.
Airborne electromagnetic systems and their approximate dimensions.
Several of these systems are in use at the present time: Scintrex HEM-701, Lockwood LHEM 200/300, Dighem (main coaxial), Barringer HEM and Sander HEM systems. The frequency employed in the systems is usually 900-1000 Hz. The Lockwood LHEM system has a choice of a high frequency of 4000 Hz besides the normal frequency of 1000 Hz. Typical inphase and quadrature anomalies for a large, outcropping conductor are around 200 ppm and 100 ppm respectively, for a normal flight height of the helicopter. A noise level of as little as 3-10 ppm is often achieved in these systems.

Besides the main coaxial receiver coil, the Dighem system uses two more receiver coils which are null coupled (Fig. 1.2.2). This means that the primary field cutting these receiver coils is zero. The horizontal receiver coil is known as the whale-tail receiver, and the vertical receiver coil is known as the fish-tail receiver. The Barringer HEM system also has a provision to use a whale-tail receiver.

In another type of the 'rigid-boom' systems, the transmitter and receiver coaxial coils are mounted on a structure attached to the frame of a helicopter or a fixed wing aircraft. The axes of the coils are in line with the flight direction (Fig. 1.2.1b). Separation between the coils is 50-83 feet. Normal flying height is 150-175 feet. The frequency employed is around 400 Hz. The
DIGHEM SYSTEM

Fig. 1.2.2

Schematic of the multicoil receivers of the Dighem helicopter towed system (Fraser, 1972).
anomalies obtained are greater than those in the helicopter systems. Typical noise level is 20-50 ppm. The Texas Gulf Sulfer-Varian, Canadian Aero Service Canso, and Newmont-Aero Service are the three existing systems.

A third kind of the 'rigid-boom' systems uses two vertical coplanar coils as the transmitter and receiver, mounted on the wing-tips of a small fixed wing aircraft (Fig. 1.2.1c). The axes of the coils are parallel to the line of flight. These systems are known as wing-tip systems. The separation between the transmitter and receiver is 62 feet for an Otter aircraft. The aircraft flies at a normal height of 150-200 feet. The frequency employed is 320 hz. The coil separation and height of the coil system above ground surface are larger than those of the helicopter systems. These are called 'medium-scale' systems and the anomalies are higher than those obtained by the helicopter systems. The noise level is 20-50 ppm. A few of these systems which are presently in use are the Geoterrex Otter, Scintrex Rio Mullard Otter, and Canadian Aero Otter systems.

1.2.2 Quadrature Systems:-

In contrast to the two component measuring 'rigid-boom' systems, there exist a kind of system in which only the quadrature components of the secondary field are measured at two different frequencies. These systems are
known as dual frequency quadrature systems, or simply, quadrature systems. Because the inphase components are not utilized, the stability requirements in the relative positioning of the receiver and transmitter coils are very much relaxed. The transmitter may be a big loop wrapped around the wings and tail of the aircraft. The receiver is towed in a bird by means of a long cable. Systems using the receiver on a bird, towed behind the aircraft, are generally known as towed bird systems (Fig. 1.2.1d). The horizontal and vertical separations between the transmitter and receiver are a few hundred feet. The aircraft flies at a normal height of about 450 feet. Due to the greater dimensions of these systems, they are often called 'large-scale' systems. Two quadrature systems exist in the industry: one is the Lockwood LEM 200 and the other is the McPhar F-400. The Lockwood system employs a horizontal coil as the transmitter, and a vertical coil, with its axis along the line of flight, as the receiver. The orientations of the coils of the McPhar system are just the opposite. It has a vertical coil as the transmitter and a horizontal coil as the receiver. The horizontal and vertical separations of the Lockwood system are about 420 feet and 230 feet, and of the McPhar system are about 200 feet and 325 feet, respectively. The frequencies of the Lockwood system are 400 hz and 2300 hz, and those of the McPhar system are 340 hz.
1070 Hz. The anomalies obtained in the field are typically a few thousand ppm. The noise level is around 500 ppm.

I.2.3 Transient (Input) System:

In all the systems already discussed the measurements are made in the 'frequency-domain'. Only in the Barringer INPUT system are the measurements made in the 'time-domain'. This is a towed bird system of the standard geometrical configuration. The coil system consists of a horizontal transmitter coil, and a vertical receiver coil with its axis along the line of flight. This system resembles the Lockwood quadrature system. The transmitter coil is energized with what is essentially a pulse current in the form of half of a sine curve. In the absence of any conductor, a sharp transient $\text{emf}$ proportional to the time derivative of the magnetic field is produced at the receiver in the form of half of a cosine curve (Fig. 1.2.3). When a conductor is present, however, the sudden change in the primary magnetic field intensity will induce in it a flow of current which will slowly decay, and will, through its secondary field induce an $\text{emf}$ in the receiver after the primary field has ceased. The primary field is alternated in polarity and lasts for 6.92 msec. It is repeated 144 times a second
Principle of the time domain INPUT system: a) Primary current pulses alternate in polarity, the fundamental frequency is 144 Hz.; b) Emf due to primary field as detected in the bird; c) Emf due to secondary field, as detected in the bird. The emf decay is sampled at six time intervals, centred at 0.26, 0.48, 0.75, 1.1, 1.57, and 2.10 msec after cessation of the primary pulse (Palacky, 1972).
as the aircraft flies, so that the signal is virtually continuous. The decay curve is sampled six times after cessation of the transmitting pulse. It should be noted that it is not decay of the magnetic field but its time derivative which is recorded, because a coil is used as a receiver. The entire decay of the secondary field is equivalent to 'frequency-domain' measurements over the whole frequency spectrum.

1.3 What is an AEM System Used For?

An AEM survey is employed as a very rapid means of economically searching large, geologically potential areas to detect sulphide ore bodies within the top few hundred feet of the earth's surface. The objectives of an AEM survey are somewhat more limited than, or are at least different from, those of a ground survey. The primary objective in both cases is to discover zones of sulphide mineralization and to discriminate between different types of conductors. Beyond this, a ground survey is usually required to provide some information of the shape of the conductive body and to pinpoint its position sufficiently well so that a drill might be accurately aimed towards it. This second objective is rarely required of an AEM survey.

The physical property of the sulphide deposit which is responsible for its detection by AEM surveys is
the high electrical conductivity. Sulphide minerals including those comprising the usual ores of copper, nickel, lead and silver possess this common property. Most unweathered igneous and metamorphic rocks have very low electrical conductivity, and they are essentially insulating as far as AEM measurements are concerned. Hence, the AEM system may produce distinct anomalies over electrically conducting bodies.

It is well known, however, (e.g. Paterson(1971)) that the electrical conductivities of sulphide ores overlap those of several uneconomical but commonly occurring geological materials, including soils, graphitic schists and carbonaceous sediments, water filled faults and shear zones, swamps, etc. So, it is easy to comprehend that an overabundance of anomalies may be obtained in an AEM survey. It is therefore expected that the AEM systems give some indication of the conductor's general characteristics so that only those which offer reasonable promise may need be further investigated. In many cases, sulphide mineralized zones occur in the form of steeply dipping sheet type bodies.

The information which could be obtained from the AEM survey are: 1) the type of model which the conductor resembles; 2) how long the conductor extends in the strike direction; 3) the direction in which the conductor dips and some idea of the dip angle; 4) the
depth to the top of the conductor, and 5) an indication of the quality of the conductor, i.e., an estimate of its conductivity ($\sigma$) or the product of the conductivity and thickness of the conductor ($\sigma t$).

Very often pyrrhotite, which is magnetic, is associated with sulphide ore bodies. It is customary to fly a magnetometer and, often also a radioactive measuring device on the aircraft along with electromagnetic equipment. The AEM survey is correlated with these before the final conclusions about the conductors are reached.

1.4 **Basis of AEM Response:**

For surveys in the Canadian shield, the single most common occurrence of conductive zones is as steeply dipping sheets. Such bodies have large dimensions along the strike and dip directions and can be approximated by a conducting half-plane model.

To investigate how the different parameters of a conducting half-plane are involved in yielding AEM response we should study the wave equation for the magnetic field which, inside the body, is

$$\nabla^2 \vec{H} = i\mu\omega\sigma_1\vec{H} - \varepsilon\mu\omega^2\vec{H}$$  \[1.4.1\]
and, outside the body, is

\[ \nabla^2 \mathbf{H} = i \mu \omega \sigma_0 \mathbf{H} - \varepsilon \mu \omega^2 \mathbf{H} = 0 \quad [1.4.2] \]

where, '\(\mu\)' = magnetic permeability, '\(\omega\)' = \(2\pi f\) = angular frequency of the field, '\(\sigma\)' = conductivity, and '\(\varepsilon\)' = dielectric constant. The frequencies employed in AEM systems are in the low audio range. For most earth materials, 
\[ \mu = \mu_0 = 4\pi \times 10^{-7} \text{ henry/meter}, \quad \varepsilon = 9\varepsilon_0 = 80 \times 10^{-12} \text{ farad/meter}, \text{ and '}\sigma' \text{ has a range of } 10^{-9} \text{ to } 10^3 \text{ mho/meter.} \]

The first term in the right-hand side of the equation [1.4.2] is three to ten orders of magnitude larger than the second term. For all practical purposes the second term can be neglected. The wave equation [1.4.2] reduces to a vector diffusion equation inside the body:

\[ \nabla^2 \mathbf{H} = i \mu \omega \sigma_0 \mathbf{H} \quad [1.4.3] \]

and, Laplace's equation outside the body:

\[ \nabla^2 \mathbf{H} = 0 \quad [1.4.4] \]

Applying dimensional analysis to the above equation (e.g. Grant and West (1965)) one can show that the response of an electromagnetic measuring system, where only a single
conductive zone is involved, is controlled by the quantity
\[ \Theta^2 = (\mu \omega \sigma) l_1 l_2 \]
where, \( l_1 \) and \( l_2 \) are linear dimensions of the model and, or the prospecting system. The quantity \( \Theta \) is a dimensionless parameter and thereby remains invariant for a particular geologic problem. The quantity \( \Theta^2 \) is known as the response parameter. In fact, \( l_1 \) and \( l_2 \) may be any linear dimensions of the problem; however, results are easiest to understand if they are chosen to be dimensions which most effectively control the volume of eddy current circulation. Since the response parameter \( \Theta^2 = \mu \omega \sigma l_1 l_2 \) is a dimensionless quantity, it serves as the basis for scale model measurements in the laboratory which will be exactly equivalent to those observed at different frequencies, conductivities, and dimensions in the field.

For an AEM system over a thin sheet type of conductor, one may choose \( l_1 = t \), and \( l_2 = H \), where \( t \) = thickness of the sheet, \( H \) = height of the system above the sheet, (and \( L = \text{coil-separation} \)). The property of the response parameter \( \Theta^2 = \mu \omega \sigma t H \) is such that provided the value of the parameter is maintained constant and the geometry of the system is kept unchanged, the individual quantities can be varied without affecting phase of the response of the system. The conductivity \( \sigma \) and \( t \) are inseparable. The thickness \( t \) is then assumed not to be of any geometrical importance. The quantities
'ω', 'L' and 'H' characterize an AEM system, and the product 'σt' characterizes the conductor. This analysis is valid for very thin conductors. For thick conductors, the thickness plays an important part in the eddy current circulation (Lamontagne, 1970).

To get a qualitative idea of how a conductive ore body may respond to an EM system one may consider the body as a one turn coil having a resistance 'R' and a self-inductance 'L'. Suppose the transmitter carrying a current equal to $Ie^{iωt}$ produces an alternating magnetic field '$H_p$'. The induced emf '$E$' at the conductor lags 90 degrees behind the primary field, and it is proportional to the rate of change of total flux linkage:

$$E = -iμ_0 ω Ie^{iωt}$$  \[1.4.5\]

The secondary field produced by the presence of the conductor depends on this emf '$E$', the resistance 'R', and self-inductance 'L'. This is given by

$$H_s = \frac{-iμ_0 ω Ie^{iωt}}{R + iωL}$$  \[1.4.6\]

This secondary field '$H_s$' lags $α = 90^\circ + φ$ degrees behind the primary field, where $φ = \tan^{-1} \frac{ωL}{R}$. The quantity
\( \frac{\omega L}{R} \) is dimensionless; and, it depends on the frequency of the transmitting current and conductivity distribution of the ore body.

![Diagram showing phase relationship between primary, secondary, and total fields](image)

**Fig. 1.4.1**

The phase relationship between the primary \( (H_p) \), the secondary \( (H_s) \), and the total \( (H_t) \) fields inside a conductor.

The relation between the primary \( H_p \), the secondary \( H_s \) and the total \( H_t \) fields is shown in Fig. 1.4.1. From Eq. [1.4.6], it follows that a poor conductor produces a secondary field \( (R \to \infty, \phi = 0) \) which is small and is almost in quadrature to the primary field. Whereas for a good conductor, the secondary field \( (R \to 0, \phi = 90^\circ) \) is almost inphase and it cancels the primary field. Between these two limits, the inphase and quadrature components undergo a smooth transition. The same effects are observed by increasing or decreasing the frequency of the primary field.
1.5 *Present State of the Art:*

AEM surveys were first performed in 1950 after development of the International Nickel Company system. The first commercially available equipment was the Hunting system, an older version of the present Lockwood quadrature system, which came into the market in 1954. It immediately met with success. Its remarkable discoveries of the seven ore bodies during 1954–1956 in New Brunswick was at least partly due to skimming, because virtually all areas then were virgin to AEM prospecting. Many of the other systems became available during 1956–1958. But the success rates of finding ore bodies declined after 1956. The mining companies relaxed their efforts in AEM prospecting and AEM surveys continued at a slower pace.

One of the reasons for the above decline is the lack of tools and techniques to aid interpretations of AEM data. Model experimental and theoretical data to compare with the actual field profiles are too scanty. The sponsors of the AEM systems have not accepted responsibility for acquiring these data. The shortage of technical information on this aspect has led not only to under-interpretation and wasteful field programs, but also to certain misconceptions concerning the relative merits of different AEM systems (Paterson, 1971). Since discrete anomalies are obtained over electrically conducting bodies,
the geophysical companies were more concerned to improve the noise level of the AEM systems than to devise means of better interpretation of AEM anomalies.

The only published efforts that have offered tools for interpretation were by Paterson (1961) and Wieduwilt (1962). Hedstrom and Parasnis (1958) described characteristics of the two plane system which was developed in Sweden. Paterson (1961) worked with North American systems. He dealt with an older version of the Lockwood quadrature system. He gave a quantitative analysis of the profiles over the sheet type conductors, and described tools for semi-quantitative interpretational techniques. Most of the analysis was based on theoretical study of infinitely conducting thin sheets and only a few on actual scale model experiments. Wieduwilt (1962) studied the Newmont Aero 'rigid-boom' coaxial coil-system over sheet type conductors by scale model experiments. He produced a phasor plot of the inphase and quadrature responses for different 'σt' values, and for different heights of the system. For small 'σt' and higher altitudes of the system, the phasor diagram is inaccurate. Boyd and Roberts (1961) described some scale model experiments over vertical sheet type conductors for the Rio Mullard wing-tip system. The results were of only qualitative value. Grant and West (1965) outlined the schemes of AEM inter-
pretation, and gave an insight to the interpretation of AEM data. Ward (1967), and Ward and Hood (1969) compiled data available from different published sources to aid interpretation. Becker (1972) did some model studies of the Barringer INPUT system. Only recently, the work of Palacky (1972) contains interpretational tools of the Barringer INPUT system for vertical half-plane models derived from the scale model work of the writer performed for this thesis. Paterson (1971) has studied performance characteristics of different AEM systems on the basis of theoretical computations of half-plane models of infinite conductivity.

1.6 **Standard Interpretation Method:**

The usual procedures of interpreting field anomalies of a) the inphase and quadrature measuring systems, b) the dual frequency quadrature systems, and c) the Barringer INPUT system are based on standard nomograms prepared from scale-model measurements in the laboratory. The single most useful model so far developed for the interpretation of all electromagnetic anomalies over mineralized zones is a thin, conducting sheet of infinite depth-extent and strike-extent, termed a half-plane. All the standard nomograms are based on the vertical half-plane model. The existing nomograms over
the vertical half-plane and how they are used are briefly described here.

1.6.1 Inphase and Quadrature Measuring Systems:

Fig. (1.6.1) shows a standard nomogram (Podolsky, 1966) of the Texas Gulf Sulfer Co. helicopter system which has a coil-separation of 50 feet and a frequency of 400 hz. The peak inphase and quadrature anomaly amplitudes, from scale-model measurements, over the vertical half-plane conductor have been plotted along x and y axes, in the same linear scales, in parts per million (ppm) of the primary field. The inclined lines represent values of constant 'σt' and the curved lines represent different flight heights of the AEM system. A diagram such as this which plots one or more (usually two) "characteristic" measures of the anomaly profile, over a vertical half-plane, as a function of one or more (usually two) model parameters is known as a "characteristic plot for a vertical half-plane". However, because in this case, the characteristic measures are inphase and quadrature components, each point in the diagram represents a phase vector or phasor, and the plot is usually referred to simply as the vertical half-plane phasor diagram. From this diagram, it is easy to comprehend how the phase and amplitude change due to variations of certain model
Fig. 1.6.1

Phasor diagram over the vertical sheet model for the Texas Gulf Sulfer AEM system. The operating frequency is 400 hz and coil-separation is 50 feet (Podolsky, 1966).
parameters. Although correct in principle, the anomalies for progressively larger heights and smaller \( \sigma t \), in this diagram, have been found to be inaccurate by the work described in this thesis.

Anomaly amplitudes fall off very rapidly with height. Therefore, it is often useful to plot them on double log scales. Fig. 1.6.2 shows such a plot (Wieduwilt, 1962) for the Newmont Aero helicopter system which has an operating frequency of 400 Hz and a coil-separation of 60 feet. This kind of plot will be called a \( P-Q \) summary diagram. This particular diagram is also found to be inaccurate for progressively larger heights and smaller \( \sigma t \).

To investigate field anomalies caused by a conductor which resembles a vertical half-plane model, a point corresponding to the inphase and quadrature anomalies is plotted in this \( P-Q \) summary diagram. The values of \( \sigma t \) and \( H \) are estimated from this point by interpolation between the closest curves of \( \sigma tf \) and \( H \). When the actual conductor is suspected of being more complicated than a simple sheet the estimate of \( \sigma t \) is known as the apparent \( \sigma t \). The flying height of the aircraft in a field survey is recorded by a radio altimeter. The depth to the top of conductor under ground surface is then obtained from the difference of estimated \( H \) from the \( P-Q \) summary diagram and height of the
HELIICOPTER SYSTEM

Fig. 1.6.2

Phasor diagram over the vertical sheet model for the Newmont Aero AEM system. The coil-separation is 60 feet (Wieduwilt, 1982).
AEM system from the altimeter trace. An unreasonable value of this depth indicates that the conductor does not resemble a vertical half-plane model, and the estimate of apparent 'σt' is probably also wrong.

I.6.2 Quadrature Systems:

Fig. 1.6.3 is a '2-f' summary diagram (Brant, et al, 1966) for the Hunting system, presently the Lockwood quadrature system, prepared from scale model measurements over the vertical half-plane. The y-axis represents log of quadrature response at the low frequency (400 Hz), and the x-axis represents log of the ratio of quadrature responses at the low (400 Hz) and high frequency (2300 Hz). Each curve is for a particular height of the system above conductor. Inclined lines are of constant 'σt'.

In a field survey, the quadrature components at low and high frequencies are recorded separately. A point is plotted in the '2-f' summary diagram derived from the anomaly amplitudes. The values of apparent 'σt' and 'H' are estimated by interpolation between the closest lines and curves.

I.6.3 The Barringer 'INPUT' System:

Fig. 1.6.4 (Palacky, 1972) shows a nomogram for the Barringer INPUT system over a vertical half-plane
LOCKWOOD QUAD. SYSTEM

Interpretive diagram of the Hunting, presently, Lockwood quadrature system for the vertical sheet model (Brant, et al. 1966).
Fig. 1.6.4

Nomogram for estimation of 'at' and conductor depth. The peak anomaly amplitudes have to be plotted on a transparent paper using the scale on the right-hand side when the data points are to be translated to fit the respective curves. The position of 100,000 ppm mark (circle) will indicate 'at' and depth (after Palacky, 1972).
conductor prepared from model measurements performed in the 'frequency-domain' (Ghosh and West, 1971). In the lower graph, the 'σt' and 6-channel amplitudes have been plotted along the 'x' and 'y' axes respectively, in double log scales. The upper graph has the same x-axis as the lower one, and the inclined y-axis represents heights of the system above the conductor.

The 6-channel amplitudes of a field anomaly should be plotted on a tracing paper with the same vertical logarithmic scale shown on the right-hand side of the lower graph. The 100,000 ppm point must also be marked. Then the line of points should be fitted to the curve family by shifting along both the x and y axes, but without any rotation. The position of 100,000 ppm mark on the upper grid will indicate the values of apparent 'σt' and 'H'.

1.7 Object of the Thesis Research:

The primary objective of the thesis research is to gather knowledge about interpretation of measurements by all the different types of AEM systems. It has been brought out (Sections 1.5 and 1.6) how field surveys by AEM systems suffer from lack of adequate interpretational tools. Model experimental and theoretical data are too scanty to compare with the actual field anomaly profiles. The available experimental data over the standard model conductors contain errors. Therefore, the first step in
the right direction is to gather a complete knowledge of responses of AEM systems over the standard model conductors. The single, most useful model so far developed for the interpretation of all ground and airborne electromagnetic anomalies over mineralized zones is a thin, conducting sheet of infinite depth-extent and strike-extent, termed a half-plane. Since the theoretical solutions of the problems of electromagnetic fields over a conductor of finite conductivity is very difficult to obtain, high sensitivity scale-model measurements have been used in the laboratory over thin half-plane like sheets. To this end, we have investigated basic behaviour of different AEM systems. Once this is done, field data over a few known geological conductors have been interpreted and a certain agreement and disagreement of results by different AEM systems have been noted.

A real AEM system uses a filtering network in the electronic equipment to smooth out weak, rapid fluctuations in the recorded signal. Effects of the smoothing operation have been studied with reference to vertical half-plane models using computer simulated filters.

Scale-model measurements have been made to see how deviations from a standard vertical half-plane model affects interpretation of field anomalies. Dipping half-
plane sheets with different strike-angles and finite-size sheets have been used to study this.

Usually, in field surveys, geological bodies of no economical importance (swamps, muskegs and underground saline aquifers) yield very large AEM anomalies. Investigations have been made using horizontal-sheet models to see how they can be distinguished from steeply dipping sulphide bodies.

Finally, responses of flat-lying poorly conducting overburdens over steeply dipping conductors, and two parallel conductors have been studied.
II. MODEL MEASUREMENTS

II.1 **AEM Systems Studied:**

Scale model measurements have been performed with six different kinds of AEM systems which characterizes almost all the systems presently in use in geophysical exploration. The systems which have been modeled are described here.

1) **Helicopter System (HEM):**— This system consists of two vertical coaxial (maximum coupled) coils as the transmitter and receiver having a separation of 30 feet.

2) **Wing-Tip System (WT-Otter):**— It consists of two vertical coplanar coils separated by 62 feet.

3) **Barringer System:**— This is a towed bird system of the standard configuration. The plane of the transmitter coil is horizontal and that of the receiver coil is vertical. The horizontal and vertical separations are 385 feet and 240 feet, respectfully. It also resembles closely the Lockwood quadrature system.

4) and 5) **Whale-tail and Fish-tail Systems:**— These are the secondary horizontal and vertical null coupled receiver coils used with the main maximum coupled receiver coil
MODEL EQUIPMENT

WHALE-TAIL CONFIGURATION
of the helicopter system. Dighem is the only real system which uses both these receivers. The Barringer helicopter system may be flown with a whale-tail receiver coil in place of the standard vertical coaxial receiver coil.

6) McPhar System:— This is an inverted towed bird system with a vertical transmitter and a horizontal receiver. The horizontal and vertical separations between the coils are 200 feet and 325 feet, respectively.

The real AEM systems may not have exactly the dimensions that have been assumed for them in this study. This is a particular problem with the towed bird systems as the dimensions are not readily controlled. They are likely to be changed when modifications have been made to the equipment and there may be considerable variation from aircraft to aircraft. It is also very difficult to find out the exact position of the bird with respect to the aircraft in any towed bird system. Though the dimensions of the towed bird systems used in this study have been selected very carefully, they are only approximate to the real dimensions. Theoretical computations for the perfectly conducting half-plane model show that minor changes in the dimensions of a towed bird system do not alter the shape of an anomaly profile; however, the magnitude of the anomaly changes appreciably. (A ten
percent change in the horizontal or vertical dimension of
the McPhar system changes the magnitude of an anomaly by
about 25 percent).

II.2 Quadrature and Transient Systems:

All model data have been obtained as continuous
inphase \((P)\) and quadrature \((Q)\) anomaly profiles at a
single frequency of 1000 Hz. Anomalies have been expressed
in parts per million of the primary field. Three of the
AEM systems: the Barringer INPUT, the Lockwood and the
McPhar systems measure different quantities. To obtain
anomaly profiles for these systems requires interpolation
of new profiles for \(\sigma t f\) values which are intermediate
between those of the model measurements. This is all that
is necessary for the quadrature systems and summary
diagrams have been obtained for them. For the 'time-domain'
INPUT system, a further computation is required: the simu-
lated anomaly profile for each time delay channel is
obtained as a weighted sum of a set of interpolated profiles.
This has been feasible (Falacky, 1972) at least for the
profile suites for the vertical half-plane model where a
complete range of \(\sigma t f\) values was covered by the models.
II.3 Model Conductors:

Only sheet-like model conductors have been used. All model conductors were cut from 3 ft. × 9 ft. sheets of low alloy aluminum (ALCAN DS2) or from rolls of aluminum foil. To change the parameter 'σtf', the thickness rather than the frequency, has been changed. A list of the various thickness and corresponding conductivity data is given in Table (2.3.1). The largest size of model conductor was 60 in. × 30 in. (strike × depth extent) and this size adequately approximated a half-plane in most cases.

The conductivity of commercial aluminum varies widely with alloy composition and probably also with fabrication process. Conductivity of model sheets has been determined by cutting a sample strip (~2 cm. × 200 cm.) from stock material of each thickness and measuring its resistance by direct voltage and current measurements, and its dimensions. Table (2.3.1) lists the surface and bulk conductivities for each thickness of sheet.

The directly measured surface conductivity of each thickness of sheet was used in the model work, rather than a mean conductivity and the measured thickness. The 'σtf' measurement accuracy is estimated at ±1%.
TABLE 2.3.1

CONDUCTORS

<table>
<thead>
<tr>
<th>Conductor No.</th>
<th>Thickness (in.)</th>
<th>$\sigma t$ ($10^4$ mhos)</th>
<th>$\sigma$ $10^6$ mho/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1285</td>
<td>11.44</td>
<td>35.1</td>
</tr>
<tr>
<td>2</td>
<td>0.0638</td>
<td>5.33</td>
<td>32.9</td>
</tr>
<tr>
<td>3</td>
<td>0.0403</td>
<td>3.36</td>
<td>32.9</td>
</tr>
<tr>
<td>4</td>
<td>0.02507</td>
<td>2.10</td>
<td>33.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0162</td>
<td>1.303</td>
<td>31.7</td>
</tr>
<tr>
<td>6</td>
<td>2x0.00526</td>
<td>0.881</td>
<td>33.0</td>
</tr>
<tr>
<td>7</td>
<td>0.00526</td>
<td>0.440</td>
<td>33.0</td>
</tr>
<tr>
<td>8</td>
<td>2x0.0010</td>
<td>0.168</td>
<td>33.2</td>
</tr>
<tr>
<td>9</td>
<td>0.0010</td>
<td>0.0841</td>
<td>33.2</td>
</tr>
</tbody>
</table>

Specifications of Conductors Used for Model Measurements
II.4 Measuring Apparatus:

The electronic system is shown in Fig. 2.4.1. The signal in the transmitting coil is derived from a stable oscillator. An electronic counter kept a check on the frequency. Great care was taken to stabilize the operating frequency because the receiving circuitry was tuned. The current in the transmitter was supplied from a stabilized power amplifier, and it was measured as the potential drop across a 10 ohm shunt by a VTVM. The primary field is approximately nulled at the receiver by means of a few turns, in series with the transmitting coil, wound on the receiver. The receiver coil was electrostatically shielded.

Before measurements were taken, any stray inphase and quadrature voltages at the receiver were finally nulled manually. This was done by passing small inphase and quadrature currents into two bucking adjustment coils on the receiver by means of potentiometers. The receiver was parallel resonated and connected to a low noise amplifier and a tuned filter. The output of the filter was fed into a phase detector system which breaks the signal into the inphase and quadrature components with reference to the transmitter current. These components were recorded by a two channel chart recorder. Because of a highly tuned receiving circuitry, the phase was checked frequently by introducing a small purely inphase signal
Fig. 2.4.1

Block diagram of electromagnetic measuring equipment for the model studies.
into the receiver by means of a calibration coil connected in series with the transmitter. The primary field amplitude was checked regularly by observing the signal strength after disconnecting the primary field bucking circuitry and reducing the preamplifier gain. To this end, it was advantageous that the preamplifier contained an accurately calibrated attenuator.

The model coil-systems were built of commercial choke coils (Superex V-70, or V-80) with their ferrite cores removed. Different scaling factors (i.e. ratio of field scale to model scale) were used for convenience in the design of the different model coil-systems. The scaling factors for the helicopter, whale-tail, fish-tail, wing-tip, the McPhar, and the Barringer systems were 290, 305, 305, 613, 762, and 1173, respectively. The coil dimensions (~2.5 cm. dia. × 2 cm.) were not small compared to the coil-separation, except in 'large-scale' towed bird systems. However, preliminary checks showed that pairs of these coils accurately obey the dipole mutual inductance formula, even for separations of only two diameters. Small deviations from a dipole and small errors in intercoil distances were corrected by a calibration procedure where the experimentally determined anomaly amplitudes of each coil-system were adjusted to fit with theoretically determined amplitudes of the same model. Once determined, the
correction factors for each coil-system were kept constant for all experiments.

Continuous anomaly profiles were obtained by moving the model conductor under the model coil system on a wooden cart driven by a synchronous motor-driven screw. Thus, by keeping the coil system fixed, any possible small background anomalies due to leads, room walls, etc., were kept constant. The horizontal position of the conductor-cart was recorded on the profile by a microswitch on the cart which actuated the phase calibration relay when the cart passed certain floor points. Tables (2.4.1) and (2.4.2) show estimated errors in the model work.

All the measurements were taken with the model conductor at right angles to axis of the AEM system except for the cases where the effect of strike-angle was investigated. To investigate a particular limited extent of the conductor, the conductor was chosen which had infinite extents in other directions. The anomaly profiles have been presented in such a way that the plotted points on the profiles correspond to the centre point of the horizontal separation of the system. For convenience, the anomalies of all systems over the vertical half-plane are assumed to be positive. All the profiles and summary diagrams for the vertical and dipping half-plane models, different depth-extents, and different strike angles are
### TABLE 2.4.1

<table>
<thead>
<tr>
<th>NOISE</th>
<th>SYSTEM</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4,5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irregular drift (P)</td>
<td></td>
<td>1.0</td>
<td>0.5</td>
<td>5</td>
<td>1.0</td>
<td>10</td>
</tr>
<tr>
<td>Irregular drift (Q)</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>2</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Noise (P, Q)</td>
<td></td>
<td>0.1</td>
<td>0.1</td>
<td>2</td>
<td>0.1</td>
<td>2</td>
</tr>
</tbody>
</table>

Receiver System Noise (ppm)

### TABLE 2.4.2

<table>
<thead>
<tr>
<th>Factor</th>
<th>Error Limit Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry of Model</td>
<td>± 1°</td>
</tr>
<tr>
<td>Height 'H'</td>
<td>± 0.3 mm.</td>
</tr>
<tr>
<td>Horizontal Scale</td>
<td>± 1%</td>
</tr>
<tr>
<td>Origin of Horizontal Axis</td>
<td>± 1/2 cm</td>
</tr>
<tr>
<td>Systematic Amplitude Error</td>
<td>± 3%</td>
</tr>
<tr>
<td>Q amplitude scale= 'P' amp. scale</td>
<td>± 1%</td>
</tr>
<tr>
<td>Phase Error</td>
<td>± 0.5°</td>
</tr>
</tbody>
</table>

System Accuracy
contained in Ghosh and West (1971). These profiles have been computer plotted to uniform scales by L. Martin after digitizing the original chart records. A summary of all the model measurements have been presented in Appendix.
III. VERTICAL HALF-PLANE CONDUCTORS

The single most useful model so far developed for the interpretation of all ground and airborne electromagnetic anomalies over mineralized zones is a thin, conducting sheet of infinite depth-extent and strike-extent, termed a half-plane. In this chapter AEM anomalies only due to a vertical half-plane model has been investigated.

III.1 Smoothing of Signals:

Smoothing of signals in the real AEM systems has been analyzed with respect to the anomalies obtained from scale-model measurements over the vertical half-plane. In all existing AEM systems, the outputs from the electromagnetometer system are recorded continuously by a chart recorder. To combat noise in the actual signals, the outputs from the electronic system to the recorder may be passed through a filtering network and a smoothed anomaly profile is thus obtained. The effect of the time-constant of the filter is to average out weak, rapid fluctuations in the output signal, and it sometimes also decreases the amplitude and shifts the peak of an anomaly towards a later time. Amplitudes of narrow profiles are reduced more than wide ones. Though the effect of smoothing was known qualitatively, the first thought to quantitative analysis has been given by Betz (1971).
Fig. 3.1.1 shows field profiles from the McPhar quadrature system, which operates on 'time-sharing' basis. Because the system is 'time-shared' between the two operating frequencies, anomaly profiles consist of discontinuous horizontal straight lines. However, this is not important to the present discussion except that the network design of 'time-sharing' in this system has increased the effective time-constant of output filtering to more than 4 seconds.

Fig. 3.1.2 shows the effect of smoothing in the McPhar quadrature system. The solid curve is obtained from scale-model measurements over a vertical half-plane (essentially zero time-constant). The dashed curve has been produced by the computer processing of the solid curve through a simulated simple R-C filter having a time-constant of 4 seconds. The exact filter function of this system could not be obtained, but a simple R-C filter was considered to be a close approximation. The negative part of the solid curve has been wiped out completely, the amplitude has decreased by about 30%, the shape of the anomaly has widened, and a little shift of the peak of the anomaly is noticed. In a field survey, an anomaly similar to the dashed curve is obtained. Since interpretation of field anomalies are done using nomograms of amplitudes of anomalies obtained from scale-model measurements, the effect of smoothing should be taken into consideration.
WHISTLE DEPOSIT
McPHAR QUAD. SYSTEM

Fig. 3.1.1
Field profiles of the McPhar quadrature system. The small horizontal lines on the profiles correspond to the time when the transmitter is 'off'.

Fig. 3.1.2
The solid curve is obtained by model measurements (zero time-constant) over a vertical half-plane. The dashed curve represents the smoothed curve obtained by computer processing of the solid curve using a R-C filter of time-constant equal to 4 seconds.
Different AEM systems use different kinds of filters. Filter functions of a few AEM systems have been calculated and scale-model profiles have been processed by the computer with appropriate time-constants. The method really is the convolution of a static condition model profile with an assumed impulse response of the recording system to obtain anomaly profile on the real AEM system flying at a given speed. The filters generally used in helicopter systems have small time-constants (less than 1/2 second), and the anomalies are little affected by smoothing. The largest change in amplitude of anomalies due to smoothing has been found in the McPhar system which operates on time-sharing basis. A few scale model profiles of vertical half-planes have been processed by the computer simulated filter of this system. Table (3.1.1) shows how the amplitudes of anomalies are changed by the smoothing operation.

An improved version of the Barringer INPUT system has recently been put into service by Questor Ltd. This system uses a time-constant of half a second and anomalies are little affected. Previously, the Barringer INPUT system used a time-constant of more than five seconds. A comparison of field anomalies obtained by the systems with two different time-constants shows that the system with large time-constant indicates a larger apparent 'dt' as the amplitudes of the first and second channels are affected the most. This, however, could hardly be
<table>
<thead>
<tr>
<th>Table 3.1.1</th>
<th>McPhar System, 4 sec. R-C filter, speed = 132 ft/sec.</th>
<th>Half-Plane Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (ft)</td>
<td>450 550 750</td>
<td>Scale-Model Smoothed</td>
</tr>
<tr>
<td>Hz (Kppm)</td>
<td>9.4 4.3 1.4</td>
<td>450 550 750</td>
</tr>
<tr>
<td>% Change</td>
<td>28 18 14</td>
<td>31 19 11</td>
</tr>
<tr>
<td>1070 Hz (Kppm)</td>
<td>15.9 6.7 2.0</td>
<td>13.1 5.4 1.6</td>
</tr>
<tr>
<td>% Change</td>
<td>34 23 17.5</td>
<td>38 23 18</td>
</tr>
</tbody>
</table>

Effect of smoothing on amplitude of anomalies. Smaller heights show larger reduction of anomaly.
Fig. 3.1.3: Field profiles of the Barringer INPUT system using two different time-constants over the Whistle and Sturgeon Lake mines. Profiles with time-constant more than 5 seconds show larger 'at'. (Vertical scales are...
explained from the theory of smoothing operation. Fig. 3.1.3 shows a comparison of the presently used and earlier used Barringer INPUT systems over the Sturgeon Lake and the Whistle ore bodies. The presently used system with half second time-constant indicates apparent 'ot' values of 20 mhos and 23 mhos for the Sturgeon Lake and the Whistle ore bodies, respectively, where the earlier system with a time-constant of 5 seconds indicates these values as 50 mhos and 40 mhos. In the diagram, the exact vertical scales are not known; but the profiles with the present system have a higher sensitivity.

III.2 Shape of Profiles:

III.2.1 Symmetrical Systems: - Profiles over vertical half-plane conductors with a wide range of 'ot' for different heights have been obtained by scale-model measurements. Because of the inherent symmetry of orientation and positioning of the transmitter and receiver coils of the helicopter and wing-tip systems, profiles over vertical conductors are symmetrical (Fig. 3.2.1). The maximum anomaly is obtained when centre of the coil-system is directly over the half-plane. As the centre of the coil-system moves away from the conductor, in either direction, the anomaly falls-off at first sharply and then gradually to zero. In ground electromagnetic systems, large coil-separations are used compared to depths of conductors. Hence, profiles of ground electromagnetic systems contain a secondary peak of opposite polarity from the main peak anomaly on either side of conductors. No such secondary peaks are seen with the vertical coaxial or vertical coplanar systems.
VERT. HALF-PLANE MODEL

(a) HELICOPTER SYSTEM

HEIGHT = 90°

(b) WING-TIP SYSTEM

HEIGHT = 217°

Fig. 3.2.1

Anomaly profiles for the symmetrical systems over a vertical conductor are symmetrical.
HALF-WIDTH OF ANOMALIES
VERT. HALF-PLANE MODEL

○ HELICOPTER SYSTEM
● WING-TIP SYSTEM

Fig. 3.2.2

Half-widths of anomalies for the helicopter and wing-tip systems over a vertical half-plane conductor equal heights of the systems above the conductor.
Profiles are wider for larger heights of coil-system over conductors. Fig. 3.2.2 shows a plot of half-widths of profiles against heights of coil-systems over conductors. It seems that the half-width of an anomaly profile equals the height of the coil-system over the conductor. This is true only for thin conductors. Use of this property on profiles obtained in field surveys should be restricted to qualitative analysis. Half-width of an anomaly is a good check to see whether the conductor is a vertical half-plane.

III.2.2 Unsymmetrical Systems:-

Due to lack of symmetry of orientation and, or positioning of the transmitter and receiver coils, profiles of the Barringer, McPhar, whale-tail, and fish-tail systems are asymmetrical over vertical conductors. Profiles of the Barringer system have one large and one very small peak close to the points where the vertical receiver coil and horizontal transmitter coil, respectively, cross the conductor. Fig. 3.2.3 shows profiles of this system both in 'frequency' and 'time' domains. Shape and location of the anomaly do not change due to transformation. The small peak might easily get wiped out from actual field anomaly if the recording system employs strong smoothing. This small peak has been found in the field surveys only
Comparison of 'frequency' and 'time' domain profiles of the Barringer system. The anomaly shape does not change after the transformation.
recently after the time-constant of the filter of the system was reduced considerably. The anomalies get wider with increase in height of the system. Half-widths of anomalies do not obey a simple relationship with heights of the system. For heights larger than 600 feet, the trough between the two peaks becomes a negative anomaly. Half-widths of anomalies also depend on channel numbers and the 'σt' of the conductor.

Scale-model profiles of the McPhar system over a vertical conductor are quite different. As the vertical transmitter coil and horizontal receiver coil cross the conductor they produce a large positive peak followed by a small negative peak in the profile (Fig. 3.2.4). The ratio of negative to positive peak amplitudes increases with increase in height of the system. However, the negative peak is not seen in the field anomaly due to smoothing of the output signal at the receiver. The profiles become wider with increase in height of the system, but no simple relationship could be found.

The whale-tail system uses an orientation of the coils similar to the McPhar system, hence profiles are also similar (Fig. 3.2.5). Shape of profiles are well-preserved in field anomalies as the system uses a very small time-constant in the filtering network. The ratio of negative to positive peak anomalies increases
Fig. 3.2.4: Scale-model profiles of the McPhar quadrature system show a large positive peak, and a negative peak as the transmitter and receiver, respectively, cross a vertical conductor. The ratio of negative to positive peak amplitudes increases with height.
Scale-model profiles for the whale-tail system over a vertical half-plane are similar to those for the McPhar system.
FISH-TAIL SYSTEM
VERT. HALF-PLANE

\[ D = 762', \quad \theta = 90^\circ \]
\[ H = 90', \quad S = 45^\circ \]
\[ \sigma_{tf} = 14400 \]

**Fig. 3.2.6**

Scale-model profiles for the fish-tail system over a vertical half-plane. The angle between the flight line and conductor (strike) is 45 degrees. (The system does not yield any anomaly for a strike angle of 90 degrees). The peak of anomaly is not directly over the conductor.
with height of the system. This property can be used qualitatively in the interpretation of field anomalies.

The fish-tail system does not show any anomaly if the flight line cuts the conductor at right angles. Otherwise, a more or less symmetrical profile is obtained over a vertical conductor (Fig. 3.2.6).

III.3 **Summary Diagrams:**

Summary diagrams, showing how anomaly strengths vary with changes in heights and '$\sigma f$' for the vertical-half-plane model have been constructed. Fig. 3.3.1 shows one $P-Q$ summary diagram of the helicopter system when the system crosses the conductor at right angles. The coil-separation of the system is 30 feet. Each curve represents a particular height '$H$', or more precisely, the ratio of height to coil-separation ($H/L$), of the system above top of conductor. Inclined lines represent values of constant '$\sigma f$'. In the diagram, the experimental points have been plotted. Due to the finite size of the conductors used in measurements, the curve for a height of 300 feet does not represent a half-plane. The dashed curve shows the adjusted values for a half-plane. For perfectly conducting half-planes, inphase responses have been calculated by means of the computer using the theoretical solution as given by West (1960). These
**Fig. 3.3.1**

P-Q summary diagram for the helicopter system over large vertical sheets. The points represent scale-model measurement data. The dashed curve for $H = 300$ feet is corrected for finite size of conductors.
responses have been shown as tick marks on the inphase axis for each height. It is interesting to note that shapes of all the curves for different heights (corrected for finite extent) are the same. If this diagram is to be used for a helicopter system with a coil-separation which is different from 30 feet, it will be necessary to recalculate all the scaled variables. For example, if the helicopter system has a coil-separation of 60 feet, 'σtf' should be halved and 'H' should be doubled in the diagram. The only P-Q summary diagram (Fig. 1.6.2) similar to this was provided by Wieduwilt (1962). The part of the diagram for small heights and large 'σt' are correct to a certain extent. Progressively larger errors are involved for larger heights and small 'σt', because finite size conductors were used and the measuring system had low sensitivity. Fig. 3.3.2 shows the same P-Q summary diagram as in Fig. 3.3.1 but the model data have been interpolated to even values of 'σtf' for convenience in use. The dashed line represents a constant 'σtfH'. This line is parallel to the line of equal phases. The curve for a particular height may be moved along this line to obtain the curve for a different height.

Fig. 3.3.3 shows the quadrature response amplitudes over the vertical half-plane model conductors for the McPhar system plotted against 'σtf' for three heights.
Fig. 3.3.2: The same P-Q summary diagram as Fig. (3.3.1) but 'σf' lines are interpolated for even numbers. The dashed line represents constant 'σfH' = 600K. This is also a line of equal phases. A curve for any height may be translated along this line to obtain the curve for another height.
McPHAR SYSTEM
VERT. HALF-PLANE

Fig. 3.3.3

Peak to peak quadrature anomalies for the McPhar quadrature system over large vertical sheets of different 'otf' at three heights.
From this, we have derived Fig. 3.3.4 which shows a '2-f' summary diagram where the y-axis represents log of quadrature response at the low frequency (340 Hz), and the x-axis represents log of the ratio of quadrature responses at the low (340 Hz) and high (1070 Hz) frequencies. Each curve represents a particular height of the system above conductor. Inclined lines are of constant 'σtf' where the low frequency (340 Hz) has been chosen as the value 'f' in the 'σtf' parameter.

It has been noted (Section 3.1) that smoothing operation in the McPhar system has strong effects on amplitudes of anomalies. A few scale-model profiles over the half-plane have been processed by the computer simulated filter of this system. In Fig. 3.3.4, the points corresponding to anomalies due to scale model measurements have been marked as crosses; those corresponding to smoothed anomalies, as open circles. If the open circles are interpreted as due to unsmoothed anomalies, it is found that estimates of apparent 'σt' are only a little affected but estimates of depths of conductors seem to be too large. The effects are more conspicuous for small heights.

III.4 Dependence on Response Parameter:

III.4.1 Ratio of Inphase and Quadrature Responses:

One of the important quantities for inter-
Fig. 3.3.4: '2-f' summary diagram for the McPhar quadrature system over large vertical sheets constructed from Fig. (3.3.3). The circles represent effect of smoothing of scale-model anomaly amplitudes (crosses) by a computer processed R-C filter. Smoothed anomalies show very little change in '2-f'.

DUAL FREQUENCY QUADRATURE SYSTEM
McPhar SYSTEM

VERTICAL SHEET
VARIABLE CONDUCTIVITY AND HEIGHT

x — MODEL
o — SMOOTHED
TIME-CONST. = 4 sec.
SPEED = 132 ft./sec.

H = 450 ft.
H = 550 ft.
H = 750 ft.

H/L = 2.25
H/L = 2.75
H/L = 3.75

0.2k
0.5k
1k
2k
5k
10k
20k

(FREQ.)₁ = 340 hz
(FREQ.)₂ = 1070 hz

LOW FREQ. P-P QUADRATURE ANOMALY (PPM)

RATIO OF P-P QUADRATURE ANOMALY (Q₃₁₀/Q₁₀₇₀)
pretation of \('\sigma t'\), especially for steeply dipping conductors, is the ratio of the inphase \((P)\) and quadrature \((Q)\) anomalies. The same scale-model measurement data, which have been used to construct \(P-Q\) summary diagrams of vertical half-plane conductors, have been used here to show the dependence of \('P/Q'\) on the response parameter.

The Fig. 3.4.1 shows one such plot for the helicopter system in double log scales. The response parameter has been chosen as \(\Theta^2 = \omega \mu \sigma t H\). There are 54 points in the graph for six flying heights over each of the nine model conductors of different \('\sigma t'\). It should be mentioned that corrections were made for the finite size of model conductors to the inphase and quadrature anomalies at the largest height. A single linear relationship is obtained in double log plot. This proves that only the response parameter \(\Theta^2 = \omega \mu \sigma t H\) controls the phase of the response, and the coil-separation \('L'\) or \('L/H'\) ratio plays no part in determining phase. If the quantities \('\sigma t'\), \('f'\), and \('H'\) are changed in such a way that the product \('\sigma t f H'\) is kept constant, the effect is purely on the amplitude of responses. The linear relationship indicates that the ratio of the inphase and quadrature anomalies has a power law relationship with the response parameter. The graph is handy for quick interpretation as all the parameters are involved in it.
Fig. 3.4.1

Ratio of the inphase and quadrature responses of the helicopter system plotted against the response parameter $\theta^2 = \omega \mu \sigma H_{tt}$ for the vertical half-plane model, in double log scales.
Ratio of the inphase and quadrature responses of the wing-tip system plotted against the response parameter $\Theta^2 = \omega \mu \sigma \theta H_f$ for the vertical half-plane model, in double log scales. The straight line is identical to one in Fig. (3.4.1) showing identical properties of the helicopter and wing-tip systems.
Fig. 3.4.2 shows a similar plot for the wing-tip system. The points fall on a straight line, as in the helicopter system. Absence of coil-separation 'L' in the response parameter also applies to this system. It should be mentioned here that even the lowest heights used for both these systems are still larger than twice the coil-separations. A careful look tells that the straight lines in both the figures are identical indicating identical properties of these systems. The equation is found to be

\[ \frac{P}{Q} = 0.24 (Q^2)^{0.656} \]  

[3.4.1]

Using this, an expression to calculate the values of 'σtfH' for a given ratio (P/Q) is given by

\[ \sigma t m_0 \int_{X_{Hz}} H_{ft} = 1100 (P/Q)^{1.5} \]  

[3.4.2]

In both the graphs, the experimental points for very large values of the response parameter bend away from the straight line. This deviation from a straight line relationship is thought to be real and it is attributed to "thickness-effect" (Lamontagne, 1970).

III.4.2 Double-Dipole Approximation:-

Grant and West (1965) suggested that the helicopter and wing-tip systems may be considered as
essentially two superposed dipoles. This means that the
distance between the transmitter and receiver coils is so
small in comparison with flight heights, for all practical
purposes both coils may be considered to lie at the same
point, and the system may be considered to behave like a
double-dipole. If this is true, the data obtained by the
helicopter and wing-tip systems are exactly comparable if
the secondary field strength is measured in terms of the
dipole moment of the transmitter. The identity of the
\[ P/Q = f(\theta) \]
relationship and the independence of this from
'\( L/H \)' suggests this view. The secondary field strength
due to a double-dipole system over the vertical half-plane
falls-off as the third power of the height. The amplitudes
of the inphase and quadrature responses of the vertical half-
plane model for the helicopter system have been normalized
by the geometry factor '\( H^3 \)'. For convenience, the
actual heights have been expressed in terms of the normal
flying height '\( H_0 \)' which is equal to 100 feet. These
have been plotted (Fig. 3.4.3) against the response para-
meter \( \theta^2 = \omega \mu \sigma H \) on a semi-log paper for 54 experimental
measurements. The points for each of the inphase and qua-
drature responses lie in one curve giving a single
functional relationship*. This proves that the helicopter

* We call it a response diagram.
VERTICAL HALF-PLANE

HELICOPTER SYSTEM

H₀ = NORMAL BIRD  H₁ = 100'

○ - IN PHASE (P)
● - QUADRATURE (Q)

H > 60 FEET.

Fig. 3.4.3: Response diagram shows that single functional relationships are obtained for the inphase and quadrature responses when they are normalized by \((H/H₀)^3\). This reveals that the helicopter system behaves like a double-double system.
system truly behaves like a double-dipole system. The scatter of the points may be due to two reasons: the deviation from exact double-dipole situation, "thickness-effect" at large values of the response parameter, and experimental errors. Especially the points corresponding to large heights - resulting in small anomalies - may have contained errors.

A similar plot of the response curves of the wing-tip system is shown in Fig. 3.4.4. Since primary field at the receiver of the coplanar configuration of the wing-tip system is half as small as for the coaxial coil-configuration of the helicopter system of the same separation, a multiplying factor of two has been introduced in the vertical axis. The normal flying height $H_0$ is 150 feet. Single functional relationships are obtained for inphase and quadrature responses. This indicates that the wing-tip system also behaves like a double-dipole system.

III.5 Fall-Off of Responses with Height:

It has been mentioned in Section 3.4.2 that the rate of fall-off of the inphase and quadrature responses for the parameter $\delta f H$ with height is as $H^{-3}$. When the conductor remains the same the rates of fall-off are different for different ranges of the response para-
Fig. 3.4.4: Response diagram shows that single functional relationships are obtained for the inphase and quadrature responses when they are normalized by \((H/H_0)^3\). This reveals that the wing-tip system also behaves like a double-dipole system.
meter. Fig. 3.5.1 shows variations of the inphase and quadrature responses of scale-model measurements over vertical half-plane conductors of the helicopter system with height, in double log scales. It is interesting to note that points of the same 'σtf' for heights larger than 90 feet fall in one straight line. Inphase responses fall-off at a rate of 'H^{-1.8}', for 'σtf' equal to 2K, and they fall-off at progressively faster rates for better conductors. At close to the induction limit the rate of fall-off is 'H^{-3}'. Quadrature responses behave in a similar way. The minimum and maximum rates of fall-off, for a range of 'σtf' between 2K and 400 K, are found to be 'H^{-2.5}', and 'H^{-3.4}', respectively.

The 'large-scale' towed bird systems have faster rates of fall-off. Fig. 3.5.2 shows rates of fall-off of quadrature responses of the Barringer and McPhar systems for five 'σtf' in the range 1 - 100 K. Between these limits, the rates of fall-off for the Barringer system varies from \( H^{-3.3} \) to \( H^{-4.2} \) and for the McPhar system from \( H^{-4} \) to \( H^{-6} \). The rates of fall-off for the Barringer system also apply very closely to the Lockwood quadrature system. It should be mentioned in this context that the "depth of exploration" does not depend on the above results; because, AEM systems of 'large' and 'small' dimensions "look" at large and small cross-sections of the ground. Sensitivity of a system also plays an important part in "depth of exploration".
Fig. 3.5.1: Rates of fall-off of responses of the helicopter system over the vertical half-plane model. They are different for conductors of different 'ct'. The maximum and minimum rates of fall-off, for the inphase response, are $H^{-3}$ and $H^{-1.6}$; and for the quadrature response, these are $H^{-3.4}$ and $H^{-2.5}$. 
Fig. 3.5.2: Rates of fall-off of quadrature responses of 'large-scale' systems over the vertical half-plane model. The maximum and minimum rates of fall-off, for the Barringer system, are $H^{-4.2}$ and $H^{-8.3}$, and for the McPhar system, these are $H^{-6}$ and $H^{-4}$. 
III.6 Field Examples:

III.6.1 The Whistle Deposit:

The Whistle deposit, located (Fig.3.6.1) on the northwest rim of the Sudbury basin 30 miles northeast of Sudbury, Ontario, is a test site for many AEM systems. Field data from the Dighem (main coaxial coils only) helicopter, Barringer whale-tail, McPhar and Lockwood quadrature systems over this deposit have been investigated.

The Whistle deposit is an outcropping, pear-shaped, inhomogeneous, "massive" sulphide deposit. The ore body is approximately 1400 feet long, 50-100 feet wide, and extends to 1000 feet in depth. It occurs in a greenstone-granite complex parallel to and north of a norite contact dipping steeply towards south. Although the mineralization is reported to be "massive", its apparent conductivity is known to be lower than many other sulphide bodies. No information is available as to the grade and tonnage of the body. Due to the large dimensions and steeply dipping nature of the ore body it can be roughly approximated by a vertical half-plane model, although its thickness is certainly not negligible.

III.6.1.1: DIGHEM SYSTEM

An extensive test over the Whistle ore body has been made by the Dighem helicopter system. The magnitudes
The Whistle Mine is located on the northeast rim of the Sudbury basin 30 miles northeast of Sudbury.
of responses of the main coaxial coil-system are available (Table 3.6.1) for 13 flight lines at different places over the ore body. Fig. 3.6.1.1. shows a plot of the inphase and quadrature anomalies in the $P-Q$ summary diagram of the helicopter system over vertical half-plane models. All the points fall between the 40 $K$ and 100 $K$ lines of $\sigma f$. The system operates at a frequency of 918 $Hz$. Except for point number 11, heights of all the other points in the diagram agree with heights of the bird within 15 feet (Table 3.6.1). An estimate of the apparent $\sigma t$ of each point has been shown in the Table (3.6.1). These estimates are somewhat variable, probably reflecting both the inhomogeneous nature and the shape of the ore body. The values of apparent $\sigma t$ are found to lie between 60 mhos to 100 mhos giving an average of 80 mhos.

In one part of the test, the system was flown at three heights over the same point in the ore body. To understand the consistency of the system at different altitudes, the ratio of the inphase and quadrature anomalies of these heights have been plotted against the parameter $\omega \mu H$ in double log scales. As expected, the points lie in a straight line. This straight line was matched with Figure (3.4.1) by shifting along the x-axis, and an apparent $\sigma t$ of 80 mhos is obtained.
### TABLE 3.6.1

<table>
<thead>
<tr>
<th>Flight No.</th>
<th>Anomaly (ppm)</th>
<th>Height of bird (ft)</th>
<th>Height from Diagram (ft)</th>
<th>Apparent 'σt' mhos</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>Q</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>144</td>
<td>36</td>
<td>130</td>
<td>120</td>
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<td>2</td>
<td>124</td>
<td>32</td>
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<td>125</td>
</tr>
<tr>
<td>3</td>
<td>108</td>
<td>24</td>
<td>150</td>
<td>135</td>
</tr>
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<td>4</td>
<td>90</td>
<td>18</td>
<td>150</td>
<td>140</td>
</tr>
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<td>64</td>
<td>12</td>
<td>180</td>
<td>165</td>
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<td>4</td>
<td>240</td>
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<td>8</td>
<td>126</td>
<td>42</td>
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</tr>
<tr>
<td>10</td>
<td>184</td>
<td>78</td>
<td>110</td>
<td>110</td>
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<tr>
<td>11</td>
<td>20</td>
<td>4</td>
<td>270</td>
<td>235</td>
</tr>
<tr>
<td>12</td>
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<td>130</td>
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<td>13</td>
<td>148</td>
<td>44</td>
<td>110</td>
<td>120</td>
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</table>

Interpretation of Dighem (coaxial coils)
Anomalies over the Whistle Body

### TABLE 3.6.2

<table>
<thead>
<tr>
<th>(H) ft.</th>
<th>(P) (ppm)</th>
<th>(Q) (ppm)</th>
<th>(P/Q)</th>
<th>(\sigma \mu H)</th>
<th>(\sigma) mho</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>250.7</td>
<td>75.9</td>
<td>3.3</td>
<td>0.725</td>
<td>80</td>
</tr>
<tr>
<td>200</td>
<td>34.2</td>
<td>6.7</td>
<td>5.13</td>
<td>1.450</td>
<td>79</td>
</tr>
<tr>
<td>400</td>
<td>4.6</td>
<td>0.55</td>
<td>8.36</td>
<td>2.900</td>
<td>81</td>
</tr>
</tbody>
</table>

Over One Part of the Whistle Body the Dighem System Shows the same Apparent 'σt' at Three Different Heights.
Fig. 3.6.1.1: Magnitudes of anomalies of the Dighem helicopter (coaxial coil) system over the Whistle deposit. All the points fall between the 40K and 100K lines of constant \( \sigma_H \).
III.6.1.2 WHALE-TAIL (Barringer Helicopter) SYSTEM:

Fig. 3.6.1.2 shows the profiles obtained by flights at four different heights over the same point of the Whistle body by the whale-tail configuration of the Barringer helicopter system. The operating frequency of the system is 400 Hz. For large heights, besides the dominant positive anomaly a small negative anomaly is seen. (The negative anomaly is visible because little smoothing is used in the system.) This is a characteristic feature of whale-tail receivers as was shown in Fig. 3.2.5. The total anomaly has been considered as the difference of two peak amplitudes. The inphase and quadrature anomalies have been plotted in a $P-Q$ summary diagram (Fig. 3.6.1.3). The field points lie on a straight line of $\sigma t_f$ equal to $24 K$ indicating an apparent $\sigma t$ of 60 mhos for all heights. This shows again that the Whistle ore body behaves like a half-plane. It will be shown in Chapter 6 that if a vertical half-plane interpretation is applied to an anomaly caused by a conductor of finite size, it should show progressively smaller apparent $\sigma t$ as the height of the system increases. The altimeter traces of three lower heights correspond to heights in the summary diagram within 20 feet. The highest height obtained from the altimeter trace is 205 feet, whereas the point in the summary diagram shows this height as 250 feet. Since, for all heights the same apparent $\sigma t$ of 60 mhos are
Flight records of the whale-tail (Barringer) system over one part of the Whistle body at four heights. For large flight heights, characteristic negative peaks in anomalies are seen.
Fig. 3.6.1.3: The magnitudes of anomalies of the whale-tail system plotted in a P-Q summary diagram. The points lie on a straight line of $\sigma_{tf}$ equal to $24k$ indicating an apparent $\sigma_{t}$ of 60 mhos.
found, it seems possible that the altimeter determination might have been in error.

III.6.1.3 LOCKWOOD QUADRATURE SYSTEM:

One flight by the Lockwood quadrature system is available over the Whistle deposit. The figure (3.6.1.4) shows the responses at 400 hz and 2300 hz, and the altimeter trace. Anomalies of the high and low frequencies are 15.7 kppm and 38.4 kppm, respectively, and the altimeter trace shows a height of 440 feet. The ratio of low and high frequency anomalies is 0.41. A point corresponding to the low frequency anomaly and ratio of low to high frequency anomalies was plotted (Fig. 3.6.1.5) in the summary diagram of the system for vertical half-plane models. The point shows an apparent 'σt' of 2 mhos which is very much smaller than those obtained by the helicopter and whale-tail systems. It should be noted here that this system flying at a height of 440 feet would show a half-plane anomaly if the conductor extends to more than 1500 feet in depth (Chosh and West, 1971). This has also been explained in Section 6.1. The Whistle ore body being only 1000 feet deep, does not accurately represent a half-plane model in this situation. As will be shown in Chapter 6, if the finite depth-extent of the ore body is considered, the 'σt' estimate will be approximately doubled. This would still be much smaller
Fig. 3.6.1.4

Flight record of the Lockwood quadrature system over the Whistle body.
Position of the field point of the Lockwood quadrature system over the Whistle deposit on the '2-f' summary diagram.
than apparent 'at' of 80 mhos and 60 mhos obtained by the helicopter and whale-tail systems. It is noted that the amplitudes of the anomalies are too large for a flying height of 440 feet; this may have been caused by the AEM system used for the test having different dimensions than those assumed for construction of the summary diagram. The effect is approximately the same as an error in amplitude calibration.

III.6.1.4 McPHAR QUADRATURE SYSTEM:

The McPhar quadrature system has surveyed on four lines over the Whistle deposit. The flight lines and location of anomalies with respect to the approximate ore body are shown in Fig. 3.6.1.6. It seems that lines 1 and 4 are away from the ore body, while line 3 passes right over the outcrop. The profiles of the low (340 Hz) and high (1070 Hz) frequency anomalies and the altimeter traces are shown in Fig. 3.6.1.7. Anomalies of the lines 2 and 1 have two peaks separated by 400 feet and 700 feet, respectively. Separation of the anomalies of these lines increases away from the outcropping ore body. These double-peak anomalies do not really represent the ore body, but these may be due to secondary mineralization starting from the main ore body.

Anomalies of all these lines have been listed in Table 3.6.3. The low frequency anomaly and ratio of the low and high frequency anomalies have been plotted
Fig. 3.6.1.6: - Flight lines of the McPhar quadrature system over the Whistle body. Line 3 passes directly over the body.
Fig. 3.6.1.7

Flight records of the McPhar quadrature system over the Whistle deposit. Double peaks are obtained on lines 1 and 2.
### TABLE 3.6.3

<table>
<thead>
<tr>
<th>Anomaly No.</th>
<th>$\delta = 340$ hz (Kppm) $Q$</th>
<th>$\delta = 1070$ hz (Kppm) $Q$</th>
<th>$R = \frac{\delta_{340}}{\delta_{1070}}$</th>
<th>Flight Ht. (feet)</th>
<th>Apparent 'd' (mhos/meter)</th>
<th>Height from Summary Diagram (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>9</td>
<td>0.45</td>
<td>570</td>
<td>1.8</td>
<td>560</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>26</td>
<td>0.54</td>
<td>425</td>
<td>3.0</td>
<td>400</td>
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<tr>
<td>2A</td>
<td>11</td>
<td>26</td>
<td>0.42</td>
<td>450</td>
<td>1.9</td>
<td>400</td>
</tr>
<tr>
<td>2B</td>
<td>9</td>
<td>16</td>
<td>0.56</td>
<td>450</td>
<td>3.1</td>
<td>450</td>
</tr>
<tr>
<td>1A</td>
<td>4</td>
<td>8</td>
<td>0.5</td>
<td>500</td>
<td>2.3</td>
<td>515</td>
</tr>
<tr>
<td>1B</td>
<td>6</td>
<td>10</td>
<td>0.6</td>
<td>500</td>
<td>3.2</td>
<td>510</td>
</tr>
</tbody>
</table>

Interpretation of McPhar quadrature anomalies over the Whistle deposit.

Estimates of apparent 'd' are too small.
Fig. 3.6.1.8: The magnitudes of anomalies of the McPhar quadrature system show that the apparent 'ohm' of conductors lie between the limit 1.8-3.2 mhos which is much smaller than those of the helicopter and whale-tail systems.
(Fig. 3.6.1.8) on the summary diagram of this system. The flight heights of lines 2 and 3 obtained from the altimeter traces are much higher than those indicated by points on the summary diagram (Table 3.6.3). Considering the effect of smoothing in this system, an opposite result would have been expected. This is quite confusing, however, the finite thickness of the body could be causing much larger anomaly than expected for a half-plane.

Anomaly number 3, which is the most representative of the ore body, indicates an apparent $\sigma t$ of 3 mhos. Apparent $\sigma t$ of all the anomalies fall within the limits 1.8-3.2 mhos. It is interesting to note that the Lockwood quadrature system indicates an apparent $\sigma t$ of 2 mhos which falls within the above limit. If the finite depth-extent of 1060 feet of the ore body is considered, the apparent $\sigma t$ estimate is approximately doubled.

Values of apparent $\sigma t$, obtained from the 'small-scale', inphase and quadrature measuring helicopter and whale-tail systems, are much higher than those obtained by the 'large-scale' quadrature measuring Lockwood and McPhar towed bird systems. There seems to be an inherent discrepancy between these two kinds of systems. This is dealt with in Chapter 7.
III.6.2 The Sturgeon Lake Ore Body:

The Sturgeon Lake ore body of Matabi Mines is located (Fig. 3.6.2.1) south of Sturgeon Lake about 50 miles east of Sioux Lookout in Ontario. The body is steeply dipping, and it occurs in rhyolite under 25-75 feet of overburden. It is a high grade ore containing 7.6% of Zn, 3.04% of Ag, 0.91% of Cu, and 0.82% of Pb. The tonnage has been estimated as 12,400,000. The ore body is approximately 1800 feet long, up to 300 feet wide, and it extends to at least 600 feet in depth. AEM data from the Scintrex HEM-701 helicopter and the Lockwood and McPhar quadrature systems are available. The ore body, for all practical purposes, may be thought to be infinitely long in strike direction. Due to 'small' dimensions of helicopter systems compared to towed bird systems, the ore body may be considered to be infinitely large in depth for the Scintrex HEM-701 system; but, this is not true for the McPhar and the Lockwood towed bird systems.

III.6.2.1 SCINTREX HEM-701 SYSTEM:

Data of five flight heights at one point over the ore body are available for the Scintrex helicopter system. The system operates at a frequency of 1600 Hz. Using the inphase and quadrature anomalies, five points have been plotted (Fig. 3.6.2.2) on the P-Q summary diagram of the
LOCATION OF STURGEON LAKE ORE BODY

Fig. 3.6.2.1

Location of the Sturgeon Lake body of Matabi Mines.
Fig. 3.6.2-1. The magnitudes of anomalies of the Scintrex HEM-701 system over one part of the Sturgeon Lake body indicate apparent 10-20 mos for five flying.

Sturgeon Lake Ore Body Scintrex HEM-701
f = 600 Hz

Vertical Conductivity and Height
Helicopter System

In-Phase Anomaly Amplitude (PPM)

Quadrature Anomaly Amplitude (PPM)
vertical half-plane model. These points show an excellent agreement in apparent \( \sigma t \). The points A, B, and C corresponding to the lower heights indicate the same apparent \( \sigma t \) of 22 mhos. However, the points D and E at higher altitudes move slightly but progressively towards lower \( \sigma t \). The apparent \( \sigma t \) for the largest height (E) has been estimated to be 19 mhos. It will be shown in Chapter 6 that the decrease in apparent \( \sigma t \) with increase of height can be accounted for by finite extent of the conductor. The variation in apparent \( \sigma t \) is about right for a depth of 600 feet.

It should be mentioned that heights obtained from the altimeter traces did not correspond to heights of the points in summary diagram. Especially the larger heights are markedly different. The heights found from the points are 110, 130, 140, 205, and 230 feet, whereas those obtained from altimeter traces are 110, 150, 200, 265, and 290 feet, respectively. From the fact that such a good agreement in apparent \( \sigma t \) has been observed, it is suspected that the altimeter traces are erroneous. Due to this reason, the depths of the conductor below ground surface could not be found.

III.6.2.2 McPHAR QUADRATURE SYSTEM:

The McPhar system has flown twice over the Sturgeon Lake ore body, along one line in opposite directions. The profiles have a mirror image symmetry. The low frequency
anomaly is 5 ppm and ratio of low and high frequency anomalies is 0.8. A corresponding point has been plotted (Fig. 3.6.2.3) on the summary diagram of this system for the vertical half-plane model. It shows apparent $\sigma t$ is 5.5 mhos. If finite depth-extent of 600 feet of the ore body is considered, the apparent $\sigma t$ is about four times the above value. This shows that apparent $\sigma t$ obtained from Scintrex helicopter and McPhar quadrature systems are in good agreement in this case.

III.6.2.3 LOCKWOOD QUADRATURE SYSTEM:

The Lockwood dual frequency quadrature system has been flown over the Sturgeon Lake ore body. Fig. 3.6.2.4 shows the anomalies at two frequencies for four heights. The time-constant used is half a second. The low frequency anomaly and the ratio of low (400 hz) and high (2300 hz) frequency anomalies have been plotted (Fig. 3.6.2.5) in the summary diagram of vertical half-plane conductors. Table (3.6.4) shows heights of these points in the diagram and those from altimeter traces. They correspond to each other within 30 feet for points 5, 4, and 3 of lower heights. Point 2 shows a height of 600 feet in the diagram, but the height according to the altimeter trace is 700 feet. All the points fall on a line of $\sigma tf$ equal to 1.2 K. This indicates an apparent $\sigma t$ of 3 mhos for all heights. If the
The McPhar quadrature system shows an apparent 'σt' of 5.5 mhos over the Sturgeon Lake body. If the finite depth-extent of the body is considered, apparent 'σt' increases about four times.
Traces of flight records of the Lockwood quadrature system over the Sturgeon Lake body.
Fig. 3.6.2.5: The Lockwood quadrature system shows an apparent '$\sigma t$' of 3 mhos over the Sturgeon Lake body. If finite depth-extent of the body is considered, apparent '$\sigma t$' increases about four times.
finite depth-extent of 600 feet of the conductor is considered, the apparent \( \sigma t \) is about four times the above value. Due to finite-extent of a conductor, apparent \( \sigma t \) should decrease with increase in height. Surprisingly, this has not been observed.

The apparent \( \sigma t \) obtained from the Scintrex helicopter and the McPhar and the Lockwood quadrature systems are therefore in reasonable agreement.

III.6.3 The Cavendish Conductors:

The Cavendish conductors are located in Cavendish Township, south of Gooderham, Ontario (Fig. 3.6.3.1) and approximately 100 miles northeast of Toronto. Extensive testing of ground EM, IP, and AEM systems has been done in this area. Data from the Lockwood helicopter and McPhar dual frequency quadrature AEM systems are available. Cavendish Township area is underlain by Precambrian Grenville sediments consisting chiefly of crystalline limestones. There exists a series of NNE trending paragneisses, intruded by acid to basic igneous rocks. The regional dip in this area is around 70 degrees. Several sub-parallel conducting zones, thought to be due to pyrite and pyrrhotite lie in the regional strike direction (NNE). Nearly all ground geophysical methods indicate two narrow anomalous zones A and B, lying roughly parallel to the geologic strike.
Fig. 3.6.3.1: The Cavendish conductors are located in Cavendish Twp. south of Gooderham, approximately 100 miles northeast of Toronto.
These zones are separated by 700 feet. Unfortunately, the area has not been thoroughly tested by drilling, but one short vertical hole about 50 feet deep located near Zone A is reported to have intersected massive sulphide mineralization. This mineralization mainly consists of pyrrhotite which has very high electrical conductivity. Zone B is reported to have smaller average conductivity than Zone A. The host rock has been identified as mica and amphibole schist. A few ground geophysical surveys covering a large area indicate the presence of several other conductive zones.

III.6.3.1 LOCKWOOD HELICOPTER SYSTEM:

The Lockwood helicopter system operates on two frequencies 1000 Hz and 4000 Hz. Most of the survey over Cavendish Township was done using a frequency of 4000 Hz. Fig. 3.6.3.2 shows the position of anomalies along the five flight lines. Tracings of the anomaly profiles are shown in Fig. 3.6.3.3. Positive anomalies were obtained over conductors C, A, B, G, F, E, and D. Two zones, 'Z' and 'X', are associated with 1500 gamma magnetic anomalies. The lakes apparently produce broad quadrature anomalies with no inphase anomaly. Due to the irregular nature of the terrain, flight heights of the helicopter varied between 170-260 feet. This had considerable influence on the data. The sharp nature of the anomalies indicates that the conductors are narrow.
Fig. 3.6.3.2

Position of anomalies along the five flight lines over the Cavendish conductors by the Lockwood helicopter system.
Fig. 3.6.3.3

Traces of flight records of the Lockwood helicopter system over the Cavendish conductors.
The inphase and quadrature anomalies of zones 'A' and 'B' have been plotted on the $P-Q$ summary diagram of the vertical half-plane conductors (Fig. 3.6.3.4). Zone 'A' has the highest apparent $\sigma t$ of 30 mhos on line E. Excluding this, apparent $\sigma t$ of zones 'A' and 'B' vary between 1.5-8 mhos and 1-4 mhos, respectively. The depths of conductors below the ground surface could not be determined due to lack of data from altimeter traces. The values of apparent $\sigma t$ as interpreted from the $P-Q$ summary diagram are shown in Fig. 3.6.3.2. According to apparent $\sigma t$ the conductors are graded as A, B, C, D, E, G, and F.

The Lockwood helicopter system was also flown using a frequency of 1000 Hz to test compatibility of the system at two different frequencies. Fig. 3.6.3.4 also shows a plot of the anomalies as triangles due to these two frequencies over the conductor 'D'. Both the points shown an apparent $\sigma t$ of 6 mhos.

III.6.3.2 McPhar Quadrature System:

Fig. 3.6.3.5 shows the quadrature profiles of the two frequencies of the McPhar system and the altimeter traces over the lines C, D, and E. With the exception of the zones 'Z' and 'X' of the magnetic mineralization, all the zones have been picked up by this system. The
Fig. 3.6.3.4: The magnitudes of anomalies of the Lockwood helicopter system over the conductors 'A' and 'B' plotted in the P-Q summary diagram. Letters by the points indicate flight lines.
McPHAR QUAD. SYSTEM
CAVENDISH TWP.

Fig. 3.6.3.5: Flight records of the McPhar quadrature system over the Cavendish conductors.
low frequency anomaly and ratio of low and high frequency anomalies of zones A and B have been plotted (Fig. 3.6.3.6) on the summary diagram of vertical half-plane models. The heights of the points in the diagram are lower than those obtained from altimeter traces. Considering effects of smoothing, opposite results would be expected.

Besides the zone A on line E and the zone B on line A, all the other points on the diagram show apparent "σt" between 2.4-5 mhos. These values of apparent "σt" are in general agreement with those of the Lockwood helicopter system. Figs. 3.6.3.7a,b are the flight path recovery showing location of all the conductors and their apparent "σt" for the McPhar quadrature and the Lockwood helicopter systems represented in approximately same scales. A comparison of these figures shows that the apparent "σt" values of the conductors obtained from the McPhar quadrature system are only a little less than those from the Lockwood helicopter system. In general, values of apparent "σt" of the conductors obtained from both the systems seem to be consistent.
Magnitudes of anomalies of the McPhar system over the conductors 'A' and 'B' plotted in '2-f' summary diagram. Letters beside the points indicate flight line numbers.
Fig. 3.6.3.7: Flight lines and estimates of \( \sigma_t \) of the McPhar quadrature and Lockwood helicopter system over the Cavendish conductors show a reasonable agreement.
IV. FLAT-LYING CONDUCTORS

Flat lying conductors are often of no economical importance. They are commonly of surficial bodies such as swamps and muskegs, and of underground layers as saline aquifers and ancient river bed deposits. These flat-lying bodies are often poorly conducting compared to massive sulphide deposits. But, due to strong coupling with most of the AEM systems, they may produce very large anomalies which may be mistaken as due to massive sulphide bodies. To study the nature of anomalies due to flat-lying conductors scale-model measurements have been made with different AEM systems over horizontal thin sheets of finite width but large strike-extent (Ghosh and West, 1971). The characteristics of anomalies due to flat-lying models will be presented here with a view to distinguishing them from those due to steeply dipping conductors.

IV.1 Scale-Model Measurements:

IV.1.1. Shape of Profiles:

IV.1.1.1 SYMMETRICAL SYSTEMS:

The anomaly profile due to a thin horizontal sheet, very large in width compared to dimensions of an
AEM system, contains separate anomalies due to the horizontal edges and the central flat portion of the sheet. The helicopter and wing-tip symmetrical systems very distinctly show this behaviour, whereas this is not very evident in unsymmetrical systems. Figs. 4.1.1a,b,c,d show the inphase and quadrature responses of the wing-tip system over thin horizontal sheets of different widths. When the width of the sheet is large (750 feet), the quadrature response in Fig. 4.1.1a shows three distinctive features: two at the edges (edge anomalies) which are symmetrical, and one at the centre (central anomaly). The anomaly for a double-dipole system over an infinite horizontal sheet can be calculated and it yields a higher response than a horizontal edge. Therefore, the central anomaly should be larger than edge anomalies if the sheet is wide enough. In Fig. 4.1.1a, the central anomaly of the quadrature component is very close to the anomaly due to an infinite sheet. The inphase anomaly in Fig. 4.1.1a shows interactions, because the two edge anomalies and the central anomaly are almost equal in magnitude. Widths of the inphase and quadrature responses are a little smaller than width of the flat sheet. Fig. 4.1.1b shows the responses as width of the sheet is reduced to 600 feet. The magnitudes of the edge anomalies of the inphase component still remain the same, but a strong negative interaction causes the central anomaly to be smaller than
Fig. 4.1.1

Scale-model profiles of the wing-tip system over horizontal sheet conductors of different widths. Wide sheets (a,b) show anomalies due to the two edges and central part. A thin sheet (d) shows anomalies due to the edges only. The anomaly profile may be mistaken to be due to two vertical conductors.
the edge anomalies. As the sheet becomes narrower (450 feet), the central anomaly tends to disappear (Fig. 4.1.1c), and peak responses diminish drastically. If width of the sheet is further reduced to 300 feet (Fig. 4.1.1d), the central anomaly disappears but the peak responses still remain approximately the same. The response consists of only two symmetrical peaks due to the two edges and may be mistaken as due to two separate vertical conductors. From the shape of the responses, it seems that a wide flat-lying conductor may be identified by wide responses and three distinctive features one at the centre and two at the ends. On the basis of shape of profiles narrow flat-lying conductors are difficult to identify due to small widths of responses and absence of a central anomaly.

VI.1.1.2 UNSYMMETRICAL SYSTEMS:

We have investigated responses due to edges of horizontal sheets of finite widths. Shape of responses of the unsymmetrical systems over horizontal sheets are quite similar to those over vertical sheets excepting a little distortion in the central part. Fig. 4.1.2 shows responses of the Lockwood quadrature system over horizontal sheets of various widths. Responses are wider for wider sheets. The response of a 1500 feet wide sheet is a little flattened at the central region. This flattening
HORIZONTAL SHEET
LOCKWOOD QUADRATURE SYSTEM

FLIGHT HT= 450 FT.
\( \sigma_{ff} = 3800 \, \text{mho. hz} \)

\[ Q \text{ (ppm)} \]

\[ 120k \]

\[ 80k \]

\[ 40k \]

\[ 0 \]

DISTANCE (FT.)

1
2
3
4

Fig. 4.1.2: Scale-model profiles of the Lockwood quadrature system over horizontal sheet conductors. The profiles do not contain separate features due to the edges and central part even for a sheet of 1500 foot wide.
may not be so clear in the field anomaly due to non-uniformity of conductors. Unlike symmetrical systems, the responses do not contain three different features due to the two edges and the central region. For a narrow horizontal sheet, the shape of the response is identical to that of a vertical sheet. Therefore, it is very difficult to identify a flat-lying sheet from the shape of a profile. We have made only a few measurements with infinitely large flat-lying sheets. In all the unsymmetrical systems an infinitely large flat-lying sheet yields much smaller responses than an edge of a flat-lying sheet.

Fig. 4.1.3 shows responses of the McPhar quadrature system over horizontal sheets of finite widths. They also show the same features as the Lockwood quadrature system. The trailing negative anomaly is less pronounced for a horizontal sheet than a vertical one, but the smoothing in the actual AEM system would obscure this difference. Fig. 4.1.4 shows the inphase and quadrature responses of the whale-tail system. Responses contain one positive peak and one negative peak at the edges depending on the flight direction. The responses of wide sheets are quite flattened in the central region (Fig. 4.1.4a) representing the amplitude of anomaly of an infinitely large horizontal sheet. The shape of a profile due to a narrow horizontal sheet (Fig. 4.1.4d) is no different from the one over a
Fig. 4.1.3: Scale-model profiles of the McPhar quadrature system over horizontal sheets of different widths.
Fig. 4.1.4: Scale-model profiles of the whale-tail system over horizontal sheets of different widths. The quadrature anomaly in (a) shows that the response due to an edge is larger than due to a flat central part. A narrow sheet (d) yields a profile similar to a vertical sheet. A positive anomaly appears at the leading edge and a negative anomaly at the trailing edge.
vertical conductor. In general, it may be concluded that unless a flat-lying conductor is very wide it can hardly be distinguished from one or two vertical conductors according to the shape of anomaly profiles.

IV.1.2 Magnitude of Responses:

Fig. 4.1.5 shows the response curves of the helicopter system over a wide (360 feet) horizontal sheet, a narrow (150 feet) horizontal sheet, and the vertical half-plane models plotted in the same way as in Fig. 3.4.3. The largest peak responses have been used to construct these response curves. No points have been shown as interpolated values are used. The curves indicate that much larger responses are obtained over horizontal sheets than vertical half-planes. Though responses of horizontal sheets depend on their widths, even a narrow sheet of 150 feet wide yields a substantially larger response than any vertical half-plane model. Most flat-lying geological bodies are poor conductors. Anomalies due to these bodies in field surveys, therefore, correspond to low values of the response parameter \(Q^2\). If a flat-lying conductor is quite wide, it can be readily identified by a very large anomaly compared to any vertical half-plane model. It has also been found in the last section (4.1.1) that the shape of the anomaly over a wide flat-lying conductor obtained by the helicopter
Fig. 4.1.5: Response diagram showing horizontal sheets yield much larger anomalies than vertical sheets. This might suggest that a thick vertical conductor would yield larger anomalies than a thin vertical conductor.
system is quite distinctive. The problem arises when the conductor is narrow. In Fig. 4.1.5 we see that at very low values of the response parameter ($Q^2$) the magnitude of responses of a narrow flat-lying conductor and a vertical half-plane occurring at the same depth may be the same. On the other hand, we know that in the field, a steeply dipping geological conductor occurs at a few tens of feet below the ground surface. They will yield smaller anomalies than any surficial conductor. Accurate altimeter readings are very important in these circumstances.

We have investigated the largest anomalies (either edge or central anomalies) obtained over horizontal sheets of various widths at a height of 120 feet for the helicopter and whale-tail systems. Figs. 4.1.6 and 4.1.7 show the phasor plots of these anomalies. Portions of the curves for 'σt' less than 10,000 mho. hz are important as far as flat-lying conductors are concerned. The phasor curves corresponding to a vertical half-plane and two vertical half-planes 75 feet apart, at a height of 120 feet, are shown as thicker lines. As concluded before, the anomalies of horizontal sheets are larger than those of one and two vertical half-planes. A comparison of the two figures shows that, in general, the whale-tail system yields larger anomalies than the helicopter system over horizontal sheets of finite widths. But the
Fig. 4.1.6: Phasor plot of anomalies of the helicopter system over flat sheets, one vertical half-plane and two vertical half-planes separated by 75 feet. Flat sheets yield more anomalies than the others. The point 'H' is due to a narrow (50 feet) flat sheet.
**Fig. 4.1.7:** The whale-tail system yields larger anomalies over flat sheets than one or two vertical half-planes. A comparison of this with Fig. (4.1.6) shows that at a height of 120 feet the whale-tail system (W) yields a larger anomaly than the helicopter system (H).
helicopter system yields larger anomalies over vertical half-planes. This is due to the fact that a horizontal receiver is more sensitive to a horizontal than a vertical edge of a conductor, and vice versa. These properties of the two systems may be effectively used to identify the nature of a conductor.

The Dighem system consists of both vertical and horizontal receivers. In field surveys, if a flat-lying conductor is present, the whale-tail system will yield larger anomalies than the coaxial helicopter system. If a vertical conductor is present, the results will be just the opposite. Therefore, in principle, the nature of a conductor may be easily identified in the Dighem system depending on which receiver yields the stronger anomaly. However, this is true only if the conductor has well defined edges and the system flies at normal flight heights. The point 'H' in Fig. 4.1.6 indicates anomalies of the helicopter system over a 50 feet wide horizontal sheet of 'σt' equal to 45 mhos. The anomalies of the whale-tail system over the same conductor are larger and they correspond to the point 'W' in Fig. 4.1.7. It has been found from the scale model experiments that magnitudes of anomalies of the whale-tail and helicopter system are equal when a half-plane dips at an angle of about 20 degrees. Relatively few sulphide ore bodies in the Canadian shield occur at such a small angle
with ground surface. Therefore, in field surveys, if the ratio of anomalies of the whale-tail system and the coaxial helicopter system is greater than unity, the conductor is likely to be surficial. This analysis has strictly been based on the fact that the height of the systems above a flat conductor is around 120 feet. This is quite practicable as far as an overburden is concerned.

In the above discussion we have considered only the largest anomaly (either edge anomalies or central anomaly) obtained over a flat sheet of finite width. It should be noted here that infinitely large flat sheets yield larger anomalies by the helicopter system than by the whale-tail system. Fig. 4.1.8 shows the anomalies of the whale-tail and helicopter systems over an infinitely large flat sheet (σ tf= 2900 mho.ha) at different heights. The anomalies have different rates of fall-off with height. The rates of fall-off of the quadrature anomalies by the whale-tail and helicopter system are found to be 4 and 2.6, respectively. This shows that one should be careful to use the ratio of quadrature anomalies of the whale-tail and helicopter system to obtain a knowledge of vertical or horizontal nature of a conductor. It should be noted in Fig. 4.1.8 that the helicopter system yields larger anomalies over an infinitely large horizontal sheet than the whale-tail system. This is in contrast to anomalies over a horizontal edge (Figs. 4.1.6 and 4.1.7).
Fig. 4.1.8: Over an infinitely large horizontal sheet the helicopter system yields larger anomalies than the whale-tail system. Rates of fall-off are higher for the whale-tail system than for the helicopter system.
IV.2 Field Examples:

The Winisk River area which is situated in the district of Kenora, Ontario was surveyed by the Lockwood quadrature, Dighem and Barringer INPUT systems. Data of the Lockwood quadrature and Dighem systems are available from two adjacent areas. A large number of anomalies have been picked up by these systems. Five anomalies of the Lockwood quadrature system were selected for priority investigation in the original interpretation. In fact, eight anomalies were studied on the ground by magnetometer and several types of EM surveys (Paterson 1971).

Little geological mapping has been done in this area. Most of the geological information has been derived from geophysical studies and drilling. The area is covered by an overburden 50 feet thick. The sedimentary section (paleozoic) consists of a 100 feet thick clay bed underlain by beds of sand, sandstone and limestone. One point was drilled and the geological section is shown in Fig. 4.2.1. A 25 foot thick saline aquifer is present at a vertical depth of 130 feet. The basement is at a depth of about 200 feet. The most common type of conductor identified by ground work was flat-lying sheet-like conductors lying at the basement surface or within the sedimentary section above the basement. These conductors
WINISK RIVER AREA

DRILL SECTION

\begin{itemize}
\item 45° OVERBURDEN
\item 50° OVERBURDEN
\item CLAY
\item SALT WATER SEAM
\item BASEMENT COMPLEX
\item 185° SAND (SALINE ACQUIFER)
\item 240° SS & LS
\end{itemize}

Fig. 4.2.1

Drill section of the Winisk River area.
are almost certainly related to electrolytic conduction in sedimentary rocks. The evidence, at present, points most strongly to the existence of saline solution in depressions on the basement surface (Paterson, 1971). These may be ancient river bed deposits lying between 100–200 feet below the ground surface.

Fig. 4.2.2 shows eight AEM anomalies of the Lockwood quadrature system from three survey lines. The location of flight lines were not available. The system was flown at an average height of 350 feet. Shape and width of anomalies do not readily identify them as flat-lying conductors. Attempts have been made to try to interpret these anomalies as due to steeply dipping conductors. Fig. 4.2.3 shows the corresponding points on the summary diagram of vertical half-plane models. All the points lie at apparent heights considerably less than 350 feet which is the average flight height. An overburden of 50 feet thick exists in this area. Hence, the anomalies are too high to be due to vertical conductors. The two dashed curves represent anomalies due to horizontal sheets of width 1500 feet and 900 feet at a height of 460 feet. The points fall around the curve due to the horizontal sheet of width 900 feet. The apparent \( \sigma t \) of the eight anomalies is in the range 4-10 mhos.

Figs. 4.2.4a,b,c,d show four typical anomalies of the Dighem multi-coil system over a different part of the Winisk River area. Channels 4 and 5 show the inphase and quadrature anomalies of the helicopter (coaxial coils) system, and channel 1 shows the quadrature anomaly of the whale-tail system. Anomalies of the coaxial coil system are very wide (3000-4000 feet) showing the flat-lying nature of the conductors. Anomaly numbers 2 (Fig. 4.2.4b)
Fig. 4.2.2: Traces of field anomaly profiles for the Lockwood quadrature system over the Winisk River area.
'2-f' summary diagram of the Lockwood quadrature system over vertical half-plane models at heights of 460 ft and 385 ft (solid lines), and over flat sheet models of widths 900 ft and 1500 ft at a height of 460 ft (dashed lines). The anomalies over the Winisk River area lie around the curve for a flat sheet of width 900 feet at a height of 460 ft.
and 3 (Fig. 4.2.4a) show very flat anomalies on the coaxial coil-system. Anomaly number 6 (Fig. 4.2.4c) indicates that 'σt' of the conductor is quite variable. The three separate peaks are not due to the two edges and the central flat portion, as the conductor is too wide (about 4000 feet) to cause interactions in anomalies. Anomaly number 5 shows two peaks (channels 5 and 4) separated by a distance of about 3000 feet. These could be due to two separate narrow flat conductors or a flat-lying conductor of very small 'σt' at the central part. Seven such anomalies of the coaxial coil-system have been plotted in the P-Q summary diagram (Fig. 4.2.5) of horizontal sheets. (This P-Q summary diagram has been constructed from maximum anomalies (either edge or central) obtained over a wide (360 feet) flat sheet. The points indicate heights of 200-300 feet showing that the conductors lie at depths between 100-200 feet below ground surface. Values of apparent 'σt' fall in the range 1-6 mhos. Both the Lockwood quadrature and Dighem coaxial coil-system show similar apparent 'σt' and depths of conductors below ground surface.

The anomalies of the whale-tail system (Channel 1) do not show cross overs at the edges of the conductors. This is probably due to tapering-off of the conductors towards their edges. The coaxial coil-system (Channel 5) in anomaly number 3 (Fig. 4.2.4a) shows a gradual build up of anomaly from the edges. It is clear
Fig. 4.2.4a: - The multicoil Dighem anomalies over the Winisk River area. The coaxial coil-system (Channel 5) shows gradual build up of the anomaly. The whale-tail system (Channel 1) does not show any cross over.
Fig. 4.2.4b: The multicoil Dighem anomalies over the Winisk River area. The coaxial coil system (Channels 4 and 5) shows flat-lying nature of the conductor.
Fig. 4.2.4c: The multicoil Dighem system anomalies over the Winisk River area. The coaxial coil-system (Channels 4 and 5) shows the anomaly is due to a flat-lying conductor of variable 'σt'.
Fig. 4.2.4d: The multicoil Dighem system anomalies over the Winisk River area.
Fig. 4.2.5: The anomalies of the Dighem helicopter (coaxial coils) show that the depth of conductors below ground surface is in the range 100-200 feet. The apparent resistivity of the conductors varies between 1.6 mho.
that the conductors do not have uniform $\sigma t$. The observed ratio of quadrature anomalies of the coaxial coil-system and whale-tail system is in the range $\frac{2}{3}-1$. From the model measurements of an infinitely large flat sheet (Fig. 4.1.8) of $\sigma t$ equal to 3 mhos for the Dighem system shows this ratio as 3 at a height of 150 ft. The deviation in this ratio has probably been caused by nonuniform thickness of the conductors. The observed whale-tail anomaly which is approximately constant across the conductor falls between the values predicted for edges and for infinitely large sheets. This suggests that the deviation in the ratio of anomalies of the coaxial coil-system and the whale-tail system has been caused by nonuniform thickness of the conductors.
V. ATTITUDE OF CONDUCTORS

V.1 Dipping Half-Planes:

V.1.1 Symmetrical Systems:

It is interesting to see how the dip angle of a conductor affects response of an AEM system. Fig. 5.1.1 shows scale-model profiles of the helicopter system over a half-plane conductor dipping at angles of 45, 60 and 90 degrees with respect to the ground surface. Profiles are not drastically different due to dip of a conductor; but a small increase in the amplitude and a change in the shape of profiles are noticed. Profiles show an asymmetry due to appearance of a tail at the dipping side of the conductor. As the dip decreases, the anomaly starts tailing off from a higher response towards the down-dip side. In field surveys, this characteristic in shape of a profile may be used to find out the direction of dip and to estimate an approximate dip angle of a conductor. It should be mentioned that due to inherent symmetry of the helicopter system, profiles of mirror image symmetry are obtained in the flight record if the system is flown in opposite directions.

Fig. 5.1.2 shows a phasor diagram for vertical half-plane conductors dipping at angles 45, 60, and 90
Fig. 5.1.1: Anomaly profiles of the helicopter system are not drastically changed due to dip of a model conductor. The direction of dip is towards the tail of the profile.
The phasor diagram of the helicopter system over dipping model-conductors. The effect of dip angle is on the amplitude of responses.
degrees. Points representing a constant \( \alpha_f \) of different dip angles fall on a straight (dashed) line. All the dashed lines, if extended, pass close to the origin. This indicates phase hardly changes due to dip of a conductor. The effect of dip is only on the amplitude. A simple power law relationship (Fig. 5.1.3) seems to exist where amplitude increases as a power of 0.37 with decrease in dip angles between 90-30 degrees. This is also true for the wing-tip system. In interpretation of field data, the dip angles of conductors should be roughly estimated from shape of anomalies and the strength of anomalies should be corrected for the estimated dip angles before they are compared with responses of vertical half-planes.

V.1.2 Unsymmetrical Systems:

In contrast to the helicopter system, profiles by an unsymmetrical system over dipping conductors are quite different. Fig. 5.1.4 shows scale-model profiles of the Barringer system over dipping half-planes. Compared to the profiles of a vertical half-plane, the profile of dip equal to 45 degrees shows a marked increase in response by about 100 percent, but little change in shape. The profile of dip equal to 135 degrees shows not only a large reduction in response, but the secondary peak has grown to an amount comparable to the main peak. Apparently, the secondary peak could be mistaken to be due to the
The amplitudes of responses of all dipping conductors increase as a power of 0.37 with decrease in dip angle between 90-30 degrees.
Fig. 5.1.4: – For the Barringer system, magnitudes of anomalies greatly increase if the flight direction is towards the down-dip side. If the flight direction is reversed, there is a large reduction in the magnitude of anomaly and the small secondary peak grows to an amount comparable to the main peak.
presence of a second conductor. If the flight direction is reversed, a conductor dipping at 45 degrees would look like one dipping at 135 degrees. In fact, in an airborne survey, two successive lines are often covered in opposite flight directions. Two completely different anomalies of the same conductor at successive flight lines has been quite mystifying to interpreters for sometime.

Fig. 5.1.5 shows a phasor plot of the Barringer system for dipping half-planes. The dashed lines represent constant $\sigma t f$ for different dip angles. Excepting the line for $\sigma t f$ equal to 17.9 $K$, all the other lines, if extended, pass through the origin indicating that these lines are constant phase lines. Therefore, the effect of dip, in general, is purely on the amplitude. Conclusions drawn about the 'frequency-domain' Barringer system will also apply to the 'time-domain' Barringer INPUT system. Amplitudes of responses seem to increase three to four times as dip changes from 135 to 45 degrees. It has been found that the anomaly amplitude for a dipping conductor varies approximately as a power of 0.8 in this range of dip angles.

Fig. 5.1.6 shows profiles of the McPhar quadrature system over a half-plane dipping at angles of 45, 90, and 135 degrees. Unlike the helicopter and Barringer systems, the responses decrease as dip decreases. The ratio of negative to positive peaks also decreases as dip decreases. But, due to inherent smoothing in the McPhar system, no negative peaks are seen in field surveys. Fig. 5.1.7 shows a phasor diagram of dipping conductors of this system. It seems there is little change in phase as dip changes from 90 to 135 degrees. But, especially for poor conductors, phase decreases as dip decreases from 90 to 45 degrees.

Fig. 5.1.8 shows profiles of the whale-tail system over a half-plane dipping at angles 45, 90, and 135 degrees. The ratio of negative to positive responses increases as dip decreases.
Fig. 5.1.5: The phasor diagram of the Barringer system over dipping model conductors. The effect of dip angle is purely on the amplitude of responses.
DIP = 45°

DIP = 90°

DIP = 135°

**Fig. 5.1.6:** For the McPhar system, magnitudes of anomalies decrease if the flight direction is towards the down-dip side.
The phasor diagram for the McPhar system over dipping half-plane models. The effect of dip is on the amplitude of responses. But, for poor conductor, phase decreases as dip decreases from 90 to 45 degrees.
Fig. 5.1.8: Anomaly profiles over dipping model conductors for the whale-tail system. The ratio of negative to positive responses increase as dip decreases (flight towards down-dip side).
This property may be used qualitatively in field surveys to estimate the dip of a conductor. Fig. 5.1.9 shows the effects of dip angles at different heights of this system. At large heights the magnitude of the response increases as a conductor dips in either direction. Fig. 5.1.10 shows profiles of the fish-tail system over dipping half-planes. Besides a little change in the amplitude, the profiles for dip angles equal to 45 and 135 degrees show a negative on the down dip side.

V.1.3 Field Examples:

Figs. 5.1.11 and 5.1.12 show the inphase and quadrature anomalies of the Scintrex HEM-701 helicopter system in a field survey over the Sturgeon Lake area. These anomalies have been traced from recording tapes and aligned along the axis of the conductor. The profiles of flight lines from north to south have been reversed to maintain consistency in shape of profiles from line to line. The inphase anomalies are much larger than the quadrature anomalies which are around the noise level of the system. This indicates a high conductivity of conductors. In each figure, shape of the inphase responses indicates that the conductor dips towards north. The dip of conductors has been roughly estimated from shape of anomalies. The conductor 'A' dips gently (30 degrees) in the west and gradually becomes steeply dipping in the east. The conductor
Fig. 5.1.9: - For the whale-tail system, the magnitude of responses increases as a conductor dips in either direction for heights larger than 90 ft.
Fig. 5.1.10: The profiles of the fish-tail system reverse by flying the system in opposite directions.
### STURGEON LAKE AREA (CONDUCTOR A)
#### HELICOPTER SYSTEM

<table>
<thead>
<tr>
<th>LINE NO.</th>
<th>INTERP. DIP</th>
<th>IN-PHASE COMP.</th>
<th>QUADRATURE COMP.</th>
</tr>
</thead>
<tbody>
<tr>
<td>II2 N</td>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II3 S</td>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II4 N</td>
<td>45°</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>90°(?)</td>
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</table>

**Table Notes:**
- **App. at mho.**
- **Depth of Cond. Below Ground**

**Figure 5.1.11:** Field anomaly profiles of the Scintrex HEM-701 system over a conductor which is very large in strike direction. The shape of profiles indicate that the conductor dips towards north. The dip angle for each profile has been estimated and apparent 'at' has been obtained after amplitude correction of the dip angle has been made.
STURGEON LAKE AREA (CONDUCTOR B)
HELICOPTER SYSTEM

IN-PHASE COMP. QUADRATURE COMP.

<table>
<thead>
<tr>
<th>LINE NO</th>
<th>INTERP.</th>
<th>STRIKE</th>
<th>App. A of</th>
<th>Depth of Cond.</th>
</tr>
</thead>
<tbody>
<tr>
<td>57 N</td>
<td>90°(?)</td>
<td>60°</td>
<td>110</td>
<td>90'</td>
</tr>
<tr>
<td>58 S</td>
<td>45°</td>
<td>30°</td>
<td>110</td>
<td>100'</td>
</tr>
<tr>
<td>59 N</td>
<td>45°</td>
<td>90°</td>
<td>120</td>
<td>80'</td>
</tr>
<tr>
<td>60 S</td>
<td>45°</td>
<td>90°</td>
<td>190</td>
<td>70'</td>
</tr>
<tr>
<td>61 N</td>
<td>60°</td>
<td>90°</td>
<td>220</td>
<td>70'</td>
</tr>
<tr>
<td>62 S</td>
<td>60°</td>
<td>75°</td>
<td>110</td>
<td>95'</td>
</tr>
<tr>
<td>63 N</td>
<td>60°</td>
<td>60°</td>
<td>75</td>
<td>85'</td>
</tr>
<tr>
<td>64 S</td>
<td>45°</td>
<td>30°</td>
<td>45</td>
<td>95'</td>
</tr>
</tbody>
</table>

S → N

VERTICAL SCALE [100 ppm]
HORIZONTAL SCALE [0 300 600 FEET]

Fig. 5.1.12

Field anomaly profiles of the Scintrex HEM-701 system.
'B' dips between 45 to 60 degrees. The anomalies of different lines have been corrected for dip angles before they are matched with vertical half-plane models. The apparent 'σt' and depth of conductors below ground surface have been estimated and they are listed against the anomalies. Conductor 'A' seems to be deeper in the west and gradually becomes shallower in the east. Apparent 'σt' of both the conductors are larger at the centre and smaller at the ends.

V.2 Effect of Strike Angles:

In a field survey, the aircraft is usually flown perpendicular to the direction of regional strike so that, if a conductor is present, the flight lines will cross it at right angles. If flight lines do not cross a conductor at right angles, quite different responses are obtained. From simple geometry it is apparent that an oblique intersection of a flight line with a conductor causes the anomaly to be stretched out by an amount \( \frac{1}{\sin \theta} \), where \( \theta \) is the strike angle (angle between the conductor axis and the profile). An AEM system also suffers from a decrease in coupling with the conductor causing a reduction in anomaly amplitude. The effects are a little more complicated if the conductor is not vertical but dips at an angle with the ground surface.
Fig. 5.2.1 shows profiles of scale model measurements of the helicopter system when it crosses a conductor at right angles and at 45 degrees. The vertical scales are different for the two strike angles. The profiles of dip equal to 45 degrees are wider. Also shape of these profiles are changed in such a way as if the dip angle is further decreased. Fig. 5.2.2 shows the effect of strike angles on magnitude of responses. The dashed lines are of constant 'σf'. They are somewhat different for the two strike angles. A line joining two points for the same conductor at two strike angles will, if extended, pass through the origin. This indicates that the effect of strike angles is purely on amplitude. It is obvious from the figure that amplitude effect of a strike angle is more serious than that of the same dip angle.

Oblique strike angles have a more complicated effect on profiles of unsymmetrical systems. Fig. 5.2.3 shows profiles of scale-model measurements for the Barringer system. The vertical scales are different for two strike angles. The strike angle of 45 degrees reduces the anomalies and also makes the anomalies wider. Peaks of profiles are shifted towards the dipping side. Fig. 5.2.4 shows the effect of strike angles on magnitude of responses in the Barringer system.
HEICOPTER SYSTEM
VARIABLE STRIKE - ANGLE

DIP = 90°

Q

P

FEET

FLIGHT

DIP = 45°

Q

P

FEET

H = 90°
σtf = 72400

STRIKE = 90°

STRIKE = 45°

Fig. 5.2.1: Scale-model profiles of the helicopter system flying at different strike angles over a conductor. An oblique strike angle reduces the amplitude and makes the anomaly profile wider. For a dipping conductor, the anomaly profile is changed in such a way as if the dip angle is further decreased.
The effect of strike angles is purely on amplitude of a response.
For the Barringer system, an oblique strike angle reduces the magnitude of an anomaly and shifts the peak of the anomaly. The effects are more complicated for a dipping conductor.
The effect of strike angles is purely on amplitude.
The fish-tail receiver of the Dighem system is a vertical null coupled coil. The coupling of this receiver is zero if the system flies at right angles to a conductor. The direction of current flow along the strike-length of the conductor may only be detected by flying the AEM system at an oblique angle to its strike. In a field survey by the Dighem system, the strike angle of a vertical conductor may be determined as (intuitively reasoned by Fraser (1971)):

$$\alpha = \tan^{-1} \frac{R_H}{R_F}$$

where 'RH' and 'RF' are peak responses of the maximum coupled (helicopter) receiver coil and the fish-tail receiver coil, respectively. In principle, either the inphase or quadrature component may be used, but only the less noisy quadrature component is recorded by the Dighem system. The above equation has been proven to be approximately true for vertical and dipping conductors from scale-model measurements (Table 5.2.1).
TABLE 5.2.1

Scale-model measurements over conductors by the Dighem system (Whale-tail and main coaxial coils) flying at an angle of 45° w.r.t. conductors (strike)

<table>
<thead>
<tr>
<th>at mhos.</th>
<th>Dip (Degrees)</th>
<th>$Q_F$ (ppm) Fish-tail</th>
<th>$Q_H$ (ppm) Helicopter</th>
<th>Estimated Strike-angle $\alpha = \tan^{-1} \frac{Q_H}{Q_F}$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>90</td>
<td>37.0</td>
<td>39.8</td>
<td>47.1</td>
</tr>
<tr>
<td>15</td>
<td>90</td>
<td>73.5</td>
<td>74.9</td>
<td>45.5</td>
</tr>
<tr>
<td>75</td>
<td>90</td>
<td>58.8</td>
<td>55.2</td>
<td>43.2</td>
</tr>
<tr>
<td>3</td>
<td>45</td>
<td>41.5</td>
<td>53.1</td>
<td>52.0</td>
</tr>
<tr>
<td>15</td>
<td>45</td>
<td>80.3</td>
<td>102.3</td>
<td>51.8</td>
</tr>
<tr>
<td>75</td>
<td>45</td>
<td>67.9</td>
<td>70.4</td>
<td>46.0</td>
</tr>
<tr>
<td>3</td>
<td>135</td>
<td>48.4</td>
<td>53.1</td>
<td>47.6</td>
</tr>
<tr>
<td>15</td>
<td>135</td>
<td>97.8</td>
<td>102.3</td>
<td>46.3</td>
</tr>
<tr>
<td>75</td>
<td>135</td>
<td>86.5</td>
<td>70.4</td>
<td>39.0</td>
</tr>
</tbody>
</table>
VI. CONDUCTORS OF LIMITED EXTENT

All the previous analysis is based on large half-plane like conductors. AEM responses are affected when a conductor does not extend far along the dip and strike directions. These will be called the effects of depth-extent and strike-extent. Since AEM systems have different dimensions, it is very important to know how large a conductor should be in depth-extent and strike-extent so as to behave like a half-plane for 'large' and 'small' scale AEM systems. This has been investigated by scale model experiments.

VI.1 Depth-Extent:

Fig. 6.1.1 shows two phasor diagrams of the wing-tip system for four different depth-extents at flight heights of 217 ft. and 112 ft. As depth-extent becomes smaller, both the inphase and quadrature anomalies decrease, but by different amounts. For large 'σtf', the decrease in anomalies is such as to cause a large reduction in amplitude accompanied by a small change in phase angle. For small 'σtf', the anomalies decrease such that a point on the phasor diagram moves towards smaller 'σtf'. Therefore, if a conductor of finite depth-extent is interpreted as a half-plane, a good conductor would appear to be a little poorer conductor which is somewhat more
Fig. 6.1.1: Phasor diagrams of the wing-tip system over conductors of different depth-extents for two heights. Due to finite depth-extent, a good conductor appears to be a little poorer conductor which is somewhat more deeply buried than it actually is; whereas a poor conductor appears to be a very much poorer conductor than it is in reality. The effects are more for a larger height.
deeply buried than it actually is; whereas a poor conductor would look like a very much poorer conductor than it is in reality.

The lower phasor diagram (Fig. 6.1.1), for flight height equal to 112 feet, has been scaled differently to compare it with the upper one. Models of the same finite depth-extents have been used. The effects are much smaller for the lower height. This indicates that an absolute value of depth-extent is not the criterion of its effects. As flight height is the largest dimension of an AEM system, the effect of depth-extent should really be judged by its ratio with height of the system above conductor. Fig. 6.1.2 shows a plot of the inphase anomalies \( P \) normalized with respect to the response \( P_\infty \) of a perfectly conducting half-plane existing at the same height, against the ratio of depth-extent to height of the system. Because the relative magnitudes of the inphase and quadrature components of an AEM response is controlled by the quantity \( \sigma tfH \) (Section 3.4), the points representing values of constant \( \sigma tfH \) for the two heights fall on the same curve. These curves show that a good conductor tends to resemble a half-plane model at a smaller depth-extent compared to a poor conductor. This is also evident from the fact that good conductors have higher rates of fall-off with height (Section 3.5).
For conductors of finite depth-extents, points representing constant $\sigma t f H$ for the two heights lie on a curve. A good conductor tends to resemble a half-plane model at a smaller depth-extent compared to a poor conductor.
All AEM systems behave similarly over conductors of finite depth-extent (Ghosh and West, 1971). The towed bird systems fly at larger heights, and therefore a conductor has to have a larger depth-extent to yield half-plane anomalies. The shapes of profiles of finite depth-extent of a conductor are indistinguishable from those due to a half-plane. It seems that the only way to determine how far a conductor extends in depth is to fly the AEM system at different heights. The anomalies should be interpreted considering the conductor to be a half-plane model. If the values of apparent \( \sigma t \) are found to be the same at different heights, the conductor resembles a half-plane model for that system. If the conductor is small along depth-direction, the apparent \( \sigma t \) should gradually decrease with increase in flight height; and for a good conductor, the apparent depth may also increase somewhat. A field example to this effect was in Section 3.6.2, where an AEM survey over the Sturgeon Lake ore body by the Scintrex HEM-701 system shows that the ore body extends approximately 600 feet in depth.

**VI.2 Strike-Extent:**

By strike-extent we mean the length of a conductor along the strike direction. To investigate effects due to finite strike-extent of a conductor,
scale-model measurements were made using sheets of variable length along the strike direction. All the sheets had large lengths along the dip direction. Shapes of the profiles do not change. The inphase and quadrature anomalies obtained by the helicopter, whale-tail, and fish-tail systems for profiles crossing the conductor in the centre have been summarized in Fig. 6.2.1. All the systems show similar behaviour. The amplitude of response decreases and the phase rotates towards the poor conductivity side as strike-extent decreases. These indicate that a conductor of limited strike-extent appears as a deeply buried half-plane of poorer conductivity. The effects are entirely similar to those of limited depth-extent.

Fig. 6.2.2 gives an idea of how large a conductor should be along strike direction so that it behaves like a half-plane. The strike-extent has been normalized by height of the system above conductor. The anomalies fall-off quite rapidly when strike-extent is less than six times the height of the system. It seems that a half-plane anomaly is obtained when the strike-extent is ten times the height. These limits of strike-extents are higher for poor conductors, and vice versa. Similar results (Fig. 6.2.3) are obtained for large scale towed bird systems.
STRIKE - EXTENT

VERT. HALF-PLANE MODEL
HEIGHT = 120 ft.
$\sigma_{tf} = 45 \text{ kmho} \ \text{hz}$

STRIKE-EXTENT = 1450', 725', 360', 290', 217', 145'

Fig. 6.2.1

Due to a finite strike-extent of a conductor, amplitude of response decreases and the phase rotates towards the poor conductivity side. The effects are entirely similar to those of limited depth-extent. All the systems behave the same way.
For 'small-scale' systems, a half-plane anomaly is obtained when the strike-extent of a moderately good conductor is ten times the height of a system. This limit is higher for a poor conductor and vice versa.
STRIKE-EXTENT

VERT. HALF-PLANE MODEL
'LARGE-SCALE' AEM SYSTEMS

FLYING HEIGHT \approx 560 \, \text{FT.}
\sigma_{tf} = 4 \, \text{k mho. hz.}

\[ Q(\text{ppm}) \]

\[ \text{STRIKE-EXTENT/HEIGHT} \]

\[ \frac{2k}{0.5} \quad \frac{4k}{1} \quad \frac{5k}{2} \quad \frac{10}{5} \]

Fig. 6.2.3

Similar results are also obtained for the 'large-scale' systems.
VI.3 End-Effect:

If an AEM system flies close to the end of a conductor, the system does not 'see' the whole strike-extent. Induced current flow is restricted at the end of the conductor failing to yield a half-plane anomaly even if the conductor is large. This problem is faced in field surveys when anomalies due to a conductor are correlated from line to line. Scale model studies have been made to investigate the effects of this on interpretation of apparent 'σt' and depth of a conductor. Fig. 6.3.1 shows how anomalies change as flight lines cross a conductor at different distances from an end. As the distance decreases anomalies of all the systems are progressively smaller. The amplitude decreases and phase rotates towards poor conductivity. These are similar to the effects observed due to finite strike-extent and depth-extent. Fig. 6.3.2 shows that half-plane anomalies are obtained at distances larger than four times the height of the system from an end for a moderately good conductor. But, if 'σt' of the conductor is increased or decreased, respectively smaller and larger strike-extents are needed to yield half-plane anomalies. The change is greater for a poor conductor.
END-EFFECT
VERT. HALF-PLAN
HEIGHT =120 ft.
$\sigma_{1f}=45 \text{ kmho hz.}$

DIST. FROM AN END = 725', 600', 425', 300', 150', 0

\[ \text{Fig. 6.3.1} \]

The effects of flying an AEM system over the end of a conductor are similar to those due to limited extent of the conductor.
Fig. 6.3.2: Half-plane anomalies are obtained at distances larger than four times the height of the system from an end of a moderately good conductor.
VII. STUDY OF SPECIAL CASES

In the previous chapters we have studied effects concerning a single conductive body. Sulphide ore bodies often occur in the form of two or more separate conductors. Two important examples of this type of occurrence are: a) a steeply dipping sulphide ore body of moderately high conductivity below a poorly conductive overburden in the form of a flat sheet, and b) two or more steeply dipping conductive zones of mineralization separated by a short distance. The AEM response is quite complicated due to mutual interactions of the conductors. The effects of these two types of cases have been studied by scale-model measurements.

VII.1 Overburden:

The presence of a conducting overburden over a steeply dipping conductor mostly affects the quadrature component. With increase in overburden conductivity the quadrature response gradually changes in such a way as to decrease the peak amplitudes of anomalies. Finally, the peaks reverse, showing a negative quadrature response. The inphase component does not show any significant change. Fig. 7.1. 1 shows a phasor diagram of the helicopter system for the vertical conductor below an
The effect of overburden is mainly to decrease the quadrature response. But, the inphase response decreases quite rapidly when the quadrature anomalies are negative.
overburden of various '\sigma tf'. The quadrature anomalies
decrease and sometimes become negative with higher over-
burden conductivity. The inphase anomalies change by a
very small amount. Change in the inphase anomalies is
more rapid when the quadrature anomalies are negative.

Figs. 7.1.2 and 7.1.3 show the more complicated
profiles of scale-model measurements by the whale-tail
system over a vertical half-plane and a half-plane dipping
at 45 degrees, respectively, under a thin horizontal sheet
overburden of various '\sigma tf'. Notice the gradual reversal
of sign of the quadrature component causing complicated
shape of the profiles.

In general, an overburden changes the quadrature
response of a good conductor more than a poor conductor.
If a field anomaly due to a vertical half-plane below a
conducting overburden is interpreted without considering
the effects of the overburden, the half-plane would seem
to be a deeply buried better conductor. These are similar
to the effects of conducting overburden on horizontal-
loop ground electromagnetic measurements (Lowrie and
West, 1965).

It should be mentioned that, in model measure-
ments, the half-plane was not in physical contact with the
overburden. Therefore, these effects are due purely to
induction. However, a few model measurements (Medstrom
Scale-model profiles of the whale-tail system over a vertical half-plane under different overburden conductivities. Quadrature anomalies show gradual reversal of sign with increase in overburden conductivity.
More complicated scale-model profiles are obtained over a dipping half-plane under an overburden.
and Parasnis, 1958) with thin sheet conductors show that conduction effects are negligible compared to induction effects of an overburden over a vertical conductor.

VII.2 Two Parallel Conductors:

Model measurements have been done to investigate the interaction of two parallel vertical half-planes separated by different distances. Fig. 7.2.1 shows the actual scale-model profiles of the helicopter system over a pair of vertical half-planes at three separations. Also shown are summed profiles, which are obtained by adding up the two profiles observed separately for each of the half-planes. At a small separation of 100 feet, the profiles show two peaks which are not completely separated. The summed profile has higher amplitudes of peak anomalies. At a separation of 150 ft, the two peaks are very distinct. Amplitudes of peak anomalies of both the summed and actual profiles are then approximately the same.

Fig. 7.2.2 shows how the interaction takes place at different separations of the half-planes. The inphase anomalies of the actual and summed profiles have been plotted against the separations of the half-planes. The three horizontal lines indicate individual responses of each of the two half-planes and of the two half-planes in physical contact with each other. At separations of less than 75 feet, the profiles show only one peak.
TWO VERTICAL COND.

HELICOPTER SYSTEM
H = 120 FEET
(\sigma tf)_4 = 72 kmho. hz
(\sigma tf)_5 = 45 kmho. hz

Fig. 7.2.1

Scale-model profiles over two parallel half-planes; summed profiles are obtained by adding up the two profiles observed separately over each half-plane.
INTERACTION OF TWO VERT. CONDUCTORS

HELICOPTER SYSTEM

\[(\sigma_{tf}) = 72 \text{ kmho hz}\]
\[(\sigma_{tf}) = 45 \text{ kmho hz}\]
\[H = 120 \text{ FEET}\]

\[P \text{ (ppm)}\]

\[\text{SEPARATION BETWEEN CONDUCTORS (FEET)}\]

\[\text{SUMMED}\]

\[\text{ACTUAL}\]

\[\text{INDIVIDUAL RESPONSE}\]

Fig. 7.2.2: The interaction of responses of two parallel half-planes is negative when the separation between them is small. Hardly any interaction is present at a large separation. It is expected that the two edges of a wide conductor yield a larger anomaly than a thin sheet.
The amplitudes of the peaks are much smaller than summed anomalies. This shows strong negative interaction at small separations. The interaction decreases at larger distances when two peaks appear in a profile. At separations larger than 180 feet, the interaction becomes positive. This interaction should slowly decrease to zero at a very large separation as indicated schematically by the dashed lines.

To see how the interactions affect interpretation of $\sigma t f$ and $H$ in field surveys, the peak anomalies have been plotted (Fig. 7.2.3) in the phasor diagram of vertical half-plane models. The points show that when separate peaks appear in a profile, the peak amplitudes indicate correct apparent $\sigma t$ of each of the half-planes. The estimate of height is only a little too small. If only one peak appears in the profile, it may be mistaken to be due to a single conductor. In this case, apparent $\sigma t$ is closer to the summation of $\sigma t$ of the conductors. The height estimate is only 10 feet less than the actual height. This indicates that interpretation of each of the peaks offers good results in anomalies having multiple peaks. Stripping of anomalies should either not be done or done only when anomalies are quite well resolved.
VERT. HALF-PLANE

HELICOPTER SYSTEM

($\sigma_f=71\text{ k mho hz}$)$_4$
($\sigma_f=45\text{ k mho hz}$)$_5$

SEPARATION:  
A = 100 ft.  
B = 65 ft.  
C = 35 ft.

---

**Fig. 7.2.3**

Use of peak amplitudes of anomalies of a multi-peak anomaly profile indicates correct estimate of $\sigma_f$. 

---
VII.3 Poor Conductors Surrounding a Good Conductor:

It was noticed in Chapter 3 that the quadrature component measuring AEM systems over the Whistle deposit show very much smaller apparent 'σt' than the inphase and quadrature component measuring systems. The Dighem (coaxial coils) helicopter and Barringer whale-tail systems show average apparent 'σt' of 80 mhos and 60 mhos respectively. On the other hand, the Lockwood and McPhar quadrature systems indicate an apparent 'σt' of 1.5-3.2 mhos for the Whistle deposit. This phenomenon was also noted by Becker (1972). In this context, it is interesting to note that AEM systems do not show a significant discrepancy in apparent 'σt' over the Sturgeon Lake and the Cavendish conductors. The Whistle body is wide (50-100 feet) and the mineralization is reported to be "massive". Often for wide bodies, the conductivity is poor at the two sides and it increases towards the centre. We can imagine a wide ore body to be made up of one good conductor at the centre and two (or more) poor conductors at about equal distances from the central conductor. We have tried to find an explanation of small apparent 'σt' of the quadrature systems over the Whistle body by studying this model.

Model measurements were made with a good conductor and also with two poor conductors, at distances
of 50 feet, on both sides of the same conductor. Two good conductors, $S_3$ and $S_5$, having 'σt' of 44 mhos and 17 mhos, respectively, have been used. The poor conductors on both sides have a 'σt' of 5 mhos.

Fig. 7.3.1 shows that by putting poor conductors on both sides of $S_3$ and $S_5$ the apparent 'σt' changes to 20 mhos and 8 mhos (points $M_3$ and $M_5$) respectively. The decrease in 'σt' is not as large as seen over the Whistle deposit. It is really interesting to note that, in Section 7.2, we have found that for an inphase and quadrature components measuring system, apparent 'σt' of a conductor increases in presence of any other conductor. The quadrature measuring systems seem to behave differently.

In the model measurements, both the inphase and quadrature components have been recorded. In Fig. 7.3.2, the experimental points of the single conductors ($S,S'$) and poor conductors on both sides of single conductors ($M,M'$) have been plotted using both the inphase and quadrature components of responses. These points show that by adding poor conductors on both sides of a single conductor, the phase of the anomaly does not shift much but the conductor seems to lie at a shallower depth. Actually, the phase seems to increase by a small amount. Similar effects are seen for a group of parallel conductors (Section 7.2). The decrease in apparent 'σt' in the two frequency quadrature systems is due to the fact that the quadrature response to a conductor is increased by the presence of the poor conductor on both sides but relatively much more so in the high frequency channel.
The McPhar quadrature system shows that by adding poor conductors on both sides of a good conductor, the apparent 'st' decreases.
Scale-model measurements using both the inphase and quadrature components of the McPhar system show that the effect of adding poor conductors on both sides of a good conductor is the same as that due to a group of parallel conductors. The apparent 'σ' does not decrease.
VIII. CONCLUSIONS

This thesis research has consisted of two parts. The first is a large number of scale-model measurements for thin sheet conductors and a variety of AEM systems. This is the first thorough study of this kind. The second part of the work has been to apply the scale-model data to some actual field data to see if real and model data can be reconciled. The anomalies studied were selected for multiple coverage and for cases where some "ground-truth" is available. Detailed conclusions are not being reviewed here. However, some general conclusions seem valid on the basis of the experience gained in the work. These are described here.

1) The data, which is obtained by one kind of AEM system (P-Q measuring or 'B-f' Q- measuring) with repeated traverses over a conductor (i.e. different heights, frequencies and locations), gives a consistent 'σt' estimate on the basis of the thin sheet model in a non-conducting space. The estimates of 'σt' obtained from different systems may be discrepant in some cases. The discrepancy is not produced by the different scales of the systems, but rather by the different manner in which the estimates of 'σt' are obtained (i.e. comparison of 'P' and 'Q' amplitudes at one frequency, or comparison of 'Q' amplitudes at two frequencies). The reason for this
discrepancy seems to be the presence of a poorly conducting halo, in which case the estimate of \( \sigma t \) from the inphase and quadrature measuring system is more nearly correct.

2) The effects of depth-extent, strike-extent and dip angle of a conductor on the AEM response, as revealed by the scale-model studies, can be properly applied to interpretation of data from real conductors in the field.

3) Narrow flat-flying surficial conductors cannot be distinguished from dipping conductors on the basis of the anomaly shape and width. However, they can be distinguished on the basis of anomaly amplitudes if the aircraft altitudes are correctly determined. If two spatial components of the secondary field are measured, as by the vertical coaxial and whale-tail receivers of the Dighem system, the relative amplitudes of anomalies indicate the attitude of the conductor without the necessity of an accurate height determination.

Moderately wide flat-lying surficial conductors having sharp edges can be identified on the basis of the anomaly shape and width. In the absence of sharp edges, they can be identified by anomaly amplitude only.
Very wide flat-lying surficial conductors can readily be identified by the anomaly width. Wide conductors with nonuniform 'σt' can only be distinguished by anomaly widths.

4) The shape of an anomaly profile is indicative of the direction and amount of dip of a conductor. For 'large-scale' systems, the dip of a long-strike conductor can be most easily ascertained by comparing the anomalies of adjacent flight lines flown in opposite directions. The anomaly amplitudes of a dipping conductor should be corrected before they are compared with the interpretative diagrams of the vertical half-plane model.

5) The oblique flight line with respect to a conductor (i.e. strike-angle) can be accurately determined by the anomaly of the fish-tail receiver of the Dighem system.

6) If two parallel conductors are separated enough to yield two peaks on the anomaly profile, their 'σt' estimates can be obtained roughly from the amplitudes of the peaks without correction for overlap.

7) Presence of conducting overburden leads to false estimates of 'σt' and 'H'.
8) With the present systems in use, it is not feasible to determine if a conductor is of finite-size, or if it is associated with a conducting overburden. A future development of a multi-frequency two height AEM system could solve these problems.

9) The single most important conclusion derived from this work is that the thin sheet model in free space seems to provide a satisfactory basis on which to build a quantitative interpretation procedure for AEM data from the Canadian shield and similar environments. Some elaborations may be necessary in certain situations (such as the multiple conductor model of a halo).

10) Though not mentioned before, recording of anomalies in magnetic tapes would be easier to work with. This is a must for a multi-channel system and the data could be very conveniently computer processed.
REFERENCES


Fraser, D.C.: 1972, Personal Communication.


## APPENDIX

<table>
<thead>
<tr>
<th>Investigation</th>
<th>System No.</th>
<th>Dip (degrees)</th>
<th>Conductor Numbers</th>
<th>No. of Heights</th>
</tr>
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<tbody>
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<td>1) Vertical Half-plane</td>
<td>1-3</td>
<td>90</td>
<td>* 0-9</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td></td>
<td>0, 1, 4, 7, 9</td>
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</tr>
<tr>
<td></td>
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<td>0, 4, 7, 9</td>
<td>1</td>
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<td></td>
<td>0-9</td>
<td>3</td>
</tr>
<tr>
<td>2) Dipping Half-plane</td>
<td>1-2</td>
<td>45,60</td>
<td>0, 1, 4, 7, 9</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>45,60,120,135</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>45,135</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>3) Strike Angle (45°) with Half-Plane</td>
<td>1-6</td>
<td>45,90</td>
<td>0, 1, 4, 7, 9</td>
<td>1</td>
</tr>
<tr>
<td>4) Depth-Extent of Conductors (4 finite lengths)</td>
<td>1-3</td>
<td>90</td>
<td>1, 4, 7, 9</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4-6</td>
<td>90</td>
<td>1, 4, 7, 9</td>
<td>1</td>
</tr>
<tr>
<td>5) Strike-Extent of Conductors (6 finite lengths)</td>
<td>1-6</td>
<td>90</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6) Flying close to end of Conductors (6 lengths)</td>
<td>1-6</td>
<td>90</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7) Overburden (4 diff. 'σt')</td>
<td>1-6</td>
<td>45,90</td>
<td>2, 4, 7, 9</td>
<td>1</td>
</tr>
<tr>
<td>8) Two parallel conductors (6 diff. separations)</td>
<td>1-6</td>
<td>90</td>
<td>4, 5</td>
<td>1</td>
</tr>
</tbody>
</table>

* '0' denotes theoretical computations of a perfectly conducting half-plane.