# 10 PROJECT REVIEW, EVALUATION AND CONCLUSION

## 10.1 Introduction

In Section 1.1, the accelerating trend in the exploration industry towards increased spatial resolution in geophysical surveys was discussed. The main issues raised were as follows:

- Geophysical data acquisition is often very labour-intensive and is, therefore, expensive, particularly when data measurement rates are slow. Exploration budget constraints and slow measurement rates often mean that wide measurement intervals are selected in order to sample the predicted signal anomaly of interest. This commonly results in inadequate sampling of the often equally important high frequency geological signature or noise profile of near-surface origin. The main consequence of inadequate sampling is data that are difficult, ambiguous or misleading to interpret.
- The advent of image processing has facilitated data fusion techniques which involve the assimilation of data sets mapping independent physical properties. These techniques are proving invaluable in assisting interpretation by reducing the impact of the inherent ambiguity often associated with the interpretation of a single physical parameter.
- Recent developments in digital electronics have had a great impact on the measurement rate of some geophysical instrumentation. Increased total field

magnetic measurement rates, in particular, have produced improvements in mapping efficiency which have enabled high spatial resolution surveys to be now performed at virtually the same acquisition cost as conventional magnetic surveys.

- Techniques which measure the electrical properties of the earth such as induced polarisation (IP), magnetic induced polarisation (MIP) and electromagnetic techniques (EM) have benefited largely from enhanced signal processing capability. However, due to various logistical constraints, including the need for grounded electrodes, those techniques have not enjoyed the same improvements in survey efficiency as have been experienced in total field magnetics.
- Having determined the limitations of electrical methods such as IP, MIP and EM, it became apparent that a high definition electrical technique that was based upon total field magnetic measurement would revolutionise electrical prospecting. Should electrical measurements become as rapid and efficient to acquire as magnetic measurements, then the recent advances experienced in magnetic exploration could be expected to flow on to the electrical methods. High definition, electrical mapping of geological signature and better quantified near-surface electrical noise must combine to make the interpretation of exploration data less difficult, ambiguous and misleading.
- A technique which could simultaneously acquire magnetic and electrical data at very high measurement rates and using the same instrumentation must result in a significant improvement in the cost-effectiveness of an exploration operation.
- A technique which could simultaneously acquire magnetic and electrical data at the same, very high spatial resolution, must benefit greatly from the data fusion capability of modern image-processing technologies.

In recognition of the potential benefits of increasing spatial resolution in electrical surveys as well as the benefits obtainable using data fusion techniques, the principal objective of the project described in this thesis was, as defined in Section 1.2, "*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*". Secondary objectives included the ability to record that information at sample intervals comparable to those achievable with High Definition

Magnetics (HDM), whilst continuously traversing the ground at walking speed. Both of these goals have been achieved in full.

Priority was given to the development of a technique whereby a total field magnetometer was used to map the behaviour of current flow introduced into the ground galvanically rather than by electromagnetic induction. This chapter evaluates the development of this technique in terms of the stated objectives. While concluding that the stated objectives have been met with a high degree of success, recommendations for on-going research into the technique using galvanic sources are proposed. Investigation of applications of the method where the galvanic source is replaced with a large loop EM source is also recommended.

## 10.2 Project Review

The strategies employed to meet the project objectives were met in three distinct stages, for which a series of sub-objectives were defined.

### 10.2.1 Stage 1 - Conceptual Development

The "Conceptual Development" stage of the project involved a review of state-of-the-art magnetic surveying techniques as well as relevant contemporary galvanic electrical methods with a view to understanding their strengths and limitations with respect to survey efficiency. The findings of that exercise are described in Chapter 2 and are summarised below:

(i). High Definition Magnetics is feasible and economical due to the ability of the survey instrumentation to continuously sample the magnetic field at close sample intervals whilst the sensor is in motion.

(ii). The electrical techniques, resistivity (ER) and induced polarisation (IP), are not readily adapted to high resolution surveying due to their requirement for grounded electrodes. The reason being that, apart from the time-consuming logistical constraint of having to emplace the electrodes, the measurements between widely spaced electrodes are essentially volume measurements which effectively filter out any high spatial frequency response that may be present in the electrical field.

In addition, the potential electrodes are susceptible to the influence of near-surface inhomogeneity.

(iii). The magnetometric techniques, magnetometric resistivity (MMR) and magnetic induced polarisation (MIP) overcome some of the restrictions inherent in the electrical methods by replacing the potential electrodes with a highly sensitive, single component magnetometer. However, the advantage attained by obviating the need for ground contact was largely negated by the time-consuming requirement to precisely orientate and level the sensor prior to taking a reading. However, unlike ER and EIP, the MMR and MIP techniques acquire point measurement data. Therefore, if time and budget permit, then high resolution mapping of the electromagnetic field resulting from galvanic current flow could be achieved.

It was clear that neither the electrical techniques nor the conventional magnetometric techniques were readily adaptable to rapid sampling and it was concluded that a non-conventional approach to electrical measurement was necessary if the parameters were to be measured at the speed and sample resolution possible with high definition magnetic mapping.

To accommodate the project objectives, a survey concept was developed which utilises a rapid sampling, total field magnetometer to measure the electromagnetic field due to induced current flow. The technique requires a constant current transmitter operating at a fundamental frequency that was in the sub-audio range. The technique was consequently called "Sub-Audio Magnetics" (SAM) and was described in detail in Chapter 3. The concept encompasses the use of either galvanic or electromagnetic modes of induction. In either case, the electromagnetic signal resulting from the time-varying current flow is measured simultaneously with the earth's spatially-varying magnetic field. The combined signals are measured at a fast enough rate to adequately sample the full spectrum of the waveform. Spectral analysis permits the separation of the individual signals.

Where galvanic current flow is used, the survey configuration closely parallels MMR and MIP except that the total magnetic intensity is measured instead of the horizontal component. In order to distinguish the information recorded from MMR and MIP, the terms Total Field Magnetometric Resistivity (TFMMR) and Total Field Magnetometric Induced Polarisation (TFMMIP) were adopted.

Factors likely to influence the quality of the recorded data from the synthetic current flow were researched and found to include several sources of electromagnetic noise in the frequency band of interest. Those sources considered most relevant include magnetic storms, micropulsations, sferics, Schumann resonances and industrial noise.

### 10.2.2 Stage 2 - Field Tests Using Existing Instrumentation

In order to demonstrate the SAM concept, a series of feasibility trials were conducted over known geology using a state-of-the-art TM-4 magnetometer incorporating an optically-pumped caesium vapour sensor. Although the instrumentation was not entirely adequate for the SAM survey technique, the feasibility studies provided information which demonstrated the concept's technical viability. Signal levels were found to be well within the resolution of the optically-pumped sensor. Data reduction procedures were developed and tested and an understanding of the requirements of a purpose-built SAM receiver was obtained. The instrumentation and field procedure used for the trials were described in Chapter 4. The results of the feasibility studies were presented in Chapter 5.

In each of the feasibility studies, the results correlated well with the known geology. The signal-to-noise ratios in the electrical and magnetic parameters were high and sub-metre sample intervals were found to be achievable at continuous walking speeds. More importantly, the higher spatial resolution was found capable of providing significantly more diagnostic information than would be possible using conventional electrical or electromagnetic methods.

### 10.2.3 Stage 3 - Instrument Development and Field-Testing

The encouragement derived from the success of the feasibility studies resulted in the initiation of the third and final phase of the project: the development and field-testing of a prototype purpose-built SAM receiver.

One of the major factors influencing the design philosophy adopted for the prototype SAM receiver was the somewhat antagonistic requirement to handle large dynamic range fluctuations in the earth's spatially-varying magnetic field as well as the need to provide high sensitivity, high bandwidth measurement of the SAM signal. The approach used was to split the Larmor signal and to adopt parallel signal processing streams. One processing stream was required to obtain the spatially-varying magnetic field measurements and the other was to extract the SAM signal parameters.

The spatially-varying magnetic field measurements were obtained with the standard TM-4 frequency counter. SAM measurements were accomplished through the implementation of a plug-in SAMCard option which interfaces with the TM-4 magnetometer data bus. The SAMCard provided features that were described in Chapter 7 and included:

(i). High bandwidth to prevent aliasing of the higher harmonics of the transmitted signal.

(ii). Constant sample interval to facilitate waveform averaging and data processing.

(iii). GPS synchronisation with the transmitter to enable the detection of polarity reversals and to quantify phase lags from the transmitted current.

Field-testing of the SAMCard-enhanced TM-4 was achieved by conducting case studies over known geology. The results of these surveys were described in Chapter 8. The studies enabled an evaluation of the strategies employed. The results indicated that, for the acquisition of TFMMR, the SAMCard performed as required. The strategies used in the SAMCard approach were found to be valid and the simultaneous acquisition of High Definition Magnetics and TFMMR was achieved. However, the characterisation of the much weaker TFMMIP response was much more difficult to obtain for the following reasons:

(i). The demodulation circuitry in the SAMCard was found to introduce an unacceptable level of noise into the system, thus limiting the accuracy of phase measurement.

(ii). Compensation must be applied to correct for the frequency response of the highpass filter used in the SAMCard if both frequency domain and time domain parameters are to be obtained. Accurate determination of the actual frequency response of the filter has proven difficult and calculation of the inverse filter response has been unreliable. A major reason was that the specifications of the electronic components of the filter are susceptible to temperature change which adversely affects the filter response.

(iii). Another factor limiting the accurate determination of induced polarisation-related parameters is the influence of electromagnetic coupling at the transmitter frequencies which were used for the trials.

## 10.3 Recommendations for Future Development and Related Research

### 10.3.1 Proposed Further SAM Receiver Development

The potential for improving the performance of the SAMCard to enable the accurate determination of IP parameters is limited by the use of the TM-4 as the host instrument. This is essentially due to the fact that the TM-4 was originally designed for magnetics only. The system has proven invaluable as a SAM concept demonstrator. However, aspects of the instrument which limit its suitability for future development are, firstly, the processing power of the CPU and, secondly, the multi-tasking operating system which is inappropriate for servicing the time-critical tasks required for the determination of SAM parameters. The added complexity of the SAM software enhancements has meant that the system is being worked to the limit of its processing capacity. The further addition of real-time processing functions such as spectral analysis would, undoubtedly, critically affect the instrument's performance. These requirements will benefit greatly from the employment of multiple processors.

In view of the above considerations, an alternative instrument design is proposed. Because SAM is a continuously sampling technique, it is readily adaptable to vehicle or airborne survey platforms and, in fact, a helicopter-borne platform (HeliSAM) is currently in the planning stage. Consequently, the design philosophy encompasses the likely requirement for those platforms and involves a significant departure from the SAMCard concept. Accordingly, the design should be:

(i). **Modular** - To enable ease of maintainability, ease of upgrade and to allow the ready addition of optional components to suit the platform required.

(ii). **Self-Contained** - The instrument should be independent of external power supplies, GPS units etc. to facilitate transfer from one survey platform to another.

(iii). **Ergonomic** - For portable operation, it is important that the system be light, robust and require minimal power consumption.

The design concept is shown in schematic form in Figure 10-1. The magnetometer side of the system comprises an optically-pumped sensor and an "Intelligent Frequency Counter" which outputs processed signal parameters via a communications link to a data logger. Positioning and timing / sampling strobes are provided by real-time GPS and / or a cotton thread odometer. The laser altimeter and compensation systems would only be required for HeliSAM use.

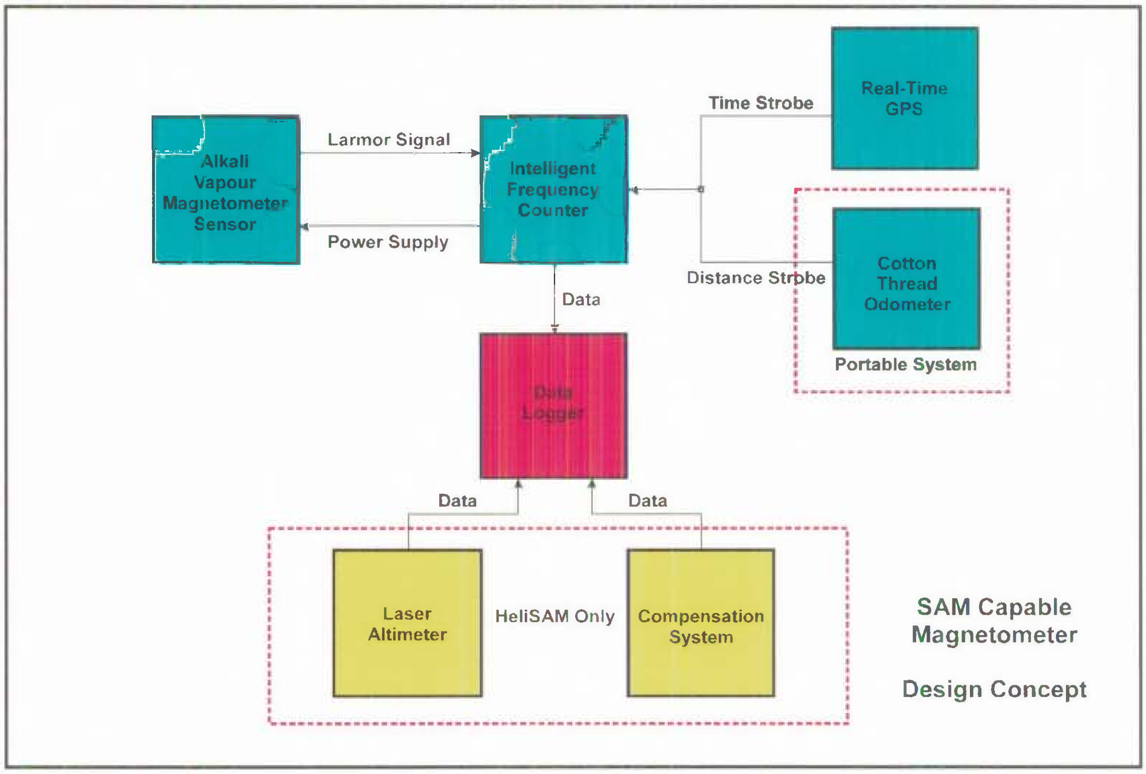


Figure 10-1. The proposed SAM Capable Magnetometer System - Design Concept.

### *10.3.1.1 The "Intelligent" Frequency Counter*

The heart of the proposed SAM receiver would be a sophisticated frequency counter. It is described as "intelligent" due to the incorporation of a powerful embedded processor and its proposed ability not only to determine the frequency of the incoming Larmor signal, but also to perform signal enhancement, spectral analysis and waveform characterisation.

Because of the problems encountered with the prototype SAMCard concept, it is considered necessary to avoid the demodulation circuitry employed by the SAMCard and it is proposed that the frequency counter would need to need to count the Larmor signal at a rate of 1 kHz to a resolution 0.02 nT. Preliminary investigations into modern engineering strategies which may achieve this requirement suggest that the specification is achievable.

In summary, functions of the counter would include the following:

(i). To provide power for the optically-pumped sensor.

(ii). To count the Larmor signal a sample rate of 1024 Hz.

(iii). To provide UTC time synchronisation (achieved via an OEM GPS receiver).

(iv). To perform real-time digital filtering to separate the spatially-varying magnetic field from the SAM signal (applying a zero-phase high order Butterworth filter).

(v). To perform optional, real-time digital notch filtering to remove mains power interference if required.

(vi). To perform real-time averaging of the recorded waveforms to enhance the signal and reduce data volume.

(vii). To perform real-time spectral analysis and extract frequency domain parameters.

(viii). To perform real-time integration to determine time domain parameters.

(ix). To store raw or averaged waveforms locally for research purposes.

(x). To output time-stamped, calculated parameters relating to HDM, TFMMR and TFMMIP via a communications port to the data logger.

The advantages of the intelligent frequency counter approach include:

(i). Time-critical functions would be performed by a powerful, dedicated embedded processor. Data logging procedures would be performed by a separate device.

(ii). Digital filtering enables more flexibility with selection of cutoff frequencies and frequency response than is possible with analogue filters. (The SAMCard requires hardware modifications to change cutoff frequencies and filter roll-offs).

(iii). Digital filtering enables zero phase response, a feature which is not possible with an analogue filter.

(iv). Digital filtering enables more effective removal of non-linear low frequency magnetic field variation (not possible with an analogue filter).

(v). Having a powerful processor would enable real-time extraction of calculated parameters rather than having to record the entire data set.

#### *10.3.1.2 The Data Logger*

The data logger would be a standard PC board running a standard operating system (Windows 95). The acquisition software would be written as a multi-threaded program capable of logging and displaying the data in real-time. It is envisaged that the display options would include a simple ASCII display for use on monochrome screens or multiple, selectable colour graphics displays appropriate to the power supply available for the application. If sufficient power is available in an airborne system, real-time imaging of the data could provide validation of data acquisition and navigation. This would require the data logger to also log GPS information.

### 10.3.2 Alternative Sensors

The achievable sample rate, resolution and bandwidth specifications of the frequency counter are largely dependent on the Larmor frequency produced by the optically-pumped sensor. The higher the Larmor frequency, the more easily the specification would be achieved. Should the desired specifications not be achievable with the caesium sensor, alternative sensors which produce higher Larmor frequencies such as the potassium or helium optically-pumped sensors would be investigated. The frequency counter would be designed to accommodate various sensor types.

### 10.3.3 Field Procedure Modifications

The successful acquisition of TFMMIP parameters will require some modification of survey procedure. This is largely due to the need to reduce the transmitter frequencies in an effort to minimise the influence of electromagnetic coupling. The transmitter fundamental frequency used for the surveys described in this thesis was 8 Hz. It is likely that, particularly for surveying in conductive areas, an attempt should be made to reduce the transmitter fundamental frequencies to about 1 Hz.

The constraints on survey speed for a SAM survey were described in Section 3.2.1 where it was shown that the highest spatial frequency in a magnetic profile will translate to a time-varying frequency given by the relationship:

$$f_{Max(Time)} = \frac{V}{2h}$$

where $V$ = the velocity of traverse, and
$h$ = the sensor height above the nearest magnetic source (ground level).

Therefore, the rate at which the spatially-varying magnetic field changes for a sensor traversing at a velocity of 2.0 m/s (7.2 km/h) and an elevation of 1 m above ground (a very fast walk) will have a 40 dB cutoff at 1 Hz. Separation of the SAM modulation from the spatially-varying magnetic field signal requires that the frequencies be spectrally distinct. Consequently, if the transmitter frequency was decreased to 1 Hz, then $f_{Max(Time)}$ would need to be lowered.

This can be achieved by reducing the survey speed and / or increasing the sensor elevation. For example, by simply constraining $V$ to a comfortable walking speed of 1.4 m/s (5 km/h) and raising the sensor to an elevation above ground of 2 m, $f_{Max(Time)}$ would be limited to 0.35 Hz which would provide sufficient frequency separation for a high order, high pass filter to operate effectively. Similarly, for a helicopter-borne system with the sensor flying at an elevation of 20 m and a speed of 17 m/s (60 km/h), $f_{Max(Time)}$ would be 0.4 Hz.

### 10.3.4 Alternative Applications of SAM

The author is cognisant of the fact that all of the work done to date on the SAM development is equally applicable to situations where alternative time-varying energy sources are used. In particular, the galvanic electrode source may be replaced by a large electromagnetic loop. Initial experiments using this source have now been performed by Boggs (1996). SAM is clearly also applicable to alternative survey configurations using either galvanic or electromagnetic sources. Such applications may include mise-à-la-masse and down-hole surveys.

The applications to date have been restricted to geological mapping for mineral exploration purposes. However, with growing world concerns over ground pollution from chemical sources, SAM is also seen as having potential for simultaneously mapping both contaminants and the geological structures containing them.

### 10.3.5 Related Theoretical Research

The achievements of the SAM project have resulted in the requirement for a greater understanding of the recorded data. This has consequently generated two other PhD projects (Fathianpour, 1996; Boggs, 1996) which are currently in progress. Subjects being investigated include presentation and interpretation strategies and include the development of modelling software.

## 10.4 Project Evaluation and Conclusions

The research described in this thesis has resulted in the development of a new, internationally patented, geophysical technique with demonstrated capability for the simultaneous acquisition of parameters related to both the electrical and magnetic characteristics of the ground. By using an optically-pumped total field magnetic sensor as an electromagnetic sensor, the technique enables the continuous recording of high definition magnetics and total field magnetometric resistivity at sample intervals of the order of one metre whilst continuously traversing the ground at walking speed.

A prototype instrument, capable of monitoring, processing and recording the required parameters was developed and the technique is now being operated commercially. The principle objective of the project has therefore been achieved and the project was, consequently, considered highly successful.

It was also concluded that the technique has the potential to concurrently acquire data related to the induced polarisation response although the first prototype SAM receiver was found to be deficient for that requirement. However, on the basis of the research described in this thesis, a strategy for accommodating that requirement has now been proposed and is currently under investigation.

Comparison of the efficiency of different geophysical techniques is difficult as many factors such as survey preparation time, terrain, vegetation and environmental factors can influence production rates. However, some guide to the efficiency of SAM was achieved by comparing its data acquisition production rates and costs with those of gradient array EIP and MIP. All three techniques employ galvanic current sources and survey preparation time and labour requirements were therefore assumed to be similar.

Because SAM is a continuous sampling technique, parameters reflecting each of the properties measured may be acquired at very close intervals (i.e. at a minimum, half a period of the transmitted waveform for TFMMR and TFMMIP). However, without the noise suppression benefit achieved by averaging the waveforms, parameters determined in that manner would not be very meaningful. Consequently, in estimating the data acquisition rates for SAM, the sample intervals assumed were believed to be the maximum required to provide a valid measurement and to adequately sample the property being measured. The surveys were assumed to be conducted on foot at an average speed of 1.5 m/s (5.4 km/hr). For all techniques, actual data acquisition time was estimated at 7 hours per day resulting in daily production rates of 15 km for SAM[1],

[1] A production rate of 15 km per day is a conservative estimate for SAM. Daily production rates of greater than 20 km are readily achievable in good conditions.

2.1 km for EIP and 2.6 km for EIP. The estimated production rates for each technique are shown in Table 10-1[2].

The results highlight the fact that the continuous-sampling SAM system is capable of production rates for the electrical parameters, TFMMR and TFMMIP, of 50-60 times those possible for EIP and MIP surveys. High definition, total field magnetics is, of course, also simultaneously acquired at rates of greater than 150 times the rate of the EIP and MIP parameters. The high SAM production rates translate to much greater spatial density of the acquired data and hence better definition of the anomalies.

| Survey Technology | Property Measured | Sample Interval (m) | Spatial Density (Samples/km$^2$) | Spatial Resolution (m × m) | Prod. Rate Samples per Day |
|---|---|---|---|---|---|
| Sub-Audio Magnetics | TFM | 0.5 × 20 | 102000 | 1.0 × 40.0 | 30000 |
| | TFMMR | 3.0 × 20 | 17000 | 6.0 × 40.0 | 5000 |
| | TFMMIP | 3.0 × 20 | 17000 | 6.0 × 40.0 | 5000 |
| Induced Polarisation | ER | 25 × 100 | 440 | 50.0 × 200.0 | 84 |
| | IP | 25 × 100 | 440 | 50.0 × 200.0 | 84 |
| Magnetic IP | MMR | 25 × 100 | 440 | 50.0 × 200.0 | 105 |
| | MIP | 25 × 100 | 440 | 50.0 × 200.0 | 105 |

Table 10-1. Survey specifications and data acquisition rates for SAM, EIP and MIP.

In order to compare the relative costs of data acquisition for SAM, EIP and MIP surveys, the data in Table 10-2 were compiled. The figures assumed a daily data acquisition cost of $1000.00 being an estimated cost of two field crew plus equipment. The cost per sample was determined by dividing the daily survey cost by the number of properties acquired with each survey technology and then dividing by the number of samples recorded per day for each property. The total cost per survey technology per

[2] The acquisition of valid TFMMIP parameters has not at this stage, been achieved. However, it is believed that the measurement of IP effects will be possible with more refined SAM instrumentation and, for the sake of discussion, TFMMIP has, therefore, been included in the figures.

km$^2$ is the total cost for all parameters measured for each survey technology per square kilometre surveyed.

The figures indicate that the SAM survey is not only the cheapest outright per square km but also provides an additional parameter (assuming acquisition of TFMMIP). However, a more important factor to note is the relative amount of information recorded for each of the surveys. For the survey costs shown, SAM permits spatial densities for the electrical parameters of 50-60 times those achievable with EIP and MIP surveys plus it has the added advantage of simultaneously acquiring High Definition Magnetics. It is clear that Sub-Audio Magnetics offers significant and unprecedented cost-efficiency benefits over EIP and MIP technologies.

| Survey Technology | Property Measured | Cost / Sample ($) | Cost per Line km ($) | Cost per km$^2$ ($) | Total Cost per Survey per km$^2$ ($) |
|---|---|---|---|---|---|
| Sub-Audio Magnetics | TFM | 0.01 | 20.00 | 1020.00 | 3376.00 |
| | TFMMR | 0.07 | 23.10 | 1178.10 | |
| | TFMMIP | 0.07 | 23.10 | 1178.10 | |
| Induced Polarisation | ER | 5.95 | 238.00 | 2618 | 5236.00 |
| | IP | 5.95 | 238.00 | 2618 | |
| Magnetic IP | MMR | 4.76 | 190.40 | 2094.40 | 4188.00 |
| | MIP | 4.76 | 190.40 | 2094.40 | |

Table 10-2. Data acquisition costs for SAM, EIP and MIP surveys.

The capability to record high spatial resolution data is particularly valuable where the geological structure of interest is relatively near-surface. In this case, fine detail in the geological structure will be reflected in the high spatial frequency component of the recorded waveform. Perhaps the most significant conclusion drawn from this study is that the diagnostic benefit of high spatial resolution information related to the electrical parameters of the ground has been positively demonstrated.

The exploration industry is traditionally reluctant to embrace non-conventional geophysical survey concepts. However, since completion of the project, in excess of 2000 line km of SAM surveys have been performed on a commercial basis and demand for services is steadily increasing. These surveys have provided further confirmation of the value of the SAM method and have contributed greatly to our knowledge and understanding of the technique. One of the most important lessons learnt from that experience is that too much reliance is often placed on a single data type, particularly magnetics, which can lead to a significant and possibly very expensive, interpretational bias. By providing a cost-effective means by which several independent physical parameters may be recorded at high spatial resolution, SAM has the potential to significantly reduce that bias.

Sub-Audio Magnetics is a new technique and, as such, will need to withstand the test of time before a thorough evaluation of its potential can be determined. However, if early indications are correct, the future of the technique looks extremely promising.