1 INTRODUCTION

1.1 An Endeavour to Increase the Spatial Resolution and Interpretability of Geophysical Surveys

To the analytical mind, one of the most challenging aspects of the science of geophysics is that of interpreting exploration data. In any mystery, the initial step in the sequence of events which comprise the investigation is to collate all available pertinent information. The information is then validated, cross-referenced for consistency and interpreted in an effort to eliminate erroneous solutions and thereby focus on a final deduction. Generally, the ease with which the mystery may be solved will depend on the wealth and accuracy or *quality* of the information gathered.

In terms of geophysical exploration data, quality has often in the past been assessed by the *precision* with which scientific measurements were made. However, given the unprecedented performance capabilities now offered by modern geophysical instrumentation, poor *interpretability* of exploration data is more frequently a consequence of undersampling as well as the inherent ambiguity often associated with the physical properties measured.

The problem of undersampling may be alleviated by simply acquiring data at higher spatial resolution, thus better defining signal anomalies and reducing the effect of aliasing on signal and noise. Ambiguity due to the nature of the physics involved is a more complex problem to remedy. An approach often used is to record multiple data sets relating to several independent physical parameters, thereby providing a cross-referencing component to the interpretation strategy. Implementation of the above solutions generally requires a significant increase in the data acquisition budget and the explorationist is, perhaps unreasonably, expected to predict the most cost-effective survey program.

The cost of data acquisition usually dictates that measurement intervals be selected to sample the predicted *signal* anomaly of interest. In fact, it is the higher frequency *noise* profile that must be adequately sampled if the signal is to be properly interpreted. Experience with *High Definition Magnetics*[1] (HDM) surveys has demonstrated that many conventional surveys have been wasted as a result of the false economy associated with compromised data sampling. Unfortunately, the explorationist is usually never aware of the information that was overlooked by undersampling. While data acquisition expenditure remains the responsibility of the explorationist, those involved in instrumentation research should aim to improve the cost-efficiency in acquiring high spatial resolution data.

Recent advances in microprocessor technology have had a great impact on geophysical instrumentation and survey efficiency. In particular, these developments have resulted in instruments which feature higher sensitivity, faster sampling rates and improved signal processing capability. When combined with navigation facilities such as Global Positioning Systems (GPS), the cost of acquiring detailed data sets for some methods has decreased dramatically and high definition surveys are becoming more common.

Another development of the last decade which has accelerated interest in these surveys has been the widespread use of image processing systems. With the filtering, image enhancement and display technologies currently available, much finer detail is being extracted from the data than previously thought possible. Consequently, the exploration industry is becoming increasingly aware of the significant benefits offered by higher spatial resolution. This was recently attested to in the form of the theme employed by the Australian Society of Exploration Geophysicists (ASEG) for their 10th Geophysical Conference and Exhibition, that is: *"Increasing the Resolution: Clearing the Haze"*.

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[1] The term *high definition* has been adopted to signify closely sampled or *high spatial resolution* surveys. The term *high resolution* was considered ambiguous as it may imply *high measurement resolution* only. *High Definition Magnetics* (HDM) is a trademark of the Geophysical Research Institute, UNE.

An area of geophysics that has benefited greatly from technological advances is magnetics. The last decade has seen the development of rapid sampling, portable magnetometers such as the TM-4 (Geophysical Technology Pty Ltd) which incorporate optically-pumped sensors. The main advantage of these systems is that, unlike conventional proton precession magnetometers, high precision data may be recorded automatically at very high sample rates while the instruments are in motion.

As a result of these developments high spatial resolution magnetometer surveys have become logistically and economically feasible and High Definition Magnetics (HDM) has greatly improved the quality of magnetic surveys for conventional applications. In addition, the enhanced capabilities of the method have meant that many new applications have been recognised (Stanley and Cattach, 1990).

While HDM has contributed substantially to exploration efficiency by providing adequately sampled data, the inherent ambiguities associated with interpreting total magnetic intensity data have not been overcome. Similarly, geological structures which do not display a contrast in magnetic properties cannot be interpreted from magnetic data. There is consequently a recognised need for technologies to map independent properties of the ground with the same spatial resolution and survey efficiency as that which has been achieved with state-of-the-art magnetics.

Improvements in survey efficiency and spatial resolution have not been achieved across all geophysical techniques. Higher precision data from electrical methods such as Resistivity and Induced Polarisation (IP) have become available from real-time signal processing enhancements. However, apart from the employment of multi-conductor cables by receivers such as the IPR-12 (Scintrex, 1993b) which allow a multiple input mode of operation, survey speed has not significantly improved.

The reason for this is the logistical constraint imposed by the requirement for grounded potential electrodes. It may be argued that due to that constraint, the speed at which IP surveys are performed can never be significantly increased. This same constraint also applies to those other methods that similarly require grounded electrodes, such as, for example, Magnetotellurics (MT), Audio-Magnetotellurics (AMT) and Controlled-Source Audio-Magnetotellurics (CSAMT).

Electromagnetic methods such as SIROTEM, Magnetometric Resistivity (MMR) and Magnetic Induced Polarisation (MIP) have also benefited from improved signal processing capability. These methods involve measuring components of the magnetic field produced by induced electrical current flow. However, a major difficulty in improving the efficiency of these methods is the time consuming requirement to precisely orientate and level the sensor prior to taking measurements.

The fact that electrical surveys would be capable of providing significantly more diagnostic information if it were economically feasible to increase spatial resolution, has been demonstrated for the dipole-dipole IP array by Cattach (1985). It is the author's belief that a high definition electrical technique would revolutionise electrical prospecting methods by better defining anomalies and hence reduce the ambiguity of interpretation. Furthermore, as has occurred with High Definition Magnetics, it is anticipated that because of the greater definition provided, such a technique would find a broader range of applications than conventional techniques.

1.2 Project Objectives

The principal objective of the project described in this thesis was:

> ***To develop a cost-effective geophysical method which would simultaneously provide high spatial resolution information related to both the electrical and magnetic characteristics of the ground.***

A secondary objective was the ability of the method to record the above information at sample intervals comparable with those achievable with High Definition Magnetics (of the order of one metre) while continuously traversing at a minimum of walking speed.

The technology that was developed to meet these objectives has been called *Sub-Audio Magnetics* or the *SAM* technique. The SAM concept arose when it was recognised that a new magnetometer system (in which the author had contributed in developing) had the potential to be simultaneously used as an electromagnetic sensor.

The strategy for achieving the above objectives was divided into the following three stages. The defined sub-objectives were to:

1. **Conceptual Development.**
    1.1. *Review state-of-the-art magnetic surveying techniques to determine the theoretical sampling requirements and how they were achieved.*

    1.2. *Review relevant contemporary electrical methods with a view to determining their technical strengths and limitations as well as their potential for improved survey efficiency and hence increased spatial resolution.*

    1.3. *Develop a theoretical survey concept which would accommodate the efficient, high resolution acquisition of parameters related to the electrical properties of the ground.*

    1.4. *Research any physical phenomena which may affect data quality.*

2. **Field Tests Using Existing Instrumentation.**
    2.1. *Design a field procedure and conduct field tests that would enable the application of existing instrumentation to test the SAM concept.*

    2.2. *Assess the performance characteristics of the transducer with respect to the requirements of the survey technique.*

    2.3. *Determine signal levels and data quality.*

    2.4. *Develop and test appropriate data reduction techniques.*

    2.5. *Identify any likely logistical difficulties which may be inherent in the field procedure.*

    2.6. *Evaluate the SAM concept with a view to determining its potential as a new exploration method and thereby assess its suitability for further development.*

3. **Instrument Development and Field Testing.**

    3.1. *Determine the technical requirements of an instrument which would be capable of measuring the geophysical phenomena of interest with the* *required sensitivity and survey efficiency (If sufficient encouragement was provided from the feasibility studies).*

3.2. *Specify the use of strategic real-time procedures that could be built into the survey instrument to improve the efficiency of the method.*

3.3. *Design and construct a prototype SAM receiver.*

3.4. *Conduct field tests of the purpose-built SAM receiver over known mineralisation where geological control was available.*

3.5. *Assess the system with a view to making recommendations for ongoing development.*

1.3 Achievements of the Research

In recognition of the need for a cost-effective means of providing detailed electrical information, a new, high definition method for mapping parameters related to the electrical characteristics of the ground has been developed. Additionally, the method simultaneously acquires high definition, total field magnetic data. The method employs a constant current transmitter operating at fundamental frequencies in the sub-audio frequency range. The magnetic fields produced as a result of the transmitted current flow are monitored together with the earth's spatially varying magnetic field, with an optically-pumped total field magnetometer. The technique has consequently been entitled *Sub-Audio Magnetics* (*SAM*). A purpose-designed SAM receiver has been developed to enable processing and recording of the required parameters and the technique is now being operated commercially.

Spectral analysis of the magnetic field changes allows a suite of geophysical parameters to be derived. Not only do these parameters allow non-magnetic targets to be mapped, they also provide information which may assist in resolving the ambiguity of magnetic interpretation. In order to differentiate the electrical measurements so obtained from parameters recorded by conventional methods, the following terminology has been introduced:

- **T**otal **F**ield, **M**agneto**M**etric **R**esistivity (TFMMR).
- **T**otal **F**ield, **M**agneto**M**etric **I**nduced **P**olarisation (TFMMIP).
- **T**otal **F**ield **E**lectro**M**agnetics (TFEM).

As well as providing the above measurements at high spatial resolution, a major benefit of SAM, particularly in terms of survey efficiency is the simultaneous acquisition of:

- **T**otal **M**agnetic **I**ntensity (TMI).

Because of its inherent cost-efficiency and superior spatial resolution, SAM has the potential to significantly enhance geophysical mapping for mineral exploration, archaeological investigation and environmental studies relating to salinity and industrial contamination.

Sub-Audio Magnetics is the subject of International Patent No: PCT/AU91/00238 (Cattach *et al.*, 1991). The technique is described in a concept paper by Cattach *et al.* (1993) which was awarded "Best Published Paper" at the Australian Society of Exploration Geophysicists (ASEG) 10th Geophysical Conference and Exhibition, Perth, WA, Feb., 1994. SAM also resulted in the presentation of the "Grahame Sands Award for Innovation in Applied Geoscience" at the ASEG 11th Geophysical Conference and Exhibition, Adelaide, SA, Sept., 1995.

1.4 Organisation of the Thesis

The layout of the thesis parallels the three stages of the project as previously outlined. Chapter 2 is a review of High Definition Magnetics and of relevant contemporary electrical methods while Chapter 3 presents the Sub-Audio Magnetics concept and describes the potential advantages of the technique over the contemporary methods.

A series of feasibility studies were conducted over a number of geological targets using readily available instrumentation. The instrumentation and field procedure employed for the trials is described in Chapter 4. An investigation of the recorded waveforms and a description of the data reduction procedures employed for the feasibility studies is presented in Chapter 5. The field results of two of the feasibility studies are presented along with the known geology and prior geophysics in Chapter 6.

Chapter 7 specifies the requirements of a purpose-built SAM receiver and describes the strategies employed to accommodate those specifications in the development the first prototype. The results of surveys conducted with the prototype SAM receiver are presented in Chapter 8 which also provides a critique of the receiver's performance.

Chapter 9 presents the results of several exploration surveys performed with the method and highlights some of the diagnostic benefits of the technique. Finally, Chapter 10 is a project review and evaluation. A summary of the conclusions drawn from the study is included and new fields of research arising from the results of the project are proposed.

Awards presented for the research described in this thesis are included in the Appendix.

2 REVIEW OF RELEVANT CONTEMPORARY GEOPHYSICAL SURVEY METHODS

2.1 Introduction

The measurement of magnetic anomalies due to magnetic susceptibility contrasts and magnetic remanence is one of the most established geophysical exploration methods. Nonetheless, it has undergone major advancement with recent improvement to magnetometer instrumentation. Taken in isolation, the magnetic method must always be limited, firstly, to targets that exhibit a contrast in magnetic properties and, secondly, by the fundamental ambiguity that magnetic properties (including unknown remanence) impose on data inversion. This study seeks to overcome these problems by the simultaneous acquisition of data reflecting independent physical properties, recorded with the same spatial resolution and, in fact, the same instrument and survey operation as a state-of-the-art magnetic survey. This is not a study of the magnetic survey method but rather an endeavour to apply the lessons learnt from recent developments in high definition magnetics to advantage in complementary exploration methods.

Electrical methods in geophysical prospecting involve measurement of physical parameters associated with the flow of electric current in the ground. The many varied techniques which have been developed involve the measurement of potentials, currents and electromagnetic fields and are often classified according to whether the energy source used is natural or artificial. Examples of techniques based on natural sources include self-potential (SP), tellurics, magnetotellurics (MT) and the audio frequency magnetic technique (AFMAG). Methods which utilise artificial energy sources include resistivity, induced polarisation (IP), electromagnetics (EM) and controlled source audio magnetotellurics (CSAMT).

The techniques which employ artificial sources may again be categorised according to the means by which the sub-surface current flow is induced, that is, whether it is by galvanic induction (resistivity and IP) or electromagnetic induction (EM methods). SAM also requires an artificial energy source and could theoretically employ either mode of induction. However, for the initial development stage of the method, research concentrated on the use of galvanic induction.

As a component of the initial "Conceptual Development Stage" of the project, this chapter describes the state-of-the-art in magnetic surveying techniques with respect to the theoretical sampling requirements, the instrument design strategies and the field procedure employed to accommodate them. In addition, the major features of contemporary galvanic techniques which are considered relevant to the project are reviewed. Special emphasis is placed on the required field procedures, conventional instrumentation and measured parameters with a view to determining their theoretical strengths and limitations as well as their adaptability for improved survey efficiency.

2.2 State-of-the-Art High Definition Magnetics

Magnetics is the oldest branch of geophysics. The first scientific investigations of terrestrial magnetism were conducted by Sir William Gilbert (1540-1603). Gilbert showed that the Earth's magnetic field is roughly equivalent to a permanent magnet lying in a general north-south direction near the Earth's rotational axis. In 1843, von Wrede first used magnetic variations in the field to locate magnetic ore. Magnetic prospecting involves the measurement and mapping of variations in the magnetic field of the earth which are attributable to changes in the structure or magnetic susceptibility of near-surface rocks.

Until the late 1940's magnetic field measurements were made with a magnetic balance, which measured a component of the earth's field, usually the vertical component. During World War II, the fluxgate magnetometer was developed in order to satisfy the requirement to detect submarines. Proton precession magnetometers were developed in the mid-1950's and due to their simplicity, reliability and low cost, they remain the most commonly used instruments today.

Magnetometers based on proton precession sensors depend on the measurement of the free-precession frequency of protons that have been polarised in a direction normal to the direction of the earth's magnetic field. When the polarising field is suddenly removed, the protons precess about the Earth's field at an angular velocity which is proportional to the magnetic field. The instruments measure the Total Magnetic Intensity (TMI), not the direction. The time required to take a measurement is one or more seconds. Consequently, these sensors are not suitable for rapid sampling.

Optically-pumped alkali-vapour magnetometers were initially investigated in the early 1960's. They are essentially electro-optical oscillators whose operation is explained by the principles of quantum mechanics (Scintrex, 1993a). They also measure the magnitude of the magnetic field but have the advantage over proton precession magnetometers of significantly improved sensitivity and continuous output. One of the first optically-pumped sensors was constructed by Stanley (1975a) who recognised the potential of the instrument for high definition, high resolution magnetic mapping at ground level and has since pioneered many new applications including archaeological, environmental and engineering site investigations (Stanley, 1975b; Stanley, 1982; Stanley, 1985; Stanley and Cattach, 1986; Stanley and Cattach, 1990).

The term "High Definition Magnetics" or HDM refers to high spatial resolution surveys involving the measurement of Total Magnetic Intensity. The basic philosophy of HDM surveys is that the magnetic field must be adequately sampled in order to remove the ambiguity of interpretation due to undersampling. In addition, the high frequency component of the magnetic field often contains information of diagnostic value which if not properly sampled, is never seen by the explorationist. Before the advent of rapid sampling magnetometers, HDM surveys were not cost-effective due to the tedious and, therefore, expensive requirement for close sample intervals.

The initial research by Stanley (1975a) has continued through the efforts of the Geophysical Research Institute (GRI) at the University of New England and has led to the development of a series of sophisticated instruments based on the optically-pumped caesium vapour sensor and designed for the precise, rapid measurement of the earth's magnetic field. The evolution of these magnetometers has largely reflected the progress of digital electronics. The original system was vehicle-borne by necessity due to the size and weight of the power supplies and logging device (Stanley, 1975a; Stanley, 1975b). The first portable memory magnetometer was developed in 1979 (Lee, 1979). The latest development in the series is the highly efficient, man-portable, quad-sensor TM-4 magnetometer.

2.2.1 Field Procedure

The sampling strategy required for magnetic surveys depends on the elevation of the sensor above ground level, as the distance separating the sensor from the anomaly source has the effect of low-pass filtering the magnetic signature of the source. If the nearest magnetic source is assumed to be at the ground surface, the highest spatial frequency will have a wavelength equal to the elevation of the sensor above ground (Stanley and Cattach, 1990). By adapting the Sampling Theorem (e.g. Bracewell, 1978), it can be shown that the magnetic anomaly waveform is adequately sampled in a plane above the ground surface when measurements are taken at intervals not exceeding one half the sensor elevation. Therefore, the magnetic field at a typical sensor elevation of one metre above ground can be adequately defined by measurements taken at 0.5 m intervals in both perpendicular directions of the plane.

For applications such as archaeological mapping or the detection of unexploded ordnance, it is particularly important that these requirements be met. Consequently, dual and quad sensor systems have been developed by GRI for use in those applications.

For mineral exploration surveys at ground level, it is not economically feasible to adequately sample the field in both directions of the plane. In those situations, measurements are taken at close sample intervals along lines spaced typically 10-20 m apart. The benefit of this procedure is that high frequency "noise" from near surface sources may be effectively removed by one-dimensional, non-linear filtering along lines resulting in relatively clean data that is properly sampled for signal sources below 20 m (where this may be the depth of weathering or depth of cover).

2.2.2 Instrumentation

It is clear from the above discussion that in order for the sampling requirements to be met, the magnetic survey instrumentation and procedures must be highly efficient. Stanley and Cattach (1990) describe the magnetometer characteristics which are necessary to achieve that efficiency as including the following:

(i). It must be capable of multi-sensor operation.

(ii). For each sensor, it must be capable of at least several measurements per second, to better than 1 nT resolution whilst in continuous motion.

(iii). It must include an automatic positioning device in order to locate each measurement of the magnetic field.

(iv). It must have sufficient processing power and memory capacity to acquire and record up to at least 200,000 measurements per day.

The TM-4 magnetometer has been specifically designed to accommodate the above requirements. It is capable of logging up to four caesium vapour sensors simultaneously at rates of up to 400 samples per second. The system is capable of being configured with either a cotton thread odometer or differential GPS to provide sampling strobes and / or positional data. On-board memory of 6 MB enables the recording of up to one million measurements before uploading to a computer is required.

The relatively recent advent of the Overhauser magnetometer (based on proton precession technology) which is capable of sample rates of up to 10 samples per second has made HDM less expensive and consequently more readily available to the explorationist. In addition, industry acceptance of the benefits of adequately sampling the magnetic field has meant that the technique has now become routine.

2.3 Contemporary Galvanic Electrical Methods

There are four commonly used electrical survey methods which employ galvanic current flow and which bear relevance to this project. Two methods employ direct detection of galvanic effects. They are:

- Electrical Resistivity (ER)
- Electrical Induced Polarisation (EIP)

The following methods are the magnetometric counterparts of ER and EIP. That is, they involve the measurement of the magnetic field associated with current flow.

- Magnetometric Resistivity (MMR)
- Magnetic Induced Polarisation (MIP®)

ER and EIP are closely related in terms of the field procedures involved. ER is, in fact, a quantity measured in EIP surveys. MMR is related to MIP in much the same way as ER is related to EIP and MMR is a fundamental parameter measured in MIP surveys. However, the four methods have been developed separately and are reviewed in this section as distinct methods. Emphasis is placed on their applications, the field procedures involved and the quantities measured.

2.3.1 Electrical Resistivity (ER)

For practical purposes, resistivity was the first electrical prospecting method. It was refined in 1912 by Conrad Schlumberger, a senior mining engineer and Professor of Physics at the Paris School of Mines. His fundamental idea was:

> *"to compare the potential distribution resulting from current applied to the real earth to that which would exist if the same current were applied to a homogeneous earth, and to draw from observed differences, conclusions concerning the nature of the real earth" (Kunetz, 1966, 2).*

® MIP is a registered trademark of Scintrex Ltd.

It is this concept which is the basis of the resistivity method and, consequently, the basis of all direct current, electrical prospecting methods.

Resistivity is a fundamental property of rock materials closely related to their lithology. Consequently, through determination of the sub-surface distribution of resistivity from surface measurements, it is possible to acquire useful information on the structure or composition of the buried formation. The method is mainly used in the search for water-bearing formations, stratigraphic correlation in oil-fields and in direct exploration for conductive ore-bodies.

2.3.1.1 Field Procedure

In resistivity methods, an artificial source of current is introduced into the ground through either point electrodes or long line contacts. By measuring the potentials at other electrodes as well as the current introduced, an *apparent resistivity* can be determined.

The field procedure used is primarily dependent on whether the prospector is interested in measuring variation in resistivity with depth extent or with lateral extent. The two procedures are known as:

(i). *Vertical Sounding*. As the fraction of current flow with depth depends on electrode separation, the general procedure is to use electrode arrays with fixed centres and expanding spreads. The technique is appropriate for the detection of horizontal or gently dipping beds of contrasting resistivities and is, therefore, commonly used for ascertaining depth of overburden and the depth and structure of sedimentary beds. Vertical soundings are also often used to determine appropriate electrode spacings for lateral exploration procedures.

(ii). *Lateral Profiling*. Lateral profiling techniques are used to map isolated bodies of anomalous resistivity. The procedure is best applied to the detection of two-dimensional structures such as steeply dipping contacts and dykes.

Electrodes

Steel, aluminium or brass stakes are commonly used for current electrodes in resistivity surveys. They are generally driven into the ground for several centimetres and watered to ensure good electrical contact with the ground. Potential electrodes usually consist of a metal bar immersed in a saturated solution of one of its salts (typically copper in a solution of copper sulphate) carried in a fritted, permeable ceramic cup. "Porous pots" as they are called are described in detail in Sumner (1976).

Electrode Layouts

A great number of electrode configurations have been used for resistivity surveying. For logistical and interpretative reasons, the arrays are normally collinear, although in principle, in-line arrays are not necessary. The arrays are designed according to the probable depth and size of the target and are generally laid out at right angles to the geological strike. Electrode spacings are selected with respect to the desired resolution and are usually no less than the desired optimum depth of exploration. The distance between survey lines is typically up to twice the electrode interval.

The most common arrays currently in use are illustrated in Figure 2-1 and are described below:

Wenner Array

In the Wenner array, the electrodes are uniformly spaced. When used for depth sounding, the electrodes are expanded about a centre point. For lateral profiling, all four electrodes are moved along the line whilst the electrode spacing remains constant.

Schlumberger (Gradient) Array

For the Schlumberger array, the current electrodes are spaced much further than the potential electrodes. In vertical soundings, the potential electrodes remain fixed while the current electrode spacing is expanded symmetrically about the centre of the spread. It is, therefore, more convenient than the Wenner array in that only two of the electrodes are moved at a time. In addition, the effect of any shallow resistivity variation remains constant with fixed potential electrodes.

When used for lateral profiling, the current electrode separation is fixed and is typically greater than 500 m. The potential electrodes are moved between them with fixed spacing. Because the current electrodes are far apart, the current density is approximately uniform over a considerable lateral extent. It is, therefore, common to measure off to the side of the centre-line thus enabling mapping in two dimensions.

Pole-Dipole (Three-Point) Array

The pole-dipole array is not appropriate for soundings but is useful as a mapping tool. Generally, one of the current electrodes is fixed at a great distance from the other three, all of which may have various spacings. As one of the current electrodes is remote, it is not necessary for it to be collinear with the other three. Exploration usually consists of surveying radial lines from a fixed position of the near current electrode. The technique is convenient for mapping in the vicinity of a conductor of limited extent and is similar to the *mise-à-la-masse* technique where the near electrode is placed in contact with the conducting zone.

Double-Dipole (Dipole-Dipole) Array

In the double-dipole array, the potential electrodes are closely spaced and are emplaced remote from the current electrodes which are also close together. In practice, the arrays are usually collinear. Electrode spacings within electrode pairs are kept constant (typically 25-50 m for mineral exploration surveys) while the spacing between electrode pairs is varied, enabling measurements related to different depths.

2.3.1.2 Instrumentation

Power Sources

The power source used for resistivity measurements may be direct current (DC) or low frequency alternating current (AC) (generally less than 60 Hz), depending on the scale and nature of the survey. Commutated current is often used to prevent the effects of *electrolytic polarisation* which is caused by unidirectional current.

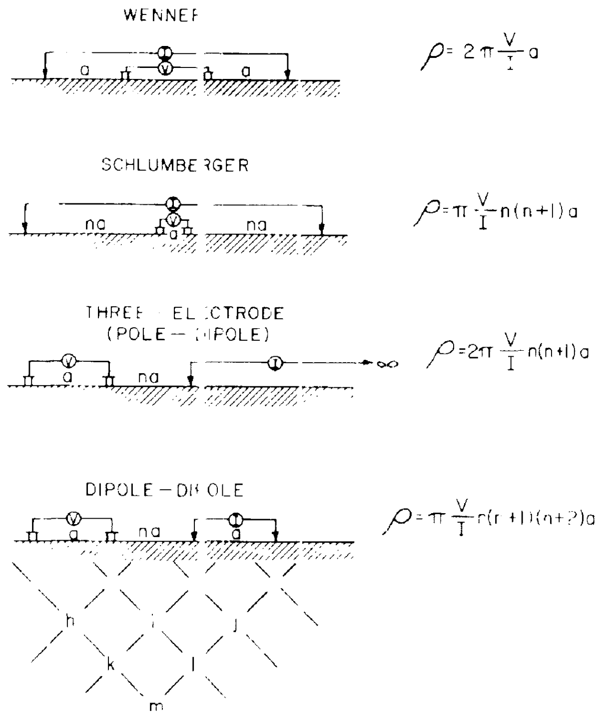

Figure 2-1. Common Resistivity Arrays (After Sumner, 1976).

The advantages of using AC current are described by Kunetz (1966) as including:

- ease of power production.
- enhanced ability to amplify signals.
- ability to filter the signal which facilitates the distinction between the useful signal and unwanted noise due to SP, electrolytic polarisation or telluric currents.

The main disadvantage of AC power sources is a phenomenon known as the *Skin Effect* which results from the concentration of alternating current near the contact between materials of different resistivities. The concentration is more pronounced for higher frequencies and for greater resistivity contrast and results in poor depth penetration.

Resistivity Meters

For DC or long-period commutated DC sources, current is measured with a DC milliammeter. The potentials are usually measured with a high input impedance DC voltmeter. AC signals require AC meters.

2.3.1.3 *Measured Parameters*

The only measurable quantity in resistivity methods is the potential difference between two points. In a homogeneous medium, the potential V at a distance r from a point source is given by:

$$V_r = \frac{I\rho}{2\pi r} \qquad \text{Eqn 2-1}$$

where I = the current emanating from the point source
ρ = the resistivity of the medium
$\frac{1}{2\pi}$ = the constant of proportionality for a homogeneous half - space of infinite extent.

The total potential at any point $V = V_{(r)} - V_{(r')}$, where r' is the distance from the negative electrode. If C_1 and C_2 are positive and negative current electrodes and P_1 and P_2 are potential electrodes and if ΔV is the potential difference between P_1 and P_2, it follows that:

$$\rho = 2\pi \frac{\Delta V}{IG} \qquad \text{Eqn 2-2}$$

where G is the geometric factor and is given by

$$G = \frac{1}{C_1P_1} - \frac{1}{C_2P_1} - \frac{1}{C_1P_2} + \frac{1}{C_2P_2}$$

In practice, ρ will vary depending on the geometry of the four electrodes and their relative positions on the ground. Substituting the measured value of resistivity for $\Delta V/I$, the value of ρ obtained from the equation is called the *apparent resistivity* (ρ_a) which is the fundamental parameter of electrical prospecting.

2.3.2 The Electrical Induced Polarisation (EIP) Method

The induced polarisation phenomenon was also first recognised by Conrad Schlumberger in 1911 during his original investigations into SP methods. However, the method of geophysical prospecting now commonly known as the induced polarisation

(IP) method first gained popularity in the mid 1950's after extensive development work by Newmont Exploration Limited (Wait, 1959). The term *Electrical Induced Polarisation* (EIP) has been adopted here to differentiate the method from *Magnetic Induced Polarisation* (MIP). EIP has been used extensively as a basic electrical prospecting method and has been remarkably successful in the search for sulphide-related ore deposits of low intrinsic conductivity, such as porphyry coppers and bedded lead-zinc deposits (Seigel and Howland-Rose, 1990). Other applications include the search for groundwater (Vacquier, 1957). A detailed account of the history of the induced polarisation method is given by Collett (1990).

2.3.2.1 Field Procedure

The IP phenomenon can be measured by passing a controlled inducing current through the ground and monitoring the resultant voltage changes. In *time domain IP*, observations are made of the decay voltage as a function of time. As the charging time is finite, the apparent resistivity also varies with frequency, decreasing as the frequency increases. *Frequency domain IP* techniques measure this frequency dependence.

Electrode Layouts

Current electrodes usually consist of either multiple metal stakes, metal plates or sheets of aluminium foil buried in shallow trenches. Porous pots are used for the potential electrodes. The electrode configurations and field procedures used for induced polarisation surveys are similar to those employed for standard resistivity exploration and apparent resistivity is a commonly measured parameter.

2.3.2.2 Instrumentation

Transmitter

The type of transmitted signal depends on whether time or frequency domain IP is being employed. Typical time domain and frequency domain waveforms are shown in Figures 2-2 and 2-3 respectively. The transmitter output may vary up to 20 A at up to 5000 V for larger transmitters. Power for the transmitter is normally provided by a petrol driven AC generator producing current at 110 or 208 V at a frequency of 400 Hz. Output power can vary from 1 to 30 kVA.

The IP Receiver

Modern IP receivers are essentially very sophisticated microprocessor based voltmeters. They are capable of real-time filtering of SP, mains power interference and telluric current effects. Signal enhancement is achieved in time domain systems by stacking waveforms. For reasons of efficiency, some receivers such as the Scintrex IPR-12 are multi-channel, enabling up to 8 channels to be recorded simultaneously.

2.3.2.3 Measured Parameters

The magnitude of the IP effect is dependent not only on the polarisability of the ground but also on the period and type of the energising waveform. The form of the decay may also vary due to geometric interactions between the voltage measurement array and sub-surface interfaces and variations in the textural form of polarisable deposits and the grain size of the constituent metallic minerals. Several parameters have been defined to measure the IP effect.

Time Domain Parameters

(i). *Millivolts per Volt (IP percent).* The simplest measure of IP is the ratio of the voltage at a fixed time after cessation of current flow V_t to the steady voltage measured during current flow V_P (see Figure 2-2). It is not practical to measure at the instant of cutoff because of transients due to mutual inductive coupling between the inducing current and the wires connecting the potential electrodes. V_t must be measured before the residual has decayed into the noise level. V_t is much smaller than V_P, therefore the ratio V_t/V_P is expressed as millivolts per volt or as a percent. The time interval t may vary between 0.1 and 10 s.

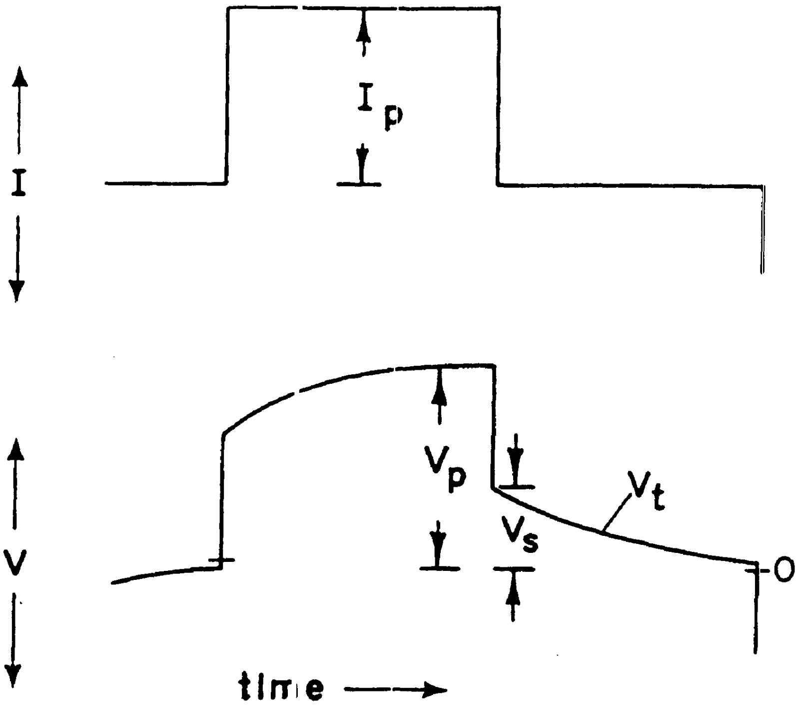

Figure 2-2. The time domain IP waveforms showing the transmitted current waveform and the received voltage waveform. The induced Primary current I_P is detected as a maximum Primary voltage V_P. When current is turned off, voltage drops to a secondary level V_S and the transient voltage V_t decays with time (After Sumner, 1979).

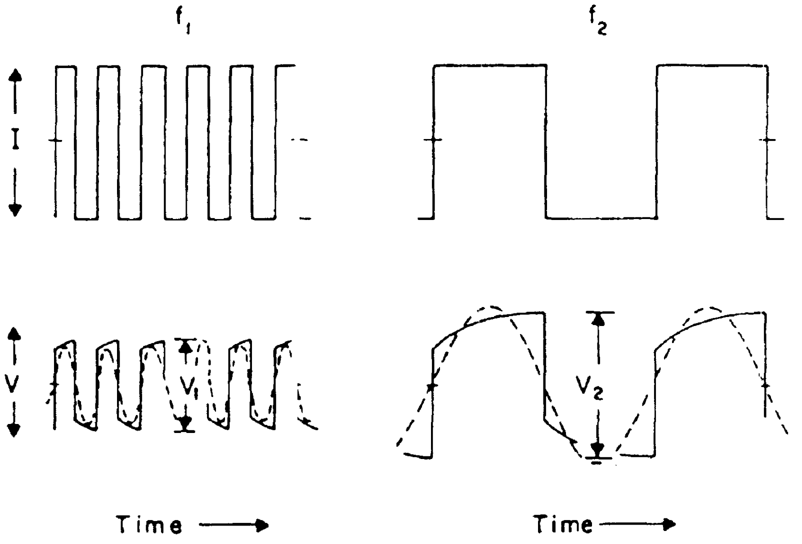

Figure 2-3. IP Frequency domain waveforms, showing a controlled, constant inducing current I being detected as voltages V_1 and V_2, where $V_1 < V_2$. The dashed line is the sinusoidal filtered voltage (After Sumner, 1979).

(i). *Chargeability.* In time domain IP systems, the most common measure of the IP effect is the dimensionless parameter defined by Seigel (1959) as *chargeability* (*M*). Commercial IP systems generally measure the potential integrated over a definite time interval of the transient decay. Chargeability is defined as:

$$M = \frac{1}{V_p}\int_{t_1}^{t_2} V_t \, dt \qquad \text{Eqn 2-3}$$

where V_p = received transmitter (Primary) voltage
V_t = voltage measured by the receiver during the integration period
t_1 = time at the beginning of the integration window
t_2 = time at the end of the integration window.

Some systems sample the decay curve for short integration periods at different times, effectively enabling characterisation of the decay curve shape. When V_t and V_p are in the same units, the chargeability is in milliseconds. Figure 2-4 illustrates the possible integration windows for the Scintrex IPR-11 receiver.

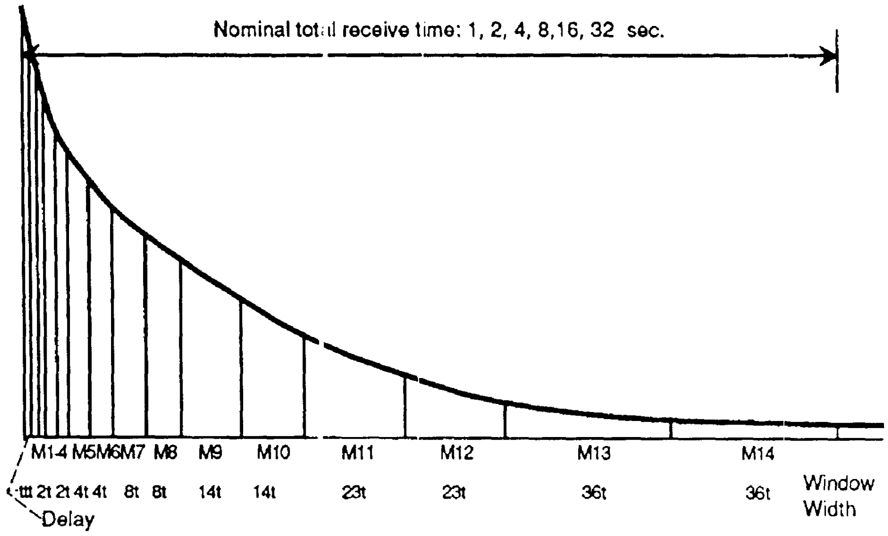

Figure 2-4. Timing for the integration windows for a Scintrex IPR-12 IP receiver (After Scintrex, 1993b).

- *Apparent Resistivity.* The maximum primary voltage is used to calculate the apparent resistivity described in Section 2.3.1.3. That is,

$$\rho_a = \frac{2\pi V_p}{IG} \qquad \text{Eqn 2-4}$$

where ρ_a = apparent resistivity
I = energising current
G = the geometric factor

- *Spectral IP Parameters.* The above parameters are all measurements of first order IP effects. In order to assist in distinguishing between different chargeable sources, modern IP receivers such as the Scintrex IPR-12 record the decay curve in sufficient detail to enable the determination of second order IP effects. The IPR-12 actually calculates the Cole-Cole parameters (Cole and Cole, 1941): true chargeability (M) and time constant (τ) assuming a fixed value of C (0.25).

Frequency Domain Parameters

- *Frequency Effect.* Traditionally, in frequency domain IP, the apparent resistivity is measured at two or more frequencies. The *frequency effect* (FE) is usually defined as:

$$FE = \frac{(\rho_{dc} - \rho_{ac})}{\rho_{ac}} \qquad \text{Eqn 2-5}$$

where ρ_{dc} and ρ_{ac} are apparent resistivities measured at two frequencies. The *dc* subscript refers to a near DC frequency generally in the range 0.05 - 0.5 Hz and the *ac* subscript denotes a higher frequency usually in the range 1-10 Hz.

- The term *Percent Frequency Effect* (PFE) is used if the ratio is expressed as a percent change in ρ_{ac} and is given by:

$$PFE = \frac{100(\rho_{dc} - \rho_{ac})}{\rho_{ac}} \qquad \text{Eqn 2-6}$$

- *Metal Factor.* The metal factor parameter was originally suggested by Marshall and Madden (1959) to correct for the variation in IP effect due to effective resistivity variations in the host rock (as a result of type of electrolyte, temperature, pore size etc.).

$$\begin{aligned} MF &= 2\pi \times 10^5 \frac{(\rho_{dc} - \rho_{ac})}{\rho_{dc}\rho_{ac}} \\ &= 2\pi \times 10^5 \frac{FE}{\rho_{dc}} \end{aligned} \qquad \text{Eqn 2-7}$$

- *Phase Shift.* A third frequency domain parameter used to measure the IP effect is the phase difference between the received voltage and the current transmitted into the ground. This determination of the phase shift requires accurate synchronisation between the transmitter and the receiver. The IP phenomenon can be observed as the out-of phase component in the received waveform. By recording the real (in-phase and imaginary (out-of-phase) voltage components the phase angle β is determined by obtaining the arctangent of their ratio as follows (see Figure 2-5).

$$\beta = \tan^{-1}\frac{V_{IMAG}}{V_{REAL}} \qquad \text{Eqn 2-8}$$

where V_{IMAG} = the imaginary component, and
V_{REAL} = the real component

The phase angle is usually measured in milliradians. An advantage of the measurement is that only a single frequency current waveform is required.

- *Apparent Resistivity.* As defined for time domain surveys.

2.3.3 Magnetometric Resistivity (MMR)

The magnetometric resistivity method was first described in a patent by Jakosky (1933). A brief description of the method also appears in his classic text on exploration geophysics (Jakosky, 1950). The rationale behind MMR is described by Jakosky (*ibid.*, 582) as follows:

> *"When current is conductively supplied to the earth, a magnetic field will be set up, and a portion of the field will exist at the surface of the earth. Since the current distribution in the earth will be influenced by the geologic structure, the magnetic field set up by the current will like-wise be influenced and measurements of this magnetic field or quantities which depend on this field give an indication of the subsurface geology".*

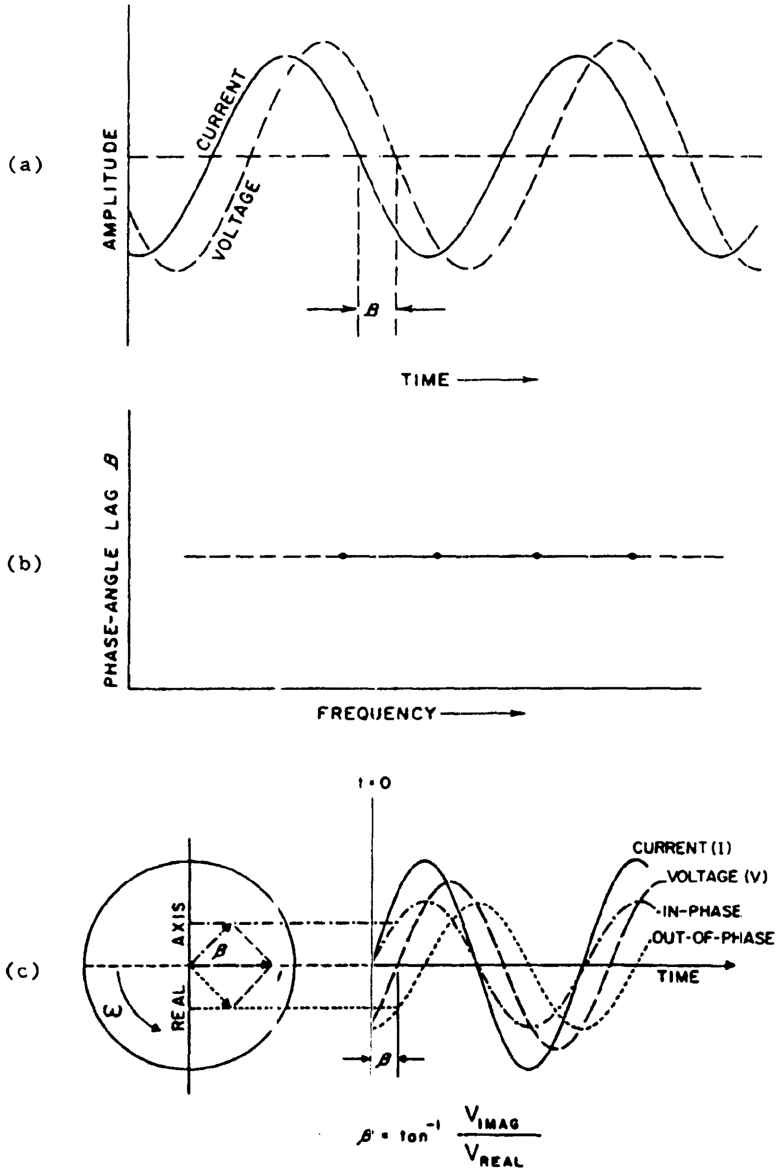

Figure 2-5. IP phase determination and vector components. (a) Phase lag between input waveform (solid) and output waveform (dashed). (b) Diagram of a flat phase response against frequency. (c) Rotating vector components showing the phase lag angle (After Sumner, 1976).

Although Jakosky's field equipment would have been adequate for the purpose, he had little success with the method at the time due to his apparent belief that it could resolve layered structures. Theoretical work by Stefanescu (1929) and Maillet (1947) on magnetic fields generated by static current flow shows that this is not possible (Edwards and Nabighian, 1991).

An excellent historical and technical account of the MMR method is given by Edwards and Nabighian (*ibid.*) where it is defined as follows:

> *"Magnetometric Resistivity is an electrical exploration method based on the measurement of the low-level, low-frequency static magnetic fields associated with non-inductive current flow in the ground".*

The authors list successful applications of the method as including:

(i). exploration for massive sulphides and for geothermal resources

(ii). mapping of regional geology

(iii). the study of hard rock sites for nuclear waste disposal

(iv). the location of reef structures in sedimentary basins, and

(v). the acquisition of conductivity profiles of the sea floor with depth.

The first field tests of the MMR method using modern instrumentation were reported by Edwards (1974) and Edwards and Howell (1976).

2.3.3.1 Field Procedure

As described earlier, the galvanic resistivity method maps the electrical properties of the earth by measuring the potential gradient resulting from galvanic current flow between a pair of current electrodes. The fundamental difference between electrical resistivity methods and magnetometric resistivity is that the potential electrodes are replaced by a highly sensitive single component magnetometer. The horizontal component of the magnetic field due to current flow is usually recorded.

Electrode Layouts

The electrode layouts appropriate for MMR surveying are essentially the same as those previously described for electrical resistivity surveys. Edwards (1974) and Edwards and Howell (1976) describe MMR case studies which employ a configuration that is comparable to the Schlumberger or gradient array. However, there is a major difference between the MMR and resistivity implementations of the gradient array configuration:

> *"In the case of a two-dimensional structure, the current electrodes in the MMR method should be arranged so that current flow is along the strike of the structure. The structure then looks like a set of resistors in parallel, which carry different currents, and a perturbation in the magnetic field is produced. In contrast, for differences in the potential gradient to be observed, the current flow should be across strike, so that the structure looks like a set of resistors in series"* (Edwards, 1974, 1137).

In an MMR survey, the horizontal component of the magnetic field at right angles to the line joining the electrodes is measured instead of the horizontal component of the electric field parallel to that line.

2.3.3.2 Instrumentation

Power Sources

Power sources for MMR surveys are usually standard IP transmitters which may produce either full square wave (100% duty cycle) or interrupted, bipolar square wave (50% duty cycle) waveforms. However, high current transmitters are preferred to enable good signal-to-noise ratios. Typical frequencies used are in the 1 to 5 Hz bandwidth. As described by Edwards (1974), the choice of that frequency bandwidth is a compromise between using low frequencies to minimise electromagnetic induction effects and using high frequencies to minimise the interference caused by geomagnetic disturbances.

The MMR Receiver

Initially, induction coils were used to monitor the MMR signal. However, they were generally found to lack both sensitivity and fidelity. Due to their interest in extending the MMR technique to measuring induced polarisation effects, Scintrex Ltd. produced a highly sensitive flux-gate magnetometer known as the MFM-3 (Seigel, 1974). The MFM-3 exhibits a sensitivity of 00 mV/nT ± 2% and a frequency response which is flat over a 0-1000 Hz bandwidth. Electronic noise level is quoted as <1 pT RMS/√Hz, for frequencies of 1-1000 Hz (Seigel and Howland-Rose, 1990). The MFM-3 is well suited to the measurement of the MMR signal and has since been used for much of the published research on MMR (Edwards, 1974; Edwards and Howell, 1976). The MFM-3 is used as the transducer for a standard IP receiver which performs the actual measurement.

The operation of the MFM-3 is described by Seigel and Howland-Rose (1990, 40):

> *"In practice, the MFM-3 is leveled horizontally and oriented along the survey line, which is approximately the direction of the magnetic field due to current flow in the earth. Before measurement is made, the earth's magnetic field is largely balanced out using a high-stability bucking current provided by the magnetometer console. The output of the console is then fed into the IP receiver for the measurement itself".*

Other operational considerations include the need to keep the console and receiver at sufficient distance from the magnetometer sensor so as to prevent any feedback or noise from being introduced into the sensor. According to Seigel and Howland-Rose (*ibid.*), any residual earth magnetic field level which is uncompensated by the magnetometer buck-out is removed from the measurement by the receiver in precisely the same technique that the SP level is removed in EIP measurements.

2.3.3.3 Measured Parameters

- *Primary magnetic field.* H_P - the Primary magnetic field is the maximum field deviation measured during the "on" time. It is analogous to the Primary voltage measured in conventional EIP surveys and has apparently been named accordingly. Unfortunately, this use of the term *Primary Field* is quite confusing as the same name has been used historically to describe the electromagnetic field produced by current flowing through the wire feeding the electrodes (See Section 2.3.3.4) or as defined by Sheriff, 1991, 231):

> *"the electromagnetic field which would be generated if the (current) source were in free space".*

2.3.3.4 Corrections

When two electrodes are embedded at the surface of a flat, uniformly conductive earth and current is supplied through flat-lying cables, the magnetic field at the surface due to the resulting circuit is comprised of two parts:

- *The Primary magnetic field* ($H_{Primary}$) - which is defined as the magnetic field due to current flowing through the cables supplying the electrodes (not to be confused with H_P), and
- *The Normal magnetic field* (H_{Normal}) - which is defined as the magnetic field expected at the surface due to current flow through a homogeneous earth.

The Primary Magnetic Field, $H_{Primary}$

The Primary magnetic field ($H_{Primary}$) may be readily calculated if the position of the wires is known (Keller and Frischknecht, 1966; Giancoli, 1988). For a flat lying cable, the Primary field in the survey area is vertical at all points in the same plane. Theoretically, as only the horizontal component of the magnetic field is measured in MMR surveys, the effects of the Primary field are negated. However, as pointed out by Edwards (1974, 1154):

> *"In any practical MMR survey, the current flowing in the cables must contribute to the measured horizontal magnetic field at any point. This contribution must be removed before the data are reduced; it is an effect of terrain. The cables do not lie in the horizontal plane through the measurement point".*

The influence of the Primary field on the data will, of course, depend on the degree of variation in topography and on the distance the wires are kept from the survey area.

The Normal Magnetic Field, H_{Normal}

The Normal magnetic field (H_{Normal}) has only horizontal components and is also readily calculated (Keller and Frischknecht, 1966; Edwards, 1976; Edwards and Nabighian, 1991). The x-component of the Normal magnetic field due to current flow between a pair of electrodes located on the y-axis and separated by a distance L is shown in Figure 2-6.

The MMR anomaly is defined by Edwards (1974, 1137) as:

> *"the difference between the measured values of the horizontal component of the magnetic field and the 'normal' values which are the values expected over a homogeneous earth'*

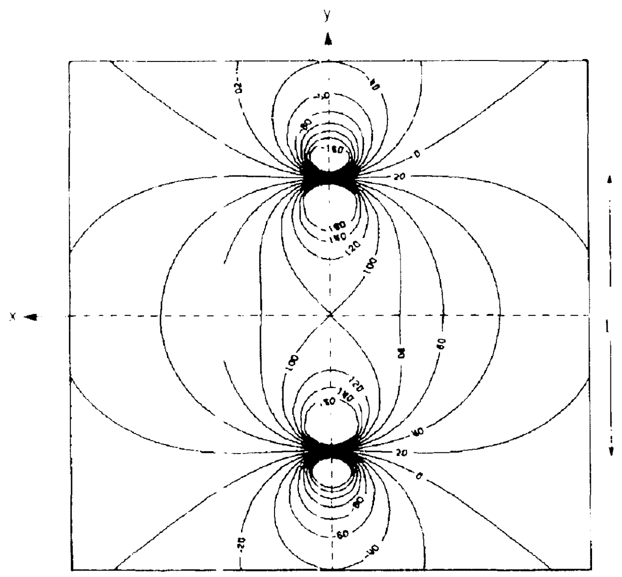

Figure 2-6. The *x*-component of the Normal magnetic field due to current flow between a pair of electrodes located on the y-axis and separated by a distance *L*. The contour values are values expressed as a percentage of the value at the centre of the array. (After Edwards and Nabighian, 1990).

After subtracting the Normal field from the observed field, the anomalous field is expressed as a percentage of the Normal field at the centre of the array. The result is defined as a dimensionless anomaly in the horizontal field.

2.3.4 The Magnetic Induced Polarisation (MIP) Method

The magnetic induced polarisation method is first described in the definitive paper by Seigel (1974) and is more recently reviewed by Seigel and Howland-Rose (1990). MIP, which is a development of Scintrex Ltd., is essentially an extension of the MMR method by which induced polarisation characteristics of the earth associated with galvanic current flow are measured. Consequently, MMR is one of the basic quantities measured in MIP. As described by Seigel (1974, 321):

> *"The MIP method responds to regions of anomalous polarisation, rather than providing physical property information. It tends to emphasise induced polarisation effects in highly conducting bodies. It has special merit in certain problem areas, for example, where highly conducting overburden exists, or where the surface conditions render ground contact difficult".*

Seigel and Howland-Rose (1990) point out two important theoretical differences between MIP and EIP:

- the ability of magnetic fields to penetrate conducting surface layers without serious attenuation, and
- MIP's insensitivity to the electrical properties of a horizontally stratified earth made up of layers each of which has uniform physical properties throughout.

The MIP method's principal application has been in regions of highly conducting overburden or weathered rock such as in Australia. Several case studies are described in Howland-Rose *et al.* (1980, Parts I and II).

2.3.4.1 Field Procedure

The field procedure is essentially the same as that for MMR. Seigel and Howland-Rose (*ibid.*, 37) describe a typical Schlumberger-configuration production array. With reference to Figure 2-7:

> *"The electrodes C_1 and C_2 are set on a line parallel to the regional strike direction at a distance of 2L on a side. A rectangular area which is L wide by 2L long may usually be surveyed from one specific current electrode set-up of this type.... The horizontal magnetic field component is measured along the survey line direction, i.e., orthogonal to the line joining the current electrodes".*

Station intervals vary from 10 m for shallow bodies to as much as 100 m for deeply buried targets. Typical current electrode separations are 1-2 km.

A second array sometimes used for MIP surveying is shown in Figure 2-8. In this configuration, the current electrodes are again established along the regional strike direction but with a much larger separation than for the previous array. Three or four profiles are surveyed off the end of the array. The current cable is then extended and C_2 advances to C_2' and the pattern is then repeated. Although less efficient than the production array, the advantage of this array is the enhanced interpretability of depth and dip of bodies. It is therefore commonly used for detailing anomalies detected by the production array.

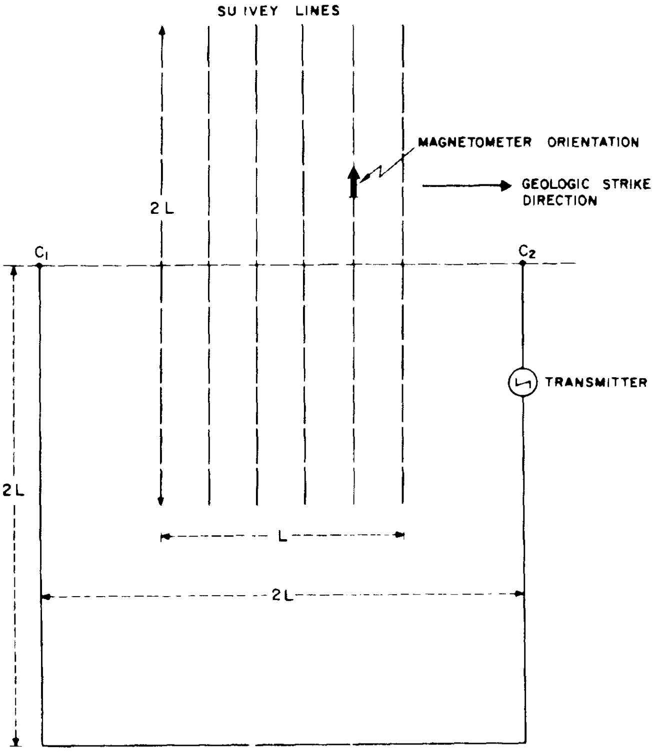

Figure 2-7. Typical MIP horseshoe array for reconnaissance surveying (After Seigel and Howland-Rose, 1990)

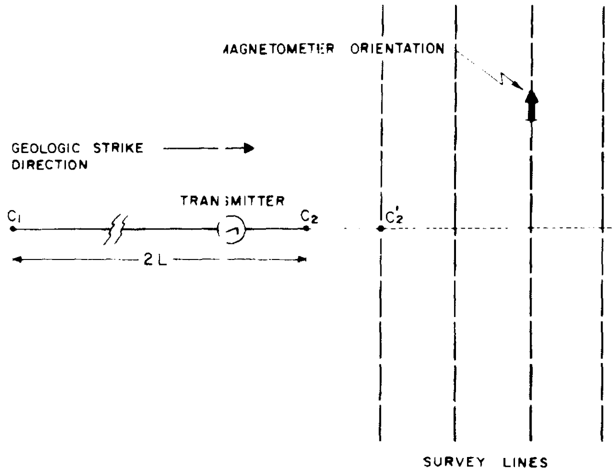

Figure 2-8. Typical MIP linear array for detailed surveying (After Seigel and Howland-Rose, 1990).

2.3.4.2 Instrumentation

Power Source

Any EIP transmitter can theoretically be used for MIP surveys. However, high current transmitters with output power ratings in excess of 3 kW are preferred to enable good signal-to-noise ratios when surveying large spreads. Scintrex customarily uses transmitters capable of both time and frequency domain output waveforms for greater flexibility in using either mode when conditions dictate.

The MIP Receiver

The two receivers commonly employed in MIP surveys are the Scintrex IPR-10A (time domain) and the IPRF-2 (frequency domain) receivers. These receivers are described in detail by Seigel and Howland-Rose (*ibid.*). The IPR-10A is a standard self-triggering IP receiver which integrates the area under the decay curve over several time gates. The IPRF-2 receiver is unique among frequency domain receivers in that its operation is based on the information contained in the transmission of a single repetitive square wave rather than through sequential transmissions of square waves of different periods. No external synchronisation is used.

The Scintrex MFM-3 fluxgate magnetometer described earlier is commonly employed for MIP surveys.

2.3.4.3 Measured Parameters

As the MIP measurements are recorded with an IP receiver, the parameters are analogous to those recorded for EIP surveys. The actual parameters recorded are described for both the time and frequency domain by Seigel and Howland-Rose (*ibid.*) and are summarised below:

Time Domain Measurements

- *Chargeability (M_i)* - corresponding to the *i*th gate, expressed in millivolts per volt (mils). Chargeability estimates are obtained from a series of mean values of the transient decay curve. They are averaged over predetermined time gates and normalised with respect to the Primary magnetic field H_P.

- *The Primary magnetic field (H_P)* - the "steady state" magnetic field measured during the current on time and normalised to produce H_N (MMR value). Note that this parameter is analogous to the Primary voltage in EIP surveys and has apparently been named accordingly. It should not be confused with the Primary magnetic field ($H_{Primary}$) produced by current flowing through the wires which supply the electrodes.

Frequency Domain Measurements[1]

- *Percent Frequency Effect (PFE)* - the percentage change in the observed magnetic field with a change in operating frequency.
- *Phase Angle* - between the observed magnetic field and the transmitted current.
- *Relative Phase Shift (RPS)* - the phase angle between two harmonically related components of the applied current.
- *Primary magnetic field (H_p)* - as measured for time domain surveys.

2.4 Comparison of the EIP and MIP Methods

A comparison of the magnetic mode of acquiring resistivity / induced polarisation data (MIP) and the electrical mode (EIP) is described by Howland-Rose (1980) by means of an *energy storage concept*. The *Energisation Process* for MIP involves applying current to the volume to be sampled by means of two electrodes placed semi-parallel to the strike of the target mineralisation. In EIP, two potential electrodes are used to measure the resistivity of a volume of material defined by equipotential surfaces which are always at right angles to the current flow (see Figure 2-9).

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[1] Note that the frequency domain method of MIP was developed by Scintrex with funding from Amdex Mining Limited as Rapid Reconnaissance Magnetic Induced Polarisation (RRMIP) (Howland-Rose, 1978).

If a polarisable body is present, energy will be stored during energisation only to be discharged on cessation of current flow. With reference to Figure 2-10, energy will discharge internally within the chargeable source and externally around the body in the medium surrounding the source. *Internal* current flow is in a direction opposite to the original energising current whereas *external* current flow is in the same direction. Figure 2-10 shows this discharge together with its related equipotential surfaces which are at right angle to the current lines which impose them. The potential electrodes used in EIP, therefore monitor the discharge via the secondary equipotential field. Howland-Rose (*ibid.*, 5) emphasises that

> *"(i) this is NOT the same volume as the resistivity measurements, and (ii) it is NOT the original IP signal as stored by the body, but a measurement distorted and processed by the environment through which it has passed".*

In MIP, the horizontal component of the magnetic field due to current flow both inside and outside the source material is monitored. The magnetic field passes relatively undistorted through the environment thus allowing both the internal and external discharge currents to be 'sensed' from the surface.

The fundamental differences between MIP and EIP are described by Howland-Rose (*ibid.*) and Clark (1981) and are summarised below:

(i). EIP data monitor only the current flow at the surface resulting from the storage of charge within the polarisable body. MIP detects both the external and the internal current flow.

(ii). In EIP, the transfer of the induced polarisation signal from the mineralisation involves a considerable "frictional" and chemical energy loss to get to the surface and is, therefore, significantly attenuated. For MIP, currents at depth are monitored from depth via their associated magnetic fields, involving much less loss of energy. Consequently, the fall-off in response with distance from the source is less for MIP than for EIP.

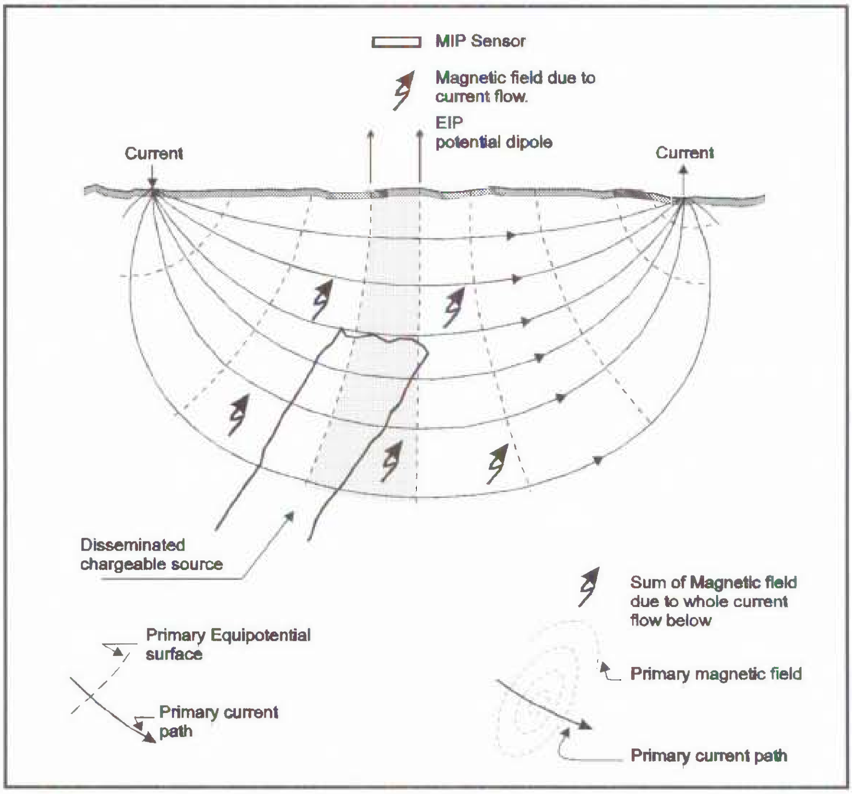

Figure 2-9. The EIP and MIP Energisation Process (After Howland-Rose, 1980).

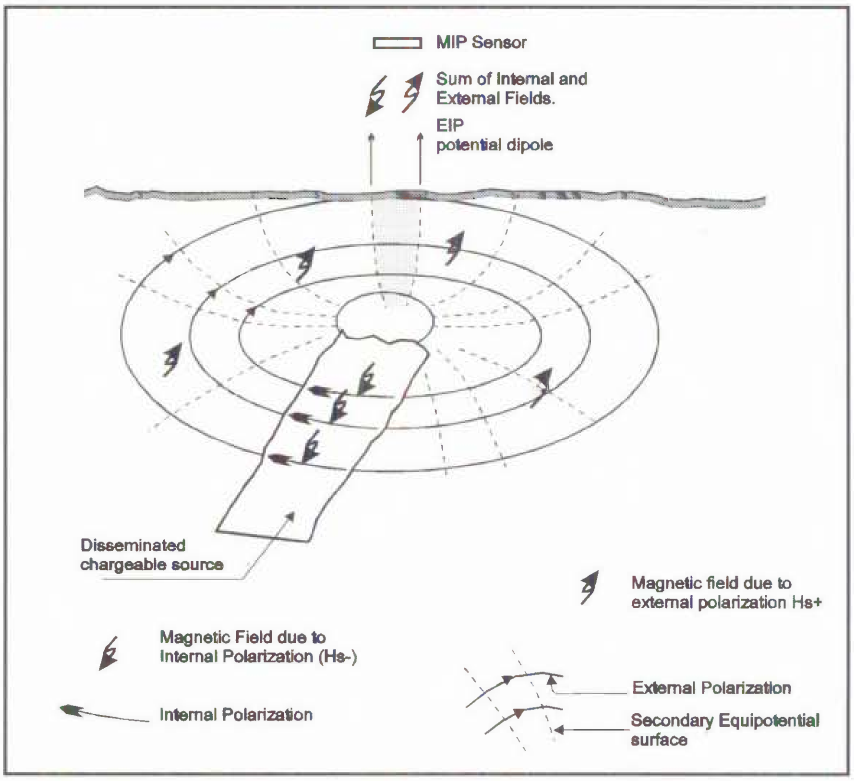

Figure 2-10. The EIP and MIP Discharge of Induced Polarisation (After Howland-Rose, 1980).

(iii). EIP measures the external polarisation effect via two potential electrodes placed a distance apart (commonly 25-100 m) effectively averaging the response. However in MIP, the sensor is only about 60 cm in length resulting in an essentially point source measurement. thus enabling greater resolution.

(iv). In areas of highly conductive overburden / oxidation, the EIP signal is often severely attenuated en route to the surface, an effect commonly known as masking. With MIP techniques, the conductive zone has no influence.

(v). In the EIP method, the measured signal is often distorted by the medium through which it passes as it flows from source to surface. The form of the signal will, therefore, largely reflect the effect of the medium rather than the source. However, as MIP monitors the magnetic field resulting from the decay within the source, much less distortion of the signal can be expected.

(vi). EIP measures absolute levels of apparent resistivity and chargeability as observed at the surface, whereas MIP measures the relative properties of chargeability and resistivity and is thus more sensitive to these differences.

(vii). In EIP, distortions of the signal often arise as a result of local and often insignificant inhomogeneities in resistivity. However, as MIP measurements are summed over a large volume of rock, they are much less sensitive to local variations in resistivity.

(viii). EIP surveys are ponderous and expensive, requiring good ground contact and access. MIP requires good ground contact for the current electrodes only. Survey speed is relatively rapid and the technique is suitable in areas of loose, sandy or rocky ground cover.

(ix). Lateral conductivity changes may reduce the relative EIP response amplitude whereas the MIP response pattern may be distorted but not the signal amplitude. MIP is thus a good lateral anomaly detector.

(x). The response patterns for EIP are generally unidirectional, and relatively simple. MIP responses tend to be more complex due to the fact that both internal and external currents are monitored. Polarity reversals are also common.

2.5 Discussion

Experience with High Definition Magnetics has demonstrated that adequate sampling of the magnetic field enables removal of the ambiguity of interpretation due to undersampling. In addition, the high frequency component of the data has been found to have significant diagnostic value for certain applications. From the point of view of field procedure, HDM is feasible and economical due to the ability of survey instrumentation to continuously sample the magnetic field at close sample spacings whilst the sensor is in motion.

ER is one of the oldest and most widely used techniques for determining sub-surface structure. EIP is the most effective technique for the direct detection of sulphide mineralisation. However, in terms of adapting these techniques to high resolution surveying, there are three major disadvantages resulting from the need for grounded potential electrodes:

(i). the time consuming logistical constraint of having to emplace the electrodes.

(ii). measurements are effectively averaged over a large volume thus filtering out any high frequency response which may be present in the electrical field.

(iii). the potential electrodes are influenced by near-surface inhomogeneity.

The magnetometric techniques have overcome some of the restrictions characteristic of the electrical techniques by replacing the potential electrodes with a single component magnetometer. The measurements are effectively independent "point" measurements and, therefore, enable greater resolution of the electromagnetic field resulting from galvanic current flow. The fact that no ground contact is required means that surveys are faster to execute compared to the electrical techniques. However, the greatest impediment on survey speed is the requirement to precisely level and orient the sensor prior to taking a reading. It is clear from the above discussion that any attempt to increase the spatial resolution of surveys using the conventional electrical or magnetometric techniques would require a significant increase in survey time as well as the exploration budget. In addition, none of the techniques appear to be readily adaptable to rapid sampling.