

MICROCOMPUTER MODELLING OF FIXED-LOOP  
TIME-DOMAIN EM SYSTEMS

by

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## ABSTRACT

Traditional methods for the interpretation of electromagnetic prospecting data have involved the in-field use of characteristic and type curves from scale modelling data, and the use of computer modelling in the office. Today, with the growing utilization of field microcomputers for data storage and presentation, a new demand has been created for interpretational programs which can be used on these systems. Since such programs can provide the user with a basis for making important day-to-day survey decisions, they must be efficient, flexible, easy-to-use, and well documented. Most importantly, they must be based on a reasonable approximation of subsurface features.

In an effort to meet these requirements, a microcomputer-based modelling package has been developed, for fixed-loop, time-domain EM systems. These programs, PLATEF, EIGCUR, and BATCHF, calculate the response of a thin, conductive, rectangular plate of any size, location, and orientation in free-space. The energizing source consists of a fixed, segmented loop of arbitrary geometry, and both the primary and secondary vector fields are measured along a completely arbitrary profile line. The new programs are based on the same mathematical algorithms as utilized in the mainframe program PLATE, developed at the University of Toronto; while maintaining the same numerical accuracy as PLATE, they offer the user a plethora of new options and features. The most notable of these are: an increase in computational speed; the provision of extensive geometrical information and control; the optional saving of all lengthy calculations; convenient batch operation; and output which can be expressed in the same units as the field data. The programs are written in FORTRAN 77, and have been compiled for use on an IBM-PC or compatible, with an 8087 math coprocessor chip.

This thesis describes the mathematical background, development, structure, and performance of the new modelling programs, as well as their role in electromagnetic interpretation and survey planning. It is hoped that this description, and the resulting software, will be of use to practicing geophysicists today.

#### ACKNOWLEDGEMENTS

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Electromagnetic Prospecting

Inductive electromagnetic prospecting methods have played an important role in the mining industry for the past several decades. Their greatest use by far has been in the detection of base-metal orebodies, such as massive sulphides, within the Precambrian Shield areas of the Earth. These deposits are generally considered to be easy targets for even the most simple EM system because they usually contain highly conductive metallic sulphides with excellent electrical continuity ( $\sim 10^2 \text{ Sm}^{-1}$ ), while the Precambrian host rock is usually very resistive ( $\sim 10^{-4} \text{ Sm}^{-1}$ ) (Telford et al, 1976). Detectable eddy currents can be made to flow selectively in the more conductive body through a suitable choice of frequency of a man-made magnetic field. Thus, early EM systems employing one or two frequencies, and a small separation of dipolar wire loops, were tremendously successful in locating near-surface sulphides in geologically favourable environments such as the Canadian Shield. Today, with the steady depletion of these easy targets, we have to look deeper and more carefully, and we are forced to unravel the complex electromagnetic interactions that take place in conductive environments.

The interpretation of early EM data relied heavily on scale model studies. The most common was that of simple eddy current induction in a thin, conductive, half plane. This model was widely used in the form of characteristic curves, which provided information on the conductor's dip, depth, and quality (Strangway, 1966). Despite the early success of such models, their application to deeper conductors ( $>60 \text{ m}$ ) and those hidden in conductive environments proved, at times, to be totally inappropriate (Scott and Fraser, 1973). With the variation of system parameters, such as frequency and loop separation, giving widely different interpretations, it was obvious that a more complex model of

EM induction in Earth structures and materials was required (ParASNIS, 1971).

The EM response of the ground can be complicated by conductive overburden, conductive host rock, disseminated mineralization and stringer zones of no economic importance, highly conductive graphite materials, fault, shear, and fracture zones containing ground water, and magnetic materials (see Figure 1.1). The additional fact that these may or may not be in contact with, or intersect, multiple target conductors of arbitrary size, shape, and orientation makes the interpretation process very difficult. In recent years, a considerable amount of research has been performed in attempting to explain the complex EM signatures produced in these conductive environments. These studies have been in the form of physical scale modelling, analytical solutions for relatively simple shapes, and numerical modelling. As a result, a much better understanding of EM induction in a "real Earth" has emerged (see Table 1.1). Excellent summaries of this important work have recently appeared in the literature (Ward, 1979; Lodha, 1977).

These theoretical studies have led to the realization that in order to separate the various induction phenomena in difficult geological environments, it is necessary to determine the EM response of the ground over a wide range of system frequencies and configurations (Lamontagne, 1975; Ward, 1979). This has led to a proliferation of multi-frequency and time-domain EM systems, in recent years, which are collectively known as wideband EM systems. Time-domain systems have become especially popular, and have been used in airborne, ground profiling, depth sounding, and borehole surveys. Their popularity over the frequency-domain method stems from their greater depth of investigation, their improved resolving power, and the elimination of geometrical survey errors. They are all designed to study either the impulse or step response of the ground.

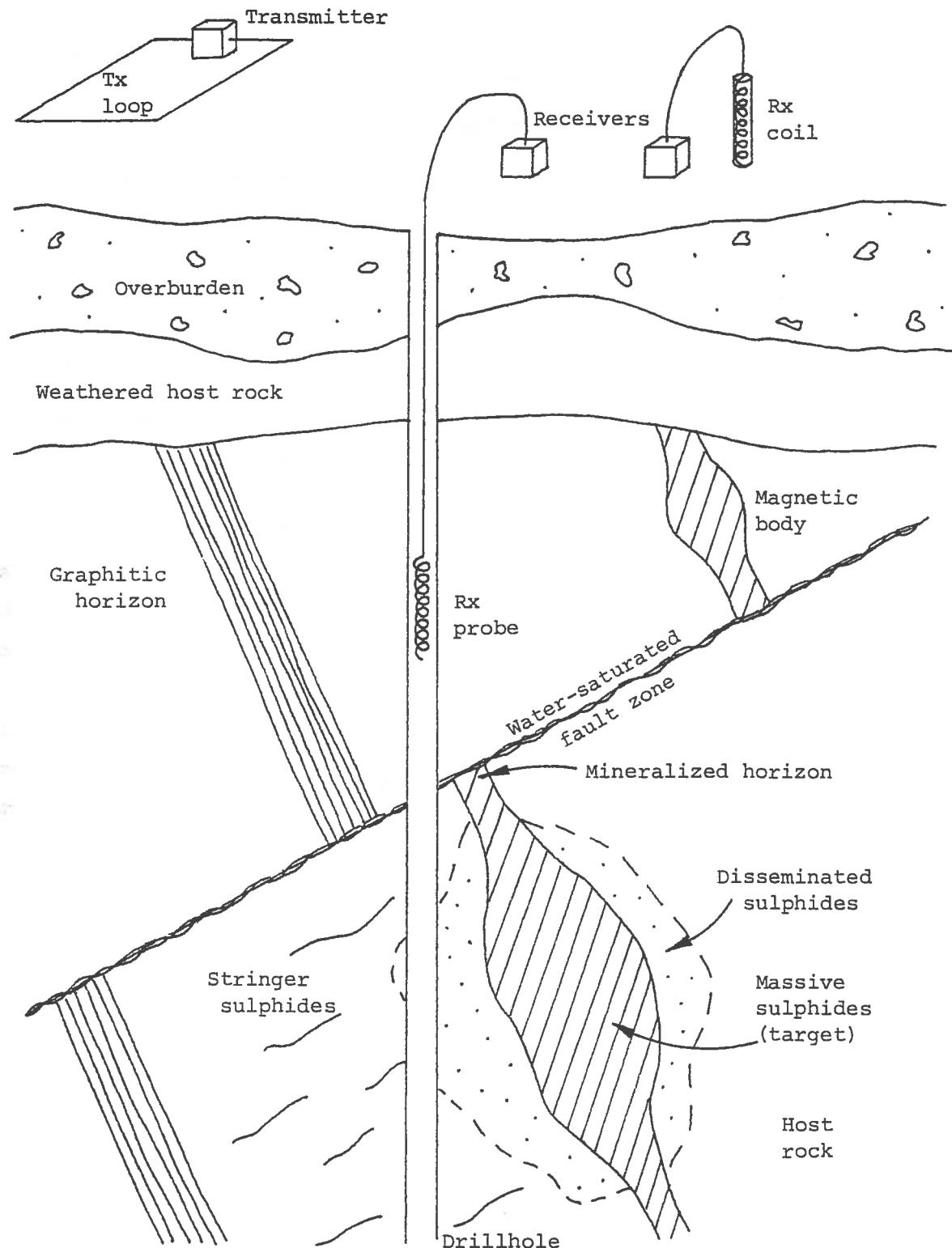


Figure 1.1 Factors contributing to complex EM responses in and over the Earth.

Feature	Effect	Interpretation problem
Overburden	rotates phase decreases amplitude	depth estimates invalid $\sigma t$ estimates invalid
Host rock	rotates phase increases amplitude for shallow conductors increases or decreases amplitude for deep conductors changes shape of profile fall-off laws change	depth estimates invalid $\sigma t$ estimates invalid dip estimates invalid
Surface and buried topography	introduces geological noise	depth estimates invalid $\sigma t$ estimates invalid dip estimates invalid may obscure sulphide anomalies
Halo of disseminated sulphides	rotates phase increases amplitude	depth estimates invalid dip estimates invalid $\sigma t$ estimates invalid
Weathered host rock	introduces geological noise	obscures sulphide anomalies may invalidate all quantitative interpretation
Faults, shears, graphitic structures	introduces geological noise	obscures sulphide anomalies may invalidate all quantitative interpretation

Table 1.1 The effects of complex EM structures (from Ward, 1979).

## 1.2 Applications of Theory

This brief summary of the recent advances in EM theory and equipment, points to one obvious question. How do all these advances help field Geophysicists? They have learned through experience that characteristic curves or nomograms based on very simple models are often incomplete and not very reliable. On the other hand, it is difficult to keep up-to-date with all the theoretical developments in analytical and numerical modelling, much of which involves extremely complicated mathematical derivations. In all likelihood, they do not have the resources to make use of the large numerical modelling programs being developed in academic circles. Finally, they must deal with the conflicting claims of instrument manufacturers, while realizing that each instrument will respond to the Earth in its own unique way.

One common solution to this predicament is for researchers to produce type curves for a particular system from numerical or scale modelling. If this is done for a variety of systems (eg. Lodha and West, 1976), it provides the explorationist with a basis on which to choose the most appropriate system for the job at hand. However, as an interpretational aid, it is obvious that not all possible geometries of the model can be provided, especially for the large loop systems in which the loop and conductor sizes are important parameters (Bosschart, 1970). Thus, once a suitable model has been chosen, one is often left wondering what the effect would be of small changes in each of the model parameters, and indeed, whether another model would be more appropriate.

A better solution, when it is possible, is to provide an in-field interpretation program to supplement the type curve catalogs. This option has become popular recently with the introduction of portable microcomputers as standard equipment in exploration camps (Johnson and Parker, 1982). Microcomputer-based modelling and inversion programs for gravity and magnetics surveys, have become commonplace. Microprocessors and storage devices have been added to nearly all the modern field equipment so that data collection, storage, filtering or correction, plotting, and interpretation can be done electronically with a minimum amount of human intervention (Seigel, 1982). One glaring omission from

this in-field computer revolution is a micro-computer based EM interpretation program (Cornwell, 1983).

### 1.3 Thesis Objective and Outline

The object of this thesis is to produce a microcomputer-based, fixed-loop, time-domain EM modelling program for a conductive, rectangular, thin plate in free space. The restriction to fixed-loop systems is a result of program size and speed requirements, while the choice of time-domain EM can be attributed to its enormous popularity. The rectangular thin plate model was chosen because it is complex enough to be useful, and because very efficient algorithms for its solution are in existence (Annan, 1974). By writing the program specifically for microcomputers, it is hoped that practicing geophysicists will benefit through its use in the field.

In order to develop a successful microcomputer-based modelling program, there are several requirements that must be fulfilled. These include size and time requirements, flexibility, user-friendliness, and documentation.

One of the most critical requirements for in-field geophysical software is its speed of operation. If a forward modelling program is to be used interactively on a microcomputer, a single model calculation should not take longer than 10 to 15 minutes. This should allow for the rough interpretation of data to keep pace with the data collection. Immediate exploration decisions such as detailing, extensions, repetitions, or even drilling, can then be made with some degree of confidence. The size of the program is another critical requirement to address. The capabilities of microcomputers are continually expanding, and an average memory size today appears to be 256 Kilobytes. While this may appear to be a huge amount of space, it can be very quickly filled by geophysical modelling programs.

In addition, the program should be flexible enough to provide for as many model geometries and system parameters as possible, while

presenting the output data in any of the commonly used units. The proper choice of units allows field data to be compared on an equal basis with model data, while the flexibility in adjusting model parameters allows the user to see what effect each parameter has on the final chosen model. Program flexibility also allows for the testing of various survey parameters in the planning stage. These might include the type of system used, conductor detectability, the hole or line spacing, the amount of data required per station (eg. number of components and channels), and the transmitter loop size and positioning.

Probably the most important requirement is for the program to be user-friendly. This is largely self-explanatory, but it includes the convenient input of data in terms understood by the user, a model summary and expedient changing of parameters, and an output file format which can be read by the user, as well as other computers.

An often neglected component of programming is documentation. A well-written user's manual, containing a concise description of the limitations and accuracy of the program, is essential. A programmer's manual should also be prepared which outlines the overall structure of the program, as well as its mathematical basis. Finally, the program code must be clearly written, and its variables completely defined, in order to facilitate future changes or additions to the program.

During the work described in this thesis, an attempt has been made to meet each of these requirements. Chapter 2 outlines the theory and practice of time-domain EM, as well as the interpretational problems which have led to this thesis definition. A description of the mainframe, numerical modelling program PLATE is provided in Chapter 3. Chapter 4 gives details of the steps to convert this program to a microcomputer, while Chapter 5 provides some examples of its use.

## CHAPTER 2

### TIME-DOMAIN ELECTROMAGNETICS

#### 2.1 Historical Perspective

Time-domain electromagnetic (TDEM) methods have received a significant amount of attention, in recent years, from academics, the mining industry, and geophysical instrument manufacturers. They have proven to be tremendously beneficial to modern mineral exploration as exemplified by their use in conductive environments, such as Western Australia, and in routine ground and airborne reconnaissance surveys. TDEM methods have also played a predominant role in locating deep-seated conductors in borehole work, and in defining extensions to existing mines. Presently, TDEM horizons are expanding to include the oil industry, with sounding applications such as layered earth and depth-to-bedrock determinations. Thus, it appears that time-domain electromagnetics has become an all-purpose EM technique which can find the "easy" targets of early exploration, as well as map the more difficult structures of interest today.

The theoretical basis of the time-domain EM method was first developed in the 1950's (Wait, 1951a, 1951b; Bhattacharyya, 1957) while increasingly complex analytical solutions to the time-domain EM problem appeared during the 1960's. By 1962, an airborne profiling system, measuring only one component of the EM field, had been successfully developed and tested (Barringer INPUT). Ground systems also appeared during this time (Dolan, 1970), but it was not until the electronic revolution of the 1970's that truly portable ground TDEM systems could be built with small, lightweight components.

During the past 15 years, a great variety of TDEM systems and modes of operation have become common-place. A small scale loop-coil profiling system capable of measuring all 3 components of the EM field was developed in 1972 (Crone PEM). In Australia and the Soviet Union,

large coincident loop systems, designed for conductive environments and sounding, were developed (SIROTEM; MPP4). These can produce only one vertical component reading for each loop location. In North America, the large-scale loop-coil systems have become very popular since they combine good depth of investigation with portability and efficiency. They can be used in surface or borehole profiling surveys, as well as in sounding applications, and can measure 1, 2, or all 3 components of the EM field (Crone borehole PEM and DEEPEM; Geonics EM37; UTEM; Newmont EMP). When they are used in the profiling mode, they are often referred to as "fixed-loop", and it is these systems which will be the focus of this thesis (see Table 2.1).

## 2.2 Fixed-loop Systems

In fixed-loop TDEM systems, a large, single-turn loop of wire is laid out on the ground. It can have any shape or dimension, but it is normally square or rectangular, and ranging from 100 m square to 1 km square. A portable power generator (typically 2500 W) feeds a voltage regulator and transmitter, which provide a precise current waveform through the loop. Once this transmitter loop has been set up, it can be left unattended for the duration of the survey, while the receiver apparatus is moved along surface lines or down boreholes (see Figure 2.1).

In the majority of these systems, the impulse response of the ground is measured. The transmitter cycle consists of slowly increasing current (for a few msec), constant current (for 10 - 200 ms), abrupt linear termination of current (0.1 - 2.0 msec), and finally zero current (for 10 - 200 msec) (see Figure 2.2). The quick decay of the primary magnetic field, caused by the current termination, induces a pulse of emf in the surrounding media, according to Faraday's Law. The resulting eddy currents produced in nearby conductive material support a surrounding secondary magnetic field for the duration of the pulse. Thereafter, with no external emf to support it, this system of currents and magnetic field decays with time, and it is this transient magnetic field, cutting the surface coil or borehole probe, which the receiver

Manufacturer	Name	Measured Parameters	Number of Channels	Current Waveform	Comments
Crone Geophysics	1. Pulse EM (PEM) 2. Borehole PEM 3. DEEPEM	( $H_V$ ), ( $H_I$ ), $H_H$ $H_I$ , ( $H_V$ ), ( $H_I$ ), $H_H$	8 or variable	Linear ramp turn-off	1. Moving loop system 2. Up to 2000m depth 3. Large, fixed tx loop
	1. UTEM surface 2. UTEM borehole	( $H_V$ ), $H_I$ , $H_H$ , $E_I$ , $E_H$			1. Large, fixed tx loop 2. Fibre-optics technol.
	1. EM37 surface 2. EM37 borehole	( $H_V$ ), $H_I$ , $H_H$ $H_I$			1. Large, fixed tx loop 2. Up to 2000m depth
Geoex.	1. SIROTEM 1 loop 2. SIROTEM roving receiver	$H_V$ $H_V$ , $H_I$ , $H_H$	10 - 32	Linear ramp turn-off	1. Large coincident moving loops 2. Large, fixed tx loop
	INPUT	$H_V$			Airborne, moving loop
Barringer	EMP	$H_V$ , $H_I$ , $H_H$	6	Half - sinusoidal	Large, fixed tx loop Not commercially available
Newmont			31	Linear ramp turn-off	

NOTE: Most commonly measured parameter is in parentheses; V - vertical, I - inline, H - cross horizontal

Table 2.1 Description of TDEM systems.

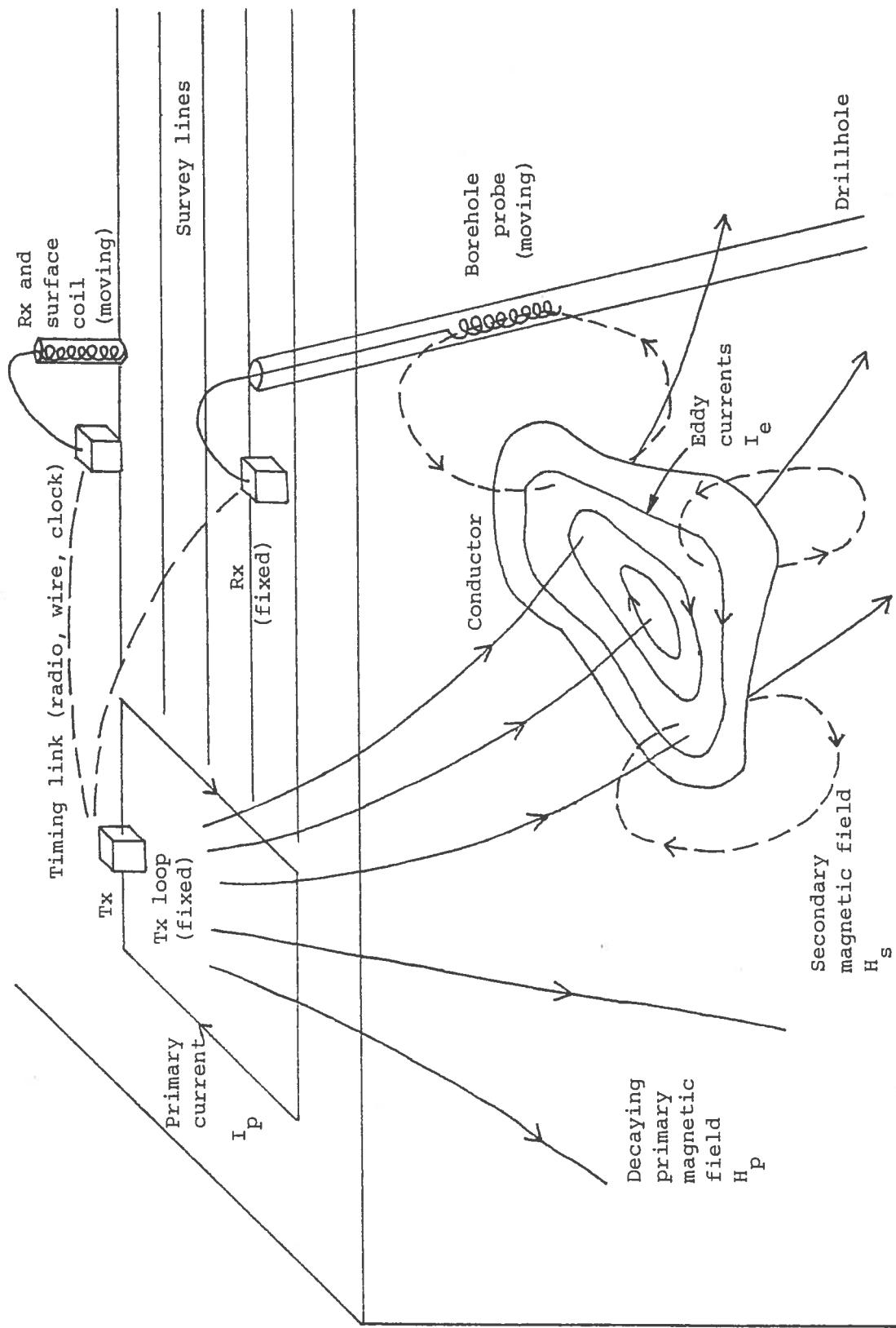


Figure 2.1 Typical operation of fixed-loop TDEM systems.

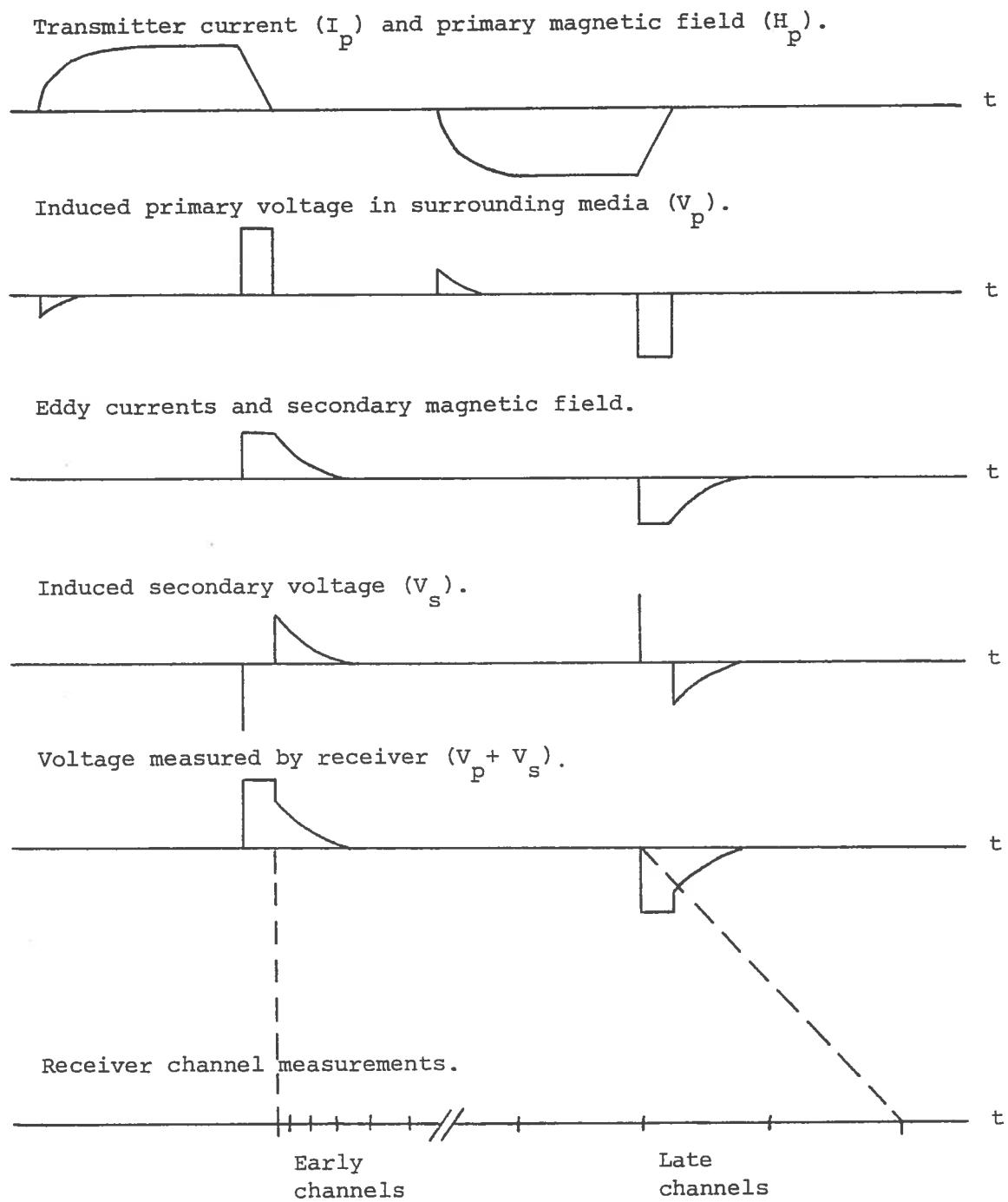


Figure 2.2 Fixed-loop current waveform and receiver measurements  
(after Woods, 1975).

measures. These measurements occur during fixed time "windows", or "channels", which occupy most of the "off-time" of the transmitter. Since the receiver must know when the transmitter is off, synchronization is provided in the form of a wire link, radio signals, or crystal clocks.

The current waveform in the transmitter, and the number and spacing of channels in the receiver are the main distinguishing features among TDEM systems. A radically different system is UTEM, which transmits a sawtooth waveform and measures the step response of the ground. Thus, the UTEM transmitter does not have an off-time, and there is always a primary emf present. However, this field is constant during measurement, and usually determinable, so that its effect can be removed from the measurements.

### 2.3 Relative Merits of TDEM

The popularity of TDEM methods stem from the many advantages they offer over the frequency-domain methods. These include:

1. lower secondary field detection limits
2. better depth of investigation
3. geometrical freedom
4. better definition and differentiation of conductors.

TDEM receivers are able to measure much smaller secondary field signals because of the absence of the primary field during measurement, and by signal stacking over several hundred transmitter cycles. This allows both smaller, and deeper conductors to be seen.

Depth of investigation can be improved further by increasing the primary field strength. Using typical survey dimensions, the magnetic field fall-off from large current loops is in the range of  $1/r$  to  $1/r^2$ , compared with  $1/r^3$  for a magnetic dipole. Thus, transmitter loops as large as one km square and with ever-increasing amounts of current are being used. Borehole surveys are the most obvious means of improving depth of investigation, and TDEM systems are particularly well-suited to

this exploration technique. Conductors have been easily detected at distances greater than 100 m from the drillhole and at depths in excess of 1000 m from surface (Crone, 1983).

The geometrical freedom offered by TDEM systems has been tremendously valuable for mine and borehole surveys. Since the primary field does not have to be removed from the measurements, there are no geometrical errors caused by the incorrect separation and orientation of the transmitter and receiver. This decoupling of the primary and secondary fields, leads to "cleaner" data which is easier to interpret.

Target definition can be achieved in the time-domain by studying both the decay and the spatial characteristics of the data. The size, position, and orientation of conductors can be determined from the spatial response of each channel, and the shape of the conductor can be inferred from how this response changes with time. Target definition can also be greatly improved by changing the direction of the primary source energization through transmitter loop movements.

Conductor differentiation is one of the most troublesome problems of modern EM exploration, and time-domain systems offer a solution. The rate of decay of a conductor's magnetic field depends primarily on its size and conductance. Eddy currents decay rapidly in poor conductors, while those due to good conductors decay slowly, and the timing of the channels is such that only the effects of eddy currents due to the good conductors are seen in the later channels. In conductive environments, therefore, the response from overburden and uneconomic ore deposits should be minimal in the later channels where the target response predominates. This also provides a means for accurate determination of target conductance.

There are, however, a number of disadvantages to using TDEM systems over frequency-domain systems. A motor generator is normally required because of the high current values, and the low frequency content of the waveform. This, along with the numerous other pieces of equipment, makes the method less portable and less efficient than simple frequency-

domain methods. Also, the large, stationary transmitter loops introduce the problem of blind zones, in which a conductor may not be energized by the primary field due to its relative orientation. This means that the survey should always be repeated with at least one other transmitter loop location. A final often stated disadvantage of the fixed-loop TDEM systems, that the loop seems to couple best with conductors of approximately the same size (Lajoie and West, 1976), will be discussed later in this thesis.

## 2.4 Interpretation of TDEM Data

### 2.4.1 General

The interpretation of electromagnetic field data is performed almost exclusively through the process of forward modelling. This consists of first generating the theoretical response of a particular EM system to an assumed model of the Earth, and then changing the model parameters until a reasonable match with the field data is achieved. This can be facilitated through the use of a published type curve atlas, and characteristic curves, which relate some obvious physical characteristic of the curves to one or more model parameters. This synthetic model data can be produced through laboratory scale model studies, analytical solutions, or numerical modelling on computers.

Scale model studies can be performed for nearly any type of model geometry, but it can quickly become impractical for generating large suites of data. Analytic solutions require a method to solve the diffusion equation subject to the appropriate boundary conditions. This means that solutions exist only for simple shapes such as spheres, cylinders, and layered half-spaces. Numerical modelling, using finite difference, finite element, or integral equation techniques, can handle very complex geometries. However, the complexity of the model is directly related to the required computing capacity and cost, and these can quickly become unreasonable (Ward, 1979).

Since the conductor's size plays such an important role in the response of fixed-loop TDEM systems, comprehensive type curve catalogues for even simple shapes would be too large to use effectively, if they could be produced at all. Thus, there appear to be three approaches that are presently utilized by interpreters. These are as follows:

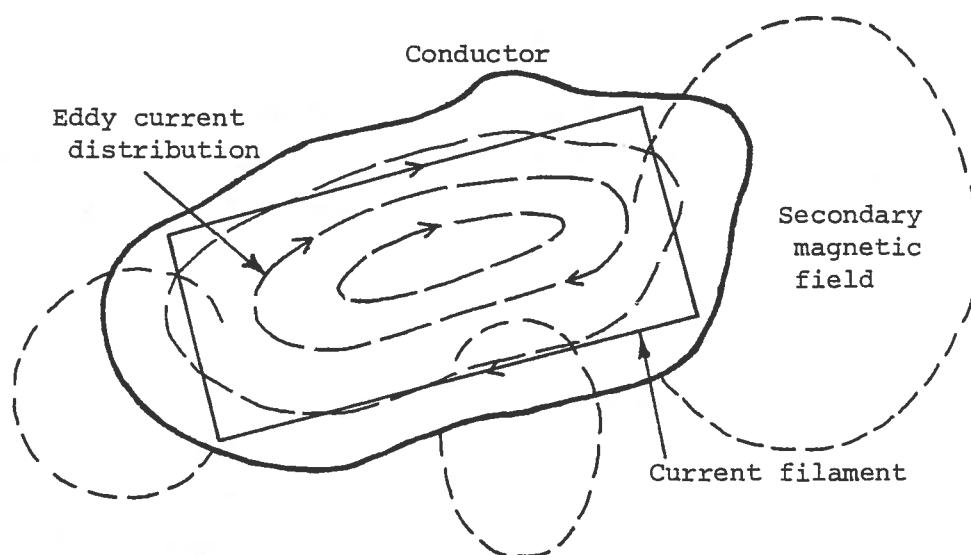
1. The Filament Approach
2. The "Real Earth" Approach
3. The Computer-assisted Simple Model Approach

Further details on each of these approaches to the TDEM interpretation problem will now be provided.

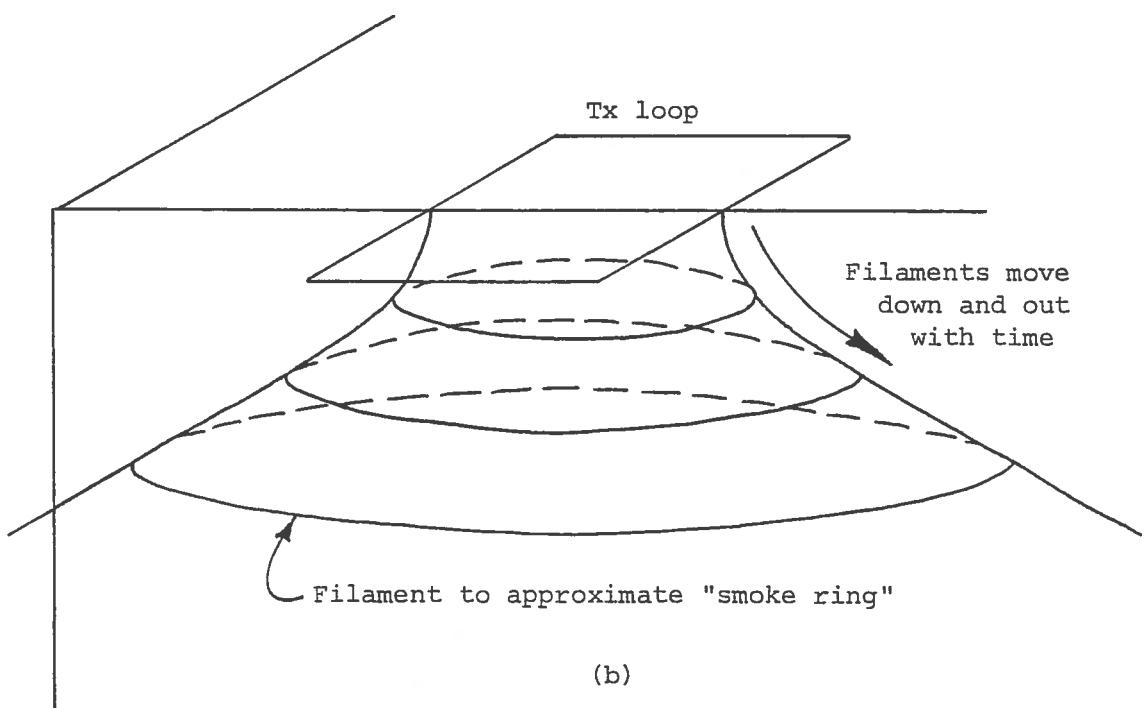
#### 2.4.2 The Filament Approach

In this approach, the secondary field is approximated with the field from a single current filament loop. In confined conductors, this filament is located near the conductor's edge for early times and diffuses inward for later times. In the case of a conductive half-space, current filaments are used to approximate the "smoke rings" that diffuse down and away from the transmitter loop with the passage of time (Nabighian, 1979) (see Figure 2.3).

Free-space magnetic field diagrams for current loops of various sizes can be used to explain the basic shape of field data curves. Best fit current loops can be achieved manually or through the use of inversion programs (Barnett, 1984, Taylor, 1985). If the filament is large enough, two components of the field data can be utilized to create vectors which point to the nearest segment of the filament loop (Crone, 1979). Although this simple model allows for direct interpretation or inversion of the field data, it has limited application, and provides little quantitative information.



(a)



(b)

Figure 2.3 Using current filaments as interpretational aids.

- (a) Approximation of eddy current distribution with a single, rectangular, current filament.
- (b) Filament approximation in a conductive half-space.

#### 2.4.3 The "Real Earth" Approach

In order to understand the predominant features of field data collected in conductive environments, it is often necessary to rely on qualitative descriptions of the complex EM interactions with Earth materials. Studies concerning the effect of conductive overburden and host rock have been performed for more than a decade. Early studies were based primarily on scale modelling (Lowrie and West, 1965; Sarma and Maru, 1971; Verma and Gaur, 1975) and analytical solutions, such as layered spheres, and layered half-spaces (Negi and Verma, 1972; Gupta et al, 1973; Ward, 1967). Today, numerical solutions can be achieved for 3-dimensional conductivity structures (Hohmann, 1975), but the cost of producing curve suites without the use of a large, dedicated computer would be astronomical. Through the use of these model studies, we now have a growing understanding of such effects as shielding, current gathering or channelling, multiple conductor responses, IP effects, and magnetic and superparamagnetic responses (Nabighian, 1984).

#### 2.4.4 The Computer-assisted Simple Model Approach

The EM response of simple models can form a valuable part of the interpretation process, if the limitations of the model are always kept in mind. This approach provides a compromise between the first approximation with a filament, and the infinite complexity of the real Earth. It depends upon the availability of computer modelling which can be performed during the interpretation process to supplement the use of type curves. The model must be simple enough to ensure that the computing is both fast and inexpensive, yet complex enough to be a useful approximation in any environment. Isolated conductors in free space fall in this category, if they have a suitable number of variable parameters, if type curves exist, and if their response can be studied either analytically or through efficient numerical methods.

Type curves for conductors in free space have been produced for most time-domain EM systems, although many of these are unpublished. An extensive suite of type curves for the Crone borehole PEM system was

produced by Woods (1975). These curves were based on a scale model study using large, conductive, thin sheets with variable parameters such as conductance, size, position, intersection angle, edge angle, and distance to the conductor's edge. Characteristic curves, based on this study, form a valuable component of borehole PEM interpretation (Woods and Crone, 1980).

One of the most useful computer models, balancing complexity with efficiency, has been that of a thin, finite plate in free-space. Lodha (1977) has shown how this simple model can be used to define conductors even under moderately conductive overburden. Similarly, Dyck (1981) and Dyck and West (1984) have described how such a model can be used effectively in the interpretation of borehole TDEM data. These studies were largely based on the numerical modelling program PLATE which was developed at the University of Toronto and uses an efficient numerical technique outlined by Annan (1974).

In theory, this program can be used together with the type curves, mentioned earlier, to illustrate a typical example of the computer-assisted simple model approach. The success of this approach, however, depends upon a broad and representative suite of type curves, and a computer program which is easily accessible. Unfortunately, type curve suites are presently very incomplete, especially for small plates, and the PLATE program can only be implemented on a large computer.

The necessity for a microcomputer-based, fixed-loop TDEM modelling program, for thin plates in free space, is now obvious. Not only would it provide the basis for routine in-field interpretation of data, but it could be used to produce inexpensive additions to existing suites of type curves. To help in this regard, the PLATE program has been rewritten for use on a microcomputer.

## CHAPTER 3

### THE PLATE PROGRAM

#### 3.1 Introduction

The PLATE program was developed at the University of Toronto through the work of three successive PhD students (Annan, 1974; Lodha, 1977; Dyck, 1981) among others. It is a large, comprehensive EM modelling package designed for interactive use on a large computer. It models a conductive, rectangular, thin plate of any dimension and orientation in free space, for any EM system (frequency or time domain; airborne, ground or borehole; uniform, dipole, or loop fields; etc.). The spectral response at one station or the response at up to 51 stations along a line can be calculated. The secondary field is either written directly in SI units or is normalized to the primary field, while normalization of times or frequencies in terms of induction numbers, is also possible (see Dyck et al, 1981). The package consists of about 20 main programs and 90 subroutines which are interconnected up to an order of 5 (Lodha, 1977).

#### 3.2 The Equivalent Source Method

The mathematical basis of the PLATE program, as developed by A.P. Annan, involves the application of the equivalent source method of Green's theory; a method which can be used as a framework for solving a variety of electromagnetic problems in geophysics (Annan, 1974). Basically, the method consists of breaking the material properties  $\mu$ ,  $\epsilon$ , and  $\sigma$  into background and anomalous parts. The background values must have a simple distribution in space so that the Green's function, or Green's dyadic, can be evaluated. This means that the background material properties are distributed in "regions of constant property value which are separated by surfaces which permit separation of the governing differential equation and boundary conditions on the electric and magnetic fields" (Annan, 1974, p. 23). An equivalent source

distribution is then used within this background (undisturbed) region to represent the effect of a perturbation on the system by the anomalous material properties. Once this equivalent source has been found, its effect at any point ( $P$ ) can be found by convolving it with the Green's function of the background medium. For example:

$$R_a(P) = \int_{V'} G(P,Q) E(Q) dQ \quad (3.1)$$

where  $P$  is the observation point in  $V$ ,  $R_a(P)$  represents the anomalous response at  $P$ ,  $G(P,Q)$  is the background Green's function,  $E(Q)$  is the equivalent source at  $Q$ , and  $V'$  is a subregion of  $V$  in which  $E \neq 0$ .

The above equation demonstrates one of the great advantages of the equivalent source method - the integral only needs to be evaluated over some subregion of  $V$  containing the anomalous material properties. The price that must be paid for this simplicity lies in determining the equivalent source distribution. Although the equivalent source is zero outside the anomalous region  $V'$ , it satisfies a Fredholm integral equation of the second kind within that region, and this must be evaluated numerically. Annan (1974) has found the general form of these integral equations for both static and time-varying fields, and has thus established a general framework for solving EM problems with complicated geometries (see Appendix B).

The method is cost-prohibitive for the general case using time-varying fields because two coupled vector integral equations must be evaluated numerically. The situation improves slightly for an electric scatterer buried in a homogeneous medium because there are no equivalent magnetic currents involved. For the case of a thin plate in free space, the problem can be reduced to finding a scalar function  $U(r)$  over the plate (see Appendix C). Annan (1974) studied this last case extensively because it was both economically feasible, as well as useful. While thin sheet models are used extensively in geophysical exploration, these are often of infinite extent in one dimension (2-D models). Annan's studies were concerned with a plate which was physically and inductively

thin in one dimension, but finite in the other two. This can be called a finite plate or  $2\frac{1}{2}$ -dimensional model, and naturally, it represents a more accurate model of a geological conductor.

### 3.3 Thin Plate in Free Space

The eddy current distribution in a thin plate ( $K_e(r)$ ) can be found once the scalar function  $U(r)$  is known over its surface (see Appendix C). Annan expanded this potential function in terms of a finite sum of 2-dimensional, Chebychev polynomials. It was found that, in most cases, a polynomial order of four was quite adequate to describe the potential distribution on the plate. Since the number of trial functions ( $N$ ) is related to the maximum polynomial order ( $M$ ) by:  $N = (M+1)(M+2)/2$ , a fourth order solution corresponds to 15 trial functions and coefficients. This clearly represents an improvement over other modelling techniques, such as the grid method (Lamontagne and West, 1971), in which several hundred point values are needed to describe the potential.

Since the current distribution is found from  $U$ , this process can be seen as summing  $N$  trial currents to approximate the eddy current distribution in the plate. The weighted eigenvector method was used to transform these trial currents into "eigencurrents" which are equiphase and non-interacting over the plate. The coefficient for each eigencurrent can be seen as the product of an electrical coefficient and an excitation coefficient (see Appendix C). The electrical coefficient is frequency-, or time-dependent, and also depends on the dimensions and conductivity-thickness of the plate. The excitation coefficient depends only on the magnetic field on the plate, and thus, it is dependent on the plate dimensions and the geometrical relationship between the plate and the transmitter. Thus, the eddy current distribution in the plate can be approximated by the finite sum:

$$K_e(r, t^W) \approx \sum_{i=1}^N K_i(r) D_i(t^W) H_i \quad (3.2)$$

where  $K_e(r, t^W)$  is the actual eddy current distribution in the plate;

$K_i(r)$  is the  $i^{\text{th}}$  eigencurrent derived from the  $i^{\text{th}}$  eigenpotential;  $D_i(t^W)$  is the  $i^{\text{th}}$  electrical coefficient; and  $H_i$  is the  $i^{\text{th}}$  excitation coefficient.

Since the eigencurrents are non-interacting, there is no mutual coupling, and hence, equation 3.2 can be seen as summing the response of  $N$  simple current loops located within the boundaries of the plate. As well, since the frequency response of each eigencurrent is similar to that of a simple loop, the frequency or time dependence is easily calculated. Although this makes for a very simple result, the effort required to find these eigencurrents is considerable. This would make the method too costly if it was not for the fact that the form of the eigencurrents depends only on the width-to-length ratio of the plate. Thus, the most laborious part of the program only needs to be completed once for a given ratio.

### 3.4 The University of Toronto PLATE Program

After the publication of Annan's thesis in 1974, a number of researchers (Lodha, 1977; Dyck, 1981) saw the potential in his technique for modelling the response of a plate to the various EM systems used in geophysical exploration. Although the technique was limited to a single plate in free space, with simple eddy current induction, such a model had proven to be useful as an aid in finding massive sulphides and other conductors in the Shield areas of the Earth. Also, time domain EM methods were just becoming popular at this time and it had been found that physical scale modelling of these systems was difficult due to the required time scaling. An economical numerical procedure for modelling finite plates was clearly in demand.

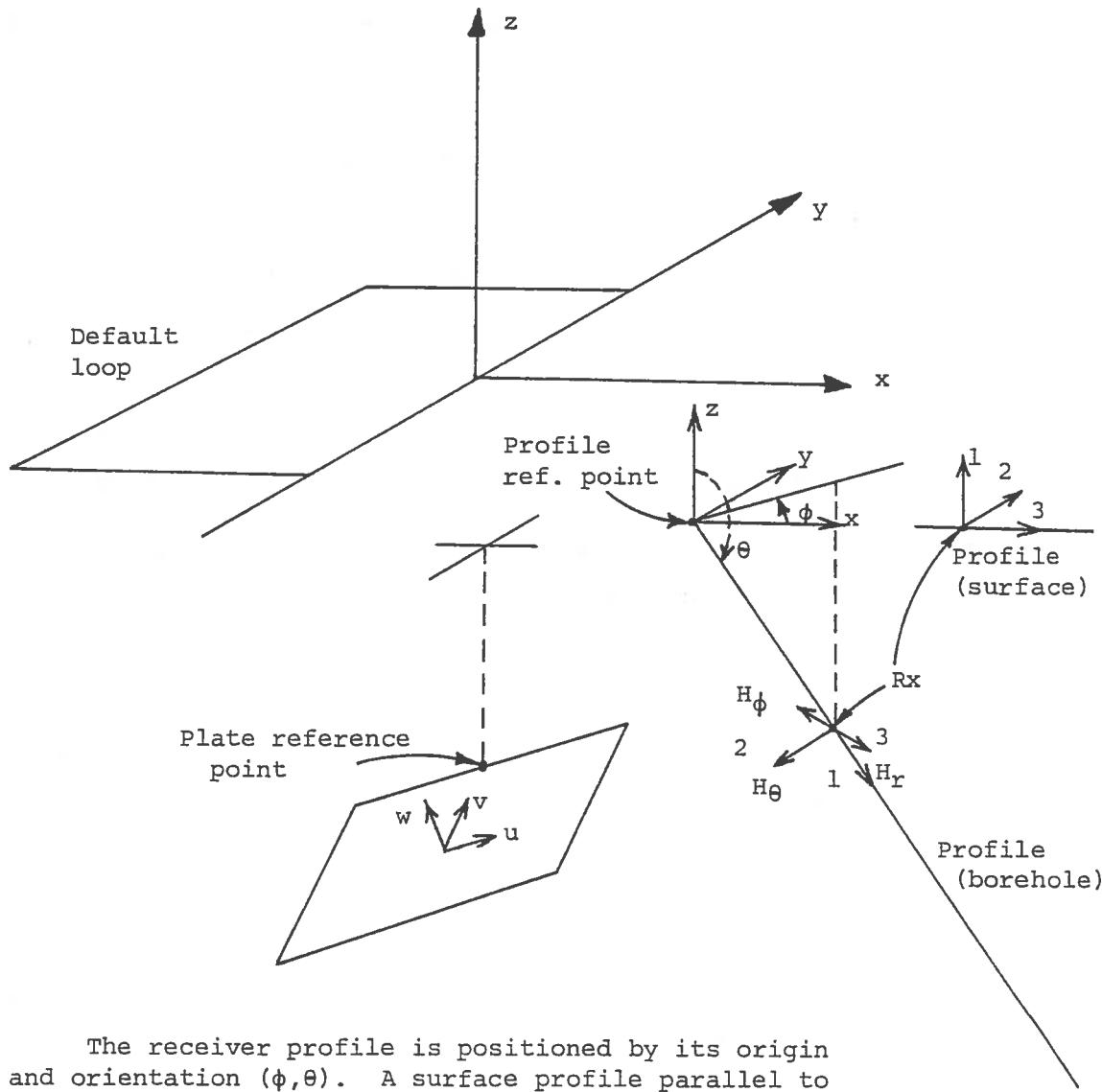
With this impetus, Annan's technique was used as the backbone for the development of the PLATE program at the University of Toronto (Lodha, 1977; Dyck, 1981). In addition to Annan's algorithms, the program had to account for the complex geometrical relationships that can exist among the transmitter, the receiver, and the plate. These complications can be appreciated when one realizes that the plate may

have any size, strike, dip, and plunge, and may be located anywhere in space; that the transmitter may consist of a polygonal loop of any orientation in space and may or may not be moving; and that the receiver can move along a line of arbitrary orientation. One further complication involved the convolution of the impulse response of the plate with the transmitter waveforms used in the various time-domain EM systems.

The three coordinate systems used in PLATE are the field system, the plate system, and the borehole system (see Figure 3.1). Nearly all of the geometrical information solicited by PLATE is in terms of the field coordinate system. Also, the final output from PLATE (the secondary field) is usually expressed in these components. It consists of the cartesian coordinates  $x$ ,  $y$ , and  $z$ , and the origin of the system is arbitrary. If the source field is a fixed, rectangular loop, however, it is convenient to choose the origin so that the loop is symmetrically placed about the negative  $x$ -axis and one edge lies on the  $y$ -axis. This procedure simplifies the loop definition.

The plate coordinate system is used internally by the program in order to calculate the eddy current distribution. The origin of the plate system lies at the center of the plate, with the  $u$  axis along its length, the  $v$  axis along its width, and the  $w$  axis perpendicular to the plate plane. It is derived from the field system by three rotations (strike, dip, and plunge), and two translations (a convenient reference point is located in both coordinate systems). It is only for this reference point specification that the user needs to consider the plate coordinate system.

The borehole coordinate system consists of the spherical coordinates  $R$ ,  $\theta$ , and  $\phi$ . The axis of the receiver coil in boreholes is constrained to lie in the direction of the hole, so this is a logical choice for one of the coordinate axes. The other two axes are chosen so that one lies in a horizontal plane, and the other points in a downward direction (unless the hole is vertical, in which case the final coordinate axis is horizontal) (see Figure 3.1). This coordinate



The receiver profile is positioned by its origin and orientation ( $\phi, \theta$ ). A surface profile parallel to the x axis has  $\phi = 0^\circ, \theta = 90^\circ$ . A vertical drillhole should be specified as  $\phi = 0^\circ, \theta = 180^\circ$ .

When  $\theta = 90^\circ$ , the field at the receiver point is determined in cartesian coordinates (surface surveys). When  $\theta > 90^\circ$ , the field is determined in spherical coordinates (drillhole surveys).

The order of the components in the output file (1,2,3) is arranged for plotting convenience as Z,Y,X and R, $\theta$ , $\phi$ . For a vertical drillhole, (R, $\theta$ , $-\phi$ ) correspond with (-Z,-X,-Y) respectively.

Figure 3.1 Positioning of receiver, transmitter, and plate for fixed source systems (after Dyck et al., 1980).

system is only needed to express the secondary field in boreholes in more useful terms.

The PLATE program contains 4 main steps (Dyck et al, 1981) which are as follows:

1. The first N eigencurrents are established, for a plate of given width-to-length ratio, by finding the eigenvector matrix and the associated eigenvalues.
2. The coupling between each eigencurrent and the transmitter is calculated and is expressed as an "excitation coefficient".
3. The secondary field at the receiver is calculated for each eigencurrent and is expressed as three "secondary field coefficients".
4. The time or frequency response of each eigencurrent is calculated for the waveform or frequency of the primary field. This is combined with the results of steps 2 and 3 to obtain the response at each receiver location.

In order to appreciate each of these 4 steps, they will be elaborated.

#### Step 1:

This is the most time consuming part of the whole program, although it only requires the maximum polynomial order and width-to-length ratio of the plate. Each element in two large matrices must be formed by integrating terms, involving the trial functions, over the surface of the plate. One of these integrals is evaluated analytically, while the other is evaluated using a Gauss-Legendre quadrature scheme (e.g. Hornbeck, 1975). The eigenvectors and eigenvalues of these matrices are then found using a Jacobi iterative method (e.g. Hornbeck, 1975). For the sake of efficiency, special properties of the Chebychev polynomials have been used in many places, and symmetric matrices are stored in compressed form. The output from this part of the program is stored in a data file which can then be used at a later date.

**Step 2:**

First the user must specify what type of source he wishes to use (uniform, dipole, or loop). The location of this source must be specified and if a loop source is chosen, a polygonal loop of up to 20 sides and any orientation may be created. The source coordinates are then transformed into normalized plate coordinates and the field perpendicular to the plate is calculated at grid points on its surface. Finally, the numerical integration of these field values with the digitized trial functions takes place using a Gauss-Legendre quadrature scheme and linear interpolation. Multiplying this result with the eigenvector matrix gives the N excitation coefficients.

**Step 3:**

The receiver position is located in field coordinates by increments, starting at a specified position. Each position, found in this way, is transformed into the normalized plate coordinates. Using the Biot-Savart Law, the vector field due to each trial function is calculated at the receiver position. This calculation consists of integrating terms, involving the trial functions, over the plate. A Gauss-Legendre quadrature scheme is used, but if the receiver is very close to the plate, the plate is first divided into a number of rectangular cells over which the integration takes place. Finally, multiplying these 3N terms with the eigenvector matrix gives the 3N secondary field coefficients at each receiver location.

**Step 4:**

The program supports the following transmitter waveforms: sine wave (frequency domain), ideal step, ideal impulse and practical impulse. As well, the following systems are supported: UTEM, early Crone PEM, and INPUT. Once the desired waveform is chosen, the frequency or time parameters must be specified, as well as the conductance of the plate. It is quite easy to calculate the frequency or impulse response of each eigencurrent since it behaves much like a simple loop. Modern time-domain systems, however, have quite complicated transmitter waveforms, and these must be convolved with the

impulse response. Using this calculation along with the secondary field coefficients and the excitation coefficients, the final response is found through successive summing. If necessary, the final response is transformed into drillhole coordinates and/or normalized before it is written to the output file.

The mathematical equations and computational methods used in each of these steps are outlined in Appendix E, and a flow chart for the PLATE program is shown in Figure 3.2. The reader is referred to the PLATE User Manual for more information (Dyck et al, 1981).

PLATE has been tested extensively at the University of Toronto mainly for the UTEM time-domain EM system, but also for TURAM, horizontal loop, Crone PEM, and INPUT. (Lodha and West, 1976) It has been found that for most cases an accuracy similar to scale modelling is achieved. When the transmitter is too close to the plate, however, errors can result from using an insufficient number of eigencurrents, or from numerical integrations which are not subdivided finely enough. The user must keep these limitations in mind when using the program since there are no warnings for these potential problems.

The program can be quite efficient under certain circumstances. The eigencurrents for a particular width-to-length ratio can be saved in a data file for later use. This represents a considerable saving in computing time. Also, by looping back into the program after an initial run, another system response for the same geometry can be calculated quite easily. Any geometrical changes, however, involve a considerable amount of recalculation. A further elaboration of these characteristics can be found in Chapter 4.

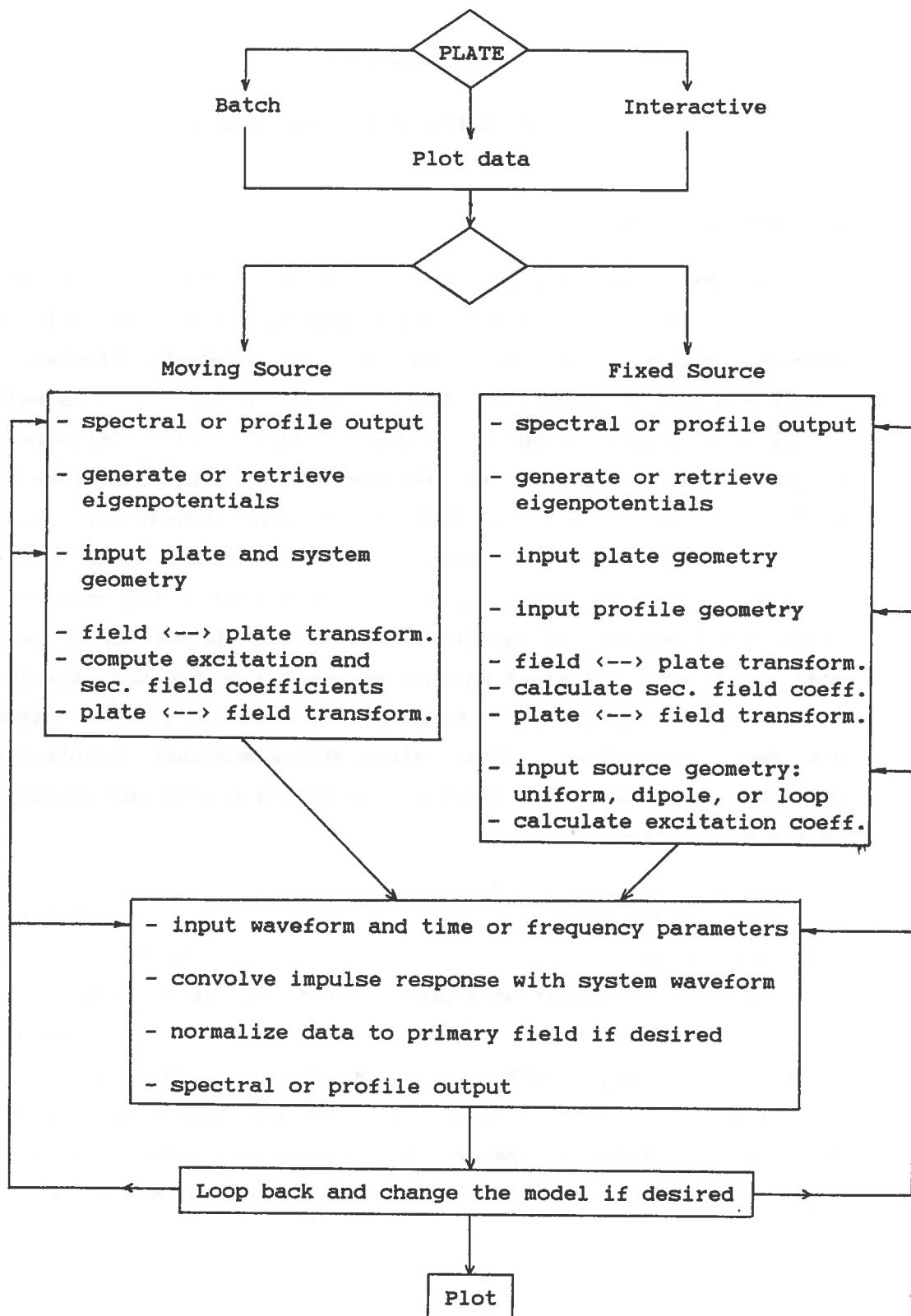


Figure 3.2 Flow chart of PLATE (after Dyck et al, 1981).

## CHAPTER 4

### A NEW PLATE MODELLING PACKAGE

#### 4.1 Introduction

In the interpretation of time-domain electromagnetic data, the University of Toronto PLATE program has played an important role for several years. It has been used in academic circles for the interpretation of field data (Lodha, 1977; Dyck, 1981), as well as for the production of type curves (Lodha and West, 1976; Gallagher, 1984; Bartel, 1984). Although the mathematical technique outlined by Annan (1974) represents one of the most efficient methods for modelling a conductive plate in free space, its use in the PLATE program has resulted in a voluminous and detailed program which can only be run on a large minicomputer or mainframe. With over 10,000 lines of FORTRAN code, and with the great amounts of "number crunching" involved, the direct transfer of the PLATE program to a typical in-field microcomputer has been impossible. This, along with a somewhat complicated user interface, has led to its limited use, by the practicing explorationist, in the mining industry.

This chapter describes the creation of a new microcomputer-based EM modelling package, based on Annan's algorithms. Within its restriction to fixed-loop transmitter sources, this package has been made to be efficient, user-friendly, and flexible, while still maintaining the same numerical accuracy as PLATE (see Appendix D). The chapter describes how the goals, listed in Table 4.1, were attained through such methods as structural changes, changes in computational methods, elimination of code, and the introduction of new code. More detail can be found in Appendix E.

Program Feature	Goals
Suitable size and time requirements	<p>Decrease program size so that it can be used on an average microcomputer (&lt; 256 kilobytes).</p> <p>Increase speed of program so that one model response can be calculated in 15 minutes or less.</p>
Flexibility	<p>Allow all commercially available TDEM systems to be modelled.</p> <p>Express the output in the same units as those used by the various system receivers.</p>
User - friendliness	<p>Simplify the procedure for the input of model parameters.</p> <p>Provide a summary of model parameters and a method of easily changing each parameter before any major calculations are performed.</p> <p>Simplify the output data file.</p>
Documentation	<p>Document the mathematical basis of each program and sub-routine.</p> <p>Document the code by defining each variable and program step.</p> <p>Provide a User's Manual and Programmer's Manual.</p>

Table 4.1 Goals for a new plate modelling package.

## 4.2 Program Size and Time Requirements

One method of reducing the size of the PLATE program, and increasing its speed, is to use only the first few eigencurrents to represent the eddy current distribution in the plate. Although this allows the program to be used on a microcomputer, it is little better than modelling the response of a single wire loop, for it is highly inaccurate in the early and intermediate time channels. Fortunately, it was found during the course of this thesis project, that such drastic measures are not necessary. Instead, the natural divisions within PLATE can be utilized to create separate programs, each of which is self-contained, and with a specific function, as well as small enough to be handled by a microcomputer.

### 4.2.1 Divisions within the PLATE Program

The intention of the original authors of PLATE was clearly to make the program as general as possible so that the response from any EM system could be calculated. This is ideal for comparing the various EM systems for a given model geometry, (e.g. Lodha and West, 1976), but of course, it is partly responsible for the large size of the program. From the point of view of an individual trying to match field data with synthetic data, it is better to have a smaller, more efficient program which is more directly concerned with a particular type of EM system. Thus, it was decided to limit the new program to TDEM systems with fixed loop transmitters (PLATEF). A dipole field can still be modelled by using a small loop, while a uniform field can be approximated by a distant loop. In the future, a separate program could be created from PLATE for the moving source systems (PLATEM).

A clear division exists within PLATE between the interactive input, and the batch input of model parameters. In an effort to simplify this batch procedure, a new program, BATCHF, was created. Instead of reading a user-prepared ASCII file for a single model as PLATE does, BATCHF reads a binary file created by PLATEF, which contains parameters for any number of successive models (see Appendix D).

Another of the natural divisions within PLATE involves plotting. The PLATE program makes use of specialized graphics software, which provides high quality plots, but also introduces hardware dependencies. Removal of this code was necessary to ensure portability of the program, and in its place, a simple listing of the numerical output is provided on the screen. Also, the structure of the output file has been greatly simplified, so that the user can more easily apply existing plotting programs of his own. Chapter 5 details such an application.

Thus, the removal of the moving source option, the dipole and uniform field options, the batch file reading and processing option, and the quality plotting capabilities, all contributed to a reduction in the amount of code needed for program PLATEF (see Figure 4.1). After a further analysis of the remaining code, it was found that the subroutines involved in the eigenfunction calculation could be run independently. This is the most time-consuming section of the original PLATE program, and it is used only to create data files for later use. By placing this section in a separate program (EIGCUR), a vast reduction in the amount of code compiled with program PLATEF was achieved.

#### 4.2.2 Programs EIGCUR and PLATEF

Once these basic program divisions had been established, an extensive editing procedure was undertaken on the remaining code in programs EIGCUR and PLATEF. This was done in an attempt to find all possible ways to reduce both the amount of code, and the time requirements for computation.

To create program EIGCUR, four original main subroutines were combined in order to eliminate the unnecessary writing and later reading of intermediate results in data files on disk. Also, by combining these subroutines, large arrays could be reused more efficiently and some repetitious code could be eliminated. A comparison of Figure 4.2 with Figure 4.3 shows that the new structure also follows a more logical mathematical sequence (see Appendix E).

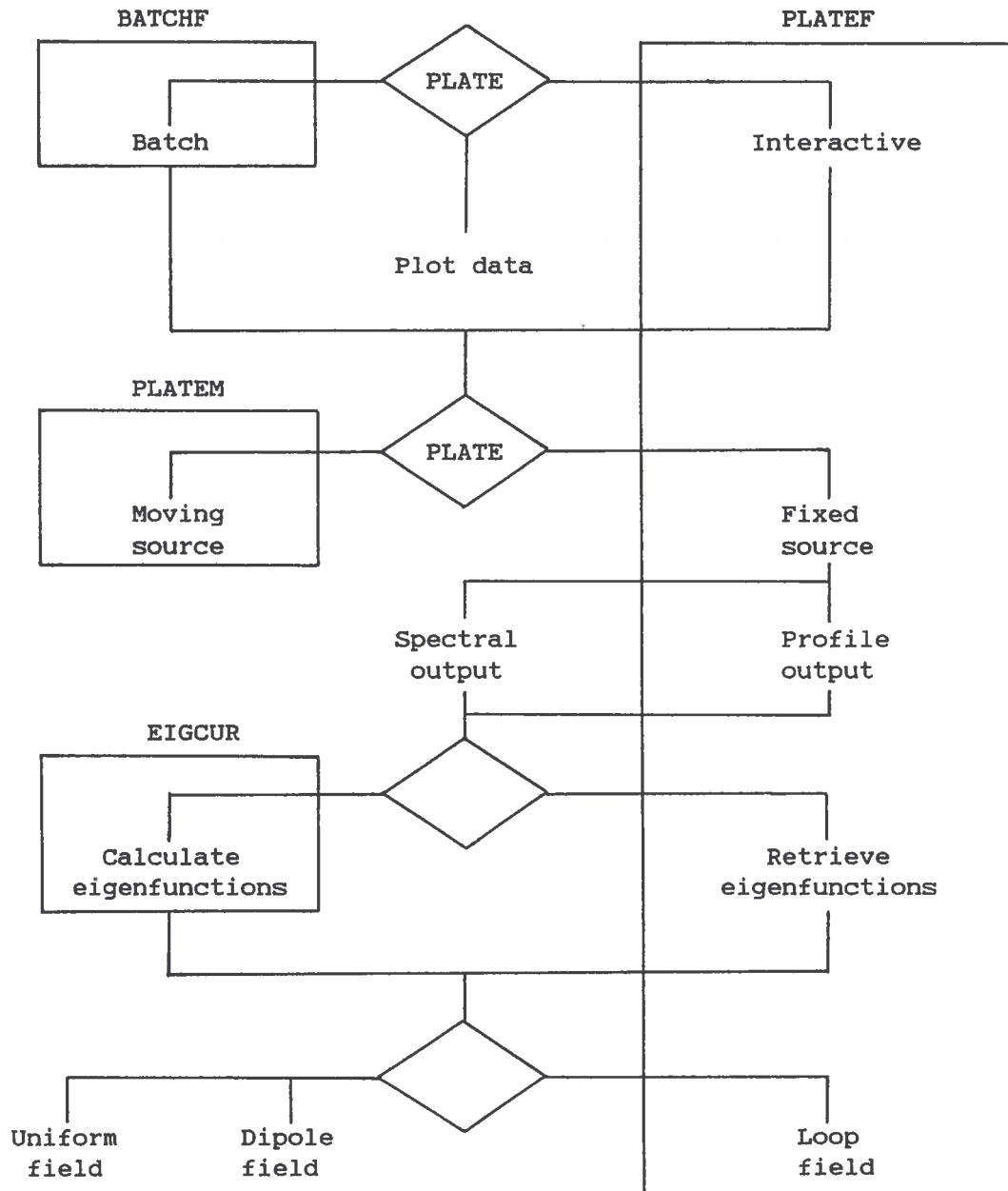


Figure 4.1 Main divisions of the PLATE program.

New programs are boxed and named.  
 PLATEM is a future program.

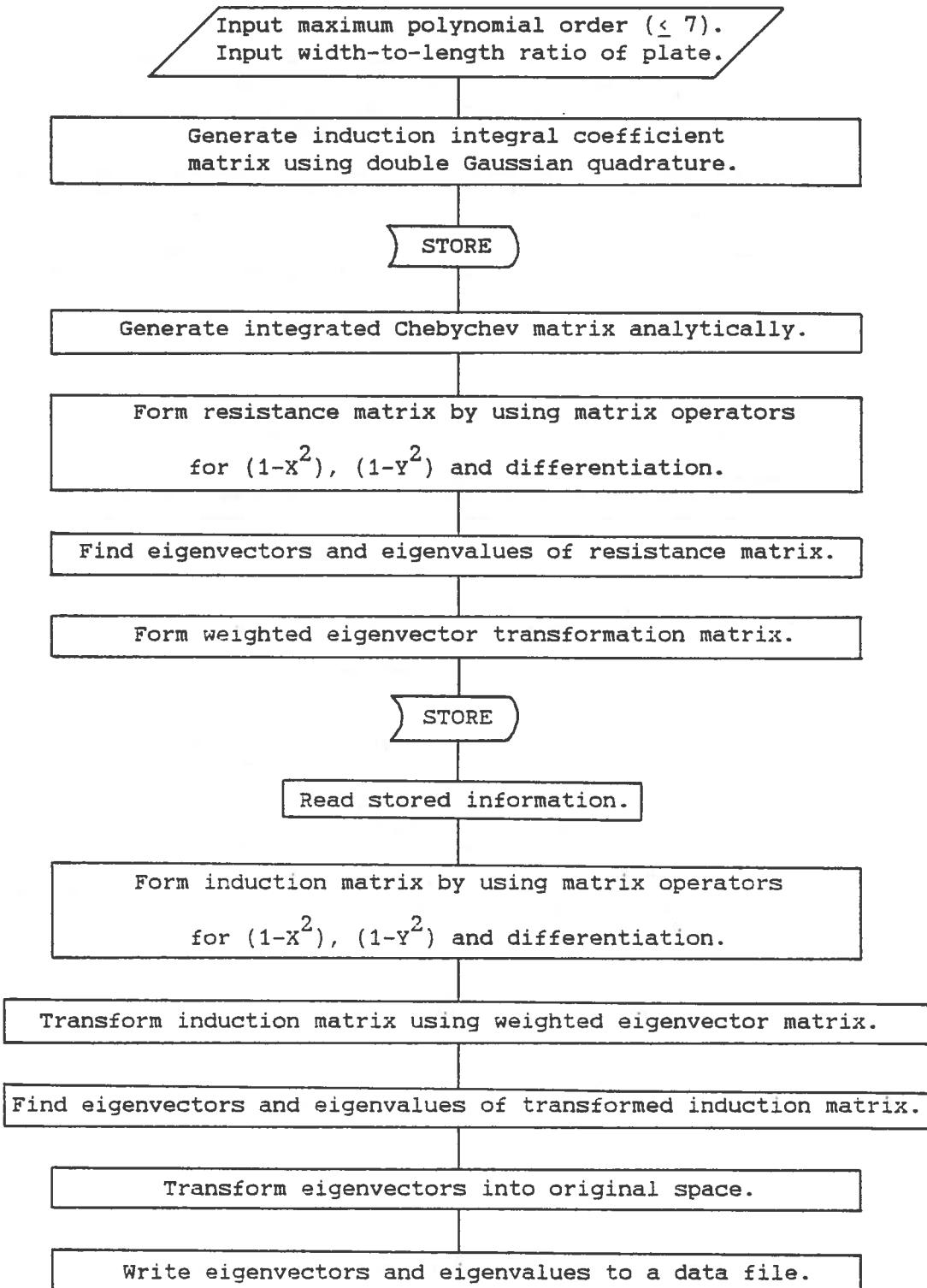


Figure 4.2 Calculation of eigenfunctions in PLATE.

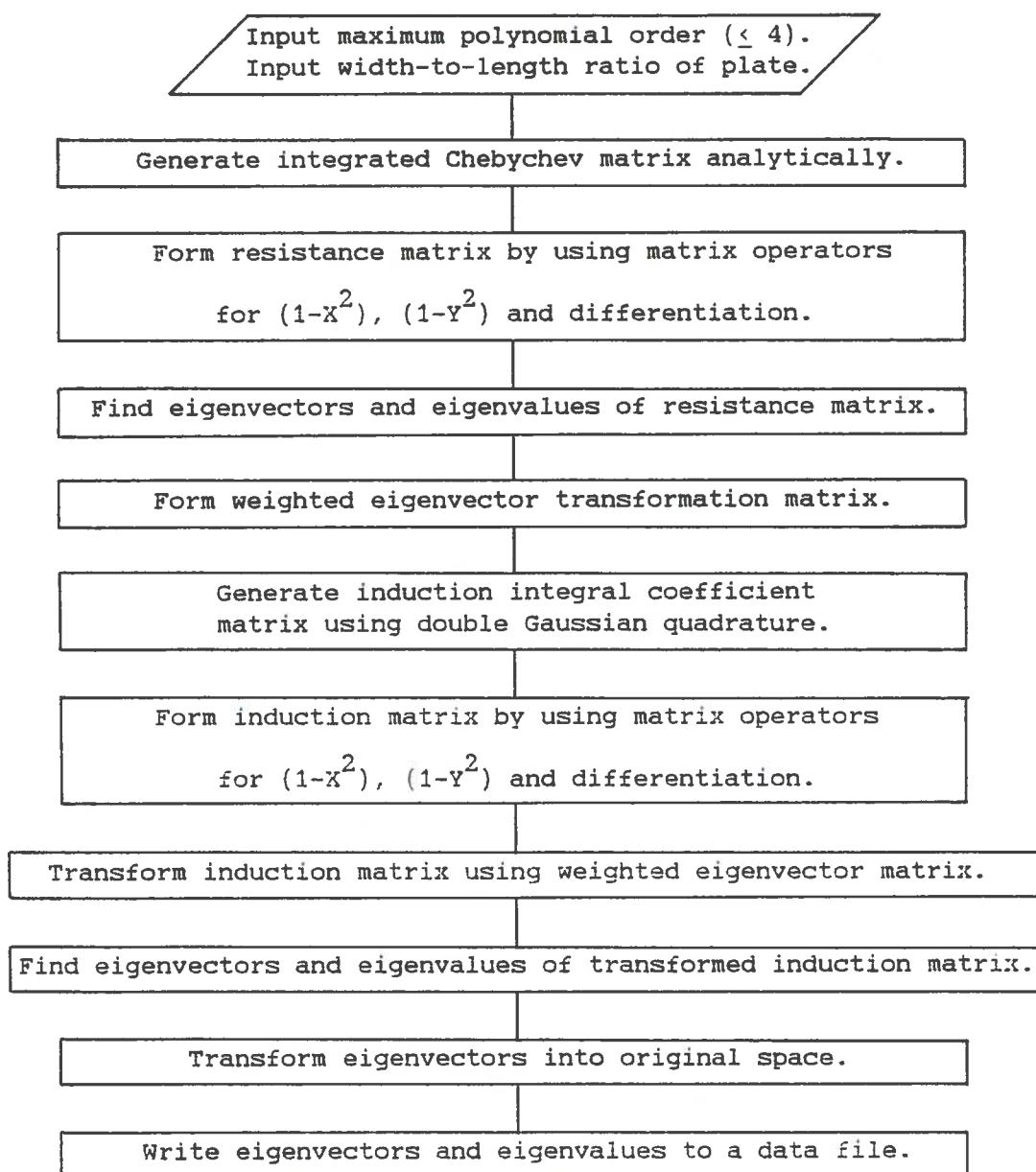


Figure 4.3 Flow chart of program EIGCUR.

Users of the original PLATE program have invariably used a maximum polynomial order of 4 (15 eigencurrents) to approximate the eddy current distribution in the plate. This value has been found to strike a good balance between numerical accuracy and programming speed (Dyck, 1981). Thus, it was possible to decrease the size of program EIGCUR by reducing the array sizes to accommodate a maximum polynomial order no greater than 4. This, along with the removal of many I/O options and some repetitious code, has slightly reduced the capacity needs of the program. Significant reductions in the size of EIGCUR were not found to be possible, since nearly all of the computational programs, written by A.P. Annan, were found to be very compact and efficient. Fortunately, the basic modern microcomputer has a minimum memory size of 256 Kilobytes, and this will easily accommodate program EIGCUR (see Appendix D).

In contrast to the ease with which program EIGCUR was moved to a microcomputer, program PLATEF had to be almost totally rewritten in order to reduce its size and time requirements to acceptable levels. Surprisingly, there were many large data arrays and sections of code which were found to be completely unused, or only partially used. A thorough editing of some 30 subroutines, and elimination of more than 30 others, was required to remove all such cases. As with program EIGCUR, array sizes were reduced to accommodate a maximum polynomial order no greater than 4. While this editing procedure provided a suitable reduction in program size, the efficiency of PLATEF was still totally unacceptable for a microcomputer.

#### 4.2.3 Restructuring Program PLATEF

The beauty of Annan's modelling technique lies in the fact that the model response can be divided into four independent terms: the eigenfunctions, the electrical coefficients, the excitation coefficients, and the secondary field coefficients. Each of these terms is affected by only a few model parameters, as listed in Table 4.2. The benefit of this method to computing efficiency is obvious - when a model is changed, only the affected term needs to be recalculated, while the

Term	Parameter changes which necessitate term recalculation	Storage Location
Eigenfunctions	maximum polynomial order plate width-to-length ratio	eigenfunction file computer memory coefficient file
Electrical coefficients	system parameters conductivity - thickness of plate strike length of plate width of plate eigenvalues	computer memory coefficient file
Excitation coefficients	transmitter geometry plate geometry eigenvectors	computer memory coefficient file
Secondary field coefficients	receiver geometry plate geometry eigenvectors	coefficient file

Table 4.2 Storage locations and conditions for recalculation of principal terms in PLATEF

remainder can be reused. Unfortunately, this philosophy was not rigorously followed in the PLATE program, and large amounts of computer time are wasted on unnecessary recalculation.

It was envisioned by the author that a typical user would often have a number of lines of field data from a single loop position, and would be trying to match these with synthetic data. Using the PLATE program under these circumstances, however, would result in the needless recalculation of the excitation and electrical coefficients for each model profile. In fact, it was found that the electrical coefficients would also be recalculated for each receiver station and for each of three field components. In other words, for a fixed loop survey consisting of 10 lines of data of 50 stations each, the excitation coefficients would be recalculated 10 times and the electrical coefficients 1500 times, while they should each be calculated only once.

Thus, program PLATEF was extensively restructured so that only the necessary calculations are performed when a model parameter is changed. This necessitated the storage of the eigenfunctions and the three coefficients for successive model variations. The eigenfunctions, electrical coefficients, and excitation coefficients could easily be stored in computer memory. The secondary field coefficients, however, would require an extremely large array, and the size of this array would limit the number of stations one could use along a profile. The PLATE program, for example, only allows for 51 stations per profile. This problem was overcome by creating a binary data file which saves all four terms, along with all the geometrical model information on disk. It is possible to read such a file for consecutive runs, or at the start of future runs of the program, so that not all the geometrical information has to be input again, and certain coefficients do not have to be recalculated. This also allows for an unlimited number of receiver stations along a profile.

By restructuring program PLATEF in this manner, the calculation of each coefficient becomes completely self-contained and independent from the other two. This is consistent with the philosophy behind Annan's

technique, in which the response is decoupled in order to take advantage of similarities between models.

#### 4.2.4 Coefficient Calculations

The most time-consuming calculations within PLATEF are the creation of the excitation coefficients, and the secondary field coefficients. The restructuring, described in the previous section, has removed any unnecessary recalculation of these coefficients. A much greater improvement in program efficiency, however, was achieved through changes in their computational method.

The calculation of the excitation and secondary field coefficients involves the use of numerical integration over the surface of the plate. The PLATE program divides this surface into a number of smaller, rectangular cells, in order to improve the accuracy of the Gauss-Legendre quadrature. Since this division varies depending on the location of the receiver, the number and location of the sample points on the surface are variable. Thus, grid digitization, and linear interpolation of the functions being integrated are used in these calculations.

After a careful analysis of the PLATE program, it was discovered that the aforementioned division process is only performed in the calculation of the secondary field coefficients, and then only when the receiver is very close to the plate. Hence, under most circumstances, the plate surface is treated as one cell, and a 20 point quadrature is applied in both directions. As a result, it is possible to digitize the functions directly at the 400 sample points, and the linear interpolations can be eliminated. This process is utilized in PLATEF, and has resulted in the elimination of a considerable amount of work. In addition, it was found that the trial functions in PLATE are digitized for every new transmitter loop and every receiver location. Since the value of these polynomials depends only on the specified polynomial order, this calculation has been moved to a point in the program immediately after this specification.

The electrical coefficient calculation performed by PLATEF has also undergone major changes in moving from PLATE. In fact, an electrical coefficient as such did not exist within PLATE, so that array handling, storage, and retrieval had to be built into the calculations. The coefficient calculations were also rewritten to follow the mathematical derivation more closely, and to account for additional system parameters (see Appendix E). This should facilitate the addition of new system waveforms to the program at a future date.

#### 4.2.5 Efficiency of PLATEF

The effect of all these changes on the efficiency of PLATEF is dramatic. The creation of a stored electrical coefficient has meant that these calculations are performed once for each model, and not for each component at each station. With all three coefficients being calculated only when necessary, and saved for future use in a binary data file, the responses from models with geometrical similarities can be quickly determined.

One of the most important improvements in program efficiency involves the number of function evaluations in calculating the excitation and secondary field coefficients. Using an earlier example in which ten profiles of 50 stations each were modelled for one loop location, the original PLATE program would have made 8,613,000 function evaluations and 8,640,000 linear interpolations within the integration routines. If the receiver is at least one-half the plate strike length away from the plate, PLATEF will only make 400,520 or 5% of the original direct evaluations and no linear interpolations at all (see Tables 4.3 and 4.4; and Appendix E).

Thus, the improvements in program efficiency have resulted from the elimination of unnecessary calculation, and not from mathematical simplification. This means that program PLATEF maintains the same accuracy as PLATE, while increasing the computational speed. In fact, the accuracy may be slightly better in PLATEF since linear interpolations are not extensively used.

Description	Repetition Factor
<b>Excitation Coefficients</b>	
Determine perpendicular component of primary field at 900 grid points on plate	900
Repeat for each transmitter loop	T
Repeat for each profile change	P
Digitize 4 degrees of Chebychev polynomials at 100 points	400
Repeat for each transmitter loop	T
Repeat for each profile change	P
Use double interpolation to find value of trial function at 400 sample points	800
Repeat for each of 15 trial functions	15
Repeat for each transmitter loop	T
Repeat for each profile change	P
Use double interpolation to find value of primary field at 400 sample points	800
Repeat for each of 15 trial functions	15
Repeat for each transmitter loop	T
Repeat for each profile change	P
<b>Secondary Field Coefficients</b>	
Digitize 4 degrees of Chebychev polynomials at 100 points	400
Repeat for each receiver location	R
Evaluate $1/R^3$ and $1/R^5$ at 400 sample points on plate	800
Repeat for each of 21 trial functions	21
Repeat for each receiver location	R
Use double interpolation to find value of trial function at 400 sample points	800
Repeat for each of 21 trial functions	21
Repeat for each receiver location	R
<b>Total</b>	
1300 T P + 17200 R evaluations	
24000 T P + 16800 R interpolations	

Table 4.3 Coefficient calculations in PLATE

Description	Repetition Factor
Preparatory Calculations  Digitize 6 degrees of Chebychev polynomials at 20 Gauss - Legendre sample points	120
Excitation Coefficients  Determine perpendicular component of primary field at 400 sample points on plate Repeat for each transmitter loop	400 T
Secondary Field Coefficients  Evaluate $1/R^3$ and $1/R^5$ at 400 sample points on plate Repeat for each receiver location	800 R
Total  120 + 400 T + 800 R evaluations	

Table 4.4 Main coefficient calculations in PLATEF

### 4.3 Flexibility

The flexibility of a modelling program is measured by the number of variable model parameters, and the number of ways that the end result can be presented. Within program PLATE, the number of variable geometrical parameters is considerable. Using the three coordinate systems, described in Chapter 3, the transmitter, the plate, and the profile line can be completely arbitrary. This flexibility has been maintained in PLATEF, and has been further enhanced, since any number of stations may be modelled along the profile lines.

Of the geometrical parameters used in the fixed-loop option of PLATE, the only one not retained in PLATEF is the profile starting point. Unlike program PLATE, PLATEF treats every profile in the same way, whether it is a borehole or surface line, in order to standardize the profile specification and the output component system. Thus, a profile reference point and the starting distance is required for every profile, and the orthogonal output vector components are always inline, horizontal, and upward trending (see Appendix D). The polarity of each of these components is controlled by three additional model parameters (see Table 4.5).

While some flexibility has been lost because only fixed-loop TDEM systems can be modelled, the total number of system options has remained almost the same (see Table 4.6). In fact, the greatest increase in flexibility of program PLATEF has resulted from concentrating on the particular systems which the program can model. By requiring the input of additional system parameters, the output can be expressed in the same units and component polarity as used by the various systems. This can be very useful, as it allows the synthetic model data to be directly compared to field data.

Several of the output parameters have not been retained in PLATEF (see Table 4.6). It was felt that these options did not add to the flexibility of the program, but instead, added to the complexity. The PPK and PPM options are just multiples of the "Percent of primary field"



	<u>Plate Geometry</u>	
	width-to-length ratio plate reference point (u,v) coordinates (x,y,z) coordinates strike length strike dip plunge conductivity-thickness	
starting point (x,y,z)	<u>Profile Geometry</u>  length interval theta phi	reference point (x,y,z) distance to start
uniform field & dipole field parameters	<u>Source Geometry</u>  coordinates of each loop corner (x,y,z)	
		<u>Component Polarity</u>  direction of primary field in center of loop left- or right-hand component system X component points to start or end of profile

Table 4.5 Geometrical model parameters in fixed-source PLATE and PLATEF.



	<u>System</u>	
frequency domain impulse response step response half-sine shut-off early Crone PEM INPUT	UTEM	repetitive pulse TDEM systems (Crone digital PEM, Crone analog PEM, Geonics EM37, SIROTEM)
	<u>System Parameters</u>	
	cycle time ramp time turn-on time constant	transmitter current effective receiver loop area external Rx gain
	<u>Output Normalization</u>	
PPK PPM	percent of primary none	
	<u>Output Units</u>	
amp/m % P <sub>total</sub> at plate ref  % P <sub>Z</sub> at surface ref % P <sub>X</sub> % P <sub>Y</sub> % P <sub>Z</sub> % P <sub>axial</sub>	% P <sub>total</sub> at receiver	nanotesla/sec <sup>2</sup> nanovolt/meter <sup>2</sup> Crone units - surface Crone units - borehole microvolt/amp % P <sub>total</sub> at a point - (x,y,z) coordinates
	<u>Channel Input</u>	
S.I. (Hertz) σ <sub>t<sub>μ</sub>L</sub> σ <sub>t<sub>μ</sub>W</sub> σ <sub>t<sub>μ</sub>S</sub>	S.I. (seconds) from file or keyboard	S.I. (seconds) - built in defaults for each system

NOTE: P represents primary magnetic field.

Table 4.6 System, output, and channel parameters for PLATE and PLATEF.

option, and can best be handled by plot scaling. The unretained options for normalized output units are rarely used with the TDEM systems because these systems are designed to ignore the primary field. Two primary field normalization schemes are used in PLATEF, however, and it should be noted that these are based on the magnitude of the primary field, and not on a single component. This removes the extreme geometrical bias that can occur when normalizing to a component which passes through zero amplitude. PLATEF writes sufficient information to the output file, so that primary field normalizations could also be done in a plotting program with little effort.

Finally, the time or frequency parameter input has also been simplified. While the channel times can still be input from an ASCII file or through the keyboard, there are built-in defaults for these values in PLATEF. These defaults represent the most often used channel times for the particular system being modelled.

#### 4.4 User-Friendliness

Probably the most time-consuming job for a programmer is to make a program user-friendly. Unfortunately, attention to this detail was not found in the original PLATE program. As a result, much work was needed in this area, and was subsequently incorporated into PLATEF.

The prompting for input was improved in PLATEF so that nearly all prompts now have default values, and those that do not, present the user with a choice of replies. In this way, the user always knows what is required of him, and he can step through the program with a "carriage-return" response. Another very convenient feature has been added, which allows the user to step backwards through the program by answering a prompt with a "control-Z". PLATEF also tests all input data to ensure that it is the proper data type, and that it falls within acceptable limits. The prompt is repeated, if the test fails.

Filenaming has also been simplified so that a user-defined default drive can automatically be affixed to all filenames. This allows all

files to be sent to a particular floppy drive, or to a particular subdirectory on a hard disk. Files which are supposed to be in existence are sought right away, and an error message appears if they are not found. Similarly, new filenames are tested, and if a file with that name exists, another prompt asks for approval for overwriting.

Another feature incorporated into PLATEF is that of error control. All possible errors in the program execution and file handling are detected and announced. Hence, when a mistake is found, the user is returned to a convenient point in the program.

In the PLATE program, model parameters are solicited when needed for calculation. Thus, it is not a simple matter to change a given parameter in the model, and the user has very little feel for the geometrical relationships among the transmitter, the plate, and the receiver. In complex cases, one almost requires a physical scale model beside him while using PLATE. In PLATEF, the model parameters are treated as vital information in their own right, and their input is separated from the rest of the program. In addition, new programs have been written which attempt to give the user a better idea of the geometrical relationships involved, and internal looping through menu selection allows for quick model changes.

Table 4.7 lists the new calculations, which are performed by PLATEF, in order to improve the user's understanding of the model (see Appendix D). The usefulness of this structure can be illustrated with three examples. If, in a field survey, a conductor is detected with one loop position, but is undetectable after the loop is moved, then the conductor must be positioned in the "blind zone" of the second loop. When modelling, the plate can be moved around until the flux is minimized based on the primary field vectors at the plate corners. This can be done quickly because no major calculations are performed. As a second example, suppose the geology of an area suggests that conductors will be found along a particular geological horizon. A drillhole finds minor sulphides in the core, and it is believed that they lie in the same geological horizon as a conductor detected by borehole EM. When

Coordinates of plate corners and center.

Primary magnetic field at plate corners and center.

Plate plane and profile line intersection point and angle.

- Distance from this point to nearest edge of plate.

Profile and plate points of closest approach.

- Closest approach distance.

Short and parallel profile characteristics.

Primary field values at each receiver location.

Table 4.7 New calculations for model description in PLATEF.

modelling, it would be possible to repeatedly move the conductor until the borehole intersects the plane of the plate at the location of the minor sulphides, and the point of closest approach to the plate corresponds with the maximum EM response. As a final example, suppose the axial component of the primary field in a borehole survey crosses over from negative to positive. This cross-over point critically defines the transmitter-receiver geometry, so that the model geometry can be adjusted until a match is achieved.

By gathering all the model information before any major calculations are performed, the user can now clearly see the model geometry and system parameters, and quickly change them. Such adjustments can continue indefinitely until the user is satisfied with the model. Once satisfied, the user can do one of two things: he can proceed with the number crunching part of the program; or, he can save all the model parameters in a temporary binary data file called a "batch file". This file is later read by program BATCHF, which then completes the calculations with no user intervention. This batch procedure is much simpler and less error-prone, than that in PLATE, where only one model can be run from a lengthy user-prepared ASCII file.

As the model response is being calculated by program PLATEF, the synthetic data can be listed on the monitor for inspection. These data are simultaneously written to a standardized ASCII output file containing 43 lines of model information, followed by the synthetic data listed station by station. This format provides compactness while still allowing the file to be read by the user. In PLATE, the model parameters are repeated in a new output header for each component and each time or frequency parameter.

#### 4.5 Documentation

The final obvious problem with the PLATE program is the limited internal and external documentation. Although this may not seem necessary once a program is running, it is essential to future programmers and should not be neglected. Several steps were taken to

overcome this problem. The mathematical basis of each part of the program was worked out, and placed in a Programmer's Manual. This manual also contains program details, such as subroutine maps, common block maps, and guidelines for changing the programs (see Appendix E). The FORTRAN code for each routine was documented with a description of each variable and an indication of its source (local, upstream, or downstream). Finally, a comprehensive User's Manual was written which contains step-by-step instructions for the use of the program, along with a description of the program's accuracy and limitations (see Appendix D).

#### 4.6 Summary

The new programs which have been described above cannot entirely replace the original PLATE program, because they only model EM systems with fixed-loop transmitters. Thus, some generality has been lost, and any study involving comparisons among all EM systems would best be done with the original program. However, the goal of producing a program which maintains the same accuracy as PLATE, but which is much smaller and cheaper to run, has been achieved along with the other goals listed in Table 4.1.

In any numerical modelling technique, it is extremely important to recognize similarities between models so that information can be reused and computation time can be saved. Annan (1974) developed the mathematical basis for the PLATE program to allow much of the response calculation to depend only on the width-to-length ratio of the plate. More importantly, the response is decoupled into two geometrical coefficients and one electrical coefficient. The new programs allow the user to take maximum advantage of model similarities arising from any of these four reductions.

A flow chart of program PLATEF is provided in Figure 4.4. It clearly shows the ubiquitous use of flags for parameter input, and for coefficient calculation, saving, and reuse. The importance placed on parameter input, and modification, can be seen by comparing this flow

chart with the one for PLATE in Figure 3.2. In addition to these obvious differences, the user of PLATEF is provided with a clear, concise summary of the model geometry, and overall, the program is much more user-friendly than PLATE. By keeping the needs of field geophysicists in mind while writing the programs, an efficient modelling package has been produced, which will be useful before, during, and after the implementation of fixed-loop EM surveys.

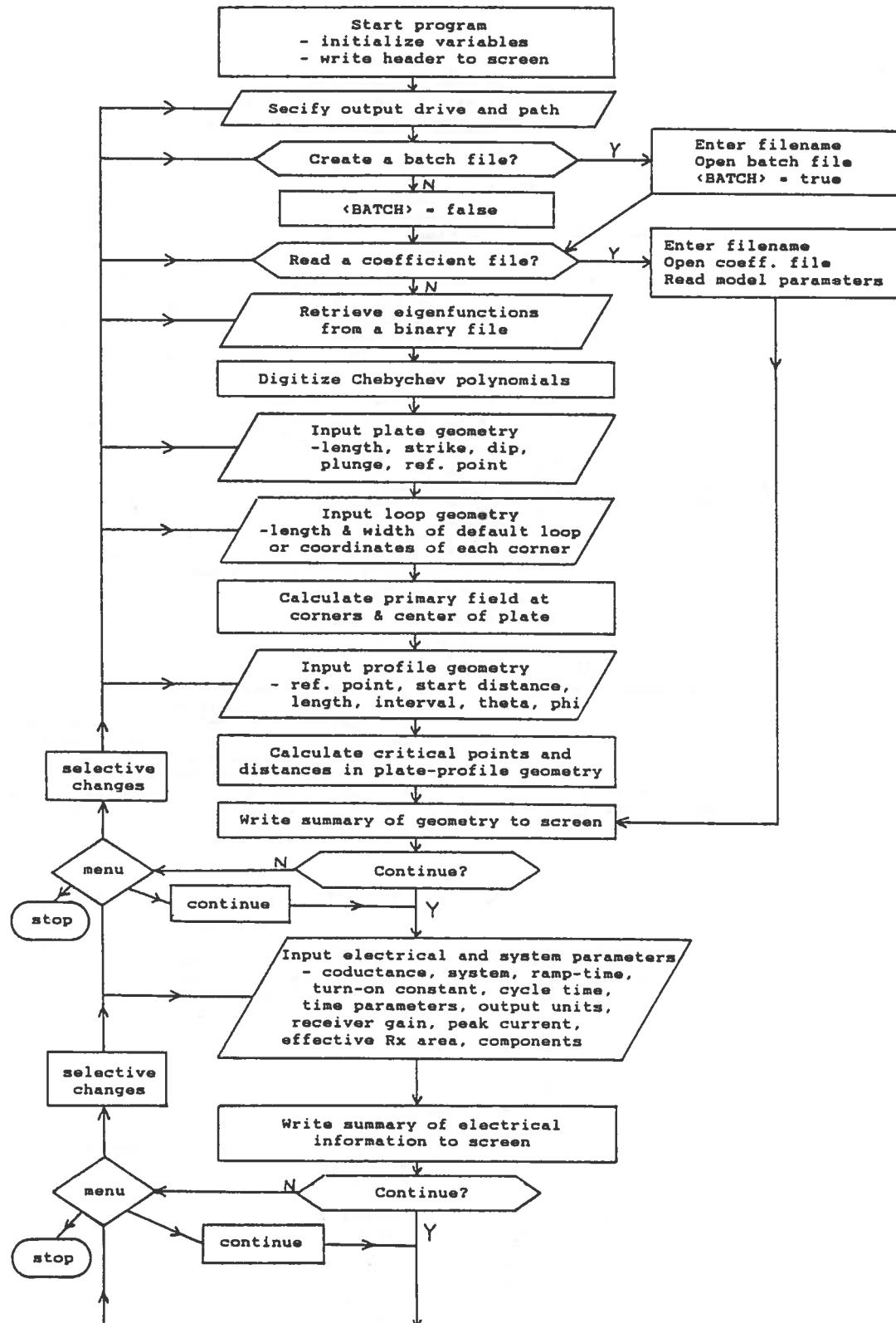


Figure 4.4 Flow chart of program PLATEF.

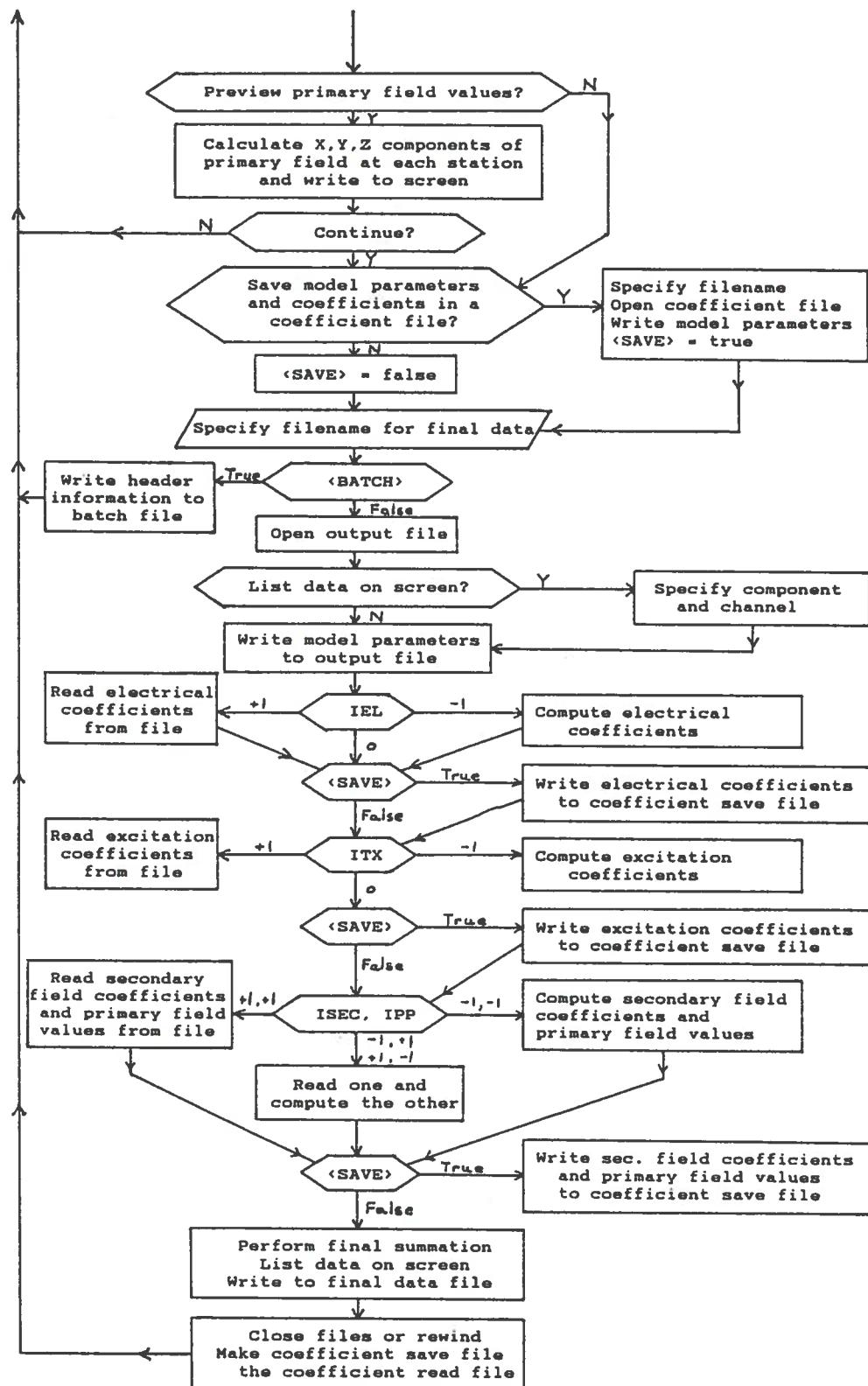


Figure 4.4 Continued.

## CHAPTER 5

### IMPLEMENTATION OF THE NEW MODELLING PROGRAMS

#### 5.1 Hardware Dependency

Programs PLATEF, BATCHF, and EIGCUR are written in Fortran 77 code, and do not perform any hardware-dependent functions, such as screen graphics. This structure was chosen, so that these programs would be as universally compatible as possible, with various computer hardware configurations. In order to produce a marketable package of executable code, however, certain hardware decisions must be made. This section describes how these decisions have been made, in an attempt to satisfy the majority of the projected audience.

The most popular computer hardware, used by mining explorationists today, consists of an IBM-PC (or compatible) microcomputer coupled with a dot-matrix printer. A typical computer of this kind would be equipped with an 8088 (or 8086) microprocessor, with 256 Kilobytes of memory, and two 5-1/4 inch floppy diskette drives. Program features which were developed as a result of this choice of hardware include: the establishment of a default drive for file handling; and, error trapping for writing to a full floppy diskette. These two features, however, should not cause problems for other hardware installations.

The compilation of the code was attempted with two different FORTRAN compilers: Microsoft FORTRAN v. 3.2, and IBM Professional FORTRAN v. 1.00. While the Microsoft compiler will allow the program to be used on machines without an 8087 math coprocessor chip, this is not the case with the IBM compiler. This "math chip" can be considered to be a hardware requirement for this modelling package because, without it, the programs take approximately 10 times longer to execute. By testing both compilers on a computer with an 8087 chip, it was found that the IBM compiler produced code which executed two to three times faster. Also, the Microsoft compiler requires FORTRAN code which is not

a full FORTRAN 77 standard. Thus, it was decided to use the IBM compiler, even though it introduces another hardware dependency.

Plotting packages for dot-matrix printers tend to be extremely hardware dependent due to the lack of standardization among printers. Although device-independent plotting software does exist, such programs tend to be quite slow on a microcomputer due to the large software overhead.

Personnel at Crone Geophysics Limited have recently developed plotting software for their PEM field data, which is fast, and allows for custom installation on virtually any dot-matrix printer. This software was converted by Crone personnel, with assistance from this author, into a plotting program for the output from PLATEF. This program can produce high-quality plots in various formats and scales for all the systems modelled by PLATEF (see Figure 5.1). As well, a printed summary of the model parameters is provided (see Figure 5.2). The plotting program is written in C and assembly language, and utilizes IBM-PC BIOS routines, screen menus, and the keyboard function keys. Thus, use of the entire modelling package is limited to the availability of an IBM-PC or compatible computer. Nevertheless, these hardware dependencies should not limit the general use of these programs in any mining exploration camp or head office.

## 5.2 Program Accuracy

It has been determined by Dyck et al (1981) that the University of Toronto PLATE program produces theoretical data which are identical to physical scale model data, when the limitations of the program are not exceeded (see Appendix D). Since the new programs developed by this author are based on a reorganization of the same numerical algorithms, similar accuracy can be expected for them. In fact, at least three- to four-figure accuracy has been maintained, in moving the programs from a DecSystem 10 mainframe computer to a microcomputer with an 8087 math coprocessor chip. As a typical example, the first 15 eigenvalues produced by program EIGCUR for a plate of length half its width were

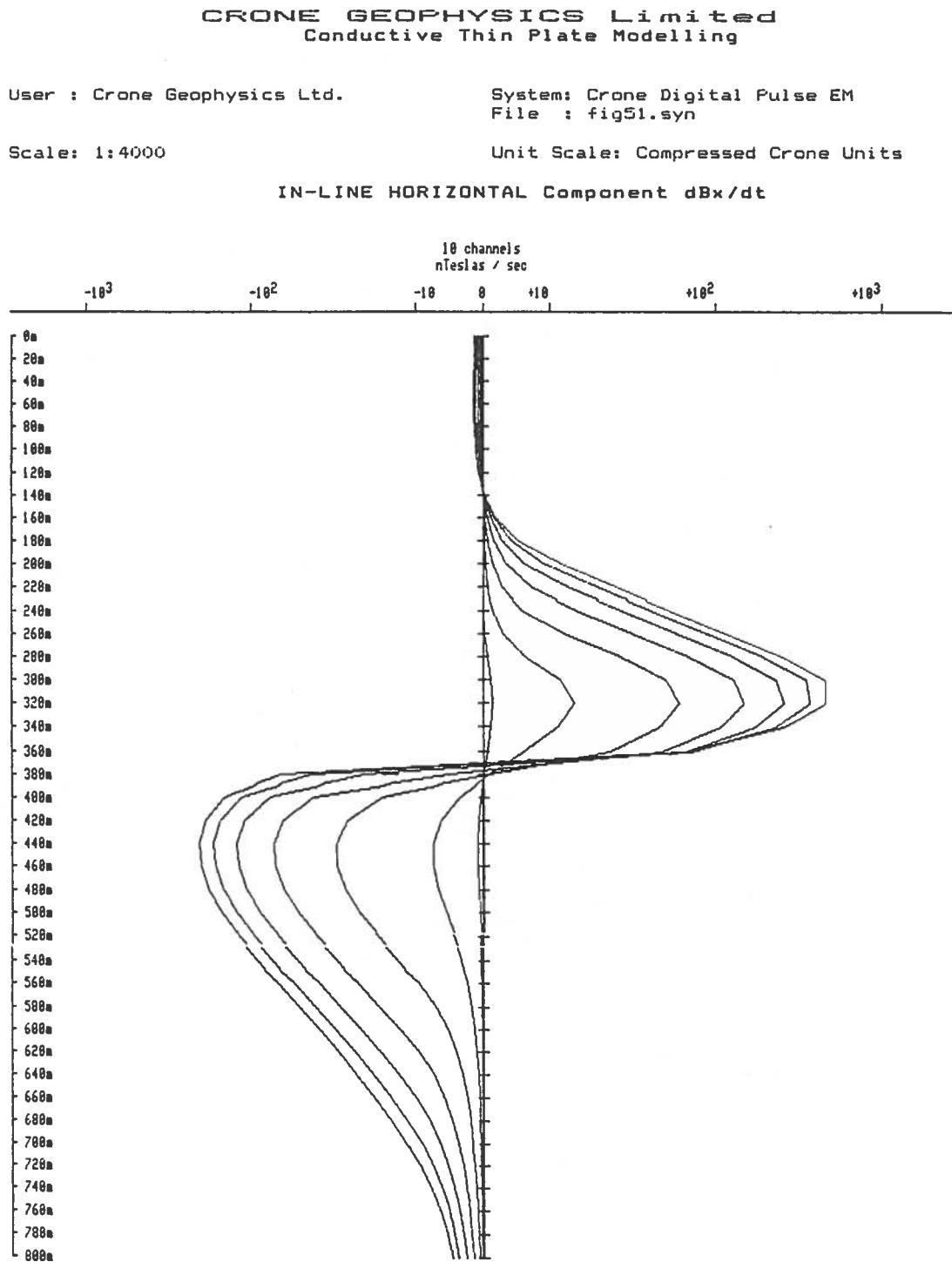


Figure 5.1 Sample plot from program PLATECRV.

### Conductive Thin Plate Modelling

User : Crane Geophysics Ltd.

System: Crane Digital Pulse EM  
File : fig51.syn

Computed by: PLATEF 1.00 and EIGCUR 1.00  
Eigenfunction file: R1P0.P4

#### Plate Parameters:

Strike Length: 200.0 m  
Width: 200.0 m  
Strike: 90.0 degrees  
Dip: 70.0 degrees  
Plunge: 0.0 degrees  
Conductance: 10.0 mhos

#### Plate coordinates:

Corner 1 ( 30.0 100.0 -300.0 )  
Corner 2 ( 30.0 -100.0 -300.0 )  
Corner 3 ( 98.4 -100.0 -487.9 )  
Corner 4 ( 98.4 100.0 -487.9 )  
Center ( 64.2 0.0 -394.0 )

plate reference point: ( 0.000 1.000 ) and ( 30.0 0.0 -300.0 )

#### Plate - Loop Coupling:

	H field on plate: (A / m x 10e-6)	Magnitude: (A / m x 10e-6)	Intersection Angle: (degrees)
Corner 1 (	47.0 -345.0 201.0 )	402.0	30.0
Corner 2 (	-47.0 -345.0 201.0 )	402.0	30.0
Corner 3 (	-22.5 -145.0 68.6 )	162.0	25.1
Corner 4 (	22.5 -145.0 68.6 )	162.0	25.1
Center (	0.0 -223.0 116.0 )	252.0	27.6

#### Profile Parameters:

Start: ( 0.0 0.0 0.0 )  
End: ( 0.0 0.0 -800.0 )  
Declination from Vertical: 180.0 degrees  
Azimuth from X-axis: 0.0 degrees  
Reference Point: ( 0.0 0.0 0.0 )  
Distance to Start from Reference: 0.0 m

#### Coordinate System:

Primary field direction in  
center of loop: UP  
LEFT-hand co-ordinate system  
for X,Y, and Z components  
Positive X field component points  
to the START of profile

#### Plate-Profile Relationship:

Profile intersects plate plane at station 217.6 and plate point  
( 0.0 187.7 0.0 ) at an angle of 20.0 degrees  
This point is 87.7 meters from the plate  
Closest approach is 30.0 meters at station 300.0 and plate point  
( 0.0 100.0 0.0 )

#### System Parameters:

Crane Digital Pulse EM  
Pulse Repetition Frequency: 23.15 Hz  
Time base: 10.80 msec  
Ramp time: 1500 usec

#### Channel configurations:

Ch. 1	50 usec to	81 usec
Ch. 2	81 usec to	140 usec
Ch. 3	140 usec to	234 usec
Ch. 4	234 usec to	392 usec
Ch. 5	392 usec to	662 usec
Ch. 6	662 usec to	1110 usec
Ch. 7	1110 usec to	1860 usec
Ch. 8	1860 usec to	3130 usec
Ch. 9	3130 usec to	5250 usec
Ch. 10	5250 usec to	8800 usec

Figure 5.2 Sample of model description provided by PLATECRV.  
(See Appendix D for an explanation of terms)

calculated on a DecSystem 10 to be:

1.1641260E-01	9.8528363E-02	7.7648886E-02	6.6548437E-02
6.2074054E-02	5.6349576E-02	5.1742699E-02	4.4778813E-02
4.3632340E-02	4.2841926E-02	3.7402462E-02	3.6254425E-02
2.7656432E-02	2.7340496E-02	2.0869317E-02.	

The same calculation on an IBM-PC with an 8087 chip produced the following eigenvalues:

1.1641263E-01	9.8528355E-02	7.7648900E-02	6.6548422E-02
6.2074028E-02	5.6349508E-02	5.1742904E-02	4.4778779E-02
4.3632284E-02	4.2841911E-02	3.7402447E-02	3.6254596E-02
2.7656445E-02	2.7340515E-02	2.0869320E-02.	

The only system waveform which is modelled in both PLATE and PLATEF is the UTEM waveform. Figure 5.3 consists of synthetic UTEM data created by program PLATEF for the model shown, and for standard UTEM channel specifications. The plotted data are identical, within measurement accuracy, to that produced by program PLATE (see Lodha and West, 1976).

A study based on the Geonics EM37 system was conducted by Gallagher (1984). She produced model curves for the Geonics EM37 system by using a modified mainframe version of PLATE. Figure 5.4 shows plotted synthetic EM37 data, from PLATEF, which are identical, within measurement accuracy, to the corresponding data produced by Gallagher. These two examples provide a direct comparison between PLATE and PLATEF, in that they utilize the only system waveforms and output units common to both programs.

A final test for the accuracy of program PLATEF is based on a physical model study, of the Crone Pulse EM system, conducted by Woods (1975). Unfortunately, a number of potential problems occur in comparing numerical model results with physical models. The numerical model assumes that the plate is infinitely thin, and that the measurement is made at a point. Physical models, of course, cannot and

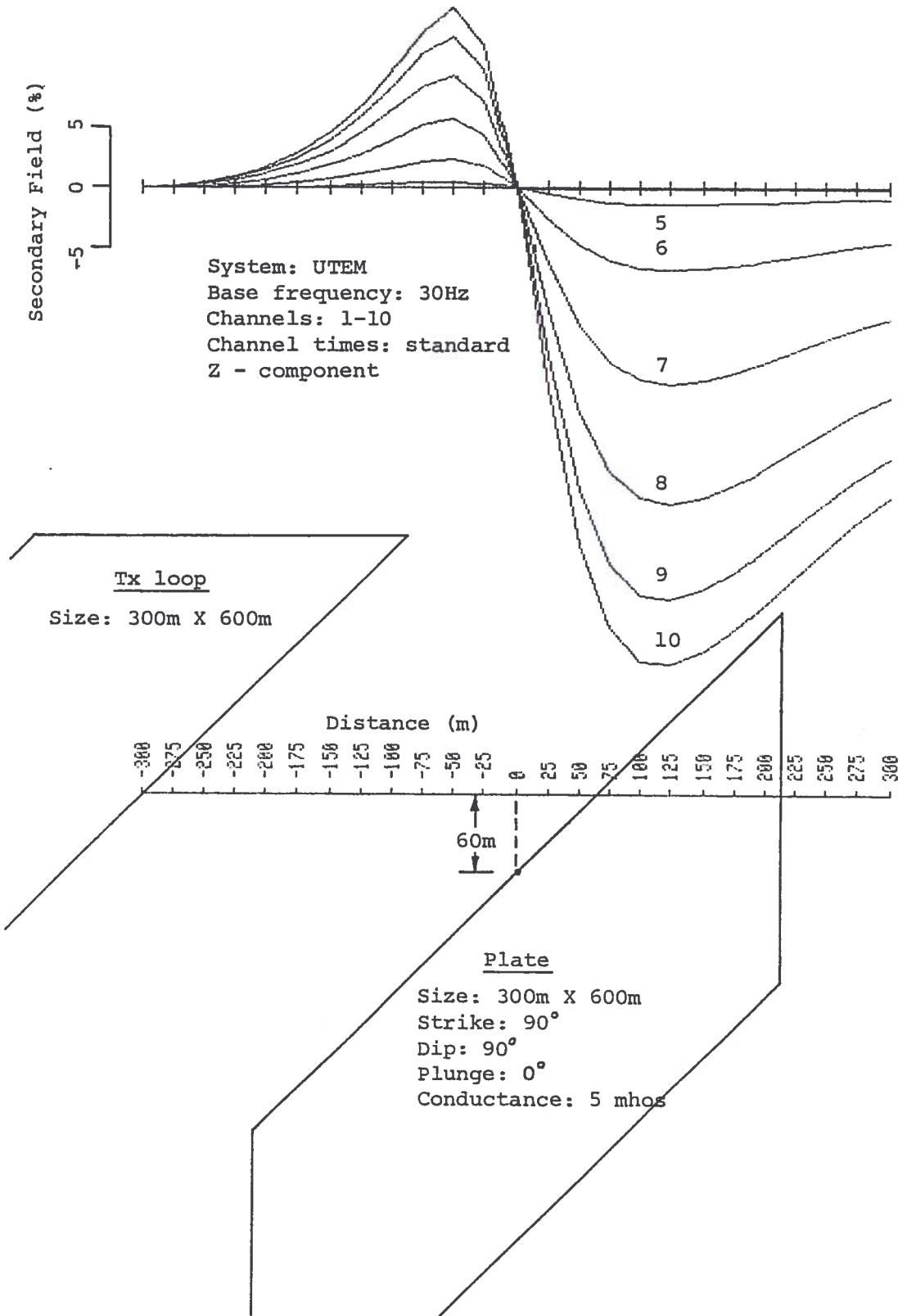


Figure 5.3 Synthetic UTEM data from PLATEF which are identical to those produced by Lodha and West (1976).

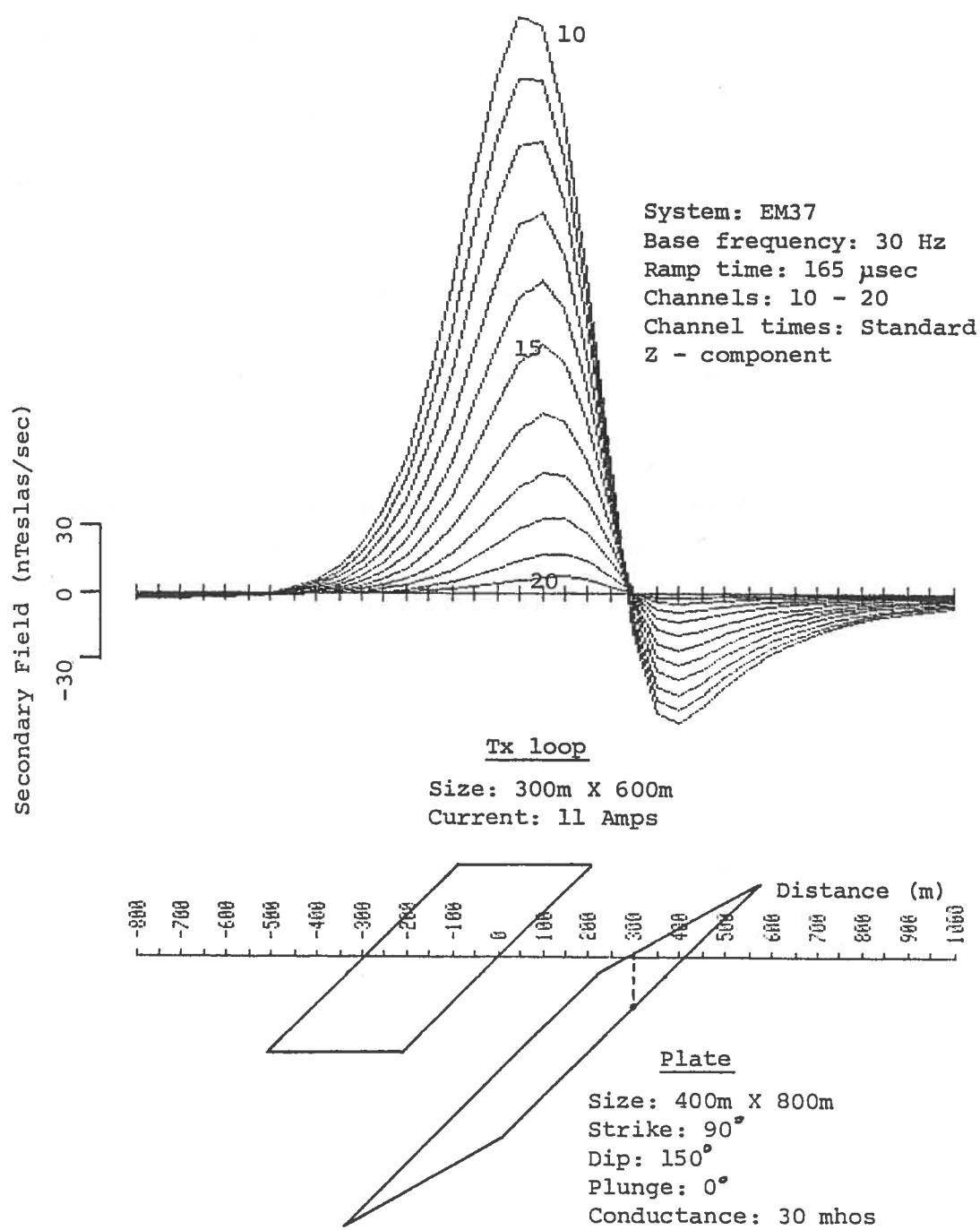


Figure 5.4 Synthetic EM37 data from PLATEF which are identical to those produced by Gallagher (1984).

should not, duplicate these assumptions because they attempt to model real conductors and receivers. In his model study, Woods (1975) was unable to scale the receiver coil by the same factor as the rest of the model, and hence, a certain amount of error was introduced. A more serious problem was that receiver coils with different effective areas produced results which varied in shape, as well as magnitude. This was explained as being a result of background noise. Finally, very few of these experiments provide enough information to locate accurately the transmitter loop in the theoretical model, and those that do, were precisely the ones that used a receiver coil which was considered to be too sensitive.

A comparison of the synthetic data generated by PLATEF, with Woods' physical scale modelling, is shown in Figure 5.5. Considering the number of problems just mentioned, the comparison appears to be quite good, especially in magnitude.

### 5.3 Program Applications

#### 5.3.1 Survey Planning

The new modelling program that has been developed can aid extensively in all stages of a TDEM survey. Its use in survey planning, for example, is immediately evident. In many routine geophysical investigations, survey parameters are based on assumed characteristics of the target, and hence, survey structural errors can occur. With the availability of an EM modelling program in the field camp, however, these errors can be avoided. As more geological and geophysical data are collected, survey parameters can be altered to improve target definition. The following section describes how synthetic data from program PLATEF can be used in this way, to define a variety of parameters, such as loop size and position; line length and hole depth; line and station spacing; and instrument characteristics. Definitions for model parameters can be found in Appendix D.

The choice of loop size and position determines the degree of coupling between the loop and conductor. These parameters are critical

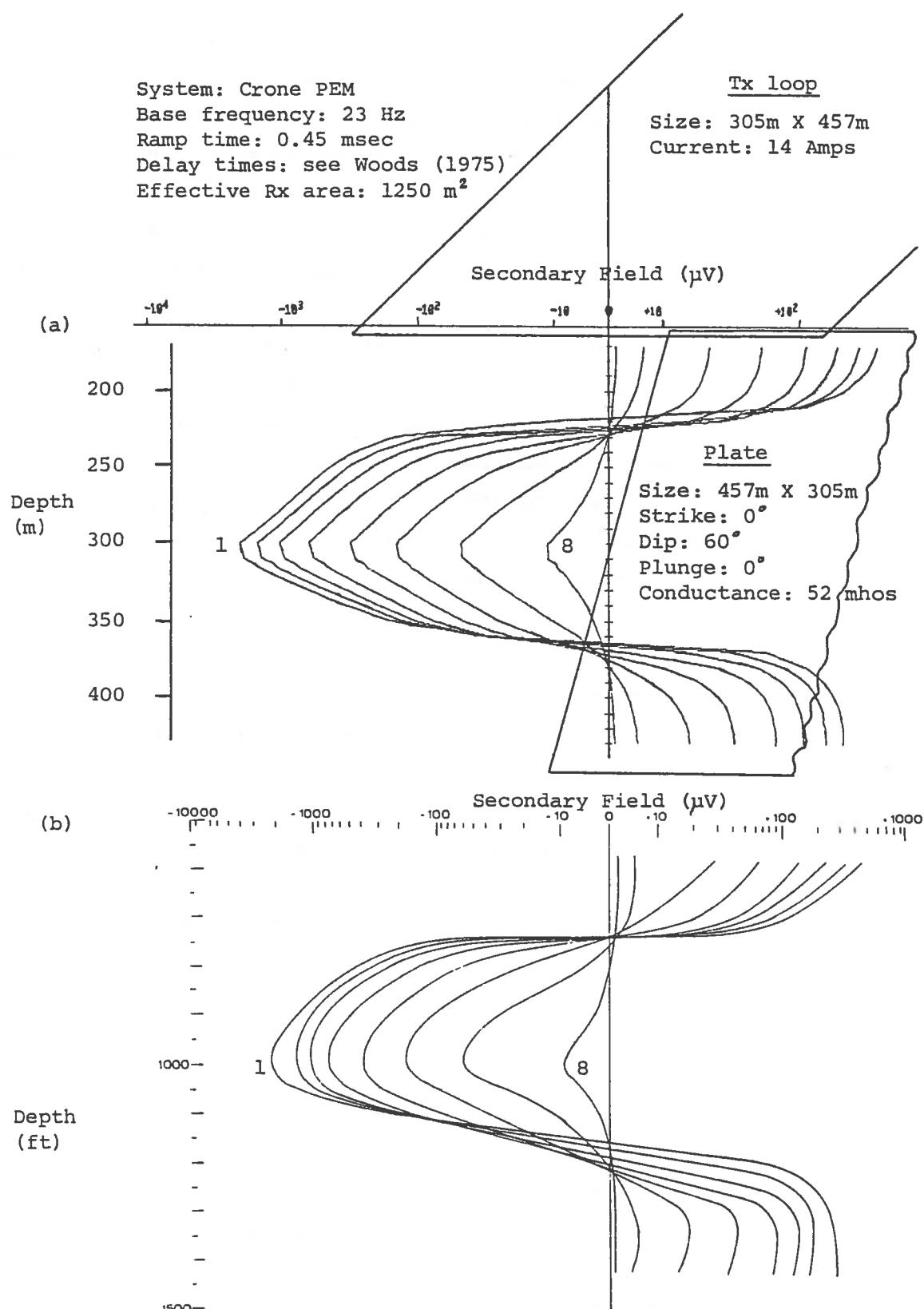


Figure 5.5 Comparison of (a) synthetic data from PLATEF with (b) physical model data from Woods (1975).

because an inappropriately placed loop could result in conductors going undetected due to poor coupling. Figure 5.6 shows the effect of loop position on the time-domain response. It can be seen that the response amplitudes pass through zero and reverse in sign, in accordance with null and reverse coupling with the primary field. Once a conductor has been detected, a null or reverse response from another transmitter loop can be very useful in determining the dip angle of the conductor.

Table 5.1 gives the coupling information provided by program PLATEF for the models just described. The u, v, and w components of the field, and the intersection angle at each plate corner and the plate center, allow the user to visualize how the field lines are intersecting the plate. The amplitude information provides a basis for comparison of the field strength from different loops. It can be seen that it is the w component of the field, which determines the direction and degree of coupling.

The transmitter loop size also has a direct effect on the degree of coupling, but this is a result of changes in field strength rather than intersection angle. Figure 5.7 shows the effect of loop size on the response from a vertical 200 m x 200 m conductor at a depth of 100 m. A continuous rise in the response amplitude is due to the greater field strength from larger loops. Thus, we can see that a large, well-placed transmitter loop may be required to detect small, deeply buried conductors.

It has been stated that conductors couple best with transmitter loops of approximately the same size (Lajoie, 1973). The previous example has shown that this is not true for systems which measure the secondary field in the absence of the primary field. In order to test the statement for systems which normalize to the primary field, the previous experiment was repeated for the UTEM system using continuous normalization (its usual form of presentation). Figure 5.3 shows that there is a decrease in peak-to-peak amplitude with increasing loop size when this form of data presentation is used. Although the largest percent anomaly is produced by the smallest loop, this assumes that both

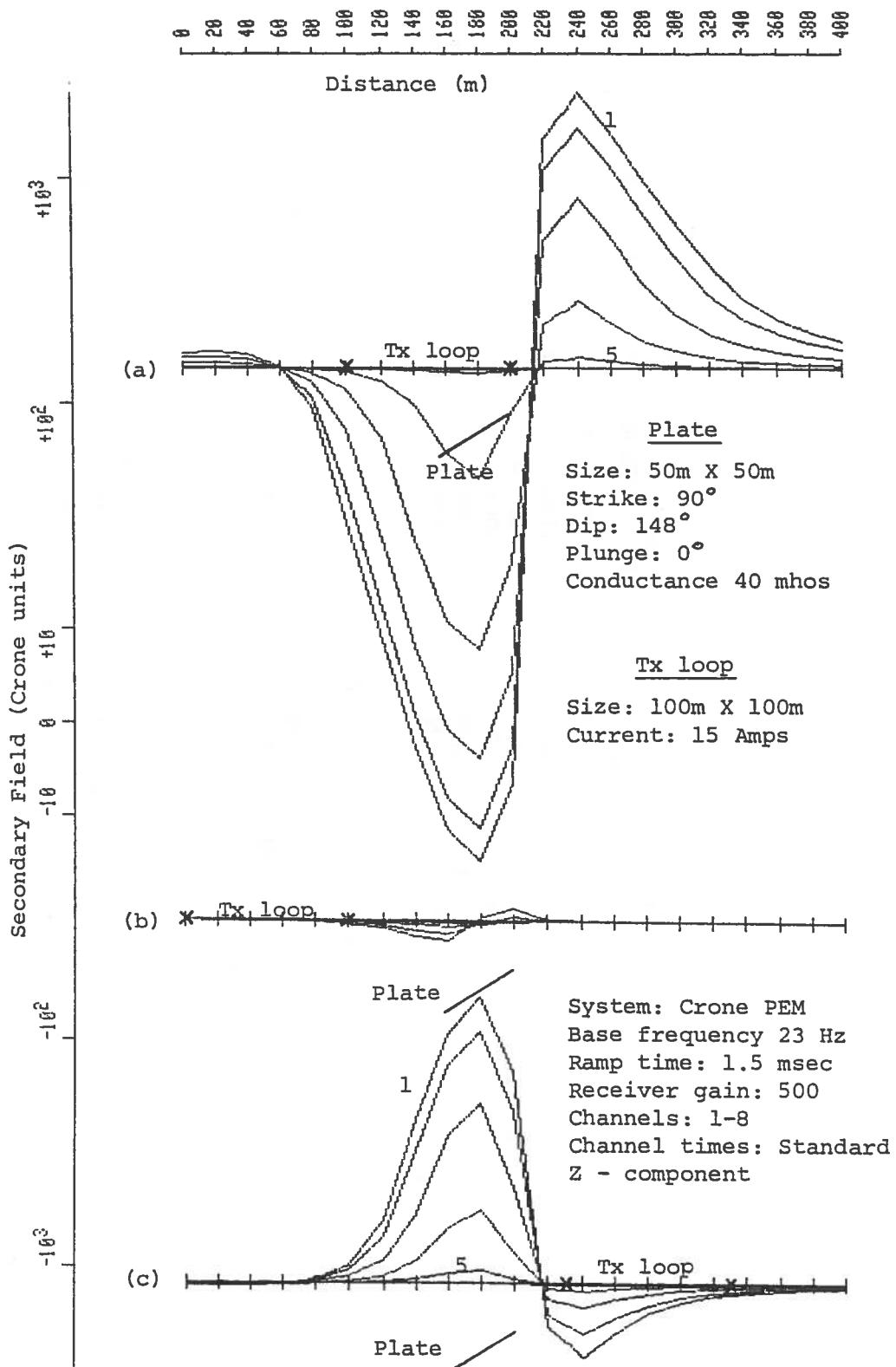


Figure 5.6 Effect of loop location on the Crone PEM response:  
 (a) coupling from above; (b) null coupling;  
 (c) reverse coupling.

Model (see Fig. 5.6)	Primary field (u,v,w) on the plate (A/m X 10E-6)	Primary field magnitude (A/m X 10E-6)	Intersection angle (degrees)
(a)	Center ( 0.0, -528.0, 4100.0) Corner 1 ( 1170.0, 2040.0, 4250.0) corner 2 (-1170.0, 2040.0, 4250.0) Corner 3 (-993.0,-1190.0, 2430.0) Corner 4 ( 993.0,-1190.0, 2430.0)	4130.0 4860.0 4860.0 2880.0 2880.0	82.7 61.0 61.0 57.5 57.5
(b)	Center ( 0.0, 423.0, 3.7) Corner 1 ( 23.6, 240.0, -98.9) corner 2 (-23.6, 240.0, -98.9) Corner 3 (-122.0, 540.0, 241.0) Corner 4 ( 122.0, 540.0, 241.0)	423.0 261.0 261.0 603.0 603.0	0.5 -22.3 -22.3 23.6 23.6
(c)	Center ( 0.0, -256.0, -440.0) Corner 1 ( 152.0, -377.0, -849.0) corner 2 (-152.0, -377.0, -849.0) Corner 3 (-41.7, -149.0, -236.0) Corner 4 ( 41.7, -149.0, -236.0)	509.0 941.0 941.0 282.0 282.0	-59.9 -64.4 -64.4 -56.7 -56.7

Note: Primary fields cutting down through the plate have negative intersection angles.

Table 5.1 Coupling information for models shown in Figure 5.6.

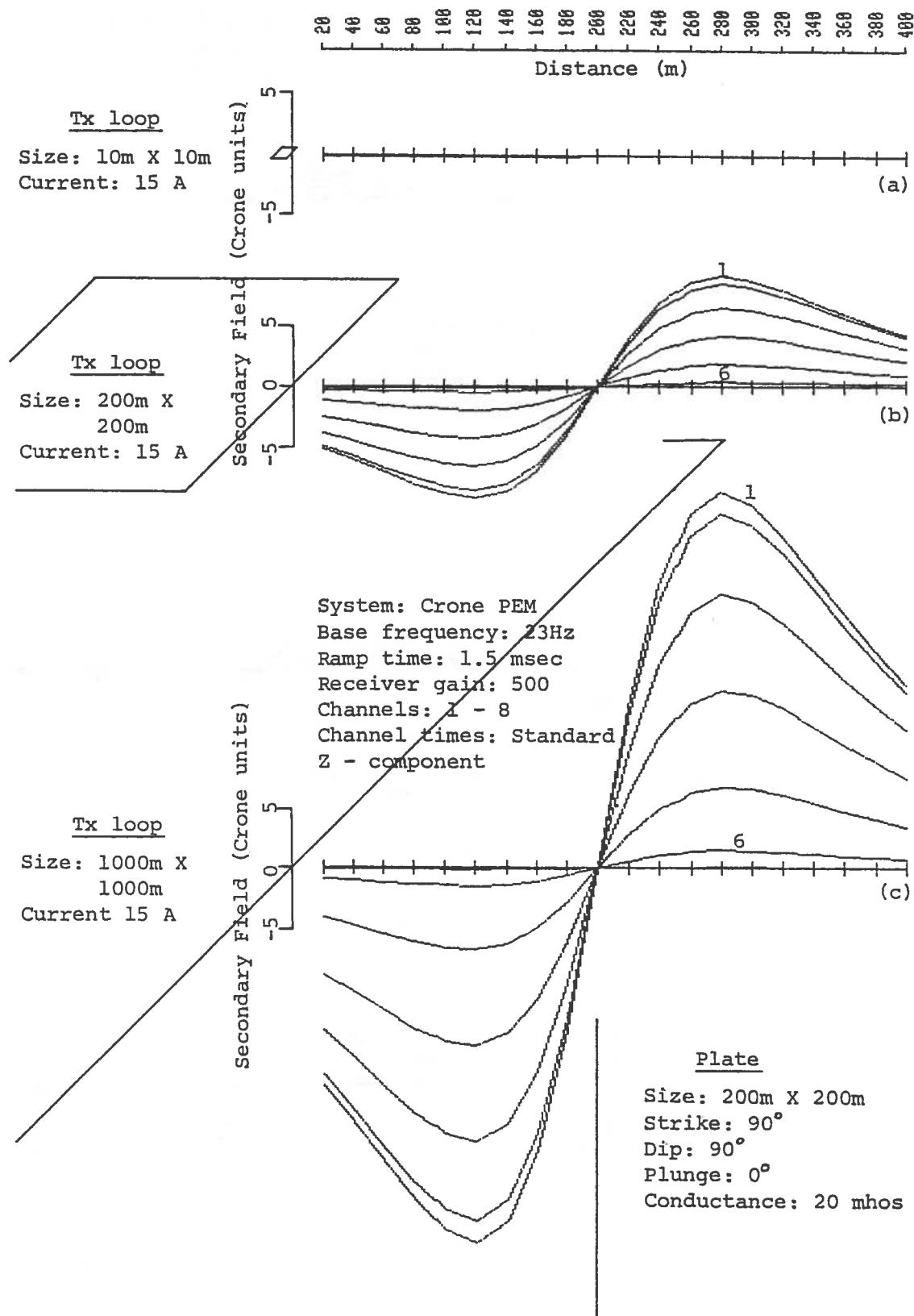


Figure 5.7 Effect of transmitter loop size on the Crone PEM response.

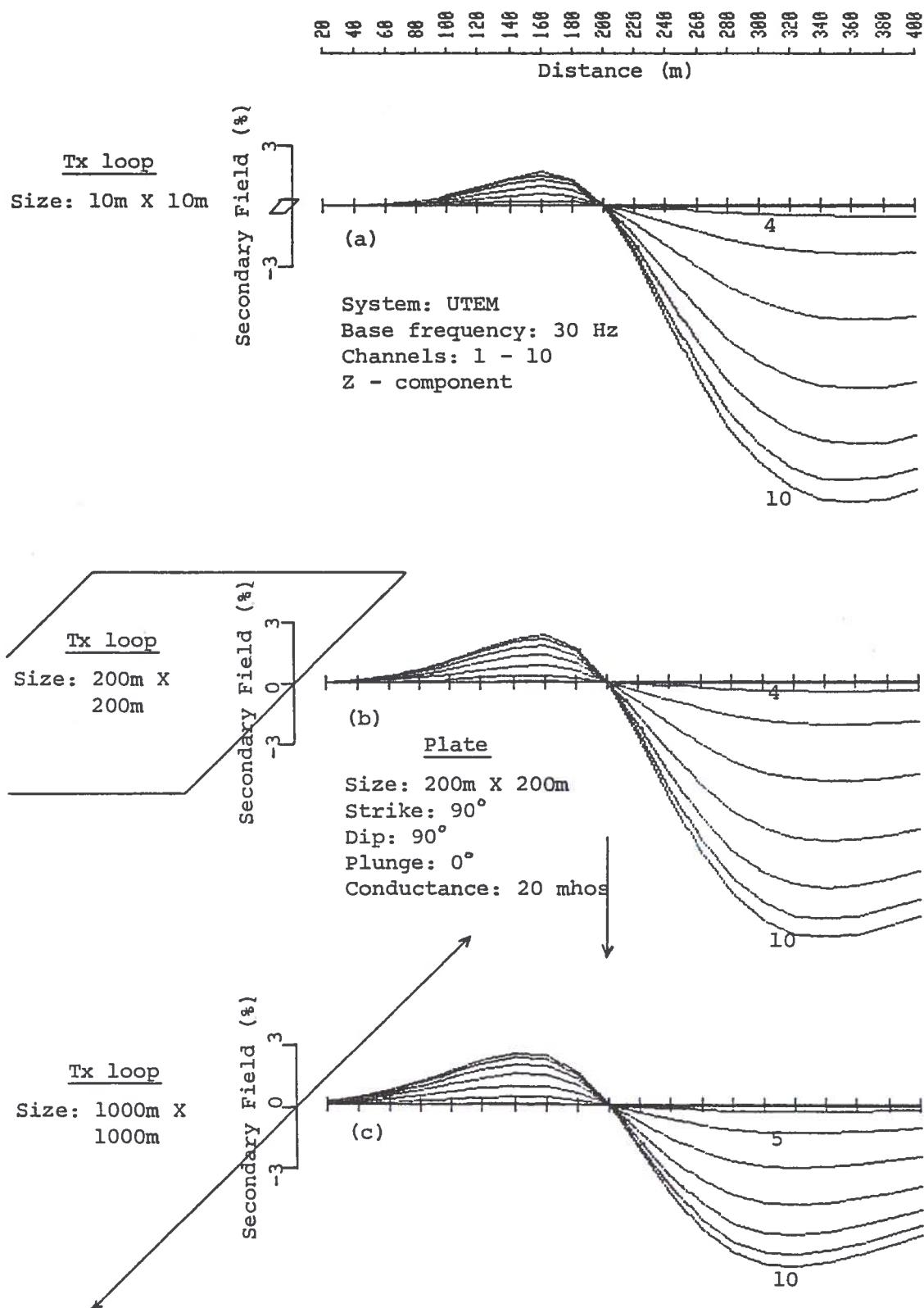


Figure 5.8 Effect of transmitter loop size on the normalized UTEM response.

the primary and secondary fields are detectable from a loop of this size. Figure 5.7 has shown that this may not be true. Thus, it appears that the observation made by Lajoie (1973) may be applicable to normalized data.

The choice of line length, hole depth, and station spacing, can mean the difference between good quality, interpretable data, and surveys which must be repeated. Figure 5.9 consists of synthetic data generated from PLATEF, and shows the effect of conductor size and closest approach distance to the profile line. From this we can see that a drillhole, which just misses a small target, does not have to be extended very far past the intersection point, to provide a complete anomaly. In contrast, a similar near miss of a much larger target will provide only a partial, and perhaps uninterpretable, anomaly unless the hole is deepened. The length of surface lines, as well, can be planned on the basis of conductor size and depth. Finally, synthetic data can be helpful in determining a station spacing, which will strike a balance between anomaly resolution and survey efficiency.

These same two opposing criteria of survey efficiency and conductor resolution, must be used to determine the spacing of the survey lines. Perhaps the most critical application of this survey parameter involves the spacing of exploration holes from a mine drift. Figure 5.10 shows synthetic model data, for a Crone PEM survey performed along a drift, 1000 meters below surface, and in two horizontal exploration holes drilled from the drift. The plate simulates a difficult target because it is small (100m X 100m), and is energized by a surface loop. Also, it is vertical, and perpendicular to the drift, so that the horizontal exploration holes, drilled at 90 degrees to the drift, will not intersect it. The large Tx loop and high receiver gain are typical for such a target. These data show that the plate model is virtually undetectable in the drift (a) and in the hole 120 meters from the plate (b), but is easily detectable in the hole 60 meters from the plate (c). If this plate model represents the smallest conductor of interest, then the holes would have to be drilled at 120 meter intervals to ensure that none of these conductors are missed.

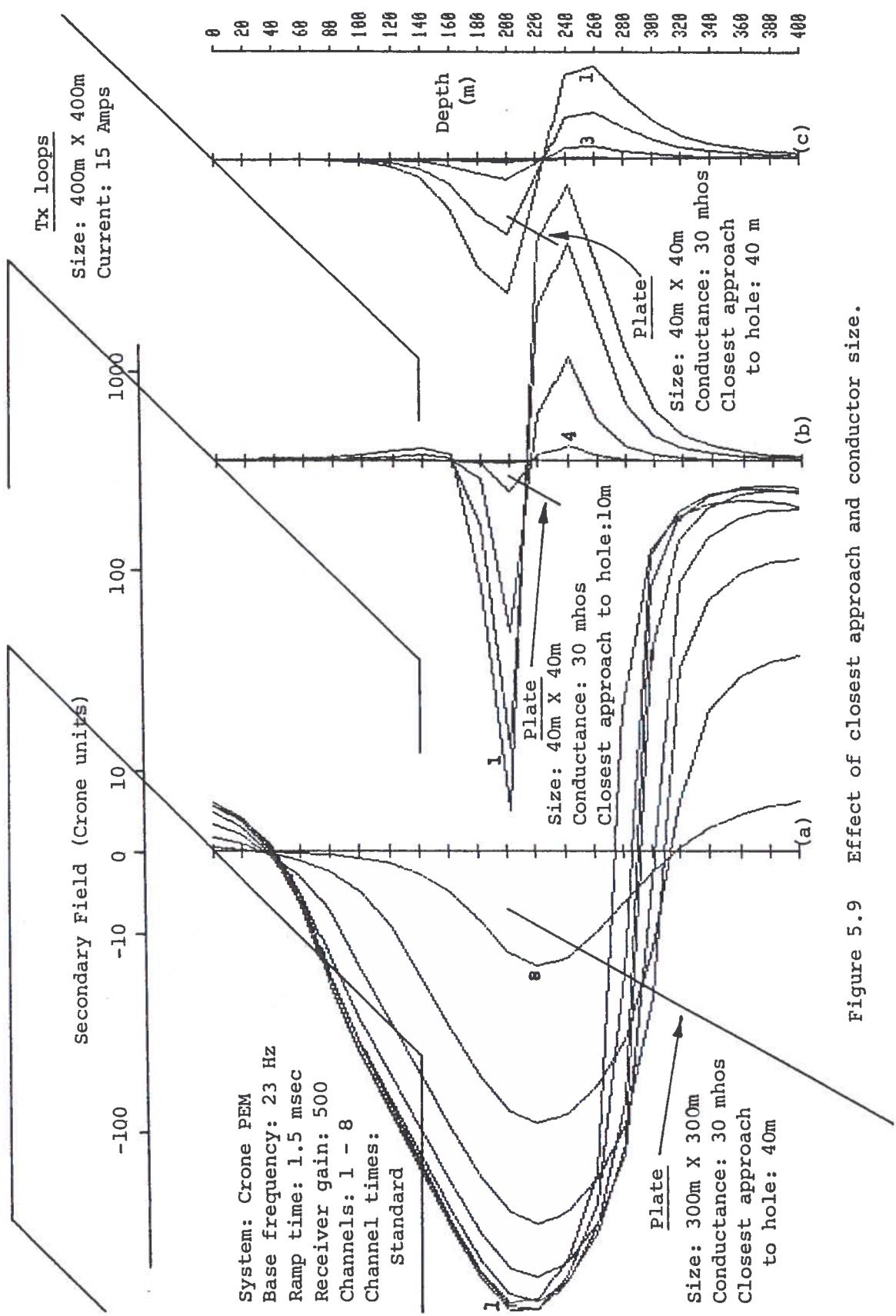


Figure 5.9 Effect of closest approach and conductor size.

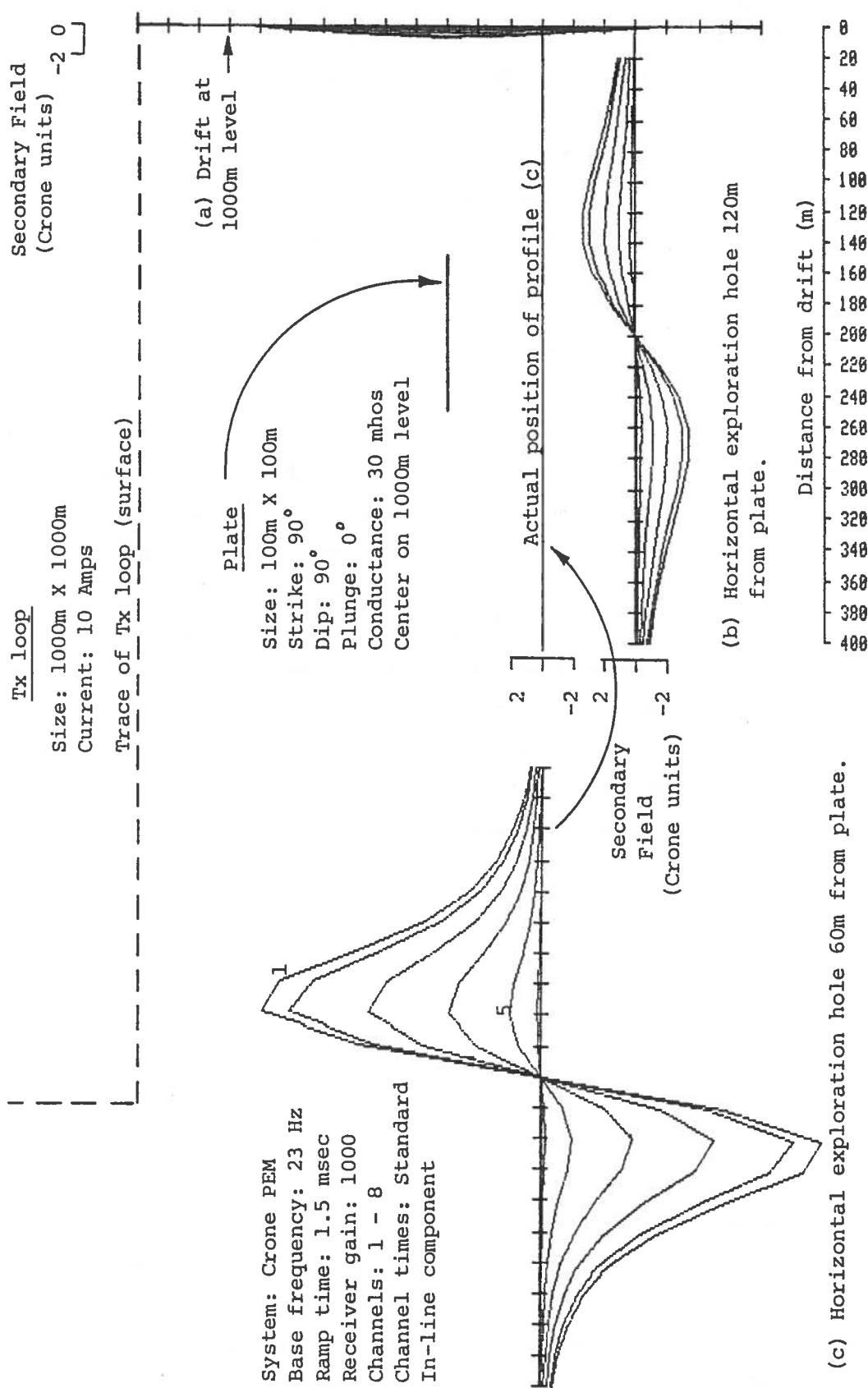


Figure 5.10 Modelling the exploration for mine extensions from a drift. Plan view at 1000m level.

Studies such as this, which involve the determination of target detectability, are particularly useful for the pulsed time-domain systems which do not involve normalization to the primary field. We have seen, in discussing the effect of loop size, that normalization can hide detectability problems with small transmitter loops, and this same problem exists in determining line spacing. With the pulsed systems, on the other hand, system characteristics, such as transmitter loop current, ramp time, and receiver gains, can be altered in the model, until a detectable secondary field amplitude is produced.

Other system parameters, which can be modelled to aid in the survey design, include the base frequency, and the number and spacing of time channels. This sort of modelling may be helpful in conductive environments where the early time responses are dominated by overburden and host rock responses, while the desired target response is prominent in late time channels. In such a case, the base frequency can be lowered to increase the available measurement time, and more time channels can be introduced in late times. While such a model may be helpful in determining the expected response in arbitrary channels, it should be noted that the only receiver, which allows complete flexibility in channel times and widths, is the Crone PEM digital receiver.

### 5.3.2 Interpretation Techniques

Perhaps the most useful application of the new modelling programs is the interpretation of field data, through curve matching. This procedure can be facilitated with characteristic curves, which relate the model parameters to the anomaly's shape, width, amplitude, and decay rate. Anomaly shape is a strong dip indicator, but this relationship is complicated when the data are normalized. Normalization introduces asymmetries which coincide with spatial change in the magnitude of the primary field, as shown in Figure 5.8. The width and amplitude of the anomaly have been shown to depend on the depth and size of the conductor, although the transmitter loop size and location also has a large effect on the amplitude for unnormalized data. When the data are

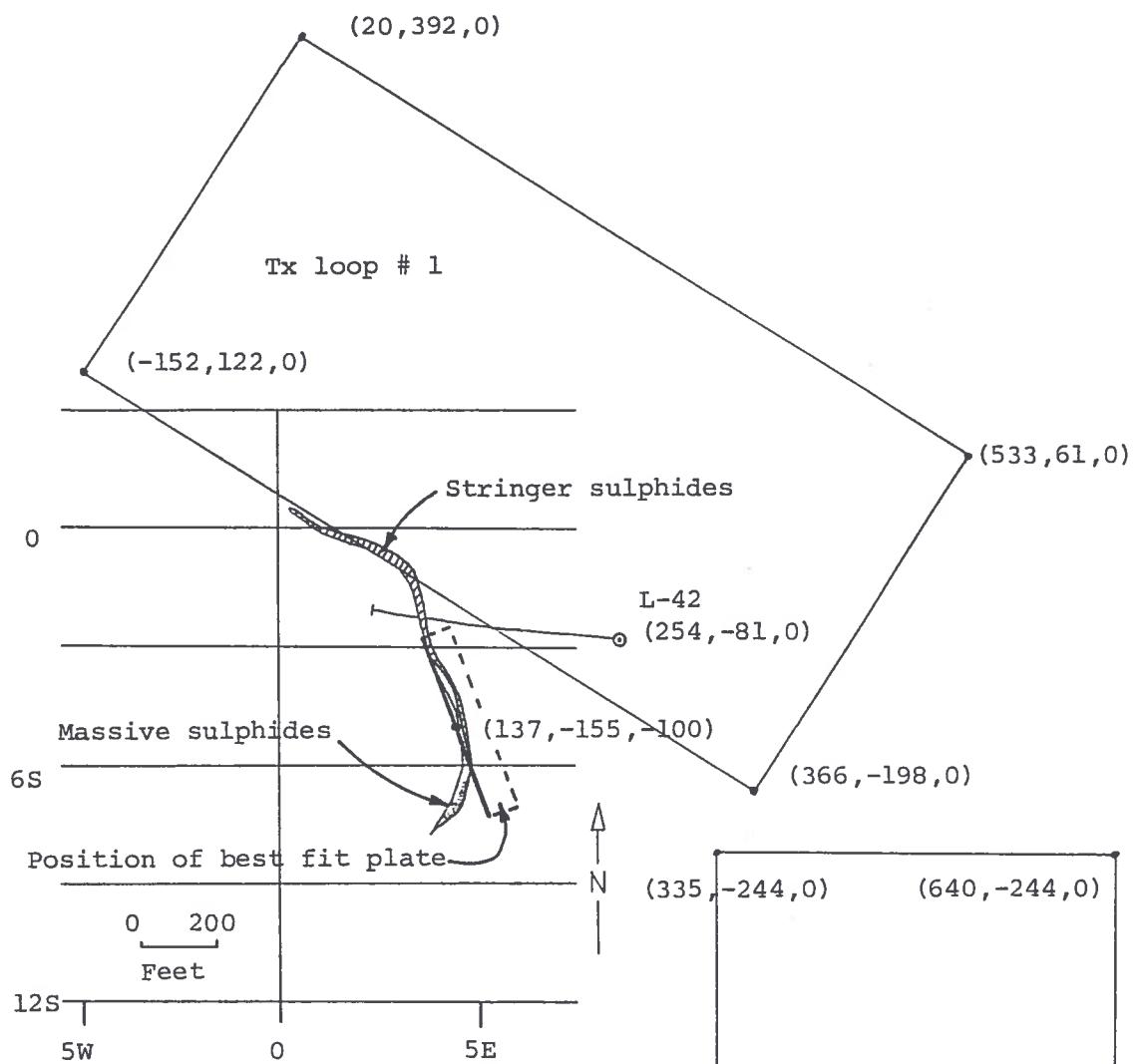
normalized, the effects of loop size and location are minimized, so that normalization may be an effective way to compare two or more anomalies in a single profile. Finally, the rate of decay of the secondary field with time is indicative of the size and conductance of the conductor.

Although characteristic curves can help to narrow the possible solutions in the data interpretation, the final modelling will normally consist of a trial and error fitting of the synthetic data to the field data. The new programs are particularly well-suited to this technique. In order to illustrate this procedure, field data from a well-studied, conductive orebody, known as the "Lessard Deposit", will now be interpreted.

### 5.3.3 Field Data Interpretation

The Lessard copper-zinc-silver deposit, located 93 km north of Chibougamau, Quebec, consists of near-surface, conductive sulphides, positioned in a nearly vertical attitude, and hosted by resistive Precambrian volcanics. It is a typical volcanogenic sulphide deposit, and the mineralized zone consists of both massive sulphides (pyrite, pyrrhotite, sphalerite, and chalcopyrite), and stringer sulphides (pyrrhotite and chalcopyrite). Since this presents an ideal electromagnetic target, geophysical methods have played a major role in its discovery and definition. Unfortunately, the deposit is uneconomic at the present time. Reserves of 1.46 million tons of copper, zinc, and silver have been outlined by drilling to a depth of 520 meters, and the zone remains open at depth (Reed, 1979).

A plan of the deposit at the 400 foot level is shown in Figure 5.11, while a section along line 6S is provided in Figure 5.12. These diagrams show the location of hole L-42 which intersected the mineralized zone of stringer sulphides at a depth of 300 meters. A Crone borehole PEM survey was performed in this hole using the two transmitter loops shown in Figure 5.11. These data are shown in Figures 5.13 and 5.14.



NOTE: Coordinates of loops, drillhole, and plate reference point are given in meters from (0,0,0).

Tx loop # 2

Figure 5.11 Plan view of Lessard Deposit at 400 feet below surface (after Reed, 1979).

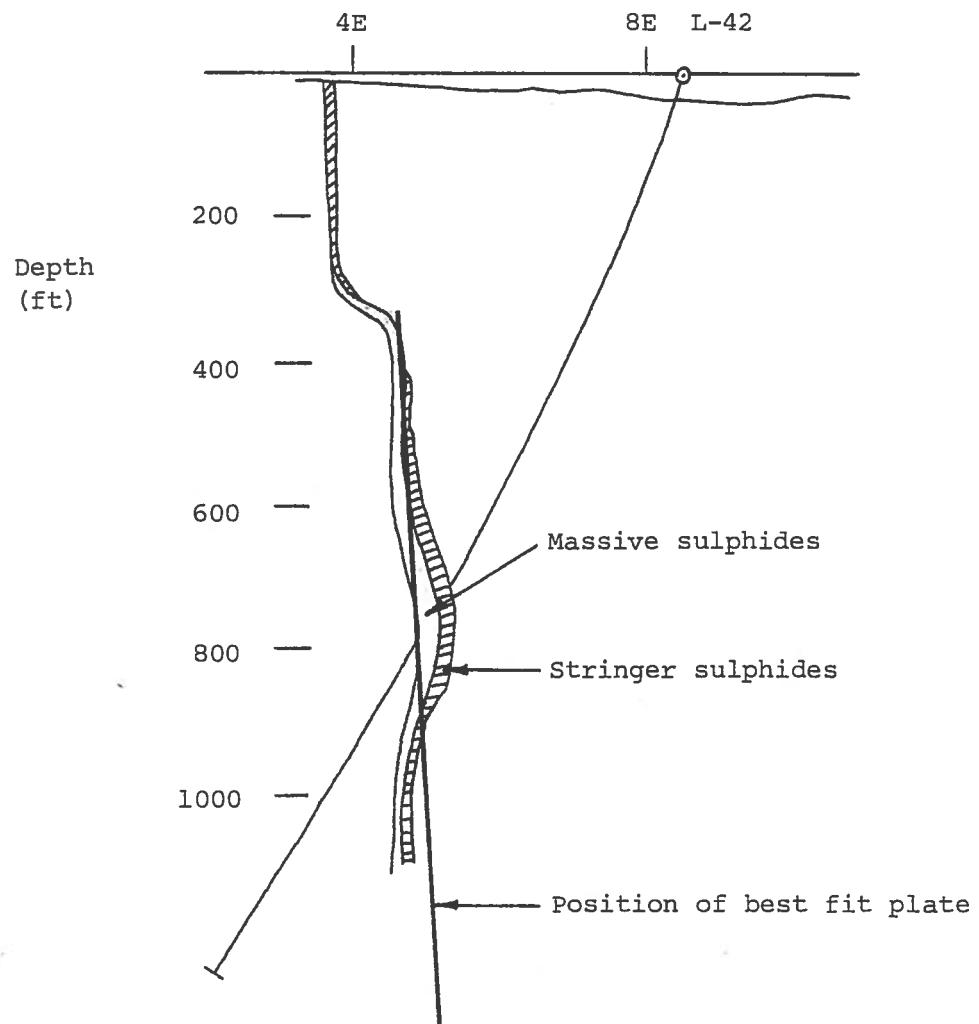


Figure 5.12 Section of Lessard Deposit along Line 6S looking north (after Reed, 1979).

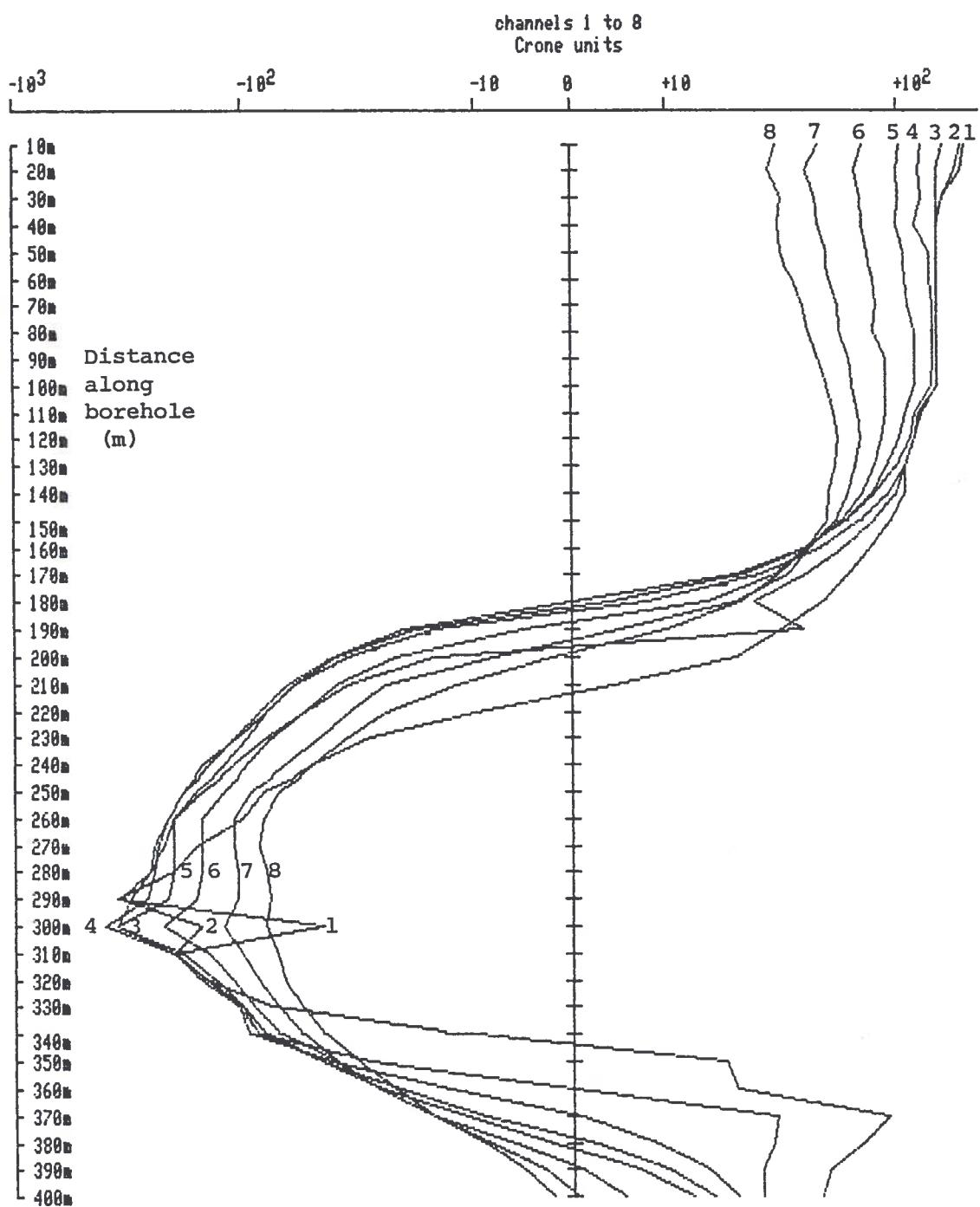


Figure 5.13 Crone PEM data for Hole L-42 using Tx loop # 1.

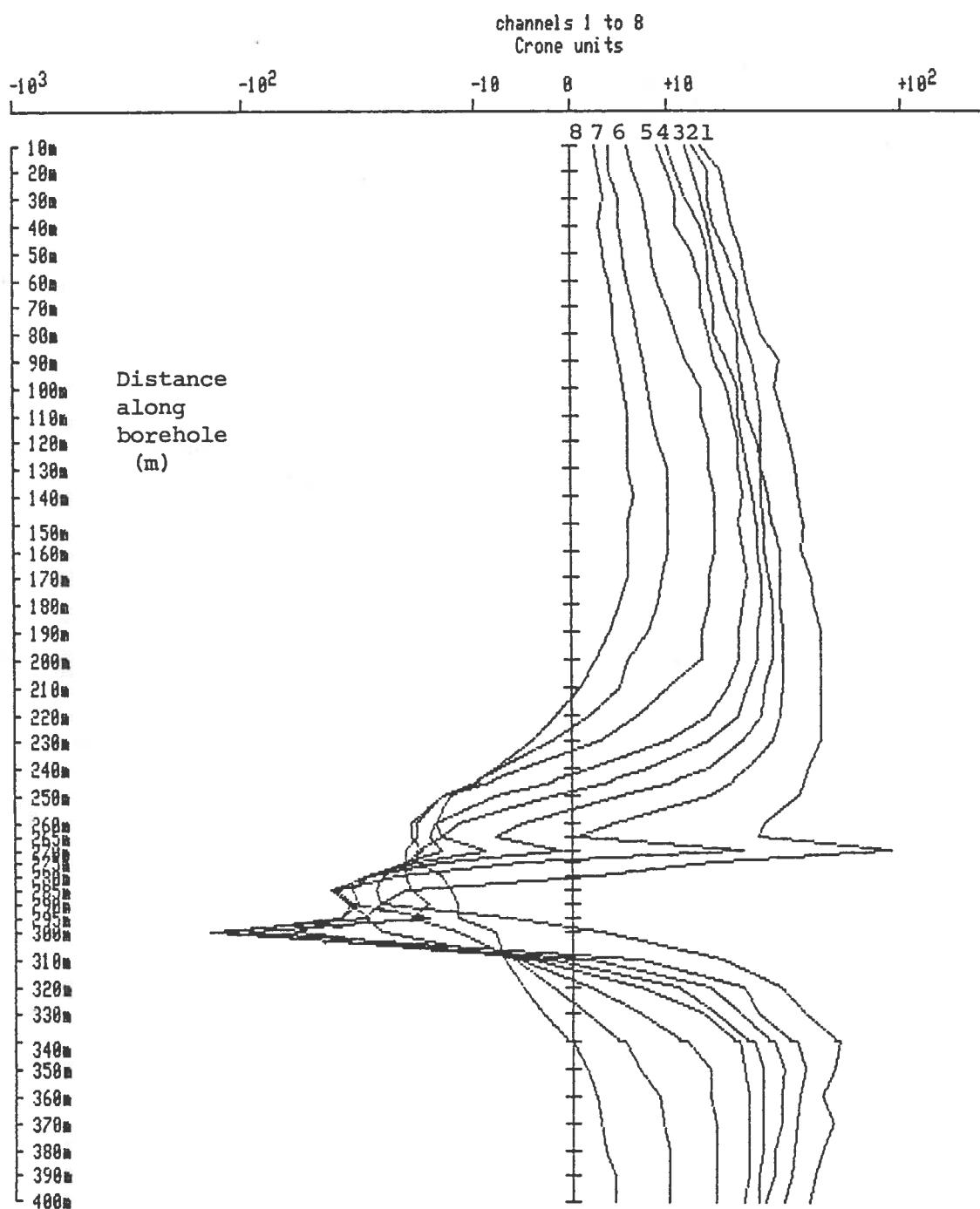


Figure 5.14 Crone PEM data for Hole L-42 using Tx loop # 2.

A strong off-hole anomaly dominates each data set and reaches a peak negative value at approximately 290 meters. This anomaly coincides with the massive sulphides which lie just to the south. Both data sets display a data "spike" in the first five channels, at a depth of 300 meters, which coincides with the intersection of stringer sulphides. A positive background response, which diminishes slightly with depth, can be seen in all the channels especially near the top of the hole, and this is due to conductive overburden effects.

Using a plate model to interpret these data, requires some simplification, in that the curvature in both the drillhole and massive sulphide zone must be removed. The drillhole was straightened in the model by using a visual best-fit line as a starting point, and modifying this slightly until the synthetic primary field values closely matched the measured "PP" values. (The "PP" is a channel measurement of the primary field strength during the current ramp, and is unique to the Crone PEM system). The plate was positioned so that the hole intersected the plate plane at approximately 300 meters down the hole, and the closest approach point was at approximately 290 meters. Using these geometrical constraints, a reasonable approximation of the field data was achieved with a plate of size 150 meters by 300 meters as shown in Figures 5.15 to 5.18. The position of this plate is also shown in Figures 5.11 and 5.12.

During the course of this modelling, the closest approach distance had to be adjusted to match the distance between the zero cross-overs, while maintaining the intersection and closest approach points. The size of the conductor also had a slight effect on the cross-over width, but its main influence was in terms of secondary field amplitude. The asymmetry in the profile resulted from the choice of strike and dip which produced a small intersection angle with the profile. The strike and dip also had a great influence on the degree of coupling with the transmitter loops. Thus, these two parameters had to be adjusted until the response amplitudes from the two transmitter loops were in the proper proportions. Finally, the conductance of the plate had to be adjusted until the decay rate of the secondary field was matched. This

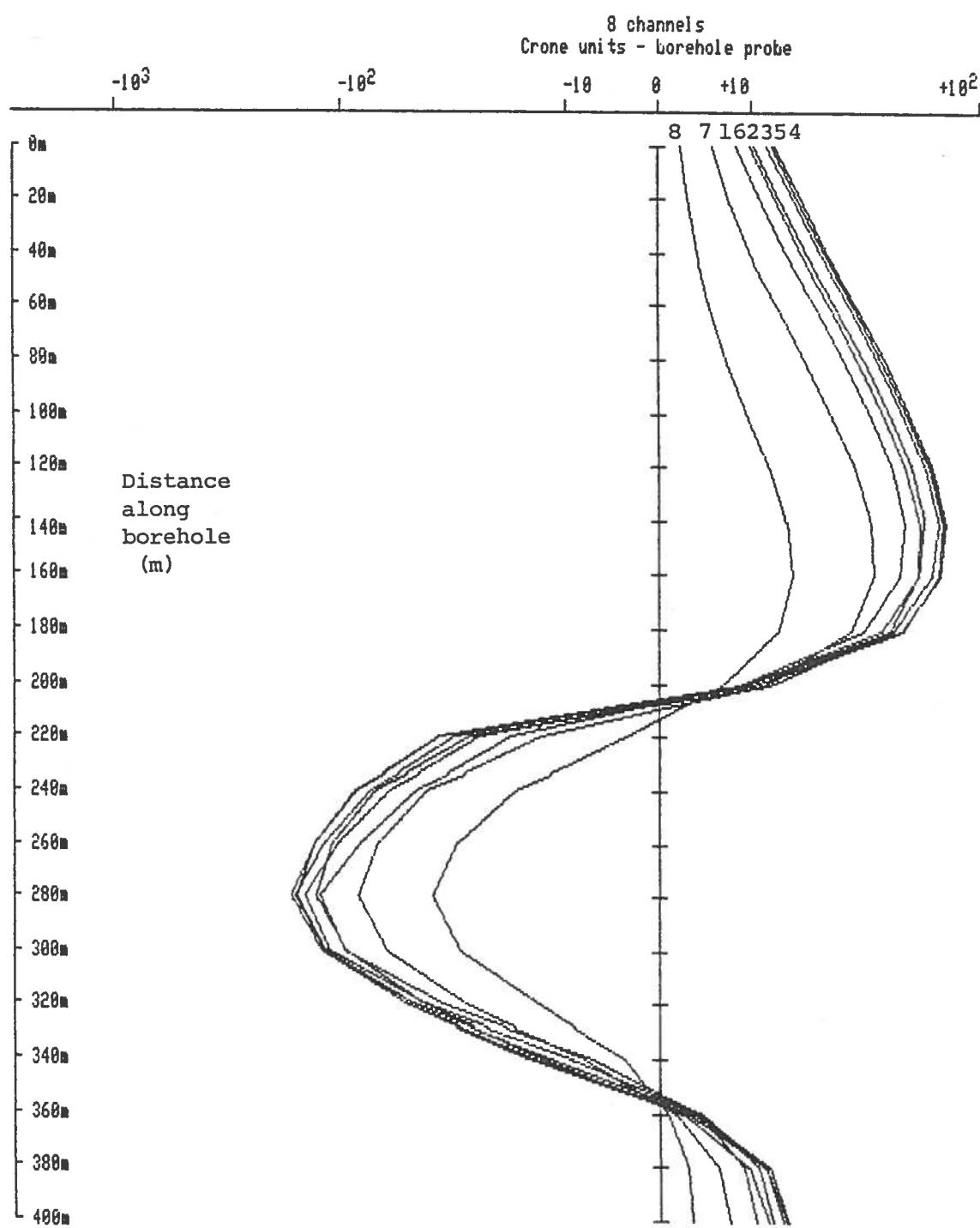


Figure 5.15 Synthetic model data for a conductive plate energized by Tx loop # 1. (Loop location on Figure 5.11)

### Conductive Thin Plate Modelling

User : Crone Geophysics Ltd.

System: Crone Analog Pulse EM  
File : 100mhos.syn

Computed by: PLATEF 1.00 and EIGCUR 1.00  
Eigenfunction file: R2P0.P4

**Plate Parameters:**

Strike Length: 150.0 m  
Width: 300.0 m  
Strike: -70.0 degrees  
Dip: 94.0 degrees  
Plunge: 0.0 degrees  
Conductance: 100.0 mhos

Plate coordinates:

Corner 1 ( 162.6 -225.5 -100.0 )  
Corner 2 ( 111.3 -84.5 -100.0 )  
Corner 3 ( 131.0 -77.4 -399.3 )  
Corner 4 ( 182.3 -218.3 -399.3 )  
Center ( 146.8 -151.4 -249.6 )

plate reference point: ( 0.000 1.000 ) and ( 137.0 -155.0 -100.0 )

**Plate - Loop Coupling:**

H field on plate: (A / m x 10e-6)	Magnitude: (A / m x 10e-6)	Intersection Angle: (degrees)
Corner 1 ( 324.0 277.0 290.0 )	516.0	34.3
Corner 2 ( 784.0 -4.5 965.0 )	1240.0	50.9
Corner 3 ( 88.8 -177.0 98.0 )	221.0	26.3
Corner 4 ( 109.0 -92.1 71.2 )	160.0	26.5
Center ( 249.0 -163.0 235.0 )	379.0	38.4

**Profile Parameters:**

Start: ( 254.0 -81.0 0.0 )  
End: ( 73.1 -65.2 -356.4 )  
Declination from Vertical: 153.0 degrees  
Azimuth from X-axis : 175.0 degrees  
Reference Point: ( 254.0 -81.0 0.0 )  
Distance to Start from Reference: 0.0 m

**Coordinate System:**

Primary field direction in  
center of loop: UP  
LEFT-hand co-ordinate system  
for X, Y, and Z components  
Positive X field component points  
to the START of profile

**Plate-Profile Relationship:**

Profile intersects plate plane at station 300.2 and plate point  
( -87.1 -17.9 0.0 ) at an angle of 28.2 degrees  
This point is 12.1 meters from the plate  
Closest approach is 11.2 meters at station 291.3 and plate point  
( -75.0 -10.2 0.0 )

**System Parameters:**

Crone Analog Pulse EM  
Pulse Repetition Frequency: 23.15 Hz  
Time base: 10.80 msec  
Ramp time: 1500 usec  
Receiver gain: 200

**Channel configuration:**

Ch. 1	100 usec to	200 usec
Ch. 2	200 usec to	400 usec
Ch. 3	400 usec to	700 usec
Ch. 4	700 usec to	1100 usec
Ch. 5	1100 usec to	1800 usec
Ch. 6	1800 usec to	3000 usec
Ch. 7	3000 usec to	5000 usec
Ch. 8	5000 usec to	7800 usec

Figure 5.16 Model parameters for synthetic data in Figure 5.15.

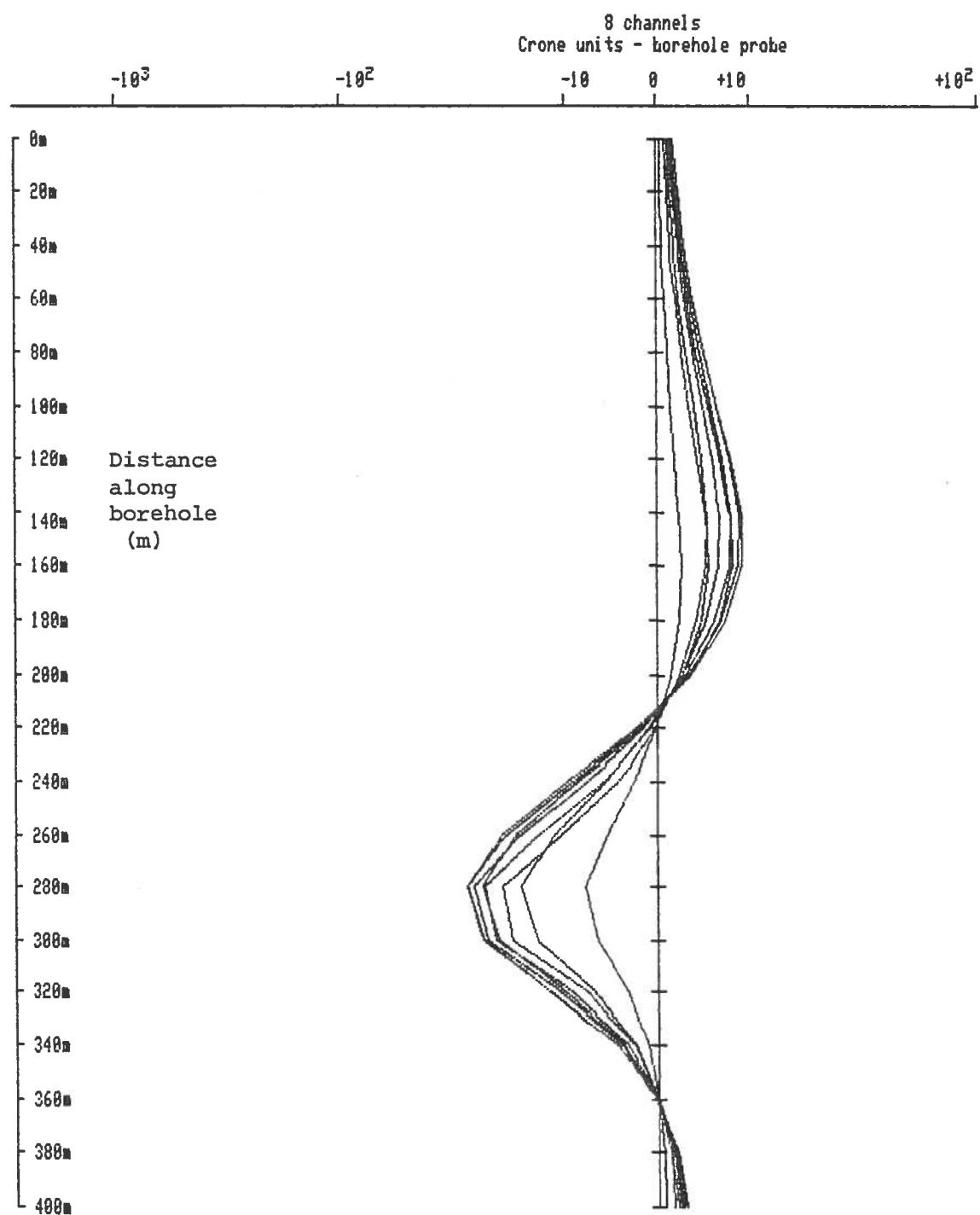


Figure 5.17 Synthetic model data for a conductive plate energized by Tx loop # 2. (Loop location on Figure 5.11)

### Conductive Thin Plate Modelling

User : Crone Geophysics Ltd.

System: Crone Analog Pulse EM  
File : 100mhos2.syn

Computed by: PLATEF 1.00 and EIGCUR 1.00  
Eigenfunction file: R2P0.P4

#### Plate Parameters:

Strike Length:	150.0 m	Current:	11.0 amp(s)
Width:	300.0 m	Corner Coordinates	
Strike:	-70.0 degrees	(	335.0 -244.0 0.0 )
Dip:	94.0 degrees	(	640.0 -244.0 0.0 )
Plunge:	0.0 degrees	(	640.0 -853.0 0.0 )
Conductance:	100.0 mhos	(	335.0 -853.0 0.0 )
Plate coordinates:			
Corner 1	( 162.6 -225.5 -100.0 )		
Corner 2	( 111.3 -84.5 -100.0 )		
Corner 3	( 131.0 -77.4 -399.3 )		
Corner 4	( 182.3 -218.3 -399.3 )		
Center	( 146.8 -151.4 -249.6 )		
plate reference point: ( 0.000 1.000 ) and ( 137.0 -155.0 -100.0 )			

#### Plate - Loop Couplings:

H field on plate: (A / m x 10e-6)			Magnitude:	Intersection Angle: (degrees)
Corner 1	( -129.0 159.0 99.1 )		227.0	25.8
Corner 2	( -47.2 78.8 19.2 )		93.8	11.8
Corner 3	( -57.2 -5.3 24.8 )		62.5	23.3
Corner 4	( -82.6 -36.2 52.6 )		104.0	30.3
Center	( -99.4 21.3 55.7 )		116.0	28.7

#### Profile Parameters:

Start:	( 254.0 -81.0 0.0 )	Primary field direction in
End:	( 73.1 -65.2 -356.4 )	center of loop: UP
Declination from Vertical:	153.0 degrees	LEFT-hand co-ordinate system
Azimuth from X-axis :	175.0 degrees	for X,Y, and Z components
Reference Point:	( 254.0 -81.0 0.0 )	Positive X field component points
Distance to Start from Reference:	0.0 m	to the START of profile

#### Plate-Profile Relationship:

Profile intersects plate plane at station 300.2 and plate point  
( -87.1 -17.9 0.0 ) at an angle of 28.2 degrees  
This point is 12.1 meters from the plate  
Closest approach is 11.2 meters at station 291.3 and plate point  
( -75.0 -10.2 0.0 )

#### System Parameters:

Crone Analog Pulse EM  
Pulse Repetition Frequency: 23.15 Hz  
Time base: 10.00 msec  
Ramp time: 1500 usec  
Receiver gain: 200

#### Channel configuration:

Ch. 1	100 usec to	200 usec
Ch. 2	200 usec to	400 usec
Ch. 3	400 usec to	700 usec
Ch. 4	700 usec to	1100 usec
Ch. 5	1100 usec to	1800 usec
Ch. 6	1800 usec to	3000 usec
Ch. 7	3000 usec to	5000 usec
Ch. 8	5000 usec to	7800 usec

Figure 5.18 Model parameters for synthetic data in Figure 5.17.

was found to be quite difficult, and probably indicates that the field is not decaying at an exponential rate at all times. This can be expected for a thick conductor.

The overall shape of both anomalies has been approximated reasonably well with a thin, conductive plate. The data "spikes" at a depth of 300 meters are not seen in the synthetic data because these are due to the stringer sulphides, within the mineralized zone, which are not modelled. The intersection point of the profile with the plate plane, however, has been fixed at this depth. A peak negative value of approximately the same amplitude as the field data was produced by the model at the correct depth for each loop location. The zero cross-over width in the synthetic data coincides with an average value for this characteristic in the first two channels of the field data. The widening of the cross-over width with time in the field data is due to the diffusion of the eddy currents away from the receiver in the thick zone of massive sulphides. This effect cannot be successfully modelled with a thin plate because the current is constrained to a single plane, and a current migration of this magnitude can only be reproduced by a low plate conductance. It was found, however, that the plate conductance must be high in order to achieve a reasonable approximation of the amplitude decay rate. Finally, the high secondary field background response could not be reproduced because this is due to conductive overburden effects. In conclusion, the Lessard Deposit has served to illustrate the effective application of conductive thin plate modelling.

## CHAPTER 6

### SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

#### 6.1 Summary

The great potential for the TDEM methods as an all-purpose EM technique stems from the fact that they can achieve, to a reasonable degree, the main objectives of modern-day EM exploration: they can find previously hidden orebodies in conductive environments and at depth. It is generally accepted that a strong, broadband stimulation of conductors, and a variety of measurement configurations are required to achieve these goals. These are performed most readily in the time-domain through a rapid termination of current in a large, stationary loop.

In addition to the popularity of wideband EM systems in mining geophysics today, one of the most noticeable trends is the increased use of computers for data collection, presentation, and interpretation. Sophisticated microprocessors are being built into all types of geophysical instruments to aid in data collection, while in-field microcomputers are being utilized for routine data manipulation and interpretation. Mainframe computers are also being used increasingly to perform complex numerical modelling of real Earth structures.

While it is important for researchers to make use of large computers in order to advance the theory of electromagnetic prospecting, it is equally important to make these advances available, in a useable form, to practicing geophysicists. The expanding capabilities of microcomputers makes this especially obvious. This problem has been noted by Cornwell (1983, p. 81) :

Although solutions are now available for many of the more difficult computational problems of induced polarization and electromagnetic modelling, the programs can be implemented only on larger mainframe computers. The development of even more powerful microcomputers and more efficient algorithms are needed to solve this problem.

While this is widely agreed upon, Barnett (1984, p. 925) has noted that EM modelling programs are time - consuming, even on large computers:

... the Toronto PLATE program takes approximately 4 minutes on a VAX 11 - 780 computer to compute a single profile of 50 stations across a plate of arbitrary dimensions. Oristaglio and Hohmann (1984) report that their technique presently requires 8 1/2 hours on a VAX 11 - 780 to produce a single model.

The need to sacrifice either computer time or model complexity is clearly evident in numerical EM modelling.

The work described in this thesis has attempted to solve this dilemma. By striking a balance between a simple current filament model and real Earth models, a microcomputer-based, fixed-loop TDEM modelling package has been developed. These new programs are based on the University of Toronto PLATE program, and they model a thin, conductive, finite plate in free-space. The three new programs that were created, PLATEF, BATCHF, and EIGCUR, all have the same numerical accuracy as the original PLATE program, but are smaller and run at a more efficient rate (e.g. PLATEF requires 200 Kbytes of RAM and its run time is approximately 8 minutes for a 50 station profile, on an IBM-PC with an 8087 math chip). Modifications from the original PLATE program have been so extensive, that only Annan's original algorithms (1974) remain intact. In addition, numerous new features have been added to enhance the quality of these programs, and these are especially obvious in the areas of flexibility, user-friendliness, and documentation. While some generality has been lost since only fixed-loop TDEM systems can be modelled with these programs, the user is now given much more geometrical information and control, as well as true secondary field amplitudes, and a simplified output.

## 6.2 Conclusions

Now that a microcomputer-based TDEM modelling package is available, the routine in-field interpretation of data using a computer-assisted simple model approach appears to be feasible. The new programs can be used to generate a representative suite of type curves, which will be helpful in determining a starting point for the interactive plate modelling. These programs should be especially useful in borehole work because the complex model geometries are described in great detail, and because borehole data tend to be relatively free from conductive overburden effects.

The programs have been designed to be useful at all stages of TDEM surveys. In the planning stage transmitter loop positions and sizes can be determined to maximize the coupling with the suspected target. The length of surface lines or boreholes, as well as the spacing of lines, holes, and stations, can be structured in such a way that complete and resolvable anomalies are ensured. Finally, system characteristics can be modelled to determine their optimal values. During a survey, these parameters can be adjusted as additional information is gathered, and new transmitter loop positions can be planned to achieve reverse coupling of plate-like conductors. In addition, several new features have been designed to facilitate the interpretation process. These include: an extensive description of the geometrical relationships among the transmitter loop, receiver profile, and plate; data output in commonly used units to allow direct comparison with field data; and a convenient method of changing model parameters with a minimum amount of recalculation.

During the course of this work, the author came to appreciate the elegance and efficiency of Annan's mathematical technique; it is hoped that this thesis will provide a bridge between this complex mathematical theory, and the needs of explorationists.

### 6.3 Recommendations for Future Work

There are a number of topics, mentioned briefly in this thesis, which require additional investigation. The number of eigencurrents, used in the eddy current approximation, could be increased to improve the accuracy of the model data when the receiver is close to the plate. This may be useful for interpreting borehole data from holes which intersect conductors, but the penalty paid for this accuracy, in terms of time requirements, may outweigh the benefits. Other areas within the programs, which limit their accuracy, could also be investigated, such as the numerical quadrature and plate division process. Finally, new programs for moving source, and frequency-domain systems, could be written using many of the features and techniques outlined in this thesis.

## APPENDIX A

### BASIC EM THEORY

#### A.1 Maxwell's Equations

$$\nabla \times \underline{E} = - \frac{\partial \underline{B}}{\partial t} \quad (A.1) \quad (\text{Faraday's Law})$$

$$\nabla \times \underline{H} = \underline{J} + \frac{\partial \underline{D}}{\partial t} \quad (A.2) \quad (\text{Ampere's Law})$$

$$\nabla \cdot \underline{D} = q \quad (A.3) \quad (\text{Coulomb's Law})$$

$$\nabla \cdot \underline{B} = 0 \quad (A.4) \quad (\text{solenoidal } \underline{B})$$

where  $\underline{E}$  = electric field intensity in v/m

$\underline{B}$  = magnetic induction, or flux density, in webers/m<sup>2</sup>

$\underline{D}$  = dielectric displacement in coulombs/m<sup>2</sup>

$\underline{H}$  = magnetic field intensity in ampere-turn/m

$q$  = electric charge density in C/m<sup>3</sup>

$\underline{J}$  = current density in A/m<sup>2</sup>

#### A.2 Constitutive Equations (linear isotropic medium)

$$\underline{D} = \epsilon \underline{E} + \underline{P}_I \quad (A.5)$$

$$\underline{B} = \mu \underline{H} + \mu_0 \underline{M}_I \quad (A.6)$$

$$\underline{J} = \sigma \underline{E} + \underline{J}_S \quad (A.7)$$

where  $\underline{P}_I$  is the intrinsic dipolar distribution

$$\epsilon = K_e \epsilon_0$$

$K_e$  is the dielectric constant (relative permittivity)

$\underline{M}_I$  is the intrinsic magnetic dipole moment density

$$\mu = K_m \mu_0$$

$K_m$  is the relative permeability

$\underline{J}_S$  is the source current

$\sigma$  is the conductivity

An EM problem is completely stated when the source terms ( $\underline{J}_S$ ,  $q$ ,  $\underline{P}_I$ ,  $\underline{M}_I$ ) and the material properties ( $K_e$ ,  $K_m$ ,  $\sigma$ ) are specified.

### A.3 Time Varying Fields with Sources

Using a harmonic time variation of the fields ( $e^{i\omega t}$ ), we get:

$$\nabla \times \underline{E} = i\omega (\mu \underline{H} + \mu_0 \underline{M}_I)$$

or

$$\nabla \times \underline{E} = i\omega \mu \underline{H} + \underline{M}_G \quad (A.8)$$

where  $\underline{M}_G = i\omega \mu_0 \underline{M}_I$  is the generalized magnetic current,

and

$$\nabla \times \underline{H} = \underline{J}_S + \sigma \underline{E} - i\omega (\underline{\epsilon} \underline{E} + \underline{P}_I)$$

or

$$\nabla \times \underline{H} = (\sigma - i\omega \epsilon) \underline{E} + \underline{J}_G \quad (A.9)$$

where  $\underline{J}_G = \underline{J}_S - i\omega \underline{P}_I$  is the generalized electric current.

Taking the curl and combining these equations gives:

$$\begin{aligned} \nabla \times \nabla \times \underline{E} &= i\omega \mu \nabla \times \underline{H} + i\omega \underline{H} \times \nabla \mu + \nabla \times \underline{M}_G \\ \therefore \nabla \times \nabla \times \underline{E} - i\omega \mu (\sigma - i\omega \epsilon) \underline{E} - i\omega \underline{H} \times \nabla \mu \\ &= \nabla \times \underline{M}_G + i\omega \mu \underline{J}_G \end{aligned} \quad (A.10)$$

$$\begin{aligned} \nabla \times \nabla \times \underline{H} &= (\sigma - i\omega \epsilon) \nabla \times \underline{E} + \underline{E} \times \nabla (\sigma - i\omega \epsilon) + \nabla \times \underline{J}_G \\ \therefore \nabla \times \nabla \times \underline{H} - i\omega \mu (\sigma - i\omega \epsilon) \underline{H} - \underline{E} \times \nabla \sigma + i\omega \underline{E} \times \nabla \epsilon \\ &= \nabla \times \underline{J}_G + (\sigma - i\omega \epsilon) \underline{M}_G \end{aligned} \quad (A.11)$$

## APPENDIX B

### EQUIVALENT SOURCE FORMULATION OF EM PROBLEMS

Annan (1974) has demonstrated the power of the equivalent source method in formulating electrical, magnetic, and electromagnetic problems in geophysics. This appendix contains a very brief summary of his results.

#### B.1 Static Fields

Whether the problem is dielectric electrostatic, magnetostatic, or static electric conduction, the general mathematical formulation is the same. The equivalent source is determined by which of the material properties is changing so that:

- $\sigma$  variations are replaced with d.c. current sources;
- $\epsilon$  variations are replaced with charge distributions; and
- $\mu$  variations are replaced with "magnetic pole" distributions.

These equivalent sources ( $g_e$ ) satisfy a scalar Fredholm equation of the second kind, namely:

$$g_e(r) = g_o(r) + \frac{\nabla n}{1+n} \cdot \nabla \int_{V'} G(r, r') g_e(r') d^3r'$$

where  $g_o(r)$  is a source term formulated from the excitation field,  $n$  is a material property ratio, and  $G(r, r')$  is the Green's function of the background material (see Annan, 1974).

#### B.2 Time-varying Fields

When the EM fields vary with time, the material property variations are replaced with electric and magnetic current densities. This is done by first separating the material properties into background and

anomalous parts ( $\mu = \mu_b + \mu_a$ ,  $\sigma = \sigma_b + \sigma_a$ ,  $\epsilon = \epsilon_b + \epsilon_a$ ). Then equations A.8 and A.9 become:

$$\nabla \times \underline{E} = i\omega \mu_b \underline{H} + i\omega \mu_a \underline{H} + \underline{M}_G$$

$$\nabla \times \underline{H} = (\sigma_b - i\omega \epsilon_b) \underline{E} + (\sigma_a - i\omega \epsilon_a) \underline{E} + \underline{J}_G$$

Now the equivalent current distributions are defined as:

$$\underline{M}_e = i\omega \mu_a \underline{H}; \quad \text{and} \quad \underline{J}_e = (\sigma_a - i\omega \epsilon_a) \underline{E}$$

so that equations A.10 and A.11 become:

$$\nabla \times \nabla \times \underline{E} - k_b^2 \underline{E} - i\omega \underline{H} \times \nabla \mu_b = \nabla \times (\underline{M}_G + \underline{M}_e) + i\omega \mu_b (\underline{J}_G + \underline{J}_e)$$

$$\nabla \times \nabla \times \underline{H} - k_b^2 \underline{H} - \underline{E} \times \nabla (\sigma_b - i\omega \epsilon_b) = \nabla \times (\underline{J}_G + \underline{J}_e) + (\sigma_b - i\omega \epsilon_b) (\underline{M}_G + \underline{M}_e)$$

$$\text{where } k_b^2 = i\omega \mu_b (\sigma_b - i\omega \epsilon_b).$$

By choosing the background material properties so that they are constant in a piecewise sense, we get:

$$\nabla \times \nabla \times \underline{E}_b - k_b^2 \underline{E}_b = \nabla \times \underline{M}_G + i\omega \mu_b \underline{J}_G$$

$$\nabla \times \nabla \times \underline{E}_a - k_b^2 \underline{E}_a = \nabla \times \underline{M}_e + i\omega \mu_b \underline{J}_e$$

and

$$\nabla \times \nabla \times \underline{H}_b - k_b^2 \underline{H}_b = \nabla \times \underline{J}_G + (\sigma_b - i\omega \epsilon_b) \underline{M}_G$$

$$\nabla \times \nabla \times \underline{H}_a - k_b^2 \underline{H}_a = \nabla \times \underline{J}_e + (\sigma_b - i\omega \epsilon_b) \underline{M}_e$$

where  $\underline{E}_b$  and  $\underline{H}_b$  are the fields which would be present without the anomalous region, and  $\underline{E}_a$  and  $\underline{H}_a$  are the anomalous fields ( $\underline{E} = \underline{E}_b + \underline{E}_a$ ,  $\underline{H} = \underline{H}_b + \underline{H}_a$ ).

These equations are now in a form in which they can be solved by convolving the source terms on the right with the Green's dyadic for the background material (in analogy with the Green's function of one-dimensional analysis). The equivalent sources thus satisfy a coupled pair of vector Fredholm integral equations:

$$\underline{J}_e = (\sigma_a - i\omega\epsilon_a) \underline{E}_b + iw\mu_b(\sigma_a - i\omega\epsilon_a) \int_{V'} \frac{\underline{E}}{J} \tilde{G} \cdot \underline{J}_e dV'$$

$$+ (\sigma_a - i\omega\epsilon_a) \int_{V'} \frac{\underline{E}}{M} \tilde{G} \cdot \underline{M}_e dV'$$

$$\underline{M}_e = iw\mu_a \underline{H}_b + iw\mu_a(\sigma_b - i\omega\epsilon_b) \int_{V'} \frac{\underline{H}}{M} \tilde{G} \cdot \underline{M}_e dV'$$

$$+ iw\mu_a \int_{V'} \frac{\underline{H}}{J} \tilde{G} \cdot \underline{J}_e dV'$$

where  $\frac{\underline{E}}{J} \tilde{G}$ ,  $\frac{\underline{E}}{M} \tilde{G}$ ,  $\frac{\underline{H}}{M} \tilde{G}$ ,  $\frac{\underline{H}}{J} \tilde{G}$  are the Green's dyadics of the background material. These equations must be solved numerically.

### B.3 Conductor in a Homogeneous Medium

Annan (1974) has shown how the coupled Fredholm equations for the equivalent current distributions are simplified when an electric scatterer is buried in a homogeneous medium. Since the magnetic properties are assumed constant,  $\mu_a = 0$  and thus  $\underline{M}_e = 0$ . The remaining integral equation becomes:

$$\frac{\underline{J}_e}{\sigma_a - i\omega\epsilon_a} = \underline{E}_o + iw\mu_o \int_{V'} \frac{\underline{E}}{J} \tilde{G} \cdot \underline{J}_e dV'$$

which can be written as:

$$\frac{\underline{J}_e}{\sigma_a - i\omega\epsilon_a} - L(\underline{J}_e) - C(\underline{J}_e) = \underline{E}_o \quad (B.1)$$

$$\text{where } L(\underline{J}_e) = iw\mu_b \int_{V'} g(r, r') \underline{J}_e(r') d^3r'$$

$$C(\underline{J}_e) = \frac{\nabla \nabla}{\sigma_a - i\omega\epsilon_a} \int_{V'} g(r, r') \underline{J}_e(r') d^3r'$$

$$\text{and } g(r, r') = \frac{e^{(ik_b R)}}{4\pi R}; \quad R = |r - r'|$$

$$k_b^2 = \omega^2 \epsilon_b \mu_b + i\sigma_b \omega \mu_b$$

The first term represents the ohmic electric field generated by  $\underline{J}_e$ . The second term ( $L(\underline{J}_e)$ ) is called the inductive term and represents the electric field generated inductively by time variations of  $\underline{J}_e$ . The third term ( $C(\underline{J}_e)$ ) is called the depolarization term and represents either the capacitive or the depolarization effect depending on the conductivity of the host medium.

When the host medium has the same properties as free space ( $\mu_b = \mu_0$ ,  $\epsilon_b = \epsilon_0$ ,  $\sigma_b = 0$ ) and there are no current sources in the conductor, the depolarization term becomes a null operator. Also, for most geophysical prospecting systems, the frequencies and distances involved are such that the Green's function  $g(r, r')$  simplifies to  $1/4\pi R$  and  $w\epsilon_a$  can be ignored in comparison to  $\sigma_a$ . These two added assumptions simplify equation B.1 further to:

$$\frac{\underline{J}_e(r)}{\sigma_a} - i\omega\mu_0 \int_{V'} \frac{\underline{J}_e(r')}{4\pi R} dV' = \underline{E}_0(r) \quad (B.2)$$

This, then, is the Fredholm integral equation of the eddy current distribution in any conductor of constant conductivity in free space.

## APPENDIX C

### THIN PLATE IN FREE SPACE

This appendix is a collection of information from four principal sources: Annan(1974); Lodha(1977); Dyck(1981); and Walker(1981). An attempt is made to resolve some of the discrepancies among these sources by providing more detail in some areas and by presenting the description of the weighted eigenvector method in a slightly different way.

#### C.1 Equivalent Source Formulation of the Problem

The integral equation for the eddy current distribution in a thin plate is found from the general equation by letting one of the dimensions of a parallelepiped go to zero while maintaining a finite value for the conductivity - thickness. Thus,  $\sigma_a$  in equation B.1 is replaced by  $\sigma_s$ , and  $J_e$  is replaced by the surface current  $K_e$  so that equation B.2 becomes:

$$\frac{K_e(r)}{\sigma_s} - i\omega\mu_0 \int_{S'} g(r, r') K_e(r') d^2r' = E''_o(r) \quad (C.1)$$

where  $E''_o$  represents the component of  $E_o$  in the plane of the plate  
 $g(r, r') = 1/4\pi R$  ;  $R = |r - r'|$

and  $\sigma_s$  is the surface conductivity or conductivity - thickness of the plate.

#### C.2 The Problem in Terms of a Potential

Since the current is caused by induction and does not cross the plate boundaries, we also have the two following conditions on  $K_e$ :

$$\nabla \cdot K_e = 0 \quad (K_e \text{ is solenoidal}) \quad (C.2)$$

$$K_e \cdot \hat{n} = 0 \quad (\text{confined current}) \quad (C.3)$$

Equation C.2 implies that  $\underline{K}_e$  can be represented by a vector potential  $\underline{K}_e = \nabla \times \underline{A}$ , but since  $\underline{K}_e$  always lies in one plane,  $\underline{A}$  is always perpendicular to it, and a scalar potential  $U$  can thus be used. For example:

$$\underline{K}_e(r) = \nabla \times (U(r)\hat{\mathbf{e}}_3) \quad \text{or} \quad \underline{K}_e = \nabla U(r) \times \hat{\mathbf{e}}_3.$$

Equation C.3 then constrains  $U(r)$  to be constant along the edges of the plate.

Taking the curl of equation C.1 at the field point  $r$  gives:

$$\frac{\nabla \times \underline{K}_e(r)}{\sigma_s} - iw\mu_0 \int_{S'} \left\{ \nabla \left( \frac{1}{4\pi R} \right) \times \underline{K}_e(r') + \frac{1}{4\pi R} \nabla \times \underline{K}_e(r') \right\} d^2r' \\ = \nabla \times \underline{E}''_o(r) \quad (\text{C.4})$$

$$\text{Now } \nabla \times \underline{K}_e(r) = -\nabla^2 U \hat{\mathbf{e}}_3$$

$$\nabla \left( \frac{1}{4\pi R} \right) = -\frac{1}{4\pi R^2} \hat{\mathbf{R}}, \quad \text{where } \hat{\mathbf{R}} = \underline{\mathbf{R}} / R$$

$$\nabla \left( \frac{1}{4\pi R} \right) \times \underline{K}_e(r') = \nabla \left( \frac{1}{4\pi R} \right) \times \nabla U \times \hat{\mathbf{e}}_3 = \left( \frac{1}{4\pi R^2} \hat{\mathbf{R}} \cdot \nabla U \right) \hat{\mathbf{e}}_3$$

$$\nabla \times \underline{K}_e(r') = 0, \quad \text{because } \underline{K}_e(r') \text{ is not a function of } r$$

$$\nabla \times \underline{E}''_o(r) = iw\mu_0 H_3 \hat{\mathbf{e}}_3, \quad \text{where } H_3 \text{ is the perpendicular component.}$$

Substituting these equations into equation C.4 yields:

$$\frac{\nabla^2 U}{\sigma_s} + iw\mu_0 \int_{S'} \left( \frac{1}{4\pi R^2} \hat{\mathbf{R}} \cdot \nabla U \right) d^2r' = -iw\mu_0 H_3 \quad (\text{C.5})$$

(see Walker, 1981). Solving this equation numerically for  $U$  is simpler than a direct method for determining the eddy current distribution  $\underline{K}_e(r)$  in the plate.

### C.3 Application of the Galerkin Technique

Annan (1974) has shown how two different variational techniques can be used to reduce equation C.5 to a finite sum of linear equations - least squares, and the Galerkin method. These were chosen over the more commonly used digitization for the sake of economy and accuracy, since an order of magnitude fewer unknowns were found to be necessary. He found that the Galerkin method was better than the least squares method, for EM problems, since it was less susceptible to ill-conditioning.

In this method, the unknown function ( $U$ ) is approximated by a finite sum over arbitrary trial functions ( $\phi_i$ ):

$$U \approx \sum_{i=1}^N c_i \phi_i.$$

Each of these trial functions is defined over the entire area being studied, and they are chosen to conform to the boundary conditions. Now equation C.5 can be seen as an integral operator  $L$  acting on the unknown potential  $U$  to give the known source term  $S$  ( $= -iw\mu_0 H_3$ ) so that:

$$L(U) = S.$$

Substituting the approximate value of  $U$  gives:

$$\sum_{i=1}^N c_i L(\phi_i) - S = R$$

where  $R$  is an error term. In the Galerkin method, this error term is forced to be orthogonal to each of the trial functions used in the approximation so that:

$$(\phi_k, R) = 0.$$

Therefore,

$$\sum_{i=1}^N c_i (\phi_k, L\phi_i) = (\phi_k, S)$$

and we have  $N$  equations in  $N$  unknowns, the  $k^{th}$  one of which is:

$$\begin{aligned} & \sum_{i=1}^N \frac{1}{\sigma_s} \int_S c_i \phi_k(r) \nabla^2 \phi_i(r) dA + iw\mu_0 \sum_{i=1}^N \int_S \int_{S'} \frac{1}{4\pi R^2} \hat{\mathbf{R}} \cdot \nabla(c_i \phi_i(r')) \phi_k(r) dAdA' \\ &= -iw\mu_0 \int_S \phi_k(r) H_3(r) dA. \end{aligned}$$

Walker (1981) has shown that this can be written as:

$$\sum_{i=1}^N \frac{1}{\sigma_s} \int_S c_i \nabla \phi_k(r) \cdot \nabla \phi_i(r) dA - iw\mu_0 \sum_{i=1}^N c_i \int_S \int_S g(r, r') \nabla \phi_k(r) \cdot \nabla \phi_i(r') dAdA' \\ = -iw\mu_0 \int_S \phi_k(r) H_3(r) dA.$$

Finally, in matrix form, this can be written as:

$$\left( \frac{1}{\sigma_s} [F] - iw\mu_0 [L] \right) [C] = -iw\mu_0 [H]$$

where  $F_{ij} = \int_S \frac{\partial}{\partial x} \phi_i(x, y) \frac{\partial}{\partial x} \phi_j(x, y) + \frac{\partial}{\partial y} \phi_i(x, y) \frac{\partial}{\partial y} \phi_j(x, y) dx dy$

$$L_{ij} = \int_S \int_{S'} g(r, r') \left\{ \frac{\partial}{\partial x} \phi_j(x, y) \frac{\partial}{\partial x'} \phi_i(x', y') + \frac{\partial}{\partial y} \phi_j(x, y) \frac{\partial}{\partial y'} \phi_i(x', y') \right\} dx dy dx' dy'$$

$$H_j = \int_S \phi_j(x, y) H_3(x, y) dx dy$$

[F] is the resistance matrix

[L] is the induction matrix

[C] is an unknown column matrix containing the coefficients of the trial functions

and [H] is a column matrix describing the interaction of the primary magnetic field with each trial function.

Annan chose to use scaled Chebychev polynomials for the trial functions because they are relatively simple to manipulate and they quickly converge to the true potential function near the edges of the plate. Thus,

$$\phi_{nm} = (1-x^2)(1-y^2)T_n(x)T_m(y)$$

where  $T_n$  is a Chebychev polynomial of the first kind and order n

$x = x/a$ ,  $a$  is half the strike length of the plate

and  $y = y/b$ ,  $b$  is half the width of the plate.

If a maximum polynomial order of  $M$  is desired, then  $n+m \leq M$  and the number of trial functions to be used in the solution is given by:

$$N = (M+1)(M+2)/2.$$

In the above development,  $\phi_i$  is the  $i^{\text{th}}$  element of a row vector  $[\phi]$  containing the  $N$  trial functions:  $[\phi] = [\phi_{00}, \phi_{10}, \phi_{01}, \phi_{20}, \phi_{11}, \dots, \phi_{0M}]$ . Thus, once the column matrix  $[C]$  is found,  $U$  can be approximated by:

$$U \approx [\phi][C]. \quad (\text{C.6})$$

#### C.4 The Weighted Eigenvector Method

The unknown coefficient matrix  $[C]$  must be found by inverting the matrix operator  $[Z] = ((1/\sigma_s)[F] - iw\mu_0[L])$ . Annan found that a very useful way of doing this was by the weighted eigenvector method. This method was possible since the Galerkin method ensured  $[F]$  to be positive definite and ensured both  $[F]$  and  $[L]$  to be symmetric. The method is a powerful one because it decouples the response of the plate into its electrical and geometrical factors as shown below. Also, by rewriting the induction equation, the inversion only needs to be done once for a given width-to-length ratio of the plate.

The resistance matrix can be written as:

$$[F] = \int_{-a}^a \int_{-b}^b \left\{ \left[ \frac{\partial \phi(x,y)}{\partial x} \right]^T \left[ \frac{\partial \phi(x,y)}{\partial x} \right] + \left[ \frac{\partial \phi(x,y)}{\partial y} \right]^T \left[ \frac{\partial \phi(x,y)}{\partial y} \right] \right\} dx dy$$

By using the change of scale:  $X=x/a$ ,  $Y=y/b$ , we get

$$[F] = \frac{b}{a} \int_{-1}^1 \int_{-1}^1 \left\{ \left[ \frac{\partial \phi(X,Y)}{\partial X} \right]^T \left[ \frac{\partial \phi(X,Y)}{\partial X} \right] + \frac{a^2}{b^2} \left[ \frac{\partial \phi(X,Y)}{\partial Y} \right]^T \left[ \frac{\partial \phi(X,Y)}{\partial Y} \right] \right\} dX dY$$

Similarly,

$$[L] = \frac{b^2}{a} \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 \int_{-1}^1 g_N(X,X',Y,Y') \left\{ \left[ \frac{\partial \phi(X,Y)}{\partial X} \right]^T \left[ \frac{\partial \phi(X',Y')}{\partial X'} \right] \right\}$$

$$+ \frac{a^2}{b^2} \left[ \frac{\partial \phi(X,Y)}{\partial Y} \right]^T \left[ \frac{\partial \phi(X',Y')}{\partial Y'} \right] \} dX dY dX' dY'$$

and

$$[H] = b \int_{-1}^1 \int_{-1}^1 [\phi(x, y)]^T H_{3N}(x, y) dx dy$$

$$\text{where } g_N(x, x', y, y') = \frac{1}{4\pi} ((x-x')^2 + \frac{b^2}{a^2} (y-y')^2)^{-1/2}$$

$$= \frac{1}{4\pi R_N}, \quad R_N = R/a$$

$$\text{and } H_{3N}(x, y) = a H_3(x, y).$$

Thus,  $g_N$  and  $H_{3N}$  are the Green's function and  $H_3$  field in the coordinate system normalized to  $a$ .

It can be seen that by normalizing the coordinate system to the half strike length ( $a$ ), the integrals can be evaluated once the ratio  $b/a$  is specified. Thus, the whole procedure needs only to be done once for a specified ratio. By writing the integral parts of the above equations with the subscript  $N$ , the induction equation can be written as:

$$\left\{ \frac{1}{\sigma_s} \frac{b}{a} [F_N] - i\omega \mu_0 \frac{b^2}{a} [L_N] \right\} [C] = -i\omega \mu_0 b [H_N]$$

$$\text{or } \left\{ \frac{1}{\sigma_s} [F_N] - i\omega \mu_0 b [L_N] \right\} [C] = -i\omega \mu_0 a [H_N] \quad (C.7)$$

It is to this equation that Annan applied the weighted eigenvector method.

By specifying the width-to-length ratio of the plate ( $b/a$ ) and the maximum polynomial order (related to the number of trial functions), the matrices  $[F_N]$  and  $[L_N]$  can be evaluated (see Appendix E). The matrix  $[F_N]$  is diagonalized by finding its eigenvectors so that

$$[e_F]^T [F_N] [e_F] = [D(f_i)]$$

where  $[e_F]$  contains the eigenvectors of  $[F_N]$

and  $[D(f_i)]$  is a diagonal matrix containing the eigenvalues of  $[F_N]$ .

$$\text{Then } [v]^T [F_N] [v] = [I] \quad (\text{C.8})$$

where  $[v] = [e_F]^T [D^{-(1/2)}(f_i)]$

and  $[D^{-(1/2)}(f_i)]$  contains the inverse square root of the eigenvalues.

By using the same transformation on  $[L_N]$ , we get:

$$[L'_N] = [v]^T [L_N] [v]$$

so that the transformed matrix operator  $[Z]$  becomes:

$$[Z'] = \frac{1}{\sigma_s} [I] - iw\mu_0 b [L'_N].$$

Now the eigenvectors and eigenvalues of  $[Z']$  can be found from:

$$[Z'][e'_z] = [e'_z] [D(\lambda_i)] \quad (\text{C.9})$$

where  $[e'_z]$  contains the eigenvectors of  $[Z']$

and  $[D(\lambda_i)]$  is a diagonal matrix containing the eigenvalues of  $[Z']$ .

Thus

$$\left\{ \frac{1}{\sigma_s} [I] - iw\mu_0 b [L'_N] \right\} [e'_z] = [e'_z] [D(\lambda_i)]$$

and

$$[L'_N][e'_z] = [e'_z] \xrightarrow{iw\mu_0 b} \left[ D\left(\frac{1}{\sigma_s} - \lambda_i\right) \right]$$

Therefore, the matrix  $[e'_z]$  can be evaluated by determining the eigenvectors of  $[L'_N]$ . The eigenvalues ( $\lambda_i$ ) of  $[L'_N]$  are given by:

$$[D(\lambda_i)] = \frac{1}{iw\mu_0 b} \left[ D\left(\frac{1}{\sigma_s} - \lambda_i\right) \right]$$

so that

$$\lambda_i = \frac{1}{\sigma_s} - iw\mu_0 b l_i. \quad (\text{C.10})$$

Using equation C.8, equation C.9 can be written as:

$$\begin{aligned} & [D^{-(1/2)}(f_i)] [e_F]^T [Z] [e_F] [D^{-(1/2)}(f_i)] [e'_z] \\ &= [D^{-(1/2)}(f_i)] [e_F]^T [F_N] [e_F] [D^{-(1/2)}(f_i)] [e'_z] [D(\lambda_i)]. \end{aligned}$$

Thus, by defining  $[e_z] = [e_F] [D^{-(1/2)}(f_i)] [e'_z]$  (C.11)

we get

$$[D^{-(1/2)}(f_i)] [e_F]^T [Z] [e_z] = [D^{-(1/2)}(f_i)] [e_F]^T [F_N] [e_z] [D(\lambda_i)]$$

or

$$[Z] [e_z] = [F_N] [e_z] [D(\lambda_i)] \quad (C.12)$$

which is the weighted eigenvector equation. Thus, the eigenvalues in this equation are found from the eigenvalues of  $[L'_N]$  using equation C.10 and the eigenvectors are found from the eigenvectors of  $[L'_N]$  using equation C.11. Now by premultiplying equation C.12 with  $[e_z]^T$  and using equations C.11 and C.8 we get:

$$[e_z]^T [Z] [e_z] = [D(\lambda_i)]$$

and therefore  $[Z]^{-1} = [e_z] [D(\frac{1}{\lambda_i})] [e_z]^T$ .

Using this equation,  $[C]$  can now be determined from equation C.7 as:

$$[C] = -iw\mu_0 a [e_z] [D(\frac{1}{\lambda_i})] [e_z]^T [H_N]$$

and finally, using equation C.6 we have:

$$U = [\phi] [e_z] [D(w)] [e_z]^T [H_N]$$

where  $[D(w)] = [D(\frac{-iw\mu_0 \sigma_s a}{1-iw\mu_0 \sigma_s b l_i})]$

and  $[D(t)] = [D(\frac{-a}{b l_i \tau_i}) e^{-(t/\tau_i)}]; \quad \tau_i = \mu_0 \sigma_s b l_i$ .

These are related by the Fourier transform.

### C.5 Results

The potential distribution over the plate is now completely decoupled. Matrix  $[e_z]$  can be found after specifying the width-to-length ratio of the plate and the maximum polynomial order. The row vector  $[\phi][e_z]$  then represents the N "eigenpotentials" ( $P_i$ ) from which the eigencurrents are computed. Figure C.1 shows the first eight eigenpotentials for a plate of length twice its width. The

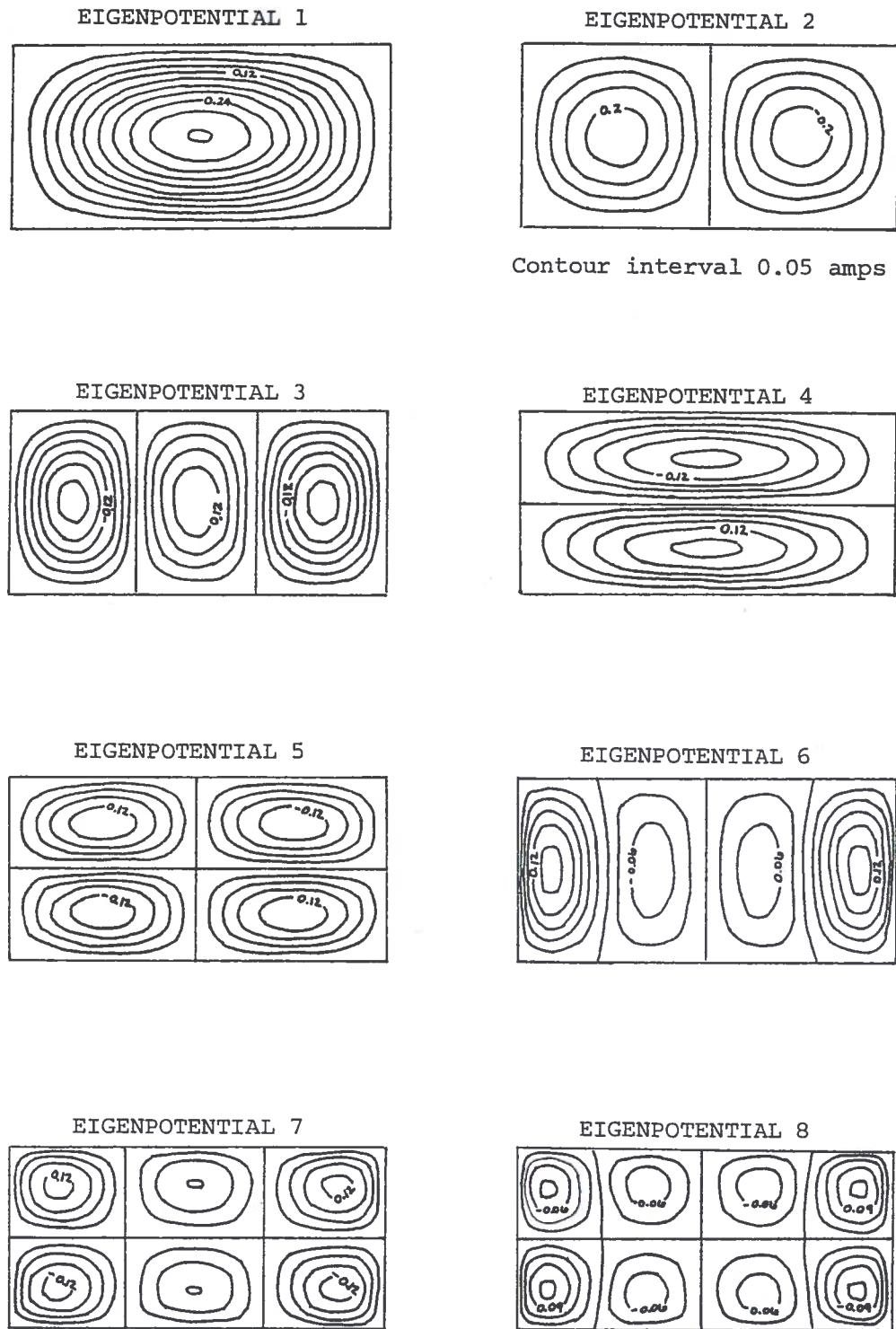


Figure C.1 Contour diagrams of the first 8 eigenpotentials for a plate of length twice its width (after Annan, 1974). Contour interval 0.03 except where noted.

eigencurrents can be visualized by following the contour lines. There are two coefficient matrices for these eigenpotentials:  $[D(\frac{W}{t})]$  and  $[e_z]^T[H_N]$ . The diagonal matrix  $[D(\frac{W}{t})]$  depends on the plate size and conductance, as well as the time or frequency parameters. These can be called the "electrical coefficients" ( $D_i$ ) of the response. The column vector  $[e_z]^T[H_N]$  depends only on the flux of  $H$  through the sheet and these are called the "excitation coefficients" ( $H_i$ ) of the response. Thus, the potential distribution is given approximately by:

$$U(r, \frac{W}{t}) \approx \sum_{i=1}^N P_i(r) D_i(\frac{W}{t}) H_i.$$

The current distribution is then found from:

$$\underline{K}_e(r, \frac{W}{t}) = \nabla U(r, \frac{W}{t}) \times \hat{\underline{e}}_3.$$

Finally, the secondary field produced by the plate can be found from the current distribution by using the Biot-Savart Law.

This process for finding the secondary magnetic field of the plate, is done more conveniently by determining the three magnetic field components produced by each trial function, multiplying these by the matrix  $[e_z]$ , and calling them the "secondary field coefficients". The secondary field is then given by:

$$\underline{H}_s(r, \frac{W}{t}) = \sum_{i=1}^N S_{x_i}(r) D_i(\frac{W}{t}) H_i \hat{i} + \sum_{i=1}^N S_{y_i}(r) D_i(\frac{W}{t}) H_i \hat{j} + \sum_{i=1}^N S_{z_i}(r) D_i(\frac{W}{t}) H_i \hat{k}$$

where  $S_{x_i}$ ,  $S_{y_i}$ ,  $S_{z_i}$  are the three secondary field coefficients for the  $i^{th}$  eigenpotential

$D_i$  is the  $i^{th}$  electrical coefficient  
and  $H_i$  is the  $i^{th}$  excitation coefficient.

## APPENDIX D

### USER'S MANUAL

#### D.1 Introduction

This appendix contains detailed information for the use of programs PLATEF, BATCHF, and EIGCUR. This program package calculates the EM response of a conductive, rectangular, thin plate of any size, location, and orientation in free space. The energizing source consists of a fixed, segmented loop of arbitrary geometry, and both the primary and secondary vector fields are measured along a completely arbitrary profile line.

Program EIGCUR is used to maintain a suite of binary data files which contain the eigenvalues and eigenvectors used in the eddy current approximation. Program PLATEF reads these files, sets all the model parameters interactively, and outputs the final synthetic data in an ASCII file. The numerical computations within program PLATEF, can be performed in batch mode (no user intervention) using the program BATCHF.

#### D.2 Features

1. The package can be run with reasonable speed on a medium-sized microcomputer. For example, the largest program, PLATEF, requires 200 KB of RAM on an IBM-PC and its run time, once the model parameters have been set, is approximately 30 seconds + 9 seconds per station (using an 8087 math co-processor chip). This means that it is now feasible to use plate modelling in the field for curve matching.
2. Since the eddy current distribution in the plate is approximated using 15 eigencurrents, early time (or high frequency) information is quite reliable (see Accuracy and Limitations).

3. Waveform and channel defaults are built-in to the program for the following systems: Crone digital PEM, Crone analog PEM, Geonics EM37, UTEM, and Sirotem. While these defaults represent the most frequently used configurations, all waveform and channel parameters can be freely changed.
4. The final output can be expressed in any of the common output units, and all the various system gains and polarity conventions are accounted for. This is accomplished by accounting for the transmitter current, the effective receive coil area and gain, the direction of the primary field, and the pointing of the receive coil. The available units are: nanoteslas/sec or nanovolts/square meter, Crone units, microvolts/amp., and percent of primary. This feature allows the user to directly compare field data with model data for any common fixed loop time-domain EM system.
5. The geometrical relationships between the transmitter, plate, and receiver are calculated and described in great detail. The transmitter-plate geometry is described through primary H field values at the plate corners and plate center. This allows the user to determine how well and in which direction the plate is coupled with the Tx loop.

The transmitter-receiver geometry is described through primary field readings as seen by the receiver. This allows the user to compare theoretical primary field readings with real field data, if available. The peak transmitter current in the model can then be adjusted accordingly, or fine adjustments can be made to the borehole geometry until a suitable match is achieved.

The receiver-plate geometry is described through a number of critical points and distances. The point and angle of intersection of the plate plane and the profile line is computed, and this point may coincide with minor mineralization detected in boreholes. The closest approach of the profile to the plate is also computed, and this point should coincide with the maximum amplitude of the secondary vector field in the field data. Short and parallel

profiles are also detected and suitably described.

The position and orientation of the plate can be easily changed until these critical points meet with the user's approval.

6. The user is given a clear, concise summary of the model geometry and any part of the model can be changed easily and quickly, through menu selection, before any lengthy calculations are performed. In addition to the extensive internal looping, the user can quickly step through the program both forwards (with a "carriage-return" to accept the default value) and backwards (with a ^Z).
7. Many input checks and warnings are provided. All input values are tested to ensure that they fall within a valid range. Warnings include those for above-surface reference points, file existence or non-existence, and lengthy calculations.
8. The model parameters and the results of all lengthy calculations can be saved permanently for future use. This feature is especially useful when several models with similar geometries are being used.
9. Any number of stations along a profile can be modelled.
10. The responses from any number of models can be calculated in batch mode without any loss of efficiency or flexibility. Since the creation of the batch file within PLATEF is completely transparent to the user, all options are still available, including the use of files for reading and saving model parameters and coefficients. Later, program BATCHF, will perform all the necessary calculations without any need for user input.
11. The final output, as well as being written to a file, can be listed on the user's terminal. This allows the user to compare synthetic data with field data without leaving the program.

### D.3 Specifications and Requirements

These programs are executable on an IBM-PC or compatible with at least two disk drives, under PC-DOS or MS-DOS v2.0 or later. They have been written in FORTRAN 77 and compiled with the IBM Professional FORTRAN Compiler. This means that the 8087 math coprocessor chip must be available to the program. There are no special video requirements since the I/O is all in text mode. PLATEF, which requires approximately 200 KB of RAM, is the largest of the three programs.

### D.4 Accuracy and Limitations

One of the key parameter required by program EIGCUR is the maximum polynomial order ( $P$ ) to be used in the numerical approximation. With increasing values of  $P$ , more "eigencurrents" are used to represent the eddy current distribution in the plate, and thus, the approximation improves. Since the number of trial functions is given by  $(P+1)(P+2)/2$ , a maximum polynomial order of 4 results in the use of 15 eigencurrents. This number appears to strike a good balance between program efficiency and numerical accuracy, and thus, it has been used as the upper limit in both EIGCUR and PLATEF. Increasing this limit would result in larger program sizes and increased computation time.

Errors may result when the eddy current pattern in the plate is very complicated such as when the transmitter is very close to one part of a large plate. When the receiver is close to the plate (approximately 0.25 of the strike length), the plate is divided into smaller cells for the numerical integration. This division may not be fine enough for a very close receiver, and errors may result here as well. A final obvious limitation of the programs is that they will only model single, isolated plates in free space, and thus, host rock conductivity must be negligible.

### D.5 General I/O Structure

In order to be able to use this package effectively, it is very important to know precisely what each program does, what it requires in the form of input, and what it provides in the form of output. Figure D.1 is a schematic representation of the programs, showing their inputs and outputs.

Program PLATEF is the main program within the package. It calculates the EM response of a conductive plate in free space when energized from a fixed loop source. Although it is based on the U of T PLATE program, it is essentially a new program in that it offers the user a plethora of new options and features. It requires 200 KB of RAM on an IBM-PC, and its run time, once the model parameters have been set, is approximately 30 seconds + 9 seconds per station.

PLATEF requires the following input (recommended filename extension is in square brackets):

- interactive terminal input (model parameters etc.)
- unformatted file containing the eigenvectors and eigenvalues of the current distribution [.P4]
- unformatted file containing parameters and coefficients of a previous model (optional) [.COF]
- free-format file containing non-standard time or frequency parameters (optional) [.PAR]

PLATEF provides the following output (recommended filename extension is in square brackets):

- interactive terminal output
- unformatted file containing the model parameters and coefficients for future modelling (optional) [.COF]
- unformatted file containing model partameters to be used by program BATCHF (optional) [.BCH]
- formatted ASCII file containing the final synthetic data [.SYN]
- formatted diagnostic file containing all the model parameters and intermediate values for debugging (optional) [.DIG]

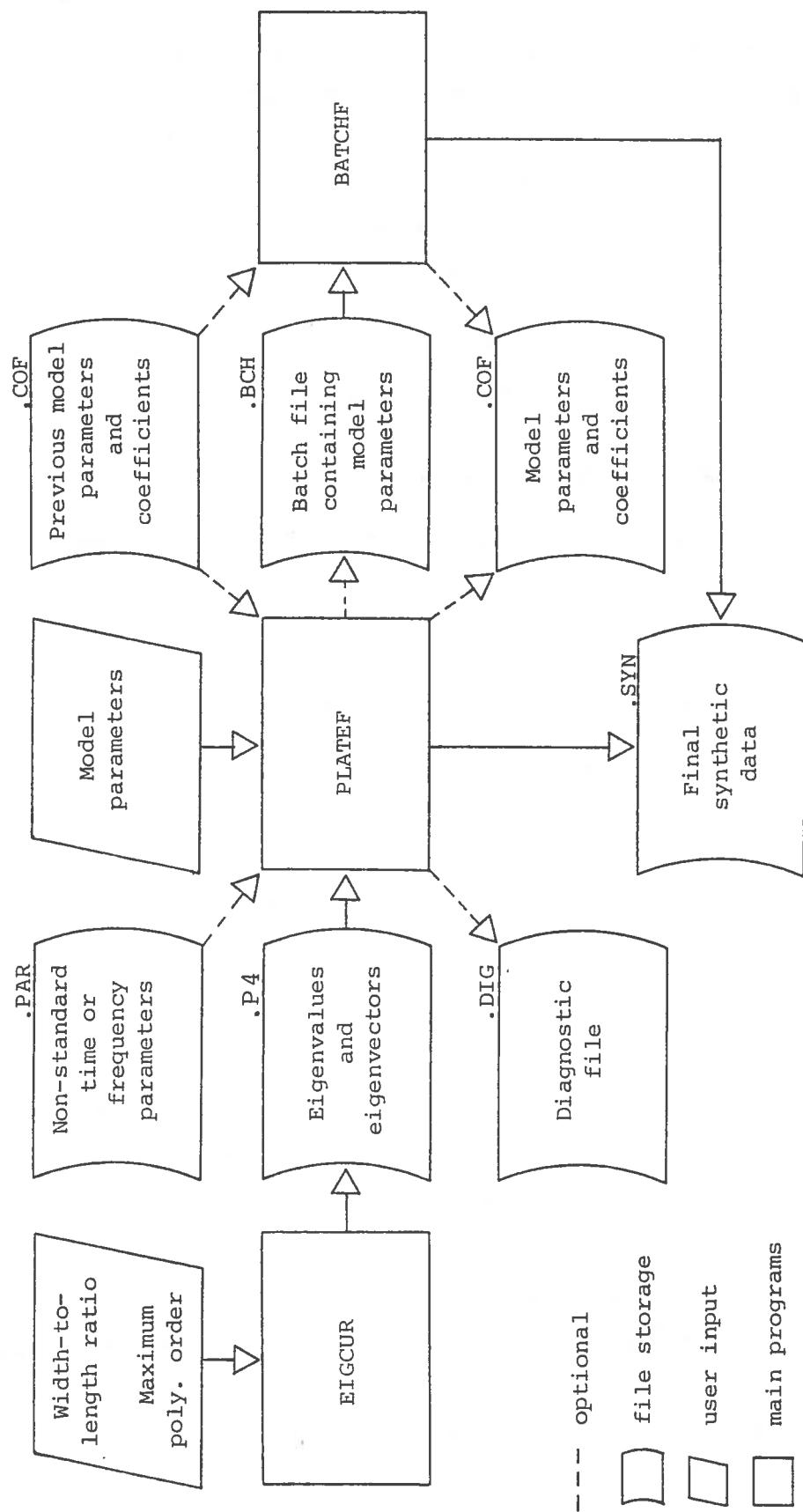


Figure D.1 Program inputs and outputs.

Program EIGCUR calculates the eigenvectors and eigenvalues needed by program PLATEF for the eddy current approximation and writes them to a binary data file. EIGCUR also allows these eigenfunctions to be re-written into an ASCII file so that they can be inspected. Normally, PLATEF will require only one binary data file for a given width-to-length ratio of the plate, so that once a suite of data files has been prepared for various ratios, EIGCUR will be rarely used. EIGCUR requires approximately 95 KB of RAM, and has a maximum execution time (when the maximum polynomial order is 4) of approximately 26 minutes.

EIGCUR requires the following input:

- interactive terminal input (plate ratio, maximum polynomial order, and filenames)
- or
  - binary or ASCII eigenfunction data file to be reformatted

EIGCUR provides the following output:

- binary data file containing the eigenfunctions
- or
  - re-written data file - binary from ASCII or ASCII from binary

Program BATCHF performs the numerical calculations for any number of models which have been set up by program PLATEF. Although BATCHF is not an essential program, its use may be convenient when large suites of models are being prepared. This program requires 105 KB of RAM on an IBM-PC and has a run time of approximately 30 seconds + 9 seconds per station for each model when all coefficients must be calculated.

BATCHF requires the following input (recommended filename extensions are in square brackets):

- interactive terminal input (batch filename)
- unformatted batch file created by program PLATEF [.BCH]
- unformatted file containing parameters and coefficients of a previous model (optional) [.COF]

BATCHF provides the following output:

- unformatted file containing the model parameters and coefficients for future modelling (optional) [.COF]
- formatted ASCII file containing the final synthetic data [.SYN]

#### D.6 Data Entry and Program Control

The following features are common to the use of all the programs:

1. A reply of '^Z' to any prompt will normally result in the repetition of the previous prompt. In some cases, where backtracking is impossible, the present prompt is simply repeated. In any case, the '^Z' reply will not cause errors, and in fact, it should be used frequently.
2. Default values are presented for most of the data requirements. When a default value is presented, it can be accepted with a carriage-return (<CR>).
3. Both uppercase and lowercase responses can be used. Thus, if a prompt asks for either a 'Y' or a 'N', a 'y' or a 'n' will also be accepted.
4. When an error is detected on reading user input, the prompt is simply repeated. If the error consists of an improper data type, the error message "\*\*\* ERROR - WRONG DATA FORMAT \*\*\*" is displayed and the prompt is repeated.
5. If applicable, data input is checked for falling within a certain range of values and if this test fails, the prompt is repeated.
6. When an existing file needs to be opened, the program checks the specified filename for file existence and warns the user if this test fails.
7. When a new file needs to be opened, the program checks the specified filename for file existence, and asks the user for permission to overwrite the file if it exists.

## D.7 Program Descriptions

The following pages provide complete descriptions of the monitor I/O which might be encountered in each program. Also provided is a step-by-step explanation of each program. The special symbols which are used in this documentation are:

- > to represent monitor output
- a> to identify a sub-step in the monitor output
- [ ] to enclose the possible user responses
- < > to enclose a description of the user response (eg. <filename>)
- <CR> to represent a carriage-return
- ^Z to represent a control-Z
- { } to enclose an explanation of the monitor I/O.

### D.7.1 Program PLATEF

There are 18 basic steps within program PLATEF. They are:

1. Start the program.
2. Specify the output drive and pathname.
3. Open a batch file if desired.
4. Read a coefficient file if desired and go to step 9.
5. Get eigenfunctions from file.
6. Input the plate geometry.
7. Input the transmitter loop geometry.
8. Input geometry of profile.
9. Approval of geometrical information.
10. Select changes to model geometry.
11. Input electrical parameters and gains.
12. Approval of electrical parameters.
13. Select changes to electrical parameters.
14. Preview the primary field readings if desired.
15. Write model parameters to coefficient, batch, and final data files.
16. Establish monitor display of final results.
17. Combine coefficients and write to monitor and output files.
18. Go back for another model or close files and stop.

PLATEF Step 1: Start the program.

MONITOR I/O:

{To start the program, take a blank, formatted diskette, label it "Model Data" and place it in drive B:. Place the "PLATEF" diskette in drive A: and type:

PLATEF

The program will load for approximately 15 seconds, and finally, the following announcement appears.}

```
->
->
->          ELECTROMAGNETIC MODELLING
->          of a
->          CONDUCTIVE PLATE IN FREE SPACE
->
->
->          PLATEF 1.00
->
->
->          Computes the response from fixed-loop EM systems
->          based on the U of T PLATE program
->
->
->          by
->          W.R. Ravenhurst
->          (C) CRONE GEOPHYSICS LTD. 1986
->          for
->          CRONE GEOPHYSICS LIMITED
->          In-House Copy for Demo and Use
```

EXPLANATION:

The user's name is located in the bottom right-hand box. This name will also appear on the top line of the output files.

PLATEF Step 2: Specify the output drive and pathname.

MONITOR I/O:

```
-> Enter prefix to be used for batch, coefficient, and final data files  
-> (N for none) The default is B:>  
  
[<drive:\path1\path2\...>]: {This string will be prefixed to output  
filenames which do not include a drive or pathname.}  
[N]: {No prefix is used}
```

EXPLANATION:

Normally, the default value of B: is accepted with a <CR> so that output files will be sent to the diskette in drive B:. This is done because of the limited space remaining on the PLATEF diskette. If a drive and pathname are entered here, then a subdirectory corresponding to the specified pathname should exist on the specified drive.

PLATEF Step 3: Open a batch file if desired.

MONITOR I/O:

a) Do you wish to create a batch file? (Y or N) The default is N >

[^Z]: {Go to step 2}  
[N]: {Go to step 4}  
[Y]: {Go to 3b}

b) Specify name of batch file [B:] >

[^Z]: {Go to 3a}  
[<filename>]: {The drive specified in the prompt is prefixed if no drive or pathname is included in the filename.  
{The file is opened to prepare for writing.}

EXPLANATION:

The batch file option allows the user to set the geometrical and electrical parameters for an unlimited number of models without the bother of waiting for the completion of lengthy calculations between model specifications. The batch file creation is completely transparent to the user, and hence, all the options within PLATEF are still available, including the use of files for reading and saving the model parameters and coefficients. The only noticeable difference is, of course, that the coefficient calculations are not performed, and the final data file is not created. The batch file can be used later by program BATCHF to complete the calculations.

The file remains open until specifically closed by the user, or until some sort of disk I/O error occurs. The number of models which can be stored in a batch file is limited only by the available disk space. However, in addition to reading the batch file and any necessary coefficient files, program BATCHF must also have enough room for writing the specified output files. Thus, on systems using 360K diskettes for data storage, it would be wise to limit the number of batch models to about 15 when coefficient files are being heavily used as well.

PLATEF Step 4: Read a coefficient file if desired.

MONITOR I/O:

a) Do you want to read an existing coefficient file? (Y or N).  
-> The default is N >

[^Z]: {Go to step 3}  
[N]: {Go to step 5}  
[Y]: {Go to 4b}

b) Specify name of coefficient file to be read [B:] >

[^Z]: {Go to 4a}  
[<filename>]: {The drive specified in the prompt is prefixed if no  
drive or pathname is included in the filename.}  
{The file is opened to prepare for reading.}

EXPLANATION:

As outlined in Step 15, all the parameters and coefficients of a particular model can be saved in a so-called "coefficient save file". If this has been done for a previous model, and the present model has many geometrical similarities, it is both convenient and more efficient to simply read this file and then make the necessary changes to the parameters. The user should establish a file-naming convention or maintain a table to help in associating the coefficient files with the models they represent. This is important because the files are unformatted, and can therefore, only be inspected through their use within the program.

PLATEF Step 5: Get eigenfunctions from file.

## MONITOR I/O:

```

->          EIGENFUNCTION RETRIEVAL
->          ****
->
->          Specify filename for eigenfunction storage.
->
->          Choose one of the following:
->
->          Filename   Plate    Maximum      Plate    Maximum
->          Width/Length Poly Order   Width/Length Poly Order
->
->          RP1.P4    0.100     4            RP2.P4    0.200     4
->          RP25.P4   0.250     4            RP33.P4   0.330     4
->          RP4.P4    0.400     4            RP5.P4    0.500     4
->          RP67.P4   0.670     4            RP8.P4    0.800     4
->          R1P0.P4   1.000     4            R1P25.P4  1.250     4
->          R1P5.P4   1.500     4            R2P0.P4   2.000     4
->          R2P5.P4   2.500     4            R3P0.P4   3.000     4
->          R4P0.P4   4.000     4            R5P0.P4   5.000     4
->          R10P0.P4  10.000    4
->
->          The default is R1P0.P4 >

[Z]: {Go to step 4}
[<filename>]: {The specified file is opened, and the eigenfunctions
               are read.}

```

## EXPLANATION:

Program EIGCUR can be used to create more of these files which contain the eigenvalues and eigenvectors of the eddy current distribution in thin sheets of various width-to-length ratios. This ratio, and the maximum polynomial order used in approximating the distribution, are all that is needed to create these files. Thus, it is recommended that the following filenames convention be followed. The filename should start with an 'R' and the extension should start with a 'P' to reflect the two key parameters used to create the file. These parameters are used to form the rest of the filename by using a 'P' to represent the decimal point in the width-to-length ratio.

PLATEF Step 6: Input the plate geometry.

## MONITOR I/O:

```

-> PLATE GEOMETRY INPUT
-> ****
->
-> Input strike length of plate (m)
-> The default is 200.000 >
->
-> Strike (degrees, u toward v about w)
-> The default is 90.000 >
->
-> Dip (degrees, v toward w about u)
-> The default is 90.000 >
->
-> Plunge (degrees, u toward v about w)
-> The default is 0.000 >
->
-> Reference point on plate (plate limits: -1 to 1, in both u and v directions)
->
-> Specify u reference (strike direction)
-> The default is 0.000 >
->
-> Specify v reference (up-dip direction)
-> The default is 1.000 >
->
-> Enter field coordinates (x,y,z) of reference point (m) (z neg. down)
-> x: The default is 200.000 >
-> y: The default is 0.000 >
-> z: The default is -100.000 >

[^Z]: {Enter this at any point to backtrack to previous prompt}

```

## EXPLANATION:

In order to perform many of the calculations in the program, a coordinate system associated with the plate is required. In this system, the origin lies at the center of the plate, the u axis lies along its strike length, the v axis lies along its width, and the w axis is perpendicular to the plane of the plate. Three rotations and a translation are necessary to transform the x,y,z field coordinates into

plate coordinates (see Figure D.2). Starting with coincident systems, the first rotation represents the strike and consists of rotating axis u towards axis v about axis w. If one is looking down axis w (also z in this case) this is a counter-clockwise rotation of a flat plate with its strike length originally in the x-direction. The second rotation represents the dip and consists of rotating axis v toward axis w about axis u. The final rotation represents the plunge which changes the orientation of the plate within the newly defined plane. It consists of rotating axis u toward axis v about axis w.

The required translation is defined by locating the origin of the new system (the center of the plate) in the field coordinate system. In order to facilitate this procedure, any point on the plate can be chosen as a reference, and this point is then located in both systems. Locating this point in the plate system is simplified by defining the limits of the plate to be at -1 and 1 in both the u and v directions regardless of its true dimensions. Normally, the default reference point is accepted, which is located at (0,1) in these special plate coordinates. Under most circumstances (dip between 0 and 180, and plunge between -45 and 45), this corresponds to the center point of the upper edge of the plate. This seems to be a convenient reference point in many cases.

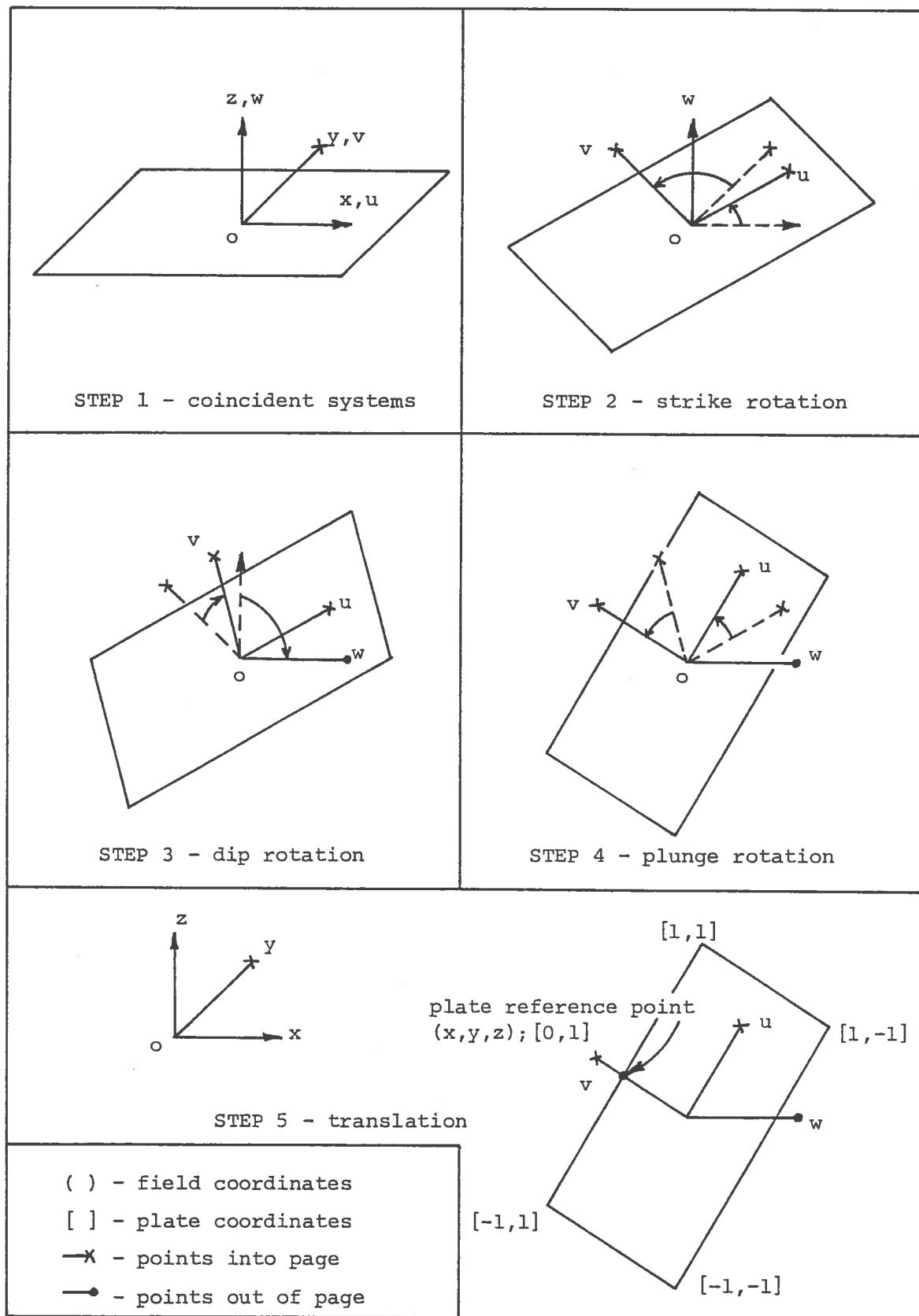


Figure D.2 Field to plate coordinate transformation.

PLATEF Step 7: Input the transmitter loop geometry.

MONITOR I/O:

```

a>      LOOP GEOMETRY INPUT
->      ****
->      Accept the default loop (2nd and 3rd quadrants)?   The default is Y >

[Z]: {Go to step 6}
[N]: {Go to 7c}
[Y]: {Go to 7b}

b>      Specify x side of loop (m)
->          The default is      400.000 >
->      Specify y side of loop (m)
->          The default is      800.000 >

[Z]: {Backtrack to 7a}
{go to step 8}

c>      Specify number of corners. (< 10)
->          The default is      4      >
->      Enter x,y,z coordinates of loop corners in clockwise order (m) (z neg down)
->          (NOTE: ^Z backwards if desired)
->          Corner  1
->              x:  The default is      -400.000 >
->              y:  The default is      -400.000 >
->              z:  The default is      0.000 >
->          Corner  2
->              x:  The default is      -400.000 >
->              y:  The default is      400.000 >
->              z:  The default is      0.000 >
->          Corner  3
->              x:  The default is      0.000 >
->              y:  The default is      400.000 >
->              z:  The default is      0.000 >

{etc.}

[Z]: {Enter this at any point to backtrack to previous prompt}

```

**EXPLANATION:**

Since the input of three coordinates for each loop corner can be a lengthy process, a four-sided default loop can be used which locates the loop in the second and third quadrants of the field coordinate system (see Figure D.3). This loop will be symmetrically placed about the x-axis, and the right-hand edge will lie along the y-axis, passing through the origin. Only the width and length of the loop need to be specified. If it is impossible to utilize the default loop, the three field coordinates of each loop corner must be specified.

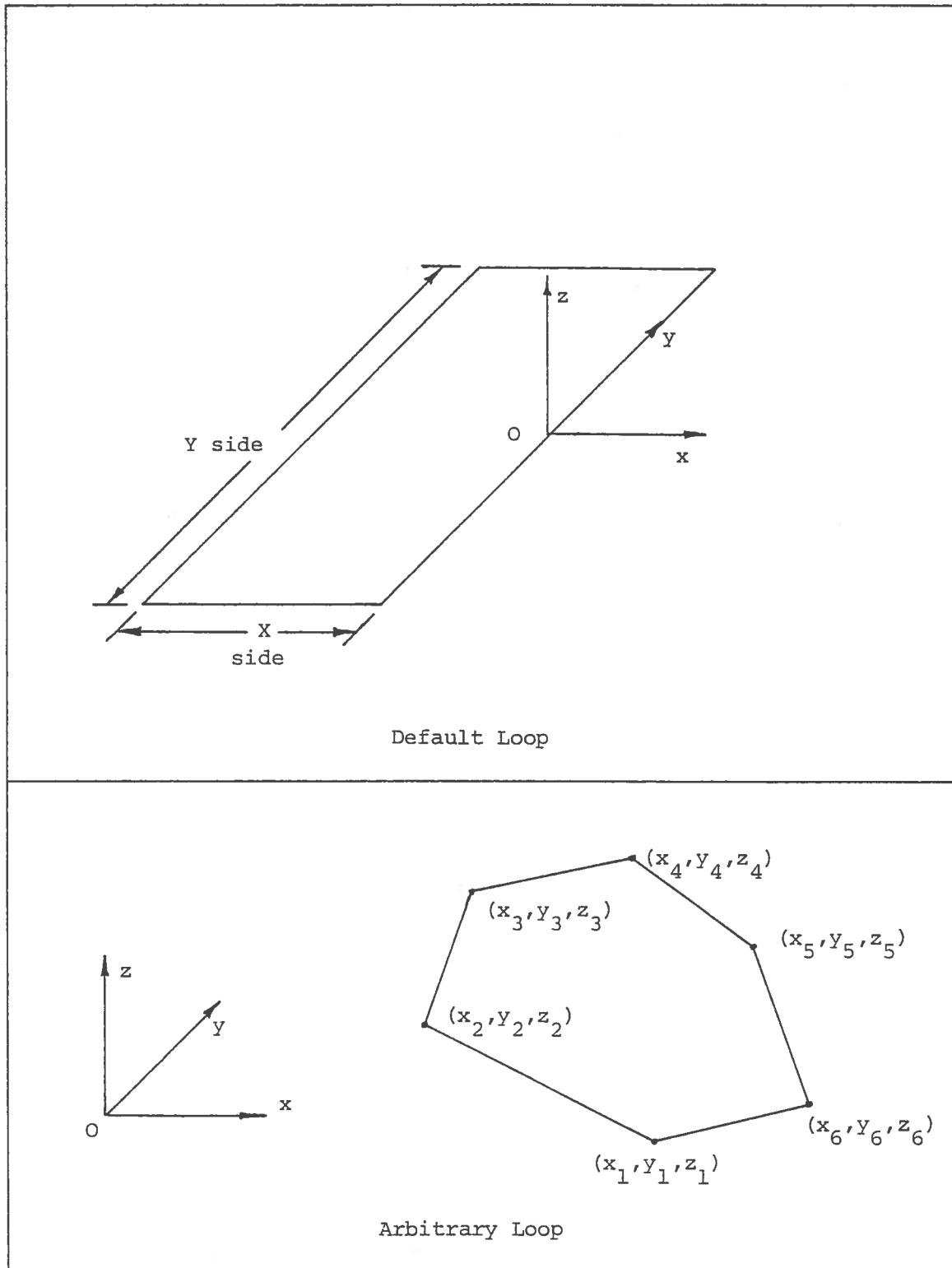


Figure D.3 Transmit loop specifications.

PLATEF Step 8: Input geometry of profile.

## MONITOR I/O:

```

-> PROFILE GEOMETRY INPUT
-> ****
-> Enter x,y,z coordinates of profile reference point (m) (z neg down)
-> (i.e. starting point or borehole collar)
-> x: The default is 0.000 >
-> y: The default is 0.000 >
-> z: The default is 0.000 >
-> Enter starting distance from profile reference point (m)
-> The default is 0.000 >
->
-> Enter LENGTH of profile (m) The default is 400.000 >
-> Enter station INTERVAL (m) The default is 20.000 >
-> Enter THETA in degrees (down from vertical z-axis)
-> The default is 90.000 >
-> Enter PHI in degrees (counter-clockwise from x-axis)
-> The default is 0.000 >

[^Z]: {Enter this at any point to backtrack to the previous prompt}

```

## EXPLANATION:

The starting point of the profile is located by specifying the coordinates of a reference point on the profile line, and a distance from this point to the starting point (see Figure D.4). This is convenient for angled drillholes, where the collar coordinates and starting depth are known. For surface profiles, the starting point can be specified as the reference point, and the starting distance set to 0.

Since the orientation of the profile is entirely arbitrary, a number of geometrical specifications are required. These profile specifications are defined as follows: the profile length is measured from the starting point; the interval is the constant separation between stations; theta is measured in degrees down from the vertical; and phi is measured in degrees counter-clockwise from the x-axis.

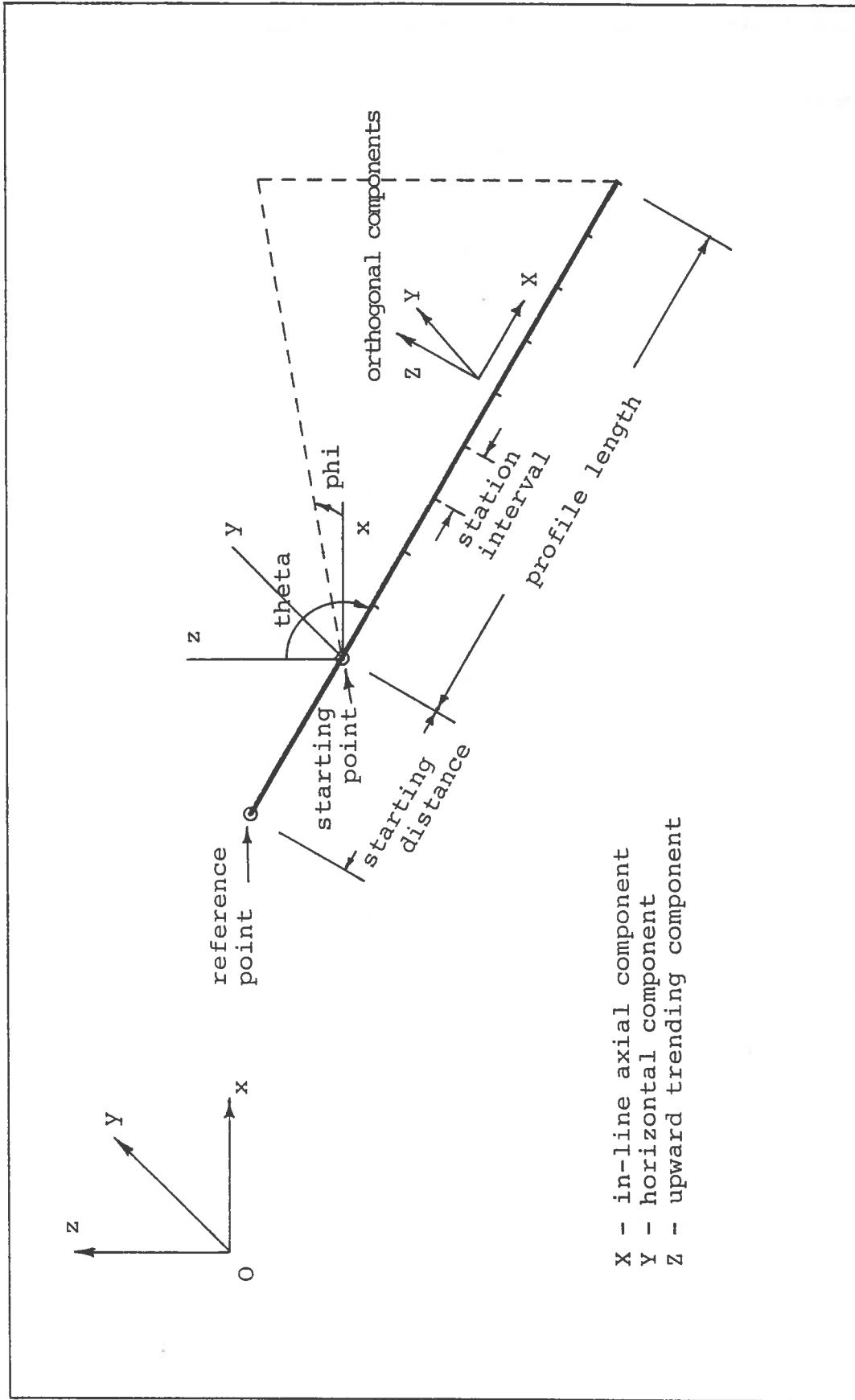


Figure D.4 Profile specifications and profile components.

PLATEF Step 9: Approval of geometrical information.

MONITOR I/O: (sample)

```

->                                GEOMETRICAL INFORMATION

->
->      Maximum polynomial order:        4      Width-to-length ratio:    1.000
->      Strike length of plate:       100.00      Width of plate:        100.00
->      Strike:        75.00      Dip angle:        80.00      Plunge:          10.00
->      Plate ref. point:  Plate ( 0.0000, 1.0000)  Field ( 120.0,     0.0,   -80.0)
->      Plate points in field coordinate system:  Center ( 130.5,      6.2,  -128.5)
->      Corner 1 ( 131.3,     48.0,   -71.4)  Corner 2 ( 108.7,   -48.0,   -88.6)
->      Corner 3 ( 129.7,   -35.6,  -185.5)  Corner 4 ( 152.3,     60.3,  -168.4)
->      Tx loop: 4 segments           Corner coordinates: (-400.0, -400.0,     0.0)
->                               (-400.0,  400.0,     0.0) (  0.0,  400.0,     0.0) (  0.0, -400.0,     0.0)
->      H Field on Plate (A/m ; u,v,w components);  Magnitude;  Intersection Angle
->      Center: ( 1.6E-04,  1.0E-04,  5.3E-04)  5.6E-04          70.41
->      Corner 1: ( 2.0E-04,  4.0E-04,  5.2E-04)  6.9E-04          49.28
->      Corner 2: ( 2.1E-04,  3.0E-04,  6.9E-04)  7.9E-04          62.23
->      Corner 3: ( 9.6E-05, -5.9E-05,  4.3E-04)  4.5E-04          75.53
->      Corner 4: ( 1.3E-04,  1.3E-05,  4.0E-04)  4.2E-04          72.45
->      Rx line: Start( 50.0,     0.0,     0.0)  End( 250.0,     0.0,     0.0)
->      Length: 200.0      Interval: 50.0      Theta: 90.00      Phi: 0.00
->      5 stations Reference( 0.0,     0.0,     0.0)  Dist. to start: 50.0
->      Profile line intersects plate plane at station 105.4 and plate point
->          ( 10.4,  130.7,     0.0) at an angle of 72.0 degrees.
->      This point is 30.7 meters from the plate.
->      Closest approach is 78.8 meters at station 123.3 and plate point
->          ( 14.4,  50.0,     0.0).

->      Geometry ok? (Y or N)  The default is Y >

[Z]: {Go to step 10}
[N]: {Go to step 10}
[Y]: {Go to step 11}

```

**EXPLANATION:**

In this step, a clear, concise summary of the model geometry is presented to the user. All the values prompted for in steps 6, 7, and 8 are listed as well as a number of calculated values. Through the presentation of the plate corner coordinates, the primary field values at the plate corners, and the critical points and distances in the receiver-plate geometry, the user should have a clear picture of the model geometry before continuing.

The magnetic  $H$  field at each plate corner is calculated in terms of its three plate components ( $u, v, w$ ), its magnitude, and the angle at which it strikes the plate (see Figure D.5). This information is valuable in determining how well or in which direction the plate is coupled with the primary field. Since these values represent the primary field associated with 1 Amp of current in the transmitter loop, they may bear no resemblance in amplitude to the primary field readings in the final output which usually represent  $dB/dt$  and may be subjected to instrument gains.

A number of critical points and distances in the receiver-plate geometry are also calculated (see Figure D.6). The point of intersection of the plate plane and profile line is found in terms of a profile station value, as well as its plate coordinates. The distance from this point to the nearest edge of the plate is also calculated, as well as the intersection angle of the plate and the line. Next, the points of closest approach of the plate to the infinite line are found, one being expressed as a station value, and the other in plate coordinates. The actual separation distance between these two points is also calculated. Finally, additional information is gathered under special geometrical circumstances. If the profile ends before the point of least separation is reached, then the closest approach of this short profile is calculated from one of its endpoints. If the profile runs alongside the plate, then a segment of the profile is found, whose points are equally far from the plate. Other parallel profiles will have a closest approach point.

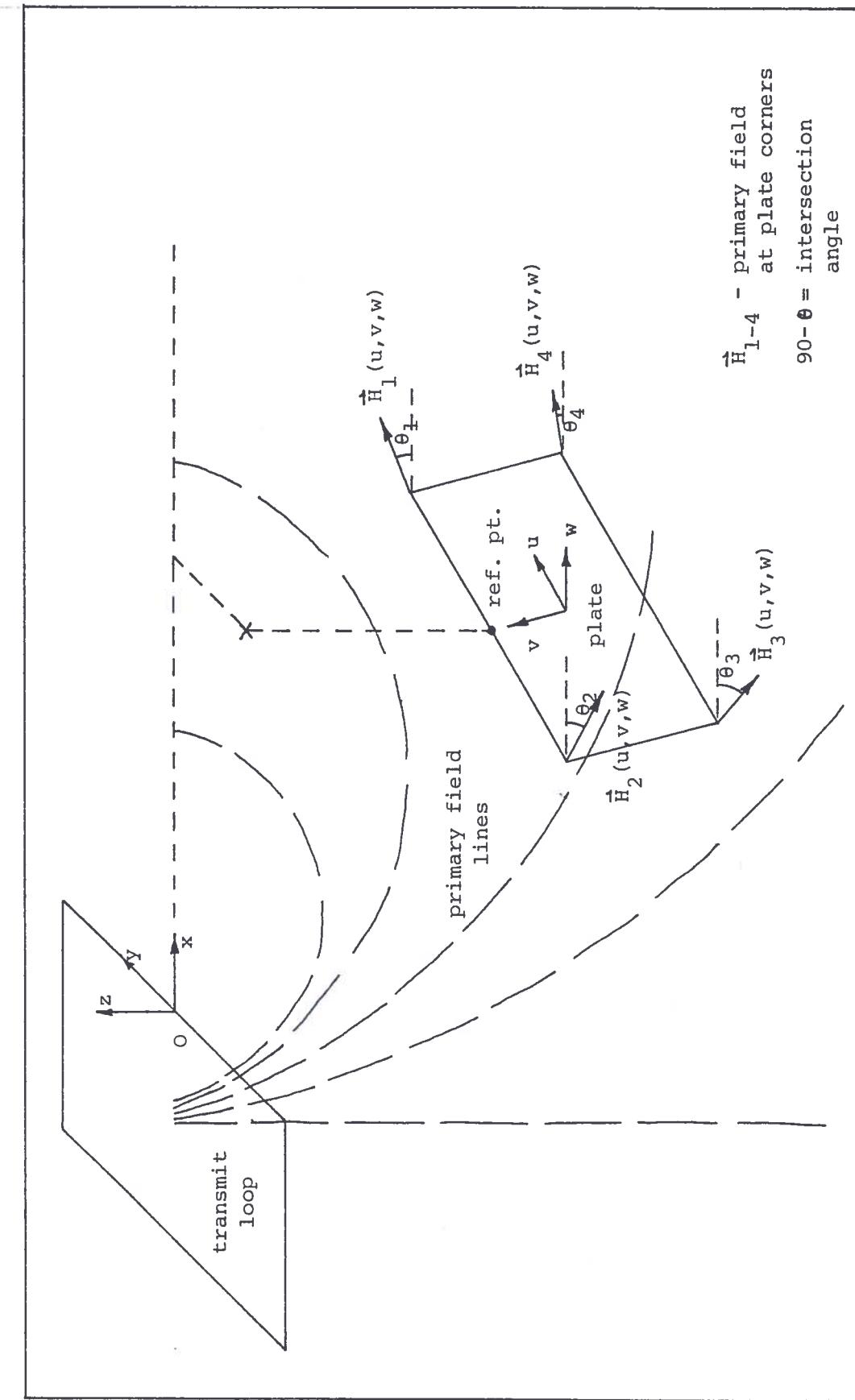
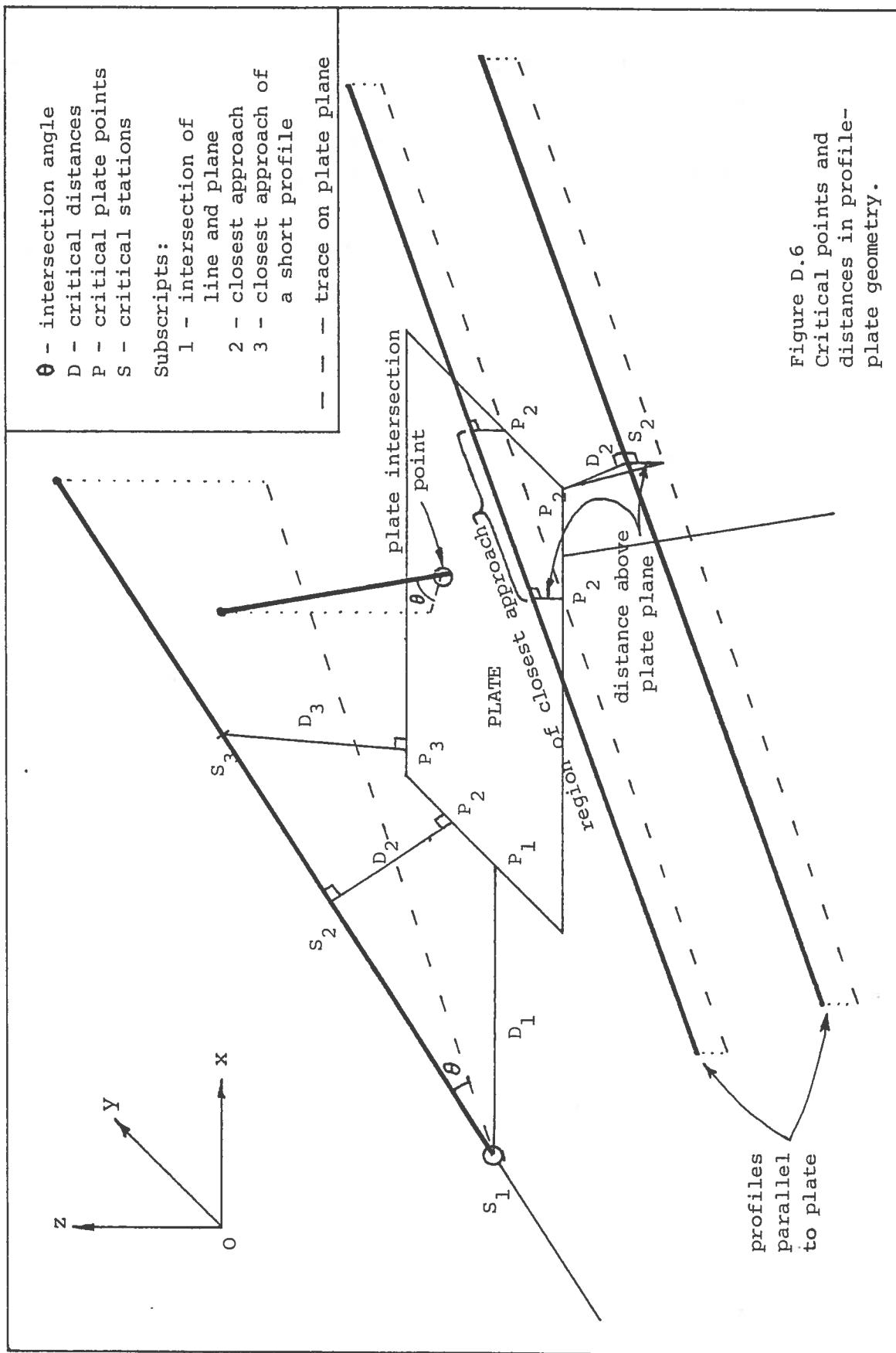


Figure D.5 Transmitter - plate geometry.



These critical points in the receiver-plate geometry may prove to be useful in complicated geometrical situations such as those involving boreholes. The point of intersection of the plate plane and the profile line can be made to coincide with minor in-hole mineralization when this mineralization is known to lie in the same geological horizon as the conductor. Also, the point of closest approach should coincide with the maximum amplitude of the secondary vector field.

The presentation of these critical points varies with the geometry.

**For short profiles:**

- > Short profile - closest approach point is not reached. End station
- > xxxxxx.x is xxxxxx.x meters from plate point (xxxxxx.x,xxxxxx.x,xxxxxx.x)

**For parallel profiles running alongside plate:**

- > Profile runs parallel xxxxxx.x meters from plate plane.
- > It runs alongside plate from station xxxxxx.x to station xxxxxx.x -->
- > plate points (xxxxxx.x,xxxxxx.x,xxxxxx.x) and (xxxxxx.x,xxxxxx.x,xxxxxx.x)

**For other parallel profiles:**

- > Profile runs parallel xxxxxx.x meters from plate plane. Station
- > xxxxxx.x is xxxxxx.x meters from plate point (xxxxxx.x,xxxxxx.x,xxxxxx.x)

**For profile line intersecting plate:**

- > Profile line intersects plate at station xxxxxx.x and plate point
- > (xxxxxx.x,xxxxxx.x,xxxxxx.x) at an angle of xxxxx.x degrees.

**For profile line missing plate:**

- > Profile line intersects plate plane at station xxxxxx.x and plate point
- > (xxxxxx.x,xxxxxx.x,xxxxxx.x) at an angle of xxxxx.x degrees.
- > This point is xxxxxx.x meters from the plate.
- > Closest approach is xxxxxx.x meters at station xxxxxx.x and plate point
- > (xxxxxx.x,xxxxxx.x,xxxxxx.x). -

PLATEF Step 10: Select changes to model geometry.

MONITOR I/O: (sample)

```
a> COEFFICIENT INPUT FILE: None
-> BATCH PROCESSING FILE: None
->
-> Choose one or more of:
-> 1 Change plate RATIO or MAX. POLY. ORDER
-> 2 Change plate ATTITUDE, SIZE or POSITION
-> 3 Change LOOP location
-> 4 Change PROFILE
-> 5 Read a COEFFICIENT FILE
-> 6 REVIEW geometry
-> 7 Geometry ok - check SYSTEM and ELECTRICAL parameters
-> 8 Change BATCH file or filename PREFIX
-> 9 STOP program
->
-> Enter chosen number(s) on 1 line in any order (eg. 8243)
-> The default is 7 >
```

```
[9]: {Stop program}
[8]: {Repeat steps 2 and 3}
[7]: {Go to step 11}
[6]: {Go to step 9}
[5]: {Repeat step 4}
[1-4]: {Go to 10b}
```

```
b> Source of coefficients (in order of decreasing computation time)
-> Sec. field coefficients: Compute
-> Excitation coefficients: Compute
-> Electrical coefficients: Compute
-> Primary field readings: Compute
-> Ok? The default is Y >
```

```
[^Z]: {Go to 10a}
[N]: {Go to 10a}
[Y]: {Repeat steps 5-8 as required}
```

**EXPLANATION:**

The first two lines of this step provide the filenames of the coefficient input file and the batch processing file. If these options are not being used, the filename is replaced with "None".

After examining the geometrical information presented in step 10, the user can easily make changes to any of the geometrical parameters. The first five options presented here are for this purpose. More than one of the first four options may be chosen. The sixth option will simply write out the geometrical information as in step 10. Option 7 provides an escape from this step, and is equivalent to approving the geometry in step 10. Option 8 allows the user to change the filename prefix or batch file specifications, while option 9 will stop the program.

If geometrical changes are requested, the new source of each coefficient is presented as either "Compute", "Read from RAM", or "Read from file". The coefficient-geometry relationship is as follows: the secondary field coefficients depend on the receiver-plate geometry; the excitation coefficients depend on the transmitter-plate geometry; the electrical coefficients depend on the plate dimensions, the conductivity - thickness, and the system parameters; and the primary field readings depend on the transmitter-receiver geometry (see Figure D.7). The electrical and excitation coefficients can be read from RAM, read from a coefficient file, or computed, while the secondary field coefficients and primary field readings are either read from a coefficient file or computed. This information can be used to monitor the efficiency of the program. Obviously, it is better to read the coefficients from a coefficient file or from RAM whenever possible. Also, one should keep in mind that the list is presented in order of decreasing computation time. Thus, during a modelling session, the user should create coefficient files and reuse them whenever possible while changing the electrical parameters most often and the receiver-plate geometry least often.

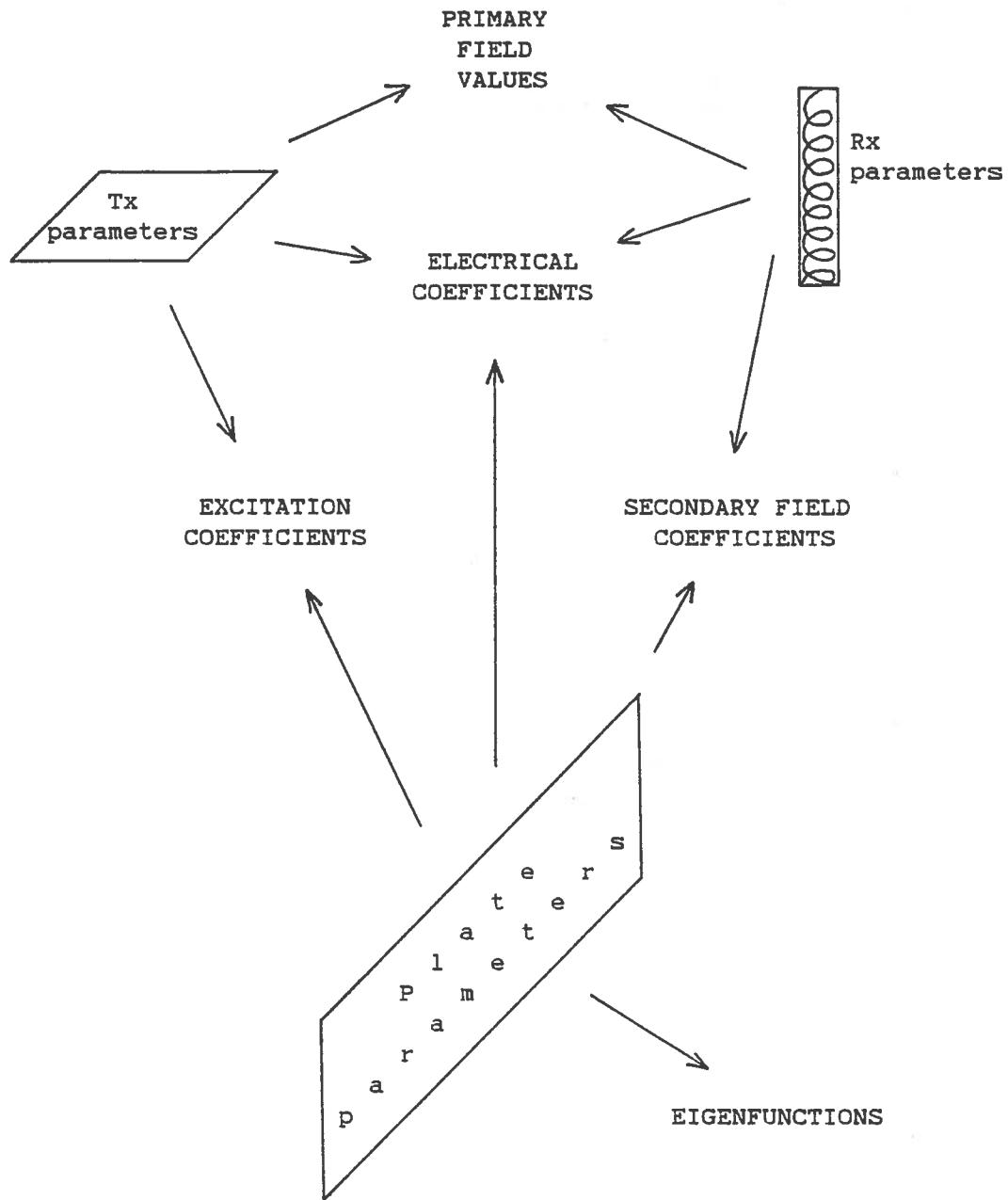


Figure D.7 Relationship between model parameters and program calculations.

PLATEF Step 11: Input electrical parameters and gains.

## MONITOR I/O:

-> SYSTEM AND ELECTRICAL INPUT  
 -> \*\*\*\*\*  
 -> a) Enter sigma-t of plate (mhos). The default is 10.000 >

[^Z]: {Go to step 10}

b) 0 Digital Crone PEM  
 -> 1 Analog Crone PEM  
 -> 2 Geonics EM37  
 -> 3 UTEM  
 -> 4 SIROTEM  
 -> Specify system desired. The default is 1 >

[^Z]: {Go to 11a}

[0-4]: {Do one or more of the following:}

{For system 1}

c) Enter length of turn-off (in sec)  
 -> The default is 1.500E-03 >  
 -> 10 or 20 millisecond time base?  
 -> The default is 10 >

[^Z]: {Backtrack to 11b}

{Go to 11k}

{For systems 0,2,3,4}

d) Accept default primary waveform? (Y or N) The default is Y >

[^Z]: {Go to 11b}

[N]: {system 3 - go to 11f; systems 0,2,4 - go to 11e}

[Y]: {Set default values and go to 11g}

e) Enter length of turn-off (in sec)  
 -> The default is 1.500E-03 >  
 -> Enter time constant of turn-on (in sec)  
 -> The default is 1.000E-03 >

```

f>           Enter cycle time of waveform (in sec)
->           The default is      4.320E-02 >

[Z]: {Backtrack to 11d}

g>           Accept default channels? (Y or N)      The default is Y >

[Z]: {go to 11d}
[N]: {go to 11h}
[Y]: {set default values and go to 11k}

h>           Parameter input from file or terminal? (F or T)      The default is T >

[Z]: {Go to 11g}
[F]: {Go to 11i}
[T]: {Go to 11j}

i>           Specify filename for channel time parameters.
->
->           Choose one of the following:

->           Filename          System          # Channels     Off Time
->           CD1010.PAR        Crone digital PEM    10            10.80 ms
->           CD2010.PAR        Crone digital PEM    20            10.80 ms
->           CD3010.PAR        Crone digital PEM    30            10.80 ms
->           CD1120.PAR        Crone digital PEM    11            21.60 ms
->           CD2220.PAR        Crone digital PEM    22            21.60 ms
->           CD3420.PAR        Crone digital PEM    34            21.60 ms
->           CD1230.PAR        Crone digital PEM    12            32.40 ms
->           CD2430.PAR        Crone digital PEM    24            32.40 ms
->           CD3730.PAR        Crone digital PEM    37            32.40 ms
->           CA810.PAR        Crone analog PEM     8             10.80 ms
->           CA820.PAR        Crone analog PEM     8             21.60 ms
->           U1017.PAR        UTEM                10            16.67 ms
->           G208.PAR         Geonics EM37       20            8.33 ms
->           S32180.PAR       SIROTEM            32            180.00 ms
->           The default is CAB10.PAR >

[Z]: {Go to 11h}
[<filename>]: {The specified file is opened and the parameters are
               read}
{go to 11k}

```

```
j>      Do you want time windows? (Y or N)    The default is Y >
->      Enter number of parameters    The default is      2    >
->      Enter parameters in ascending order >

[^Z]: {Backtrack to 11h}

k>      Output units? 1 - nanoVolt/m^2   or   nanoTesla/sec
->          2 - Percent of primary at each point
->          3 - Percent of primary at specified point
->          4 - Crone units - borehole probe    (For system 1 only)
->          5 - Crone units - surface coil      (For system 1 only)
->          6 - microVolt/Amp                  (For system 4 only)
->      The default is      1    >

[^Z]: {system 1 - go to 11c; systems 0,2,3,4 - go to 11d}
[1-6]: {Do one or more of the following:}

{For units 4,5}
l>      Enter external receiver gain    The default is      500.000 >

{For units 1,4,5}
->      Enter peak transmitter current (Amps)
->      The default is      15.000 >

{For unit 6}
->      Enter effective receiver loop area (square meters)
->      The default is      10000.000 >

{For unit 3}
->      Enter x,y,z coordinates of normalization point  (z neg. down)
->          x:    The default is      0.000 >
->          y:    The default is      0.000 >
->          z:    The default is      0.000 >

[^Z]: {Enter this at any point in step 111 to return to 11k}
```

{For all systems and units}

- m> Enter direction of primary field in center of loop - up or down (U or D)
- > The default is D >
- >
- > Left- or right-hand system for components? (L or R)
- > The default is L >
- >
- > Positive X-component points to start or end of line (S or E)
- > The default is S >

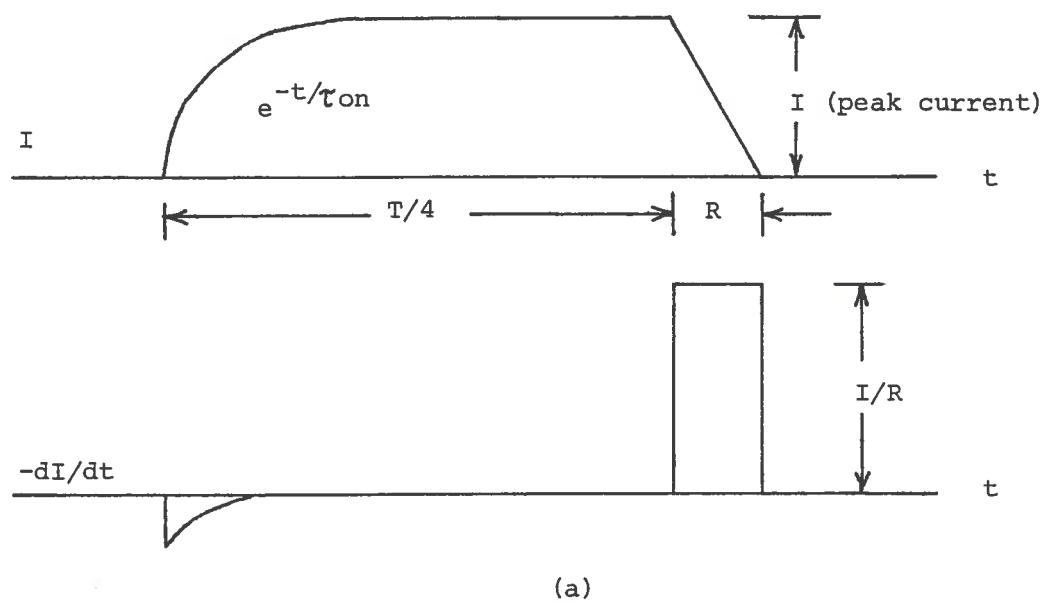
[^Z]: {Enter this at any point to backtrack to 11k}

#### EXPLANATION:

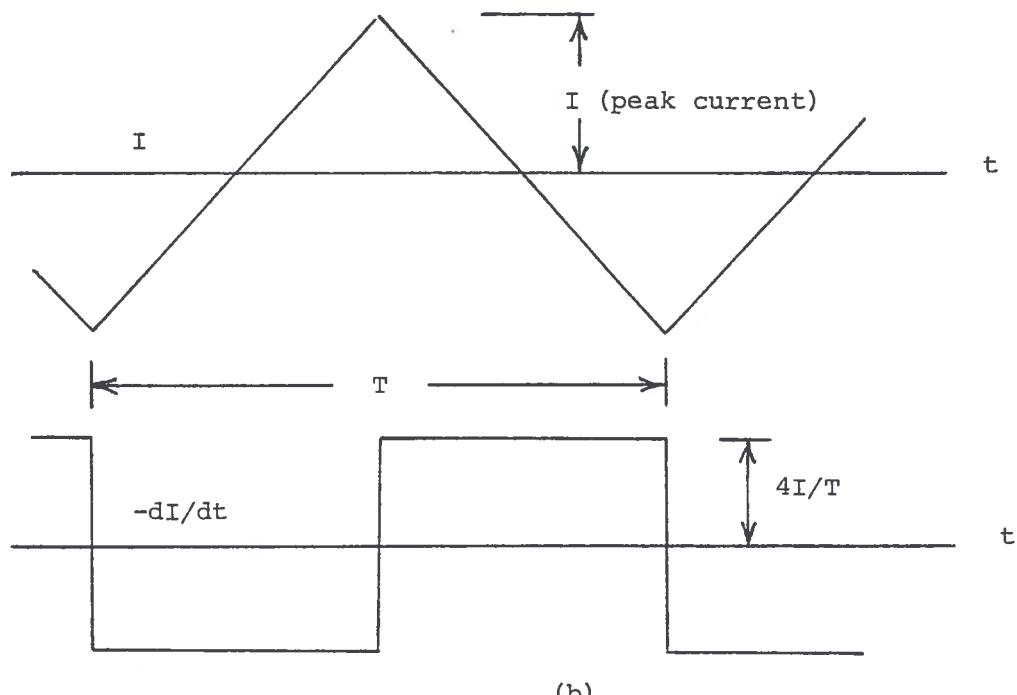
Default primary waveforms and time channels are set up for each system. If the user does not wish to use these defaults, then the waveform characteristics and the time parameters must be specifically input. The current waveforms for systems 0,1,2, and 4 are based on a slow exponential turn-on (time constant in the order of a millisecond), and a ramped turn-off, while system 3 uses a regular, symmetric, sawtooth waveform (see Figure D.8). A cycle time is required for all the systems. Parameter input can be accomplished from the terminal or through reading a prepared file (see "PLATEF Advanced Features").

There are six options presented for output units. If units 4 or 5 are chosen (for Crone analog PEM systems), the user must supply an external receiver gain (the gain set by the operator). The peak transmitter current must be provided for units 1,4, or 5. It may not be directly available from the field survey, and may have to be calculated or approximated from the voltage and resistance in the loop. For unit 6, (microvolts/amp), the effective area of the receiver coil must be provided. Finally, for unit 3, the coordinates of the normalization point is required. These options have been provided so that the final output can be directly compared to real field data.

Three mutually perpendicular components of the secondary field are always computed at each receiver location. The X component is always in-line (axial), the Y component is always horizontal, and the Z component is upward trending. Present technology in borehole systems



(a)



(b)

Figure D.8 Waveforms modelled in PLATEF.

- (a) Fast turn-off (practical impulse response).  
Crone PEM, Geonics EM37, SIROTEM.
- (b) Sawtooth waveform (step response). UTEM.

allows for only one component to be read, which corresponds to the X component. In surface surveys, where X is the horizontal in-line component, Z would be vertical. In order to satisfy various conventions, the sign of these components has been made to be completely arbitrary. All three components can have their sign reversed by changing the direction of the primary field in the center of the transmit loop. The sign of the X and Y components can be switched by changing the direction in which the positive X component points, while the sign of the Y component can be switched by defining a left- or right-hand orthogonal coordinate system.

PLATEF Step 12: Approval of electrical parameters.

MONITOR I/O: (sample)

```
->          ELECTRICAL INFORMATION
->
->          Conductivity-thickness of the plate:    10.00 mhos
->
->          Digital Crone PEM
->
->          Duration of turn-off: 1.500000E-03 sec
->          Turn-on time constant: 1.000000E-03 sec
->          Cycle time of waveform: 4.320001E-02 sec
->          8 windows          Time parameters (millisec):
->          0.100- 0.200    0.200- 0.400    0.400- 0.700    0.700- 1.100
->          1.100- 1.800    1.800- 3.000    3.000- 5.000    5.000- 7.800
->
->          Output units and gains
->          Output in nanoVolt/m^2 or nanoTesla/sec
->          External receiver gain:      N/A
->          Peak transmitter current:   15.00 Amps
->          Effective loop area of receiver:  N/A
->
->          Component specifications
->          Direction of primary in center of loop: DOWN
->          LEFT -hand component system
->          Positive X-axis points to START of line
->
->          Electrical parameters ok? (Y or N)    The default is Y >

[^Z]: {Go to step 10}
[N]: {Go to step 13}
[Y]: {Go to step 14}
```

**EXPLANATION:**

All the electrical information gathered in step 11 is written to the monitor for inspection. The user can approve, disapprove, or return for some geometrical changes.

PLATEF Step 13: Select changes to electrical parameters.

MONITOR I/O:

- > Choose one or more of:
  - > 1 Change SIGMA-T
  - > 2 Change SYSTEM (+ TIMES, UNITS, and GAINS)
  - > 3 Change channel TIMES
  - > 4 Change output UNITS and GAINS
  - > 5 Change COMPONENT specifications
  - > 6 REVIEW electrical parameters
  - > 7 Electrical parameters ok - CONTINUE
  - > 8 GO BACK - Change model geometry
  - > 9 STOP program
- > Enter chosen number(s) on 1 line in any order (eg. 8243)
- > The default is 7 >

[9]: {Stop program}  
[8]: {Go to step 10}  
[7]: {Go to step 14}  
[6]: {Go to step 12}  
[1-5]: {Go to step 11}

EXPLANATION:

After examining the electrical information presented in step 12, the user can easily make changes to any of the electrical parameters. The first five options presented here are for this purpose and more than one of these may be chosen. The sixth option will simply write out the electrical information as in step 12. Option 7 provides an escape from this step, and is equivalent to approving the electrical parameters in step 12. Option 8 allows the user to go back to the menu for geometrical changes to the model, while option 9 will stop the program.

PLATEF Step 14: Preview the primary field readings if desired.

MONITOR I/O:

a) Would you like to preview the PP readings? (Y or N) The default is N >

[^Z]: {Go to step 13}

[N]: {Go to step 15}

[Y]: {Go to 14b}

b>	Station	X,Y,Z Components of Primary Field		
->	50.00	0.00	0.00	33621.
->	100.00	0.00	0.00	14212.
->	150.00	0.00	0.00	8057.5
->	200.00	0.00	0.00	5171.1
->	250.00	0.00	0.00	3563.1
->	Continue? (Y or N, ^Z to change electrical parameters only)			
->	The default is Y >			

[^Z]: {Go to step 13}

[N]: {Go to step 10}

[Y]: {Go to step 15}

EXPLANATION:

It may be advantageous, when comparing theoretical data to actual field data, to compare the primary field data prior to the secondary field data. This allows the user to adjust the peak transmitter current to best match the field data, or perhaps make fine adjustments to borehole geometry when it is not precisely known. If this option is accepted, 20 stations at a time will be displayed on the monitor with the three components of the primary field readings. If more stations remain in the profile, the message:

More? (Y or N) The default is Y >

will be displayed so that the user can see the field values along the entire profile in 20 station units. When viewing is completed, the user can accept the model and continue, or he can go back and change any part of the model.

**PLATEF Step 15:** Write model parameters to coefficient, batch and final data files.

MONITOR I/O:

- a) Do you wish to save model parameters and coefficients in an intermediate file for later use? The default is N >

  - [^Z]: {Go to step 14}
  - [N]: {Go to 15c}
  - [Y]: {Go to 15b}

- b) Specify name of coefficient save file [B:] >

  - [^Z]: {Go to 15a}
  - [<filename>]: {The drive specified in the prompt is prefixed if no drive or pathname is included in the filename.}
  - {The file is opened to prepare for writing.}

- c) Specify filename for final data [B:] >

  - [^Z]: {Go to 15a}
  - [<filename>]: {The drive specified in the prompt is prefixed if no drive or pathname is included in the filename.}
  - {The file is opened to prepare for writing.}

EXPLANATION:

If the user plans to use similar models in the future, it would be wise to save the present model parameters and coefficients in a "coefficient save file". Such a file can later be read (step 4) in order to save input and calculation time. As mentioned in step 4, the user should establish some convention for file naming, or maintain a table to help in associating the coefficient files with the models they represent. Using an extension of .COF should be of help in this regard.

If a batch file is being written, this is the point at which all the model parameters are written to the batch file. Another model can then be established, or the program can be terminated (step 18).

PLATEF Step 16: Establish monitor display of final results.

MONITOR I/O:

a> Would you like to see some results? (Y or N) The default is Y >

[^Z]: {Go to 15c}

[N]: {Go to step 17}

[Y]: {Go to 16b}

b> Which component? X (inline), Y, Z, OR A (all) The default is A >

-> Which channel? (0 for all) The default is 0 >

[^Z]: {Enter this to backtrack to 16a}

EXPLANATION:

The final output, as well as being written to a file, can be displayed on the user's monitor as it is being calculated. This allows the user to match synthetic data with field data without leaving the program. In this step, the user can choose which component and which channel he wishes to see.

PLATEF Step 17: Combine coefficients & write to monitor & output files.

## MONITOR I/O

```

->      -- COMPUTING ELECTRICAL COEFFICIENTS --
->      -- COMPUTING EXCITATION COEFFICIENTS --
->      -- COMPUTING SECONDARY FIELD COEFFICIENTS AT EACH POINT --
->
->      STATION          COMPONENT      PRIMARY FIELD          ALL CHANNELS
->
->      50.0              X            4.33471E-04
->      5.55              1.67         0.23        0.02    0.00    0.00    0.00    0.00
->      50.0              Y            0.00000E-01
->      4.70              1.40         0.20        0.01    0.00    0.00    0.00    0.00
->      50.0              Z            33621.
->      -17.9             -5.29        -0.74       -0.05   0.00    0.00    0.00    0.00
->
->      100.0             X            3.54136E-04
->      24.3               7.18         1.01        0.07    0.00    0.00    0.00    0.00
->      100.0             Y            0.00000E-01
->      6.88               2.03         0.28        0.02    0.00    0.00    0.00    0.00
->      100.0             Z            14212.
->      -7.85             -2.31        -0.32       -0.02   0.00    0.00    0.00    0.00
->
->      150.0             X            2.30190E-04
->      20.1               5.99         0.84        0.05    0.00    0.00    0.00    0.00
->      150.0             Y            0.00000E-01
->      5.17               1.53         0.21        0.01    0.00    0.00    0.00    0.00
->      150.0             Z            8057.5
->      23.2               6.32         0.95        0.06    0.00    0.00    0.00    0.00
->
->      200.0             X            2.38335E-04
->      -0.70              -0.16        -0.02       0.00    0.00    0.00    0.00    0.00
->      200.0             Y            0.00000E-01
->      2.58                0.77         0.11        0.00    0.00    0.00    0.00    0.00
->      200.0             Z            5171.1
->      25.4               7.55         1.06        0.07    0.00    0.00    0.00    0.00

```

**EXPLANATION:**

The procedure of coefficient reading or calculation is invisible to the user, except for the messages shown above and possibly some delay during the calculations. The coefficients are written, if applicable, to a coefficient save file. Finally, the coefficients are combined, gains applied, and the result is written to the monitor and/or the final data file.

PLATEF Step 18: Go back for another model or close files and stop.

MONITOR I/O:

- a) Another model? (Y or N) The default is Y >  
[N]: {Go to 18b}  
[Y]: {Go to step 10}
  
- b) EXITING PROGRAM. OK? (Y or N) The default is N >  
[N]: {Go to step 10}  
[Y]: {Stop program}

EXPLANATION:

The user may set up another model, or terminate the program.

PLATEF Error Messages and Notes:

## Data Input

```

** ERROR - WRONG DATA FORMAT **

    {Character has been entered for an integer or real.}
    {Spaces between characters in a character string not allowed.}

Testing filename: <filename>
File already exists!! Overwrite? (Y or N)      The default is N >
    { Y - The existing version of the file will be lost}

Non-existent filename: <filename>
    {A file which should exist cannot be found. Wrong drive?}

** ERROR - INCLUDE A VALID PREFIX-FILENAME SEPARATOR **

    {Haven't included a ':' or '\' as last character in prefix.}

** ERROR - TOO MANY CORNERS **

    {More than 10 sides have been specified for the tx loop.}

** ERROR - LOOP WITH LESS THAN 3 SIDES? **

    {Can't have less than 3 sides on a loop!}

NOTE: Point is not on plate.
    {Normally a point on the plate is referenced.}

NOTE: Reference point is above surface. Ok?      The default is Y >
    {Sub-surface points have negative z coordinates.}

NOTE: Profile points upward. Ok? (Y or N)      The default is Y >
    {For drillholes, use theta greater than 90 degrees}

```

## Filehanding

```

** ERROR READING COEFFICIENT FILE **

    {Bad coefficient file.}

** ERROR READING COEFFICIENT FILE - INSUFFICIENT DATA **

    {Bad coefficient file.}

** ERROR READING UNFORMATTED FILE HEADER **

    {Bad coefficient file.}

```

```
** ERROR - INSUFFICIENT DATA IN UNFORMATTED FILE HEADER **  
    {Bad coefficient file.}  
  
** ERROR WRITING TO BATCH FILE **  
    {Diskette is probably full.}  
  
** ERROR WRITING TO COEFFICIENT FILE **  
    {Diskette is probably full.}  
  
** ERROR WRITING UNFORMATTED FILE HEADER **  
    {Diskette is probably full. This is for batch or coeff. file}  
  
** ERROR WRITING TO FINAL DATA FILE **  
    {Diskette is probably full.}  
  
** ERROR WRITING TO FINAL DATA FILE HEADER **  
    {Diskette is probably full.}  
  
** ERROR WRITING TO DIAGNOSTIC FILE **  
    {Diskette is probably full.}
```

#### Eigenfunction Retrieval

```
** ERROR READING FILE 'FILES.EIG' **  
    {File is not on the PLATEF diskette?}  
  
** ERROR - POLYNOMIAL ORDER GREATER THAN 4 **  
    {Bad eigenfunction file.}  
  
** ERROR - INSUFFICIENT DATA IN FILE <filename> **  
    {Bad eigenfunction file.}  
  
** ERROR READING DATA IN FILE <filename> **  
    {Wrong file?}  
  
** ERROR OPENING FILE <filename> **  
    {Non-existent file.}
```

#### Electrical Parameters

```
** ERROR READING FILE 'FILES.PAR'  
    {File is not on the PLATEF diskette?}
```

```
** ERROR - CAN'T HAVE NEGATIVE TIME WINDOWS **
    {Zero time starts at end of current ramp}

** ERROR OPENING PARAMETER FILE <filename> **
    {Specified file is not on the diskette.}

** ERROR READING PARAMETER FILE <filename> **
    {Specified file has improper format}

** ERROR - INSUFFICIENT DATA IN PARAMETER FILE <filename> **
    {Number at top of file does not correspond to # parameters}

** ERROR - TOO MANY PARAMETERS; MAXIMUM IS: 80 **
    {Array size in program limits number parameters to 80}

** ERROR - NEED EVEN NUMBER PARAMETERS FOR WINDOWS **
    {Windows require a starting and ending time}

** ERROR - CRONE UNITS ONLY VALID WITH ANALOG CRONE PEM **
    {Crone units based on 8 channels with channel gains}
```

PLATEF Advanced Features:

When a filename is requested and the reply includes a ':', '\', or ']', the default prefix is entirely ignored. Thus, if the default prefix is 'B:', and you want to write a file in a subdirectory on B: (say B:\data1\file1.syn), then you would have to include the 'B:' specifier in your filename.

When coefficients are saved in a file, that file becomes the new coefficient read file on the next model.

When an error occurs during the reading of a coefficient file and you then decide not to read such a file afterall, you will have to re-enter all the geometrical and electrical parameters and all the calculations will be performed. This is because some of the data may have been altered during the aborted read operation.

A diagnostic file can be created for debugging and inspection which contains: model descriptions identical to steps 9 and 12; the eigenvalues and eigenvectors; the electrical coefficients; the excitation coefficients; and the secondary field coefficients. The user must specify that a batch file is desired and then use a '!' as the first character in the filename extension. If the first two characters of the extension are '!!', then a more detailed diagnostic file is created containing all the parameters used in the coefficient calculations and the raw coefficients before eigenvector multiplication (see Programmer's Manual).

Parameter files can be created which contain the non-standard channel time parameters, and the format of these should follow that used in the supplied parameter files. The following sample listing is one of these files (CD1010.PAR).

-20	
.0500E-3	.0810E-3
.0839E-3	.1395E-3
.1406E-3	.2340E-3
.2358E-3	.3915E-3
.3955E-3	.6615E-3
.6633E-3	1.112E-3
1.112E-3	1.863E-3
1.866E-3	3.128E-3
3.129E-3	5.247E-3
5.247E-3	8.798E-3

The first number is the total number of times listed in the file, and this number should be made negative if the times are to be treated as windows. After the file has been created, it should be copied onto the "PLATEF" diskette, and the file "FILES.PAR" should be updated so that PLATEF will know of its existence. This involves using a text editor to add the new filename and the identifying parameters: "System", "# Channels", and "Off Time". The file presently looks like this:

' CD1010.PAR',	'Crone digital PEM',	10,	10.8
' CD2010.PAR',	'Crone digital PEM',	20,	10.8
' CD3010.PAR',	'Crone digital PEM',	30,	10.8
' CD1120.PAR',	'Crone digital PEM',	11,	21.5
' CD2220.PAR',	'Crone digital PEM',	22,	21.6
' CD3420.PAR',	'Crone digital PEM',	34,	21.6
' CD1230.PAR',	'Crone digital PEM',	12,	32.4
' CD2430.PAR',	'Crone digital PEM',	24,	32.4
' CD3730.PAR',	'Crone digital PEM',	37,	32.4
' CA810.PAR',	'Crone analog PEM',	8,	10.8
' CA820.PAR',	'Crone analog PEM',	8,	21.6
' U1017.PAR',	'UTEM',	10,	16.67
' G208.PAR',	'Geonics EM37',	20,	8.33
' S32180.PAR',	'SIROTEM',	32,	180.

The new filename and parameters can be added anywhere in this list.

### D.7.2 Program EIGCUR

There are 4 main steps in EIGCUR:

1. Start the program.
  2. Choose the desired operation.
  3. Calculate eigenfunctions.
  4. Re-write an eigenfunction file.

EIGCUR Step 1: Start the program.

## MONITOR I/O:

(To start the program, place the "EIGCUR" diskette in drive A: and type:

EIGCUR

After a few seconds, the following announcement appears.}

### **EXPLANATION:**

The user's name is located in the bottom right-hand box. This name will also appear on the top line of the output files.

EIGCUR Step 2: Choose the desired operation.

**MONITOR I/O:**

- a) Choose one of the following:
    - > 1 Calculate eigenfunctions
    - > 2 Re-write an eigenfunction file
    - > 3 Stop program
    - >
  - > The default is 1 >
- [1]: {Go to step 3}  
[2]: {Go to step 4}  
[3]: {Stop program}

**EXPLANATION:**

This menu reappears after completion of steps 3 or 4.

EIGCUR Step 3: Calculate eigenfunctions.

MONITOR I/O:

```
-> EIGENFUNCTION CALCULATION
-> ****
->
a> Enter plate ratio (width/strike length)
-> The default is 1.00 >

[^Z]: {Go to step 2}

b> Enter maximum polynomial order for the eddy current approximation ( <=4 )
-> The default is 4 >

[^Z]: {Go to 3a}

c> Specify filename for eigenfunction storage >

[^Z]: {Go to 3b}
[<filename>]: {The file is opened to prepare for writing}

-> VERIFICATION
-> Plate width-to-length ratio: 1.000
-> Maximum polynomial order: 4
-> Eigenfunction output filename: B:TRY
->
-> NOTE: This calculation will take approximately 26 minutes on an IBM-PC
-> with an 8087 math chip
->
-> Ok? (Y or N) The default is Y

[^Z]: {Go to 3c}
[N]: {Go to 3a}
[Y]: {Go to 3d}

d> Working
-> Done
{Go to step 2}
```

**EXPLANATION:**

As explained earlier, the maximum polynomial order determines the accuracy of the numerical approximation. Although a larger number achieves greater accuracy, it does so at the expense of program efficiency, and thus, the present program is limited to a maximum polynomial order of 4.

The user can specify any name for the output file. It is recommended, however, that the files be named R???????.P# where ?????? represents the width-to-length ratio, and # is the maximum polynomial order (eg. R1P25.P4).

**EIGCUR Step 4: Re-write an eigenfunction file.****MONITOR I/O:**

```
->      FILE RE-WRITING
->      ****
->
->
->      Specify desired operation: 1 ASCII -->      Binary
->                           2 Binary -->      ASCII
->
->      The default is      2      >
->
->      Specify old filename >
->      Specify new filename >
->
->      Done
```

**EXPLANATION:**

The binary-to-ASCII option is provided so that the user can inspect the eigenvalues and eigenvectors in the data file. The ASCII-to-binary option is provided so that eigenfunction data files from other sources (eg. mainframes) can be used with PLATEF.

EIGCUR Error Messages:

## File Re-writing

```
** ERROR OPENING FILE <filename> **  
    {Wrong drive, or file doesn't exist}  
  
** ERROR READING FILE <filename> **  
    {Wrong file has been specified.}  
  
** ERROR WRITING FILE <filename> **  
    {The diskette is probably full.}  
  
** ERROR - MAXIMUM POLYNOMIAL ORDER TOO LARGE **  
    {Can't re-write a file with a polynomial order greater than 4}
```

## Data Input

```
** ERROR - WRONG DATA FORMAT **  
    {Character input when a real or integer is expected.}  
    {Spaces have been used in a character string}
```

```
Testing filename: <filename>  
File already exists!! Overwrite? (Y or N)      The default is N >  
    { Y - The existing version of the file will be lost}
```

```
Non-existent filename: <filename>  
    {A file which should exist cannot be found. Wrong drive?}
```

EIGCUR Advanced Features:

A number of cases can be computed using a data file which answers all the program prompts. For example, one such file ('test') used to compute ratios of 1.75 and 3.5 would look like this:

```
1
1.75
4
R1P75.P4
y
1
3.5
4
R3P5.P4
y
3
```

The program would then be started with the command: EIGCUR < test

Use of a '!' as the first character in the filename extension results in diagnostic information being written to the file 'NOSTIC'. This file contains listings of the various matrices used in the calculation as well as the eigenvalues, eigenvectors, and tests on the eigenfunction accuracy.

The following page contains a sample listing of an eigenfunction file in ASCII format. In this file, the first line contains the important variables MAX, NFP, MFP, MFP2, and RAT (see Programmer's Manual). The next three lines contain the 15 eigenvalues, and the rest of the file contains the eigenvectors.

4	15	120	225	2.00000
1.1641260E-01	9.8528363E-02	7.7648886E-02	6.6548437E-02	6.2074054E-02
5.6349576E-02	5.1742699E-02	4.4778813E-02	4.3632340E-02	4.2841926E-02
3.7402462E-02	3.6254425E-02	2.7656432E-02	2.7340496E-02	2.0869317E-02
-3.4778230E-01	0.0000000E+00	0.0000000E+00	1.0448110E-01	0.0000000E+00
1.2936040E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-5.0940574E-04	0.0000000E+00	-2.0195235E-02	0.0000000E+00	-2.6945509E-03
0.0000000E+00	0.0000000E+00	-5.2674030E-01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	2.3532070E-01	0.0000000E+00	2.3751890E-01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-3.3118270E-01	0.0000000E+00	0.0000000E+00	1.6850740E-01	0.0000000E+00
-3.1500580E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-1.2098204E-03	0.0000000E+00	2.0782810E-01	0.0000000E+00	2.7263740E-01
0.0000000E+00	-3.7359800E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	1.6653010E-01	0.0000000E+00	1.3616330E-01	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	-6.5544610E-01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	3.9775830E-01	0.0000000E+00	2.9851730E-01	0.0000000E+00
0.0000000E+00	0.0000000E+00	-1.3870210E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	9.3577862E-02	0.0000000E+00	-7.7220170E-01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	1.3226690E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	-1.4154568E-02	0.0000000E+00	1.8253040E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	2.8844410E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	-6.3243002E-02	0.0000000E+00	1.6848190E+00	0.0000000E+00
3.7995470E-01	0.0000000E+00	0.0000000E+00	-1.9664130E-01	0.0000000E+00
9.2708460E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
1.2078470E-01	0.0000000E+00	-4.6684414E-02	0.0000000E+00	4.7211130E-01
6.4847930E-01	0.0000000E+00	0.0000000E+00	5.0778985E-02	0.0000000E+00
7.6583840E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-1.3645600E-01	0.0000000E+00	-1.5413060E-01	0.0000000E+00	4.2511230E-01
0.0000000E+00	0.0000000E+00	1.458010E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	1.3985320E+00	0.0000000E+00	2.0083010E-02
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
9.7458440E-01	0.0000000E+00	0.0000000E+00	1.0717690E+00	0.0000000E+00
1.2234310E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-1.3806392E-02	0.0000000E+00	1.5047330E+00	0.0000000E+00	2.9566169E-02
0.0000000E+00	8.2911400E-01	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	4.1322070E-01	0.0000000E+00	1.4374346E-02	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	-2.1253500E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	-1.0789190E+00	0.0000000E+00	-1.4171243E-02	0.0000000E+00
-4.7724400E-01	0.0000000E+00	0.0000000E+00	-7.1779660E-01	0.0000000E+00
-3.1141937E-02	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00
-3.2237950E-01	0.0000000E+00	-2.1599799E-02	0.0000000E+00	-5.3683929E-03

Sample of Eigenfunction File in ASCII Format.

Whenever a new binary data file is created by EIGCUR, it should be copied onto the PLATEF diskette and the file "FILES.EIG" should be updated. This involves using a text editor to add the new filename and the two key parameters R (plate width-to-length ratio) and P (maximum polynomial order) to the file. The file presently looks like this:

```
' RP1.P4 ', 0.1, 4
' RP2.P4 ', 0.2, 4
' RP25.P4 ', 0.25, 4
' RP33.P4 ', 0.33, 4
' RP4.P4 ', 0.4, 4
' RP5.P4 ', 0.5, 4
' RP67.P4 ', 0.67, 4
' RP8.P4 ', 0.8, 4
' R1P0.P4 ', 1.0, 4
' R1P25.P4 ', 1.25, 4
' R1P5.P4 ', 1.5, 4
' R2P0.P4 ', 2.0, 4
' R2P5.P4 ', 2.5, 4
' R3P0.P4 ', 3.0, 4
' R4P0.P4 ', 4.0, 4
' R5P0.P4 ', 5.0, 4
' R10P0.P4 ', 10.0, 4
```

A new member to this suite can be inserted anywhere in this file using the same format (filename,R,P). Failure to include the new data file in "FILES.EIG" will only mean that PLATEF will not inform the user of the file's existence.

### D.7.3 Program BATCHF:

## MONITOR I/O:

{To start the program, place the "BATCHF" diskette in drive A: and type:

BATCHF

After a few seconds, the following announcement appears.}

ELECTROMAGNETIC MODELLING of a <b>CONDUCTIVE PLATE IN FREE SPACE</b>	
<b>BATCHF 1.00</b>	
Computes the response from fixed-loop EM systems using models set up in PLATEF batch mode	
by  W.R. Ravenhurst  (C) CRONE GEOPHYSICS LTD. 1986	for  CRONE GEOPHYSICS LIMITED  In-House Copy for Demo and Use
Specify name of batch file to be read >	

[^Z]: {Stop program}

[<filename>]: {The file is opened and the model parameters read.}

```
->          Model 1
->          -- COMPUTING ELECTRICAL COEFFICIENTS --
->          -- COMPUTING EXCITATION COEFFICIENTS --
->          -- COMPUTING SECONDARY FIELD COEFFICIENTS AT EACH POINT --
->          Model 2
->          {etc.}
->          Done
```

**EXPLANATION:**

Since the operation of this program is almost entirely transparent to the user, some messages have been included in order to monitor the progress of the program. The program requires only the batch filename, but note that coefficient files may have to be available as well because the program reads and writes these files as specified in PLATEF during the creation of the batch file. The program basically consists of the "number-crunching" parts of PLATEF without the interactive parts.

BATCHF Error Messages:

## Data Input

```
** ERROR - WRONG DATA FORMAT **  
    {Character has been entered for an integer or real.}  
    {Spaces between characters in a character string not allowed.}  
  
Testing filename: <filename>  
File already exists!! Overwrite? (Y or N)      The default is N >  
    { Y - The existing version of the file will be lost}  
  
Non-existent filename: <filename>  
    {A file which should exist cannot be found. Wrong drive?}
```

## Filehanding

```
** ERROR READING COEFFICIENT FILE **  
    {Bad coefficient file.}  
  
** ERROR READING COEFFICIENT FILE - INSUFFICIENT DATA **  
    {Bad coefficient file.}  
  
** ERROR READING UNFORMATTED FILE HEADER **  
    {Bad coefficient file.}  
  
** ERROR - INSUFFICIENT DATA IN UNFORMATTED FILE HEADER **  
    {Bad coefficient file.}  
  
** ERROR WRITING TO COEFFICIENT FILE **  
    {Diskette is probably full.}  
  
** ERROR WRITING UNFORMATTED FILE HEADER **  
    {Diskette is probably full. This is for coefficient file}  
  
** ERROR WRITING TO FINAL DATA FILE **  
    {Diskette is probably full.}  
  
** ERROR WRITING TO FINAL DATA FILE HEADER **  
    {Diskette is probably full.}
```

**Batch File**

```
** ERROR - INSUFFICIENT DATA IN BATCH FILE **  
    {The specified file is not a batch file}  
** ERROR OPENING FILE <filename> **  
    {The specified file cannot be found. Wrong drive?}  
** ERROR READING BATCH FILE **  
    {The specified file is not a batch file}  
** BATCH RUN TERMINATED WITH ERRORS **  
    {Message at end of program when errors have occurred}
```

## APPENDIX E

### PROGRAMMER'S MANUAL

#### E.1 Introduction

This appendix contains programming information for the programs PLATEF and EIGCUR. BATCHF consists mostly of the computational part of PLATEF, and thus, it is not included.

All the programs have been written in FORTRAN 77, although some of the less common features of the language were avoided in an attempt to increase portability.

#### E.2 PLATEF Structure and I/O

The structure of the program PLATEF can be seen in the flow chart in Figure 4.4 and the subroutine map shown in Table E.1. The source code is divided into 54 separate routines which are interconnected up to an order of 5.

The program can be roughly divided into three steps. In the first step, the model parameters are established. This is facilitated by the use of menus, which allow the user to selectively change any group of parameters. If the batch mode is chosen, there are no further steps, and the parameters are written to a batch file. The second step consists of the coefficient calculations. This is the most time-consuming part of the program, but it can be expedited by the use of coefficient files. The final step is that of combining the coefficients to produce the final synthetic data, displaying these values on the screen, and writing them in the final data file.

The subroutine map also shows that only six I/O units are required, including the keyboard and screen. The four logical unit numbers used

Name of routine	I/O	Description
PLATEF	S R-2 W-1,3,4 O&C-1,2,3,4	Calculates the EM response of a conductive plate in free space when energized from a fixed loop source.
BLKDAT	S	Block data - initial values for model parameters.
FIRST	S	Writes program header to the screen.
IIN	K S	Prompts for input of integer values.
RIN	K S	Prompts for input of real values.
TIN	K S	Prompts for input of single character values.
TIN30	K S	Prompts for input of 30 character values.
FILES	K S	Prompts for filename, prefixes default drive, checks existence.
TIN*	K S	
UNIFORM	S R-2,3 W-1,3	Reads or writes binary files containing model parameters.
GETEIG	S R-2 O&C-2	Retrieves eigenfunctions from a data file.
TIN30*	K S	
CBDGIT	S	Digitizes the scaled Chebychev polynomials.
CHBCHV	K S	Digitizes the Chebychev polynomials at a point.
PLTGEO	S	Solicits information on the plate geometry.
RIN*	K S	
TIN*	K S	
CORNER	S	Finds the corners of the plate in field coordinates.
ROT123	K S	Performs 3 coordinate rotations for strike, dip, plunge.
LSOURC	K S	Solicits loop location in field coordinates.
TIN*	K S	
RIN*	K S	
IIN*	K S	
REFER	S	
PFIELD	S	Calculates H field at plate corners and plate center.
FLDLIN	S	Calculates H field due to a wire loop.
SUMV	S	Computes quasi-static H field due to linear wire segment
ROTD123*	S	Computes vector functions.
PROFIL	S	Solicits information on desired profile line.
RIN*	K S	
TIN*	K S	
SPHER	K S	
CLOSER	S	Performs coord. transformations: cartesian <-> spherical
ROTD123*	S	Calculates critical points in receiver-plate geometry.
LINES2	S	Calculates least separation between 2 lines.
SUMV*	S	Calculates least separation between a point and a line.
PNTLIN	S	Calculates least separation of a point and a plane.
SUMV*	S	
SHORTY	S	
SUMV*	S	
WRTGEO	S	Writes plate and Tx geom. info. to a file or terminal.
XPLAIN	S	Writes Rx-plate geometry to a file or terminal.
REDEW	S	Sets flags for model geometry.
TIN30*	K S	
TIN*	K S	
SYSTEM	S	Sets the electrical parameters.
RIN*	K S	
IIN*	K S	
TIN*	K S	
RDPARM	K S R-4 O&C-4	Reads the time or freq. params. from terminal or a file.
IIN*	K S	
TIN*	K S	
TIN30*	K S	
DIGITL,RAMPEM,EM37,UTEM10,SIROTM	K S	Sets the waveform and channels for specific systems.
IIN*	K S	
RIN*	K S	
TIN*	K S	
RDPARM*	K S R-4 O&C 4	
IIN*	K S	
TIN*	K S	
TIN30*	K S	
WRTSYS	S	Writes the electrical parameters to a file or terminal.
CHANGE	S	Resets the flags for electrical parameters.
TIN30*	K S	
PFIELD*	S	
FLDLIN*	S	
SUMV*	S	
PPVIEW	S	Lists the primary field readings on the terminal.
PFIELD*	S	
FLDLIN*	S	
SUMV*	S	
VECT1	K S	Performs vector transformations: surface <-> borehole.
TIN*	R-4	
WRTHED	W-4	
ELECT	W-4	
EXPO		Reads or writes the header of the final data file.
LOOP		Calculates electrical coefficients.
ROTD123*		Function which controls underflow on EXP function.
FLDLIN*		Computes the excitation coefficients.
SUMV*		
RTRNA		
SECOND		Computes the matrix product R (transpose) A.
ROTD123*		Computes the sec. field coeff. and the primary field.
PETE7		
DIVIDE		Computes the secondary field coefficients at a point.
CDQUAD		Divides the plate into rectangular cells for integration.
F1		Integrates a complex function over a rectangle.
POT		Computes function to be integrated.
H1COF		Interpolates trial functions from digitized values.
H2COF		Arranges the integrated functions into raw H1 coefficients.
H3COF		Arranges the integrated functions into raw H2 coefficients.
RTRNA*		Arranges the integrated functions into raw H3 coefficients.
VECT1*		
PFIELD*		
FLDLIN*		
SUMV*		

S - Screen write; K - Keyboard read; R - Read; W - Write; O - Open; C - Close  
 Repeated subroutines are marked with an asterisk.

Table E.1 Subroutine map for PLATEF

for disk file I/O are:

LUN 1: Output - Unformatted file saving the model parameters and coefficients for future use.

LUN 2: Input - Unformatted file containing the eigenvalues and eigenvectors of the current distribution.

and/or

Input - Unformatted file containing parameters and coefficients of a previous model.

LUN 3: Output - Formatted diagnostic file containing all the model parameters and many intermediate calculations.

and/or

Output - Unformatted file containing model parameters to be used by program BATCHF.

LUN 4: Input - Free-format file containing non-standard time or frequency parameters.

and/or

Output - Formatted output file containing the final synthetic data.

The keyboard input is handled entirely by five subroutines: IIN, RIN, TIN, TIN30, and FILES.

### E.3 Global Variables in PLATEF

#### E.3.1 Common Block Variables

A common block map, listing the location of the various blocks, is shown in Table E.2. The following is a list of the contents of these blocks which have fixed names throughout.

/DMSN/

MAX	- integer	maximum polynomial degree for current approx.
NFP	- integer	matrix and array dimension.
MFP	- integer	array dimension for symmetric matrices.
MFP2	- integer	array dimension for non-symmetric matrices.
RAT	- real	width-to-length ratio of the plate.

Block	Location - underlined routine indicates data origin
VERSN	PLATEF, <u>FIRST</u> , UNFORM, WRTHED
IGNORE	PLATEF, <u>BLKDAT</u> , FILES
EIGVER	PLATEF, <u>BLKDAT</u> , <u>GETEIG</u> , <u>UNFORM</u> , WRTHED
DMSN	PLATEF, <u>UNFORM</u> , <u>GETEIG</u> , WRTGEO, WRTHED, LOOP, SECOND, PETE7
EIGPOT	PLATEF, <u>UNFORM</u> , <u>GETEIG</u> , LOOP, PETE7
EIGVAL	PLATEF, <u>UNFORM</u> , <u>GETEIG</u> , ELECT
POLDAT	PLATEF, <u>UNFORM</u> , <u>CBDGIT</u> , POT
POL20	PLATEF, <u>UNFORM</u> , <u>CBDGIT</u> , LOOP, PETE7
XANDW	PLATEF, <u>BLKDAT</u> , CBDGIT, LOOP, PETE7
ORDER	PLATEF, <u>UNFORM</u> , <u>CBDGIT</u> , LOOP, PETE7, H1COF, H2COF
GEOM	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>PLTGEO</u> , <u>CORNER</u> , REFER, CLOSER, WRTGEO, WRTHED, LOOP, SECOND
REFPT	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>PLTGEO</u> , CORNER, CLOSER, WRTGEO, WRTHED, LOOP, SECOND
PLTCOR	PLATEF, <u>UNFORM</u> , <u>CORNER</u> , REFER, WRTGEO, WRTHED
TXSEG	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>LSOURC</u> , PFIELD, WRTGEO, WRTHED, LOOP
FIELDS	PLATEF, <u>UNFORM</u> , <u>REFER</u> , WRTGEO, WRTHED
RXLINE	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>PROFIL</u> , XPLAIN, PPVIEW, WRTHED, SECOND
DDHOLE	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>PROFIL</u> , XPLAIN, PPVIEW, WRTHED, SECOND
PROACH	PLATEF, <u>UNFORM</u> , <u>CLOSER</u> , XPLAIN, WRTHED
CHECKS	PLATEF, <u>UNFORM</u> , <u>CLOSER</u> , XPLAIN, WRTHED
PARAM	PLATEF, <u>UNFORM</u> , <u>RDPARM</u> , <u>DIGITL</u> , <u>RAMPEM</u> , <u>EM37</u> , <u>UTEM10</u> , <u>SIROTM</u> , WRTSYS, WRTHED, ELECT
WAVFOR	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>SYSTEM</u> , <u>RDPARM</u> , <u>DIGITL</u> , <u>RAMPEM</u> , <u>EM37</u> , <u>UTEM10</u> , <u>SIROTM</u> , WRTSYS, WRTHED, ELECT
SYSGAN	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>SYSTEM</u> , <u>DIGITL</u> , <u>RAMPEM</u> , <u>EM37</u> , <u>UTEM10</u> , <u>SIROTM</u> , WRTSYS, WRTHED, PPVIEW
PONENT	PLATEF, <u>BLKDAT</u> , <u>UNFORM</u> , <u>SYSTEM</u> , WRTSYS, WRTHED
NORMAL	PLATEF, <u>UNFORM</u> , <u>SYSTEM</u> , WRTSYS, PPVIEW, WRTHED
DVISION	PLATEF, <u>BLKDAT</u> , <u>DIVIDE</u> , PETE7
BLOK1	PLATEF, <u>BLKDAT</u> , CDQUAD
POINT	PLATEF, <u>PETE7</u> , F1
DEGREE	PLATEF, <u>PETE7</u> , F1

Table E.2 Common block map for PLATEF.

```

/EIGPOT/
U      - real      (225) eigenvectors of the current distribution.

/EIGVAL/
DIG    - real      (15) eigenvalues of the current distribution.

/POLDAT/
DEL    - real      distance between sample points in array CC.
NIT    - integer   number of values per point in CC array.
NCC    - integer   size of CC array.
CC     - real      (400) digitized Chebychev poly. (between 1 and -1).

/POL20/
NT     - integer   # trial functions needed for sec field coeffs.
NTR    - integer   size of TRIAL array.
TRIAL  - real      (120) digitized trial functions at quadrature pts.

/XANDW/
NPOINT - integer  # points in the "quick" numerical quadrature.
XP     - real      (20) zeros for Gauss-Legendre quadrature.
WP     - real      (20) weights for Gauss-Legendre quadrature.

/ORDER/
NPOL   - integer   # 2-D trial functions for sec field coeffs.
NX     - integer   sequence of polynomial degree in X.
NY     - integer   sequence of polynomial degree in Y.

/GEOM/
S      - real      strike length of plate.
W      - real      width of plate.
STR   - real      strike of plate (rotation of U twd V about W).
DIP   - real      dip of plate (rotation of V toward W about U).
PLU   - real      plunge of plate (rotation of U twd V about W).

/REFPT/
FACTS - real      U coordinate of plate reference pt. (-1 to 1).
FACTW - real      V coordinate of plate reference pt. (-1 to 1).
XS    - real      (3) field coordinates of plate reference point.

/PLTCOR/
XPLT  - real      (5,3) coordinates of each plate corner and center.

/TXSEG/
NSEG1 - integer   number of loop segments + 1.
TLINE - real      (11,3) coordinates of each corner of the tx loop.

```

**/FIELDS/**

XPPF	- real	(5,3)	primary field (plate components) at corners.
XPMAG	- real	(5)	primary field magnitude at each plate corner.
XPANG	- real	(5)	intersection angle of primary field at corners.

**/RXLINE/**

X0	- real	(3)	starting point of profile.
XEND	- real	(3)	end point of profile.
PL	- real		length of profile.
THETA	- real		dip of profile from vertical (in degrees).
PHI	- real		azimuth of profile counter-clock from X-axis.
PINT	- real		distance between receiver stations.
NMB	- integer		number of stations along the profile.
SPH	- real	(3)	receiver interval in 3 field components.

**/DDHOLE/**

XC	- real	(3)	collar coordinates of the borehole.
DDH	- real		distance along the borehole to starting point.

**/PROACH/**

SEP	- real	(3)	separation btwn plate and Rx at critical pts.
DIS	- real	(3)	three critical station points.
PINCP	- real	(3)	plate plane coords of Rx line intersection.
PCLOSE	- real	(3)	point on plate of closest approach to Rx line.
END	- real	(3)	plate pt. of short profile's closest approach.
ANG	- real		intersection angle of Rx line and plate plane.

**/CHECKS/**

SHORT	- logical		.TRUE. if profile doesn't reach least septn pt.
PARAL	- logical		.TRUE. if profile runs parallel to the plate.

**/PARAM/**

PARM	- real	(80)	time or frequency parameters.
NPARM	- integer		number of time or frequency parameters.

**/WAVFOR/**

NSPONS	- integer		electrical coefficient option number.
NWIN	- integer		number of output values.
WINDOW	- logical		.TRUE. if time windows are used.
DT	- real		length of turn-off in current waveform.
TAUON	- real		time contant of primary current turn-on.
TTC	- real		cycle time of time-domain waveform.

SIGT - real conductivity-thickness of the plate.  
 /SYSGAN/  
 INSTR - integer determines which instrument gains are used.  
 PPGAIN - real primary waveform gain for 1A peak current.  
 RXGAIN - real external gain setting of the receiver.  
 TXGAIN - real waveform gain (peak current).  
 AREA - real effective area of Rx loop.  
 PMULT - real total gain for the system.  
 /NORMAL/  
 XNORM - real (3) coordinates of normalization point.  
 PNORM - real (3) primary field component at normalization point.  
 PMAG - real magnitude of field at normalization point.  
 DIR - real (3) component direction.  
 COMSYS - character\*3 component specifications.  
 /DVISON/  
 NCELLS - integer # cells in plate division.  
 CXY - real (32) X and Y limits for the 8 cells.  
 LCXY - integer (8) starting points in CXY array for each cell.  
 NUMC - integer (8) I.D. numbers of the cells used.  
 NQUAD - integer (16) X and Y numerical quadrature numbers for cells.  
 /BLOK1/  
 ZERO - real (53) zeros for numerical quadrature.  
 WEIGHT - real (53) weights for numerical quadrature.  
 LZW - integer (20) table location of weights and zeros.  
 NEAR - integer (20) nearest available order of numerical quadr.  
 /POINT/  
 XRX - real x coordinate of sample point during integratn.  
 YRX - real y coordinate of sample point during integratn.  
 ZRX - real z coordinate of sample point during integratn.  
 /DEGREE/  
 JX - integer polynomial degree required during integration.  
 JY - integer polynomial degree required during integration.  
 RT - real = RAT.

### E.3.2 Other Global Variables in PLATEF

BACKUP - logical	allows for backtracking on terminal input.
EXN - real (15)	excitation coefficients.
FILENM - character*30	name of batch or diagnostic file.
FILE1 - character*30	name of coefficient read file.
FILE2 - character*30	name of coefficient save file.
FILE3 - character*30	name of final data file.
FLAG - logical (9)	input control for geometry and electrical info.
HR - real (80,15)	electrical coefficients.
ICHAN - integer	channel number desired for terminal viewing.
ICOFF - integer	logical unit number (1).
IEL - integer	flag for electrical coefficient calculation.
IERROR - integer	flag for error control in reading and writing.
IPP - integer	flag for primary field calculation.
ISEC - integer	flag for secondary field coeff. calculation.
ITX - integer	flag for excitation coefficient calculation.
KPOL - integer	# sample pts for Chebychev digitization.
LEVEL2 - logical	flag for writing detailed diagnostics.
LIMIT - integer	maximum allowable value for MAX.
MAXP1 - integer	maximum poly degree needed for sec. field coef.
MHEAD - integer	number of records in output file header.
NEL1 - integer	number of elec. coeff. channels/binary record.
NEL2 - integer	number of elec. coeff. records in binary file.
NHEAD - integer	number of records of header data in binary file.
NEIG - integer	logical unit number (2).
NF - integer	station number.
NINT - integer	base integration number for n-point quadrature.
NVAR - integer	number of variable per binary record.
NOST - integer	logical unit number (3).
NUNIT - integer	logical unit number (4).
OK - character*1	test variable for user approval.
PP - real (3)	primary field components at one station.
REUSE - logical	.TRUE. when coefficient read file is open.
SEEDAT - character*1	test for desire to see data on terminal.
SKEEP - real (15,3)	secondary field coefficients at one point.
STA - real	distance along profile to station.

### E.3.3 Overlays

If a particular variable is required at several points in the program, it is stored in the main program PLATEF. Thus, all common block variables can be found in the main routine even though they are not all used there. This structure allows the program to be divided into "branches", corresponding to each subroutine call, for the purpose of overlays. Thus, a simple overlay such as the one in Table E.3 could be used if necessary.

## E.4 Programming Background for PLATEF

This section details the theoretical background for the PLATEF subroutines, as well as their implementation and special features. Also detailed are the differences with respect to the University of Toronto (U of T) PLATE program. Table E.4 provides an overview of these changes. Mathematical derivations, by the author, have been included where appropriate.

All of the routines in the PLATEF program which require user input, make use of the input routine IIN, RIN, TIN, TIN30, and FILES which are described later. The calling routine tests the variable BACKUP immediately after calling one of these routines to see if a ^Z response has been used. If so, the routine branches - usually backwards. When a backwards step occurs, certain procedures must be undone, such as file opening and flag setting. More complicated resetting procedures are necessary when backtracking is used halfway through an optional procedure which is later avoided.

Error control in PLATEF routines is extensive. All OPEN, READ, and WRITE statements for disk files have end detection and/or error detection. A message is displayed for all detected errors, and control is returned to a convenient part of the program.

ROOT:	PLATEF - BLKDAT - IIN - RIN - TIN - TIN30 - FILES - PFIELD - FLDLIN - SUMV - ROT123 - VECT1 - RTRNA
BRANCHES:	FIRST  UNFORM  GETEIG  CBDGIT - CHBCHV  PLTGEO  CORNER  LSOURC  REFER  PROFIL - SPHER  CLOSER - LINES2 - PNTLIN - SHORTY  WRTGEO  XPLAIN  REDEW  SYSTEM - RDPARM - DIGITL - RAMPEM - EM37 - UTEM10 - SIROTM  WRTSYS  CHANGE  PPVIEW  WRTHED  ELECT - EXPO  LOOP  SECOND - PETE7 - DIVIDE - CDQUAD - F1 - POT - H1COF - H2COF - H3COF

Table E.3 Possible overlay structure.

Category	Name	Approximate PLATE equivalent	Approximate contribution by author
1. Main	PLATEF	LOPLOP	100%
2. Start-up	BLKDAT FIRST	some block data	80% 100%
3. Coordinate rotations and vector functions	ROT123 SPHER VECT1 SUMV	ROT1, ROT2, ROT3 SPHER VECT1 SUMV	20% 0% 30% 0%
4. Prompting for input	IIN, RIN, TIN, TIN30 FILES	PINPUT	60% 100%
5. Disk file I/O	UNFORM GETEIG WRTHED	GETIMA, PUTIN LOPLOP	100% 80% 100%
6. Geometrical parameters	PLTGEO CORNER LSOURC PROFIL WRTGEO XPLAIN REDEW	LOPLOP SOURC2 PROFIL	70% 100% 70% 70% 100% 100% 100%
7. Magnetic field determinations	FLDLIN PFIELD REFER PPVIEW	FLDLIN NORML2	10% 30% 100% 100%
8. Profile-plate critical points and distances	CLOSER LINES2 PNTLIN SHORTY		100% 100% 100% 100%
9. Electrical parameters	SYSTEM RDPARM DIGITL, RAMPEM, EM37, UTEM10, SIROTM WRTSYS CHANGE	GETIMB, SETUP1, SETUP3 RDPARM GETIMB	95% 80% 95% 100% 100%

Table E.4 Differences between PLATE and PLATEF.

Category	Name	Approximate PLATE equivalent	Approximate contribution by author
10. Electrical coefficients	ELECT	GETIMC, SPONS	80%
11. Excitation coefficients	LOOP	PETE6, LINSET, INGRAT, DQADM TERPIT, POT	90%
12. Secondary field coefficients	SECOND PETE7 DIVIDE CDQUAD F1 POT H1COF, H2COF, H3COF	LOPLOP PETE7, CINGRT DIVIDE CDQUAD F1 POT H1COF, H2COF, H3COF	70% 90% 10% 10% 10% 10% 10%
13. Common sec. field and exc. coeff. routines	CBDGIT CHBCHV RTRNA	CBDGIT CHBCHV RTRNA	70% 10% 0%

0 - 25% - Original routine is intact within new program.  
New documentation or control has been added.

25 - 50% - Parts of old code are intact, but there are some additions or modifications.

50 - 75% - There are substantial additions to the code and many new features are added.

75 - 99% - Very small amounts of the old code are used, if at all.

Table E.4   Continued.

#### E.4.1 Main Program PLATEF

The most obvious features of the main routine PLATEF are its modular nature for parameter input, and the storage of model information and calculations in "coefficient files" for later use. Both of these features require the use of flags. Nine flags are used for the input of model parameters, and these are reused for the input of electrical parameters. They are set in the menu routines REDEW and CHANGE and determine which input and geometrical calculation routines are called. Through the use of these flags, the user can quickly, and indefinitely, make changes to the model geometry prior to any lengthy calculations.

Coefficients are calculated on the basis of three flags: IEL, ITX, and ISEC. A value of -1 means that a calculation is required, a value of 0 means that the coefficient values in computer memory should be used, while a value of +1 indicates that the values should be read from a coefficient file. IEL and ITX are set to 0 after their calculation because the electrical and excitation coefficients are stored in memory. ISEC is never set to 0 because the secondary field coefficients are only stored in a coefficient file. All are set to 1 when a coefficient file is opened, and each can be set to -1 when particular model parameters are changed.

A complete rewrite of the U of T PLATE subroutine LOPLOP was required to implement the two features mentioned above. Large, unused data arrays were eliminated during this process, along with a long and confusing output section. In addition, code for handling dipole fields, uniform fields, and tertiary responses was eliminated; the latter two because bugs were known to exist. Finally, the batch procedure was greatly improved so that any number of models can now be set up and run without user intervention, instead of just one at a time.

#### E.4.2 Start-up Routines

Subroutine BLKDAT contains two BLOCK DATA routines from the U of T PLATE program: the boundaries of the plate division process (/DVISON/); and the Gauss quadrature table (/BLOK1/). This table, however, has been revised so that it is much easier to understand and expand if necessary. BLKDAT also contains a new Gauss quadrature table (/XANDW/) which is used for the new quick integrations in PLATEF. It simply contains the weights and zeros for a 20th order Gauss-Legendre quadrature. The much greater use of common block variables in PLATEF accounts for the rest of the initialization in BLKDAT. These are mostly user-defined variables which require reasonable default values.

Subroutine FIRST simply writes the program header and user name to the screen, and returns the user name to PLATEF. It is the only part of the program which has to be recompiled for different users.

#### E.4.3 Coordinate Rotations and Vector Functions

Subroutine ROT123 performs the strike, dip, plunge rotations of the plate (see User's Manual). The three forward [and reverse] rotations are:

```

strike: u' = u cos (strike) + [-] v sin (strike)
        v' = v cos (strike) - [+] u sin (strike)
        w' = w
dip:    u' = u
        v' = v cos (dip) + [-] w sin (dip)
        w' = w cos (dip) - [+] v sin (dip)
plunge: u' = u cos (plunge) + [-] v sin (plunge)
        v' = v cos (plunge) - [+] u sin (plunge)
        w' = w

```

The program is used in the transformation from field to plate coordinates in the forward (strike-dip-plunge), and reverse (plunge-dip-strike) directions. A feature of the U of T version, which allowed each rotation to be performed separately, was eliminated because it was never

used. The new version also allows all three reverse rotations to be performed with one call instead of three.

Subroutine SPHER performs coordinate transformations between spherical and cartesian systems. The cartesian coordinates ( $x, y, z$ ) are derived from the sphericals ( $R, \theta, \phi$ ) by:

$$\begin{aligned}x &= R \sin \theta \cos \phi \\y &= R \sin \theta \sin \phi \\z &= R \cos \theta\end{aligned}$$

while the reverse transformation is:

$$\begin{aligned}R &= (x^2 + y^2 + z^2)^{1/2} \\ \theta &= \arctan ((x^2 + y^2)^{1/2} / z) \quad [ + \pi \text{ if } \theta < 0] \\ \phi &= \arctan (y/x) \quad [ + 2\pi \text{ if } \phi < 0]\end{aligned}$$

This routine is used to facilitate the input of the profile parameters (see User's Manual). A reference point, starting distance, profile length, and two angles are input, and SPHER is used to calculate the start and end points.

Subroutine VECT1 transforms vectors from field to profile components (see User's Manual). Two rotations of the ( $x, y, z$ ) field coordinate system are performed so that the new system ( $X, Y, Z$ ) has X pointing along the profile, Y horizontal, and Z pointing in an upward direction. These rotations are:

$$\begin{aligned}X &= x \cos \phi \sin \theta + y \sin \phi \sin \theta + z \cos \theta \\Y &= -x \sin \theta + y \cos \theta \\Z &= -x \cos \phi \cos \theta - y \sin \phi \cos \theta + z \sin \theta\end{aligned}$$

The program is used to express the final secondary vector field data in useful components. The U of T version used similar components, but Y and Z were reversed in order and sign. The new definition, used here, allows one component system to be used for borehole and surface profiles, because the ( $X, Y, Z$ ) system is identical to the ( $x, y, z$ ) system when the profile lies along the x-axis.

Subroutine SUMV actually consists of six, simple vector function routines as follows:

summation -	SUMV
difference -	DIFV
dot product -	DOTV
cross product -	CROSV
unit vector -	UNITV
scalar product -	SCLV

#### E.4.4 Prompting for Input

The subroutines IIN, RIN, TIN and TIN30 are used to prompt for integers, reals, single characters, and 30 character variables respectively. They are the most widely used routines in PLATEF, and are based on the U of T PLATE subroutine PINPUT. Both versions write prompts to the screen, present default values, and test for a carriage-return response. The new routines, however, will leave any number of blank lines before the prompt; will test for embedded spaces in the response; will test for a control-Z response which returns a flag to the calling routine; and will convert lower case character responses to uppercase.

Other coding changes include: the removal of the ENTRY statement which led to the division of PINPUT into the new, more specific subroutines; the removal of the CHARACTER(\*) statement which resulted in two routines for character input (TIN and TIN30); and the replacement of the LEN function with the INDEX function ( a '\$' is now required at the end of the prompt). These changes should make the code more portable.

FILES was created to simplify the prompting for filenames where default values do not exist. A default drive or path can be prefixed to the filename, if none is used in the response. The existence of both old and new files is tested, and the user is given a warning if the test fails.

All of these input subroutines contain a new feature which allows the user to respond with the special character ^Z. When this response is detected, a flag is set and returned to the calling routine. Although it is normally used to backtrack to the previous prompt, it can be used for other purposes. This feature requires that the standard input unit (keyboard) is closed after receiving the ^Z, and this has been incorporated into the code.

#### E.4.5 Disk File I/O

Subroutine UNFORM is used to write binary data files containing the model parameters. This procedure has been introduced to PLATEF for the reading and writing of coefficient files, and the writing of batch files. The number of bytes per record is adjustable, but must be greater than 800 (PLATEF uses a value of 1000 so as to be within the default value of 1024 of most microcomputers). The variables NHED, NEL1, and NEL2 are calculated in order to control file positioning.

Subroutine GETEIG is used to retrieve the eigenfunctions from the binary data file written by program EIGCUR. The program presents all the available filename choices by reading the ASCII file "FILES.EIG" (see User's Manual). A record length of 1000 bytes is used. The U of T PLATE subroutine GETIMA provides little help in choosing from available files, and in fact, is primarily concerned with controlling the calculation of the eigenfunctions. This control has now been moved to program EIGCUR. The presentation and user approval of the eigenvalues has been removed because these are meaningless to most users.

The writing of model parameters to the final data file is performed by WRTHED. PLATEF solicits and calculates considerably more model information than PLATE, and WRTHED writes this information once in a file header. The output from PLATE, on the other hand, is complicated, hard to read, and the model parameters are rewritten for each component and time or frequency parameter.

#### E.4.6 Geometrical Parameters

Subroutine PLTGEO is used to input the plate parameters FACTS, FACTW, S, STR, DIP, PLU, and XS. While the same input is acquired by LOPLOP in PLATE, it only provides defaults for FACTS and FACTW. PLTGEO presents default values for all the required input making it much easier to change one of the parameters. It also checks for valid ranges on all of the parameters ( $S > 0$ ;  $|STR| \leq 360^\circ$ ;  $|DIP| \leq 360^\circ$ ;  $|PLU| \leq 360^\circ$ ). Other new features include: warnings if the reference point lies off the plate or above surface; and backtracking to the previous prompt with a  $^Z$  response.

CORNER is a new subroutine which calculates the field coordinates of each plate corner and the plate center. This is done by first expressing these points in plate coordinates with respect to the reference point. These are then transformed into field coordinates using the strike, dip, plunge rotations (subroutine ROT123) and a translation to the reference point.

Subroutine LSOURC provides the transmitter loop parameters TLINE and NSEG1. The user can specify the number of loop corners and proceed to enter three coordinates for each. Alternatively, a default loop can be set up so that only two parameters, XFACT, YFACT, need to be input (see User's Manual). These two features were retained from the U of T subroutine SOURC2. The most obvious new feature in LSOURC is that default values are used for each coordinate of each loop corner. This greatly simplifies this input, especially with the addition of the new  $^Z$  feature which allows for backtracking. As well, the first loop coordinate does not have to be input twice to close the loop, as the program now does this automatically. Other new features include the testing of input ( $XFACT > 0$ ;  $YFACT > 0$ ; warning if TLINE (I,3)  $\neq 0$ ), and the elimination of the loop mid-point calculation which was not used.

Subroutine PROFIL is used to input the profile parameters XC, DDH, PL, PINT, THETA, and PHI. In addition, it calculates XO, XEND, NMB, and

SPH. The input of XC and DDH, and the calculation of XEND do not exist in the PLATE subroutine PROFIL. The new variables allow a user to specify a known point on the profile as a reference (such as a drillhole collar), and locate the starting point by a distance from this reference. The profile start and end points are calculated by subroutine SPHER, as are the cartesian increments SPH. The other new features include: default values for all required input; backtracking by responding with a ^Z; and checking the valid range of input (PL > 0; PINT > 0; warning if XC(3) > 0). As in the PLATE program, THETA and PHI are adjusted so that  $0^\circ \leq \text{THETA} \leq 180^\circ$  and  $0^\circ \leq \text{PHI} \leq 360^\circ$ , but values for THETA >  $180^\circ$  can now be input (PHI is adjusted by  $180^\circ$ ). If the adjusted value of THETA is <  $90^\circ$ , a warning appears that the profile is pointing upward.

Subroutines WRTGEO and XPLAIN are two new routines which write out a description of the model geometry. All the input parameters are presented along with the plate corner and center coordinates, the magnetic H field at the plate corners and center, and the plate-profile critical points and distances. The information is presented in a compact form so that it can be viewed easily on the screen (see User's Manual).

Subroutine REDEW is a new routine which allows any part of the model geometry to be changed through menu selection (see User's Manual). Nine numbered choices are presented, but these numbers are treated as character data on input so that several choices can be made and strung together into a single character string. Depending on which parameters are changed, certain coefficients may have to be recalculated. Thus, the flags which control these calculations (IEL, ITX, ISEC) are reset in this routine. If sufficient changes are made so that none of the coefficients are read from an open coefficient file, then that file is closed.

#### E.4.7 Magnetic Field Determinations

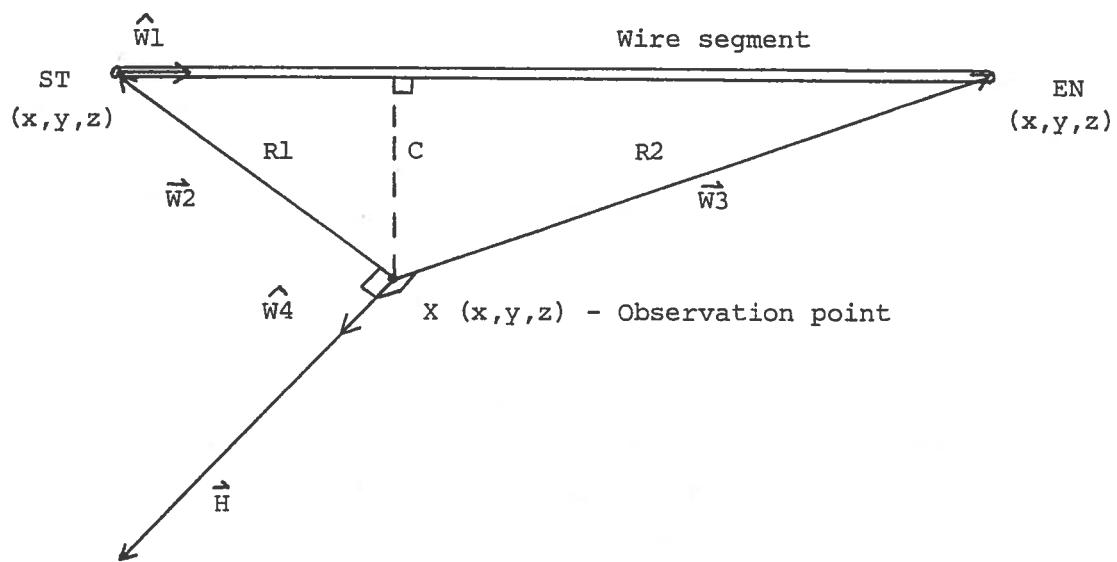
Subroutine FLDLIN calculates the magnetic vector field at a point from a wire segment carrying one Amp of steady current. Figure E.1 illustrates the geometry of the problem using the variables defined in the code. FLDLIN is used by subroutine LOOP to calculate the coupling between the plate and the transmitter loop; and by subroutine PFIELD as described below.

Subroutine PFIELD simply applies FLDLIN successively over each of the loop segments, and adds their contributions. A small section of code was removed from the U of T PLATE subroutine NORML2 to create this subroutine. PFIELD is used by subroutine SECOND to calculate the primary field at each receiver location, and by subroutines REFER and PPVIEW as described below.

Subroutine REFER uses PFIELD to calculate the magnetic field at each plate corner and plate center. The  $H_x$ ,  $H_y$ ,  $H_z$  components are rotated into the plate coordinate system using subroutine ROT123 to produce  $H_u$ ,  $H_v$ ,  $H_w$  at each point. Finally, the magnitude of each vector, and its intersection angle with the plate, are calculated. The latter calculation is given by:

$$\arctan ((H_u^2 + H_v^2)^{1/2} / H_w).$$

Subroutine PPVIEW calculates each receiver location by using the profile starting point X0 and the cartesian increments SPH. For each location, PFIELD is used to calculate the primary field components, and VECT1 transforms these into profile components. The system gains are then applied, and the results written to the screen, 20 stations at a time. If the user is not satisfied with these values, he can go back and change the model parameters.



$$\begin{aligned}
 \vec{H} &= \frac{\hat{\vec{w}_1} \cdot \vec{w}_3 - \hat{\vec{w}_1} \cdot \vec{w}_2}{4\pi C} \hat{\vec{w}_4} \\
 &= \frac{\vec{w}_1 \cdot \vec{w}_3 - \vec{w}_1 \cdot \vec{w}_2}{4\pi |\vec{w}_1 \times \vec{w}_2|^2} \vec{w}_1 \times \vec{w}_2
 \end{aligned}$$

Figure E.1 The magnetic field produced by 1 Ampere of steady current in a wire segment.

#### E.4.8 Profile-plate Critical Points and Distances

A new set of programs have been written to calculate:

- 1) the intersection point and intersection angle of the profile line and plate plane.
- 2) the distance from the intersection point to the nearest plate edge.
- 3) the plate point and profile station of closest approach.
- 4) the separation between closest approach points.
- 5) parallel and short profile characteristics.

The subroutine CLOSER first performs coordinate rotations using subroutine ROT123, so that the plate is centered at the origin and lies in the plane  $z = 0$ . This transformation is applied to the profile starting point, and the end point, which has been calculated by PROFIL from the profile length and direction. Next, the profile is assumed to be an infinite line, and the plate an infinite plane, and their intersection point is found. This point is represented by both a profile station value, as well as a point in the plate coordinates. The angle of intersection with the plate surface is also found.

Depending on which area of the plane  $z = 0$  has been intersected (see Figure E.2), the shortest distance from this point to the plane can be easily calculated. In general, however, there will be a point on the line where the separation is less. If the intersection has occurred in regions B or C, the closest approach between the survey line and one edge needs to be calculated. If the intersection has occurred in D, the survey line could be closer to one of two plate edges.

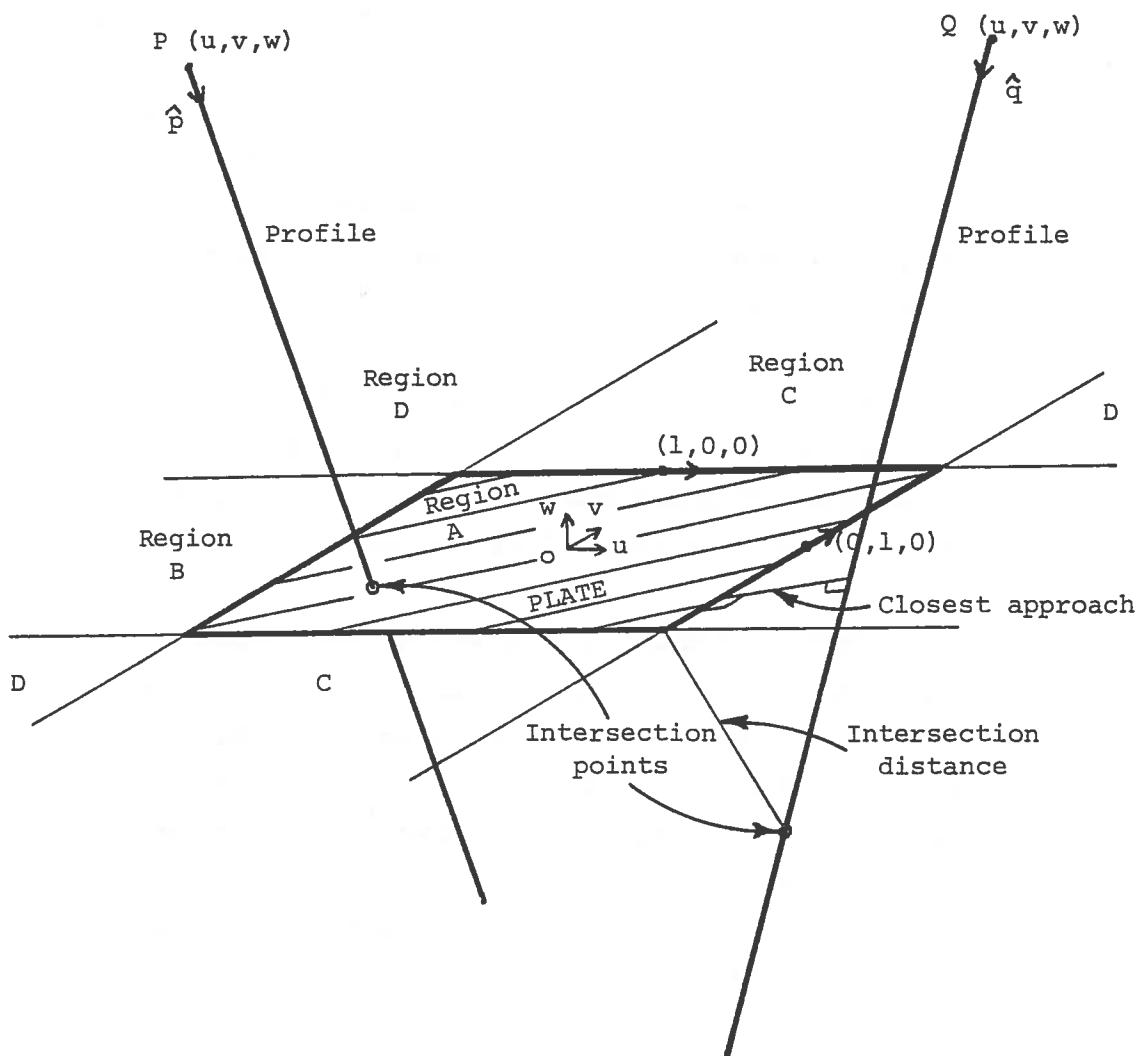


Figure E.2 Critical point and distance calculations.

In finding the closest approach of a line to a line segment, the segment is first treated as an infinite line, and the information is found using subroutine LINES2. If the closest point is found to lie off one end of the segment, the closest approach to that endpoint is calculated using subroutine PNTLIN.

Since this analysis is based on the survey line intersecting the plane  $z = 0$ , it is obvious that lines parallel to that plane will present a problem. There are two cases of interest: lines whose vertical projection onto the  $z = 0$  plane miss the plate; and ones that do not. In the first case, a plate point and a profile station can still be found which have a minimum separation. In the second case, two plate points, and two stations between which the separation is least but constant, can be found.

In all cases, the survey line may end before reaching the point of least separation. In this case, one of the endpoints of the line will be closest and this distance will be calculated using subroutine SHORTY. A flow chart of subroutine CLOSER is shown in Figure E.3.

Subroutine LINES2 calculates the least separation ( $S$ ) between two lines given by their zero points and unit vectors (see Figure E.4). The distances to the least separation points along each line are also calculated ( $Y$  and  $D$ ). The value of  $S$  will always be positive, as it should be, but  $Y$  and  $D$  can be negative, indicating that the closest approach point is in the opposite direction to the unit vector. If  $|(\hat{a} \cdot \hat{b})| = 1$ , a logical flag (PLL) is set to indicate that the lines are parallel, and  $Y$  is set to 0.  $D$  and  $S$  are still calculated, however.

PNTLIN is a simple routine for finding the least separation between a point and a line. The distances along the line, at which this least separation occurs, is also to be calculated (see Figure E.5).

Subroutine SHORTY calculates the closest approach of a point to a finite plate. It is used in program PLATEF when the profile is not long enough to reach the point of least separation. The nearest endpoint of

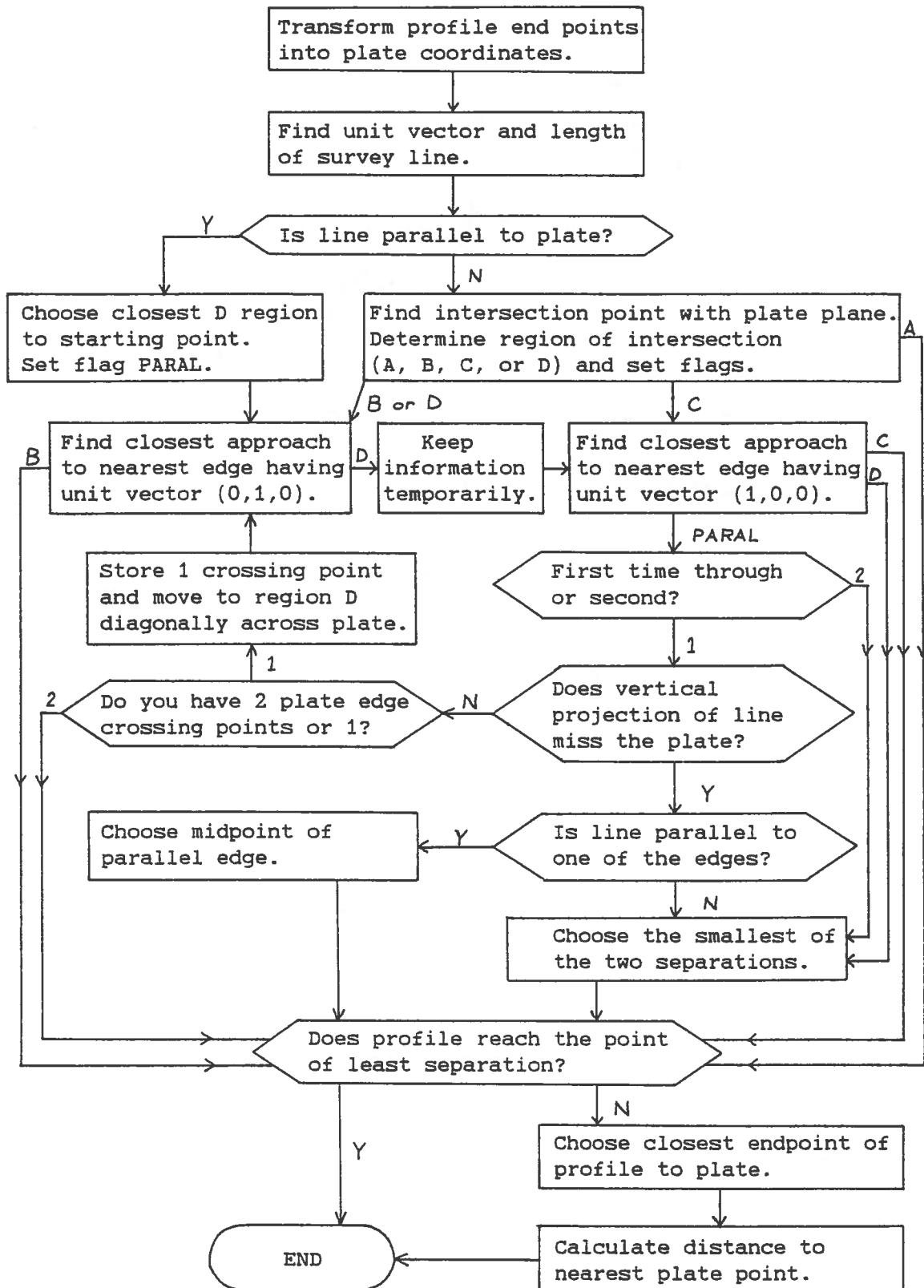
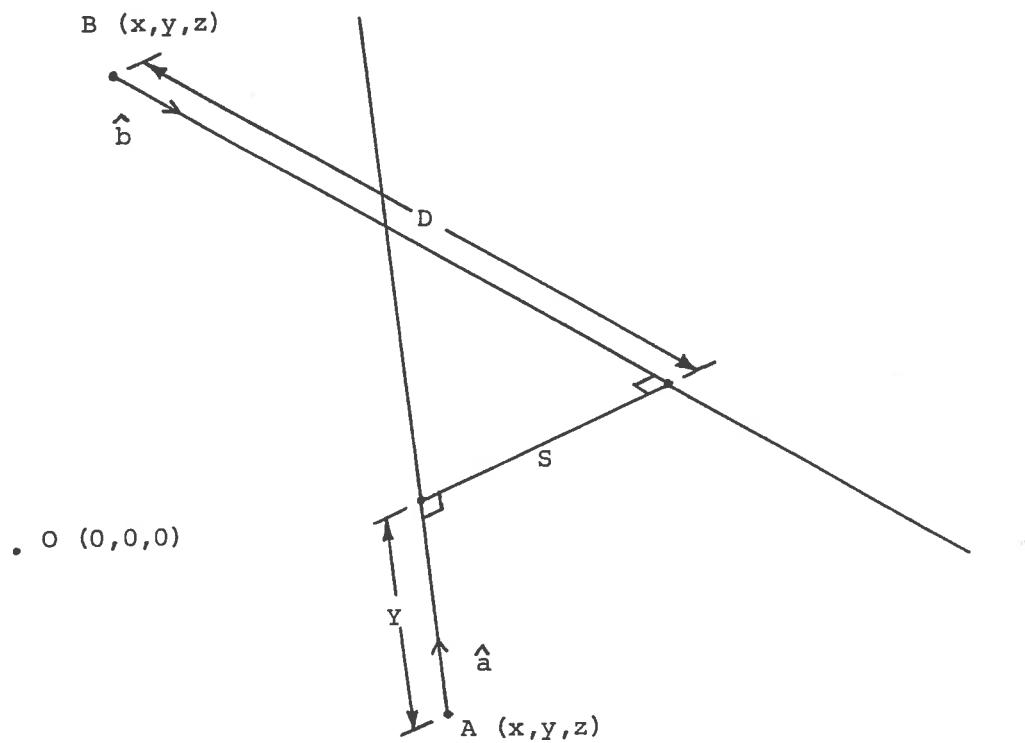


Figure E.3 Flow chart of subroutine CLOSER.

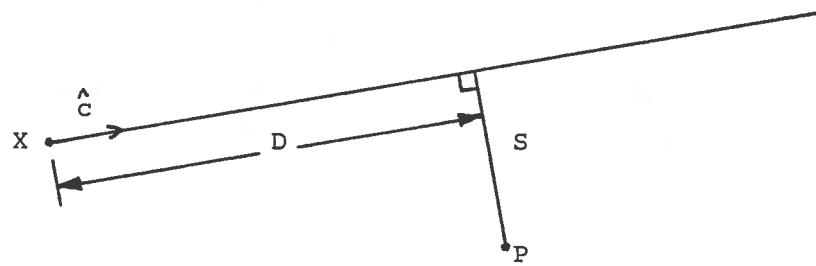


$$Y = \frac{(\vec{A} - \vec{B}) \cdot (\hat{a} - \hat{b}(\hat{a} \cdot \hat{b}))}{(\hat{a} \cdot \hat{b})^2 - 1}$$

$$D = (\vec{A} - \vec{B}) \cdot \hat{b} + Y(\hat{a} \cdot \hat{b})$$

$$S = \left| ((\vec{A} - \vec{B}) + Y\hat{a}) \times \hat{b} \right|$$

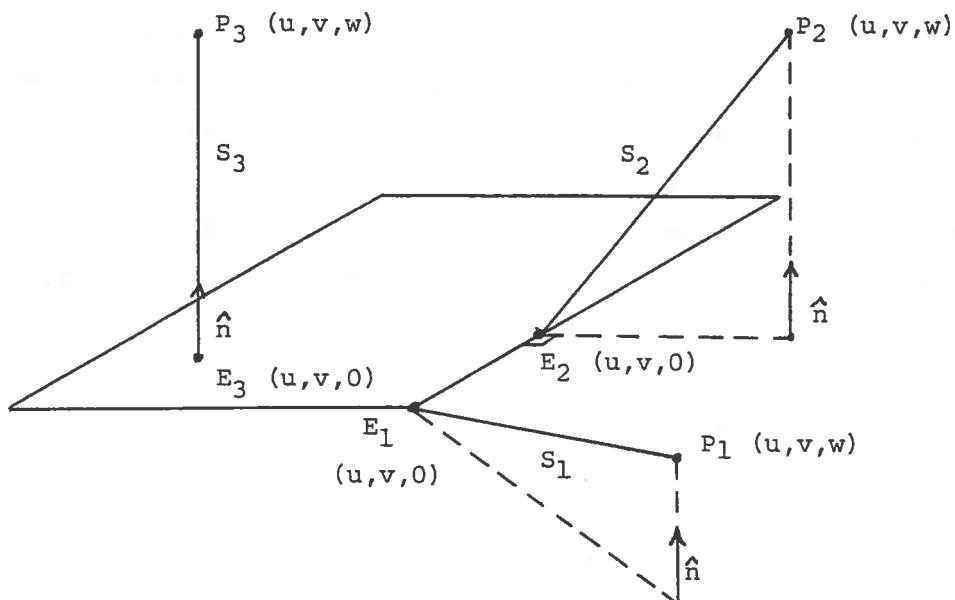
Figure E.4 Closest points on two lines.



$$S = \left| (\vec{P} - \vec{X}) \times \hat{c} \right|$$

$$D = (\vec{P} - \vec{X}) \cdot \hat{c}$$

Figure E.5 Shortest distance from a point to a line.



$P_1, P_2, P_3$  - observation points

$E_1, E_2, E_3$  - closest plate points

$s_1, s_2, s_3$  - shortest distance to plate from  $P$

$\hat{n}$  - unit normal anchored on plate plane

Figure E.6 Closest point on a plate.

the profile (P) is chosen, and is projected onto the plate plane. The point on the plate (E) which comes closest to this projected point is easily found by perpendicular projection to an edge, by choosing a plate corner, or by using the point coordinates themselves (see Figure E.6). Finally the separation (S) between P and E is calculated using their coordinates.

#### E.4.9 Electrical Parameters

The subroutines SYSTEM, RDPARM, DIGITL, RAMPEM, EM37, UTEMIO, and SIROTM are concerned with the input of a large number of electrical and system parameters. It can be seen in Tables 4.5 and 4.6 that this part of the model definition is considerably different from that in the PLATE program.

Many of the system choices have been eliminated, while new ones have been added, so that only TDEM systems are modelled. While the three system parameters defining the waveform have remained the same (DT, TAUON, TTC), three new parameters are primarily concerned with system gains and output units (RXGAIN, TXGAIN, AREA). Thus, while PLATE presents the output in units of amp/m or various primary field normalizations, output from PLATEF is presented in the same units as field data (see User's Manual). The following theory explains how this change came about.

The primary magnetic field from the transmitter loop can be expressed as:

$$\underline{H}_p = \underline{H}_{p1} I$$

where  $\underline{H}_p$  is the total field

$\underline{H}_{p1}$  is the field due to 1 Amp steady current (calculated by subroutine FLDLIN)

and  $I$  is the current.

Coil receivers, however, measure the time rate of change of the field, and thus, we have:

$$\frac{\partial \underline{H}_p}{\partial t} = \underline{H}_{p1} \frac{\partial I}{\partial t}$$

The U of T PLATE program avoids this complication by normalizing the current waveform so that  $\partial I / \partial t = 1A/sec$ . This produces the result:

$$\frac{\partial \underline{H}_p}{\partial t} = \underline{H}_{p1} \quad (\text{ignoring units})$$

and this has led to the misconception that the output from PLATE is in amp/m (in fact, it is in amp/m-sec). While system receivers do measure the field in various units, none seem to measure it in amp/m-sec. The most common measurement unit appears to be Tesla/sec (=Volt/m<sup>2</sup>), which is a measurement of  $\partial \underline{B} / \partial t$ . For the primary field in free space we have:

$$\frac{\partial \underline{B}_p}{\partial t} = \mu_0 \frac{\partial \underline{H}}{\partial t} = \mu_0 \underline{H}_{p1} \frac{\partial I}{\partial t}$$

where  $\underline{B}_p$  is the magnetic induction produced by the loop, and  $\mu_0$  is the permeability of free space.

Since this effect, and the effect of the waveform normalization, is the same for the secondary  $\underline{H}$  field, a correction of  $\mu_0 \partial I / \partial t$  must be applied to both the primary and secondary field data produced by PLATE. For ramped current systems, this amounts to:

$$4\pi \times 10^{-7} \times \text{TXGAIN} / \text{DT}$$

where TXGAIN is the peak current, and DT is the ramp time.

Other common units used by TDEM systems are Crone units, and uVolt/Amp. To produce these units from  $\partial B / \partial t$  requires an additional multiplication by the effective area of the receiver loop (AREA). Crone unit conversion also requires multiplication by the external gain setting (RXGAIN), while division by the transmitter current (TXGAIN) is required for uV/A.

In addition to the system characteristics and the output units, the channel times are also input at this point. Subroutine RDPARM can be used, as in PLATE, to input these parameters through the keyboard, or by reading a prepared ASCII file. New features were added which provide default values for the terminal entry and provide a list of available ASCII files which can be chosen. A third method for the input of these parameters was also introduced. This consists of simply accepting standard channel times which have been built into the code for each system.

Finally, a new feature allows the sign of each of the measured components to be defined. The Z component always points in an upward direction (unless the profile is vertical), but its sign can be changed by changing the sense of the primary magnetic field (field points up or down in center of loop). The sign on the X component is directly input, while that of the horizontal Y component is set by having it complete a left or right-hand orthogonal component system.

WRTSYS and CHANGE present the electrical parameters to the screen, and allow the user to make changes. In general, changes can be made to specific parameters. The exception is that a system change requires a change in channel times, and output units and gains. This is because times and units are quite system-specific.

#### E.4.10 Electrical Coefficients

ELECT calculates the electrical coefficients for the various system waveforms and channel times. This calculation was also performed in PLATE, but not for the ramped current systems such as Crone PEM, Geonics EM37, and SIROTM. Also, PLATE repeated this calculation unnecessarily for each component and each receiver station.

The electrical coefficients for the impulse response are given by:

$$D_n(t) = -e^{-(t/\tau_n)} / \tau_n l_n (b/a); \quad \tau_n = \mu_0 \sigma_s b l_n$$

where  $D_n(t)$  is the  $n^{\text{th}}$  electrical coefficient  
 $t$  is the measurement time  
 $\tau_n$  is the time constant  
 $\mu_0$  is the permeability of free space  
 $\sigma_s$  is the conductivity - thickness  
 $l_n$  is the  $n^{\text{th}}$  eigenvalue  
 $b$  is the half - width of the plate  
 $a$  is the half - length of the plate

The general time-domain response for systems which use complicated current waveforms, can be found by convolving the impulse response with the waveform ( $f(t)$ ):

$$D_n(t) = \int_{-\infty}^t f(t') \frac{e^{-((t-t')/\tau_n)}}{\tau_n l_n (b/a)} dt'$$

Since the final output from PLATEF must be a measure of  $\partial B / \partial t$ ,  $f(t')$  is taken to be the time derivative of the current waveform.

Another complexity of the system waveforms is that they normally alternate in sign and are repetitive with a fixed period  $T$ . However, we only need to integrate over the preceding half cycle of the waveform since the contribution from earlier half cycles are simple fractions of this basic integral. Thus, for a repetitive, alternating waveform,

$$\begin{aligned} D_n(t) &= (1 - e^{(-T/2\tau_n)} + e^{2(-T/2\tau_n)} - \dots) \int_{t-T/2}^t f(t') \frac{e^{-((t-t')/\tau_n)}}{\tau_n l_n (b/a)} dt' \\ &= \frac{1}{l_n \tau_n (b/a) (1 + e^{(-T/2\tau_n)})} \int_{t-T/2}^t f(t') e^{-((t-t')/\tau_n)} dt' \end{aligned}$$

and it can be seen that the term  $1/(1+e^{-(T/2\tau_n)})$  accounts for the alternating repetitions of the waveform at time intervals of  $T/2$ , while the limits on the integral determine the length of waveform which is

repeated.

Finally, most TDEM receivers find an average value of  $\frac{\partial B}{\partial t}$  over a time window defined by the time limits  $t_1$  and  $t_2$ . This effect can be accounted for in the electrical coefficient calculation by defining an average coefficient at the center of the time window ( $\bar{D}_n(t_c)$ ):

$$\bar{D}_n(t_c) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} D_n(t) dt$$

Since the time dependence of  $D_n(t)$  is just

$$e^{-(t/L_n)}$$

we have

$$\bar{D}_n(t_c) = \frac{\tau_n D_n(t_1) - \tau_n D_n(t_2)}{t_2 - t_1}$$

Two basic current waveforms are modelled in the PLATEF program (see User's Manual). For the purpose of this calculation, these are normalized so that  $|\partial I / \partial t| = 1$  just before zero time. As mentioned in the previous section, the true value of  $\partial I / \partial t$  is applied as a correction factor later in the program.

For the ramped current waveforms, there are two non-zero parts that must be analysed: the exponential turn-on, and the ramped turn off. The equations for these are:

$$\frac{R (1 - e^{-((t' + T/4 + R)/\tau_{on})})}{1 - e^{-((T/4)/\tau_{on})}}; \quad -(T/4 + R) \leq t' \leq -R$$

and

$$-t'; \quad -R \leq t' \leq 0$$

respectively. These produce the normalized time derivatives:

$$\frac{R e^{-((t' + T/4 + R)/\tau_{on})}}{\tau_{on} (1 - e^{-((T/4)/\tau_{on})})}$$

and

$$-1$$

respectively.

Thus, the turn-on contribution to  $D_n(t)$  is given by:

$$\begin{aligned} D_{n1}(t) &= \frac{R}{l_n \tau_n (b/a) \tau_{on}} \int_{-T/4 - R}^{-R} \frac{e^{-((t' + T/4 + R)/\tau_{on})}}{1 - e^{-((T/4)/\tau_{on})}} e^{-((t-t')/\tau_n)} dt' \\ &= \frac{-R}{(\tau_{on} - \tau_n) l_n (b/a) (1 - e^{-((T/4)/\tau_{on})})} \\ &\quad \cdot \{ e^{-((T/4)/\tau_{on})} e^{-((t + R)/\tau_n)} - e^{-((t + T/4 + R)/\tau_n)} \} \end{aligned}$$

while the ramp contribution is given by:

$$\begin{aligned} D_{n2}(t) &= \frac{-1}{l_n \tau_n (b/a)} \int_{-R}^0 e^{-((t-t')/\tau_n)} dt' \\ &= \frac{e^{-(t/\tau_n)} (1 - e^{-(R/\tau_n)})}{l_n (b/a)} \end{aligned}$$

The total contribution from the repetitive waveform is:

$$D_n(t) = \frac{D_{n1}(t) + D_{n2}(t)}{1 + e^{-(T/2\tau_n)}}$$

#### E.4.11 Excitation Coefficients

Subroutine LOOP calculates the excitation coefficients in PLATEF in a much more efficient way than that done by PETE6, LINSET, INGRAT, DQADM, POT, and TERPIT in the U of T PLATE program.

A coefficient needs to be calculated for each trial function based on the following formula:

$$H_{\phi_i} = \int_{-1}^1 \int_{-1}^1 \phi_i(x, y) H_{3N}(x, y) dx dy$$

where  $H_{3N}$  is the perpendicular component of the primary field in a coordinate system normalized to the half strike length.  
and  $\phi_i$  is the  $i^{\text{th}}$  trial function.

Thus, LOOP first transforms the transmitter loop corner coordinate into plate coordinates using subroutine ROT123, and then normalizes these to the half strike length. A Gauss-Langendre quadrature scheme is used to evaluate the integral with the functions  $\phi_i$  and  $H_{3N}$  being evaluated at each sample point. The way in which these evaluations are performed distinguishes LOOP from the corresponding routines in PLATE.

LOOP evaluates  $H_{3N}$  directly at each of the 400 Gauss quadrature sample points (using subroutine FLDLIN), and combines each in turn with pre-determined trial functions at that point (from subroutine CBDGIT). The U of T PLATE routines, on the other hand, evaluate  $H_{3N}$  at 900 grid points over the plate, and digitize  $\phi_i$  at 100 points between -1 and 1. Two-dimensional linear interpolation must then be used to determine their values at the quadrature sample points. As well, the interpolation is repeated unnecessarily for each trial function.

Once the  $H_{\phi_i}$  coefficients have been calculated, they are premultiplied by the transform of the eigenvector matrix (using subroutine RTRNA) to form the excitation coefficients  $H_i$ . These represent the degree of coupling between the transmitter loop and each eigencurrent in the plate.

#### E.4.12 Secondary Field Coefficients

The routines involved in this calculation produce three coefficients for each eigencurrent, which represent the magnetic vector field from these currents at the receiver location. The three field components due to each trial function ( $S_{x\phi_i}$ ,  $S_{y\phi_i}$ ,  $S_{z\phi_i}$ ), are calculated by subroutine PETE7, and these are then multiplied by the eigenvector matrix to produce the field from each eigencurrent ( $s_{x_i}$ ,  $s_{y_i}$ ,  $s_{z_i}$ ). The mathematical basis for these calculations follows.

Trial currents ( $K_i$ ) can be derived from the trial functions by:

$$K_i(r') = \nabla \phi_i(r') \times \hat{e}_3$$

$$= \frac{\partial \phi_i}{\partial y'} \hat{i} - \frac{\partial \phi_i}{\partial x'} \hat{j}$$

The magnetic field at a point  $P(x,y,z)$ , due to such a current, is given by the Biot-Savart Law as:

$$S_{\phi_i}(r) = \int_{-a}^a \int_{-b}^b \frac{k_i(x',y') \times R}{4\pi R^3} dx' dy'$$

where  $R = |\underline{r} - \underline{r}'| = |(x-x')\hat{i} + (y-y')\hat{j} + z\hat{k}|$ .

Therefore,

$$S_{\phi_i}(r) = \frac{1}{4\pi} \int_{-a}^a \int_{-b}^b \left\{ \frac{-z}{R^3} \frac{\partial \phi_i}{\partial x'} \hat{i} + \frac{-z}{R^3} \frac{\partial \phi_i}{\partial y'} \hat{j} + \left( \frac{y-y'}{R^3} \frac{\partial \phi_i}{\partial y'} + \frac{x-x'}{R^3} \frac{\partial \phi_i}{\partial x'} \right) \hat{k} \right\} dx' dy'$$

Using integration by parts, and the fact that  $\phi(a,y) = \phi(x,b) = 0$ , we get, for example:

$$S_{x\phi_i}(r) = \int_{-a}^a \int_{-b}^b \frac{\phi_i(r')}{4\pi} \frac{3z(x-x')}{R^5} dx' dy'$$

Applying the substitutions:  $X'=x'/a$ ,  $Y'=y'/b$ ,  $X=x/a$ ,  $Y=y/a$ ,  $Z=z/a$ ,  $R_N=R/a$ , we get:

$$S_{x\phi_i}(r) = \frac{b}{a^2} \frac{3zx}{4\pi} \int_{-1}^1 \int_{-1}^1 \frac{\phi_i(X',Y')}{R_N^5} dX' dY' - \frac{b}{a^2} \frac{3z}{4\pi} \int_{-1}^1 \int_{-1}^1 \frac{X' \phi_i(X',Y')}{R_N^5} dX' dY'$$

Similarly,

$$S_{y\phi_i}(r) = \frac{b}{a^2} \frac{3zy}{4\pi} \int_{-1}^1 \int_{-1}^1 \frac{\phi_i(X',Y')}{R_N^5} dX' dY' - \frac{b^2}{a^3} \frac{3z}{4\pi} \int_{-1}^1 \int_{-1}^1 \frac{Y' \phi_i(X',Y')}{R_N^5} dX' dY'$$

and

$$S_{z\phi_i}(r) = \frac{b}{a^2} \frac{3z^2}{4\pi} \int_{-1}^1 \int_{-1}^1 \frac{\phi_i(X',Y')}{R_N^5} dX' dY' - \frac{b}{a^2} \int_{-1}^1 \int_{-1}^1 \frac{\phi_i(X',Y')}{R_N^3} dX' dY'$$

By using two relations involving the Chebychev polynomials:

$$x' \phi_{nm}(x', y') = \frac{1}{2} \phi_{n-1,m}(x', y') + \frac{1}{2} \phi_{n+1,m}(x', y')$$

$$\text{and } y' \phi_{nm}(x', y') = \frac{1}{2} \phi_{n,m-1}(x', y') + \frac{1}{2} \phi_{n,m+1}(x', y')$$

the determination of the secondary field coefficients can be reduced to finding the integrals

$$\int_{-1}^1 \int_{-1}^1 \frac{\phi_i(x', y')}{R_N^5} dx' dy' \quad \text{and} \quad \int_{-1}^1 \int_{-1}^1 \frac{\phi_i(x', y')}{R_N^3} dx' dy'$$

These are combined in subroutines H1COF, H2COF, and H3COF to form the three  $S_{\phi_i}$  components. The integrals are normally evaluated in subroutine PETE7 using a 20 point Gauss-Legendre quadrature scheme, in which  $\phi_i$  has been pre-determined by subroutine CBDGIT, while  $R_N^3$  and  $R_N^5$  are determined directly at each of 400 sample points. A complex function is used so that the two integrals can be evaluated simultaneously over the plate.

The point  $P(x, y, z)$  in the mathematical derivation is, of course, the receiver location in plate coordinates. Subroutine SECOND finds these coordinates by making use of the profile parameters, and the subroutine ROT123. As each such location is found, it is normalized to the half strike length of the plate, as required in the derivation, and is tested for closeness to the plate. If it comes within approximately 0.25 strike lengths of a plate edge, the plate is divided into a number of cells (as many as 8) by subroutine DIVIDE.

Numerical quadrature is applied to each cell in such a way that the total number of sample points is still approximately 400, but these are, of course, redistributed (closer to the receiver). Thus, new sample points and weights are used, and the values of  $\phi_i$  must be interpolated at these points from digitized values. This interpolation procedure for close receivers, was used in the U of T PLATE program for all receiver locations. Its removal for distant receivers, has greatly increased the speed of computation.

Once the  $S_{n\phi_i}(r)$  coefficients are formed by combining the integrated terms, they are multiplied by the eigenvector matrix (using subroutine RTRNA) to form the secondary field coefficients. Finally, subroutine SECOND calculates the primary field values at each receiver location (using subroutine PFIELD) and transforms these, along with the secondary field coefficients, into profile components.

#### E.4.13 Common Routines for Coefficient Calculation

Subroutines CBDGIT and CHBCHV digitize the trial functions used in the numerical integrations. They perform the same function they did in the U of T PLATE program, in that they find 100 values between 1 and -1, but they also find the values at the 20 sample points used in the PLATEF quick integrations. In addition, they calculate sequencing numbers for reading the proper function degrees from the arrays.

Subroutine RTRNA is used to multiply the transpose of the eigenvector matrix by the column vectors formed from the raw excitation and secondary field coefficients.

#### E.5 Changing the Capabilities of PLATEF

A few key variables control many of the array sizes in PLATEF. A description of these variables, and their present size limits, is given in Table E.5. The arrays affected by these variables, and the routines in which they are used, are given in Table E.6.

Since the variables MAX, NPARM and NSEG1 are input either directly or through file reading, their values are tested by comparing them to their maximum allowable values. Thus, the constants LIMIT in PLATEF, NPARM in RDPARM, and NEND in LSOURC must be set to the maximum values for MAX, NPARM, and NSEG1 respectively.

Variable	Description	Present size limit
MAX	Maximum polynomial order used in eddy current approximation.	4
NT	MAX + 2	6
NFP	(MAX + 1) * (MAX + 2) / 2	15
NPOL	(MAX + 2) * (MAX + 3) / 2	21
MFP2	NFP * NFP	225
KPOL	Number of sample points in Chebychev polynomial digitization.	100
NPARM	Number of time or frequency parameters.	80
NSEG1	Number of loop sides + 1	11

Table E.5 Key size control variables in PLATEF.

Array	Location
U (MFP2)	PLATEF, UNFORM, GETEIG, LOOP, PETE7
DIG (NFP)	PLATEF, UNFORM, GETEIG, ELECT
EXN (NFP)	PLATEF, LOOP
SKEEP (NFP,3)	PLATEF, SECOND
HLD (NT)	CBDGIT, CHBCHV
COF (NFP)	LOOP
H1 (NFP)	SECOND, PETE7
H2 (NFP)	SECOND, PETE7
H3 (NFP)	SECOND, PETE7
C1 (NFP)	PETE7, H1COF, H2COF, H3COF
P (NPOL)	PETE7
C (NPOL)	PETE7, H1COF, H2COF, H3COF
NX (NPOL)	PLATEF, UNFORM, CBDGIT, LOOP, PETE7, H1COF, H2COF
NY (NPOL)	PLATEF, UNFORM, CBDGIT, LOOP, PETE7, H1COF, H2COF
CC (MAX*KPOL)	PLATEF, UNFORM, CBDGIT, POT
HR (NPARM,NFP)	PLATEF, ELECT
BR (NPARM)	PLATEF
PARM (NPARM)	PLATEF, UNFORM, DIGITL, RAMPEM, EM37, UTEM10, SIROTM, RDPARM, WRTSYS, WRTHED, ELECT
XL (3*NSEG1)	LOOP
KLINE (NSEG1,3)	LOOP
TLINE (NSEG1,3)	PLATEF, BLKDAT, UNFORM, LSOURC, PFIELD, WRTGEO, WRTHED, LOOP

Table E.6 Arrays using key variables, and their location in PLATEF.

#### E.6 Program EIGCUR

The structure of program EIGCUR can be seen in the flow chart in Figure 4.3, and the subroutine map in Table E.7. The source code is divided into 26 separate routines which are interconnected up to an order of five. Four of these routines are identical to ones used in PLATEF (IIN, RIN, TIN, FILES), while two others are similar (BLKDAT1, FIRST1).

The subroutine map shows that only four logical units are required for I/O, including the two used for the keyboard and screen. The final data are written by the main routine EIGCUR on unit 2 to an unformatted binary file. Subroutine REFORM reads from unit 2 and writes to unit 1, in reformatting data files between ASCII and binary formats. Finally, a diagnostic file can be created on unit 1 which contains all the intermediate calculations.

The subroutine map also shows the location and use of the common blocks in EIGCUR. All of these blocks reside within the main routine EIGCUR, although they are not all read there. As with PLATEF, this allows the program to be divided into "branches" corresponding to the subroutine calls, so that a simple overlay can be formed, if required.

Main routine EIGCUR was created from four routines within the U of T PLATE program - GETIMA, PETE1, PETE2, and PETE3. By combining these routines, common calculations need to be performed only once; common sections of code can be reused; and there is no need for file storage of intermediate results. In addition, variable arrays have been reduced in size so that a maximum polynomial order no greater than four is accommodated, and these arrays are reused whenever possible.

As well as these improvements in program size and efficiency, extensive error control and user-friendly features, such as those in PLATEF, were incorporated. These features are most evident in subroutines REFORM and INTRO which make use of the input routines IIN, RIN, TIN, and FILES, and perform file handling procedures.

Name of routine	Common block	I/O	Description
EIGCUR	<u>GRNF</u> <u>INFO</u> <u>BLOK1</u>	S W-1,2 C-1,2	Generates eigenvectors and eigenvalues for a conducting thin plate. Common block initialization.

BLKDAT1	K S		Prompts for input of integer values.
IN	S		Writes program header to the screen.
FIRST1	S O&C-1,2		Rewrites eigenfunction files. ASCII <-> binary
REFORM	R-2 W-1,2		
IIN*	K S		
FILES	K S		
TIN	K S		
INTRO	<u>INFO</u>	S W-1	Filename prompt, prefixes default drive, checks existence.
RIN	O&C-1,2		Prompts for input of a single character.
IIN*	K S		Opens output files and gets basic parameters.
FILES*	K S		
TIN*	K S		
CHEBMT	K S		Prompts for input of real values.
CHEBIN	K S		
SYMRT			
OPXRT			
DIVGNC			
EIGEN			
DIAGL			
COLRT			
EIGCHK			
INTCOF			
RSETUP(RSETON,RQUICK)			
DEGREE			
<u>GRNF</u>			
<u>BLOK1</u>			
DQADM			
B			
GREEN			
P			
P*			
RTNRAR			
MPPRD			

S - Screen write; K - Keyboard read; R - Read; W - Write; O - Open; C - Close  
 Repeated subroutines are marked with an asterisk.  
 Underlined common block indicates data origin.

Table E.7 Subroutine map for EIGCUR.

The computational part of the program was written by A.P. Annan. Very few changes were made to this part of the program because it was found to be quite efficient. In coming to this conclusion, the mathematical basis of these routines had to be derived beyond that which has been published (see Appendix C).

The  $ij^{\text{th}}$  element of the resistance matrix  $[F_N]$  is given in Appendix C as:

$$F_{Nij} = \int_{-1}^1 \int_{-1}^1 \frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x} + \frac{a^2}{b^2} \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y} dx dy$$

where  $\phi_i$  is the  $i^{\text{th}}$  element of  $[\phi_{00}(x,y), \phi_{10}(x,y), \dots, \phi_{0M}(x,y)]$

and  $\phi_{nm} = (1-x^2)(1-y^2)T_n(x)T_m(y)$ .

This can be solved analytically by using some special properties of the Chebychev polynomials. For example, using the relation

$$\frac{\partial}{\partial x} (1-x^2) T_n(x) = -nxT_n(x) + nT_{n-1}(x)$$

the integrals can be broken down into a sum of terms such as:

$$\int_{-1}^1 \int_{-1}^1 x^n y^m T_p(x) T_q(x) T_r(y) T_s(y) dx dy$$

where  $n, m = 0, 1, 2, \text{ or } 4$ . Using the recursion formula:

$$xT_n(x) = \frac{1}{2} T_{n+1}(x) + \frac{1}{2} T_{n-1}(x)$$

these can again be written as a sum of terms such as:

$$\int_{-1}^1 \int_{-1}^1 T_p(x) T_q(x) T_r(y) T_s(y) dx dy$$

Finally, we have:

$$\begin{aligned} & \int_{-1}^1 \int_{-1}^1 T_p(x) T_q(x) T_r(y) T_s(y) dx dy \\ &= \frac{1}{4} \left\{ \left[ \int_{-1}^1 T_{p+q}(x) dx + \int_{-1}^1 T_{p-q}(x) dx \right] \left\{ \int_{-1}^1 T_{r+s}(y) dy + \int_{-1}^1 T_{r-s}(y) dy \right\} \right\} \end{aligned}$$

Thus, the original integral can be evaluated by a judicious combination of such terms as:

$$\int_{-1}^1 T_n(x) dx$$

which can be easily evaluated analytically.

The  $i^{th}$  element of the induction matrix  $[L_N]$  is given in Appendix C as:

$$L_{Nij} = \int_{-1}^1 \int_{-1}^1 \frac{1}{4\pi R_N} \left\{ \frac{\partial \phi_i}{\partial x} \frac{\partial \phi_j}{\partial x'} + \frac{a^2}{b^2} \frac{\partial \phi_i}{\partial y} \frac{\partial \phi_j}{\partial y'} \right\} dx dy dx' dy'$$

where the variables have been previously defined. As for the resistance matrix, this integral can be broken down into a sum of simpler integrals of the form:

$$\int_{-1}^1 \int_{-1}^1 \frac{1}{4\pi R_N} T_n(x) T_m(y) dx dy.$$

This integral is evaluated numerically using a Gauss-Legendre quadrature scheme. The value of  $R_N$  ( $=R/a$ ) is found directly at each zero of the Legendre polynomials as are the values of  $T_n(x)$  and  $T_m(y)$ .

Annan chose to use the Jacobi method to determine the eigenvectors and eigenvalues of the matrices  $[F_N]$  and  $[L'_N]$ . Although there are much more efficient techniques available to find the eigenvalues of real, symmetric matrices, this technique is very reliable and also provides the eigenvectors as required.

### E.7 Changing the Capabilities of EIGCUR

The following is an explanation of the key variables used in program EIGCUR. The values in parentheses are the maximum allowable values in the present version of the program.

RAT - width-to-length ratio of the plate

7 MAX - maximum polynomial order used to represent the surface current distribution (4)

8 N1 = MAX+1 - maximum poly order before differentiation (5)

10 N2 = MAX+3 - maximum poly order before 1-X\*X operation (7)

36 NFP = (N1\*N1+N1)/2 (15)

66 MFP = (NFP\*NFP+NFP)/2 | - size parameters for final matrices (120)

1296 MFP2 = NFP\*NFP (225)

66 NIP = (N2+1)\*(N2+2)/2 | - size parameters for original matrices (36)

2211 MIP = (NIP\*NIP+NIP)/2 (666)

45 INP = (N1+1)\*(N1+2)/2 | - size parameters for intermediate matrices (21)

1035 NIMP = (INP\*INP+INP)/2 (231)

21 MAX1 = (2\*N2)+1 - number of integrated Chebychev polynom. needed (15)

The original marices formed by EIGCUR (the integrated Chebychev polynomials and the induction integral coefficients) contain Chebychev polynomials up to order N2 and thus are of dimension NIP X NIP. Since they are symmetric matrices, only MIP values need to be stored. After application of the 1-X\*X or 1-Y\*Y operation, the order is reduced by two and the new matrices are of dimension INP X INP with NIMP values stored. Finally, differentiation reduces the maximum order to MAX so that the matrices are of dimension NFP X NFP with MFP values stored. The eigenvectors, however, are contained in an NFP X NFP matrix which is not symmetric, and MFP2 values must be stored.

The program is designed to handle arrays for a maximum polynomial order no larger than 4. It is quite easy, however, to alter the program to accept higher values. A simple statement used to check the size of the variable, must be changed in subroutine INTRO. As well, the following arrays would have to be dimensioned accordingly.

Program EIGCUR: C(MIP), HOLD(MFP), VEC(MFP2), DIG(NFP),  
WORK(NIMP or MFP2) whichever is larger

Subroutine REFORM: C(MFP2), DIG(NFP)

Subroutine CHEBMT: C(MAX1)

Subroutine CHEBIN: I(MAX1), J(MAX1), K(MAX1), VAL(MAX1)

Parameters set in subroutine INTCOF for the double Gaussian quadrature integration can be changed if a more accurate integration is required. The following limits on these values must be observed, however, due to the limitations of the Gaussian quadrature table.

N - number of points in unprimed X	$\leq 20$	4
M - number of points in unprimed Y	$\leq 20$	4
NOX(23) - number of points in primed X intervals	NOX(I)	4, 3, 3, ...
NOY(23) - number of points in primed Y intervals	or	+ NSPC $\leq 20$ 4, 3, 3, ...
NSPC - enhancement for singular region	NOY(I)	4

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