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A MAGNETIC INTERPRETATION PROGRAM BASED ON WERNER DECONVOLUTION

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SUMMARY

A magnetic interpretation program based on the Werner deconvolution technique has been developed and written in FORTRAN IV. The model adopted in the interpretation assumes that the observed magnetic field effect arises from the discrete sources and a quadratic magnetic background. This program has been applied successfully to both theoretical and observed marine magnetic data using the CYBER 76 system at CSIRO's Division of Computing Research.

1. INTRODUCTION

A computer program has been developed for quantitative interpretations of magnetic data. The process of interpretation involves analyses of magnetic data to provide information on the source of an anomaly. It was programmed in FORTRAN IV and applied successfully to both theoretical and observed marine magnetic data using the CYBER 76 computer at CSIRO's Division of Computing Research.

The initiative and idea of developing such a program was derived from a document published by Aero Service Corporation (1974). The technique of interpretation is known as Werner deconvolution (Werner, 1953; Hartman and others, 1971; Jain, 1976). The model adopted in our interpretation procedure assumes that the observed magnetic field arises from two discrete sources and a quadratic magnetic background as explained in Chapter 3.

The data input module described in Chapter 2 is designed to retrieve magnetic data from a data file. Interpreted results are printed as well as saved on scratch files for use by further programs for display purposes. The displays are vertical section graphic plots of interpreted sources in the line of traverse.

The interpretation procedure is performed by a generalised routine (WERNER) described in Chapter 4. The routine can accept equispaced magnetic data along a line of traverse with the interpretation parameters properly specified.

With some modifications on the data input mode, this magnetic interpretation program can be used on airborne, ground, or marine magnetic data. If necessary the users can write their own data input module and display to suit their requirements.

The first working version of this Werner deconvolution program included plot routines to give an immediate display of the estimates. However, it was found that the user generally replotted the estimates at various scales, and also applied various consistency tests to the results in an endeavour to screen out some of the 'bad' estimates. Also as the Werner deconvolution portion of the program was the most expensive part to run, it was advantageous to minimise the number of computer runs. It was therefore decided to save the estimates on a card-image file which could be accessed as required. The removal of the plot facility simplifies the logical flow in the program and the generalisation of the program, as plot software varies considerably from one ADP system to another.

The interpretation program presented in this report is only a preliminary version, and several improvements are envisaged. Instead of using an upward continuation filter as a shallow-source suppressor, an anti-aliasing filter will be used before resampling of the data. Consistency tests can optionally be applied to the results to screen out 'bad' estimates.

2. PROGRAM MAGINVT

This program uses the technique of Werner deconvolution to compute estimates for position, depth, direction, and intensity of magnetisation of magnetic sources by direct inversion of the magnetic profile. It is written in Fortran IV and presently implemented on the Cyber 76 system at the Division of Computing Research, CSIRO. The program, as presented, is the version used by the Marine Geophysics Group of BMR, and consequently much of the program is designed specifically for the Marine Group's processing system. However, the major mathematical routines, viz. WERNER, UPCONT, HTDERVS, and MATRIX, are generalised and only need to be called with the appropriate parameters.

Data input is by marine data files from which station number, latitude, longitude, water depth, magnetic value, and magnetic diurnal can be extracted at specified intervals. Marine data files store the basic information in survey time: that is, 32 channels of data for each hour are saved in a buffered block of size 32 x 60. Other processing variables are input as data cards.

The program has a reasonable degree of flexibility in that it cycles for each survey line to be processed for one model type and then if required cycles for the other model type. This means that with one computer run, all survey lines can be processed for both model types.

An outline of the processing flow is shown in Figure 1.

After reading the interpretation parameters etc. in the first three data cards (see below), the program enters the main processing cycle. It reads a baseline data card (see below) containing identifying information for one survey line, processes this line, and returns to read another baseline data card. The program cycles through successive baseline data cards and the corresponding data until an end-of-file is encountered, at which time the processing flow jumps back to the start of the program ready to read another model type or new data file.

Following the reading of a baseline data card the processing flow enters subroutine READATA. This subroutine extracts the basic data from magnetic tape, according to the survey times specified in the data cards. It also computes the projected distance along the baseline. The basic data stored in the work array are station number, latitude, longitude, water depth, projected distance, and magnetic value corrected for diurnal variation.

Subroutine REGULAR then resamples the data at constant intervals along the baseline to provide an equispaced data array for the magnetic values by linear interpolation.

The processing flow is directed to one of two paths at this point (Fig. 1) depending on whether a thin-sheet or interface model is assumed. For the thin-sheet model, the regional constant is subtracted from the corrected magnetic data and the resulting array is passed to subroutine WERNER. For the interface model, subroutine DHTERVS is used to calculate the horizontal derivatives of the original data, and the derivatives are passed to WERNER.

Subroutine WERNER carries out mathematical interpretation based on the Werner deconvolution technique and outputs to a scratch file estimates of position relative to the base point, depth, and direction and intensity of magnetisation. The subroutine loops for each level specified on the third data card (see below). A detailed description of the mathematical basis and the subroutine is given in later chapters.

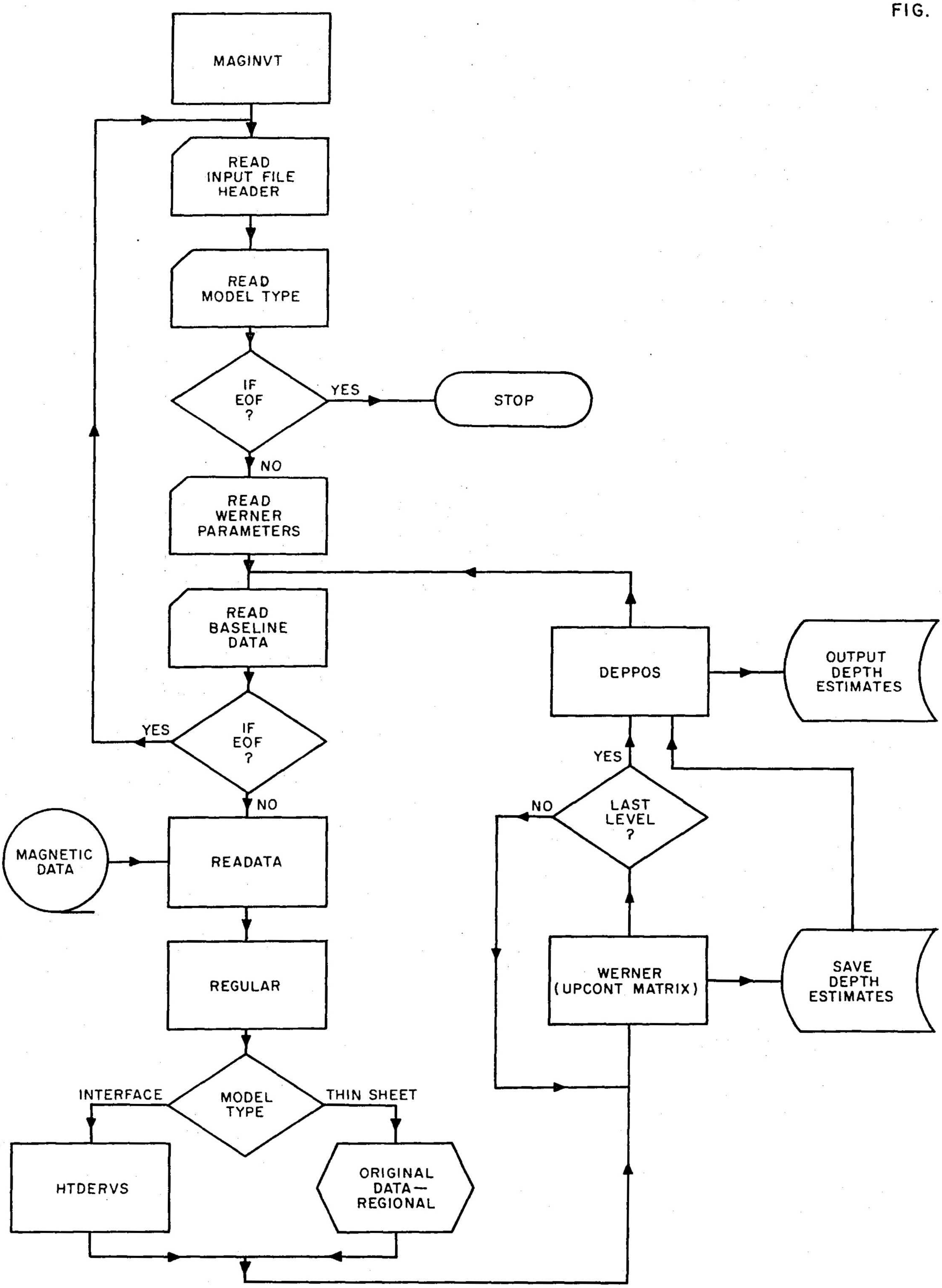
The estimates are then read in subroutine DEPPOS, plus station number, latitude, longitude, and water depth associated with each estimate. The eight parameters, viz. station number, latitude, longitude, water depth, relative position, depth, and direction and intensity of magnetisation are then output to permanent file in card image form for permanent retention. Other programs are used later to plot and display the results.

Following this the program cycles to read the next baseline card and the process is repeated.

<u>Explanation of data cards</u>

The first data card is the input file label: an 80-character label which is used to locate the input basic data file.

FIG. 1



OUTLINE OF PROCESSING FLOW

FOR WERNER DECONVOLUTION PROGRAM

The second data card identifies the model type, either 'thin sheet' where the corrected total magnetic intensity data is used in the Werner deconvolution, or 'interface' where the horizontal derivatives are used. When an end-of-file is encountered the processing is terminated.

The third data card provides the Werner processing parameters. These are the start and stop levels of interpretation, scanning step, extraction increment, and magnetic regional. The start and stop levels determine the minimum and maximum depths for which estimates are to be computed (Table 1).

The scanning step is the data space stepping applied to the 11-point window which scans along the profile during the Werner deconvolution. Its magnitude is related indirectly to the definition of an interpreted magnetic source. The smaller the scanning step, the more estimates will be produced. With more estimates an interpreted source will be better defined. However, the program will cost more to run when a smaller scanning step is used.

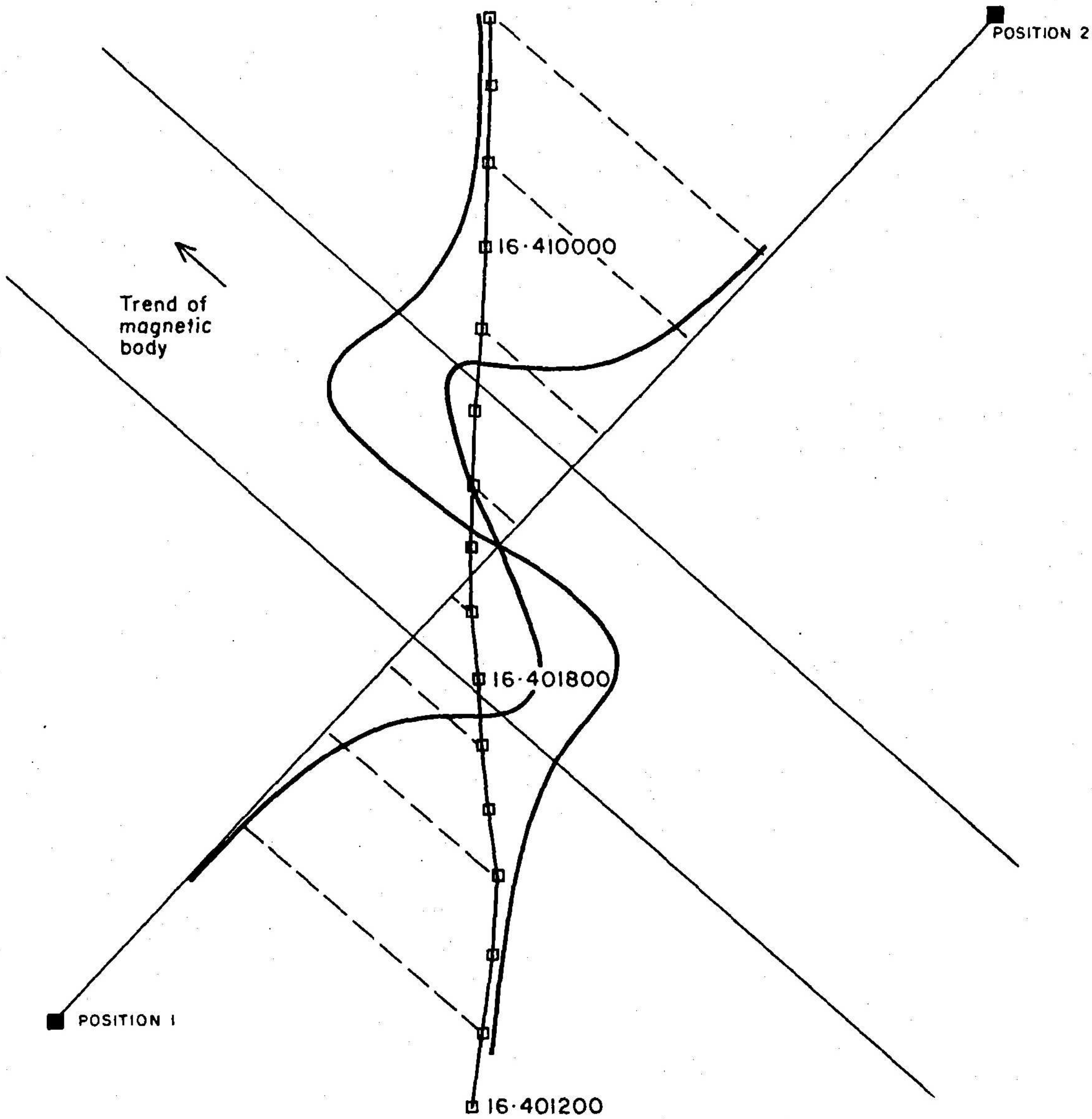
The extraction increment is the increment in minutes between the consecutive data points to be extracted from the basic marine data tape. The magnetic regional is an approximate regional constant which is subtracted from the data to keep numbers small.

Following the first three described above are baseline data cards. Each baseline data card contains a start and stop time, latitudes and longitudes relating to these times, and an alphanumeric descriptor of the line. The start and stop times indicate the survey times between which data is extracted from the Marine data tape. The associated positions are the end points of the baseline onto which the data is projected. If it is known that the traverse line does not intersect the trend of the magnetic body at right angles, the data can be projected onto an appropriate baseline to correct for the obliqueness of the track (Fig. 2). In any case the projection of the data will remove distortions in the data caused by minor perturbations in the track.

3. THEORY

To develop the interpretation procedure, we must first of all choose a model as our basis of interpretation. For a simple model such as a thin sheet, the equation of its magnetic field intensity can be written in the form

FIG. 2



PROJECTION OF DATA ONTO BASELINE

$$T(x) = \frac{Ah + B(x-x_o)}{(x-x_o)^2 + h^2} \quad \text{..........} \quad (1)$$

where x represents distance along a line perpendicular to the strike of the thin sheet;

T(x) is the total magnetic field intensity at x;

h is the depth to the top of the thin sheet;

x_o is the position of the top, projected vertically to intersect the line;

A and B are parameters related to the magnetic properties and the thickness of the thin sheet as well as its orientation relative to the direction of the Earth's field.

For a more complex model which we shall adopt in our interpretation procedure, the anomalous magnetic field effect is considered to be a resultant of those due to two thin sheets and a quadratic magnetic interference (background). The magnetic field intensity arising from such a model has the following mathematical expression

$$T(x) = \frac{A_1h_1 + B_1(x-x_1)}{(x-x_1)^2 + h_1^2} + \frac{A_2h_2 + B_2(x-x_2)}{(x-x_2)^2 + h_2^2} + (a_o + a_1x + a_2x^2) \quad \text{......} \quad (2)$$

The first two terms on the right of this equation define the magnetic field intensity at x produced by two thin sheets. The third term, in brackets, represents the quadratic magnetic interference. Parameters A_1, B_1, x_1, h_1, and A_2, B_2, x_2, h_2 correspond to A, B, x_o, h described above.

Since no one single model irrespective of its complexity can validly cover all situations, it is necessary to define the range of validity of any model. The chosen range of validity of a model shall be called the window of interpretation. The lower limit of a window is dictated by the degree of complexity of the model adopted, whereas the upper limit is determined by the technique of solution.

On the basis of the model described in Equation (2), the problem is to determine the unknown parameters (A, B, x, h) of the magnetic sources that produce the magnetic field effect observed within the window of interpretation. Altogether there are eleven unknowns in the equation, viz. A_1, B_1, x_1, h_1, A_2, B_2, x_2, h_2, a_o, a_1, and a_2. To solve these unknowns <u>analytically</u>, we will require eleven observed data values. We have decided on an analytical solution to the problem, so the window of interpretation is set to cover eleven data points or ten data spacings wide with equispaced data.

Equation (2) can be linearised into the following form

$$x^4T = C_1x^3T + C_2x^2T + C_3xT + C_4T + C_5x^2 + C_6x + C_7 + C_8x^3 + C_9x^4 + C_{10}x^5 + C_{11}x^6 \qquad (3)$$

where

$$\left.\begin{aligned}
C_1 &= 2x_1 + 2x_2 \\
C_2 &= -W_1^2 - W_2^2 - 4x_1x_2 \\
C_3 &= 2x_1W_2^2 + 2x_2W_1^2 \\
C_4 &= -W_1^2W_2^2 \\
C_5 &= A_1h_1 + A_2h_2 - B_1x_1 - B_2x_2 - 2B_1x_2 - 2B_2x_1 - C_2a_o + C_3a_1 - C_4a_2 \\
C_6 &= B_1W_2^2 + B_2W_1^2 + 2x_1x_2(B_1 + B_2) - 2A_1h_1x_2 - 2A_2h_2x_1 - C_3a_o - C_4a_1 \\
C_7 &= A_1h_1W_2^2 + A_2h_2W_1^2 - B_1x_1W_2^2 - B_2x_2W_1^2 + W_1^2W_2^2a_o \\
C_8 &= B_1 + B_2 - C_1a_o - C_2a_1 - C_3a_2 \\
C_9 &= a_o - C_1a_1 - C_2a_2 \\
C_{10} &= a_1 - C_1a_2 \\
C_{11} &= a_2 \\
W_1^2 &= x_1^2 + h_1^2 \\
W_2^2 &= x_2^2 + h_2^2
\end{aligned}\right\} \qquad (4)$$

The relations between the original unknowns and the new set of unknowns (C values) are given in Equation (4). In matrix form, the C values are given by

$$\underset{\sim}{C} = [A]^{-1} \underset{\sim}{x^4T} \qquad (5)$$

To solve for C, we have to compute the inverse of matrix A. If matrix A is not singular or ill-conditioned, solution array C, can be uniquely determined. After C values are determined, we can go ahead to solve for the original unknowns using the relations described in Equation (4).

Note that a_o, a_1, and a_2 are relatively simple to determine as follows

$$\begin{aligned}
a_2 &= C_{11} \\
a_1 &= C_{10} + C_1C_{11} \\
a_o &= C_9 + C_1(C_{10} + C_1C_{11}) + C_2C_{11}
\end{aligned}$$

To determine x_1, x_2, h_1, and h_2, we simply use the equations

$$2x_1 + 2x_2 = C_1$$
$$-W_1^2 - W_2^2 - 4x_1x_2 = C_2$$
$$2x_1W_2^2 + 2x_2W_1^2 = C_3$$
$$-W_1^2W_2^2 = C_4$$

where
$$W_1^2 = x_1^2 + h_1^2$$
$$W_2^2 = x_2^2 + h_2^2$$

Based on this set of equations, we can produce a polynomial equation in terms of x_1

$$P(x_1) = \tfrac{1}{4}\left[C_2(C_1 - 2x_1) + 2x_1(C_1 - 2x_1)^2 + C_3\right]\left[2C_2x_1 + 2x_1^2(C_1 - 2x_1) + C_3\right] - \tfrac{1}{2}C_4(4x_1 - C_1)^2 \quad \ldots\ldots\ldots\ldots \quad (5)$$

The roots of this polynomial equation are solutions of x_1. We can determine the roots by searching for the zero-crossing of $P(x_1)$. Once x_1 is determined, then

$$x_2 = \tfrac{1}{2}C_1 - x_1$$

$$W_1^2 = \frac{x_1(C_2 + 4x_1x_2) + \tfrac{1}{2}C_3}{x_2 - x_1}$$

$$W_2^2 = \frac{x_2(C_2 + 4x_1x_2) + \tfrac{1}{2}C_3}{x_1 - x_2}$$

Thus, $h_1 = (W_1^2 - x_1^2)^{\frac{1}{2}}$

and $h_2 = (W_2^2 - x_2^2)^{\frac{1}{2}}$

With the solutions for a_o, a_1, a_2, x_1, h_1, x_2, and h_2, we can determine A_1, B_1, A_2, and B_2 by a number of techniques. The least-squares fit is used in the program.

The solutions of real interest are those describing the magnetic thin sheets, i.e. x_1, h_1, A_1, and B_1 and x_2, h_2, A_2, B_2. The A and B are more usefully expressed in the forms of intensity of magnetisation as $(A^2 + B^2)^{\frac{1}{2}}$ and angle of magnetisation as Arctan (A/B).

Although the theory has been developed on the basis of magnetic thin sheets, it applies just as well to a model of magnetic interfaces. The horizontal derivative of the magnetic field intensity over a magnetic interface has the same mathematic expression as that of a thin sheet:

$$T(x) = \frac{ah + b(x-x_o)}{(x-x_o)^2 + h^2} \quad \ldots\ldots\ldots \quad (6)$$

where x_o is the position of the top of the interface, projected vertically to intersect the traverse

h is the depth to the top of the interface

a and b are parameters related to the magnetic contrast of the interface as well as its orientation relative to the direction of the Earth's field.

Therefore, the same procedure of interpretation can be applied to the horizontal gradients of the observed magnetic field, and we obtain results indicating the position, depth, and magnetic contrast of interfaces as interpreted. In addition, the second-order interferences assumed in the horizontal gradient field are actually third-order interferences in the original observed magnetic field.

One should bear in mind that the window of interpretation produces a set of solutions based on a model consisting of either all interfaces or all thin sheets, but not a mixture of both. If the assumed model is not a good approximation to the real situation, i.e. 'bad' magnetic sources with respect to the assumed model are encountered, then the interpreted results will become erratic as the window scans over the 'bad' magnetic source. On the other hand, if the magnetic source conforms well to the model, the interpreted results will be fairly consistent as the window scans over such a 'good' magnetic source.

4. DESCRIPTION OF SUBROUTINE WERNER

This routine actually carries out the interpretation procedure based on the Werner deconvolution technique described in the previous chapter.

Given a magnetic profile, this routine scans the profile in specified steps with a window of interpretation. The magnetic data samples within this window are analysed as described in the previous chapter. The magnetic data can be the corrected magnetic field values or the derived horizontal gradients depending on the model chosen.

(3

The interpretation procedure repeats a specified number of times, with the window of interpretation opening wider each time, in effect searching for deeper magnetic sources. The magnetic effects due to shallow sources are reduced by way of upward continuation so as not to mask the effects from deeper magnetic sources. All interpreted sources are checked by comparing the observed anomaly values with theoretical values calculated for that source. If the standard deviation exceeds 10 percent of the root-mean-square of the observed anomaly values, the interpreted source is rejected.

Results of interpretation for each scan are stored in four arrays and printed or saved for display at the end of the scan. Figure 3, parts 1 & 2, show a flow chart of this routine.

The critical parameters in this routine are :

(1) The level of interpretation (LVL)

This determines the depth of interpretation. Table 1 indicates the ranges of depth of interpretation for each level from 1 to 7. Note that their depth ranges overlap from one level to another. This is designed to check the repeatability of an interpreted magnetic source at successive levels.

The start and stop levels (LVF and LVS) of interpretation specify the depth ranges of interpretation. They are set by the user in the third data card of the computer job deck (see Chapter 2).

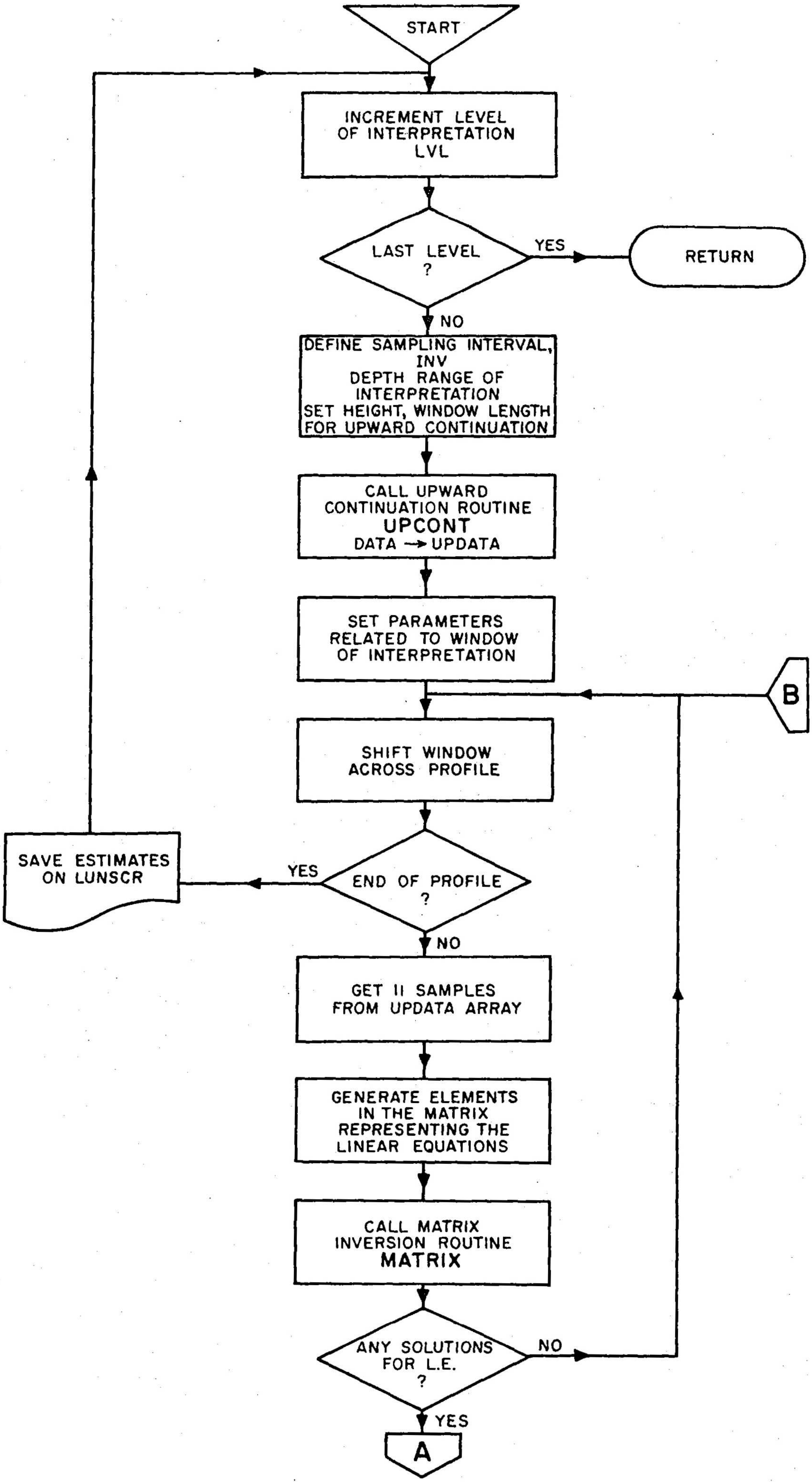
(2) The sample interval (INV)

This is the interval between selected samples in the window. It is measured in units of data spacing, and related directly to the level of interpretation as shown in Table 1.

(3) The length of the window of interpretation

This parameter is related indirectly to the level of interpretation through the sample interval. The wider the window the greater the depth at which the interpretation procedure can derive valid magnetic sources. Table 1 also shows the window length for various levels. The window of interpretation always covers eleven equispaced samples, so the window length is determined purely by the size of sample interval, hence, by the nominated level of interpretation. The relations between these parameters are summarised in Table 2.

FIG. 3



FLOW CHART FOR SUBROUTINE WERNER

(PART I)

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SHEET 1 OF 2

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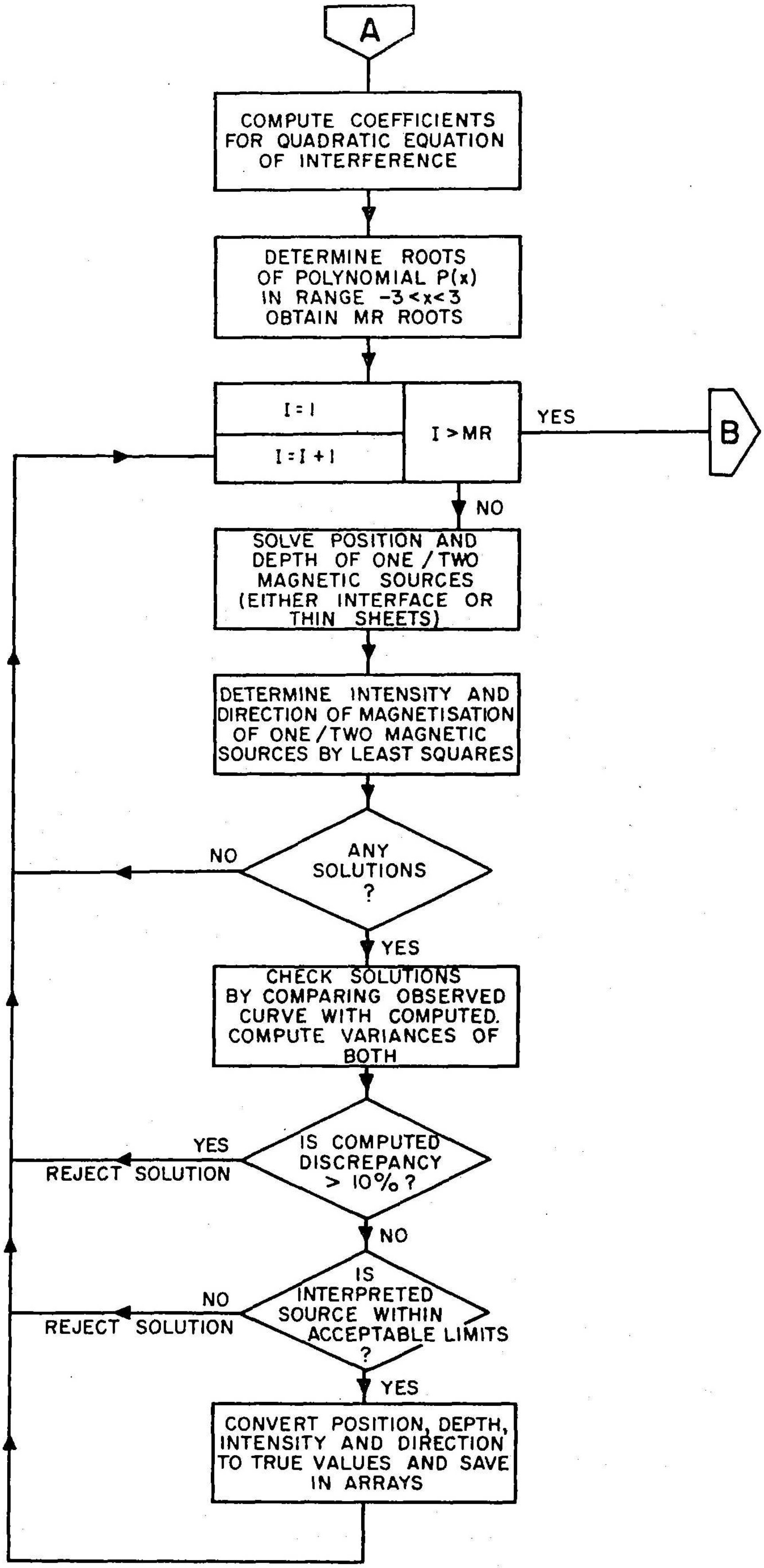


FLOW CHART FOR SUBROUTINE WERNER

(PART 2)

(4) The height of upward continuation (ZL)

This parameter is set equal to the sample interval (INV) except at level one where ZL = 0, i.e. no upward continuation is applied to the magnetic data at level one.

(5) The scanning step (ISTEP)

This defines the interval at which the window of interpretation scans along the profile. Thus, it controls the number of estimates to be generated, and indirectly determines the definition of interpreted sources.

TABLE 1. TABLE OF INTERPRETATION PARAMETERS
(in unit of data spacing)

Level interpretation	Sample interval	Depth range lower limit	Depth range upper limit	Window length of interpretation	Height of upward Cont.
LVL	INV	DLC	DUC		ZL
1	1	0.0	4.5	10	0
2	2	1.0	9.0	20	2
3	4	2.7	18.0	40	4
4	8	4.0	36.0	80	8
5	16	12.8	72.0	160	16
6	32	26.7	144.0	320	32
7	64	54.0	288.0	640	64

TABLE 2. SUMMARY OF EQUATIONS RELATING THE PARAMETERS

INV = 2 ** (LVL-1)
DLC = (LVL-1) * INV/LVL
DUC = 4.5 * INV
ZL = INV except LVL = 1, ZL = 0
Window length = 10 * INV

Driving instructions

(1) Set up the main program to input equispaced magnetic field data and store data in an array DATA for each profile.

(2) Determine the start and stop levels of interpretation (LVF & LVS), and also the scanning step (ISTEP) (Refer to Chapter 2).

(3) Call SUBROUTINE WERNER (DATA, UPDATA, NPOINTS, TRUEDIS, POSAVE, ISTEP, LVF, LVS, POS, DEP, SS, AS, LUNSCR).

(4) All interpreted results from a profile are stored temporarily on file LUNSCR. If results are to be used later, they should be saved on a permanent file or magnetic tape in the main program.

(5) Note that the size of arrays DATA, UPDATA, POS, DEP, SS, and AS depends on the number of magnetic data points in each profile. For a profile of 1000 data points, dimensions of DATA and UPDATA should be at least 1000 and POS, DEP, SS, and AS should be at least 500 each.

(6) Each set of POS (I), DEP(I), SS(I), and AS(I) holds the results for an interpreted source.

(7) Explanation of the formal parameters in the subroutine call.

DATA is the input magnetic data array;
UPDATA is the upward continued data array;
NPOINTS is the total number of data points on that profile;
TRUEDIS is the true distance of data spacing;
POSAVE is the true position of the first data point;
ISTEP is the scanning step;
LVF defines the lower limit of level of interpretation;
LVS defines the upper limit of level of interpretation;
POS is the array holding the position of an interpreted source;
DEP is the array holding the depth of an interpreted source;
SS is the array holding the intensity of magnetisation source;
AS is the array holding the angle of magnetisation source.

Routines

(1) UPCONT (NOC, DATA, UPDATA, DT, ZL, NC, NLT)

NOC is the length of upward continuation coefficients to be used;
DATA is the input data array;
UPDATA is the upward continued data array;
DT is the data spacing (always set = 1.0);
ZL is the height of upward continuation;
NC is the first data point to be upward continued;
NLT is the last data point.

(2) MATRIX (A, N, B, L, DET, IRR)

A is the N x N matrix to be inverted;

B is the vector on RHS of the matrix equation;

L = 0 inverse only,

 >0 solution only,

 <0 both;

DET is the determinant of the A matrix on return;

IRR = 1 matrix is singular

 = 0 matrix has inverse.

Input/output files

The only file used in this routine is LUNSCR. For printing interpreted results, set LUNSCR = 60. For saving the results for display purpose, LUNSCR could be any scratch file. Results for each level of interpretation are stored as one file, i.e. terminated with an EOP. In case more than one profile is interpreted, the results for different profiles should be saved on a different scratch file in the main program.

Error messages

********** ARRAY LIMITS EXCEEDED FOR: POS, DEP, AS, SS

This means the number of magnetic sources interpreted in a level exceeds the present limit of 1000. In such an event, the interpretation procedure ceases to apply at that level and moves to the next level.

Action: increase the dimension of those arrays.

5. APPLICATIONS

The Werner deconvolution technique has been applied to both theoretical and observed magnetic data. Theoretical magnetic anomaly profiles were calculated for two-dimensional bodies traversed at right angles, using the method of Talwani & Heirtzler (1964). Magnetic data from the southern margin of Australia collected during the BMR Continental Margin Survey were used as a practical example of the technique.

Display of estimates

The program output provides estimates of depth, position, and direction and intensity of magnetisation. The presentation of these results is critical to the interpreter, and even the method used in this report is not considered by the authors to be the final answer. In the examples presented, the estimates are plotted as a vertical section showing the anomaly profile and the outline of the causative bodies. Estimates are plotted with the size of the symbol dependent on the square of the log of intensity of magnetisation, normalised such that 200 intensity units is equivalent to 0.1 inch. Also the direction of annotation of the symbol, as defined by the straight line segment within the symbol, is related to the direction of magnetisation in the plane of the section.

Other methods of presentation may be adopted at the interpreter's discretion, and in general a variety will be required to obtain the maximum benefit from the computer-interpreted data. A useful presentation is the plotting of each level of interpretation (see Chapter 4 for definition) separately on transparent paper, then overlying results during the interpretation. Alternatively, separate colours or different symbols could be used for each level.

Further presentation methods are possible, for example by first applying a consistency test to the interpretation data, by checking whether other estimates fall within a certain radial distance of each estimate point and discarding those lacking supporting points. This method will screen out all but the good clusters. An average for each of these clusters can be obtained and the resulting point estimates plotted. This has the disadvantage that an unfavourable profile may yield few estimates.

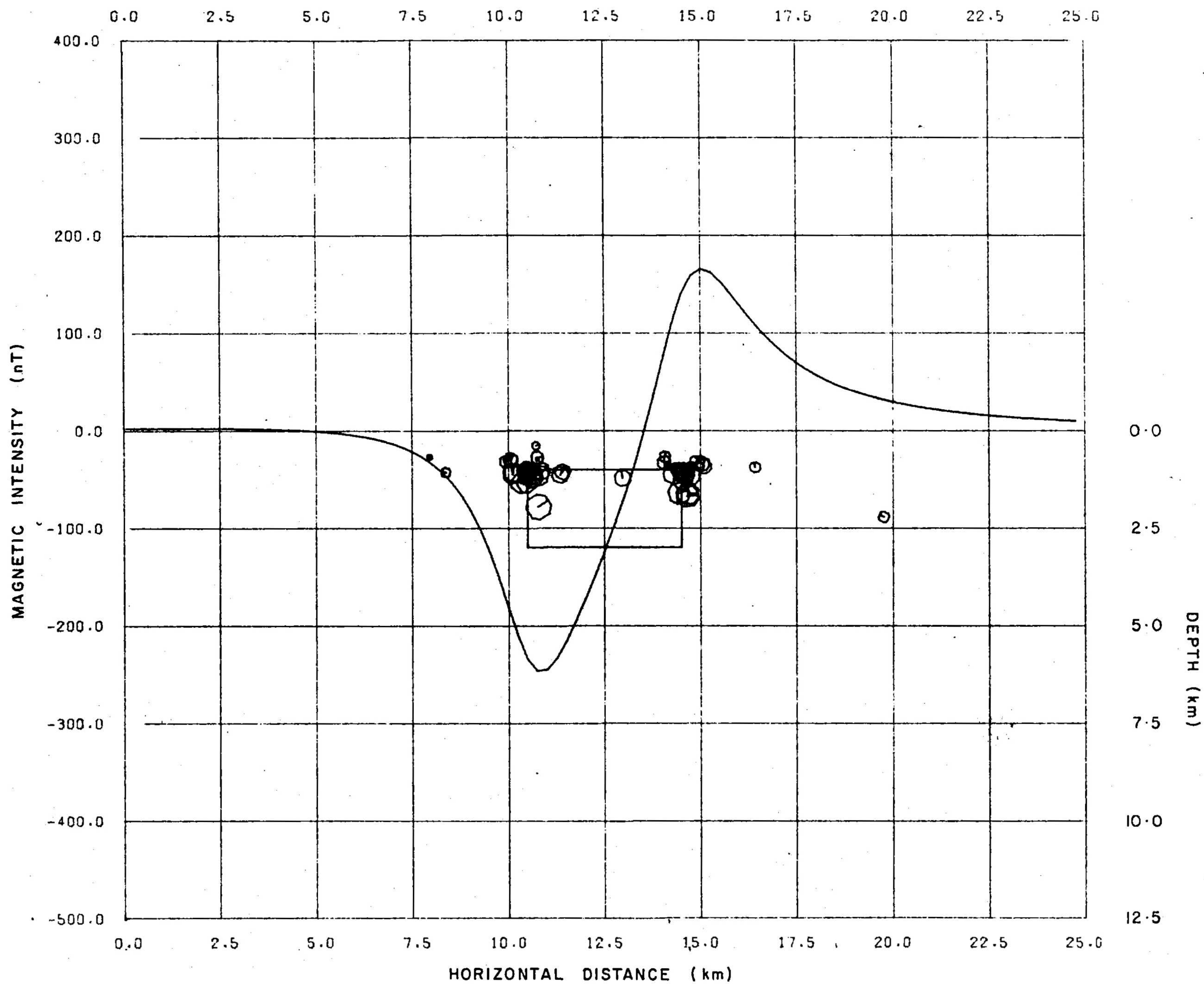
However, for single body models, as presented in this report, the authors have restricted the presentation simply to show all the interpretation data, with size and direction of symbol relating to the intensity and direction of magnetisation.

Theoretical models

A simple rectangular body is modelled in Figures 4 and 5. This body, of 0.003 susceptibility contrast, is 4 km wide, 2 km thick and, buried to a depth of 1 km. The interface model is assumed in both cases. The difference between them is that the body is situated at different magnetic latitudes, namely at inclinations of 30° and 60° respectively. Together, the two cases show that the technique is independent of magnetic latitude.

The technique defines the top corners of the bodies extremely well, as shown by the major clusters of estimates in Figures 4 and 5. However, the bottom corners are transparent to this method (and to most magnetic inversion methods). Note that outliers occur in both figures even though we

DEPTH ESTIMATES FOR A RECTANGULAR BODY
AT 30° MAGNETIC LATITUDE



THEORETICAL MODEL - RECTANGLE 30 DIP

FIG. 4

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are dealing with a simple theoretical curve. In practice, with many bodies and observed data, these outliers can disguise the true form of the magnetic basement. It is this aspect, of distinguishing between 'good' and 'bad' estimates, that is most difficult in the interpretation.

Aero Service example

A simulated geological cross-section is shown in Figures 6 and 7. This cross-section is similar to the example given in a publication by Aero Service (1974) and was chosen by the authors for comparison when testing the Werner deconvolution program. The cross-section simulates, from left to right in these figures, a reversely polarised vertical dyke, a normally polarised vertical dyke, a normally polarised dipping dyke, a suprabasement plate terminated by small normal faults, a graben with dipping faults (or contacts) on each side, and two vertical interfaces (or contacts) forming a 'well' in the basement. The theoretical anomaly was computed using a susceptibility of 0.001 for the main basement block, susceptibility contrasts of 0.001 for the dykes, and field parameters of 7°E declination, 60° inclination, and 60,000 nT total field.

Figure 6 displays the results using the interface model option in the Werner program. The top corners of the major interfaces on the graben and 'well' are reasonably well-defined, but the depth extents of these features are poorly expressed. Estimates over the minor features on the section, namely the dykes and small faults, are under-estimated: that is, the depths to the bodies are too shallow, and the clusters are more diffuse.

In Figure 7, the thin sheet model is used on the same anomaly profile. This gives better, although not outstanding, estimates over the minor features, and appears to outline the depth extent of the major interfaces.

As mentioned earlier, the method of display of the estimates is critical. For the data in Figures 6 and 7, if the estimates are plotted separately for each level of interpretation several points are noted. The first level including the depth range of the causative bodies gives the best estimates, and the scatter of the depth estimates increases with the higher levels of interpretation. Also the intensity of magnetisation tends to increase at higher levels and this may tend to mask the smaller and sometimes better estimates from the lower levels.

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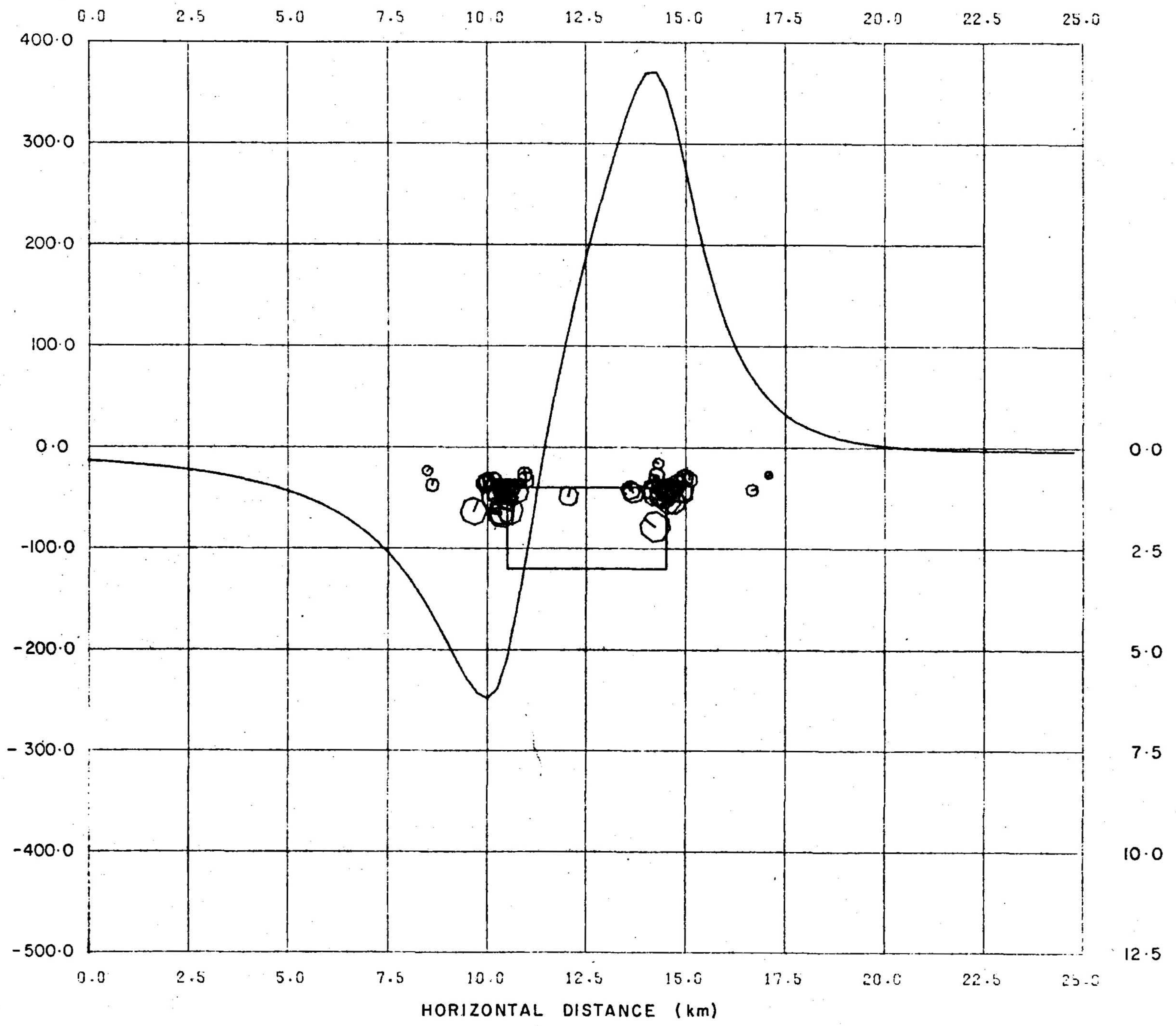
DEPTH ESTIMATES FOR A RECTANGULAR BODY AT 60° MAGNETIC LATITUDE

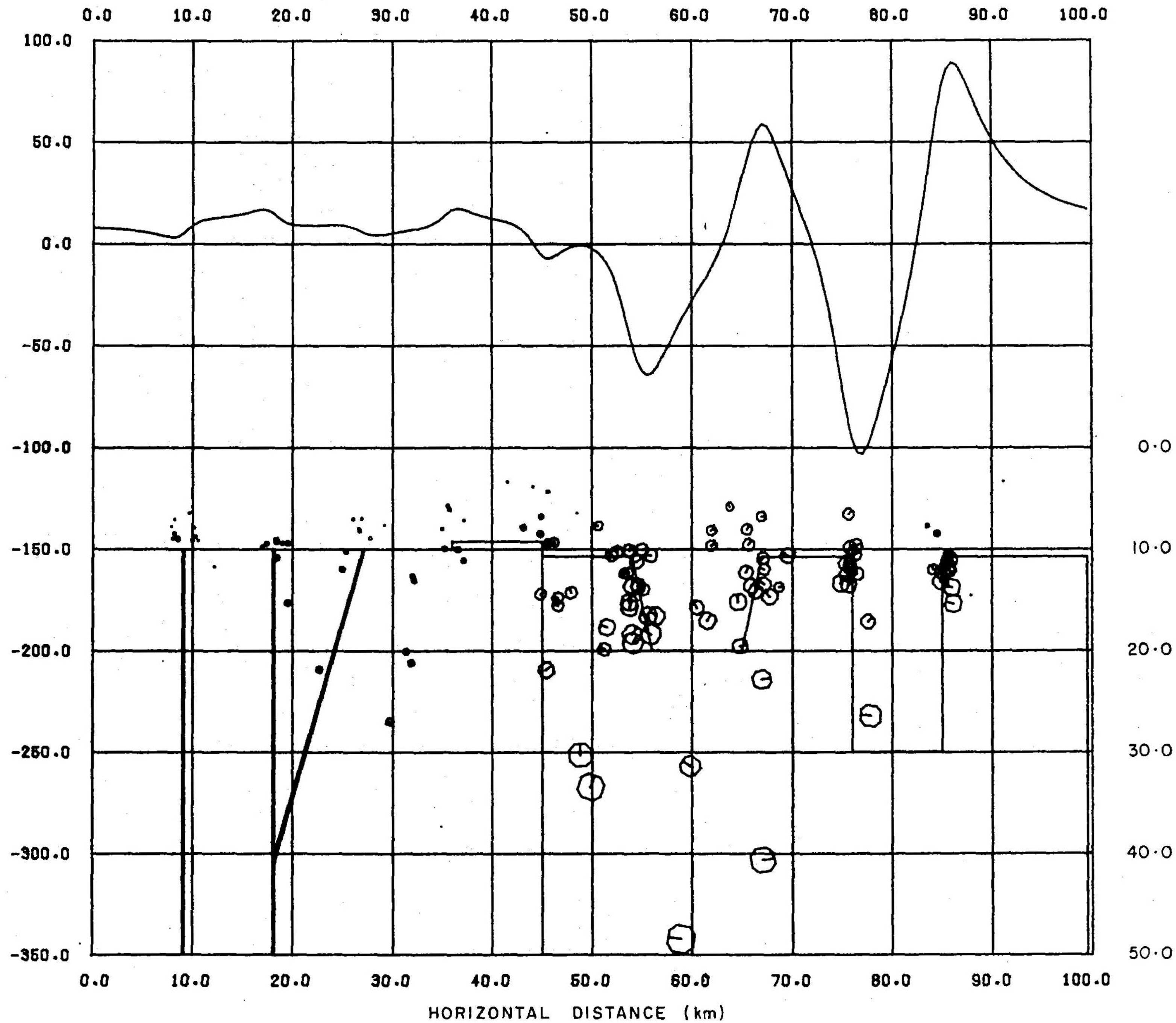


THEORETICAL MODEL - RECTANGLE 60 DIP

FIG. 5

G465-43A

DEPTH ESTIMATES FOR AERO SERVICE EXAMPLE — INTERFACE MODEL

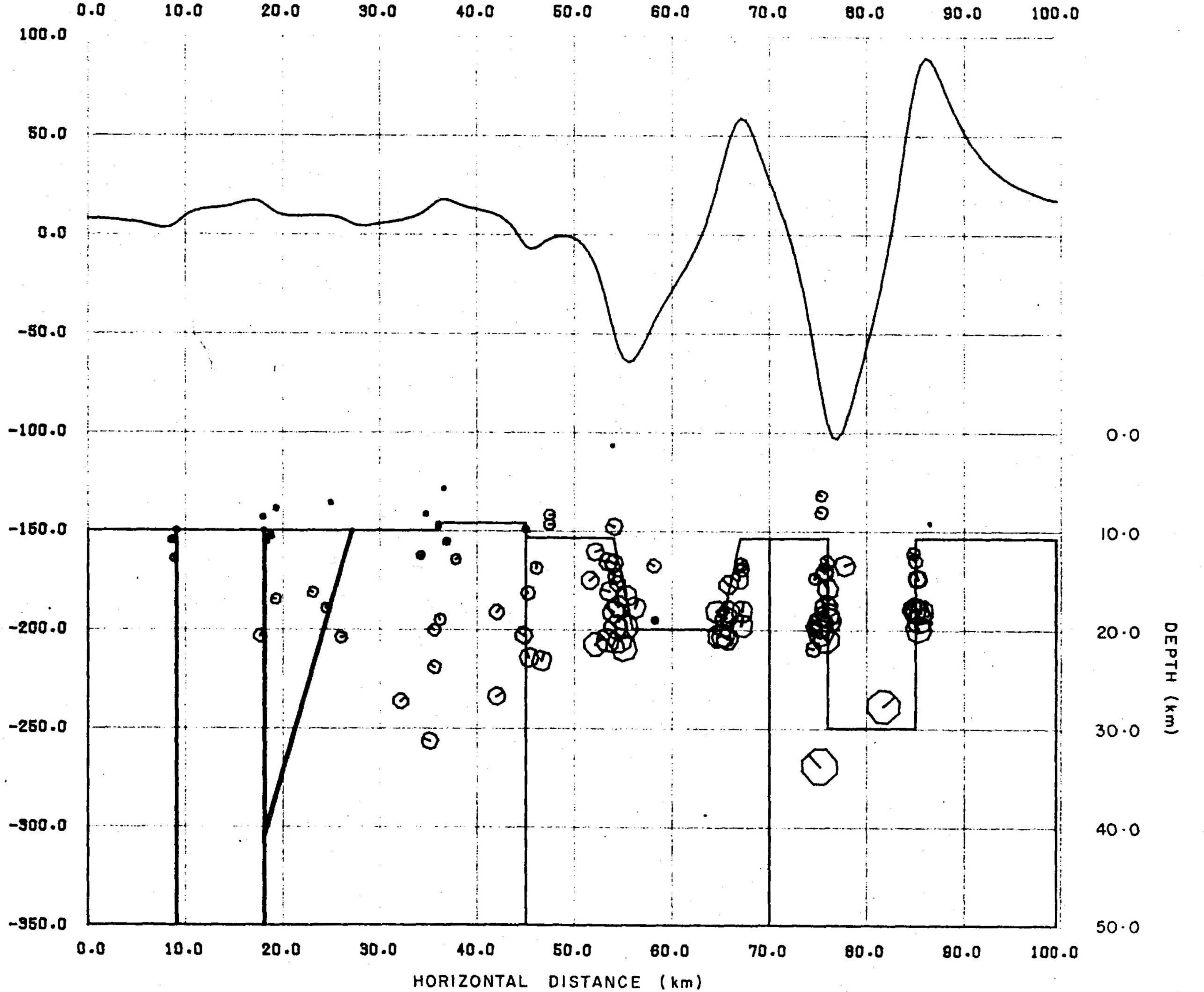


THEORETICAL MODEL - AERO SERVICE EXAMPLE

FIG. 6

G465-42A

DEPTH ESTIMATES FOR AERO SERVICE
EXAMPLE — THIN-SHEET MODEL



THEORETICAL MODEL - AERO SERVICE EXAMPLE

G465-41A

FIG. 7

Southern margin of Australia

A practical application of Werner deconvolution has been carried out on a marine magnetic profile across the southern margin of Australia. This traverse runs from south to north along longitude 132°40', and crosses the Ceduna Terrace and Polda Trough. Data have been projected onto a north-south baseline and then resampled at 0.25-km intervals - the approximate spacing of the original data. No correction for the diurnal variation has been made.

Results plotted in Figure 8 show the estimates calculated for levels 1 to 6 for the interface model option. A bathymetric profile is also plotted to aid in the interpretation. The observed magnetic trace is plotted at 50 nT/cm from the original one-minute data.

The shallow basement region is extremely well-defined. Basement gradually shallows northwards from 1.3 km at the shelf break to 0.5 km near the coast. Several disruptions occur in the estimated depths, especially in the vicinity of the Polda Trough between the 300 and 330 km mark on the profile. Here the good shallow estimates are absent, and weak sources between 2 and 4 km reflect the depth extent of the trough. In fact, the trough is a half graben normal-faulted on the northern margin and defined by a hinge line on the southern margin. Although the depth extent is poorly expressed, the estimates show the top corners of the interfaces, and possibly the faulting on the northern margin. The southern margin is not identifiable from these estimates.

South of the shelf break, the basement surface is ill-defined, except for several good point estimates. The major deepening of the basement surface from 1 to 10 km between 190 and 210 km is easily distinguishable. There is also an extremely good cluster at 12 km at the 160 km mark; seismic evidence indicates that this cluster arises from a basement high at this point. The basement surface drops to 14-15 km at about 180 km, rises to 12 km at 160 km, and then drops away again. This broad basement high gives rise to the anomaly shown in the profile.

Further south apparently there are no interpretable anomalies. This region is in the so-called Magnetic Quiet Zone. Small-intensity estimates may reflect small magnetic contrasts within the sedimentary sequence. On adjacent profiles, some of these diffuse clusters are in the region of faults, as defined by seismic data, which presumably have some igneous material associated with them. However, these small estimates are almost lost in the

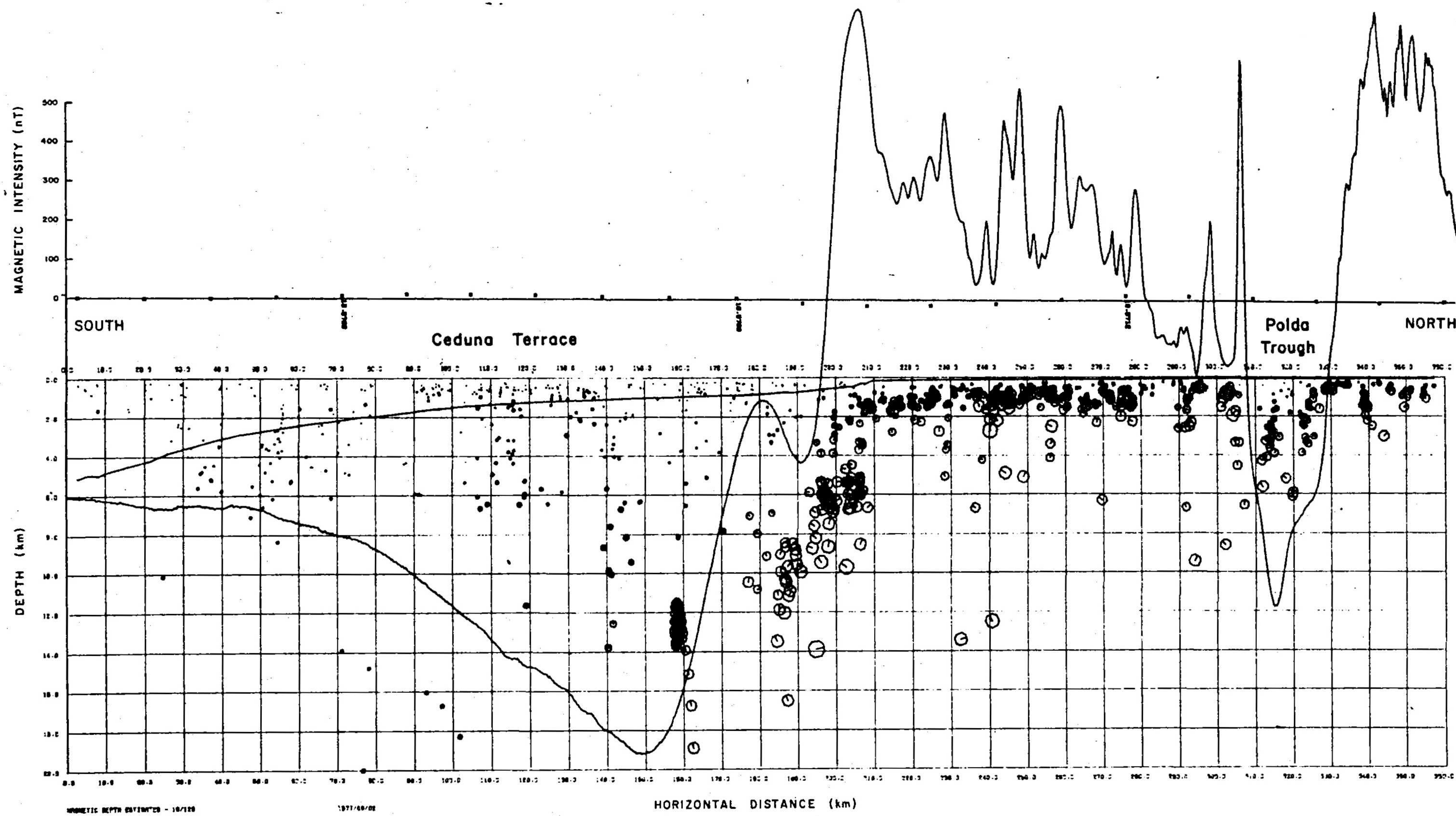


Fig.8

DEPTH ESTIMATES FOR A PROFILE

ACROSS THE SOUTHERN MARGIN OF AUSTRALIA

normal background 'noise' level of the estimates. The background 'noise' arises from several sources. It may arise from the mathematical technique as shown in the theoretical models where 'bad' estimates are found using a theoretical anomaly. It may also arise from the observed data which may be noisy and influenced by diurnal effects.

The sample line did not extend far enough south to encounter oceanic type anomalies. However, on the lines that do reach these anomalies, good estimates are obtained within 1 or 2 km of the seabed.

Results from the above examples show that the Werner deconvolution program is very useful for obtaining anomaly source estimates from magnetic profile data with minimal effort and time. Hence, it forms a useful building block in the development of an automatic magnetic interpretation system.

6. REFERENCES

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APPENDIX A

PROGRAM LISTING

```
      PROGRAM MAGINVT(TAPE10,TAPE1,TAPE30,INPUT,TAPE60=INPUT,OUTPUT)

C***        MAGINVT
C**         THIS PROGRAM PERFORMS A WERNER DECONVOLUTION TECHNIQUE ON
C**         MAGNETIC DATA TO PROVIDE MAGNETIC DEPTH ESTIMATES
C**         MODEL ADOPTED IS A DOUBLE SOURCE ON A QUADRATIC BACKGROUND
C**         TWO MODELS ARE AVAILABLE :
C**          (1) THIN SHEETS - ORIGINAL DATA USED IN ANALYSIS
C**          (2) INTERFACES     - HORIZONTAL DERIVATIVES USED IN ANALYSIS

C**         AUTHORS : L. TILBURY AND D. HSU

      DIMENSION ARRAY(12000),LABEL(8),METHOD(2)
      DIMENSION UPDATA(2000),POS(1000),DEP(1000),SS(1000),AS(1000)
      COMMON/REG/ DATAMAG(2000),HDERIV(2000),NPOINTS,NTOTAL,TRUEDIS,POS1
      COMMON/BASLINE/ STN1,STN2,RLAT1,RLONG1,RLAT2,RLONG2
      COMMON/LUN/ MTIN,MTOUT,MTSCR,LUNSCR,LUNDOC,LUNSAVE,LUNPLOT
      DATA (MTIN = 1),(MTOUT = 10),(LUNSCR = 30)

C*          READ INPUT MAGNETIC DATA LABEL,LOCATE - IF NOT FOUND STOP
   10 REWIND MTIN
      READ 20, LABEL
   20 FORMAT(8A10)
      IF (EOF(60))  190,30
   30 CALL LOOKUP(LABEL,MTIN,1,1,NFLAG)
      IF (NFLAG.EQ.1)  CALL ABORT

C*          READ MODEL TYPE - *INTERFACE     OR     *THIN SHEET
   40 NTYPE = 0
      READ 50, METHOD
   50 FORMAT(2A10)
      IF (EOF(60)) 190,60
   60 IF (METHOD.EQ.10H*INTERFACE)  NTYPE = 1
      IF (METHOD.EQ.10H*THIN SHEE)  NTYPE = 2
      IF (NTYPE.GT.0)  GO TO 80
      PRINT 70,METHOD
   70 FORMAT(10X,10(1H*),* INCORRECT CALLING SEQUENCE - CARD READ*,
     1 2X,1H*,A10,1H*)
      CALL ABORT

C*          READ START AND STOP LEVELS(LVF,LVS),SCANNING STEP(ISTEP),
C*          EXTRACTION INCREMENT(INC),MAGNETIC REGIONAL(CONST)
   80 READ 90, LVF,LVS,ISTEP,INC,CONST
   90 FORMAT(4I10,F10.0)

      IF (ISTEP.LE.0)  ISTEP = 2

C*          READ BASE LINE DATA - IF EOF CHECK FOR NEXT MODEL
  100 READ 110, STN1,STN2,LATD1,RLATM1,LONGD1,RLONGM1,
     1                    LATD2,RLATM2,LONGD2,RLONGM2,LINE
  110 FORMAT(2F10.0,4(I5,F6.2),A10)
      IF (EOF(60))  10,120

  120 RLAT1 = LATD1 + RLATM1/60.0
      RLONG1= LONGD1+ RLONGM1/60.0
      RLAT2 = LATD2 + RLATM2/60.0
      RLONG2= LONGD2+ RLONGM2/60.0

      PRINT 130, LABEL,LINE,STN1,STN2,INC,LVF,LVS,ISTEP,CONST,METHOD
  130 FORMAT(1H1,///,10X,*WERNER DECONVOLUTION FOR FILE *,1H*,8A10,1H*,
     1 /,10X,112(1H-),///,10X,*DATA EXTRACTED FOR LINE *,A10,*  BETWEEN
     2*,F11.6,* AND *,F11.6,//,
     3 10X,*EXTRACTION INCREMENT*,I5,*  MINUTES*,/,
     4 10X,*LEVELS                  *,I5,*  TO*,I3,/,
     5 10X,*SCANNING STEP           *,I5,/,
     6 10X,*REGIONAL CONSTANT       *,F10.0,/,
     7 10X,*MODEL ASSUMED           *,4X,2A10,//)

C*          INPUT THEORETICAL MAGNETIC DATA - IF APPLICABLE
      IF (LABEL(1).NE.10HTHEORETICA)  GO TO 140
      CALL READMOD(ARRAY,NODATA)
      GO TO 150

C*          INPUT MAGNETIC DATA
  140 CALL READATA(ARRAY,INC,NODATA)
  150 IF (NODATA.EQ.1)  GO TO 100

C*          INTERPOLATE TO REGULAR POSITIONS
      CALL REGULAR(ARRAY,INC)

      IF (NTYPE.NE.1)  GO TO 160

C*          COMPUTE HORIZONTAL DERIVATIVES IF INTERFACE MODEL REQUIRED
      NSTART = 1    $    DT = 1.0
      CALL HTDERVS(DATAMAG,HDERIV,DT,NSTART,NPOINTS)

C*          CALCULATE DEPTH ESTIMATES USING WERNER (INTERFACE)
      CALL WERNER(HDERIV,UPDATA,NPOINTS,TRUEDIS,POS1,ISTEP,LVF,LVS,
     1             POS,DEP,SS,AS,LUNSCR)
      GO TO 180

C*          SUBTRACT REGIONAL CONSTANT FROM ORIGINAL DATA IF THIN SHEET
C*          MODEL REQUIRED
  160 DO 170  I = 1,NPOINTS
      DATAMAG(I) = DATAMAG(I) - CONST
  170 CONTINUE

C*          CALCULATE DEPTH ESTIMATES USING WERNER (THIN SHEETS)
      CALL WERNER(DATAMAG,UPDATA,NPOINTS,TRUEDIS,POS1,ISTEP,LVF,LVS,
     1             POS,DEP,SS,AS,LUNSCR)

C*          OBTAIN TIME AND POSITIONS FOR DEPTH ESTIMATES (ONLY APPROX.)
  180 CALL DEPPOS(ARRAY,LINE,METHOD)

C*          READ NEXT BASE LINE CARD
      GO TO 100

  190 PRINT 200
  200 FORMAT(10X,10(1H$),* END OF WERNER DECONVOLUTION*)

      END
```

PROGRAM LISTING

PROGRAM MAGINVT

```
SUBROUTINE READATA    76/76    OPT=1                    FTN 4.6+439          15/09/77  14.06.50
```

```
      SUBROUTINE READATA(ARRAY,INC,NODATA)

C***       READATA
C**        THIS ROUTINE INPUTS DATA FROM STANDARD PHASE TWO TAPES AND
C**        SAVES TIME,POSITION,MAGNETIC AND BATHYMETRIC DATA BETWEEN
C**        TWO SPECIFIED TIMES

C**        ARRAY - ARRAY CONTAINING BASIC DATA
C**        INC   - EXTRACTION INCREMENT
C**        NODATA- SET TO 1 IF NO DATA FOUND

C**        ARRAY(1,N) - TIME
C**        ARRAY(2,N) - LATITUDE
C**        ARRAY(3,N) - LONGITUDE
C**        ARRAY(4,N) - MAGNETICS
C**        ARRAY(5,N) - PROJECTED DISTANCE (KMS)FROM BASE POINT
C**        ARRAY(6,N) - WATER DEPTH

      DIMENSION STORE(32,60),ARRAY(6,1)
      COMMON/REG/ DATAMAG(2000),MDERIV(2000),NPOINTS,NTOTAL,TRUEDIS,POS1
      COMMON/BASLINE/ STN1,STN2,RLAT1,RLONG1,RLAT2,RLONG2
      COMMON/LUN/ MTIN,MTOUT,MTSCR,LUNSCH,LUNDOC,LUNSAVE,LUNPLOT
      DATA (FIVESEC = 5.0E-8),(DUBIOUS = 1.0E9),(UNKNOWN = 1.0E10)
      DATA (NSTART = 0)

C*         COMPUTE PARAMETERS FOR PROJECTION OF DATA ONTO BASE LINE
      XKMS = 111.12   $   RADIAN = 57.2957795
      AVLAT = (RLAT1+RLAT2)/2.0
      ALPHA = COS(AVLAT/RADIAN)
      XN = - (RLAT2-RLAT1)*XKMS
      XE = (RLONG2-RLONG1)*ALPHA*XKMS
      THETA = ATAN2(XN,XE)
      COSROT = COS(THETA)   $   SINROT = SIN(THETA)

      L = 32   $   M = 60
      KOUNT = NODATA = 0
      NERROR = 0
      TSTART = STN1   $   TSTOP = STN2

      IF (NSTART.GT.0)  GO TO 50
   10 BUFFER IN (MTIN,1)  (STORE(1,1),STORE(L,M))
      IF (UNIT(MTIN)) 40,90 ,20
   20 PRINT 30, STORE(1,1),STORE(1,M)
   30 FORMAT(/,10X,10(1H*),10X,*PARITY ERROR BETWEEN*,F11.6,*AND *,
     1 F11.6)

C*         SKIP BLOCK IF OUTSIDE REQUIRED TIMES
   40 NSTART = 1
   50 IF (TSTART.GT.STORE(1,M)+FIVESEC)  GO TO 10
      IF (TSTOP.LT.STORE(1,1)-FIVESEC)  GO TO 90

C*         LOOP THROUGH BLOCK EXTRACTING VALUES AT NOMINATED INCREMENT
C*         SKIP INDIVIDUAL POINTS IF OUTSIDE REQUIRED TIME
      DO 80   J = 1,60,INC
      IF (TSTART.GT.STORE(1,J)+FIVESEC)  GO TO 80
      IF (TSTOP.LT.STORE(1,J)+FIVESEC)  GO TO 90
      IF (KOUNT.GE.2000)  GO TO 100
C*         SKIP IF POSITION DATA IS UNKNOWN
      IF (STORE(27,J).GT.DUBIOUS)  GO TO 80

C*         PLACE REQUIRED PARAMETERS IN "ARRAY"
      KOUNT = KOUNT+1
      ARRAY(1,KOUNT) = STORE(1,J)
      ARRAY(2,KOUNT) = STORE(27,J)
      ARRAY(3,KOUNT) = STORE(28,J)
      ARRAY(6,KOUNT) = STORE(12,J)

C*         SUBTRACT DIURNAL FROM MAGNETIC VALUE
      IF (STORE(14,J).LT.DUBIOUS.AND.STORE(13,J).LT.DUBIOUS)  GO TO 60
      ARRAY(4,KOUNT) = UNKNOWN
      NERROR = NERROR + 1
      GO TO 70
   60 ARRAY(4,KOUNT) = STORE(14,J) - STORE(13,J)

C*         CALCULATE DISTANCE ALONG BASE LINE IN KMS
   70 X =  (STORE(28,J) - RLONG1)*ALPHA
      Y = -(STORE(27,J) - RLAT1)
      XX = X*COSROT + Y*SINROT
      YY = -X*SINROT + Y*COSROT
      ARRAY(5,KOUNT) = XX*XKMS

   80 CONTINUE

      GO TO 10

C*         RETURN NODATA EQUAL TO 1 IF NO DATA FOUND
   90 IF (KOUNT.EQ.0)  NODATA = 1
  100 NTOTAL = KOUNT
      IF (NODATA.EQ.0)  PRINT 110, NTOTAL
  110 FORMAT(10X,10(1H*),10X,*TOTAL OF*,I10,*  RECORDS SAVED IN READATA*
     1 ,//)

      IF (NERROR.GT.0)  PRINT 120, NERROR
  120 FORMAT(10X,10(1H*),10X,*TOTAL NUMBER OF UNKNOWN VALUES*,I10,//)

      RETURN

      END
```

32

SUBROUTINE REGULAR 76/76 OPT=1 FTN 4.6+439 15/09/77 14.06.50

```
      SUBROUTINE REGULAR(ARRAY,INC)

C***      REGULAR
C**       THIS SUBROUTINE RESAMPLES MAGNETIC DATA AT REGULAR DISTANCES

C**       ARRAY - ARRAY CONTAINING BASIC DATA
C**       INC   - EXTRACTION INCREMENT
C**       ARRAY(1,N) - TIME
C**       ARRAY(2,N) - LATITUDE
C**       ARRAY(3,N) - LONGITUDE
C**       ARRAY(4,N) - MAGNETICS
C**       ARRAY(5,N) - PROJECTED DISTANCE (KMS)FROM BASE POINT
C**       ARRAY(6,N) - WATER DEPTH

      DIMENSION ARRAY(6,1)
      COMMON/REG/ DATAMAG(2000),MDERIV(2000),NPOINTS,NTOTAL,TRUEDIS,POS1
      DATA (SMALL = 1.0E-6)

C*        CALCULATE SAMPLING INCREMENT AS A FUNCTION OF EXTRACTION INC,
C*        ONE MINUTE IS EQUIVALENT TO 0.25 KM (APPROX)
      KOUNT = 0
      SPACE = INC*0.25
      TRUEDIS = SPACE
      IF (ARRAY(5,1).GT.ARRAY(5,NTOTAL))  SPACE = -SPACE
      POSN = INT(ARRAY(5,1))
      POS1 = POSN

C*        LOOP THROUGH TOTAL NUMBER OF DATA VALUES, INTERPOLATE VALUES
C*        AT REGULAR DISTANCES
      DO 70   I = 2,NTOTAL

   10 IF (SPACE.GT.0.0)  GO TO 20
C*        INTERPOLATION TEST FOR DECREASING DISTANCES
      IF (POSN.GT.ARRAY(5,I-1))  GO TO 60
      IF (POSN.LT.ARRAY(5,I))   GO TO 70
      GO TO 30
C*        INTERPOLATION TEST FOR INCREASING DISTANCES
   20 IF (POSN.LT.ARRAY(5,I-1))  GO TO 60
      IF (POSN.GT.ARRAY(5,I))   GO TO 70

   30 KOUNT = KOUNT + 1
      DX = ARRAY(5,I) - ARRAY(5,I-1)
      IF (DX.GT.SMALL)  GO TO 40
      FRACTN = 0.0
      GO TO 50
   40 FRACTN = (POSN - ARRAY(5,I-1))/DX
   50 DATAMAG(KOUNT) = ARRAY(4,I-1) + FRACTN*(ARRAY(4,I)-ARRAY(4,I-1))

   60 POSN = POSN + SPACE
      GO TO 10

   70 CONTINUE

C*         SAVE AND PRINT NUMBER OF INTERPOLATED POINTS
      NPOINTS = KOUNT
      PRINT 80 , NPOINTS
   80 FORMAT(10X,10(1HS),10X,*TOTAL OF*,I10,*  RECORDS INTERPOLATED*,//)

      RETURN

      END
```

SUBROUTINE READMOD 76/76 OPT=1 FTN 4.6+439 15/09/77 14.06.50

```
      SUBROUTINE READMOD(ARRAY,NODATA)
C***      READMOD
C**       THIS ROUTINE INPUTS A BUFFERRED BLOCK OF THEORETICAL DATA
C**       PRODUCED IN MAG2D

C**       ARRAY - ARRAY CONTAINING BASIC DATA
C**       NODATA- SET TO 1 IF NO DATA FOUND

C**       ARRAY(1,N) - TIME
C**       ARRAY(2,N) - LATITUDE
C**       ARRAY(3,N) - LONGITUDE
C**       ARRAY(4,N) - MAGNETICS
C**       ARRAY(5,N) - PROJECTED DISTANCE (KMS)FROM BASE POINT
C**       ARRAY(6,N) - WATER DEPTH

      DIMENSION ARRAY(6,1)
      COMMON/REG/ DATAMAG(2000),MDERIV(2000),NPOINTS,NTOTAL,TRUEDIS,POS1
      COMMON/BASLINE/ STN1,STN2,RLAT1,RLONG1,RLAT2,RLONG2
      COMMON/LUN/ MTIN,MTOUT,MTSCR,LUNSCR,LUNDOC,LUNSAVE,LUNPLOT
      COMMON/MAG2D/ L,DX,XORIGIN,HEIGHT,DEVN,DATA(6,1000)
      DATA (FIVESEC = 5.0E-8),(DUBIOUS = 1.0E9),(UNKNOWN = 1.0E10)

      KOUNT = 0
   10 BUFFER IN (MTIN,1)  (L,DATA(6,1000))
      IF (UNIT(MTIN)) 40,70 ,20
   20 PRINT 30, ARRAY(1,1),ARRAY(1,L)
   30 FORMAT(/,10X,10(1H*),10X,*PARITY ERROR BETWEEN*,F11.6,*AND *,
     1 F11.6)


C*        TRANSFER INPUT ARRAY TO WORK ARRAY
   40 DO 60   J = 1,L
      DO 50  I = 1,6
      ARRAY(I,J) = DATA(I,J)
   50 CONTINUE
   60 CONTINUE
      KOUNT = L


C*        RETURN NODATA EQUAL TO 1 IF NO DATA FOUND
   70 IF (KOUNT.EQ.0)  NODATA = 1
      NTOTAL = KOUNT
      IF (NODATA.EQ.0)  PRINT 80 , NTOTAL
   80 FORMAT(10X,10(1HS),10X,*TOTAL OF*,I10,*  RECORDS SAVED IN READMOD*
     1 ,//)

      RETURN

      END
```

```
      SUBROUTINE DEPPOS(ARRAY,LINE,METHOD)

C***     DEPPOS
C**      THIS SUBROUTINE ASSOCIATES BASIC DATA (TIME ETC) WITH THE
C**      CALCULATED DEPTH ESTIMATES BY INTERPOLATING DISTANCES
C**      WITHIN THE BASIC DATA ARRAY
C**      DATA IS ONLY FOUND TO THE NEAREST MINUTE

C**      ARRAY - ARRAY CONTAINING BASIC DATA
C**      LINE - DESCRIPTOR FOR LINE

C**      ARRAY(1,N) - TIME
C**      ARRAY(2,N) - LATITUDE
C**      ARRAY(3,N) - LONGITUDE
C**      ARRAY(4,N) - MAGNETICS
C**      ARRAY(5,N) - PROJECTED DISTANCE (KMS)FROM BASE POINT
C**      ARRAY(6,N) - WATER DEPTH

      DIMENSION ARRAY(6,1),LABEL(8),METHOD(2)
      COMMON/REG/ ESTMATE(4,1000),NPOINTS,NTOTAL,TRUEDIS,POS1
      COMMON/LUN/ MTIN,MTOUT,MISCR,LUNSCR,LUNDOC,LUNSAVE,LUNPLOT

      REWIND LUNSCR

C*       CONSTRUCT AND OUTPUT FILE LABEL
      CALL TODAY(IDATE)
      ENCODE(80,10,LABEL(1))  LINE,METHOD,IDATE
   10 FORMAT(*MAGNETIC DEPTH ESTIMATES - LINE *,A10,*  MODEL *,3A10)
      WRITE(MTOUT,40)  LABEL
      PRINT 20, LABEL
   20 FORMAT(//,10X,1H*,8A10,1H*)

C*       READ AND OUTPUT SUBFILE HEADER
   30 KOUNT = 0
      READ(LUNSCR,40)  LABEL
   40 FORMAT(8A10)
      IF(EOF(LUNSCR)) 180,50
   50 IF(IOCHEC(LUNSCR)) 60,60
   60 WRITE(MTOUT,40)  LABEL
      PRINT 20, LABEL

C*       READ ESTIMATES UP TO EOF - IE FOR ONE LEVEL AT ONE OFFSET
   70 KOUNT = KOUNT + 1
      READ (LUNSCR,80)  (ESTMATE(I,KOUNT),I=1,4)
   80 FORMAT(10X,4F15.4)
      IF (EOF(LUNSCR)) 100,90
   90 IF (IOCHEC(LUNSCR)) 70,70

C*       WORK OUT DIRECTION OF INTERPOLATION (UP OR DOWN)
  100 KOUNT = KOUNT - 1
      DIRECT = 1.0
      IF (ARRAY(5,1).GT.ARRAY(5,NTOTAL))  DIRECT = -1.0
      PRINT 110, KOUNT
  110 FORMAT(/,10X,*NUMBER OF ESTIMATES*,I5,/)

C*       SORT ESTIMATES INTO INCREASING DISTANCE ORDER
      CALL ARRANGE(ESTMATE,4,KOUNT,2,1,KOUNT)

C*       LOOP THROUGH FOR EACH ESTIMATE, SEARCHING BASIC DATA ARRAY
C*       FOR NEAREST VALUE (ONE DIRECTION ONLY)
C***     REVERSE INTERPOLATION WONT WORK
      ISTART = 1
      DO 170  J = 1,KOUNT
      DO 160  I = ISTART,NTOTAL
      ISTART = I
C*       JUMP TO CORRECT INTERPOLATION DIRECTION
      IF (DIRECT.GT.0.0)  GO TO 120
      IF (ESTMATE(1,J).LT.ARRAY(5,I))     GO TO 160
      GO TO 130
  120 IF (ESTMATE(1,J).GT.ARRAY(5,I))     GO TO 160

C*       SET BASIC DATA VALUES FOR ESTIMATES
  130 TIME = ARRAY(1,I)
      LATD = ARRAY(2,I)
      RLATM = (ARRAY(2,I) - LATD)*60.0
      LONGD = ARRAY(3,I)
      RLONGM = (ARRAY(3,I) - LONGD)*60.0
      WD = ARRAY(6,I)

C*       SAVE AND PRINT BASIC DATA AND ESTIMATES
      WRITE(MTOUT,140) TIME,LATD,RLATM,LONGD,RLONGM,WD,
     1                 (ESTMATE(K,J),K=1,4)
  140 FORMAT(F10.6,2(I4,F6.2),F10.0,4F10.2)
      PRINT 150, TIME,LATD,RLATM,LONGD,RLONGM,WD,(ESTMATE(K,J),K=1,4)
  150 FORMAT(10X,F10.6,2(I4,F6.2),F10.0,4F10.2)
      GO TO 170
  160 CONTINUE

  170 CONTINUE

C*       CLOSE OUTPUT SUBFILE AND GO TO READ NEXT SET OF ESTIMATES
      ENDFILE MTOUT
      GO TO 30

C*       AT END OF LINE, CLOSE FILE AND PRINT MESSAGE
  180 PRINT 190
  190 FORMAT(//,10X,10(1H$),10X,*END OF POSITION INTERPOLATION*,//)
      ENDFILE MTOUT

      RETURN

      END
```

```
      SUBROUTINE WERNER(DATA,UPDATA,NPOINTS,TRUEDIS,POSAVE,ISTEP,LVF,
     1  LVS,POS,DEP,SS,AS,LUNSCR)

      DIMENSION DATA(1),UPDATA(1),POS(1),DEP(1),SS(1),AS(1)
      DIMENSION A(11,11),C(11,1),T(11),TS(15),P(101),S(10),FT(10)
      DATA (SMALL = 1.0E-6),(PA= 57.29578),(DT=1.0),(NTH=6),(NOD=51)

      REWIND LUNSCR

   10 LVL=LVF-1

C*         SET LEVEL OF ANALYSIS , LVL
   20 LVL=LVL+1

C*         IF NO MORE LEVEL, SAVE RESULTS- THEN RETURN
      IF(LVL.GT.LVS) RETURN

C*         SET SAMPLE INTERVAL
      LV=LVL-1
      INV=2**LV
      DLC=LV*INV/LVL
      AIN=0
      NOC=(INV-1)*6+1   $  NC=(INV-1)*3+1
      NCS=NC
      NLT=NPOINTS-NC+1
C*         SET HEIGHT OF UPWARD CONTINUATION
      ZL=INV   $  IF(LVL.EQ.1) ZL=0.

C*         CALL UPCONT TO UPWARD CONTINUE DATA
      CALL UPCONT(NOC,DATA,UPDATA,DT,ZL,NC,NLT)

   30 NS=0 $ JN=-ISTEP
C*         SHIFT SAMPLE ARRAY ACROSS PROFILE
   40 JN=JN+ISTEP
      NX=NCS+JN
      NL=NX+INV*10
      IF(NL.GT.NLT) GO TO 200
C*         SAMPLE PROFILE
      DO 50  J=1,11
      JJ=NX+(J-1)*INV
      T(J) = UPDATA(JJ)
   50 CONTINUE
C*         GENERATE ELEMENTS IN LINEAR EQUATION MATRIX
      DO 70  I=1,11
      X=I-NTH
      TS(4)=T(I)
      TS(3)=T(I)*X
      TS(2)=TS(3)*X
      TS(1)=TS(2)*X
      TS(5)=X*X
      TS(6)=X
      TS(7)=1.
      TS(8)=X**3
      TS(9)=X**4
      TS(10)=TS(9)*X
      TS(11)=TS(10)*X
      C(I,1)=TS(1)*X
      DO 60  J=1,11
   60 A(I,J)=TS(J)
   70 CONTINUE

      N=11 $ L=1

C*          CALL MATRIX TO OBTAIN SOLUTIONS(IN C)
      CALL MATRIX(A,N,C,L,DET,IRR)
      IF(IRR.EQ.1) GO TO 40
C*         COMPUTE THE COEFFICIENTS OF QUADRATIC INTERFERENCE
      BG2=-C(11)
      BG1=-C(10)-C(11)*C(1)
      BK0=-C(9)+BG1*C(1)-C(11)*C(2)

C*         SOLVE UNKNOWNS FOR ONE OR TWO SOURCES  - POSITION  - DEPTH
   80 C(1)=C(1)*0.5
      C(2)=-C(2)
      C(3)= C(3)*0.5
      C(4)=-C(4)

C*         SOLVE  X BY SEARCHING FOR ZERO-CROSSING OF P(X).
      DO 90  I=21,81
      X=0.1*(I-NOD)
      Y=C(1)-X
      W=C(2)*Y-4.*X*Y*Y-C(3)
      V=C(2)*X-4.*X*X*Y-C(3)
      U=C(4)*(X-Y)*(X-Y)
      P(I) = U+V*W
   90 CONTINUE
      MR=0
      DO 110 I=21,81
      IF(P(I).EQ.0.0) GO TO 100
      FR=P(I+1)*P(I)
      IF(FR.GE.0.0) GO TO 110
  100 MR=MR+1
      S(MR)=0.1*(I-NOD)-0.1*P(I)/(P(I+1)-P(I))
  110 CONTINUE

C*         IF NO SOLUTION OF POLYNOMIAL P(X) JUMP TO NEXT WINDOW POSITION
      IF (MR.EQ.0)  GO TO 40

C*         LOOP AROUND FOR NUMBER OF ROOTS MR
      DO 250 M=1,MR
      X = S(M)
      Y=C(1)-X
      CX=ZX=WXS=CY=ZY=WYS=999999.
      XYS=(X-Y)*(X-Y)
      IF(XYS.LT.SMALL) GO TO 120
      WX=(C(2)*X-4.*X*X*Y-C(3))/(X-Y)
      WY=(C(2)*Y-4.*X*Y*Y-C(3))/(Y-X)
      GO TO 130
  120 CS=C(2)-4.*X*Y
      RS=CS*CS-4.*C(4)
      IF(RS.LT.SMALL) GO TO 150
      WX=(CS+SQRT(RS))/2.
      WY=(CS-SQRT(RS))/2.
  130 YS=Y*Y
      XS=X*X
      IF(WX.LT.XS) GO TO 140
      WXS=SQRT(WX)
      ZS=WX-XS
      ZX=SQRT(ZS)
  140 IF(WY.LT.YS) GO TO 150
      WYS=SQRT(WY)
      ZS=WY-YS
      ZY=SQRT(ZS)
  150 CONTINUE
```

SUBROUTINE WERNER PART I

35

```
C*        CHECK IF ONE OR TWO SOURCES HAVE BEEN DETECTED.

C*            DETERMINE INTENSITY AND ANGLE OF MAGNETIZATION
C*            BY LEAST SQUARE FITTING.
      LF=1  $  LL=4
      IF(ZY.EQ.999999.) LF=1
      IF(ZY.EQ.999999.) LL=2
      IF(ZX.EQ.999999.) LF=3
      IF(ZX.EQ.999999.) LL=4
      DO 160 I=1,11
      C(I,1)=0.
      DO 160 J=1,11
      A(I,J) = 0.0
  160 CONTINUE
      DO 180 I=1,11
      XN=I-NTH
      XA=XN-X
      XB=XN-Y
      DX=XA*XA+ZX*ZX
      DY=XB*XB+ZY*ZY
      TS(1)=ZX/DX
      TS(2)=XA/DX
      TS(3)=ZY/DY
      TS(4)=XB/DY
      TF=T(I)+BKG+BG1*XN+BG2*XN*XN
      DO 170 J=LF,LL
      C(J,1)=C(J,1)+TF*TS(J)
      DO 170 K=LF,LL
  170 A(K,J)=A(K,J)+TS(J)*TS(K)
  180 CONTINUE

      NN=LL-LF+1
      DO 190 I=1,NN
      DO 190 J=1,NN
  190 A(J,I)=A(J+LF-1,I+LF-1)

C*            CALL MATRIX TO OBTAIN SOLUTIONS
      CALL MATRIX(A,NN,BB,0,DET,IRR)
      IF(IRR.EQ.1)  GO TO 250
      DO 200 L=LF,LL
      DO 200 K=LF,LL
  200 A(K,L)=A(K-LF+1,L-LF+1)
      DO 210 L=1,4
  210 FT(L)=0.

      DO 220 L=LF,LL
      DO 220 K=LF,LL
  220 FT(L)=FT(L)+A(K,L)*C(K,1)

C*          CHECK SOLUTIONS, IF UNFIT, REJECT THEM
      STS=0.
      STH=0.
      DO 230 N=1,11
      XN=N-NTH
      XA=XN-X
      XB=XN-Y
      TAA=(FT(4)*XB+FT(3)*ZY)/(XB*XB+ZY*ZY)
      TH=(FT(2)*XA+FT(1)*ZX)/(XA*XA+ZX*ZX)+TAA
      BK=BKG+BG1*XN+BG2*XN*XN
      TDT = T(N) - TH + BK
      TB = TDT + TH
      STH = STH + TB**2
      STS = STS + TDT**2
  230 CONTINUE

      STT=SQRT(STS)
      SHS=SQRT(STH)
      EPC=STT/SHS*100.
      IF(EPC.GT.10.0)  GO TO 250
C*          CHECK RANGE OF DEPTH AND POSITION, IF OUTSIDE, REJECT IT
      XT=(3.-X)*(X+3.)
      YT=(3.-Y)*(Y+3.)
      IF(XT.LT.0..OR.ZX.GT.4.5) GO TO 240

C*          CONVERT POSITION, DEPTH, INTENSITY AND ANGLE INTO TRUE VALUES
C*          FOR SOURCE 1.
      DPT=ZX*INV-ZL
      IF(DPT.LT.DLC) GO TO 240
      NS=NS+1
      IF(NS.GT.1000) GO TO 260
      DEP(NS) = DPT*TRUEDIS
      POS(NS) = (NX-1+(X+5)*INV)*TRUEDIS + POSAVE
      SQ=FT(1)*FT(1)+FT(2)*FT(2)
      SS(NS)=SQRT(SQ)*INV
      IF(FT(1).EQ.0.0) FT(1)=0.000001
      AR=FT(2)/FT(1)
      AS(NS)=ATAN(AR)*PA
  240 IF(YT.LT.0..OR.ZY.GT.4.5) GO TO 250
C*          FOR SOURCE 2.
      DPT=ZY*INV-ZL
      IF(DPT.LT.DLC) GO TO 250
      NS=NS+1
      IF(NS.GT.1000) GO TO 260
      DEP(NS) = DPT*TRUEDIS
      POS(NS) = (NX-1+(Y+5)*INV)*TRUEDIS + POSAVE
      SQ=FT(3)*FT(3)+FT(4)*FT(4)
      SS(NS)=SQRT(SQ)*INV
      IF(FT(3).EQ.0.0) FT(3)=0.000001
      AR=FT(4)/FT(3)
      AS(NS)=ATAN(AR)*PA
  250 CONTINUE

C*          JUMP TO START FOR NEXT WINDOW POSITION
      GO TO 40

  260 PRINT 270
  270 FORMAT(10X,10(1H*),* ARRAY LIMITS EXCEEDED FOR : POS, DEP AS, SS*)

C*          IF NO SOURCES JUMP TO START FOR NEXT LEVEL
  280 IF (NS.LE.0)  GO TO 20

C*          WRITE ESTIMATED SOURCES ONTO LUNSCR
      JNTOT=JN/ISTEP
      WRITE(LUNSCR,290)  LVL,JNTOT
  290 FORMAT(*DEPTH ESTIMATES - LEVEL*,I2,* NUMBER OF SCANS*,I5,30(1H ))
      DO 310 I=1,NS
      WRITE(LUNSCR,300)  POS(I),DEP(I),AS(I),SS(I)
  300 FORMAT(10X,4F15.4)
  310 CONTINUE
      ENDFILE LUNSCR

C*          JUMP TO START FOR NEXT LEVEL
      GO TO 20

  320 RETURN

      END
```

SUBROUTINE MATRIX 74/74 OPT=1 FTN 4.6+439 15/09/77 14.06.58

```
      SUBROUTINE MATRIX(A,N,B,L,D,IRROR)
C***      MATRIX
C**       SPECIAL VERSION OF MATINV FOR WERNER DECONVOLUTION

C**       A IS AN NXN MATRIX TO BE INVERTED, OR CONTAINING EQUATION COEF
C**       B IS AN NXM RHS MATRIX FOR EQUATIONS
C**       IF L=0,INVERSE ONLY GIVEN,L POSITIVE,SOLUTIONS ONLY,L NEGATIVE
C**       BOTH,   M=ABS(L).
C**       D CONTAINS THE DETERMINANT OF THE A MATRIX ON EXIT
C**       A IS REPLACED BY THE INVERSE ,B BY THE SOLUTIONS.
C**       METHOD OF GAUSS-JORDON PIVOTAL ELIMINATION

      DIMENSION A(11,11),B(11,1),IPIV(11),IND(11,2)

      M=IABS(L)
      D=1.0
      DO 10 I=1,N
   10 IPIV(I)=0

      DO 220 I=1,N
      AMAX=0.0

C*        SEARCH SUB-MATRIX FOR LARGEST ELEMENT AS PIVOT
      DO  60 J=1,N
      IF(IPIV(J)) 70,20,60
   20 DO  50 K=1,N
      IF(IPIV(K)-1) 30,50,70

C*        THIS ROW COLUMN HAS NOT BEEN A PIVOT
   30 IF(ABS (A(J,K))-AMAX) 50,50,40
   40 IROW=J
      ICOL=K
      AMAX=ABS (A(J,K))
   50 CONTINUE
   60 CONTINUE

C*        PIVOT FOUND
      IPIV(ICOL)=IPIV(ICOL)+1
      IF(AMAX-1.0E-90 ) 70,70,80

C*        MATRIX SINGULAR,ERROR RETURN
   70 IRROR=1
      RETURN

   80 IF(IROW-ICOL) 90,130,90

C*        MAKE PIVOT A DIAGONAL ELEMENT BY ROW INTERCHANGE.
   90 D=-D
      DO 100 K=1,N
      AMAX=A(IROW,K)
      A(IROW,K)=A(ICOL,K)
  100 A(ICOL,K)=AMAX
      IF (M) 130,130,110
  110 DO 120 K=1,M
      AMAX=B(IROW,K)
      B(IROW,K)=B(ICOL,K)
  120 B(ICOL,K)=AMAX
  130 IND(I,1)=IROW
      IND(I,2)=ICOL
      AMAX=A(ICOL,ICOL)
      D=D*AMAX
      A(ICOL,ICOL)=1.0

C*        DIVIDE PIVOT ROW BY PIVOT
      DO 140 K=1,N
  140 A(ICOL,K)=A(ICOL,K)/AMAX
      IF(M) 170,170,150
  150 DO 160 K=1,M
  160 B(ICOL,K)=B(ICOL,K)/AMAX

C*        REDUCE NON-PIVOT ROWS
  170 DO 220 J=1,N
      IF(J-ICOL) 180,220,180
  180 AMAX=A(J,ICOL)
      A(J,ICOL)=0.0
      DO 190  K=1,N
  190 A(J,K)=A(J,K)-A(ICOL,K)*AMAX
      IF(M)  220,220,200
  200 DO  210 K=1,M
  210 B(J,K)=B(J,K)-B(ICOL,K)*AMAX
  220 CONTINUE

C*        AFTER N PIVOTAL CONDENSATIONS,SOLUTIONS LIE IN B MATRIX
      IF(L) 230,230,270

C*        FOR INVERSE OF A, INTERCHANGE COLUMNS
  230 DO 260 I=1,N
      J=N+1-I
      IF(IND(J,1)-IND(J,2)) 240,260,240
  240 IROW=IND(J,1)
      ICOL=IND(J,2)
      DO 250  K=1,N
      AMAX=A(K,IROW)
      A(K,IROW)=A(K,ICOL)
  250 A(K,ICOL)=AMAX
  260 CONTINUE

  270 IRROR=0

      RETURN

      END
```

SUBROUTINE MATRIX

SUBROUTINE HTDERVS   76/76   OPT=1   FTN 4.6+439   15/09/77 14.06.50

```
      SUBROUTINE HTDERVS(TM,DXM,DT,NSL,NSU)
C***      HTDERVS
C**       THIS SUBROUTINE COMPUTES HORIZONTAL DERIVATIVES FOR
C**       EQUI-SPACED POTENTIAL DATA
C**       TM  - ARRAY ON WHICH HORIZONTAL DERIVATIVES ARE CALCULATED
C**       DXM - HORIZONTAL DERIVATIVE ARRAY
C**       DT  - DATA UNIT (ALWAYS EQUAL TO 1.0)
C**       NSL - NUMBER OF STARTING DATA POINT (USUALLY 1)
C**       NSU - NUMBER OF END DATA POINT (USUALLY NPOINTS)
      DIMENSION TM(1),DXM(1)
      NSN=NSL+2
      NSS=NSU-2
C*        COMPUTE HORIZONTAL DERIVATIVES
C*        FOR FIRST POINT
      DXM(NSL)=(TM(NSL+1)-TM(NSL))/DT
C*        FOR SECOND POINT
      DXM(NSL+1) =(-TM(NSL)/3.-TM(NSL+1)/2.+TM(NSL+2)-TM(NSL+3)/6.)/DT
C*        FOR SECOND LAST POINT
      DXM(NSU-1)=(-TM(NSU-3)/3.-TM(NSU-2)/2.+TM(NSU-1)-TM(NSU)/6.)/DT
C*        FOR LAST POINT
      DXM(NSU)=(TM(NSU)-TM(NSU-1))/DT
C*        FOR ALL INTERNAL POINTS
      DO 10  I=NSN,NSS
      DX=TM(I-2)/6.-4.*TM(I-1)/3.-TM(I+2)/6.+4.*TM(I+1)/3.
   10 DXM(I)=DX/(2.*DT)
      RETURN
      END
```

SUBROUTINE UPCONT   76/76   OPT=1   FTN 4.6+439   15/09/77 14.06.50

```
      SUBROUTINE UPCONT(NOC,DM,TM,DT,ZL,NSL,NSU)
C***      UPCONT
C**       THIS SUBROUTINE UPWARD CONTINUES EQUI-SPACED POTENTIAL DATA
C**       NOC - LENGTH OF UPWARD CONTINUATION FILTER
C**       DM - INPUT DATA ARRAY
C**       TM - UPWARD CONTINUATION ARRAY
C**       DT  -  DATA UNIT (ALWAYS EQUAL TO 1.0)
C**       ZL - HEIGHT OF UPWARD CONTINUATION
C**       NSL - NUMBER OF STARTING DATA POINT
C**       NSU - NUMBER OF END DATA POINT
      DIMENSION C(300),DM(1),TM(1)
      DATA (SMALL = 1.0E-8),(PI = 3.1415927)
      NC = (NOC-1)/2
      XNORM = 0.0
C*        IF NO UPWARD CONTINUATION, SET COEFFS EQUAL TO 1
      IF (ZL.GT.SMALL.AND.NOC.GT.1)  GO TO 10
      C(1) = 1.0
      XNORM = 1.0
      GO TO 30
C*        COMPUTE COEFFS OF UPWARD CONTINUATION
   10 DO 20  II = 1,NOC
      I = II-NC
      DL = DT*(I-1)
      C(II) = ZL/(PI*(ZL*ZL+DL*DL))
C*        NORMALIZATION CONSTANT
      XNORM = XNORM + C(II)
   20 CONTINUE
C*        CONVOLUTION OF DATA WITH UPWARD CONTINUATION ARRAY
   30 DO 50  I = NSL,NSU
      SUM = 0.0
      DO 40  J = 1,NOC
      NM = I+J-1-NC
      SUM = SUM + DM(NM)*C(J)/XNORM
   40 CONTINUE
      TM(I) = SUM
   50 CONTINUE
      RETURN
      END
```

SUBROUTINES HTDERVS AND UPCONT