THE PROCESSING AND INTERPRETATION OF LONG WAVELENGTH AEROMAGNETIC ANOMALIES

A THESIS

PRESENTED TO

THE FACULTY OF GRADUATE STUDIES

UNIVERSITY OF MANITOBA

IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE, GEOPHYSICS

BY

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OCTOBER 1980

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A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

ABSTRACT

Digital data processing techniques are now available and widely used in the study of aeromagnetic surveys. It allows detailed analysis to be made of the shallow and deep crustal magnetic units and also enables the short and long wavelength anomalies to be separated and evaluated.

The origin and nature of the long wavelength anomalies are believed to be closely associated with the deep crustal magnetization. These deep crustal magnetic units in turn are related to crustal structure seen on surface geologic maps. The processing sequence of aeromagnetic data that yields long wavelength aeromagnetic anomalies is compiled and evaluated in this study. Different digital processing techniques are examined and employed in an attempt to put together an efficient aeromagnetic processing system.

A long wavelength aeromagnetic map portraying deep crustal magnetic anomalies in the project area (60.00 to 61.75 degrees North and 102.00 to 94.75 degrees West) is presented. The derived map shows a definite alignment of various long wavelength aeromagnetic anomalies of different sizes in a Northeast-Southwest and East-West orientation. As an aid to the interpretation of these aeromagnetic

anomalies, a method of "inverse" depth and magnetic intensity determinations is introduced. The automated interpretation method is based on the optimization of the best fit anomaly field generated by a vertical-sided prismatic model. This interpretation procedure has eliminated the use of the tedious method of type-curve fitting and manual calculations.

The long wavelength anomalies show a good correlation with the broad features of deep crustal structure. The regional geology of the surrounding areas is reviewed and a strong relation between the long wavelength anomaly system and a major structural feature is found.

ACKNOWLEDGEMENTS

The writer wishes to express his sincere thanks and gratitude to Dr. D.H. Hall of the Department of Earth Sciences, University of Manitoba, for his supervision and for his invaluable advice and encouragement during the various stages of this project.

Thanks are due to Dr. A.G. Green for his help and advice on various research problems that arose during the period of this study.

The invaluable discussion and assistance provided by Mr. C. Hasselfield during the difficult time in programming and processing in this project is much appreciated.

The author also gratefully acknowledges the receipt of a student Fellowship and Assistantship from the Department of Earth Sciences of the University of Manitoba.

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CHAPTER 1

INTRODUCTION

When the total anomaly system composed of short wavelengths anomalies are filtered out of an aeromagnetic map, there remains a realtively broad-trend, low-amplitude and long wavelength anomaly field. These anomalies are termed long-wavelength aeromagnetic anomalies.

Long-wavelength aeromagnetic anomalies show considerable correlation with broad crustal structure and provide valuable information in the study of magnetic units lying in the upper and lower layers of the earth's crust. The present study is part of a continuing program of detailed deep crustal magnetic investigations in Manitoba with extensions up to the Northwest Territories.

In recent years, there has been a rapid development in the digital processing techniques of geophysical data. This study deals with the digital processing and interpretation of aeromagnetic data located in the Northwest Territories directly north of the Manitoba provincial boundary. An attempt is made in this thesis to develop a more efficient processing sequence for regional magnetic anomalies,

including the design of a two-dimensional filter for the aeromagnetic data in the frequency (or wave-number) domain. This is achieved with the fast Fourier transformation algorithm developed by Cooley and Tukey (1965).

Two-dimensional aeromagnetic data can be converted into the frequency domain by applying the forward Fourier transformation. The procedure of using one-dimensional transform to calculate the two-dimensional transform is used so as to cut down the available storage space and computing time. Pretreatment of data is essential. The presence of undesired spikes and trends were acknowledged and a computer program package was written to carry out every step of the processing sequence including the filtering of high frequency components of the anomaly field in the frequency domain.

McGrath and Hall (1969) developed a seventeen-point numerical filter in the space domain to remove short wavelength anomalies from an aeromagnetic map. Linear filtering in the frequency domain is under investigation here and a comparison of the nature of the two types of filter is done on the aeromagnetic map in this project. Moreover, various attempts have been made to display the frequency response of the frequency domain filter.

A great deal of interest has been laid on the representation of potential field data in the frequency domain. For

this reason, spectral analysis has become a routine and essential technique in the processing of aeromagnetic maps. One dimensional power spectrum analysis was performed on a few profiles running east-west within the area of concern. Two dimensional power spectrum was also displayed on part of the area. The Maximum Entropy Method for the power spectral density estimation as developed by Burg (1967, 1968) is also reviewed in this thesis and it was experimentally investigated on a few profiles across the area to serve as a comparison to the more conventional power spectral estimation via the fast Fourier transform algorithm.

One of the major characteristics of deep crustal magnetic anomalies are their low amplitude. The amplitudes of this type of anomaly are often less than 200 nanotesla. This is because of the vertical magnetic field decreases as the depth of source increases. Hence the core generated background field plays an important role in the interpretation of the long wavelength aeromagnetic anomalies. A computer Fortran program issued by the Institute of Geological Sciences, Hailsham, Sussex was used for computing the background field values of the project area. It is based on a specified model adopted after the International Association of Geomagnetism and Aeronomy (IAGA) Symposium held in October, 1968 and is termed as the International Geomagnetic Reference Field (IGRF).

The question of uniqueness and ambiguity of potential field interpretations have been discussed by Skeels (1947), and by Roy (1962). For a given magnetization distribution, there is always a predictable magnetic field but the inverse is not always unique. A given magnetic anomaly field may be caused by an infinite number of magnetic distributions and no unique solution can be clearly defined. In the present project, a direct interpretation using the BLOCK model-fit by Coles (1973) was first used for the anomaly interpretations. Then, an inverse problem[1] was set up, with the input of the field values and using optimization processes, the configuration of the blocks that were most acceptable both physically and geologically were then determined.

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1. The computer program "INVBLOCK" to provide an indirect iterative method to solve the inverse problem was originally derived and implemented by Mr. C. Hasselfield, programmer, Geophysics Section, University of Manitoba.

CHAPTER 2

DIGITAL PROCESSING OF AEROMAGNETIC DATA

2.1 Processing Sequence

The long-wavelength aeromagnetic anomaly system can be separated from the local anomalies due to shallow, narrow sources by eliminating the high wave number (short wavelength) components of the aeromagnetic map. This can be done in several ways; for example, by upward continuation of low-level magnetics. Alternatively, based on the difference in the frequency (wave-length) characteristics of the two major anomaly types, direct filtering can be used. The processing sequence used here for the preparation of the long-wavelength aeromagnetic maps was based on the direct wavelength filtering technique.

Figure 2.1.1 is a flow diagram of the processing sequence of the digitized aeromagnetic map. The computer program FILTER 2D in Appendix B is a FORTRAN routine based on this sequence.

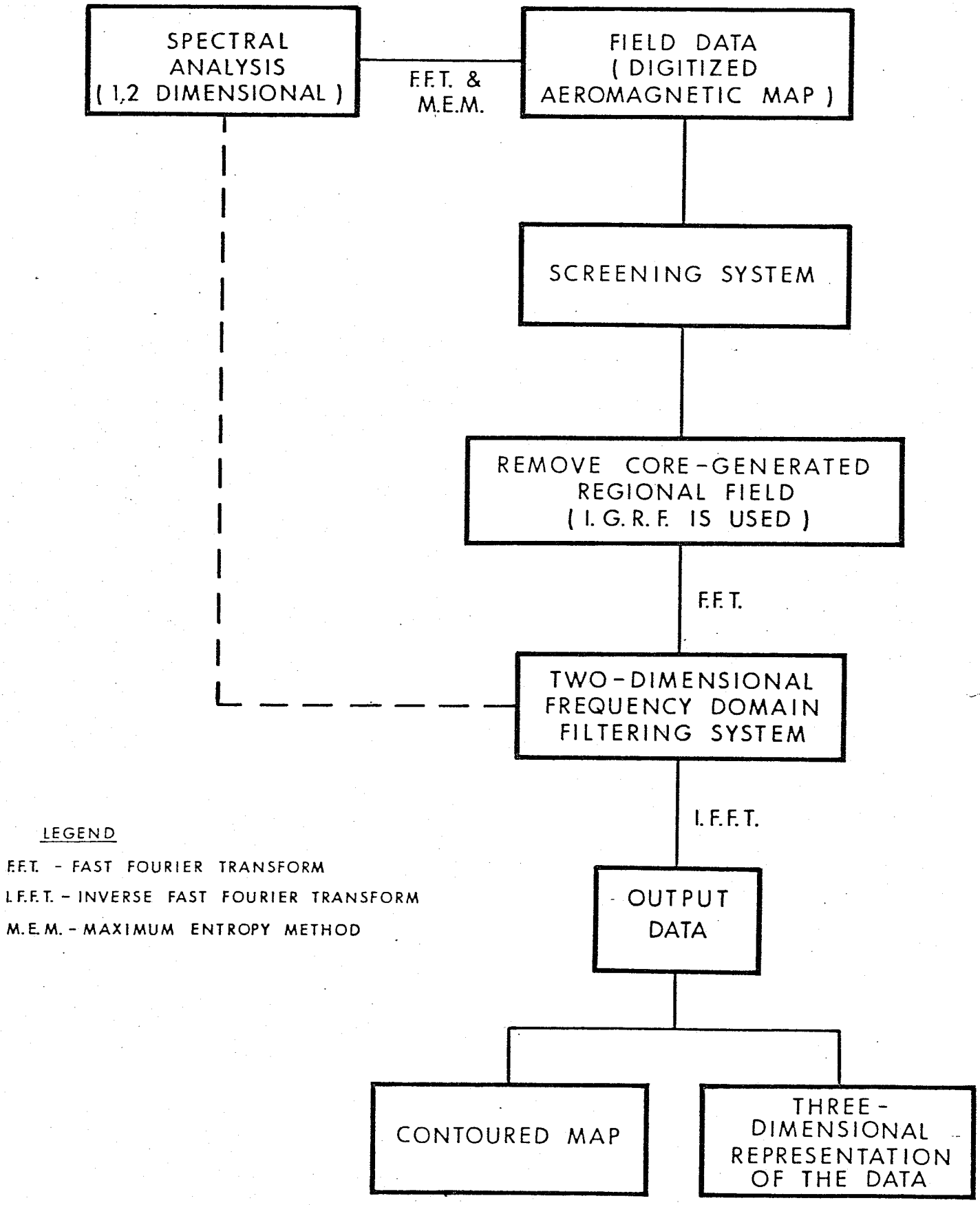

FIGURE 2.1.1. FLOW DIAGRAM OF THE PROCESSING SEQUENCE

It is assumed that the input map consists of digitized data on a regular spaced square or rectangular grid. The sampling (or digital) interval must be equal in the x and y directions.

Both one and two dimensional power spectra were constructed on the data. This analysis provides a spectral scan of the frequency contents of the input map before the filtering technique was applied. Details of the spectral analysis can be found in a later chapter.

Preconditioning of data is also very important. Different screening and smoothing operations were done on the input data before passing the map through the filter system.

After the above steps had been accomplished, the data was then passed into the filter system. Direct filtering in the frequency domain was used in this study. The filter was designed for a series of different cutoff wavelengths and impulse-response of the study map area. To aid interpretation, different displays both in contour map and three-dimensional representation forms were drawn using the IBM calcomp plotter.

2.2 Two-Dimensional Frequency Aliasing

Frequency aliasing is a well-known effect caused by the insufficient sampling of a signal frequency. It occurs when a band limited function is sampled at interval that exceeds $\frac{1}{2fi}$ where fi is the highest frequency component of interest recorded.

For two-dimensional data, such as the potential field data, it is necessary to digitize the data from the maps at a suitable sampling interval. A small sampling interval may be desirable since it enables us to study the shorter wavelength anomalies and throw out the aliasing problem. However, one should be aware of the computer limitations in analysing enormous amounts of data and the tedious digitization problem.

Analogous to the one-dimensional case, two-dimensional frequency aliasing rule can be obtained. In order to avoid frequency aliasing when sampling a continuous function band-limited at frequencies of K and L, the sample interval must be selected so that

$$\Delta x \leq \frac{1}{2K} \quad \text{and} \quad y \leq \frac{1}{2L}$$

In the present project, long-wavelength anomalies with wavelengths usually greater than 60 km are of major concern,

hence, K and L have very high values. The sampling interval of 6.5 km in both x and y directions were selected for the project. This sampling interval was found to be sufficient and reasonable in the computer processing viewpoints and it was done by decimating the unwanted data points in the original data.

2.3 Preconditioning of Data

Preconditioning of data is essential and necessary, especially when filtering in the frequency domain. Spikes appearing in the data, due to digitization error or other data preparation errors, produce problems in the frequency filtering process. It will produce output in the Fourier transform at all frequencies and it must be removed with a search and screening routine. One of the simpler devices for testing doubtful observations is known as "Chauvenet's Criterion of Rejection", according to which rejectability is determined as a function of deviation, dispersion, and number of measurements. This criterion was used in this study as the selection system of the input data set[1]. The standard deviation was first determined and a dispersion of ± 3 standard deviations was found to be the bound of the input data

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1. The "Chauvenet's Criterion of Rejection" was first designed and programmed by P. McGrath, University of Manitoba.

set. The data values which exceed the boundary limits will then be cut down to the appropriate boundary values. This not only served the purpose of removing unwanted spikes, it also removed the anomalous peaks which might result from local iron formation.

Additional rows and columns of numeric zeros were added to the data matrix during the data preparation stage in order to satisfy the prime factor assumption of the fast Fourier transform algorithm (see Section 2.4). The presence of these zeros in the data matrix introduced a step-like function at the boundaries and severe edge effects resulted if they were not eliminated. This search and elimination process was also introduced into the screening system of this project. This was done by means of replacing numeric zeros found in the input matrix by the average value (or mean) of the data set.

If the data have a regional trend, spurious components at all frequencies will be introduced in the Fourier Transform. Best-fit plane produced by a least-squares fit has been commonly used for regional trend extraction. The plane was subtracted from the data set to produce a new set of data with zero regional trend. This approach was not used in the present study. Instead, a numerical model of the sufficient complexity, including adequate secular variation correction was used as a suitable representation of the

regional field. This is the best known and most widely used field model: the International Geomagnetic Reference Field (IGRF). The IGRF values were computed at every grid point of the data matrix by means of a computer program[2] and it was subtracted from the field value at that grid point. This removes the regional trend from the data before the filtering process. A more detailed account of the IGRF surface can be found in Section 2.5.

2.4 The Fast Fourier Transform

The Fourier transform has long been a principle analytical tool in such diverse fields as linear systems, optics and signal analysis. The advent of the development of the fast Fourier Transform (FFT), an algorithm that efficiently computes the discrete Fourier transform which reduces the enormous amount of computation time adds even more applications to this powerful analytical technique. The fast Fourier transform algorithm was the principal tool used in this thesis to study the potential field data.

The potential field data f(x,y) is considered as a mixture of random noise and aperiodic signals. The spectral

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2. Computer program supplied by the Institute of Geological Sciencies, Haillsham.

decomposition of the potential field data f(x,y) can be represented by the following complex Fourier transform relations in the digital domain.

$$F(K_1,K_2) = \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y) \; e^{\frac{2\pi i}{N}(K_1 x + k_2 y)}$$

for $K_1, K_2 = 0,1,2, \ldots (N-1)$

and conversely

$$f(x,y) = \frac{1}{N^2} \sum_{K_1=0}^{N-1} \sum_{K_2=0}^{N-1} F(K_1,K_2) \; e^{-\frac{2\pi i}{N}(K_1 x + K_2 y)}$$

for $x,y = 0,1,2, \ldots (N-1)$

where $F(K_1,K_2)$ are N complex-valued vectors. The wavelengths λ_1 and λ_2 are given by $\frac{2\pi}{K_1}$ and $\frac{2\pi}{K_2}$, where K_1 and K_2 are the wave-numbers along the x and y directions.

The fast Fourier transform was developed from these fundamental equations. The criteria for the formulation of these equations and their various properties have been dealt with thoroughly by Good (1958), Cooley and Tukey (1965) and Gentleman and Sande (1966). In general, direction computations of the Fourier transform require N^2 operations, where N is the size of the input vector. Fast Fourier transform (FFT) algorithm offers a much faster route of less than $KN\log_K N$ operations (K is a factor of N). In other words,

one can obtain the transforms $(\frac{N^2}{KN\log_K N})$ times faster. The accuracy of the results is also increased by the same ratio.

The fundamental basis of the fast Fourier transform algorithm is to decompose each data vector into simple factors. (For example, $N = K_1 \cdot K_2 \cdot K_3 \cdot \ . \ . \ K_n$). Then, the elementary transformations were followed by a permutation sorting procedure to produce the required coefficients. In the same manner, a two-dimensional data set such as the aeromagnetic field data in this project can be considered as a vector (size N_1 by N_2) of length $N = N_1 N_2$ which the fast Fourier algorithm can be applied in the usual way.

2.5 Background Field Analysis

The earth's total magnetic field is composed of the field generated by the earth's core plus anomalous fields which are attributed to the magnetic properties of shallow and deep crustal sources. An important application of aeromagnetic surveys is to interpret the magnetic properties or characteristics of deep crustal magnetic sources. These deep magnetic sources generate long wavelength anomalies which are often low in amplitude, usually less than 200 nanotesla. As a result, the core generated background field plays an important role in the interpretation of the long-wavelength aeromagnetic anomalies. This core generated field