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THE 1998 POLAR MARGIN AEROMAGNETIC PROGRAM (PMAP) SURVEY OVER THE LINCOLN SEA*

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ABSTRACT

The multi-agency PMAP group has collected high-resolution aeromagnetic data along the Canada-Greenland polar margin since 1989. The surveys use the National Research Council Convair 580 aircraft flying at 220 knots and 300 m altitude (draped over land) along flight lines 3-4 km apart. The data are collected at 8 Hz. GPS is used for flight guidance and DGPS for track recovery. Two unconventional processing techniques were used in analysing the 1998 survey. Aircraft-generated noise was reduced by an additional level of post processing. Each survey and tie line flown contained a few aircraft manoeuvres in low magnetic gradient areas. Corrections derived from these data were applied, and resulted in significantly lower noise than did conventional processing. In addition, the horizontal gradients along the survey line were measured directly using two wingtip magnetometers. The gradient values were used to compute total-field estimates along pseudo-lines on either side of the flight lines. A total-field grid was then computed using twice as many line-km of data as in the original flight lines. These gradient-enhanced maps show more short-wavelength detail and have fewer leveling errors than conventional maps.

1. INTRODUCTION

The Polar Margin Aeromagnetic Program was begun in 1989 for the purpose of mapping the magnetic anomalies along the Arctic continental margin and developing and demonstrating magnetic gradiometer methods. Since then, surveys have been conducted over northern Ellesmere Island, north-western Greenland and the Lincoln Sea (1989-91) [Nelson, 1991, Forsyth, 1997], northern Sverdrup Basin (1991-1993) [Nelson, 1995a], and the Beaufort Sea (1994) [Nelson, 1995b]. The most recent surveys were conducted over northern Greenland and the Lincoln Sea in the Spring of 1997 and the Autumn of 1998. The purpose of these surveys was to determine the offshore limits of mapped geological features on northern Greenland seen in the 1989-1991 PMAP surveys and to resolve the marine anomalies in the northern Lincoln Sea seen in both the 1989-1991 PMAP surveys and regional surveys [Kovacs, 1982]. Funding for the 1997 PMAP survey was provided by Natural Resources Canada (NRCan), the Department of National Defence (DND), the National Research Council (NRC), the German Bundesanstalt fur Geowissenschaften und Rohstoffe (German Polar Research Institute), and the Danish Geological Survey.

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This paper describes the data processing steps required to obtain a final total-field magnetic anomaly map of the 1998 survey area. Two novel methods were employed - one to reduce aircraft magnetic noise and another to enhance the high-frequency content of the total-field map using the measured lateral gradient. These methods will be described in detail.

2. THE SURVEY

The survey was conducted with the Convair 580 aircraft, operated by the Institute for Aerospace Research (IAR) of NRC from a base at the Canadian Forces Station (CFS) Alert from 14 September to 1 October, 1998. Twenty flights, each approximately 4.5 hours in duration, were flown for a total of nearly 13000 line kilometers. A total of 26 survey lines, and 14 tie lines were completed. The survey lines were oriented approximately east-west and were flown at a constant altitude of 300 metres with a spacing of 3 km. Tie line separation was approximately 30 km. The flight lines and tie lines flown during the survey are shown in Figure 1.

The aircraft was instrumented with four cesium total-field magnetometers and two sets of vector magnetometers. This allowed us to measure the total-field (tf), longitudinal gradient (Gx), lateral gradient (Gy), and vertical gradient (Gz) of the total-field. One set of Narod vector magnetometers was used to model the aircraft-generated magnetic noise using a 26-term model developed at IAR. Data collected during a series of pitches and rolls on the four cardinal headings at the beginning of the first survey flight were used to determine the coefficients for the total-field and gradient models. The standard deviation of the residual total-field noise after aircraft compensation was less than 0.03 nT. These coefficients were then applied in real time to the total-field and gradient measurements taken during the survey.

The aircraft was equipped with an inertial navigation system and two CA-Code GPS receivers (Novatel RT-20 and Novatel Millenium). The navigation data used for both flight guidance and initial flight track recovery consisted of Novatel GPS data sampled at 2 Hz, updated with inertial velocity information to generate a 32 Hz navigation data rate. Raw GPS pseudo-range data were recorded on a PC during each flight. A Novatel Millenium GPS receiver was set up on the ground and, by combining these GPS base-station data with the aircraft pseudo-range data, post-flight differential GPS processing was possible.

A magnetic base-station consisting of a cesium magnetometer and a PC was set up at CFS Alert by the project participants. Data were recorded at 2 Hz. The PC clock was manually set to aircraft system time in order to synchronize the magnetic base-station and airborne measurements.

3. EXTRA PROCEDURE FOR REDUCING AIRCRAFT NOISE

To ensure that the total-field and gradient noise levels remained very low for the entire survey, a short series of rolls and pitches were flown on each survey line in an area where the magnetic gradients were small. A second set of "trim compensation coefficients" was generated for each survey/tie line. These coefficients were applied to the conventionally-compensated total-field and gradient signals along the line on which they were calculated. This ensured that noise levels always remained below the following levels:

standard deviation of	tf (measured in		0.1-1 Hz band)	<0.03nT
"	gx (	"	0-1.6 Hz band)	<0.001 nT/m
"	gy (	"	0-1.6 Hz band)	<0.002 nT/m
"	gz (	"	0-1.6 Hz band)	< 0.009 nT/m .

Figure 2 compares the conventionally-compensated and the trim-compensated lateral gradient (Gy) residuals along a portion of survey line # 76. Note the flattening of the trim-compensated residual from data point 400-600 which corresponds to a slow aircraft roll to get back onto the desired track.

4. LEVELING THE TOTAL-FIELD

The trim-compensated magnetics, navigation, and magnetic base-station data were inspected and any steps or spikes removed. The total-field data were leveled with the commercial software package 'MONTAGE' from Geosoft Inc. A variety of methods were tried but the following techniques resulted in the best-leveled total-field data set:

1) The base-station magnetic field was filtered with a 30-minute smoother, then subtracted from tf.
2) The IGRF - based on DGPS latitude, longitude and altitude - was subtracted from tf.
3) The DC offset on each tie line was adjusted so that the average value of the crossing point errors along that tie line were zero.
4) A trend was fitted to the crossing errors along each survey line, then this trend was subtracted from the survey line data.

Using two iterations of DC offset correction along the tie lines and trend removal along the survey lines, the standard deviation of the crossing point errors was reduced from 23.6 to 4.9 nT .

5. ENHANCED GRIDDING USING MEASURED LATERAL GRADIENT

In an aeromagnetic survey, very high-resolution data are available along the survey lines. However, the magnetic anomalies are under sampled in the across-track direction and features can be missed or distorted by aliasing. In the gridding process, between-line features are estimated by cross-line interpolation, but unless the line spacing is very tight (as set by the nominal vertical distance to the magnetic sources), the estimates are not particularly accurate. Cross-line interpolation algorithms, such as cubic spline or Akima, use an estimate of the first derivative of the total-field at the on-line node points, derived by simple differencing from adjacent-line node points. These derivatives can be considered rough estimates at best. With the lateral gradient, as measured by differencing two wingtip magnetometers, the derivative of the total-field in the cross-line direction is known and can be used in the gridding process to obtain a higher accuracy mapping of the between-line anomalies. One method of using the gradient in this way is that of "pseudo-lines".

Pseudo-lines consist of estimates of the total-field at a fixed distance from the survey lines, based on the on-line value of the field plus the product of lateral gradient and the offset distance:

$$tf_{ps} = tf_{line} + Gy * (\pm)\text{offset} \qquad (1)$$

where "tf_{ps}" is total-field value interpolated to the pseudo-line, "tf_{line}" is the on-line value of total-field, "Gy" is measured lateral gradient in nT/m, and "offset" is the distance to the pseudo-line in metres. Thus, for each line, there are two pseudo-lines and these, if used in the interpolation-gridding process, can provide increased definition of the between-line structures. The question remains, how accurate are the estimated pseudo-line total-field values? Obviously, the linear extrapolation of the total-field using the lateral gradient can only be accurate for a limited distance from the lines. In practice, this question is settled quite simply by interpolating across the survey lines using different offset distances and comparing the result with the *true* cross-line total-field as measured along a tie line. (Tie lines are usually flown perpendicular to the survey lines). A tie line across an active area gives the best result; the pseudo-line offset distance is adjusted until the interpolated result closely matches the total-field along the tie line. Too small an offset results in the anomalies being under-sampled, as in conventional interpolation, while too large an offset results in overshoots. The gradient-enhanced gridding process is described in more detail below.

5.1 GEO-CODING

The measured horizontal gradients Gx (longitudinal) and Gy (lateral) must be appropriately rotated into the nominal axes of the survey. These lines were flown roughly east-west direction with respect to a meridian that ran through the centre of the area so East was selected as positive for Gx and South positive for Gy.

In the Convair, the longitudinal gradient is not directly measured, but is calculated from the derivative of total-field divided by ground speed. Thus, Gx is measured in the track axis of the survey. However, Gy is measured in the heading axis of the aircraft and must therefore be corrected to the track axis (+90 °) by the aircraft drift angle β. (Heading + Drift = Track).

$$Gy_{track} = Gx_{track} \cos \beta \; + Gy_{heading} / \sin \beta \quad . \tag{2}$$

5.2 PROJECTION FROM LAT-LONG TO X-Y

For gridding, the data have to be registered in some form of linear, orthogonal frame, usually Universal Transverse Mercator (UTM). This transformation was carried out in MONTAGE. To be consistent with the GPS measurements, the datum for the transform was WGS-84 and to be consistent with adjoining PMAP surveys, UTM Zone 23 (N) was used, corresponding to a central meridian of 48° W.

5.3 LATERAL GRADIENT LEVELING

Although Gy is not affected by diurnal and micropulsation and the compensation reduces the aircraft's magnetic interference to less than 20 pT/m, there are still small DC bias errors from line to line caused primarily by hysteresis and other non-linear magnetic effects in the aircraft. Since the DC value of Gy is essential for the gradient enhancement process, it needs to be leveled. Fortunately, this can be done quite easily by using Gx on the tie lines as a reference. In calculating Gx as described above, DC offsets and very long wavelength effects associated with diurnal are eliminated. Thus, Gx forms a good DC reference.

In MONTAGE, the nearest X-Y coordinates for tie line and survey line crossing points are identified and then all data parameters are interpolated to true crossing points, accurate to within less than a metre in terms of the given X-Y positions. With Gx forming the tie line values, a table of Gy crossing point errors is created. These errors for each survey line can be fitted with a polynomial of order 0 to *n* and then used to correct Gy for each line. For these data however, Gy was corrected with only a zero-order polynomial fit of the errors for each line.

5.4 ROTATION OF THE SURVEY LINES TO X-Y ALIGNMENT

In the calculation of pseudo-line field values as per Equation 1, the offset distance must be measured in units normal to the lines. The projected survey lines are seldom, if ever, aligned with one of the principal axes. However, alignment is easily accomplished in MONTAGE by rotating the X and Y coordinate pairs through an appropriate angle to form a new set. The survey lines were at an average angle of 8.86° to the X-axis of the UTM Zone 23 projection. The lines were rotated counter-clockwise through this angle, to form a new X-Y set.

5.5 SELECTION OF PSEUDO-LINE SPACING

Gradient enhancement is only relevant in areas of short-wavelength anomaly activity; the line-to-line interpolation in normal gridding handles the long-wavelength anomalies quite adequately. The highest anomaly activity was along Tie Line 3 so this was selected as the reference for trial pseudo-line spacings. Several spacings were tested and in each case, the data were gridded at 300-m cell size and the grid was then sampled along the tie line. The resulting profiles were compared to the measured total-field along the tie line and this was repeated until an offset was found that produced a good match. The profiles in Figure 3 illustrate the process.

The most active anomaly in Figure 3 is the sharp, negative-going one. The trace for the 800-m offset (i.e. ± 800 m from the survey lines) comes very close to matching the measured total-field. The 150-m offset trace tends towards matching for all short wavelength anomalies, and certainly does a better job than the normally gridded profiles. It can be seen that the 800-m offset is starting to overshoot on the small, sharp, positive-going anomalies. The 800-m offset was chosen as a good compromise between short-wavelength anomaly restoration and overshoot.

5.6 ROTATION BACK TO THE ORIGINAL ORIENTATION AND FINAL GRIDDING

The 800-m database was rotated clockwise 8.86° to the original orientation in the UTM frame, and the original tie lines were imported into the 800-m database to strengthen the total-field data. For the final gridding, a straightforward linear, down-line interpolation, followed by an Akima cross-line interpolation was used. Figure 4 shows the gradient-enhanced grid of the whole PMAP'98 survey area.

6. DISCUSSION

It is very hard to distinguish the differences between the standard total-field gridding and gradient-enhanced gridding methods when one looks at the entire PMAP'98 map. However, they are clearly evident in the zoomed Area "A" shown in Figures 5a and 5b. In the gradient-enhanced version, there is much more continuity of the larger anomalies and medium-sized separated ones appear to coalesce into more meaningful structures. Even the very small isolated anomalies that do not unite are shown in slightly more detail with gradient-enhancement. Figures 6a and 6b compare the standard total-field and gradient-enhanced gridding for Area "B". Similar enhancement trends and certain small anomalies appear for the first time in the gradient-enhanced version. It can be seen that some of the small anomaly outlines appear unreasonably sharp; this is probably due to the tendency to overshoot seen in the tie line profile in the previous section.

7. CONCLUSIONS

The procedure of flying "trim manoeuvres" on each flight line and using those data to derive "trim coefficients" have led to significantly lower noise levels on the measured lateral gradient. However, caution had to be exercised in applying these coefficients because they were not very robust. They were usually only applied to the line on which they were derived. The gradient-enhanced total-field gridding routine offers an advantage in terms of better rendering of anomalies between the lines. The process described in this report is robust, provided that care is taken in selecting the pseudo-line offsets.

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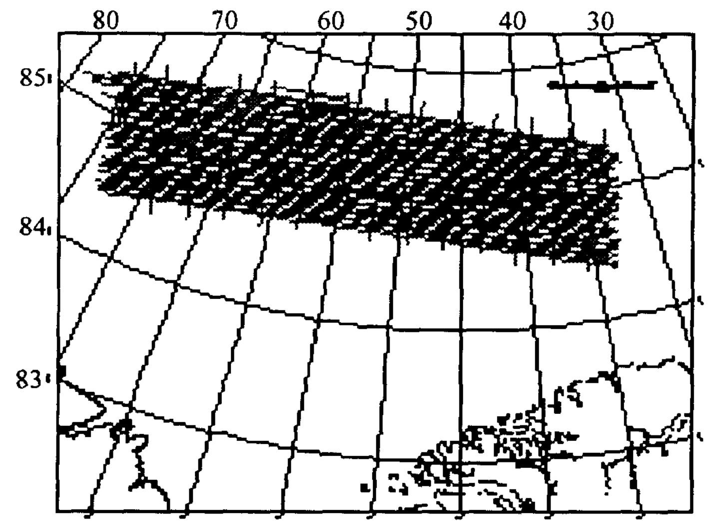

Figure 1. Survey and tie lines flown during the 1998 PMAP survey.

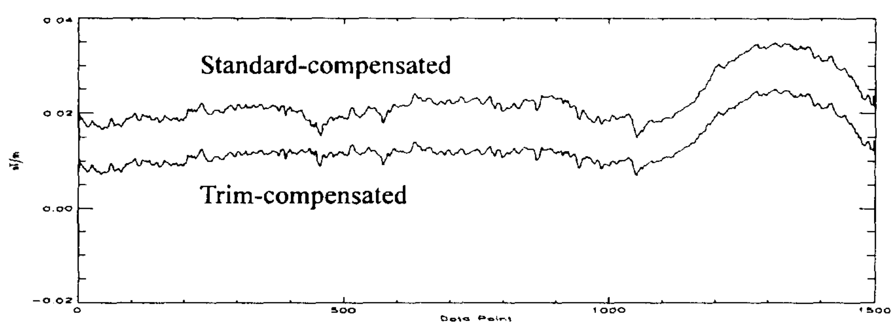

Figure 2. Standard-compensated residual vs trim-compensated Gy along survey line # 76.

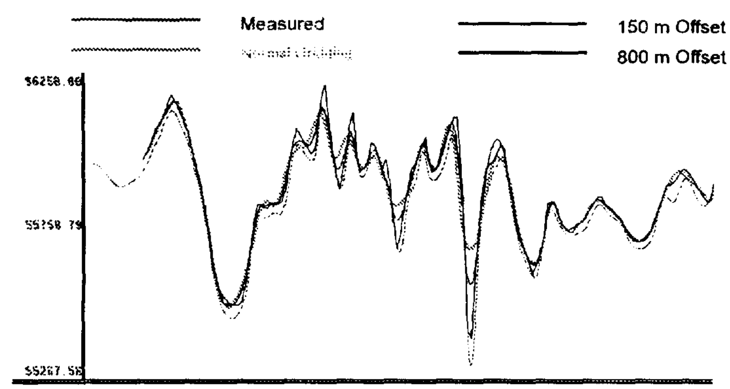

Figure 3. Measured, regularly gridded, and pseudo-line gridded (150 and 800 m) total-field along Tie Line 3.

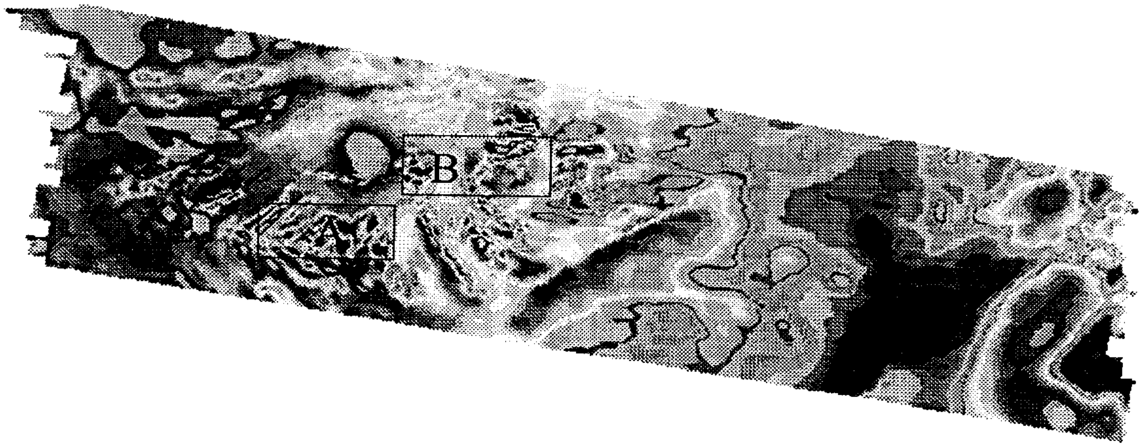

Figure 4. Gradient-enhanced gridded total-field of PMAP'98 survey area.

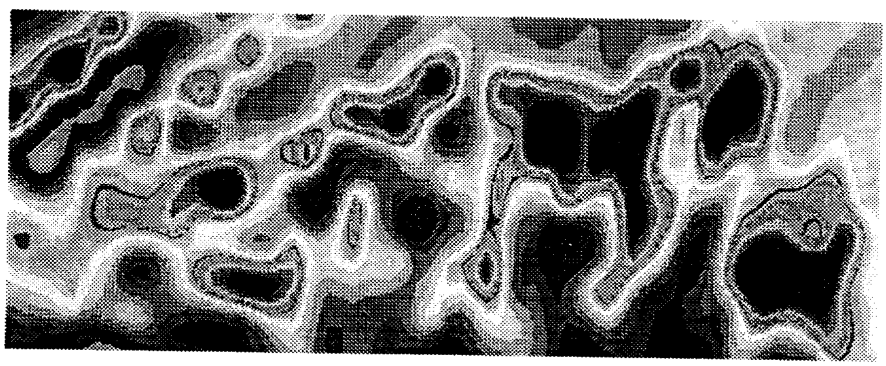

Figure 5a. Standard gridded total-field in Area A.

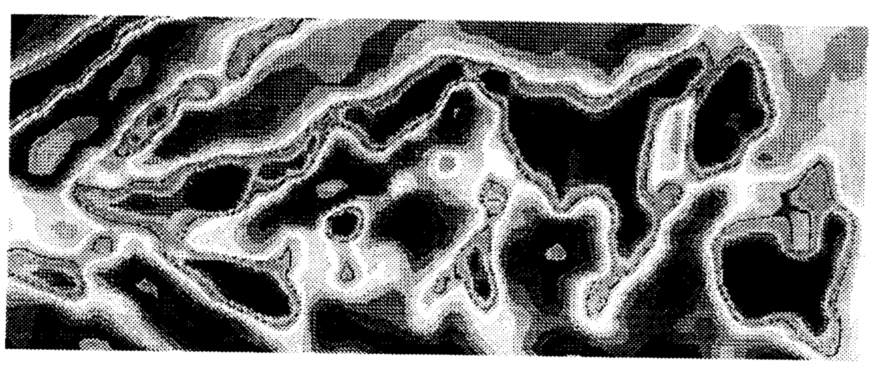

Figure 5b. Gradient-enhanced gridded total-field in Area A.

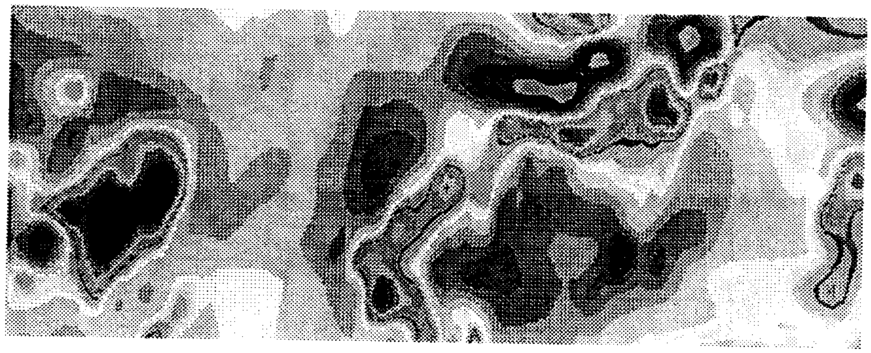

Figure 6a. Standard gridded total-field in Area B.

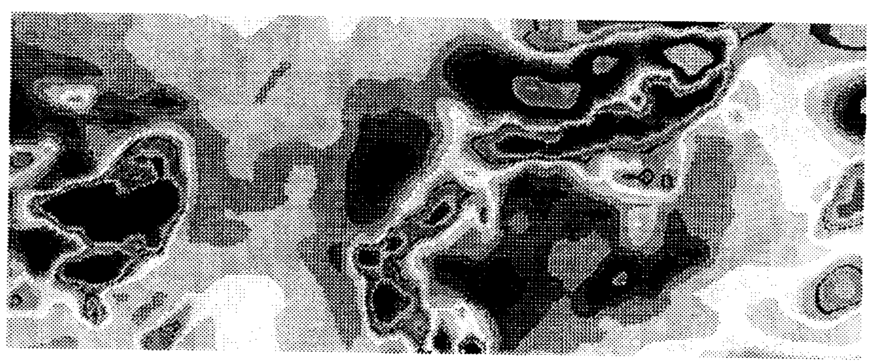

Figure 6b. Gradient-enhanced gridded total-field in Area B.

The 1997-1998 Polar Margin Aeromagnetic Program (PMAP) surveys over northwest Greenland and the Lincoln Sea

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Abstract

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