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FROM ANALOG AEROMAGNETIC CONTOUR MAPS TO ENHANCED COLOUR IMAGES: GETTING THE MOST FROM AN EXISTING POTENTIAL FIELD DATASET

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ABSTRACT

Flight-line profile data, digitized from aeromagnetic contour maps of the province, have been obtained from the Geological Survey of Canada. When gridded for image processing, these data exhibit the levelling errors that exist at boundaries between different survey blocks, discontinuities along individual map-sheet boundaries within survey blocks, and the levelling errors among adjacent flight-line profiles.

A project is currently underway to correct positional errors, contour labelling errors, and omitted flight-line segments in the data. Flight-line segments from adjoining map sheets are being merged interactively on a PC to reconstruct, as closely as possible, the original recorded database. Inter-survey levelling errors will then be effected and the corrected profile data will be gridded to a 150-m grid interval. Much of the levelling errors that exist between adjacent flight lines, will be efficiently removed by subsequent application of wave-number domain filtering. Finally, smaller grid segments will be joined to yield a single, corrected and levelled grid for insular Newfoundland, any portion of which can be made available to researchers in industry, university, other government departments and internally. This process is nearing completion for insular Newfoundland and the data will be made available in the immediate future. Similar processing will then commence on the aeromagnetic dataset for Labrador.

INTRODUCTION

Image analysis and enhancement of aeromagnetic data has proven extremely effective in extracting, subtle spatial features for a variety of purposes, and moreover, to present these features clearly. This type of approach aids both the data interpretation and presentation. To carry out the enhancement process, the data must be organized as a regular grid. To improve the final image, the many errors and inconsistencies that exist in the data must be identified and corrected. As these steps of error correction and gridding must always be done before image analysis, this project was undertaken to provide a corrected and levelled aeromagnetic dataset for the entire island of Newfoundland, gridded in such a way to retain as much as possible of the detailed information, while at the same time making the overall grid size (150 by 150 m) no smaller than necessary. This basic corrected, levelled and gridded version of the standard Geological Survey of Canada aeromagnetic data can be very rapidly and easily re-gridded on a PC to any interval size that meets the objectives of most users.

The Aeromagnetic Flight-Line Profile Data

In July 1988, digital aeromagnetic data, covering the whole of Newfoundland and Labrador, were received from the Geological Survey of Canada (GSC, 1988). Figure 1 shows the airborne magnetic survey blocks that comprise the coverage for insluar Newfoundland. Given the option of obtaining the data as flight-line profiles or as a standard gridded dataset, the former was chosen on the basis that the readily available grid intervals (812.5- and 200-m cell) and map projection (Lambert Conformal) may not be best suited for the scale or type of investigation at hand; a more representative grid could be be produced by gridding the original profile data than by averaging or interpolating from an existing grid. Since the original flight-line data were not recoverable, the points of intersection of contours with flight lines were digitized from 1 inch to 1 mile (1:63,360 scale) copies of aeromagnetic contour maps covering each 1:50,000 NTS map area. This method is considered the most accurate for reconstructing the aeromagnetic field because only the data recorded along flight lines, in the original dataset, were used to constrain contours of the field.

In addition to an uncertain amount of smoothing that was originally applied to the data to generate contour maps, a necessary consequence of this digitizing procedure is that 'sample density' is proportional to the variation in the aeromagnetic field. That is, the density of points defining an aeromagnetic profile in a particular area is determined by the density of contours, locally. Since the contour interval is 10 nT on these maps, subtle features in the magnetic field of amplitudes on the order of the contour interval are not well-defined in areas that are magnetically 'flat' or calm. As well, several aeromagnetic maps were digitized at *every* contour—

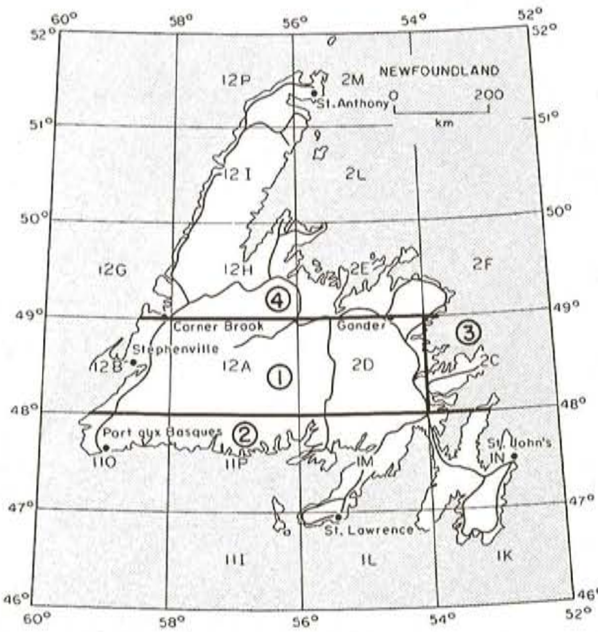

Figure 1. *Map showing locations of the four major survey blocks that comprise the regional aeromagnetic database for insular Newfoundland. Block 1, flown in 1953 using a fluxgate magnetometer, was not referenced to the total magnetic field of the earth. Blocks 2, 3 and 4 are surveys flown between 1966 and 1971 using a proton precession magnetometer referenced to the total magnetic field. All surveys were flown by the Geological Survey of Canada at a 320-m terrain clearance and flight paths were generally oriented east-west.*

flight-line intersection, whereas others were digitized with only those points deemed sufficient to define the field. Therefore, the data density or the resolution of the profile dataset, which ultimately dictates the resolution that can be attained in a gridded dataset, varies from sheet to sheet.

Several types of errors exist in the digitized flight-line profiles that are not readily apparent from initial plots of the gridded datasets. Foremost among these is incorrect assignment of the magnetic contour level at the contour–flight-line intersections during digitizing. This problem is especially prevalent in areas where an undulating magnetic field occurs near an NTS map sheet boundary, and where the contour levels are not clearly labelled on the printed maps. This type of error is expressed in the gridded data as a level shift across adjacent map boundaries.

Positional errors also exist in the digitized flight-profile data. The primary source of positional errors is improper registration of paper maps on a map digitizer causing all the coordinates of points for particular map sheets to be askew to varying degrees. In addition, certain flight-line segments may be missing from the data. This problem commonly occurs when a flight line, oriented east–west, lies very close to an east–west map boundary and crosses the boundary at several locations, such that small segments are missed during the digitizing.

Each of these errors cause 'edge effects' or distortions at map boundaries that, as a result of interpolation during gridding, render the boundaries visible. In addition, the fact that all digitized profiles terminate at map boundaries introduces discontinuities during the gridding process.

The Levelling Process

During the past year, the aeromagnetic profile data for individual 1:250,000 NTS map areas, were gridded to a 300-m grid-cell size, to yield gridded datafiles. The input datafiles for this process were constructed from profile datafiles for individual 1:50,000 map areas. Gridding was performed using a GEOSOFT bi-directional splining routine on a PC. The grid files for adjoining map areas were then merged as required to produce contiguous datafiles for larger areas. Grids from adjacent aeromagnetic surveys were 'levelled' along their mutual boundary by adding a constant to grid-cell values from each grid during the merging process. The grids that result, exhibit a distortion in the field along each 1:50,000 NTS map boundary. The distortion is a result of both systematic descrepancies in the positions of the ends of flight lines on adjacent map sheets and non-systematic errors in choosing the contour levels near each map boundary. In addition, systematic levelling errors occur between adjacent flight lines as well as between surveys of different vintages.

A program was written to interactively display and merge flight-line profiles from adjacent aeromagnetic maps. Design of the routine is more complicated than might first be supposed. The user is permitted to choose flight lines that join from either of two input files, modify or delete values at the junction and store the merged profiles in either of three output files. As successive profiles are highlighted on the screen, the positional and total-magnetic field values of the three last points of the profile segment from the first file are displayed, along with the first three of the adjacent second file, in addition to the flight-line numbers of highlighted profiles. As each profile is displayed, the user is allowed to cycle in either direction through the digitized points, encoding the magnetic value corrections where necessary. An option was added, which allows either profile segment to be reversed previous to merging or output. By choosing the sequence of profiles to join, ordered output datafiles are generated from disorganized initial files. Through iterative applications of the program to adjoining datafiles, flight-line profiles spanning several map areas can be reconstructed. Often, positional errors are made obvious just by the display of the flight-line profiles on the console (Figures 2 and 3).

The systematic positional error resulting from improper registration during digitizing is corrected by 'rubber-sheeting' digitized coordinates relative to their known values. First, a representative number (20 to 30) of digitized contour–flight-line intersections, evenly distributed throughout the improperly registered map sheet, are selected as control points and their incorrect coordinates, as listed in the datafile, are recorded. The corresponding points are then located on the paper contour and their correct coordinates digitized manually. A third-order, least-squares trend surface (Whitten,

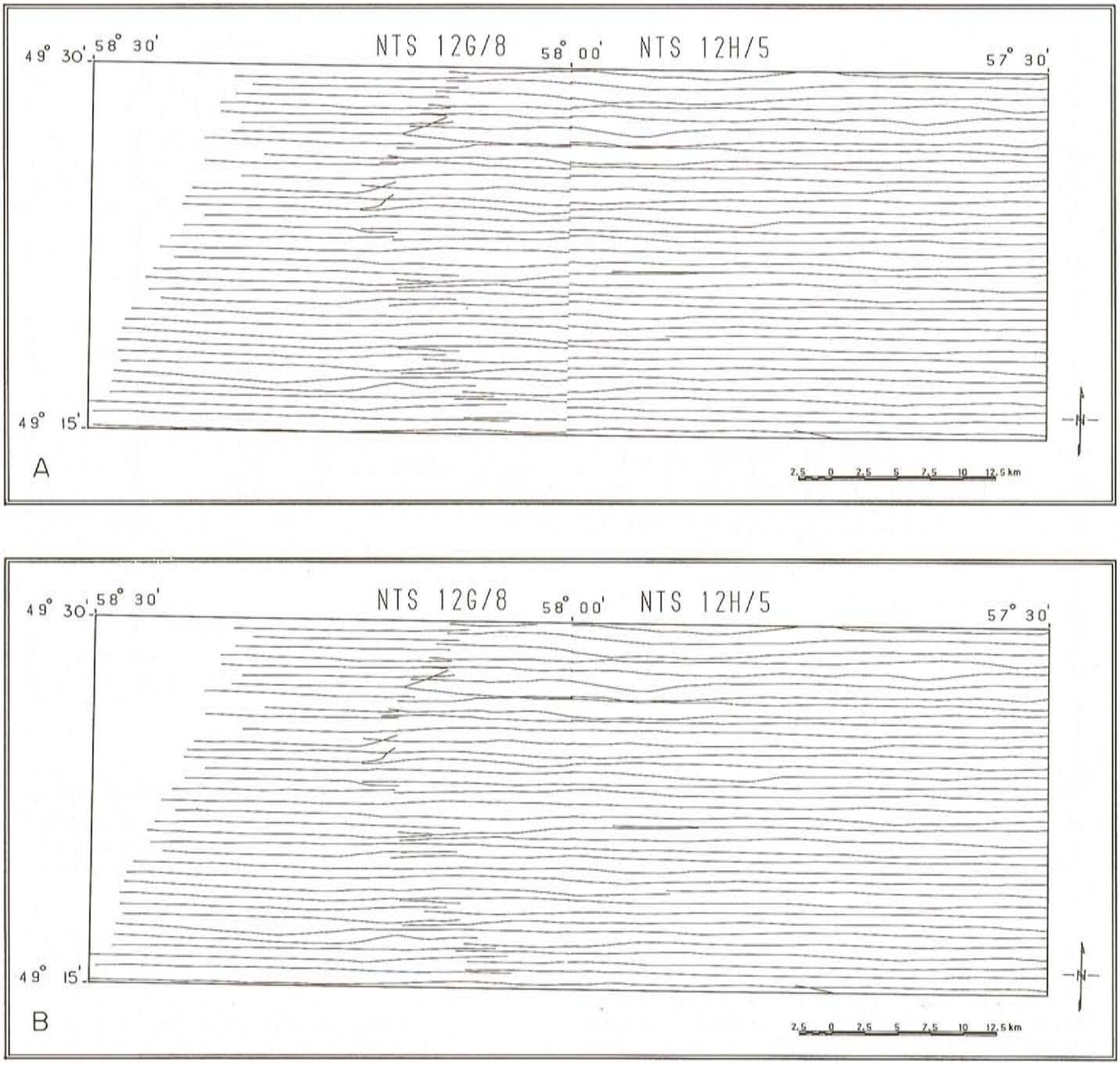

Figure 2. *Flight-line profile location map for map areas NTS 12G/8 and 12H/5, western Newfoundland, before a) and after b) application of 'rubber-sheeting' to correct for systematic positional errors that exist in the NTS 12G/8 datafile. Note in a, that the magnitude of positional errors in both the X and Y directions varies from north to south along the 58° W longitude boundary between the two datafiles. Also note that a portion of the third profile from the southern boundary (49°15' N longitude) is missing from the NTS 12G/8 datafile in a, and has been manually digitized and incorporated into b.*

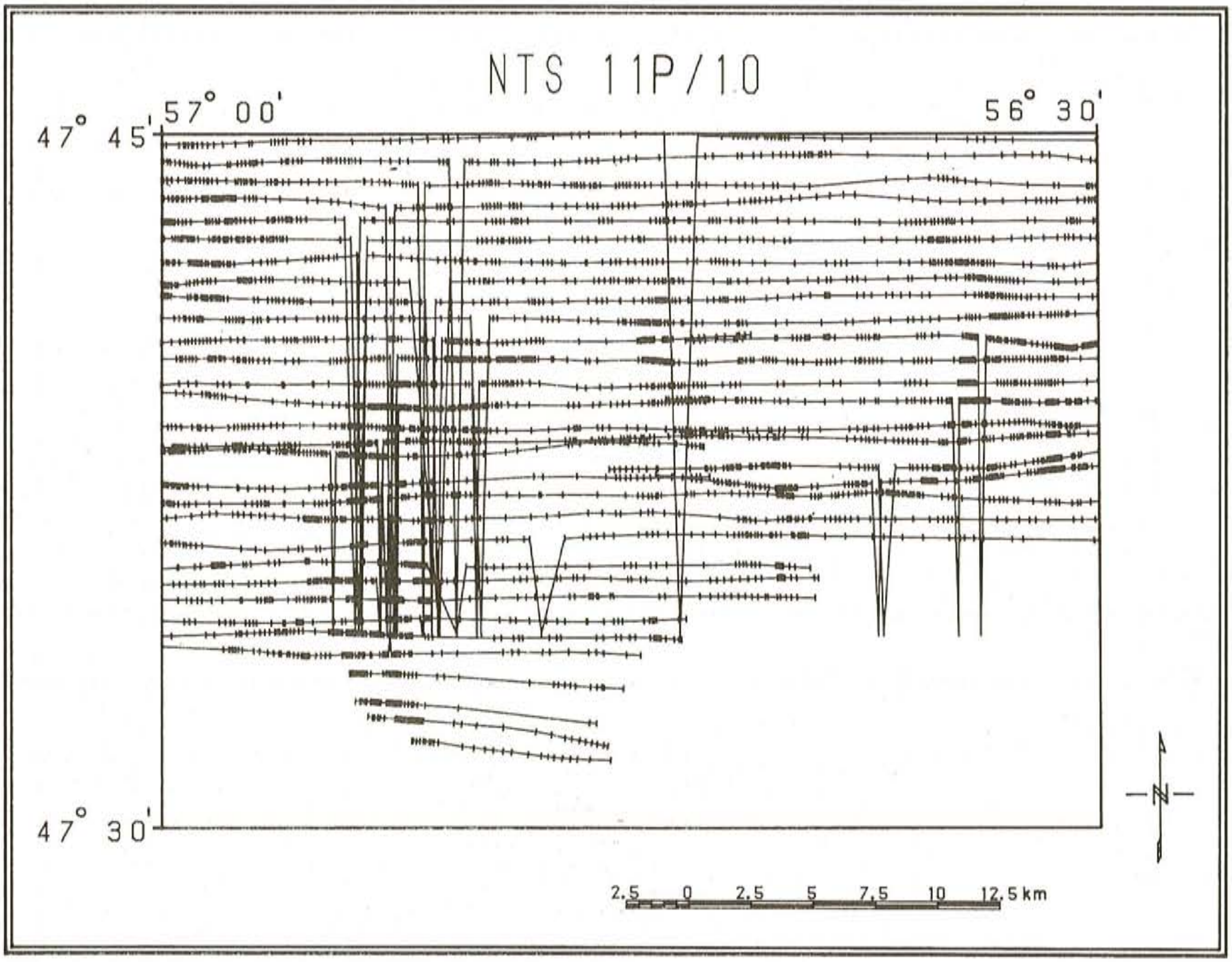

Figure 3. *Location map of flight-line profiles for NTS 11P/10, south coast, Newfoundland. Vertical tick marks along profiles are the digitized positions of profile/magnetic contour intersections and therefore their density is dependent on the local variation in magnetic field. Each spike, apparent in the data, is caused by an erroneous Y position of a single digitized point along each of the northern profiles.*

1971) is fitted through each of the spatial distribution of differences in both the X and Y locations of control points. The coefficients describing these surfaces are then used to calculate the corrections to adjust the coordinates of all points within the digitized magnetic map file. The occasional non-systematic positional errors (Figure 3), such as may be due to malfunctioning equipment, were corrected by manually digitizing coordinates and editing the datafiles.

Survey Boundary Levelling

The oldest GSC aeromagnetic survey block, occupying the region in central Newfoundland between 48 and 49 degrees North latitudes (Figure 1), was surveyed in 1953 using a flux-gate magnetometer, measuring variations in the vertical magnetic field and not referenced to total-magnetic field strength. Correction of the levelling error that exists between this survey block, and the adjacent survey blocks to the north and south, was handled in the following manner:

1) The east–west-oriented flight lines near, and to either side of the both survey boundaries are interpolated to produce sets of magnetic values at locations spaced at regular intervals in latitude.
2) Coefficients of low-order, least-squares, fit curves oriented perpendicular to the boundary (i.e., along constant longitudes) are generated from these interpolated values. These curves are then used to generate a set of magnetic values spaced at regular intervals (in longitude) along the boundary. Two sets of interpolated aeromagnetic values are thus generated for each boundary, one set from each survey located to either side of the boundary.
3) A single set of values are generated at regular intervals along each boundary from the differences

of the two sets of values interpolated at each boundary from either survey.

4) Two least-squares, low-order polynomial curves are fitted through the differences along either boundary. Difference values can then be generated at *any* location along each boundary. Corresponding sets of differences at opposite boundaries are linearly interpolated to obtain the correction, to be applied to any point within the survey block contained between the survey boundaries.

Low-order polynomials are used in the boundary-fitting process so that the high-frequency signal integrity may be maintained, while retaining the ability to correct for any relative tilt, which may exist between adjacent surveys. If, after levelling, local discontinuities still exist along the survey boundaries, a long wavelength taper may be applied to the data from either survey, near the boundaries. The above approach was shown to be effective, when similarly used, in a detailed geophysical study in western Newfoundland (Kilfoil, 1988).

Aspects of Gridding

Having applied survey-block corrections to bring all aeromagnetic data to a uniform level, the positional data will be converted to Universal Transverse Mercator (UTM) projection for the purposes of gridding. At the same time, the International Geomagnetic Reference Field (IGRF) will be subtracted from the data to reduce the aeromagnetic field to a constant datum.

A gridding interval must be chosen that maintains the maximum possible resolution that can be attained from the data, without creating a grid that is excessively large and cumbersome, for the projected use. The two are inter-related, as the data resolution restricts its possible uses. Considering the 300-m ground clearance during survey, a grid interval of 150 m was chosen as being sufficient to retain all the information contained in the data, even in regions of high magnetic variability.

Once the raw digital data has been corrected, the next step is to examine the gridding procedure used to generate a grid best representing the original dataset, as digitized from contour maps. During the early attempts at gridding, linear interpolation between points on individual flight lines was used to give values equidistant (300-m spacing) in the X direction. Minimum curvature splines (Akima, 1972; Briggs, 1974; Swain, 1976) were then fitted through all points of equal X, from which grid-cell values were determined at equidistant (300-m spacing) locations in Y. The initial linear interpolation used along flight lines can lend a 'chunky' appearance to the resulting gridded data, particularly evident when the grid is subsequently filtered. A smoother and locally more accurate grid can be generated by the GEOSOFT bi-directional (Bigrid) gridding routine by specifying minimum curvature spline interpolation in both the X and Y directions.

The GSC advocates use of a minimum curvature *surface*-fitting routine (Akima, 1974) for interpolating a smooth surface through unequally spaced data values. The Bigrid routine very closely approximates minimum curvature surface fitting, where the gridding interval is small and where the gridding is performed in incremental steps. However, for the sake of consistency, the routine of Akima (1974) was adapted to work on the PC and output a grid compatible with the Geosoft format.

Filtering

The final step in generating a consistent database is to filter the data, to remove any systematic error or 'noise' that remains subsequent to gridding. By far, the largest source of error that remains in the data is a result of systematic relative level shifts between adjacent flight lines. Flight-line levelling error can be caused by such factors as diurnal variation in the magnetic field that is not monitored for proper correction, positional errors in flight path recovery, and altitude errors. These factors are, in turn, influenced to varying degrees by weather conditions, relative flight direction, intrumental accuracy and survey location.

Since flight lines within any area are generally uniform in orientation (usually east—west) and relatively equally spaced, the magnetic variation due to flight-line levelling error has a characteristic signataure in the spatial frequency (or wavenumber) domain that can be detected and remedied. Knowing the flight-line orientation, the extent of systematic flight-line noise can be determined by applying directional filters that detect and pass only those wavenumbers in the transformed data that correspond to the flight-line spacing and in a direction perpendicular to the orientation of flight profiles.

The Geosoft Magmap software package takes advantage of the computational efficiency of the Fast Fourier Transform, to transform a gridded dataset to the wavenumber domain, thereby allowing digital filters to be applied. Indeed, the ease with which digital filters can be applied to the spatial frequency spectrum represents a major advantage of having data in digital form.

To generate a grid, consisting largely of flight-line levelling error, one can design and apply a high-pass Butterworth filter with a cut-off wavenumber corresponding to four times the flight-line spacing. The residual transform, composed of only variations in the magnetic field, having wavelengths shorter than the cut-off is then filtered with a directional cosine filter, which discriminates the spatial distributions of wavenumbers and passes only those in the direction specified, that is perpendicular to survey orientation. The wavenumber transform that results can be inversely transformed to the spatial domain to create a representative grid of flight-line levelling error. This noise grid is then subtracted from the original grid to correct the levelling error problem.

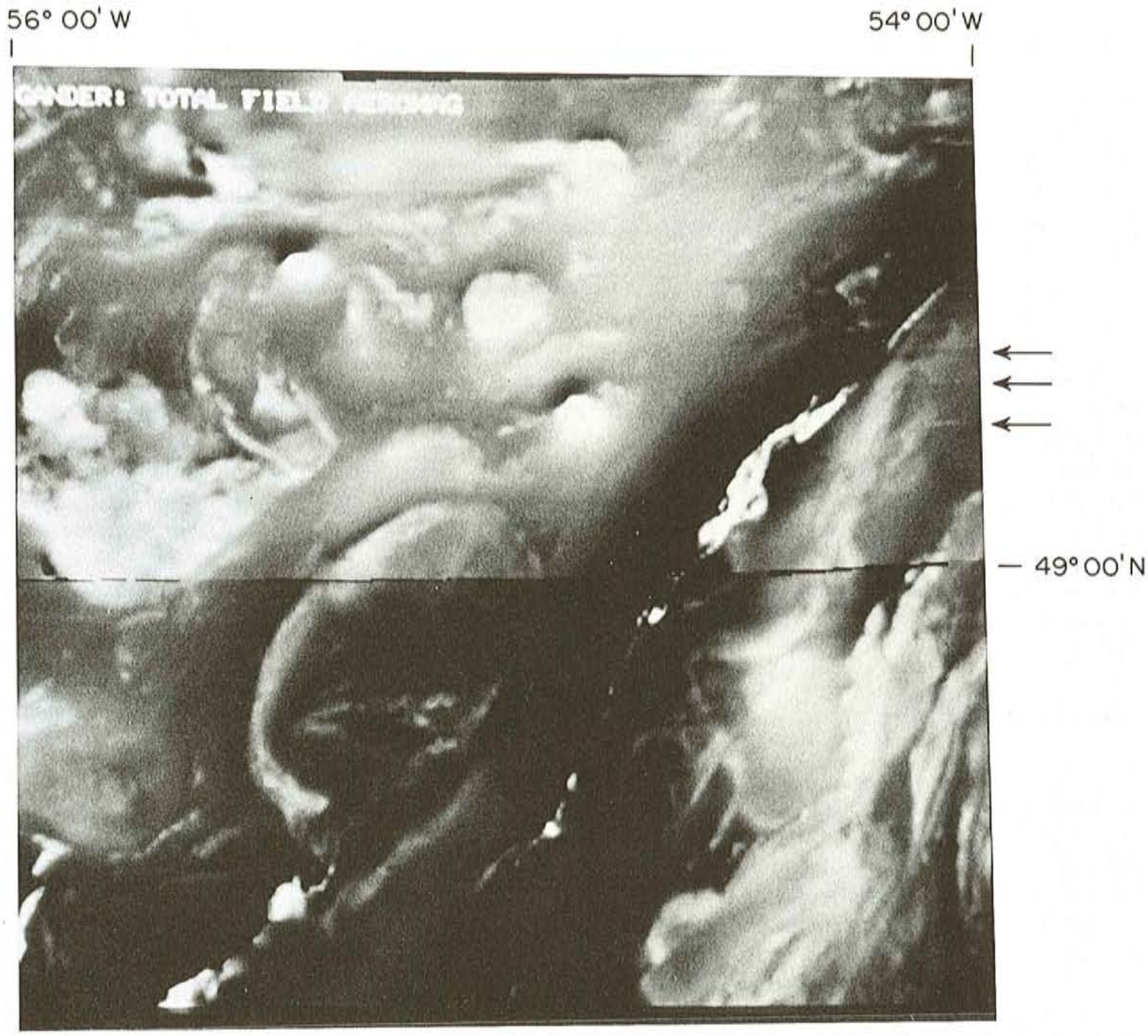

Plate 1. *Grey-scale image created by joining the gridded datasets for NTS 2D (lower) and NTS 2E (upper) 1:250,000 map areas, and by introducing false illumination from the southeast. The large oval feature, in the central region of the image, is caused by the Mount Peyton Intrusive Suite. In this image, note the obvious (east-west) break between the two map areas, the east-west lineations due to flight-line levelling errors (see arrows) and the subtler discontinuities (north-south) between individual 1:50,000 NTS map sheets.*

CONCLUSIONS

Once the correction, gridding and levelling has been completed for the various survey areas, a large, contiguous grid can be constructed by merging smaller grids from adjoining areas. Plate 1 displays an enhanced image that represents the results of an initial attempt at gridding the merged datafiles, for NTS map areas 2D and 2E, from central Newfoundland. The levelling error that exists along the east–west survey boundary (centre) of the uncorrected image is most apparent. The overall chunky appearance of the image and the discontinuities that trace individual NTS map-sheet boundaries may be observed upon closer inspection. These features, together with the flight-line levelling 'noise', will be virtually eliminated in the corrected dataset. Many of the errors causing discontinuities in the original gridded data could have been subdued using various filters, but only at the expense of a degraded resolution in the data signal. The PC-based merging program was designed to be as interactive as possible, in order to reduce the tedium involved with checking the digitized datafiles against their map copies for error detection.

The correction, merging of profiles and levelling of some 185 aeromagnetic datafiles digitized from analog contour maps from four separate survey blocks comprising insular Newfoundland is well underway. Once complete, the process will begin on digital aeromagnetic data from Labrador. Digitized aeromagnetic data from Labrador should present fewer problems, since the original data, being of more recent vintage, was referenced to total-field and was flown using more accurate navigational techniques.

The result of these labours will be a relatively noise-free archival data grid for the whole of insular Newfoundland,

and eventually for Labrador, from which any data window may be extracted, averaged or re-gridded to suit the requirements of individual projects. The corrected data for Newfoundland, gridded to a 150-m grid interval is scheduled to be released later this year.

In future, as digital elevation data becomes available, the data may be corrected for variations in terrain (Grauch, 1987). However, terrain correction would only be required for the purposes of accurate modelling in areas of rugged relief, such as exist in certain areas of Newfoundland's south coast and the Long Range Mountains of the Great Northern Peninsula.

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