

GRØNLANDS GEOLOGISKE UNDERSØGELSE

RAPPORT Nr. 114

**GEUS**

Report file no.

22451

*The Geological Survey of Greenland  
Report No. 114*

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Processing and interpretation of  
aeromagnetic data in  
The Geological Survey of Greenland

*by*

*Leif Thorning*

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KØBENHAVN 1982



# Grønlands Geologiske Undersøgelse

(The Geological Survey of Greenland)

Øster Voldgade 10, DK-1350 Copenhagen K

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Processing and interpretation of  
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*by*

*Leif Thorning*

1982

## **Abstract**

This report gives a brief, general description of a system of computer programs for the processing, interpretation and presentation of mainly aeromagnetic data. The system consists of data bases for aeromagnetic and accessory data, programs for the correction and compilation of magnetic data, a contouring package with some special features and a package of interpretation programs.

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## INTRODUCTION

Computer programs for the processing and interpretation of aeromagnetic data have been developed parallel to the acquisition and compilation of basic aeromagnetic data by The Geological Survey of Greenland (GGU). The first few programs of the system were designed by the end of 1974, and since then there has been a gradual increase in the number of programs and their effectiveness. The programs have been developed by the Survey in close cooperation with Geokon A/S. GGU was mainly responsible for the theoretical work, the search for suitable methods, the overall design of the system, lay-out of plots etc., while Geokon A/S carried out the computer processing work connected with the coding and implementation of the programs. GGU's own programmers coded a few of the programs, mainly those used on the local GGU installation.

This note gives a general description of the methods and programs now used by the Geophysics Section of The Geological Survey of Greenland in the processing of aeromagnetic data. The description covers the whole system and explains the use of the different data files. It is not a user's manual. This note is intended as an introduction to the system and is the only publication in which the interrelationships of the individual programs and data files for the entire system are explained. Separate detailed user manuals exist for all programs.

Many of the programs presented here are of a mathematical nature. However, in this presentation mathematics has been kept to a minimum, so that the note will also be of use to readers who may want a general understanding of methods applied to data in their sphere of interest. Potential users of programs in the system should also study the methods in mathematical detail through the references supplied. Some of the programs can be used without a proper understanding of the methods in the sense that results will be produced, but the correct understanding and use of these results depends entirely on the correct understanding of the methods and the correct use of the programs.

Implicitly given in this account is also the status of the system at the end of 1982. It is thus a general documentation of the results obtained during several years of development, producing more than sixty major programs, many of which are described in the following. It is expected that 1982 will prove to have been a turning point for the system, because it now contains sufficient facilities to allow the emphasis to be shifted from development to production.

This note replaces an earlier description given by Thorning (1977b).

## HARDWARE

The facilities of the Regional Computer Center of Copenhagen University (RECKU), (Kofoed & Larsen, 1976) are mainly used for the aeromagnetic computational work, although for some minor tasks the in-house facilities at GGU are utilised.

The RECKU system is a UNIVAC 1100/80 system with primary and extended storage and other facilities normal to a large computing center supporting both batch and demand (interactive, on-line) processing.

The GGU installation is centered around a PDP 11/44 minicomputer and consists (1982) of the PDP 11/44 computer with two 62.4 Mbyte discs, two discettes, two printers, two 800/1600 bpi tape stations, a CalComp 936 plotter, two digitising tables, fast paper tape reader and punch, a cassette tape station and a number of terminals for alpha-numeric and graphic use. The system is connected to the computer at RECKU via the PDP 11/44 system and in this way users can carry out interactive runs at RECKU. Transfer of prints is also possible, and CalComp plots generated at RECKU, with the programs there, can be transferred in the form of files and plotted on the GGU plotter under control of the GGU user.

For final plots of maps a flatbed Kongsberg plotter at the Geodetic Institute in Copenhagen is used. This can produce indian ink plots or inscribe directly. Recently a facility for the presentation of maps in colour based on Applicon plots has been added.

## SOFTWARE IN GENERAL

In the design and production of the programs comprising the system, care has been taken to make the system flexible and facilitate the addition of new programs at any point in the system.

Most of the programs are written in FORTRAN IV or V; only some specialised routines performing certain machine dependant operations are written in ASSEMBLER or COBOL. Recently, Univac, and therefore also RECKU, have decided to support the ASCII Fortran, and to downgrade the old Fortran V. New additions to the system will, therefore, whenever possible be coded in ASCII Fortran. Some of the programs exist in two versions for use on RECKU or the GGU computer.

Most programs are designed for both demand and batch processing, so that they can be used both ways depending on the amount of data and the stage in the processing. Thus trial runs of compilation or contouring can be carried out interactively on reasonably small amounts of data, so testing the parameters before larger runs are carried out in batch. This significantly decreases the risk of expensive, but unsuccessful batch runs.



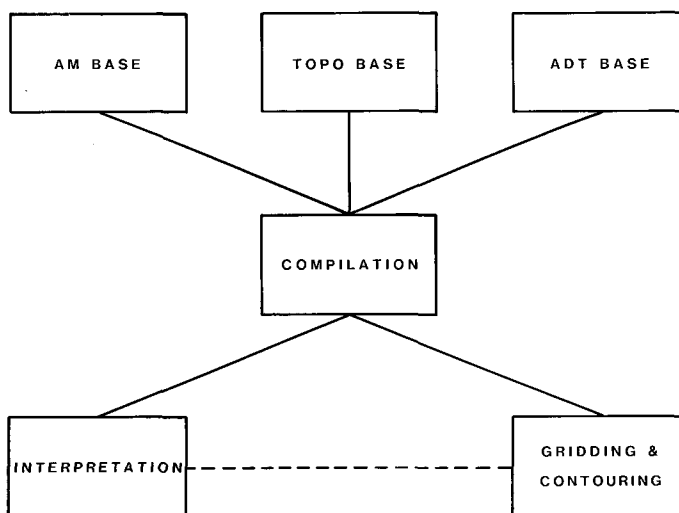


Fig.1. Principle of program package used in the processing of aeromagnetic data in The Geological Survey of Greenland.

In order to make the programs perform as effectively as possible and at the lowest possible cost on the RECKU installation, the coding and design are adapted very closely to RECKU. Unfortunately, this means that programs cannot easily be transferred to other installations without considerable reprogramming. This is further complicated by extensive use of dynamic storage allocation in the programs. Thus, although the methods and procedures used in the system are generally applicable, this is not the case for the actual programs in relation to different installations.

A number of basic principles have been applied throughout the development of the system. Once the data have been entered into the system (i.e. the data bases) further processing is based entirely on data files maintained by the system. There is no punching of cards or paper tape, and magnetic tape is only used as media for the data bases and for long time storage of data files. Data which is being worked upon is easily accessible via the programs. These have been constructed so as to call for a minimum knowledge of electronic data processing in their use. Wherever possible operations concerning administration and movement of data are included in the programs and the user only has to give directions in clear language. For demand runs this takes the form of answers to questions put to the user by the program.

In Fig. 1 the basic principle of the system is illustrated. It can be divided into six subsystems of programs: two aeromagnetic data bases (AM and ADT), a data base for topographic data (TOPO), a number of compilation programs, programs for interpretation of aeromagnetic data, and finally a group of programs for gridding and contouring of the aeromagnetic data. In Fig. 2 this is shown in more detail, although still schematically. The programs are interfaced in as many ways as possible to provide multiple paths through the system. The number of different formats for the data files have been kept to a minimum. The data files in GBT format (see later) are central to the system. Data are delivered in this format from the aeromagnetic data bases (AM and ADT) and all compilation programs read and produce data

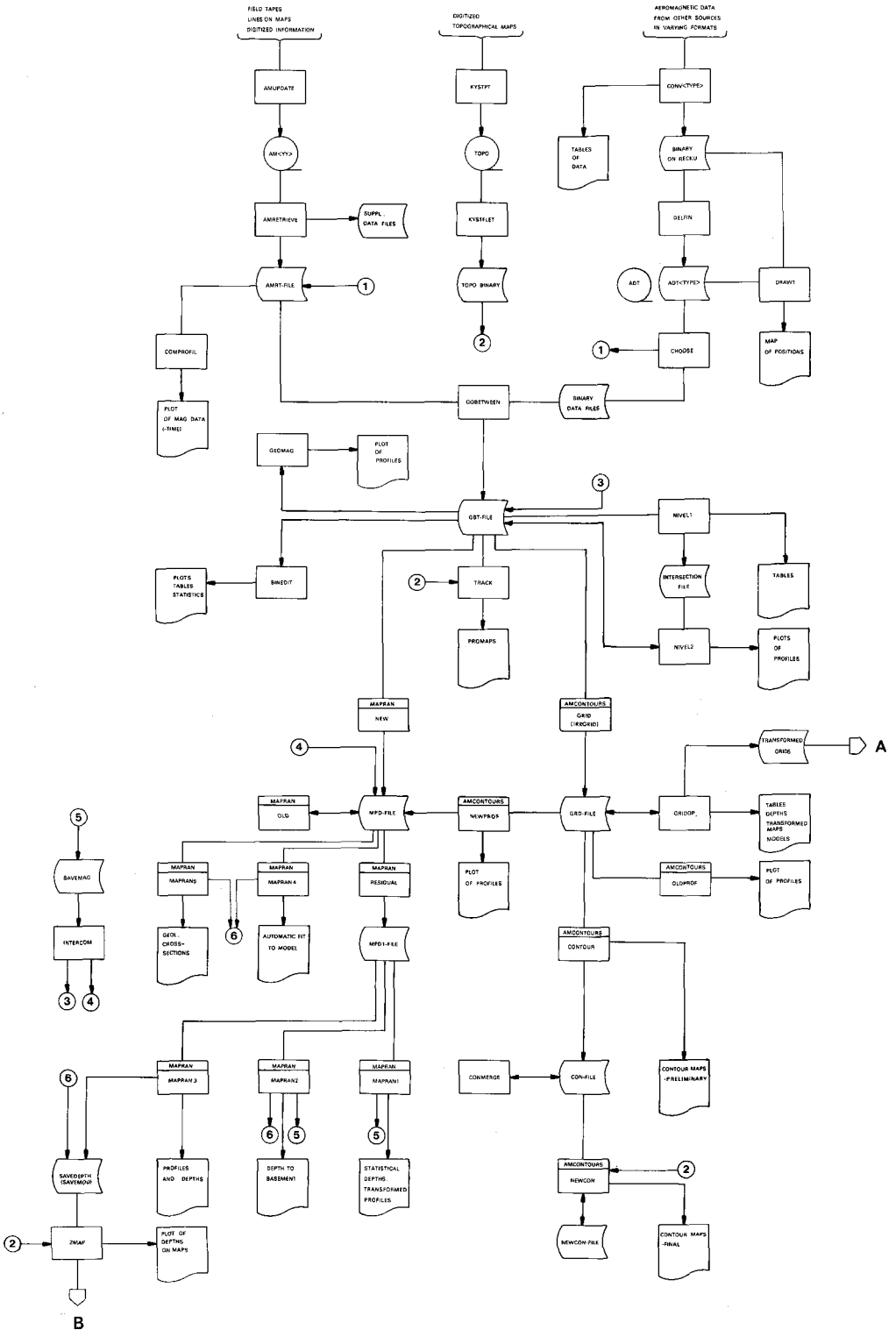


Fig.2. Simplified system diagram showing the main programs and data files used in the treatment of aeromagnetic data. A and B indicate potential extensions of the system. Some paths through the system are indicated by numbers in small circles rather than by lines. For detailed explanation see text.

in GBT format. The input modules of the interpretation programs and the contouring programs also use the same basic GBT format, and can produce derived data in the same format. This makes the compilation process very flexible, and data in intermediate stages of treatment can be contoured for testing etc.

The diagram does not show all the programs of the system, and a number of programs placed before the data bases are mentioned in the text but are not shown on the diagrams. For clarity some administrative and security programs are omitted from both the diagrams and the text. Further, some of the boxes on the diagrams represent more than one program. Thus the diagram is a simplified picture of the system to illustrate the possible flow of data through the system and the position of individual programs (groups of programs) relative to one another. The principle data files have been included because these are the links between the programs. The diagram also shows at a glance how data must be processed before a particular method of interpretation can be applied. Apart from the format of some of the first data files in the system (e.g. AMRT files) all the files are in binary format and thus are not accessible to the normal editor processor of RECKU. These files can only be read by programs in the system. Therefore, a number of facilities for listing the contents of such files are included in many of the programs. Also, a number of checks on the format and contents of the files are performed by the programs, which will only accept a data file in the correct format and with the correct content.

As many of the programs are meant primarily for interactive use, wrong answers to the program from the user are caught before they result in a crash of the program. The user is given a second and a third chance of providing a correct answer before the program terminates in an orderly manner without destroying the content of any data file. Of course, some types of computer system failure cannot be handled in this way and if they occur may result in destruction of data files. The effect of such events are minimised by observing certain working rules.

The system utilises graphical output to a very high degree. Some of the more specialised functions will be described in the following, but generally, two forms of graphical output are produced. The basic routines for these are identical for all the programs. Primary graphical output is plotted on-line by the programs on a Tektronix 4014 screen. These plots are used for evaluation, interpretation and testing and any program can produce a number of different plots when relevant. If necessary, graphical input can be given to some programs by means of a screen cursor. A permanent hard copy of the plot can be obtained by using the Tektronix Hard Copy Unit or by requesting the program to produce CalComp plots. These can be of a standard format or the parameters of the plot lay-out (scale, tick marks, text etc.) can be provided by the user. In the case of standard plots no information is requested from the user, the programs automatically producing a plot with all relevant information.

The main programs of the system will be described below.

## THE AM DATA BASE

This is a data base system designed specifically for the storage of low resolution aeromagnetic data acquired by GGU and is thus tailored to the method of data acquisition (Thorning,

1976, 1977a). As newer and better instrumentation is applied many of the data management programs attached to this data base will become obsolete and will be phased out or replaced with other programs.

The aeromagnetic data are organised in the data base so as to make it fairly easy to extract any combination of data. Extraction of data from the base is handled by AMRETRIEVE; input to the base is handled by AMUPDATE. For reasons of safety the system always maintains two versions of the data base, one containing all updatings and one containing all updatings but the last.

During one summer aeromagnetic surveys may be carried out over several regions and with different survey parameters. Each such survey area is labelled with two letters and each flight line within the area is given a number. In this way all profiles are unambiguously defined. Each year has its own data base, and the data are subdivided according to survey area and map. Special files in the data base contain all necessary relations between profiles, maps and survey areas.

The position of profiles on a map is given in coordinates referring to a rectangular coordinate system, defined by geographical coordinates of the origin and with the  $y$ -axis pointing due north. Indirectly, geographical coordinates can also be used in plots and data files.

For each measurement with the airborne equipment the data base contains the following information:

- (1) Profile identification
- (2) Map identification
- (3)  $x,y$  coordinates
- (4) Date
- (5) Time
- (6) Radar altitude
- (7) Barometric altitude
- (8) Magnetic total field
- (9) Magnetic base station field
- (10) Corrected total field
- (11) Point qualifier (plotted or interpolated point)

## CONVERTRISQ

Data recorded with the GGU low resolution system were stored on paper tape. These tapes were treated at the Electronics Department of Risø National Laboratory combining both radiometric and magnetic data on magnetic tape in sequential order. The program CONVERTRISQ extracts the magnetic data with relevant additional parameters and produces a magnetic tape with this data in a format suitable for further treatment on the installations at RECKU. At the same time it is possible to carry out corrections of date and time, if these happen to have been erroneously entered, and a few other simple corrections can be made.

## **DIGLINE**

Positions along flight paths were recorded with vertical photographs at regular intervals. These positions are plotted on stable base maps, and the flight paths are digitised using the program DIGLINE. This program enables the user to utilise the minicomputer system with the Tektronix screen and graphic tablet as an on-line digitiser. Additional parameters (e.g. time and fiducial numbers) and commands to the program are entered via the keyboard. The data are collected in a file, which can be inspected at any time and, if necessary, corrected in a number of ways. DIGLINE also includes a routine enabling the user to plot the digitised map with flight lines on the screen for fast visual control. When the data are found to be satisfactory, transfer of the data to RECKU takes place directly over a line or via magnetic tape. At RECKU the data undergo certain coordinate transformations and are brought to a format suitable for input to AMUPDATE.

## **PAPERTAPE**

The name dates back to the early start of the AM data base, when only papertape could be used as data-carrying media. The program carries out the coordinate transformation from the coordinate system of the digitising table (produced by DIGLINE) to the coordinate system of the map. This has its origin at the central longitude and smallest latitude of the map with the x-axis pointing east and the y-axis pointing due north. The output data file contains the digitised flight track information and map border points in a format which can be used as input to AMUPDATE. This file can be read with the RECKU editor.

## **BASEMAG**

This is actually a number of modules used for the treatment of the temporal (diurnal) variation of the geomagnetic field as recorded digitally at a local station set up for the purpose. Most of these programs are implemented on the GGU system. A simple data base can be constructed and maintained with all the magnetic data from a magnetometer base station. Base station measurements corresponding to a particular period of time (flight or profile) can be extracted and given special attention. As a result of this treatment, which takes place partly at RECKU and partly at GGU, a number of files with all relevant information for the data base are produced in a format suitable for the input program AMUPDATE. At the same time it is possible to calculate certain statistical parameters and to obtain a measure of the geomagnetic activity in user-defined periods of time.

## **AMUPDATE**

This program initiates an AM data base for a given year and provides the facilities for all

future updating of the base. The program is safeguarded, making it nearly impossible to damage the base through user's error. By using different commands to the program the user can: (1) merge raw data from the flight recordings (from CONVERTRISQ) with position data (from PAPERTAPE), (2) update the data base with ground station recordings (from BAsEMAG), (3) update with barometric altitude if this was not included in the original digital flight recordings, (4) correct magnetic total field values if for some reason the digital recording system has failed; this operation utilises digitisation of the analogue recording, (5) delete profiles from the data base. The time interval between successive records is determined by the setting of the sampling rate of the airborne equipment.

### **AMRETRIEVE**

This program makes it possible to extract data from the AM data base in any desired combination. The data retrieved are written in a file in well defined FORTRAN formats and can thus be directly inspected by means of the RECKU editor. These files were at an early stage found to be too expensive and cumbersome to use and a program (GOBETWEEN) was made to rewrite the data in a more suitable format (see later). Data can be retrieved on the basis of flight paths or maps. When extracting the data from several maps in one operation the user can define a master coordinate system, and the position of all profiles will then be transformed into coordinates of the master system. The user can also define the scale of the output maps. A certain combination of data is obtained by using a corresponding combination of options on the execute statement. Some of the parameters (1) to (11) will then be written in a file ordered firstly according to maps, and secondly according to profiles.

### **COMPROFIL**

This program is used for the presentation of single profiles with time as one axis. Input to the program is an AMRT file with profile information only, and no map information. COMPROFIL plots against time three curves for total field airborne measurements, base station measurements, and corrected airborne measurements, respectively. The plot is automatically divided into a number of A4 size plots, and the first 'page' also contains a table with statistical information on the profile, and a measure of geomagnetic activity during the time it took to record the profile.

## **THE ADT DATA BASE**

The ADT (**Aeromagnetic Data Tapes**) data base was developed as a new and more expedient version of the AM data base. It is used for new data acquired by GGU from a number of sources, including data acquired by commercial companies under contract with GGU. It is



more flexible than the AM data base, but the same principles concerning safety of operation have been applied. Input to the ADT base is handled by DELFIN, and data is retrieved from the ADT base by CHOOSE. The data are stored on one or several magnetic tapes according to the wishes of the user.

Areas are not limited to map sheets, but can be defined arbitrarily by the user. Geographical coordinates are included, and there are two data channels, which can be defined for particular uses with a given batch of data.

A measurement point can be referred to by time and/or measurement number (fid no). These do not have to be integers.

For each measurement the following information is stored:

- (1) Flight number
- (2) Profile identification
- (3) Date
- (4) Time
- (5) Fiducial number
- (6) open 1
- (7) open 2
- (8) Geographical longitude
- (9) Geographical latitude
- (10) x-coordinate
- (11) y-coordinate
- (12) Barometric altitude
- (13) Radar altitude
- (14) Magnetic total field
- (15) Residual magnetic field
- (16) Magnetic gradient field
- (17) Magnetic base station field
- (18) Correction indicator
- (19) Point qualifier

## CONV <TYPE> PROGRAMS

When GGU receives aeromagnetic data from outside sources in formats foreign to GGU, programs are constructed which translate the data into binary files of a format suitable for the programs to be used in the processing of the data. Practically no processing is carried out by the program, which just rewrites the data, checks that measurements are in correct sequence, and produces printed tables to be used in the following processing. The tables can give information on all measurements of all parameters and will give each measurement a number. The user can define an allowable difference between two successive measurements, and if the difference is exceeded, it will be marked as a possible spike for later treatment. Such programs have been constructed for data from a number of external sources. Where already fully corrected data is received in GGU defined formats, e.g. surveys planned and bought by GGU,

the conversion programs are made to be more automatic, producing ADT files directly, at the same time checking the data to be entered.

All conversion programs produce a file that can be used as input to DRAW1. Plots produced by DRAW1 are used in the process of defining profiles to be stored.

### **DELFIN**

From data files produced by the CONV<TYPE> programs, and additional information from the user, the program DELFIN defines and stores the profiles in ADT format. The profiles are defined by the user from information provided by CONV<TYPE> (printed tables of measurements) and DRAW1 (plots of position of points). Some points are given a status as plotted points, and points between these are interpolated. The position of interpolated points may be projected onto a straight line connecting the plotted points. Measurement points at a greater distance from the straight line defined by the user can be omitted. Single points identified by their number may also be omitted. Spikes in the data, defined through criteria provided by the user in the conversion program, are replaced with interpolated magnetic data. ADT files are then put on magnetic tape for long time storage and these can be updated using a procedure similar to the one used by the AM data base system.

### **DRAW1**

DRAW1 is used for the display of position data for new aeromagnetic data being entered into the system via the ADT base. It can take as input the binary files produced by the conversion programs or the files in ADT format. In the first case the plot produced is used in the definition and naming of profiles to be stored. In the second case it is used as a fast check of the navigational data of profiles stored in an ADT base. The program plots each measurement point as a cross, and numbers them with the number plotted according to the directives of the user. The plot shows geographical coordinates.

### **CHOOSE**

CHOOSE has a function similar to AMRETRIEVE. It takes data from ADT format files (or tapes), and merges different areas, if necessary calculating new coordinates relative to a new origin. The resultant data file can be produced in AMRT format, which can be inspected using the RECKU editor, or in a binary format, which can also be used as input to GOBETWEEN. After this stage data follow the same flow as data from the AM data base. CHOOSE can also be used to produce magnetic tapes for delivery outside GGU with data in formats suitable for use at other installations.

## THE TOPOGRAPHIC DATA BASE

For working purposes and for simple publication of aeromagnetic maps it is often practical to facilitate orientation by plotting magnetic data superimposed on an outline topographic map. Several areas in Greenland have been digitised and stored in a data base. The individual maps are digitised at GGU using DIGLAND, and after transformation each map is stored as an element in a RECKU file. From here topographical information can be combined with TRACK maps, AMCONTOURS maps, and ZMAP maps.

### DIGLAND, DIGPOINT

DIGLAND is similar to DIGLINE, but is used to digitise coast lines, lakes, ice margins, and rivers. The data format of the resulting file is therefore slightly simpler. DIGPOINT will give  $x,y$  coordinates of any point in the coordinate system of the map in question. This is all carried out on the GGU computer, and resulting data files are transferred to RECKU for further treatment.

### KYSTPT

At RECKU the digitised information is transformed into the map coordinate system and reformatted into a file used as input to KYSTFLET. These files are kept in the topographic data base from which they can be retrieved and combined into areas suitable for a particular purpose. The coordinate system is identical to that used for digitising flight lines. The function of KYSTPT is similar to that of PAPERTAPE.

### KYSTFLET

This program has the same function as GOBETWEEN, but deals with topographic data. Input to the program is one or several KYSTPT output files. The data in these files are merged into a new file containing a digitised map of an area, the limits and origin of which are specified by the user. The output file, which is binary, can be used by TRACK, AMCONTOURS and ZMAP, providing the maps these programs produce with superimposed topographic maps.

## COMPILATION PROGRAMS

The data files in GBT format (as produced by GOBETWEEN) are the basis of further

compilation of the aeromagnetic data. All programs performing compilation processes take a GBT file as input, but also produce a GBT file containing the processed data. In this way the compilation processes of the following programs can be used in any order, and data at any stage of compilation can be used as input to the interpretation programs and be presented as profile maps or contour maps. Transformed magnetic profiles produced by MAPRAN, can be written in GBT files and are thus available for a second pass through MAPRAN or can be presented as contour maps. The basic design of this part of the system has proved very effective and time-saving. Data received from outside sources and already sufficiently processed can go straight through the compilation part of the system without actually being processed and will be directly available for interpretation.

### **GOBETWEEN**

For certain purposes the AMRT files are not practical. GOBETWEEN was originally made as a 'go-between' between the AM data base and the interpretation programs. Since then the output file of GOBETWEEN, the GBT file, has been adapted as the basic data file format of the system during compilation of the data. GOBETWEEN still performs its original purpose. It can arrange the AMRT data in a more convenient way, but it will now also process data from binary files produced by CHOOSE in the same way. GOBETWEEN rearranges data, so that data from different map sheets (or subareas) belonging to the same profile are gathered and arranged chronologically or according to fiducial number. It is possible simultaneously to pass the magnetic data through a simple, triangular, noise-reducing filter prior to being stored in the output file. This is in binary GBT format and very well suited for fast access and inexpensive, repeated readings by a large number of programs in the system.

The geographical area in the output file can be the same as the total area of the input files. It is, however, also possible to define new limits to the rectangular area to be contained in the output file. Magnetic data positioned outside the defined area of interest will not then be included in the output file. Single profiles can also be excluded from the output file.

The user can define the areas of interest as a whole survey, parts of such areas, a single or a few profiles, all magnetic data inside a map sheet, etc. Later in the processing it is possible to further modify the area and other parameters (see BINEDIT).

### **TRACK**

This program plots on a map the variations of the aeromagnetic field along the true position of the profiles contained in the GBT file. It is used to present data unsuitable for contouring, such as single profiles, and to plot closely spaced profiles so as to get an effect similar to that of 'stacking' profiles. The information obtained by DIGLAND can be superimposed on the plot produced by TRACK, and a geographical grid can also be superimposed. The map can be plotted in any scale. If the resulting plot size is too large for the physical limitations of the plotter, the plot is automatically divided into parts sufficiently small to be plotted. The magnetic data can be plotted in a number of ways. Besides actually plotting the data as a curve

along the profile (profile maps or promaps), it is possible to indicate only the position of maxima, minima, and/or inflection points by crosses. This is useful for correlation and structural analysis. In all cases, the flight line itself can be plotted or omitted according to the wishes of the user. A facility for semi-three-dimensional presentation of profiles placed vertically using a hidden line technique will be developed.

## GEOMAG

The aeromagnetic data from Greenland will usually be related to the International Geomagnetic Reference Field (IGRF), at least until new and significantly better models have been generally accepted (e.g. from MAGSAT data). The program takes the profiles in a GBT file and calculates the IGRF along the profiles. The reference field can be subtracted and the resulting profiles stored in a new GBT file. It is also possible to store the reference field itself in a GBT file. CalComp plots of original profiles and the corresponding ambient reference field can be produced. Several sets of coefficients are available corresponding to different models besides the IGRF 1970, 1975 and 1980; coefficients for the American magnetic charts and the British magnetic charts, as well as a set calculated as an average of these two (all obtained from S.Barker, U.S. Naval Oceanographic Office, personal communication). The core of the program is the routine of Barraclough & Malin (1971). Another slightly modified version of this routine is included in the program to achieve reference fields in which the secular acceleration is taken into account (Barraclough *et al.*, 1975).

A simple version of the program without plotting facilities is available on the GGU installation. This will take starts and ends of profiles in geographical coordinates and produce tables, listing values of all geomagnetic parameters along the profile.

## NIVEL1

This is the first program to be used in the magnetic adjustment of the data. The basic problem arises from the fact that geomagnetic variations, even within given specifications, as well as horizontal and vertical navigation inaccuracies, have the effect that two measurements of the magnetic field at the (supposedly) same position will probably not show the same value of the magnetic field. In order to check this deviation and later correct for it, profiles (tie lines) are flown in a direction perpendicular to the strike of the main profiles (traverses). The differences in values of the magnetic field at the intersections of these lines are then utilised in order to carry out a net-work levelling of the magnetic data (NIVEL2).

NIVEL1 calculates a number of parameters for further use in the magnetic adjustment. From a GBT file the positions of all intersection points are calculated, and for each point the two values of the magnetic field and the corresponding difference are calculated. Horizontal gradients of the magnetic field along traverses and tie lines are also calculated. Everything is printed in tables, and a special table is produced giving schematically the position of intersection points with the differences produced ('intersection landscape'). Finally, a file with intersection values is prepared for NIVEL2.

## NIVEL2

The intersection file produced by NIVEL1 and the GBT file originally used as input to the NIVEL1 program are used as input to NIVEL2, which can only be used in demand mode. NIVEL2 carries out the actual correction of the data through a number of operations available to the user. The theoretical background of the method is given by Yarger *et al.* (1978). It is a relatively simple method of removing diurnal drift from aeromagnetic data. The basic assumption is that during the flight of a profile the diurnal drift is a smoothly varying, low order polynomial in time. The coefficients of this polynomial are determined using least squares to minimise the intersection differences. Assuming that the traverses and tie lines have been flown at the same altitude, or later corrected to the same altitude, and that navigational errors are minimal, the method produces good results in magnetic adjustment. Leveling of the data is automatically included in the process. The drift terms along tie lines are determined first as a tie line usually has more intersections than a traverse. A set of linear equations can be obtained from a condition of minimum residuals and solved for the coefficients of the drift in time. The maximum order of the drift (and consequently of the correction) is determined by the user with the limitation that it cannot exceed the number of intersections minus one (two if number of intersection points exceeds three). This is enforced by the program. This is carried out under the assumption that no drift existed along traverses, which obviously is often not true. The ambient intersection values of the traverses will therefore now scatter around the corrected tie lines. The next step is to correct the traverses using the same process. In doing this it is assumed that the corrected tie lines approximate the true field value at the intersection points. As the adjustment is a least square process the total field values at a given intersection will not necessarily be the same for the tie line and the traverse after correction. When contouring such data the tie lines will, therefore, have to be omitted from the contouring. The information contained in the tie lines has, however, been utilised in the magnetic adjustment carried out by NIVEL2. In its gridding module AMCONTOURS has a facility for omitting the tie line data. Corrected tie lines can therefore still be stored in the new GBT file resulting from the NIVEL2 process, and they can be used in interpretation based on profiles.

There is a limit to how high in order the correction of any tie line or traverse should be allowed to go. A zero order correction corresponds to a level shift of the entire profile, a first order correction may further apply a slope over the length of the profile, and higher order corrections may successively introduce higher frequencies into the drift curve.

NIVEL2 offers a number of special facilities. It is possible to plot the profile (tie line or traverse) together with intersection values and ambient correction curve. The correction can be carried out on all tie lines or all traverses simultaneously or for one or a few profiles only. The latest adjustment of a profile will be remembered by the program. The corrections can gradually be taken up through higher and higher orders, the program itself stopping higher order corrections of profiles with an insufficient number of intersection points. Sometimes large local horizontal gradients in the magnetic data may indicate that positional errors dominate. Such intersections can be omitted from the analysis individually or through a maximum size of intersection difference or horizontal gradient determined by the user. A number of different tables can also be printed by the program, and the entire data set can be retrieved in its original form at any time for new attempts at magnetic adjustment. 'Artificial' intersection points can be inserted to prevent excessive corrections of the parts of a profile that



lie outside the outermost intersection points of the profile. Whenever a correction is carried out for a group of profiles, or just a single profile, the corresponding *rms* is calculated and printed. Histograms of intersection differences can be produced at any time for all intersections, a group of intersections, or intersections of just one profile.

When the user has decided on a sequence of operations being the best for a particular data set, the adjustment is carried out, and resulting profiles can be saved in a new GBT file. This can be done automatically by the program for all profiles in the original GBT file, or for just the corrected ones, or the user can check each profile numerically or through a plot showing original profile, corrected profile, drift curve, intersection values, position of intersections, and status of intersection points (i.e. used or not used in the analysis), before it is decided whether to accept the corrected data.

### NIVEL3

The method used by NIVEL2 has the disadvantage that it is assumed that the intersection points are correctly positioned. If the user knows, or perhaps just has a feeling that this is not the case for some points, the only remedy is to omit such intersection points from the analysis. Plans exist for a new program, called NIVEL3, which will allow the intersection points to be moved and also carry out the same type of correction as NIVEL2, although probably in a slightly different manner. The implementation of the program may, however, be postponed to a time when this facility will be needed in the compilation of new data.

### BINEDIT

The GBT files are in a binary format that cannot be read by the normal RECKU editor. There is often, however, a need for a quick look at some profiles, or for some non-standard corrections to be carried out. A binary editor has therefore been included in the system for this purpose. BINEDIT has a number of facilities normal to an editor, but also includes facilities for graphical output and specialised correction of magnetic data partly through graphical input via a screen cursor. New special functions, which are not applied to all data, will be implemented as new facilities in BINEDIT. The program at present has the following facilities:

(1) Generation of statistical information from a GBT file. Besides listing profile identifications, number of measurements, etc., the program can find the range and average of sampling distances and magnetic values. Marking of profiles where steps in sampling distance or magnetic field values exceed limits defined by the user can also be carried out.

(2) From several different GBT files from different areas the program can generate a new GBT file with new origin, scale and size. All or selected profiles can be included in the new GBT file.

(3) Profiles in a GBT file can be plotted quickly on the Tektronix screen, or later as Cal-Comp plots in a defined scale with data from up to five channels. In the latter case, the user

can define the layout of the CalComp plot.

(4) Spikes in the magnetic data can be deleted and replaced by new magnetic data, which can be interpolated from magnetic data around the spike, or given by the cursor on the graphic screen.

(5) Part, or all information in a GBT file can be printed in tables.

(6) Some or all profiles in a GBT file can be redigitised automatically with user-defined parameters and maximum acceptable deviations in magnetic field from the original profile.

(7) The profiles in a GBT file can be filtered by means of a variety of filters. These are typically numerical in character and no assumptions on magnetic models are involved.

(8) The level of profiles can be changed by adding a constant or a function. This can be defined in a data file or by cursor.

(9) New data files in the basic formats of the MAPRAN programs can be produced directly.

## THE CONTOURING PACKAGE: AMCONTOURS

This is a major program in the system. It is a versatile program providing a number of useful facilities for examination and representation of data. There are several main modules in the program, all described in the following. The contouring package has been developed by GGU and Geokon A/S, and most of it is original and especially suited for aeromagnetic data. Apart from the normal procedures connected with contouring, it contains facilities for production of new profiles and for comparison between original profiles and the surface produced to be presented as contours. Input to the package can be final, corrected data or data at any stage of processing as long as the data file is a GBT file. Besides contour maps, a number of complementary plots can be produced as CalComp drum plots, Tektronix plots, Kongsberg flatbed plots, or Applicon colour plots. Although developed principally for magnetic data, AMCONTOURS can be used successfully for other types of data.

### GRID

The first module to be used on data to be contoured is the GRID module, which will take magnetic data in a GBT file, and produce a grid with interpolated magnetic data according to the directions given to the program by the user. The user can omit profiles in the GBT file from contouring, e.g. tie lines in NIVEL2 corrected GBT files. The area to be contoured can be limited by a polygon defined by the coordinates of its corners. In order to minimise edge effects in the final contour map, the program extends the data according to certain mathematical procedures outside the area actually covered by aeromagnetic flight lines. This area is defined automatically by the program as a rectangular area of a minimum size, but still encompassing all the flight lines. All the following modules in the contouring package will

automatically keep track of these different areas. Sometimes individual profiles are shorter than adjacent profiles, leaving gaps in the data coverage. The mechanism for the extension of the data will then sometimes give rise to troughs or ridges in the contours along the extensions of such profiles, depending on the differences of the anomaly picture in the area actually covered by the profile, and the area into which the profile is automatically extended. To avoid this the user can prevent the extension of individual profiles in both directions along the profile, or just in one direction. The gridding will then be based only on the neighbouring profiles, and no distortion of the contours will take place.

Interpolation to a grid is carried out by means of a method similar to that of, e.g. Bhattacharyya (1969), using linear bicubic splines in two orthogonal directions. However, the improvement is included that the flight lines are not approximated by straight lines determined by least squares, but are used directly. Thus there are no errors connected with the interpolation to straight lines before the actual interpolation to grid.

The user can define the grid by giving the distance between grid lines. The interpolation procedure will then calculate the magnetic field values in the intersection points of the two sets of grid lines. These calculated, regularly spaced values of the magnetic field are referred to as *the grid*.

When using this program interactively, several grid sizes can be tried out before deciding on the final one to be used. A number of plots, primarily on the Tektronix screen, secondarily on a CalComp plotter, can also be provided by the program including the area to be contoured, all the flight lines, and the polygon to limit the contouring. Once a grid size has been accepted, it is possible in a demand run to plot the original profiles individually and to compare them to superimposed plots of the contoured surface along the profile. The maximum deviation of the contour surface from the original data along the profile will also be given. If the result is not satisfactory a new attempt can be made. The accepted grid is stored in a GRD file.

Where there are very large amounts of data or closely spaced gridding lines, it is not practical to carry out the gridding interactively. The batch version of the program can then be used, which has the same facilities except that the grid size cannot be changed during the processing.

The GRID program will also store in the GRD file the original magnetic data and position of the profiles used in the gridding of the data.

## IRRGRID

The gridding procedure described above works well with data acquired along lines, but is not well suited for irregularly sampled data. In order to be able to treat such data a method by Briggs (1974) using the principle of minimum total curvature is included in the system. The program is that of Swain (1976), implemented at RECKU by Geokon A/S in a form fitted to the present system of programs. The program produces satisfactorily gridded values also of irregularly sampled data, and in the IRRGRID version produces the output in the GRD file format, so that the contouring and other treatment can be applied without further preparation. IRRGRID is mainly used for the gridding of digitised old magnetic contour maps, but is actually well suited for any type of data.

## OLDPROF

In the GRID module it is possible to plot original data and contour surface along given profiles, but it is not always practical to do so, e.g. when gridding in batch. Instead, OLDPROF can be used to carry out the same check. Plots can then be made directly on the Tektronix screen or as CalComp plots. The input to the program is taken from the GRD file, which also contains the original data of the profiles used in the gridding. The user only has to give the original profile identification. The profile representing the surface to be contoured is then calculated from the magnetic values at intersections of the original profile position with the grid lines and digitised at the same sampling distance as the original profile, using spline functions.

## NEWPROF

In the interpretation of magnetic data, the direction of the flight lines is often not perfect for all the magnetic anomalies mapped by the survey. Sometimes, anomalies are found to be due to three-dimensional structures once the contour map has been completed, or the strike of anomalies can be seen not to be perpendicular to the direction of the original flight lines. For these and other reasons magnetic data are often required along other directions than that of the original flight lines or along more closely spaced profiles, e.g. over three-dimensional structures. NEWPROF is a program which, if given the coordinates of any two points in an area covered by a grid of magnetic data (in the GRD file format), will produce a 'new profile' between the two points. This can be done to check the contouring in other directions than along the original profiles, in which case a plot may be sufficient. It can also be used to create a new data file with profile data relevant to a particular structure or anomaly. The profile is created by a method similar to the one described under OLDPROF, and the sampling distance used is determined by the user. Such profiles can be stored in a data file in MPD format (see the MAPRAN system) and are thus immediately available for analysis using the MAPRAN system.

## CONTOUR

The GRD file is the basis for the actual drawing of contours, which is done by the CONTOUR module. The operation can be carried out in demand or in batch. The contouring interval and range is determined by the user. The program can also estimate magnetic field maxima and minima and mark their position on the map by means of small triangles and inverted triangles, respectively. The process can be carried out without actually plotting a contour map, in which case the contours are stored in the CON file, later to be plotted by NEWCON. It is also possible to simultaneously store and plot a map at any given scale, and if so required to include flight tracks, the limiting polygon, and position of extreme points. Two colours (or line thicknesses) can be used at any defined magnetic level. The contour map can be plotted interactively on a Tektronix screen, and later on a CalComp plotter. In batch the plot is drawn directly on a CalComp plotter.

## NEWCON

The contours stored in the CON file can be plotted using the NEWCON module while further improving the quality and general appearance of the contour map. NEWCON in batch or demand will carry out the following operations, producing Tektronix, CalComp, or Kongsberg plots:

(1) Thinning of contours in high gradient areas. The user defines an acceptable density of lines per centimetre in a direction perpendicular to the strike of the contours. If the density of contour lines exceeds this, segments of the contour lines are deleted according to a procedure ensuring maximum continuity of as many contours as possible. Specific contours can be excepted from the process.

(2) Individual contours can be plotted separately.

(3) Labelling of contours. The values of contours are printed on the contours.

(4) A topographic map can be superimposed on the magnetic contour map.

(5) A geographical grid with specified lines of latitude and longitude can be superimposed on the map.

(6) The plot can have standard frame and text, or it can be without any frame at all. A number of intermediate possibilities exist.

(7) The scale of the map can be changed.

(8) The program has a number of facilities for minor 'cosmetic' operations.

(9) The resultant contour map can later be saved in a NWC file and can be plotted again with or without topography and geographical grid, or can be further processed. However, labelling and thinning of contours cannot be changed or repeated without returning to the original CON file.

(10) The final contour map, perhaps with topography, stored in a NWC file can be re-plotted in its totality, or selected items alone can be plotted. This is, for instance, utilised in the engraving of different forms for printing.

(11) Contouring of magnetic data is usually done in areas having the same characteristics of altitude, line separation etc. NEWCON can merge such different contour maps within a given geographical area.

## CONMERGE

Sometimes the size of an area or large variations in the magnetic field to be contoured make it difficult, expensive or perhaps impossible to contour the entire area in one run. Such areas can be divided into smaller areas, which can be contoured individually and then later be fitted together. This sometimes creates problems with the fitting of contours at the edges of the different subareas. AMCONTOURS provides an alternative method; the large area is maintained, but the contouring is carried out in several runs, with each run only drawing

specific contours from the same GRD file. Taken together the contours will cover the whole range of magnetic variation. In this way a number of CON files are created from the same area, but with different contours. CONMERGE will take up to five such CON files and merge them into one CON file with all the information. This can then be treated with NEWCON as usual. Before the merging of the input files, CONMERGE checks that the input files are identical with respect to origin, scale, grid, limiting polygon, as well as number of flight lines and measurements.

## INTERPRETATION PROGRAMS

In the following a number of programs are described which are used in the interpretation of magnetic data. The programs come from various sources. Some have been programmed directly from a published description, some are versions of existing programs received by the author from other institutions. All programs contain significant contributions from GGU/Geokon in the way they have been implemented, with better numerical routines, adaptations to the RECKU system, and through the style of programming. Programs dealing with magnetic data along profiles have been gathered in the MAPRAN system. Programs dealing with data in map form are gathered in the GRIDOP system.

The methods used in the programs are selected with two principle objectives in mind: (1) to obtain a set of interpretational facilities which will ensure a reasonable rate of production using mainly generally accepted methods, and (2) to allow at the same time sufficient flexibility for experimentation to take place.

## THE MAPRAN SYSTEM

This is a system of programs designed for **magnetic profile analysis**. The first modules deal with arranging the data along profiles, digitising of magnetic data at regular intervals, and other data-administrative tasks. Most of the programs are used interactively with the Tektronix screen as primary output medium, and the CalComp plotter as secondary output medium. Apart from the actual aeromagnetic data supplied from data files, input can be added from the screen by cursor or from files. In this way it is possible, for instance, to define regional fields and calculate residuals. When a profile has been ordered and represented at regular intervals within the most suitable limits and perhaps gone through a regional/residual separation, it is stored in a MPD or MPD1 file (see later) and a number of operations can be performed on the profile by using one or several of the modules described in the following sections. Whichever operation is performed the results will be displayed immediately on the screen for fast visual check before being accepted. The results of the interpretation as well as transformed profile data produced during the interpretation process can be stored in data files for later use. MAPRAN is a powerful tool in magnetic profile analysis, being used for routine interpretation and also in more experimental interpretational work.



## **NEW**

The NEW module takes profile data from a file in GBT format and allows the user to rearrange the data in a form suitable for the other MAPRAN programs. The magnetic data along a profile can be redigitised using regular sampling distance by means of spline functions. From information printed on the screen or from a plot with both the original data and the digitised data the user can see whether the digitising interval chosen is acceptable. If not, another attempt can be made. When a profile has been digitised satisfactorily it can be stored in an MPD file, and the next profile in the GBT file can be treated. The user only has to provide some of the information required in the processing the first time that a given MPD file is created. In later processing using this file all relevant information will be in the file.

## **OLD**

This program carries out the same functions as NEW, but takes its input from an MPD file and creates a new MPD file. The program is used for changing the digitising interval of profiles already processed once with NEW.

## **RESIDUAL**

Many modern methods using Fourier transformations or similar mathematical functions assume the data to be residual data with a number of points equal to an integer power of two. With the RESIDUAL program the user can: (1) make a separation of anomalies using cursor or figures in a file, and (2) extend the number of points in the profile to  $2^N$  by tapering the magnetic data to zero outside the original ends of the profile. Such profiles can be saved in an MPD1 file.

## **GOBMAP**

The programs NEW and RESIDUAL are used interactively in an initial evaluation of the magnetic data. Once a suitable set of parameters for the initial processing in preparation for the interpretation has been determined, GOBMAP can be used to carry out initial processing in batch producing a MPD or MPD1 data file for further use.

## **MAPRAN1**

This is a program for statistical analysis of magnetic data in profile form. Data must be in a MPD1 file for input. The program uses a statistical model approach, the theory of which is

explained in Green (1972), and is the two-dimensional equivalent of the method by Spector & Grant (1970) dealing with three-dimensional, contoured data. It is a direct method of finding average depths to ensembles of bodies using the profile data in the wave-number domain. The program was developed primarily on the basis of Green (1972) and was the first to be implemented in the MAPRAN system.

### *Theory of the program*

The basic model is that of a two-dimensional prism extending to infinity in directions perpendicular to the direction of the magnetic profile. In this description following Green (1972) the fundamental assumption is made that the most probable value (expectation) and the ensemble average of the energy spectrum are equal, and that the profile contains contributions from an ensemble of prisms defined by certain parameters independent of each other. However, the method will also work if more than one such ensemble of prisms is present.

Under these conditions an expression for the energy spectrum of the magnitude of the total magnetic field of such an ensemble of prisms can be calculated. The logarithm of the ensemble average of the energy spectrum is an additive expression containing a number of terms. These terms can be solved numerically provided certain conditions are fulfilled. These conditions have a bearing on the use of the method of statistical depth calculation, and the terms will be described individually in the following.

### *The geomagnetic field vector term*

The expression for this term can be solved if the variations in the field vector parameters are within certain limits. A good rule-of-thumb is that variations in declination and inclination of the geomagnetic field vector should not exceed  $\pm 20^\circ$ . Quite long profiles can be analysed without violating this condition, which usually is not critical.

### *The magnetic moment term*

This term can be solved the same way, i.e. the condition is that the declination and inclination of the resultant magnetic moment of the bodies in the ensemble should not vary by more than  $\pm 20^\circ$ . In the case of dominant induced magnetisation this term may be equal to the geomagnetic field vector term, but if the remanent magnetisation of the source is dominant, the magnetic moment vector may fluctuate considerably along the profile. If this is so, parts of the profile for which the above condition is fulfilled, must be analysed separately.

### *The width of bodies term*

This is an important term and should always be taken into account when using the energy spectrum for depth estimations. Part of the term contains the average width of the bodies, which may be estimated from the second derivative curve of the profile (distance between zeros). In the program this estimated average for the width of the bodies (supplied by the user) is used to correct the energy spectrum for the width term. If this correction is not performed, overestimates in excess of 30% may occur. If the average width can be determined within 30 to

40%, depth estimates will usually be better than within 15% of true depth. Green (1972) recommends that the estimate of average width be made in conjunction with the original profile and a number of upward continued profiles (see later), especially if more than one ensemble of bodies is present.

### *The thickness of bodies term*

A solution exists to this term, which does not require fulfilment of any special condition. For sufficient lengths of profile this term will, combined with the average depth term described below, produce broad peaks in the energy spectrum. The presence of such peaks may indicate that certain ensembles of bodies are limited with respect to depth, i.e. have a limited thickness. Peaks can be defined mathematically by an expression containing an estimate of an average depth. If this average depth is known (see later), there is a theoretical possibility of calculating the average thickness of certain ensembles of bodies. However, the calculation involves an iteration, and even very small errors in the estimate of depth produce extremely large errors in the average thickness. Generally, it is advisable only to take such peaks as an indication that the thickness of the bodies is limited with respect to the length of profile used.

The energy spectrum may also contain peaks, which are not a result of this, but just occur because a limited amount of data has been used. It can be difficult to discriminate between the two peak types.

### *The depth to bodies term*

This term is found to dominate the spectrum and its effect is seen as a slope in the spectrum. If a significant change of slope can be seen, this may indicate that more than one ensemble of bodies is present. In such cases, linear parts of the spectrum must be analysed separately. The average depth is approximated by the simple expression that the gradient of the slope is proportional to the average depth. Although depth to bodies and thickness of bodies are linked, the effect of thickness on the gradient of the spectrum is negligible after the first few harmonics after a peak. Linear parts of the spectrum will thus depend mainly on the average depth.

### *The Fourier transformation*

The program calculates the FFT (Fast Fourier Transform) of the profile data. Since the profile data is taken from an MPD1 file, the profile has been digitised at regular intervals and the number of points has been extended to the next integer power of two, by tapering the data to zero outside the ends of the original profile. When digitising the data in the NEW or OLD modules the user has to consider how the data is to be used in MAPRAN1. MAPRAN1 further assumes that the regional field has been removed. For long profiles this will usually be the IGRF (see GEOMAG). For smaller profiles or specific groups of anomalies a further separation of anomalies may be necessary (RESIDUAL). The program is not safeguarded against aliasing effects. It is up to the user to take this into account. When the program transforms the data into the wave-number domain, the shortest wavelength (corresponding to the Nyquist wave-number) will be equal to twice the length of the digitising interval. The

longest wavelength will be equal to the length of the profile plus one digitising interval. The calculated Fourier coefficients are stored by the program and used for the calculation of the spectrum and the filtering of the data described in the following.

#### *The statistical depth determination*

The peridiogram is calculated by squaring and adding the real and imaginary coefficients and can be smoothed by a triangular filter to give a better estimate of the energy spectrum. Since sharp peaks in the spectrum may be indicative of a periodicity in the underlying structure, up to five peaks can be preserved throughout the filtering of the spectrum. When the user has obtained a satisfactory energy spectrum, this should be corrected for width of bodies. The program (the average width given by the user) actually calculates the width of bodies term and subtracts this from the spectrum. Special care has to be taken if more than one ensemble is present. After these corrections are made, the user can divide the spectrum into linear parts by using the cursor on a screen plot of the corrected energy spectrum. For each linear part a corresponding depth is calculated from the gradient of a least square straight line approximating each of the linear parts of the spectrum. The user can go through several attempts at depth determination on the same profile before moving on to the next profile in the input file. The fact that such depths can be calculated does not necessarily mean that they are real. Apparent depths can be due to deficiencies in the data. Therefore, correlative evidence should always be considered.

#### *Upward and downward continuation*

The program can also use the calculated Fourier coefficients to perform upward and downward continuation of the profile data. Such processes are fast and reliable in the wave-number domain. The user has only to give the program a figure for the required change in height. The program then calculates the downward (negative figure) or upward (positive figure) continued magnetic profile by multiplying the raw Fourier coefficients by an exponential function with change of height and length of profile in the exponent, and passing the filtered coefficients through the reverse FFT. Such filtered profiles, as well as any of the transformed profiles mentioned in the next two sections, can be saved in a SAVMAG file for further use; see the description of the SAVEMAG facility.

#### *Vertical derivatives*

The  $n^{\text{th}}$  vertical derivative can similarly be calculated by multiplying the Fourier coefficients by an exponential expression, with the order of the derivative in the exponent, and passing the new coefficients back through the reverse FFT. The user has to give the program the order of the required derivative. The resultant derivative profiles can be saved in a SAVMAG file.

#### *Low and high pass filtering*

The magnetic profile data can be low pass filtered by truncating the Fourier coefficients at the desired wave-number and passing the remaining coefficients through the reverse FFT. The

necessary information can be provided by marking the required wave-number with a cursor on a plot of the energy spectrum, or by giving a cut-off wavelength. The user can also plot and save a 'high pass filtered' profile, which actually shows the variations cut out of the profile by the low pass filtering.

### *Using MAPRAN1 in interpretation*

MAPRAN1 is a program well suited for use on new sets of data in order to get a general idea of the type of information contained. The analysis should always be performed on several, preferably closely spaced profiles, and results averaged over several profiles of nearly identical characteristics. The user should have a fair understanding of the influence of the conditions specified above. The program will produce results even if several of these conditions are violated, but the resulting depth determinations will be much less reliable. It will sometimes be necessary to divide profiles into several parts in order to isolate the effects of certain ensembles only encountered in parts of the profile. It should also be remembered that the digitising interval and total length of the profile influence the results. Finally it should be checked that the basic assumption of prismatic, horizontally to infinity extended bodies is reasonable. In practice this means that the length of the bodies perpendicular to the direction of the profile should be four to five times the width of the bodies along the profile.

## **MAPRAN2**

This program can only be operated at present as a batch program. It may however be implemented in a demand version later.

The original program by A.Cooper (personal communication, 1974) was implemented at RECKU after some systematic and numeric changes and adaption of the program to the conventions used for MAPRAN programs.

### *Theory of the program*

The basic theoretical work is that of Nabighian (1972, 1974). The fundamental assumption is that the magnetic sources are uniformly magnetised, two-dimensional bodies with polygonal cross-sections. Nabighian (1972) shows that such bodies can be obtained by the superposition of a finite number of magnetised steps. Differentiating with respect to length along profile ( $x$ ) the magnetic attraction of such a magnetic step, an expression can be obtained for the horizontal derivative representing the magnetic anomaly of a thin infinite sheet. Taking the vertical derivative of the magnetic effect of a magnetised step it can be shown that the horizontal derivative is the negative Hilbert transform of the vertical derivative. Forming the complex analytical signal function from these two derivatives (analytical function  $A(x) = (\text{horiz. deriv. } (x)) - i(\text{vert. deriv. } (x))$ ), a number of interesting properties can be derived for use in magnetic interpretation.

The properties utilised in MAPRAN2 can be summarised as follows: (1) The amplitude of  $A(x)$  is a symmetrical function with respect to  $x = 0$ . (2) The complex  $A(x)$  has simple poles at

each corner of the polygon. (3) The amplitude squared is a bell-shaped function with the property that the 'bells' are centered over the polygon corners and the half-maximum half-width is equal to the depth to the polygon corner. In the general case of several complicated bodies or a magnetic interface, each corner in the irregular polygons composing the cross-section of the body, or each corner in the magnetic interface, will contribute a symmetric bell-shaped component, each of which will have the above mentioned relationship to its corresponding corner.

The program will go through the following steps in a depth analysis for thick bodies. The total field profile is differentiated with respect to  $x$  in order to obtain the horizontal derivative curve. Next a Fourier transformation, a spectrum modification, and a reverse Fourier transformation are performed, and the complex analytical signal function is obtained. From this the amplitude square curve is calculated, which will have a number of bell-shaped components. In order to identify these components the amplitude squared curve is deconvolved using a non-linear least square optimisation method. MAPRAN2 uses a routine developed by Marquardt (1963) which is similar to the method used in the iteration process of MAPRAN5 (see later).

The amplitude square curve can also be expressed in terms of magnetic susceptibility of the body, dip of polygon side, depth to polygon corner, and position of corner along profile. The bell-shaped curves will thus be controlled by these parameters. Before the optimising process can start, initial values must be found for the parameters, and these initial values will influence how well the final optimised model will fit the data. MAPRAN2 automatically finds a first estimate for the parameters using the following criteria after checking the local maxima of the amplitude squared curve. *Depth* is taken from the local half-maximum half-width of local maxima. *Magnetic susceptibility* is taken indirectly from the amplitude squared value at the peak of the local bell-shaped curve. Finally, *position along profile* is taken from the position of the peak of the local bell-shaped curve.

When these initial estimates have been made by the program it proceeds to obtain a trial solution by means of the least square optimisation process. This will result in a calculated amplitude squared curve which subtracted from the original curve will give a residual curve (in the numerical sense of the word). This is then examined in the same way to see whether any bell-shaped curves are still present. The final solution found by the program will be the best fitting curve obtained with the least square routine using all bell-shaped components found by the program. The depths and locations of the polygon corners are derived from the final solution to the amplitude squared curve.

If the user feels, or knows, that thin magnetic sources (here defined as thin if thickness less than depth) are present, a thin body analysis should be performed. The program will also do this. It is basically the same procedure with the exception that the total field profile is not differentiated as a first step.

The expressions derived by Nabighian (1972) also conveniently provide a new and easy way to calculate the total field profile reduced to the pole. This facility is included in the MAPRAN2 program. Such profiles can be stored in the SAVMAG file.

### *Using MAPRAN2 in interpretation*

Using the theory and procedures explained briefly above, MAPRAN2 will automatically produce depth determinations in the form of position along profiles and depth to corners of



polygons or points along a magnetic interface from magnetic profiles in a MPD1 file. The user has to guide the program regarding how many local bell-shaped curves should be included in the analysis and how far the iteration should be taken. The results produced by MAPRAN2 can, if the user so requires, be plotted in the form of CalComp plots of depth determinations together with plots of the original amplitude squared curve and the calculated curve. The program also provides ample information illustrating the course of the iteration. When the SAVEDEPTH facility is implemented in MAPRAN2, the calculated depths can be stored in a SAVDEP file and used elsewhere.

The depths produced by MAPRAN2 are given to the user in the form of points. These points represent corners of polygons or positions along a magnetic interface, where the slope of the magnetic interface is changing or where the susceptibility of the magnetic source is changing. It is up to the user to decide how these points should be interconnected in order to produce a model which is geologically relevant and will give a magnetic total field profile close to the original profile. The iteration process is based on amplitude squared curves and not on the original magnetic data. It will be a help for the user making these decisions to compare with the original magnetic profile, or even better with the profile reduced to the pole. Points found by MAPRAN2 can also be used as starting points for MAPRAN5 models, where the iteration can be continued on profile data, and the model may be more refined taking into account strike-length of the submodels. Some of the relationships in Nabighian (1972) can be used to obtain figures for susceptibility and slope of surfaces if one or the other is known or can be inferred. These values can also be used as input to MAPRAN5. Finally, Nabighian (1974) describes procedures by which the resolution of the method can be increased. These methods are not included directly in MAPRAN2, but a combination of facilities in MAPRAN1 and MAPRAN2 can produce the same increase in resolution.

### MAPRAN3

This program has been developed from an original program (ADEPT) by Phillips (1975, 1978, 1979). Phillips' method is concerned with finding the depth to a magnetic basement directly and automatically from a total magnetic field profile.

#### *Theory of the program*

The magnetic basement is here defined as a two-dimensional surface, which can be thought of as constructed of a large number of very thin vertical 'dykes'. The method assumes each of these dykes to be extended to infinity in directions perpendicular to the direction of the profile, and vertically downwards. The dykes terminate in an upper surface (the basement surface) at a certain depth below the profile. This depth can vary from dyke to dyke. A cross-section of all these dykes placed next to one another gives the topography of the magnetic basement. It is further assumed that each dyke has a magnetisation which may differ from that of the adjoining dyke. Both the basement surface, in terms of the depth to this surface, and the magnetisation of the dykes making up the surface, can be thought of as functions of position along the profile. The magnetic total field is also a function of position along profile, but in terms of the above model it can be thought of as the superposition of the

anomalies produced by each dyke. The problem is now to *estimate* the depth to the basement surface as a function of position along profile. Phillips does this by passing a short window along the magnetic profile, estimating a depth for each position of the window. All these depths are combined (see later) into the basement surface.

In order to calculate this numerically, it has to be assumed that the anomaly within such a given window originates entirely from sources at a certain depth. In that case the magnetic anomaly can be represented as the convolution of the magnetisation function and an impulse response function equivalent to the anomaly of a single thin dyke at a certain depth. Using known rules for the calculation of autocorrelations, this means that the autocorrelation for the magnetic profile is given by the convolution of the autocorrelation of the magnetisation function and the autocorrelation of the impulse response function. The latter is known, and the autocorrelation of the magnetic profile can be calculated within the window. Practical solutions for depth estimation can only be found if the magnetisation of each dyke is totally independent of all other dykes, or if the mean magnetisation of the basement is a constant, but with the magnetisation of each dyke varying independently around this mean. Phillips (1975) gives several formulas for the calculation of depths in both cases. Depth can be calculated as a function of sampling interval and the  $n^{\text{th}}$  lag of the autocorrelation of the magnetic anomaly. There will be one depth for each lag used. These depths for the whole profile are referred to by Phillips (1975) as the 'profile solution'. In later publications (Phillips, 1979) the expression 'primary analysis' is adopted. Depths can also be calculated as a function of sampling interval and depths calculated by the first formula. This is referred to by Phillips (1975, 1979) as 'implicit derivative analysis' and 'secondary analysis', respectively.

The program MAPRAN3 applies this theory at several stages. The input is taken from a MPD file, as the program has its own procedure for extending the number of points to an integer power of two. First, the mean of the magnetic field along the profile is removed. This can be followed by the removal of a regional trend in the form of a least square line. Next, the data is extended off both ends of the profile using a Burg prediction filter (Ulrych *et al.*, 1973). This filter smoothly drives the magnetic field to zero outside the measured profile using, however, a method different from that of RESIDUAL. When the extensions have been added, the profile is a periodic function with a length (number of points) of an integer power of two.

When the profile data have been thus prepared the actual depth determinations are carried out. This is a numerically quite complicated process, and only the principle will be explained here. For a full account of the functioning of this part of the program see e.g. Phillips, 1979.

The program first carries out the primary analysis. The user has to decide on the number of points in the window to be used over the profile, but the program will provide some guidance for this. For each position of the window several autocorrelations are calculated and averaged. It is a process of adaption using already calculated depths in the subsequent estimates. For each autocorrelation lag a depth is calculated. Altogether, four depths are calculated, as well as a parameter DIFF, which is the difference between the depths calculated from the first and fourth lags, respectively. In a number of plots the estimated depths, the DIFF curve, and other intermediate parameters calculated by the program can be displayed. A threshold value of DIFF can be decided upon by the user and applied in the interpretation (see later).

Next, the program uses the depths from the primary analysis in the secondary analysis applying the second of Phillips' formulas. As in the primary analysis a suite of plots can be produced. Here the DIFF is the difference between certain pairs of depth estimates.

### *Using MAPRAN3 in interpretation*

According to Phillips (1975) the depth estimates produced by MAPRAN3 must be interpreted using a *convergence of depth criteria*. From the primary analysis, four depth curves will be produced, each from a different lag of the autocorrelation function of the magnetic profile. Where these four depth curves converge, the depth estimates can be expected to be valid; where the four curves diverge, there is a discrepancy between the data and the model assumed by MAPRAN3. By choosing suitable upper and lower threshold values of the DIFF, the user can select the parts of the profile for which the depth estimates are valid. The threshold values can be chosen with a cursor positioned on a histogram of all DIFF values. The resultant, preliminary interpreted profile can then be plotted with different symbols for the parts of the depth curve, where the estimates are valid, and where they cannot be trusted for one of two main reasons. Comparing a DIFF curve and the corresponding depth estimates, it can be seen that the model can fail in two ways. If the depth estimates for higher lags of the autocorrelation function become significantly shallower, this suggests that the sources of the magnetic anomaly are three-dimensional, and therefore the corresponding depths should be rejected. The opposite case, where depths become significantly greater for higher lags, is evidence of correlated magnetisation or one-dimensional (very flat) topography of the magnetic basement. Also in this case the model is invalid, and the depths should be rejected. However, over a large area (many profiles), this can be used in the mapping of subareas of similar reaction to the method, which in itself can be of geological significance.

According to Phillips (1975) the best estimate is always the depth curve calculated from the first lag. However, in the case of three-dimensional sources this depth can be significantly shallower than the true depth. Conversely, in the case of correlated magnetisation or flat topography, the true depth will be less than the depth calculated from the first lag of the autocorrelation function of the magnetic profile.

Interpretation can be attempted with several different values of the threshold DIFF before going on to the next step in the interpretation. Different negative and positive values can also be used.

The same process can now be repeated with the secondary solution. The different meanings of the DIFF parameter must be remembered, it being now the minimum difference between pairs of the three depth estimates. If the DIFF value is less than the chosen threshold the depth given by the first or second depth curve, according to which is involved in the pair of depths mentioned above, will be the best estimate. The program will automatically adopt the best depth for DIFF values within the threshold interval.

The next step is to combine the two depth curves accepted from the primary and the secondary analyses, respectively. In this phase of the interpretation, the two possible solutions have to be brought into reasonable agreement. The program plots the two solutions superimposed on each other, and it may be necessary to analyse the plot and corresponding DIFF curves again, and decide on new threshold values in better agreement with the combined depth curves. Any available geological information should be used in this phase. If the interpreter feels reasonably certain that there is only one basement, and the two curves, nevertheless, do not agree, this means that the DIFF values will have to be changed in such a way that one of the curves comes out as the only depth. The cross-over points of the two depth curves can be used in this analysis. In other cases the existence of two different depths over the same parts of the profile may indicate the presence of more than one magnetic basement.

Using all the previous plots and all other relevant information, the user may now choose,

perhaps after a second calculation of depth curves, which parts of the depth curves of the profile under analysis should be used in the final result. This is done by means of the cursor, marking sections where the primary solution, secondary solution, both solutions, or neither solution are to be accepted. This final section can be saved in the SAVDEP file, to be plotted on maps later by ZMAP.

Phillips (1979) contains an example illustrating one possible way of using the results of a single profile following the above procedure.

## MAPRAN4

This is a GGU version of an original program by McGrath & Hood (1973). The GGU version was developed on the basis of the original source text of this program (P.H. McGrath, personal communication). The original program was a batch program. MAPRAN4 is a demand program with the usual MAPRAN facilities.

### *Theory of the program*

McGrath & Hood (1973) show how many geologically relevant shapes of bodies may be obtained through a numerical integration of the expression for the magnetic field produced by a finite thin plate. Geometric models like thin and thick sheets, horizontal bars, sloping steps, thin and thick plates, vertical prisms with finite or infinite depth extent, etc., can all be generated from a thin plate model. Each of the models is composed of a number of thin, dipping plates, and the magnetic effect of the ambient model can be calculated as a numerical integration of the magnetic effect of each of the composite plates. The thickness of the elemental plates is considered infinitesimal, and the distance between each of the plates will depend on a compromise between: (1) distance required to minimise the difference between the approximate value calculated by numerical integration using the parabolic rule, and the value calculated from an exact formula for a given model, and (2) reasonable minimum of computer time. McGrath & Hood (1973) base their accuracy demand on the thickness-to-depth ratio of a model and, following this, MAPRAN4 determines the number of plates to be used in the approximation of a body.

The models are described by a number of parameters:

- (1) Effective susceptibility contrast
- (2) Azimuth of polarising vector
- (3) Inclination of polarising vector
- (4) Origin shift along profile
- (5) Origin shift across profile
- (6) Strike length of body
- (7) Dip of elemental plates
- (8) Width of elemental plates
- (9) Depth of source body
- (10) Thickness of source body
- (11) Dip of upper/sloping surface
- (12) Base level

The profile input data to MAPRAN4 come from an MPD file which can be created from NEW (OLD) or the AMCONTOURS (NEWPROF) program. Before the above twelve parameters are initiated, the user has to provide some general information to MAPRAN4, such as an average azimuth for all the profiles which are supposed to be parallel. Along and across profile refer to this direction. The profiles to be analysed must also be chosen from the MPD file. If these have been created by NEWPROF they will be suitable for analysis without further treatment, if they have been created by NEW or OLD, some redigitising or selection of particular parts of the profiles (anomalies) may be necessary, and such facilities are provided by MAPRAN4.

The program uses non-linear optimisation in a combination of methods by Marquardt (1963) and Powell (1965). This combination, originally suggested by McGrath & Hood (1973), speeds up the iteration significantly. From initial estimates of the twelve parameters the program changes the model in such a way as to produce the least square best fitting magnetic anomaly curve(s) to the measured profile(s).

The program will carry out this iteration over several parallel profiles positioned over a three-dimensional body, or over just one profile, passing over the centre of the body. All model parameters may be changed in the iteration, but the user can lock the values of certain parameters if they are accurately known, or may give an interval to which the variation of a given parameter must be contained. The status of these conditions can be changed during the processing with MAPRAN4. The iteration can be attempted, the effect on the model observed and changes made to the parameters or their allowable variation. Both plots and prints will be provided to aid the interpreter in the evaluation of the process. The final accepted model can be saved in a SAVMOD file for later use.

#### *Using MAPRAN4 in interpretation*

The main reason why MAPRAN4 has been included in the program is to provide a possibility of interpreting three-dimensional structures on the basis of profile data, original or created from an anomaly map using NEWPROF. MAPRAN1, MAPRAN2, and MAPRAN3 all assume that the sources are two-dimensional. In the case of MAPRAN3 there will be indications if some of the source bodies are three-dimensional. The theory behind MAPRAN2 does not hold true if the bodies are three-dimensional.

MAPRAN4 is thus mainly intended for use on parts of profiles where three-dimensional bodies are thought to be present. MAPRAN4 only works well if one body is present, which can be described in the terms mentioned above. It will therefore often be necessary to limit the data under interpretation to precisely the parts of the profiles which are being studied and analyse each anomaly separately. If the data have been taken from a contour map, this presents no problem, since the profiles can then be created from the GRD file in such a way that they represent exactly the one circular or elongated anomaly under study. If the data are taken from a MPD file, the profiles will have to be shortened in order to represent just one magnetic anomaly.

MAPRAN4 works well on just one profile (with data from just one magnetic anomaly). The results will be comparable to results obtained with two-and-a-half-dimensional methods. If the extension of the model perpendicular to the strike of the profile approaches infinity, the results approach those from two-dimensional methods. MAPRAN4 can thus also quite well be used for least square optimisation of isolated elongated structures like faults and grabens.

In the case of isolated anomalies, approximations to the model obtained with MAPRAN2 can be refined with MAPRAN4 taking possible three-dimensionality into account.

When defining the model in terms of the 12 parameters it is important to get as much information as possible on all the parameters in order to be able to lock certain parameters, or at least put limits to their possible variation. The facilities of locking certain parameters can also be used to test the effect of single parameters of a given model. It is always advisable to test out a model in as many ways as possible, and this is done very easily using MAPRAN4.

## MAPRAN5

As MAPRAN4 works only on isolated simple anomalies a second modelling program working on complicated geological cross-sections is necessary. This is provided in MAPRAN5, a demand orientated program dealing with the creation of models representing whole geological cross-sections and the fitting of these models to observed magnetic data. This program is being tested at the time of writing.

### *Theory of the program*

The basic theoretical work is that of Talwani & Heirtzler (1964) using two-dimensional bodies with polygonal cross-section. The actual program, however, has been based on the work of Johnson (1969) and using the suggested two-and-a-half-dimension modification of Shuey & Pasquale (1973). This modification means that the models can have finite strike length or half length.

Briefly, the method is based on models of polygonal cross-section. The magnetic effect of the body is calculated as the combined effect of a number of prisms, of which the terminating faces are the sides in the polygon. The effects must be added with proper regard to sign. In the algorithm originally suggested by Talwani & Heirtzler (1964) this effect could be calculated assuming that the structure was two-dimensional. Shuey & Pasquale (1973) suggest a modification which allows the structures to be of finite extent, and a corresponding algorithm, which is simpler and cheaper to use than the algorithm of Talwani & Heirtzler (1964). Although the theory of complex mathematics is used, as in MAPRAN2, the theorems of Nabighian (1972) do not hold true in the two-and-a-half-dimensional case and thus cannot be used in MAPRAN5.

In MAPRAN5 a model is built of a number of *submodels*, each given by an arbitrary, polygonal cross-section, a finite strike length, and parameters of magnetic properties. The program has a number of facilities for defining the model of a particular profile using data files and screen cursor. The program can be used both for calculation of the magnetic effect of a model and for comparison with observed data. An iteration process is under construction to obtain a least square best fit between observed and calculated magnetic data. Parameters can then be completely locked, or variations of any parameter can be confined to a user-defined interval around the initial values, as in MAPRAN4.

MAPRAN5 has a facility for storing models for later use in other programs or for later renewed analysis using MAPRAN5. This is the SAVEMODEL facility described below.

### *Using MAPRAN5 in interpretation*

MAPRAN5 is best used as the final check on an interpretation of a magnetic profile. The other interpretation modules focus on different aspects of interpretation, and they all provide information which can be utilised in the construction of a final geological model. MAPRAN1 provides statistical information on depths and transformed profiles, which can be used further by the other programs. MAPRAN2 produces depths to corners of polygons or to points along a magnetic interface and assumes the same model as MAPRAN5 with the exception of infinite strike length of the structure. These points can be made part of the model information to MAPRAN5 and then be further refined as MAPRAN5 is not limited to two dimensions. MAPRAN3 will give depth curves for segments of the profile and tell the user where other, perhaps three-dimensional models will have to be used. That information can be used directly in MAPRAN5. Finally, MAPRAN4 is very good for the analysis of single anomalies, and structures emerging from such analysis can often be approximated in terms of a polygonal cross-section and a strike-length and can be part of the model for the whole profile analysed by MAPRAN5.

From all these analyses the user will also have a fair idea of the uncertainty in the various parameters in the composite model to be analysed by MAPRAN5. This information should be used to minimise the acceptable variation on parameters which, according to the other methods, seem to be well-determined. The final refinement of models can take place mainly by changing parameters which are quantitatively less well known.

### **The SAVEMAG facility**

This is implemented in MAPRAN1 and MAPRAN2. The facility makes it possible to store a magnetic profile which has been produced by some transformation of the original magnetic data resulting in a filtered magnetic profile. A given SAVMAG file may contain several versions of a profile as long as the transformations used are different. The basic idea is to have one SAVMAG file for a given area under interpretation, but special SAVMAG files made for a specific purpose can of course also be used. The program INTERCOM allows the interpreter to create new data files in GBT or MPD format containing selected profiles from the SAVMAG file (see the description of INTERCOM).

### **The SAVEDEPTH facility**

MAPRAN2 and MAPRAN3 have a facility for storing depth information in a form and manner similar to that used in the SAVMAG files. The information is stored with details on the method used in the production of the depths, and the facility can be used in a number of different ways when actually storing the data. With SAVDEP files as input the program ZMAP can produce printed tables of information, or plots of specified information, or of all information contained in the SAVDEP file.

### **The SAVEMODEL facility**

In MAPRAN4 and MAPRAN5 a model of individual bodies or a whole geological cross-section can be produced. In order to save these models and make them available for renewed interpretation with the two programs, a facility for storing such models is being developed. In principle it is similar to the SAVEMAG and SAVEDEPTH facilities, and the SAVMOD file is equivalent to the data files used in the other two cases. A particular model is characterised by profile number, model number and version and method. The user can thus save models and later update them with new information or through one of the iteration processes of the above programs. The model data will also be available for plotting programs allowing the data to be plotted on maps (ZMAP).

### **INTERCOM**

Through the methods of several of the MAPRAN programs, a number of transformed magnetic profiles can be generated. In order to make these available for re-analysis and for plotting on a map (TRACK and AMCONTOURS), the transformed profiles can be selected from the SAVMAG file according to the criteria for the manner in which the transformed profiles are stored in the SAVMOD file, and the data can be rewritten in GBT format or MPD format without changing the original SAVMAG file.

### **ZMAP**

This program is under construction and will make it possible to plot the information in SAVDEP and SAVMOD files on a map of an area under interpretation. Input to the program is one of these data files together with criteria for the search for relevant models or depth determinations. The data on depths and models will be represented in a number of ways.

## **THE GRIDOP SYSTEM**

The development of this system of programs was started at the beginning of 1981, and only the programs described below are operational at the present time. Other programs in the GRIDOP system will also operate on gridded values of the magnetic field as represented in the GRD file produced by AMCONTOURS. One group of programs will carry out transformations or filtering of data and produce a new GRD file with new values in the grid points, but otherwise similar to the input file. Such filtered data can then be contoured or used in profile interpretation via NEWPROF. Another group of programs will be concerned with the interpretation of three-dimensional data and will produce information on depths and structures in map form.



## GRIDOP1

This program calculates certain statistical parameters based on values of the magnetic field at grid points as stored in a GRD file. For instance, the total number of grid points within the limiting polygon (see description of GRID) can be obtained together with a corresponding histogram. Such information is valuable when planning contouring parameters and when preparing for print lay-out of the contour maps to be produced. These facilities are operational in demand mode.

## GRID2

This program calculates derivatives and upward and downward continuations of gridded magnetic data in the traditional way according to the formulas of Henderson (1960). The program is that of Rudman & Blakely (1975) implemented at RECKU after some minor alterations. Besides the printer output described in Rudman & Blakely (1975), it can also deliver the output field in a GRD file for further treatment. The program has been included in the system mainly to provide a well-known and well-tested method for comparison with newer methods.

## RSDRIVER

Recently a new program has been added to this group of programs. It has been developed by Geokon A/S following specifications by the author and partly using existing programs at RECKU. It provides a software interface between the programs described in this report and program packages for computer graphics available elsewhere. One or several GRD files (see description of GRID) can be used as input and from these the program will produce a raster type data file, and further produce from this graphical output in one or more of the following forms: printer plot with contours simulated by various letters, matrix printer plot with grey tones, and magnetic tape for use on an Applicon colour plotter. Scale, resolution, dynamic range of data etc. are under the control of the user, although default values are available. This program will be used for the production of regional aeromagnetic maps in colour.

## FUTURE DEVELOPMENTS

The programs of the AM system are constantly being updated and optimised in order to keep up with the facilities available and in order to include new methods. The main efforts are at present being concentrated around the interpretational programs in the MAPRAN system and the GRIDOP system. In the MAPRAN system the MAPRAN5 module is being completed now, and the SAVEMODEL and SAVEDEPTH facilities are being tested. The design of

some additional GRIDOP programs is also well in progress. A couple of programs providing shortcuts through the system for large amounts of data are being made as batch versions of the corresponding demand modules in the system.

As stated earlier, a shift of emphasis from development to production took place during 1982. This will mean that fewer new programs will be implemented in the following years, and efforts will go towards an overall improvement of the system. However, if significantly better methods are developed they will gradually be included in the system. Programs for another entrance into the system for other kinds of magnetic data, shipborne or ground measurements, are being tested. The interpretational methods contained in the system also work well on such data.

### Acknowledgements

In the course of the development of the programs described here it has been a pleasure to work with colleagues at home and abroad who have supplied programs, offered comments, tested programs, and discussed methods. The cooperation with Geokon A/S has been especially rewarding. Acknowledgements are gratefully expressed to all.

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ISSN 0418-6559

AiO Tryk as, Odense