FORWARD-MODELING COMPUTER PROGRAM FOR THE INDUCTIVE ELECTROMAGNETIC GROUND-CONDUCTIVITY METHOD: EM34.FOR

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CONVERSION FACTORS AND ABBREVIATIONS

This report uses metric (International System) units as the primary system of measurements. The units commonly are abbreviated using the notations shown in parentheses. Metric units can be converted to inch-pound units by multiplying by the factors given below:

Multiply SI units	By	To obtain inch-pound units
	<u>Length</u>	
meter (m)	3.281	foot (ft)
	<u>Resistivity</u>	
ohm-meter (ohm-m)	3.281	ohm-foot (ohm-ft)
	<u>Conductivity</u>	
millisiemen per meter (ms/m)	0.3048	millisiemen per foot (ms/ft)

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ABSTRACT

This documentation describes the use of an interactive microcomputer program, EM34.FOR, that calculates the apparent conductivity that would be measured by a two-coil inductive electromagnetic instrument at the surface of the Earth for a given sequence of conductive horizontal layers. The report describes the operation of the electromagnetic instrument and the approximations upon which the instrument is based. Included are detailed instructions and an example for using the program, and the assumptions made in developing the code. A brief discussion of the theory behind the program algorithm is included as an appendix. The program code listing is included as an attachment.

INTRODUCTION

This documentation describes the use of a Fortran[1/] microcomputer program designed to forward model a given sequence of horizontal conductive earth layers and to calculate the apparent conductivity at the surface of the Earth as measured by two-coil inductive electromagnetic techniques. The program is useful for determining the feasibility of using the electromagnetic induction technique in field investigations and for interpreting the results of field survey. The program is used interactively and has monitor, hardcopy, or disk data file output options.

The EM34.FOR was written for a microcomputer, compiled on the MicroSoft FORTRAN compiler. It has been run on an IBM-AT, IBM-PC portable, Leading Edge, and Compaq microcomputer and on a minicomputer--the U.S. Geological Survey's DIS (Distributed Information System) computer system.

The EM34.FOR program is a completely rigorous mathematical solution of the equations that produce the apparent conductivity for any instrument frequency. Simplified formulas for calculating the apparent conductivity of a layered Earth are available (McNeill, 1980b) but are approximations based on operation of the instruments at frequencies that result in very small induction numbers.

Acknowledgments

Acknowledgments are due G. M. Levy, Geonics Limited, Ontario, Canada, for the BASIC program LAYF which has been used as a model for the EM34.FOR program and to G. M. Levy and Duncan McNeill, Geonics Limited, Ontario, Canada, and Frank Frischknecht, U.S. Geological Survey, Denver, CO, for their technical review of this report.

1/ Use of brand, firm, or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

GENERAL PRINCIPLES OF A LOW INDUCTION NUMBER ELECTROMAGNETIC GROUND-CONDUCTIVITY INSTRUMENT: GEONICS EM34-3

The Geonics EM34-3 (fig. 1) is a commercially available instrument patented in the United States that can be used to measure ground conductivity directly in ms/m (millisiemens). Because of the Geonics Ltd. patent, the output of other small induction number instruments must be in units other than conductivity such as the ratio of the voltage in the receiver

FIGURE 1:--The Geonics EM34-3, showing the transmitter coil and electronic module (operator to the left in photograph), the receiver coil and module (operator to the right), and the connecting cable.

coil to the voltage in the transmitter coil in parts per million or percent. This report is written primarily for use with the Geonics EM34-3 instrument.

The EM34-3 has a transmitter and a receiver, each consisting of a portable coil and an electronic module. The coils are held coplanar (in the same plane) and placed in a position that is either on edge, the vertical coplanar orientation, or flat lying, the horizontal coplanar orientation. The magnetic dipole associated with each coil passes through the center of the coil and is perpendicular to the plane of the coil. The vertical coplanar orientation is also referred to as the horizontal dipole position and the horizontal coplanar orientation is referred to as the vertical dipole position. The vertical coil orientation is less sensitive to misalignment of the coils from their coplanar position (McNeill, 1980b). The instrument has coil spacing options of 10, 20 and 40m (meters).

Six data points, used to develop two geometric sounding curves, are obtained by making measurements in both coil orientations at all three coil spacings. The unique response of the instrument in each coil position to conductive material at different depths in the Earth gives the EM34-3 a limited depth-sounding capability. Figure 2 shows the response of the EM34-3 to a thin layer of conductive material when the layer is at different depths. Figure 3 shows the cumulative response of the instrument to all conductive material below a certain depth. In both these figures a dimensionless normalized depth, the depth-to-coil-spacing ratio, is used so that each of these curves represents the response of the instrument to material at varying depth for all of the coil spacings. The real depth of the conductive material for a particular coil spacing is found by multiplying the depth-to-coil-spacing ratio by the coil spacing.

When used in the vertical coplanar coil position, the instrument is most responsive to material at the surface and at depths down to one-half the coil spacing. When used in the horizontal coplanar coil position, the instrument is most responsive to material at depths of one-quarter and three-quarters the coil spacing (fig. 2 and 3). Increased coil separation (table 1) proportionately increases the depth of penetration of the instrument in both coil positions (McNeill, 1980b). The instrument has a greater depth of penetration for a given coil spacing when used in the horizontal coplanar coil position.

After placement of the coils, the transmitter is energized by an alternating current at an audio frequency of 0.4 kHz (kiloHertz) , 1.6 kHz, and 6.4 kHz. The alternating current generates a time-varying primary magnetic field which in turn induces eddy currents in the ground. The eddy currents generate a secondary magnetic field, which is measured by the voltage induced in the receiver coil (Keller and Frischknecht, 1966, p.

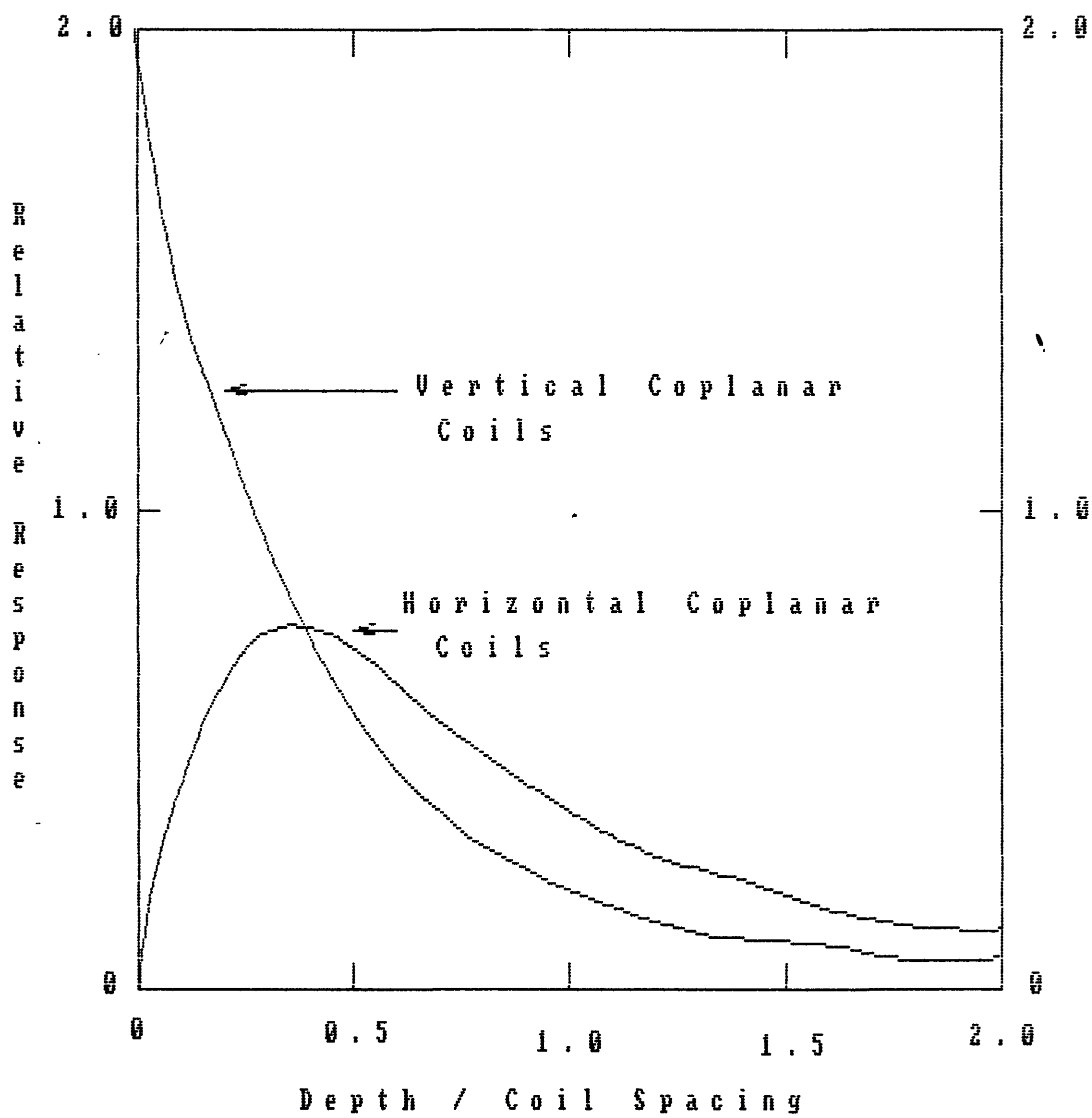


FIGURE 2:--Relative response of the EM34-3 to a thin conductive layer at varying depth/coil-spacing ratio for horizontal and vertical coplanar coils (modified from McNeill, 1980b)

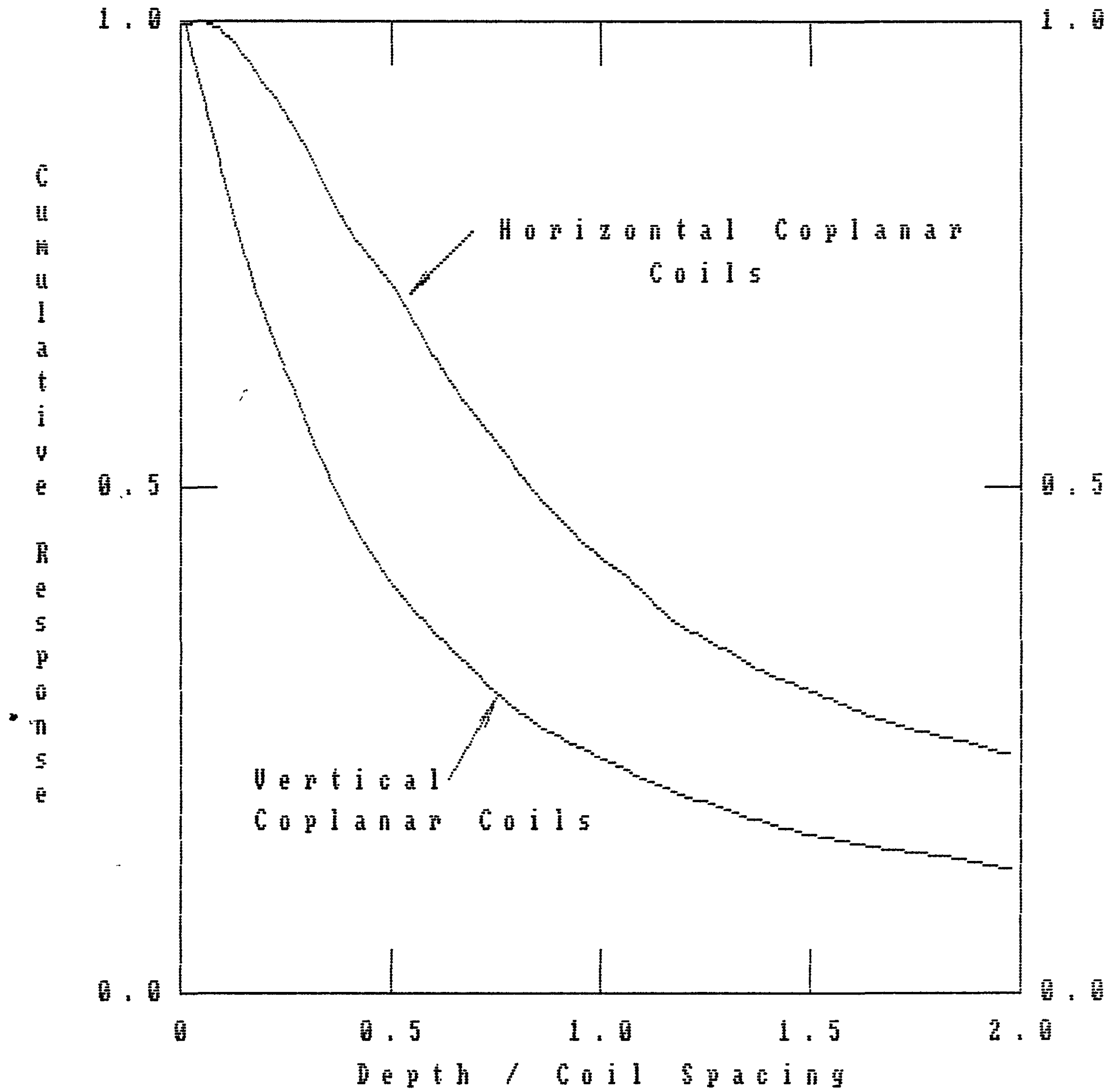


FIGURE 3: Cumulative response of the EM34-3 to all conductive material below a varying depth/coil-spacing ratio for horizontal and vertical coplanar coils (modified from McNeill, 1980b)

TABLE 1.--Exploration depth for EM34-3 instrument at various coil spacings (modified from McNeill, 1980b)

	Exploration depth (meters)	
Coil Spacing (m)	Vertical Coils	Horizontal Coils
10	7.5	15
20	15.0	30
40	30.0	60

278). The magnitude and phase of the secondary magnetic field are functions of the coil spacing, the ground conductivity, and the operating frequency of the instrument. Figure 4 shows the primary and secondary magnetic fields and eddy currents generated by the instrument.

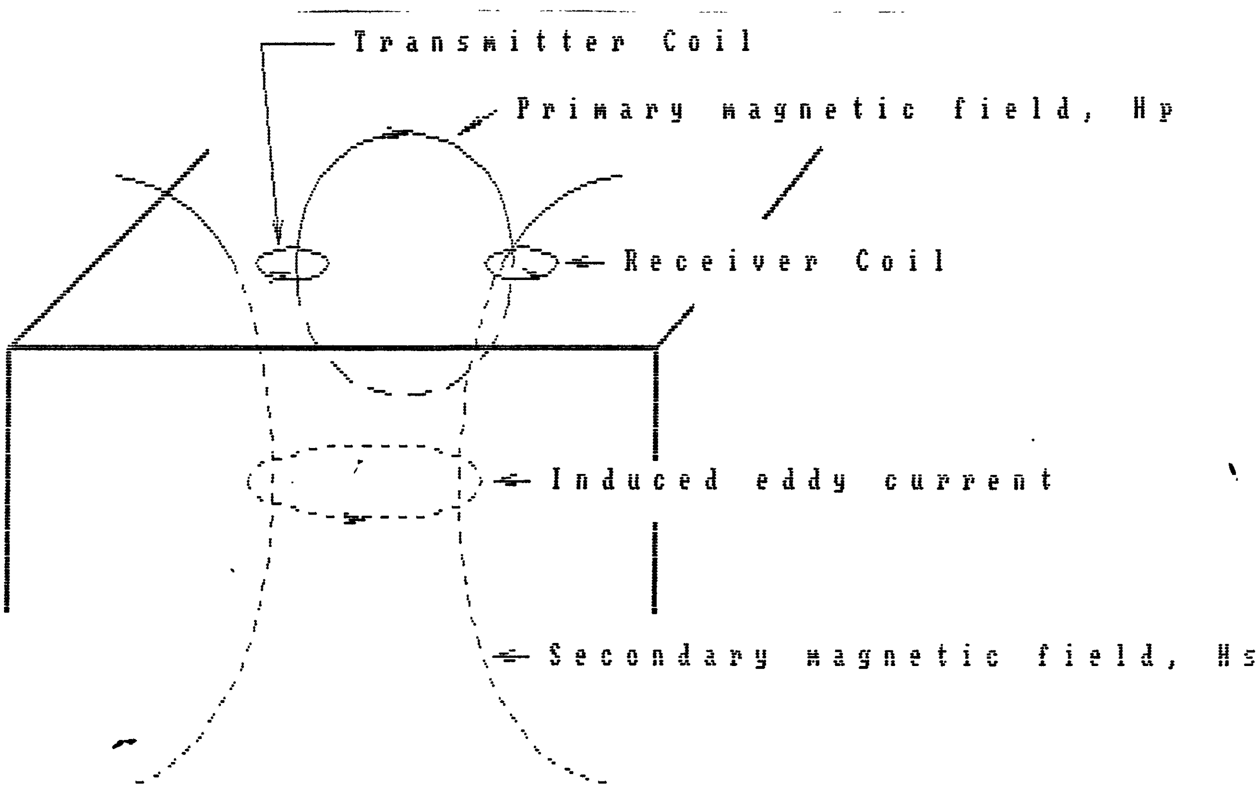
The response of a layered Earth to an induced magnetic field can be expressed as a function of a parameter called the induction number B where:

$$B = (s^2 \omega \mu_0 \sigma / 2)^{1/2} \qquad (1)$$

in which:

σ = conductivity of the upper layer, in millisiemens per meter;
μ_0 = magnetic permeability of free space = 4 x 10-7 (dimensionless);
ω = angular frequency of the signal = $2\pi f$, in radians;
f = operating frequency, in kiloHertz, and;
s = coil spacing, in meters.

The instrument is calibrated so that it directly measures apparent conductivity in mS/m based on the low induction number assumption that:



$$\sigma = [4/2\pi f \mu_0 s^2]\, Im(Hs/Hp)$$

in which σ = apparent conductivity;

f = operating frequency;

μ_0 = magnetic permeability of free space;

s = coil spacing;

$Im(Hs/Hp)$ = imaginary component of the ratio of the secondary to the primary magnetic field.

Figure 4: Primary and secondary magnetic fields and eddy currents generated by the EM34-3 (modified from McNeill, 1982)

When the coil spacing is much less than the skin depth (skin depth being the distance through a propagating medium that a plane wave travels before being attenuated to 1/e = 0.3679 of its amplitude at the surface of the medium; skin depth is defined by the following equation: $\delta = (2/\omega\mu_0\sigma)^{1/2}$), it can be seen from equation (1) that B = s/δ is very small so the low induction number assumption can be stated more concisely as B must be very small. For the EM34-3 this condition is met as long as the ground conductivity is reasonably low (less than 100 mS/m) (McNeill, 1980b).

If the low induction number assumption is satisfied, the ratio of the secondary magnetic field to the primary magnetic field is directly proportional to the ground conductivity. This relationship is given by (McNeill, 1980b):

$$Hs/Hp = (iB^2)/2 \qquad (2)$$

in which Hs/Hp = ratio of primary field to secondary magnetic field;
i = square root of -1, and;
B = s/δ from above.

Taking the imaginary part of equation (2) gives:

$$Im(Hs/Hp) = (B^2)/2 \qquad (3)$$

in which Im(Hs/Hp) = imaginary component of Hs/Hp.

Rearranging equation (2) and substituting for B^2 yields the following equation for calculating the apparent conductivity for a layered Earth:

$$\sigma = Im(Hs/Hp)\ 4/(s^2 w\mu_0), \text{ in millisiems/meter.} \qquad (4)$$

The instrument measures Im(Hs/Hp), and for each coil spacing is electronically calibrated to calculate equation (4) so that the instrument meter reads conductivity directly. For a homogeneous Earth, σ is the true conductivity.

PROGRAM CALCULATIONS

The EM34.FOR program calculates the apparent conductivity of a horizontally layered subsurface that would be measured at the surface by horizontal and vertical, coplanar coils at coil spacings of 10, 20, and 40 m. The quantity used in this calculation is the mutual coupling ratio. For coil spacings much larger that the coil diameters, as with the EM34-3, this ratio is equivalent to the ratio of the secondary magnetic field to the primary magnetic field (equation 2). The method used in this program for evaluating the mutual coupling ratio and the apparent conductivity and a more detailed discussion of the theory are presented in appendix A for the interested user.

Assumptions

The following simplifying assumptions (Kozulin, 1963) are used in deriving the equations used in the EM34.FOR algorithm from electromagnetic theory:

1) The Earth's subsurface consists of horizontal, infinite, homogeneous, and isotropic layers.

2) The conductance of each layer is constant and changes abruptly at each boundary.

3) The deepest layer is assumed to have an infinite thickness.

Output

The output of the program lists values of apparent resistivity (reciprocal of the apparent conductivity), apparent conductivity, and the mutual coupling ratio for horizontal and vertical coil positions for each of the three coil spacings.

Adapting the Program to Other Instruments

Although the program is not limited by the low induction number simplification upon which the instrument is based, the algorithm used in the EM43.FOR program is designed specifically for data obtained using the Geonics EM34-3 with output in apparent conductivity. The program can be adapted for use with other two-coil, coplanar-coil systems by changing the operating frequencies and coil spacings wherever the algorithm subroutine APPCON is called by the main program (lines 90 through 96 of the code, attachment A) or by adding or deleting call statements for the APPCON subroutine in lines 90 through 96 and using the appropriate operating frequencies and coil spacings in the added call statements. Calculation of the output (line 220) must also be changed so that the units of output match those of the selected instrument.

USER PROCEDURES

Loading The Program

An IBM or IBM-compatible personal computer with a floppy disk drive and a minimum of 84K bytes of memory is required to run this program. The program runs significantly faster on a system that has a math co-processor.

Data Input

The program interactively requests the number of horizontal layers assumed to be present and the thicknesses (in meters) and resistivities (in ohm-meters) of each layer. Layer resistivities and thicknesses can be based on direct-current electrical, seismic refraction, or borehole geophysical surveys; geologic knowledge; test holes; wells; or other sources.

Interacting with the Program

The program prompts the user for all of the input data. All responses should be in UPPER-CASE LETTERS and entered by striking the ENTER key.

There is opportunity, after the initial data input and after each computational run, to change all or some of the input parameters. Typically, parameter changes would be made when trying to match the model output with field data. Changes should be made after the relationship between the apparent conductivity and the relative response of the instrument to conductive material at different depths (fig. 2 and 3) have been considered. For example, the apparent conductivity of a three layer model as measured by horizontal coils might be most strongly affected by the material in the first layer for a 10-m coil spacing but in the 20- and 40-m spacings the instrument would respond most to the material in the second and third layers, depending on the thicknesses of the layers.

Upon completing a session, the user can change any of the input parameters, can begin a new problem, or can terminate the program, returning to DOS (disk operating system) by responding appropriately to the prompts.

Output

The program outputs to the console, a printer, or a disk file. The program output consists of a listing of the input parameters, apparent resistivities, apparent conductivities, and mutual coupling ratios for each combination of coil spacing and orientation.

Example Problem

In ground-water applications, a typical problem might be to determine the extent of ground-water contamination from a landfill by defining the lateral and vertical dimensions of the volume of ground water that has a conductivity higher than background levels. The first step is to decide whether or not the ground-conductivity technique would detect the contaminant plume at this site. This can be accomplished by testing a preliminary model of the subsurface, based on any available hydrogeologic information about the site, with the EM34.FOR program.

The field area considered in this application is in Farmington, Conn., where a landfill (Grady and Haeni, 1984) is a source of groundwater contamination. From available borehole geologic data, it was known that the depth to the water table was about 3 m and that the subsurface in uncontaminated areas can be generalized as four layers: a resistive layer representing the unsaturated material, a conductive layer representing the fine-grained saturated material, another resistive layer representing the coarse-grained saturated material, and resistive bedrock.

In the contaminated areas, the subsurface can be generalized as four to five layers: a resistive, unsaturated layer, a conductive saturated, contaminated zone with a resistive stringer appearing at two stations, a deep resistive layer, and resistive bedrock.

The input parameters for this subsurface model are summarized in table 2.

The EM34.FOR program was used to calculate the values for apparent conductivity that would be measured by the Geonics EM34-3 first in the uncontaminated areas and then in the contaminated area.

To use the EM34.FOR program, load and run the program from the operating system of the PC (personal computer) by typing the following command and striking the ENTER key:

```
>B:EM34.EXE
```

TABLE 2.--Input data for example problem

Layer	Thickness (meters)	Resistivity (ohm-meters)
Uncontaminated area:		
1	3	2000
2	10	250
3	10	1500
4		250
Contaminated area:		
1	3	2000
2	10	100
3	3	1500
4		250

After an introduction to the program, the user will be prompted to input and correct the number of subsurface layers, the resistivities in ohm-meters, and the thicknesses in meters. Strike the ENTER key after each response:

```
    TYPE THE NUMBER OF MODEL LAYERS: 3
    THE NUMBER OF LAYERS IS 3. IS THIS CORRECT?
    TYPE (Y/N) AND THEN HIT (ENTER)
  > Y
    TYPE THE THICKNESS (METERS) AND RESISTIVITY (OHM-METER)
    OF LAYER 1 AND THEN HIT (ENTER). SEPARATE THE NUMBERS
    WITH A COMMA.
  > 10,2000
```

Enter the parameters for layers 2 and 3 in the same way, as requested, and continue with the program:

```
    ARE THE INPUT DATA OK?
    TYPE (Y/N) AND HIT (ENTER)
  > Y
```

The program will now ask for the destination of the output. The user will be offered a choice of filing the output, printing the output, or displaying it on the console.

```
          TYPE EITHER:
               -A FILENAME TO SEND THE RESULTS TO THE DEFAULT
                DISK OR
               -PRN TO SEND THE RESULTS TO THE PRINTER OR
               -CON TO SEND THE RESULTS TO THE CONSOLE
          THEN HIT (ENTER).
```

Respond with:

```
          > CON
```

The output will be sent to the console only. It is not possible to have more than one destination for the output.

The calculations are now made and the results are displayed on the console.

The next few interactions will allow changes to be made in the data so that the same calculations can be made for the contaminated area.

```
          ARE YOU FINISHED WITH THE PROBLEM?
          TYPE (Y/N) AND THEN HIT (ENTER).
        > N
          ARE THE DATA CORRECT?
          TYPE (Y/N) AND THEN HIT (ENTER)
        > N
          YOU WILL CORRECT ONE PARAMETER AT A TIME.
          TYPE THE NUMBER OF THE LAYER FOR WHICH A
          CHANGE WILL BE MADE AND HIT (ENTER).
        > 2
          TYPE T TO CHANGE LAYER 2 THICKNESS OR R TO
          CHANGE ITS RESISTIVITY AND HIT (ENTER).
        > R
          TYPE THE NEW RESISTIVITY AND HIT (ENTER).
        > 50
```

The user will again have an opportunity to correct the input data and choose a destination for the output. The new calculations will be made and routed as requested.

The user then terminates the program and exits to DOS:

```
          ARE YOU FINISHED WITH THIS PROBLEM?
          TYPE (Y/N) AND THEN HIT (ENTER)
        > Y
          ARE YOU FINISHED WITH THIS SESSION?
          TYPE (Y/N) AND THEN HIT (ENTER).
        > Y
```

TABLE 3.--EM34.FOR output data and format

UNCONTAMINATED AREA

LAYER	THICKNESS (meters)	RESISTIVITY (ohm-meter)
1	3.0	2000.
2	10.0	250.
3	10.0	1500.
4	10000.0	250.

COIL SPACING (meter)	COIL SETUP*	APPARENT RESISTIVITY (ohm-meter)	APPARENT CONDUCTIVITY (mmho/meter)	MUTUAL COUPLING RATIO (Z/ZO) REAL	IMAG
10	H	378.	2.6	.1000E+01	.3339E-02
	V	495.	2.0	.1391E-03	.2552E-02
20	H	363.	2.8	.1000E+01	.3477E-02
	V	408.	2.4	.1648E-03	.3093E-02
40	H	340.	2.9	.1000E+01	.3716E-02
	V	366.	2.7	.1851E-03	.3447E-02

CONTAMINATED AREA

LAYER	THICKNESS (meters)	RESISTIVITY (ohm-meter)
1	3.0	2000.
2	10.0	100.
3	3.0	1500.
4	10000.0	250.

COIL SPACING (meter)	COIL SETUP*	APPARENT RESISTIVITY (ohm-meter)	APPARENT CONDUCTIVITY (mmho/meter)	MUTUAL COUPLING RATIO (Z/ZO) REAL	IMAG
10	H	178.	5.8	.1001E+01	.7314E-02
	V	228.	4.4	.3362E-03	.5541E-02
20	H	192.	5.2	.1001E+01	.6585E-02
	V	196.	5.1	.2873E-03	.6443E-02
40	H	237.	4.2	.1001E+01	.5340E-02
	V	201.	5.0	.2534E-03	.6288E-02

NOTE: mmho/m are equal to and referred to as mS/m in this report.
*10H = horizontal coplanar coils at 10m spacing
10V = vertical coplanar coils at 10m spacing
20H = horizontal coplanar coils at 20m spacing
20V = vertical coplanar coils at 20m spacing
40H = horizontal coplanar coils at 40m spacing
40V = vertical coplanar coils at 40m spacing

The calculations made by the EM34.FOR program, displayed in printout form in table 3, indicated that the differences in the apparent conductivities over the uncontaminated and the contaminated areas that would be measured if an EM34-3 survey was conducted would be large. This would make detection of the contaminated ground-water plume possible.

After the preliminary model showed that the EM34-3 technique could detect the plume, a field EM34-3 conductivity survey was planned and conducted. Field measurements of the apparent conductivity were made on a series of transects perpendicular to the estimated axis of the plume. The axis of the plume was assumed to be in the direction of the ground-water flow, as determined from the available subsurface data. The EM34-3 field values for one transect are summarized in table 4.

TABLE 4.--Example EM34-3 field survey data

Station	Apparent conductivity (millisiemens/meter)					
	Coil spacing and orientation (meters)					
	10H	10V	20H	20V	40H	40V
C	4.3	4.2	3.0	2.7	1.3	1.5
D	4.2	3.9	3.0	3.0	0.4	1.4
F	6.7	4.2	4.0	2.3	1.1	2.3
H	6.8	4.3	4.8	3.0	2.6	3.6
J	13.0	7.2	6.6	5.4	5.0	4.8
L	15.0	7.4	11.0	7.4	6.5	7.5
N	16.0	9.5	14.2	11.3	8.1	10.5
P	11.4	6.2	10.4	7.7	8.0	8.4

The EM34 program was next used to generate a subsurface model whose calculated apparent conductivity matches the observed data at each station. From the field data, in table 4, stations C through F represent one subsurface condition (the uncontaminated area) and stations H through P represent another subsurface condition (the contaminated area). The original model (table 2) can now be adjusted until the calculated values match the average field values of apparent conductivity.

The final interpreted Earth models (table 5) produced values of apparent conductivity for both coil positions and all three coil separations that compare fairly well with the field data.

TABLE 5.--EM34.FOR output data and format for interpreted Earth model

Station	Layer	Thickness (meters)	Resistivity (ohm-meters)
Uncontaminated area:			
	1	2	2000
	2	8	140
	3	15	800
	4(bedrock)		250
D	1	2	2000
	2	10	150
	3	13	1700
	4(bedrock)		250
F	1	3	2000
	2	9	140
	3	14	1700
	4(bedrock)		250
Contaminated area			
H	1	3	2000
	2	8	100
	3	4	1700
	4	13	300
	5(bedrock)		250
J	1	4	2000
	2	7	50
	3	4	1700
	4	14	200
	5(bedrock)		250
L	1	4	2000
	2	20	50
	3	4	1700
	4(bedrock)		250
N	1	3	2000
	2	23	40
	3	3	1700
	4(bedrock)		250
P	1	1	2000
	2	22	90
	3	3	1700
	4(bedrock)		250

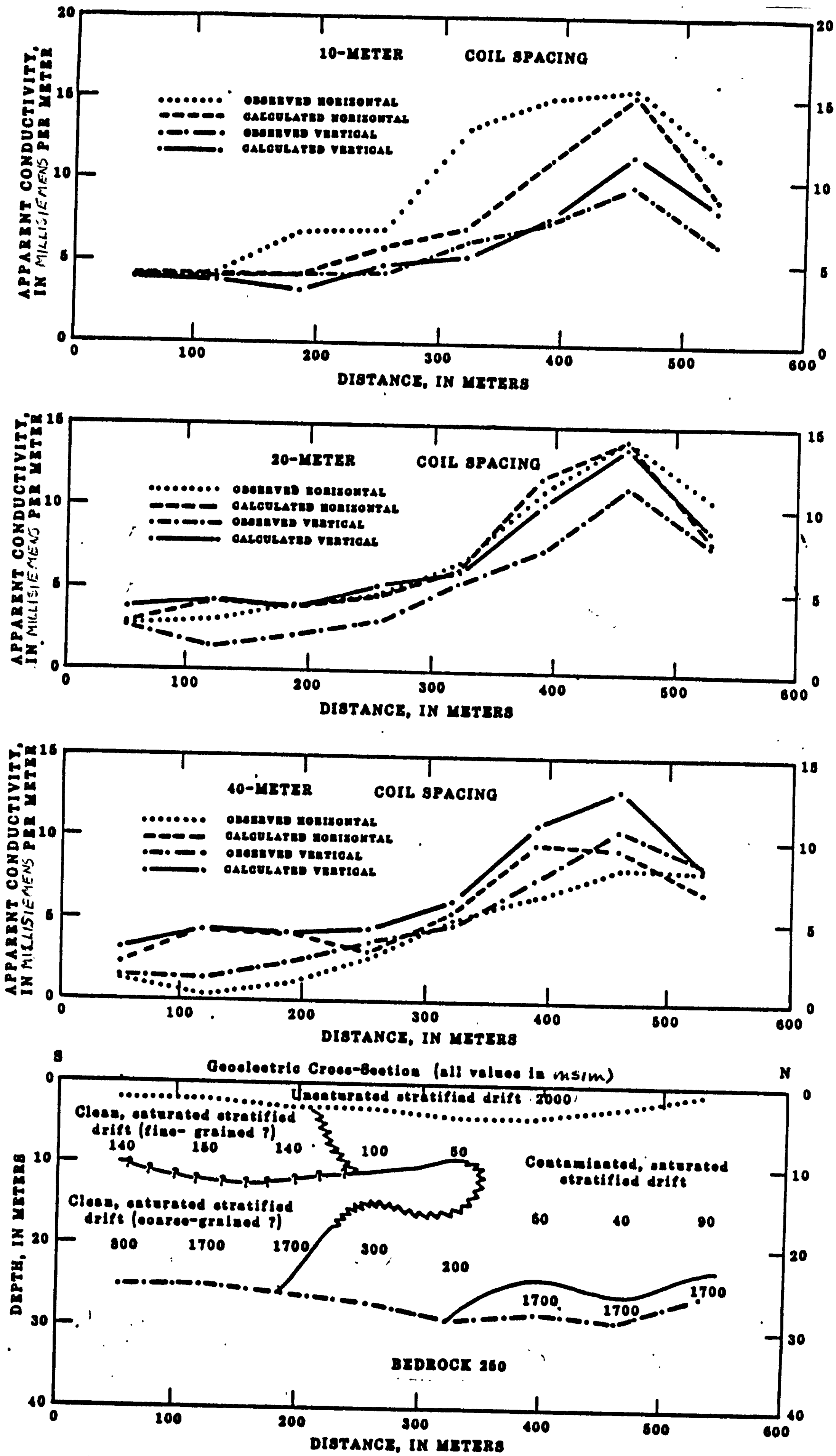


Figure 5: Observed and calculated conductivity and geoelectric and geologic cross-section at a landfill in Farmington, Conn. (modified from Grady and Haeni, 1984).

The subsurface models generated by the program are not unique solutions and, therefore, have been closely constrained by the available geologic data. Figure 5 compares the calculated (table 3) with the observed (table 4) EM34-3 responses for the transect in the Farmington, Conn., landfill site.

In this modeling process, it is difficult to match the observed values of apparent conductivity for all coil positions and spacings exactly, because the instrument is calibrated to output conductivity according to the low induction number approximation and the EM34.FOR program is a rigorous solution. The user must decide which coil position and spacing will be most responsive to the material of interest and use values for that position as reference values.

CONCLUSIONS

The EM34 program can be used to predict the results of a field survey based on available geologic data. Upon completion of the field survey, the program can be used to adjust the preliminary models to match the field data as closely as possible. This procedure can be used for any field investigation using inductive electromagnetic methods and the EM34.FOR program.

The EM34.FOR program must be used with its limitations and those of the EM34-3 instrument in mind. Specifically, there is no unique Earth model that produces a particular set of apparent conductivities, so the accuracy of the models generated by program is limited by type, quality, and quantity of geologic data. In addition, the instrument and the program are based on the low induction number approximation. When these limitations are kept in mind, the EM34.FOR program is a useful tool for the hydrogeologist.

McNeill (1980a; 1980c) has published a discussion of EM34-3 data interpretation techniques and of the electrical conductivity of Earth materials. Case histories of the EM34-3 technique applied to landfill sites and other groundwater applications have been published by Duran and Haeni (1982), Koerner and others (1982), McNeill (1982), Slaine and Greenhouse (1982), Stewart (1982), Greenhouse and Harris (1983), Ladwig (1983), and Barlow and Ryan (1985). Studies using the EM34.FOR program to determine the feasibility of the EM34-3 technique and to model field results have been conducted by Grady and Haeni (1984) and Mack (1986).

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GLOSSARY

<u>Angular frequency</u>: Repetition rate measured in radians per second; equal to $2\pi f$ in which f is the frequency in Hertz.

<u>Apparent conductivity</u>: Conductivity measured using inductive electromagnetic techniques that differs from true conductivity due to inhomogeneities of the Earth.

<u>Apparent resistivity</u>: Resistivity measured using inductive electromagnetic techniques that differs from true resistivity due to inhomogeneities of the Earth.

<u>Bytes</u>: Computer unit of binary digits usually in eight bits, each bit of which represents two numerals or one character.

<u>Conductivity</u>: Ability of a material to conduct electrical current; in an isotropic material, the reciprocal of resistivity.

<u>Dipole</u>: Poles of opposite signs, ideally infinitesimally close together; in electromagnetic techniques, an electric or magnetic field transmitting or receiving antenna which is small enough to be represented mathematically as a dipole.

<u>DOS (Disk operating system)</u>: Instructions and procedures for operating a computer disk drive.

<u>e</u>: base of natural logarithm; e = 2.7183.

<u>Eddy current</u>: Circulating electrical currents induced in a conductive body by a time-varying magnetic field; the direction of eddy current flow is such as to produce a secondary magnetic field which opposes the primary field; the secondary field has a quadrature component which depends upon the ratio of the resistance to the reactance of the eddy-current path.

<u>Floppy disk</u>: Flexible magnetic-coated plastic disk used for storing data.

<u>i</u>: In complex-number plane, i = square root of -1.

<u>Induction</u>: Process by which electric currents are generated in a conductor by placing it in an electromagnetic field.

<u>Kernel function</u>: Mathematical function of resistivity and depth which can be calculated from apparent resistivity data, from which a model of resistivity stratification is derived.

<u>Linear filter</u>: Operator that has as output at an instant of time the weighted linear combinations of the input.

Magnetic permeability: Ratio of the magnetic field, B, to magnetizing force, H; units are weber per ampere-m.

Reactance: The opposition to alternating current flow offered by inductance or capacitance.

Resistance: The opposition to the flow of direct current.

Resistivity: Property of a material which resists the flow of electrical current; units are ohm-meters.

APPENDIX A: EM34.FOR ALGORITHM

Magnetic Field Equations

The fundamental equations for the magnetic field generated by a vertical magnetic dipole in free space, or the primary field, are (Wait, 1958; Keller and Frischknecht, 1966; and Frischknecht, 1967):

$$H_{x,p} = (3mx(z-h))/(4\pi r^5)$$
$$H_{y,p} = (3my(z-h))/(4\pi r^5)$$
$$H_{z,p} = (3m(z-h)^2)/(4\pi r^5) - m/(4\pi r^3) \qquad (5)$$

in which Hx,p, Hy,p, and Hz,p are the horizontal and vertical components of the magnetic field (fig. 6) and

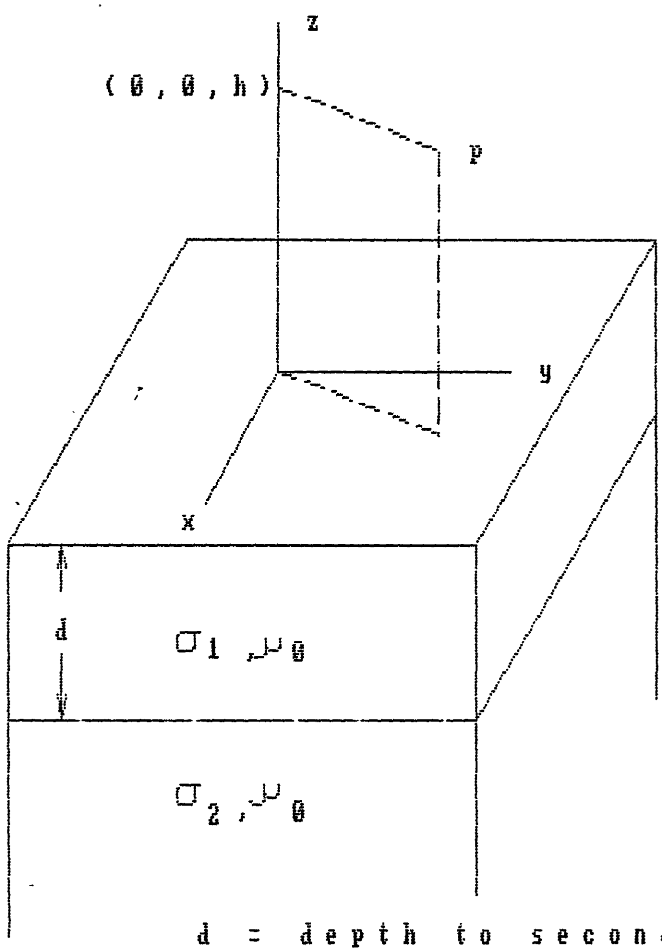
m = nAI = strength of the dipole;
n = number of turns on the coil;
A = area of the coil;
I = current through the coil;
$r = x^2 + y^2 + (z-h)^2$;
h = height of dipole above a layered Earth.

The magnetic field components of a vertical dipole scattered by the Earth, or the secondary fields, are:

$$H_{x,s} = -[m/(4\pi \delta^3)]T_1(A,B)(x/s)$$
$$H_{y,s} = -[m/(4\pi \delta^3)]T_1(A,B)(y/s)$$
$$H_{z,s} = -[m/(4\pi \delta^3)]T_0(A,B) \qquad (6)$$

The primary magnetic field components of a horizontal dipole are:

$$H_{x,p} = (3mxy)/(4\pi r^5)$$
$$H_{y,p} = (3my^2) - [m/(4\pi r^3)]$$
$$H_{z,p} = (3my(z-h))/(4\pi r^5) \qquad (7)$$



d = depth to second layer;

σ_1, σ_2 = conductivity of layers 1 and 2;

μ_0 = magnetic permeability of free space

p = point at which magnetic field is measured;

h = height of p above surface;

x, y, z = coordinate system.

Figure 6: Notation used in defining magnetic field components in a two-layer model (modified from Frischknecht, 1967)

The secondary magnetic field components of a horizontal dipole are:

$$H_{x,s} = [m/(4\pi\delta^3)][xy/s^2][(2/B)T_2(A,B)]$$

$$H_{y,s} = [m/(4\pi\delta^3)][y^2/s^2][(1-x^2/y^2)(1/B)T_2(A,B) - T_0(A,B)]$$

$$H_{z,s} = [m/(4\pi\delta^3)][y/s][T_1(A,B)] \qquad (8)$$

in which:

$$T_0(A,B) = \int_0^\infty R(D,g)g^2 e^{-gA} J_0(gB)dg;$$

$$T_1(A,B) = \int_0^\infty R(D,g)g^2 e^{-gA} J_1(gB)dg;$$

$$T_2(A,B) = \int_0^\infty R(D,g)g e^{-gA} J_1(gB)dg;$$

$$R(D,g) = 1 - 2g \frac{(u+v) + (u-v)e^{-uD}}{(u+g)(u+v) - (u-g)(u-v)e^{-uD}};$$

$$U = (g^2 + 2i)^{1/2};$$

$$V = (g^2 + 2ik)^{1/2};$$

$$\delta = (2/\sigma_1\mu_0\omega)^{1/2} = \text{skin depth};$$

$$k = \sigma_2/\sigma_1;$$

$$A = (z + h)/\delta;$$

$$B = s/\delta = \text{induction number};$$

$$D = 2d/\delta;$$

d = depth to nth layer;

J_0 = Bessel function of the first kind of order 0;

J_1 = Bessel function of the first kind of order 1;

$$g = \text{variable of integration.}$$

In the case where the source and the point of observation are on the ground, A = 0 and the integrals T0, T1, and T2 do not converge. These integrals may be rewritten as (Frischknecht, 1967):

$$T_0 = T' + T'' = \int_0^{\infty} [R(D,g) - R(\infty,g)] g^2 J_0(gB) dg + \int_0^{\infty} R(\infty,g) g^2 J_0(gB) dg \tag{9}$$

$$T_1 = T'_1 + T''_1 = \int_0^{\infty} [R(D,g) - R(\infty,g)] g^2 J_1(gB) dg + \int_0^{\infty} R(\infty,g) g^2 J_1(gB) dg$$

$$T_2 = T'_2 + T''_2 = \int_0^{\infty} [R(D,g) - R(\infty,g)] g^2 J_1(gB) dg + \int_0^{\infty} R(\infty,g) g^2 J_1(gB) dg$$

The first integrals in these equations are convergent. The second integrals represent the secondary field at the surface of a homogeneous Earth and can be expressed in closed form.

Mutual Coupling Ratios

Under the approximation that the separation between the coils is small compared to the wavelength and large compared to the diameters of the coils, the mutual impedance between the loops is simplified. This makes the concept of mutual impedance and ratios of mutual impedance convenient to use in two-coil electromagnetic measurements (Wait, 1958).

The mutual impedance Z between a source and a receiver is the ratio of the voltage V induced in the receiver to the current I in the source:

$$Z = V/I = -(i\mu\omega nAH)/I \tag{10}$$

in which:

n = number of turns on the receiver coil;
A = area of the receiver coil, and;
H = field at the receiving coil.

The mutual coupling ratio Z/Z0 is defined as the ratio of the mutual impedance between a source and a receiver in the presence of the Earth to the mutual impedance between the same source and receiver in free space or as the ratio of the field at the receiver in the presence of the Earth to the primary field:

$$Z/Z_0 = H/H_0 \tag{11}$$

For a two-coil system with the source and the receiver on the ground surface, the mutual coupling ratios for horizontal coplanar coils and vertical coplanar coils, respectively, are (Wait, 1958; Keller and Frischknecht, 1966; and Frischknecht, 1967):

$$(Z/Z_0)_H = 2/(\gamma^2 s^2)\left[9 - (9 + 9\gamma s + 4\gamma^2 s^2 + \gamma^3 s^3)e^{-\gamma s}\right] + B^3 T'_0 \tag{12}$$

$$(Z/Z_0)_V = 2\left[1 - \frac{3}{\gamma^2 s^2} + (3 + 3\gamma s + \gamma^2 s^2)\frac{e^{-\gamma s}}{\gamma^2 s^2}\right] + B^2 T'_2 \tag{14}$$

in which $\gamma^2 s^2 = i\sigma\mu_0\omega s^2 = 2i\beta^2$.

The first terms in equations (12) and (13) represent the mutual coupling ratio for a homogeneous Earth using the closed form of the second integrals in equation (9). The second term in each equation represents the contribution of a layered Earth. These integrals are evaluated in the EM34.FOR program according to a method developed by Koefoed and others (1972).

Computation

Early methods of evaluation of equations (12) and (13) were by numerical integration which is a tedious and time-consuming procedure due to the oscillation and the slow decay of the Bessel functions. The EM34.FOR program uses an alternative method for evaluation of the integrals developed by Koefoed and others (1972) and based on their observation that the integrals can be turned into convolution integrals by making the substitutions x=ln(s) and y=ln(1/g). The integrals can now be evaluated by application of a linear filter which can be designed by comparison with known integrals of the same form, such as the Lipschitz integral.

This computation procedure is much faster than direct integration although it is not necessarily as accurate. Traditional methods of computing the integrals have computed the contribution of a homogeneous Earth as a separate term. In the linear filter method, the method of computation of the term for the homogeneous Earth is based on accuracy and speed. Koefoed and others (1972) compute the term for a homogeneous Earth for the case of horizontal coils as a separate term, as given in equation, to increase the accuracy of the computation. In the case of vertical coils the computation of the contribution from a homogeneous Earth as a separate term does not significantly increase the accuracy and this effect is therefore included in the input function.

The integrals in equations (12) and (13) represent the convolution of two functions when the substitutions x=ln(s) and y=ln(1/g) are made. These two functions are known as the filter function and the input function to the filter. The integral itself is referred to as the output function.

The input function for horizontal coplanar coils is:

$$(\text{input})_H = -(g^2 s^2) R(g, d_n, \sigma_n, f) \qquad (14)$$

The input function for vertical coplanar coils is:

$$(\text{input})_V = -(sg) R(g, d_n, \sigma_n, f) \qquad (15)$$

The kernel function R in the input function is given by the following iterative expression (Koefoed and others, 1972):

$$R(g, d_n, \sigma_n, f) = \frac{\dfrac{V_{i-1} - V_i}{V_{i-1} + V_i} + R_{i+1}\, e^{-2V_i D_i}}{1 + \dfrac{V_{i-1} - V_i}{V_{i-1} + V_i} R_i\, e^{-2V_i D_i}} \qquad (16)$$

Evaluation is carried out by starting with the deepest layer n and calculating upwards through the shallowest layer, 1 (fig. 7).

The input function is then calculated using the kernel function and is multiplied by a set of stored filter coefficients, tabulated by Verma and Koefoed (1973), to find the output function. In the case of vertical dipoles, the mutual coupling ratio for a homogeneous Earth is added to the output function.

The mutual coupling ratios for horizontal coplanar coils and vertical coplanar coils, respectively, are:

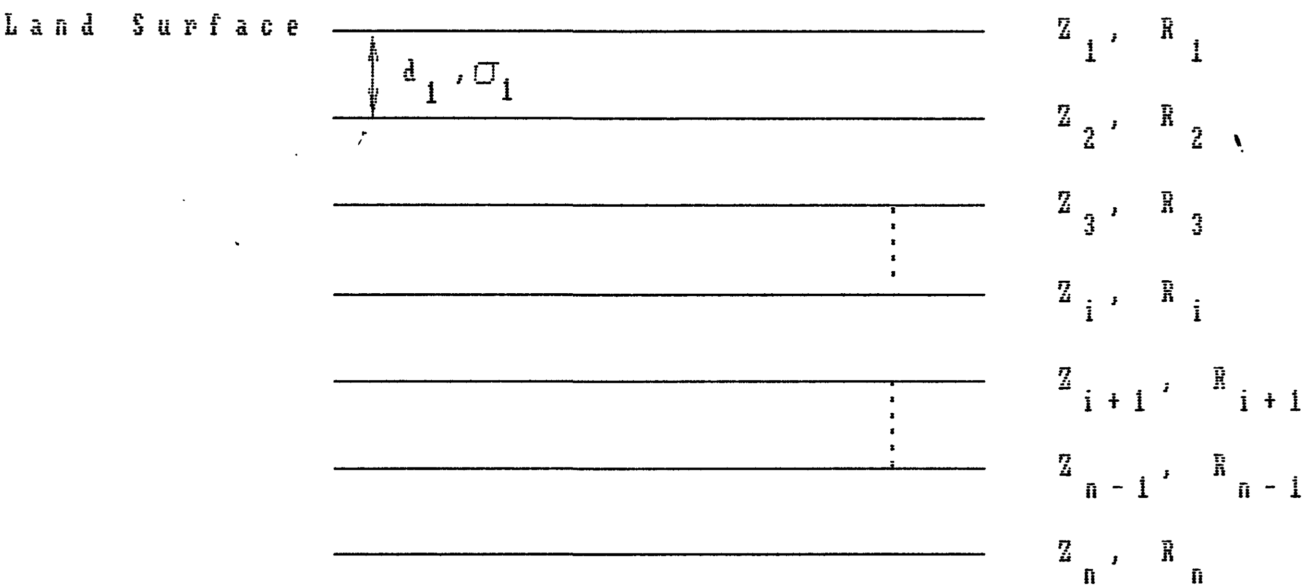
$$(Z/Z_0)_H = (Z/Z_0)_{homog} - \sum(input)x(Hcoeff) \qquad (17)$$

$$(Z/Z_0)_V = \sum(input)x(Hcoeff) \qquad (18)$$

Finally, the conductivity is calculated according to:

$$Im(Z/Z_0)(4/2\pi\mu_0 fs^2) \qquad (19)$$

These derivations and theory are discussed in depth by a number of authors including: Wait (1962a; 1962b); Keller and Frischknecht (1966); Frischknecht (1967); Koefoed and others (1972); Verma and Koefoed (1973) and Wait (1982). Anderson (1979) developed an adaptive technique for a more efficient evaluation of equations (12) and (13). Biewinga (1979) is one author who published a computer program, similar to the EM34.FOR, for the computation of the mutual coupling ratio over a layered Earth.



Z_i = mutual coupling of layer 1 (ohms);

R_i = kernel function;

d_i = thickness of layer 1 (m);

σ_i = conductivity of layer 1 (ms/m).

Figure 7: Layered Earth model parameters and notation scheme

ATTACHMENT A: LISTING OF EM34.FOR CODE

```
C$DEBUG
      COMMON D(5),RHO(5),LAYERS
       COMMON/BLK1/HCOEF(51),VCOEF(38)
      INTEGER LAYERS
      REAL*4 CONDUC
      COMPLEX*8 Z
      CHARACTER ANSWER*1,FILEOT*72
C LAYERS = NUMBER OF LAYERS IN THE EARTH MODEL
C D(J)   = THICKNESS (IN METERS) OF LAYER J
C RHO(J) = RESISTIVITY (IN OHM-METERS) OF LAYER J
C CONDUC = APPARENT CONDUCTIVITY (IN MHOS/METER) AS MEASURED
C          BY THE EM-34.  (THIS IS PROPORTIONAL TO THE QUADRATURE
C          COMPONENT OF THE SECONDARY MAGNETIC FIELD STRENGTH - H.)
C-----------------------------------------------------------------------
      WRITE(*,10)
   10 FORMAT
     1(//,2X,'PROGRAM FOR THE CALCULATION OF APPARENT RESISTIVITY')
      WRITE(*,12)
   12 FORMAT(//,2X,'GIVEN AN EARTH MODEL, THIS PROGRAM CALCULATES ITS AP
     1PARENT RESISTIVITY AS WOULD BE MEASUSED BY THE GEONICS EM-34 IN TH
     2E HORIZONTAL, COPLANAR',/,2X,'AND VERTICAL, COPLANAR COIL CONFIGUR
     3ATION.')
      WRITE(*,14)
   14 FORMAT(//,2X,'ASSUMPTIONS',/,4X,'-THE MEASUREMENTS ARE MADE ON THE
     1 SURFACE OF THE EARTH.',/,4X,'-THE EARTH MAY BE MODELED AS A HALF-
     2SPACE CONSISTING OF SEVERAL HORIZONTIAL',/,6X,'LAYERS.',/,4X,'-THE
     3 RESISTIVITY WITHIN EACH LAYER IS CONSTANT.')
C-----------------------------------------------------------------------
   20 WRITE(*,22)
   22 FORMAT(//,2X,'TYPE THE NUMBER OF LAYERS AND THEN HIT <ENTER>.')
      READ(*,'(I1)')LAYERS
      IF((LAYERS.LT.1).OR.(LAYERS.GT.5))THEN
        WRITE(*,26)
   26   FORMAT(//,2X,'THE VALUE WHICH YOU HAVE ENTERED FOR THE NUMBER OF
     1 LAYERS IS UNACCEPTABLE.',/,2X,'IT MUST BE GREATER THAN OR EQUAL T
     2O 1 AND LESS THAN OR EQUAL TO 5.')
        GO TO 20
      ENDIF
C CHECK VALUE FOR LAYERS
   27 WRITE(*,28)LAYERS
   28 FORMAT(//,2X,'THE NUMBER OF LAYERS IS ',I1,'.  IS THIS CORRECT?',/
     1,2X,'TYPE (Y/N) AND THEN HIT <ENTER>.')
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'N')THEN
          GO TO 20
        ELSEIF(ANSWER.NE.'Y')THEN
          WRITE(*,29)
```

```
29      FORMAT(//,2X,'THE CHARACTER WHICH YOU HAVE ENTERED IS UNACCEPT
     1ABLE.')
        GO TO 27
      ENDIF
C----------------------------------------------------------------------
      DO 32 I1=1,LAYERS-1
      WRITE(*,30)I1
30    FORMAT(//,2X,'TYPE THE THICKNESS (METER) AND RESISTIVITY (OHM-METE
     1R) OF LAYER ',I1,/,2X,'AND HIT <ENTER>.  SEPARATE THE NUMBERS WITH
     2 A COMMA.')
      READ(*,*)D(I1),RHO(I1)
32    CONTINUE
      WRITE(*,34)LAYERS
34    FORMAT(//,2X,'TYPE THE RESISTIVITY (OHM-METER) OF LAYER ',I1,' AND
     1 HIT <ENTER>.')
      READ(*,*)RHO(LAYERS)
      D(LAYERS) = 10000.
      CALL INLIST(0)
35    WRITE(*,36)
36    FORMAT(//,2X,'ARE THE INPUT DATA OK ?',/,2X,'TYPE (Y/N) AND HIT <E
     1NTER>.')
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'N')THEN
          CALL CORRECT
        ELSEIF(ANSWER.NE.'Y')THEN
          WRITE(*,29)
          GO TO 35
      ENDIF
C---------------------------------------------------------------------
40    IF(D(1).LT.0.04)THEN
        WRITE(*,42)
42      FORMAT(//,2X,'THE RATIO OF THE THICKNESS OF LAYER 1 TO THE INTER
     1COIL SPACING IS TOO SMALL',/,2X,'FOR ACCURATE COMPUTATION OF THE A
     2PPARENT RESISTIVITY WHEN THE COILS ARE IN',/,2X,'THE HORIZONTAL, C
     3OPLANAR CONFIGURATION.')
43      WRITE(*,44)
44      FORMAT(//,2X,'TYPE',/,4X,'-M TO MODIFY INPUT DATA',/,4X,'-C TO C
     1ONTINUE EXECUTION DESPITE THE POSSIBLE ERRONEOUS RESULT',/,2X,
     2'AND HIT <ENTER>.')
        READ(*,'(A1)')ANSWER
        IF(ANSWER.EQ.'M')THEN
            CALL CORRECT
                 GO TO 40
          ELSEIF(ANSWER.NE.'C')THEN
            WRITE(*,29)
            GO TO 43
        ENDIF
      ENDIF
```

```
C-----------------------------------------------------------------------
   79 WRITE(*,80)
   80 FORMAT(//,2X,'TYPE EITHER',/,4X,'- A FILENAME TO SEND THE RESULTS
     1TO THE DEFAULT DISK OR',/,4X,'- PRN TO SEND THE RESULTS TO THE PRI
     2NTER OR',/,4X,'- CON TO SEND THE RESULTS TO THE CONSOLE',/,2X,'AND
     3 THEN HIT <ENTER>.')
      READ(*,'(A72)')FILEOT
      OPEN(1,FILE=FILEOT,STATUS='NEW')
      CALL INLIST(1)
      WRITE(1,90)
   90 FORMAT(///,4X,'COIL',17X,'APPARENT',7X,'APPARENT',15X,
     1'MUTUAL COUPLING',/,
     21X,'SPACING',6X,'COIL',4X,'RESISTIVITY',3X,'CONDUCTIVITY',
     218X,'RATIO  (Z/Zo)',/,1X,'(METER)',4X,'SETUP*',4X,
     3'(OHM-METER)',3X,'(MMHO/METER)',14X,'REAL        IMAG',/)
      CALL APPCON(10.0D0,6.4D03,'H',CONDUC,Z)
      WRITE(1,91) 1.0/CONDUC,1000.*CONDUC,Z
   91 FORMAT(6X,'10',9X,'H',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4)
      CALL APPCON(10.0D0,6.4D03,'V',CONDUC,Z)
      WRITE(1,92)1.0/CONDUC,1000.*CONDUC,Z
   92 FORMAT(17X,'V',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4,/)
      CALL APPCON(20.0D0,1.6D03,'H',CONDUC,Z)
      WRITE(1,93)1.0/CONDUC,1000.*CONDUC,Z
   93 FORMAT(6X,'20',9X,'H',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4)
      CALL APPCON(20.0D0,1.6D03,'V',CONDUC,Z)
      WRITE(1,94)1.0/CONDUC,1000.*CONDUC,Z
   94 FORMAT(17X,'V',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4,/)
      CALL APPCON(40.0D0,0.4D03,'H',CONDUC,Z)
      WRITE(1,95)1.0/CONDUC,1000.*CONDUC,Z
   95 FORMAT(6X,'40',9X,'H',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4)
      CALL APPCON(40.0D0,0.4D03,'V',CONDUC,Z)
      WRITE(1,96)1.0/CONDUC,1000.*CONDUC,Z
   96 FORMAT(17X,'V',6X,F9.0,6X,F9.1,8X,E10.4,2X,E10.4,//
     1 ,2X,'* H - HORIZONTAL, COPLANAR COILS (VERTICAL DIPOLE)',/,
     2  4X,  'V - VERTICAL, COPLANAR COILS (HORIZONTAL DIPOLE)')
  100 WRITE(*,101)
  101 FORMAT(//,2X,'ARE YOU FINISHED WITH THIS PROBLEM?',/,2X,'TYPE (Y/
     1N) AND THEN HIT <ENTER>.')
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'N')THEN
        GO TO 35
      ELSEIF(ANSWER.NE.'Y')THEN
        WRITE(*,29)
        GO TO 100
      ENDIF
  105 WRITE(*,106)
  106 FORMAT(//,2X,'ARE YOU FINISHED WITH THIS SESSION?',/,2X,'TYPE (Y/N
     1) AND THEN HIT <ENTER>.')
```

```
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'N')THEN
        GO TO 20
      ELSEIF(ANSWER.NE.'Y')THEN
        WRITE(*,29)
        GO TO 105
      ENDIF
      STOP
      END
      BLOCK DATA
      COMMON/BLK1/HCOEF,VCOEF
      REAL*4 HCOEF(51),VCOEF(38)
      DATA HCOEF   /-.00001787D0,+.00000935D0,+.00000375D0,-.00001754D0,
     1 +.00001084D0,-.00000942D0,+.00000456D0,+.00000394D0,-.00001576D0,
     2 +.00003025D0,-.00004683D0,+.00006539D0,-.00008669D0,+.00011278D0,
     3 -.00014748D0,+.00019692D0,-.00027055D0,+.00038337D0,-.00056557D0,
     4 +.00085297D0,-.00134318D0,+.00224120D0,-.00404751D0,+.00812962D0,
     5 -.01859531D0,+.04821827D0,-.13070863D0,+.31328618D0,-.51302191D0,
     6 +.31003396D0,+.34216522D0,-.20142842D0,-.36288158D0,-.22914055D0,
     7 -.03202792D0,+.10252302D0,+.16941035D0,+.18559086D0,+.17656063D0,
     8 +.15523408D0,+.13149777D0,+.10841834D0,+.08826593D0,+.07109834D0,
     9 +.05708674D0,+.04555925D0,+.03635105D0,+.02892500D0,+.02289634D0,
     1 +.01843169D0,+.01454755D0/
      DATA  VCOEF/  -.00001323D0,+.00003397D0,-.00006292D0,+.00010397D0,
     1 -.00016337D0,+.00025153D0,-.00038653D0,+.00060158D0,-.00096163D0,
     2 +.00160407D0,-.00284834D0,+.00552295D0,-.01202839D0,+.02983246D0,
     3 -.08103193D0,+.21267387D0,-.43674023D0,+.49063145D0,+.04195061D0,
     4 -.43651651D0,-.22404767D0,+.09474711D0,+.26322713D0,+.28286168D0,
     5 +.23816634D0,+.17652451D0,+.12333557D0,+.08243897D0,+.05416555D0,
     6 +.03489808D0,+.02239027D0,+.01424526D0,+.00903156D0,+.00574492D0,
     7 +.00359571D0,+.00231841D0,+.00141123D0,+.00094868D0/
      END
C
C
C
      SUBROUTINE INLIST(UNIT)
      COMMON D(5),RHO(5),LAYERS
      INTEGER LAYERS,UNIT
C THIS SUBROUTINE LISTS THE INPUT DATA (I.E., THICKNESS AND DENSITY OF
C EACH LAYER.)
      IF(UNIT.EQ.0)THEN
        WRITE(*,1)
      ELSE
        WRITE(1,1)
      ENDIF
    1 FORMAT (///,17X,'THICKNESS',10X,'RESISTIVITY',/,2X,'LAYER',12X,'(M
     1ETER)',10X,'(OHM-METER)',/)
      DO 5 I=1,LAYERS
```

```
      IF(UNIT.EQ.0)THEN
        WRITE(*,3)I,D(I),RHO(I)
      ELSE
        WRITE(1,3)I,D(I),RHO(I)
      ENDIF
    3 FORMAT(5X,I2,7X,F12.1,9X,F12.0)
    5 CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE CORRECT
      COMMON D(5),RHO(5),LAYERS
      INTEGER LAYERS,NUMBER
      CHARACTER*1 ANSWER
C THIS SUBROUTINE CHANGES THE INPUT DATA.
      WRITE(*,3)
    3 FORMAT(//,2X,'YOU WILL CORRECT ONE PARAMETER AT A TIME')
    4 WRITE(*,5)
    5 FORMAT(//,2X,'TYPE THE NUMBER OF THE LAYER FOR WHICH A CHANGE WILL
     1 BE MADE AND HIT <ENTER>.')
      READ(*,'(I1)')NUMBER
      IF((NUMBER.LT.1).OR.(NUMBER.GT.LAYERS))THEN
        WRITE(*,9)
    9   FORMAT(//,2X,'THE NUMBER WHICH YOU HAVE ENTERED IS UNACCEPTABLE'
     1)
        GO TO 4
      ENDIF
   10 WRITE(*,11)NUMBER
   11 FORMAT(//,2X,'TYPE T TO CHANGE LAYER ',I1,' THICKNESS OR R TO CHAN
     1GE ITS RESISTIVITY.')
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'T')THEN
          WRITE(*,13)
   13     FORMAT(//,2X,'TYPE THE NEW THICKNESS AND THEN HIT <ENTER>.')
          READ(*,*)D(NUMBER)
        ELSEIF(ANSWER.EQ.'R')THEN
          WRITE(*,15)
   15     FORMAT(//,2X,'TYPE THE NEW RESISTIVITY AND THEN HIT <ENTER>.')
          READ(*,*)RHO(NUMBER)
        ELSE
          WRITE(*,17)
   17     FORMAT(//,2X,'THE CHARACTER WHICH YOU HAVE ENTERED IS UNACCEPT
     1ABLE.')
          GO TO 10
      ENDIF
      CALL INLIST(0)
```

```
   18 WRITE(*,19)
   19 FORMAT(//,2X,'DO YOU WISH TO CHANGE ANY OTHER INPUT DATA?',/,2X,
     1'TYPE (Y/N) AND THEN HIT <ENTER>.')
      READ(*,'(A1)')ANSWER
      IF(ANSWER.EQ.'Y')THEN
          GO TO 4
        ELSEIF(ANSWER.NE.'N')THEN
          WRITE(*,17)
          GO TO 18
      ENDIF
      RETURN
      END


      SUBROUTINE APPCON (DIST,F,SETUP,CONDUC,Z)
C
C SUBROUTINE APPCON COMPUTES THE APPARENT CONDUCTIVITY (MHO/METER) FOR
C A GIVEN EARTH MODEL.  THE ALGORITHM WAS DEVELOPED BY KOEFOED, ET AL.
C (1972) AND MODIFIED BY VERMA, ET AL. (1973).  (SEE  FILE EM34.HLP.)
C INSOFAR AS POSSIBLE, THE VARIABLE NAMES ARE IDENTICAL TO THOSE IN
C THE PAPERS WRITTEN BY THE PREVIOUSLY MENTIONED AUTHORS.
C
      COMMON D(5),RHO(5),LAYERS
      COMMON/BLK1/HCOEF,VCOEF
      INTEGER LAYERS,KS,K,I
      REAL*4 RHOMIN
      REAL*4 TEMPR,Y(51),LAMDA,LAMDA2,GAMMA2,CONDUC,PI,MU,
     1       HCOEF(51),VCOEF(38),X1,X2,X3,TEMP1,TEMP2
      REAL*8 F,DIST
      COMPLEX*8 TEMPC1,TEMPC2,Z,V(5),P,R,L,M,INPUT
      CHARACTER*1 SETUP
C DIST   = DISTANCE (IN METERS) BETWEEN TRANSMITTING AND RECEIVING
C          COILS
C F      = FREQUENCY (IN HERTZ)
C GAMMA2 = CONSTANT IN HELMHOLTZ EQUATION FOR MAGNETIC VECTOR POTENTIAL
C HCOEF  = FILTER COEFFICIENTS FOR HORIZONTAL, COPLANAR COILS
C I      = INDEX FOR RECURSIVE CALCULATION OF THE KERNEL FUNCTION - R
C INPUT  = INPUT FUNCTION TO BE CONVOLVED WITH FILTER COEFFICIENTS
C K      = NUMBER OF FILTER COEFFICIENTS
C KS     = SUBSCRIPT OF FIRST FILTER COEFFICIENT THAT MUST BE USED FOR
C          THE DISCRETE CONVOLUTION
C LAMDA  = VARIABLE OF INTEGRATION IN THE ORIGINAL EQUATION DESCRIBING
C          THE MUTUAL COUPLING RATIO FOR A MULTILAYERED EARTH (EXP(-Y))
C LAMDA2 = SQUARE OF LAMDA
C MU     = MAGNETIC PERMEABILITY OF FREE SPACE
C R      = KERNEL FUNTION WHICH DEPENDS UPON FREQUENCY OF THE SIGNAL
C          AND THE THICKNESSES AND RESISTIVITIES OF THE SUBSURFACE
C          LAYERS
```

```
C RHOMIN = SMALLEST RESISTIVITY IN THE LAYER SEQUENCE
C SETUP  = HORIZONTAL, COPLANAR OR VERTICAL, COPLANAR ARRANGEMENT
C          OF THE COILS
C V      = VARIABLE USED IN CALCULATION OF KERNEL FUNCTION (V(1) IS
C          RELATED TO SURFACE ADMITTANCE)
C VCOEF  = FILTER COEFFICIENTS FOR VERTICAL, COPLANAR COILS
C Y      = ABSCISSA VALUES FOR DISCRETE CONVOLUTION
C Z      = MUTUAL COUPLING RATIO
C P,L,M  = TEMPORARY VARIABLES USED TO CALCULATE  THE KERNEL FUNCTION
C TEMPR  = TEMPORARY VARIABLE (REAL)
C TEMPC1,TEMPC2 = TEMPORARY VARIABLES (COMPLEX)
C USE DBLE INTRINSIC FUNCTION TO REPLACE DREAL WHICH DOES NOT WORK
      PI = 3.14159265359D0
      MU = (4.0D-07) * PI
C-----------------------------------------------------------------------
C DETERMINE KS
      IF (SETUP.EQ.'H') THEN
          KS = (4.0D0) * DLOG( (1.0D03)*D(1)/DIST ) + 1.0D0
          IF (KS.GT.23) KS = 23
          IF (KS.LT.1) KS = 1
        ELSE
C FIND MINIMUM VALUE OF RHO IN LAYER SEQUENCE (INTRINSIC FUNCTION
C TO FIND MINIMUM DOES NOT WORK)
          RHOMIN = 1.0E07
          DO 200 J1 = 1,LAYERS
            IF(RHO(J1).LT.RHOMIN) RHOMIN = RHO(J1)
  200     CONTINUE
          KS = (1.3D0) * DLOG( (1.0D09)*RHOMIN/(F*DIST**2) ) - 2.0D0
          IF (KS.GT.12) KS = 12
          IF (KS.LT.1) KS = 1
      ENDIF
C-----------------------------------------------------------------------
C DETERMINE K
      IF (SETUP.EQ.'H') THEN
          K = 51
        ELSE
          K = 38
      ENDIF
C-----------------------------------------------------------------------
C DETERMINE THE MUTUAL COUPLING RATIO FOR A HOMOGENOUS EARTH MEASURED
C WITH HORIZONTAL, COPLANAR COILS.  FOR VERTICAL, COPLANAR COILS THIS
C RATIO IS INCORPORATED IN THE FILTER.
      IF (SETUP.EQ.'H') THEN
          TEMPR = (DIST**2)*MU*2.0D0*PI*F/RHO(1)
          TEMPC1 = DCMPLX(0.0D0,TEMPR)
          TEMPC1 = CDSQRT(TEMPC1)
          TEMPC2 = 9.0E0 + 9.0E0 * TEMPC1 + 4.0E0 * TEMPC1**2
     1             + TEMPC1**3
```

```
          Z = 2.0E0 * ( 9.0E0 - TEMPC2 * CDEXP(-TEMPC1)) / TEMPC1**2
        ELSE
          Z = (0.0E0,0.0E0)
      ENDIF
C-----------------------------------------------------------------------
C DETERMINE Y
      DO 210 J2=KS,K
        TEMP1 = (J2-1) * LOG(1.0E01)
        IF (SETUP.EQ.'H') THEN
            TEMP2 = LOG(DIST) - 8.75198087E0
            Y(J2) = TEMP2 + TEMP1 / (1.0E01)
          ELSE
            TEMP2 = LOG(DIST) - 6.10113727E0
            Y(J2) = TEMP2 + TEMP1 /  (1.0E01)
        ENDIF
  210 CONTINUE
C-----------------------------------------------------------------------
C DISCRETE CONVOLUTION TO DETERMINE MUTUAL COUPLING RATIO - Z
C
      DO 220 J3=KS,K
        LAMDA = EXP( -Y(J3) )
        LAMDA2 = LAMDA**2
        DO 221 J4=1,LAYERS
          GAMMA2 = 2.0E0 * PI * MU * F / RHO(J4)
          TEMPC1 = CMPLX(LAMDA2,GAMMA2)
          V(J4) = CSQRT(TEMPC1)
  221   CONTINUE
        R = (0.0E0,0.0E0)
C       DETERMINE KERNEL FUNCTION - R
        DO 222 J5=1,LAYERS
          I = LAYERS + 1 - J5
          IF (I.EQ.1) THEN
              P = ( LAMDA - V(1) ) / ( LAMDA + V(1) )
            ELSE
              P = ( V(I-1) - V(I) ) / ( V(I-1) + V(I) )
          ENDIF
          L = -(2.0E0) * D(I) * V(I)
          IF (DBLE(L).GT.-50.) THEN
              M = CEXP (L)
            ELSE
              M = (0.0E0,0.0E0)
          ENDIF
          R = ( P + R*M ) / ( 1.0E0 + P*R*M )
  222   CONTINUE
        IF (SETUP.EQ.'H') THEN
C           FOR HORIZONTAL, COPLANAR COILS, THE INPUT FUNCTION TO THE
C           FILTER IS THE DIFFERENCE BETWEEN THE INPUT FUNCTION FOR
C           THE LAYERED EARTH AND THAT FOR A HOMOGENOUS EARTH.
```

```
            INPUT = -(DIST**2) * LAMDA2 * (R - P)
            Z = Z + INPUT * HCOEF(J3)
          ELSE
            INPUT = - DIST * LAMDA * R
            Z = Z + INPUT * VCOEF(J3)
        ENDIF
  220 CONTINUE
C------------------------------------------------------------------------
C DETERMINE APPARENT CONDUCTIVITY
C
      CONDUC = 4.0E0 * DIMAG(Z) / ( MU * 2.0E0 * PI * F * DIST**2 )
      RETURN
      END
```