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Draping corrections for aeromagnetic data: line- versus grid-based approaches

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ABSTRACT

In drape-flown aeromagnetic surveys, operational factors such as weather and rugged ground topography may result in certain lines flown at average heights significantly different from the nominal terrain clearance. Such changes in the distance from sensor to magnetic source lead to variable attenuation of the magnetic field and result in spurious anomalies oriented along flight lines. A recent survey flown in Namibia was subjected to high wind conditions that led to some anomalously high flight lines and severe corrugation effects in the gridded data parallel to the line direction. Computational draping of the measured field to correct for the line-height variation was carried out on both gridded and line data using a Taylor series approach. The line-based approach produced the best results. Gradients calculated from the gridded data (perpendicular to the traverse lines) were overwhelmed by errors caused by the large line-to-line height variation.

INTRODUCTION

When aeromagnetic surveys are flown in draped mode, operational factors may result in lines flown at average heights significantly different from the nominal terrain clearance. Over rugged terrain, the climb and descent rate of the aircraft determines the flight path over a topographic feature. This path usually varies with the direction in which the line is flown resulting in line-to-line differences in terrain clearance. Changes in the distance from sensor to magnetic source lead to variable attenuation of the observed magnetic field. This effect is particularly serious if the near-surface material is strongly magnetic, in which case topographically-induced anomalies may become indistinguishable from those caused by buried sources. A commonly observed effect of line-to-line height differences is corrugation or herringbone patterns oriented along flight lines. Even if the amplitudes of these false anomalies are small, they can obscure useful geologic signals, especially when data enhancements such as shading or derivatives are used.

Methods for performing drape corrections can be classified as either direct (e.g. Taylor series method), or indirect (e.g. chessboard method). All these methods can be implemented on either a profile or a grid basis. There is a limited body of literature dealing with comparisons between some of the techniques that suggests that most yield similar results provided parameters for stabilising the results are properly tuned. However, there is a shortage of published research on whether these corrections should be applied on a profile or grid basis. Flis and Cowan (2000) concluded the best results were obtained by using a combination of line-based draping prior to levelling, followed by grid-based draping using a modified chessboard method. Intuitively one might expect that a grid-based procedure is superior, as such an approach takes into account 3-D source bodies. However, it has been our experience that when the distortion is due to severe changes in aircraft elevation coupled with moderate near-surface changes in susceptibility (as opposed to, for instance, moderate changes in aircraft elevation coupled with severe changes in near-surface susceptibility), then a line-based approach is superior. In this paper, we document such an example from southwestern Namibia, by comparing the results from grid- and profile-based Taylor-series drape corrections, and suggest reasons why the line-based approach is superior for these data.

GEOLOGICAL AND OPERATIONAL CONSIDERATIONS

In this study we use a portion of a larger (> 150 000 line km) survey conducted in 1999 by CGG-Geoterrex-Dighem (now Fugro Airborne Surveys) in southwestern Namibia on behalf of the Geological Survey of Namibia (GSN). This survey is part of an ongoing mapping project currently being undertaken by the GSN (Eberle et. al, 1994; Hutchins et al., 1997). The part of the survey that we use in this study lies on the eastern edge of the Namib Desert within the middle Proterozoic (Grenville-age) Namaqualand Metamorphic Complex in southern Namibia. The complex is a 150-200-km wide, polyphase, deformed and metamorphosed gneissic-granitic belt that stretches from Natal to the Atlantic coast (Joubert, 1986). Regionally, magnetic trends are northwesterly, particularly to the north of the survey area within the Sinclair sequence, which comprises a volcano-sedimentary succession hosted by northwest-trending, fault-bounded troughs that parallel the structural grain in the underlying basement (Hoal and Heaman, 1995). Based on magnetic character, Andritzky et al. (1997) place the survey area within the Sinclair domain, which they interpret to be an accreted terrane. Epigenetic copper and gold mineralisation is found to the northeast and magnetic data indicate large fracture zones and evidence of extensive intrusive and extrusive magmatism along the Sinclair/Namaqualand boundary. Hence, the region is considered to have high mineral potential (Andritzky et al., 1997).

The airborne magnetic data were acquired with a Cessna Caravan 208. The survey was flown at a nominal terrain clearance of 100 m, with north-south traverse lines spaced 200 m apart, and east-west tie lines spaced 2500 m apart (Figure 1a). The average sample spacing along flight lines is 16 m resulting in along-line and cross-line Nyquist frequencies of 31.25 and 2.5 cycles/km, respectively. Locally, the Earth's magnetic field has an intensity of 34682 nT, an inclination of -71.4° and declination -4.9°. Ground elevations vary from sea level in the west, to approximately 2000 m above sea level in the northeast. The relief is moderate over much of the survey area; so it was possible for the pilots to

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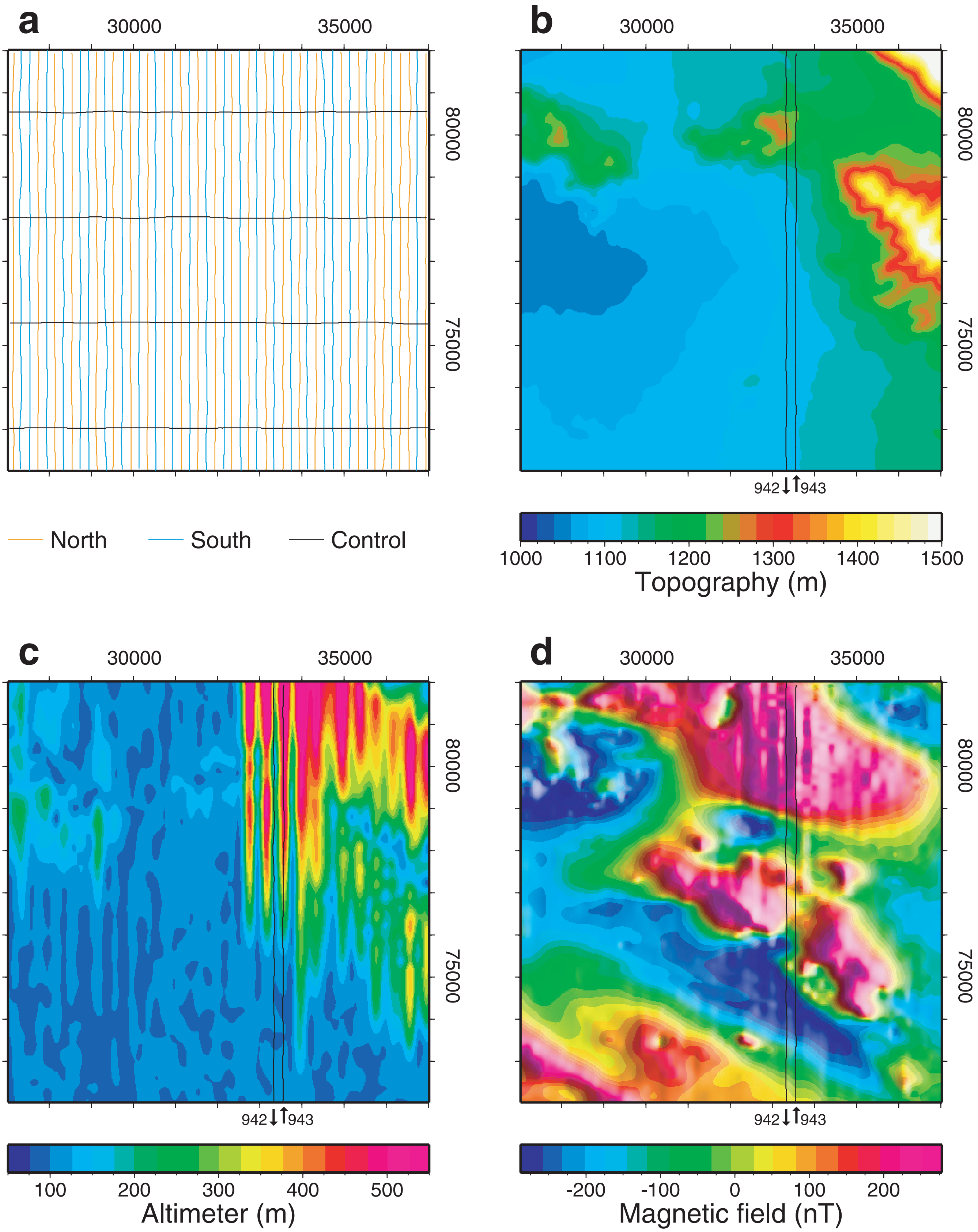

Fig. 1. (a) Fight-line map of study area. Lines were flown alternatively north-south. Co-ordinates are referenced to an arbitrary datum. (b) Digital terrain model computed by subtracting a grid of the GPS elevations from a grid of the radar altimeter readings. Adjacent flight lines 942 and 943 discussed in the text are shown. (c) Gridded radar altimeter values. Larger ground clearance is observed on lines flown from the south to the north. (d) Total field data after standard levelling procedure. The corrugation is due to differences in ground clearance (radar altimeter) between adjacent lines.

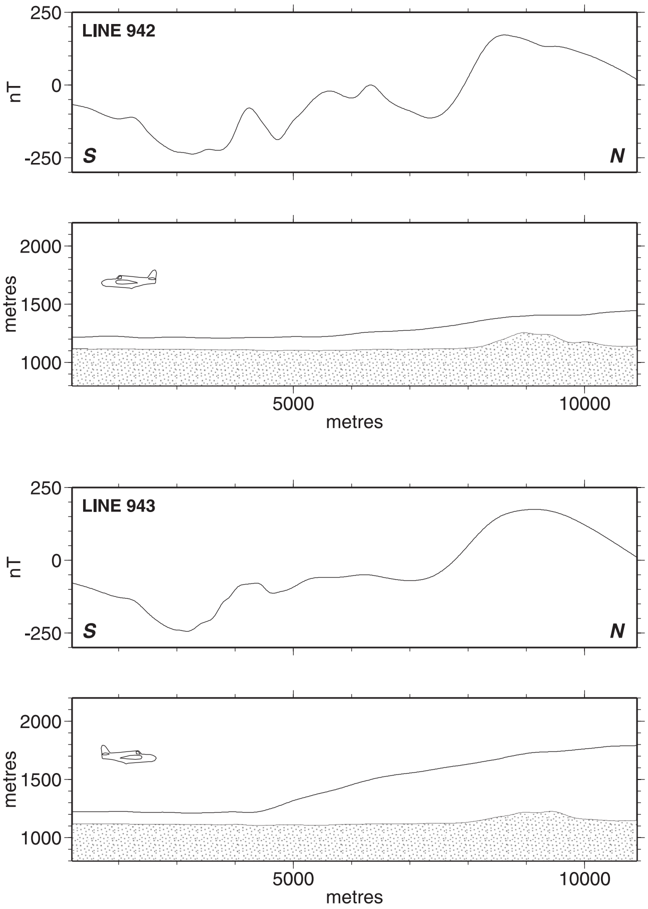

Fig. 2. Comparison of north- and southbound (adjacent) flight lines showing the effects of wind on the terrain clearance. Turbulence over hills requires an early ascent for the northbound line. Line locations are shown in Figures 1 and 3.

maintain an essentially constant terrain clearance of 100 m. However, near the centre of the survey area there are a series of northwest-trending escarpments (Figure 1b). In typical operational conditions, the climb and descent rate of a Caravan is sufficient to contour relief of this magnitude. However, parts of this survey were flown during the onset of the seasonal 'bergwind', during which the wind reached speeds of over 60 knots (roughly 110 km/h). This caused turbulence and down draughts that were particularly severe in the vicinity of the topographic highs. Thus, the ground clearance is greater near the crests of the hills. In addition, there are larger ground clearances, that extend over greater distances, on lines flown in the uphill direction (north-going lines), as the pilot began ascending well in advance of the hill tops and continued the climb a considerable distance past the hilltops. Descents down the hills (south-going lines) were more rapid. Consequently, there are significant along line, as well as line-to-line variations in the radar altimeter in the vicinity of these escarpments (Figure 1c).

An example of the relationship between radar altimeter, topography, and flight direction is shown in Figure 2. Along line 942, flown in a southerly direction, ground clearance reaches a maximum value of 303 m at the northern end of the line. For northbound line 943, which is adjacent to line 942, the early ascent of the aircraft that continues well past the topographic high leads to a maximum terrain clearance of 642 metres. Such large height variations between adjacent flight lines causes variable attenuation of anomalies leading to corrugations in the gridded magnetic field data (Figure 1d). Gridding also magnifies the problem by interpolating values between the anomalously high lines. The data in Figure 1d were also microlevelled (Minty, 1991) as part of the standard processing stream. However, the change in anomaly amplitudes from line to line can be as much as 40 nT, which is much larger than the microlevelling correction limit of 2 nT.

The size of the corrugation effects requires a correction based on the measured elevations. The often-used strategy of arbitrary directional filtering can suppress these effects but at the detriment of the useful signals in the data. Wherever possible, it is desirable to avoid filters that are not comprehensible in terms of the underlying physics, as these diminish the credibility and the interpretability of filtered responses (Jacobsen, 1987). The approach taken here is to apply corrections by draping the data onto a surface set at the nominal terrain clearance.

DRAPING OF POTENTIAL FIELDS

A variety of approaches exist for the continuation or draping of potential field data between arbitrary surfaces, and can be divided into direct and indirect methods. Direct methods produce the continued field directly from the observations and consist of the Taylor series method (Grauch and Campbell, 1984; Cordell and Grauch, 1985; Pilkington and Roest, 1992) and the wavelet approach of Ridsdill-Smith and Dentith (2000). Taylor series methods have a long history of use (Evjen, 1936) and are computationally simple and amenable to processing with Fast Fourier Transforms. Wavelet approaches are relatively new, and offer promise since the wavelet transform is a spatially-based quantity, thus allowing continuation characteristics to vary, depending on local measures such as data quality and continuation distance. This does, however, translate into increased computation time. These two direct methods are, strictly speaking, valid only for data measured on a horizontal plane.

Indirect methods involve the intermediate steps of either level-to-level field continuations or calculating equivalent source distributions. The former is the basis for the chessboard approach of Cordell (1985), available commercially as Compudrape™ (Paterson et al., 1990). Data are continued (using a flat surface approximation) to several parallel surfaces, either above or below the observation level. The field on the required surface is then constructed by vertical interpolation of values from the set of continued fields at each grid point. Since the continuation to each level is done independently, any filtering used can be varied as a function of the continuation distance. The accuracy of this type of approach is governed by the number of continuation levels used. Flis and Cowan (2000) used a modified form of the chessboard method on profile data to reduce the unwanted effects of significant line-to-line flight height variation. As in the case of the direct methods, this approach is strictly valid only for data measured on a horizontal plane. Equivalent source methods do not suffer from this limitation (Bhattacharyya and Chan, 1977; Hansen and Miyazaki, 1984, Xia et al., 1993) but require the intermediate step of determining an equivalent source distribution, on some specified surface either below or on the observation level, that reproduces the observed field. These sources can then be used to calculate the field on any arbitrary surface above them. A choice exists between the type of source that is used to represent the observations. Since the sources are placed at or below the observation level, some low-pass filtering may be required to stabilise the computed source magnitudes.

Direct comparisons of these approaches are, unfortunately, limited. Pilkington et al. (1995) used the Taylor series and Compudrape methods to drape data flown at constant altitude and showed the similarity between the results and measured data flown on the draping surface. Ridsdill-Smith and Dentith (2000) also compared these two techniques plus their own wavelet-based

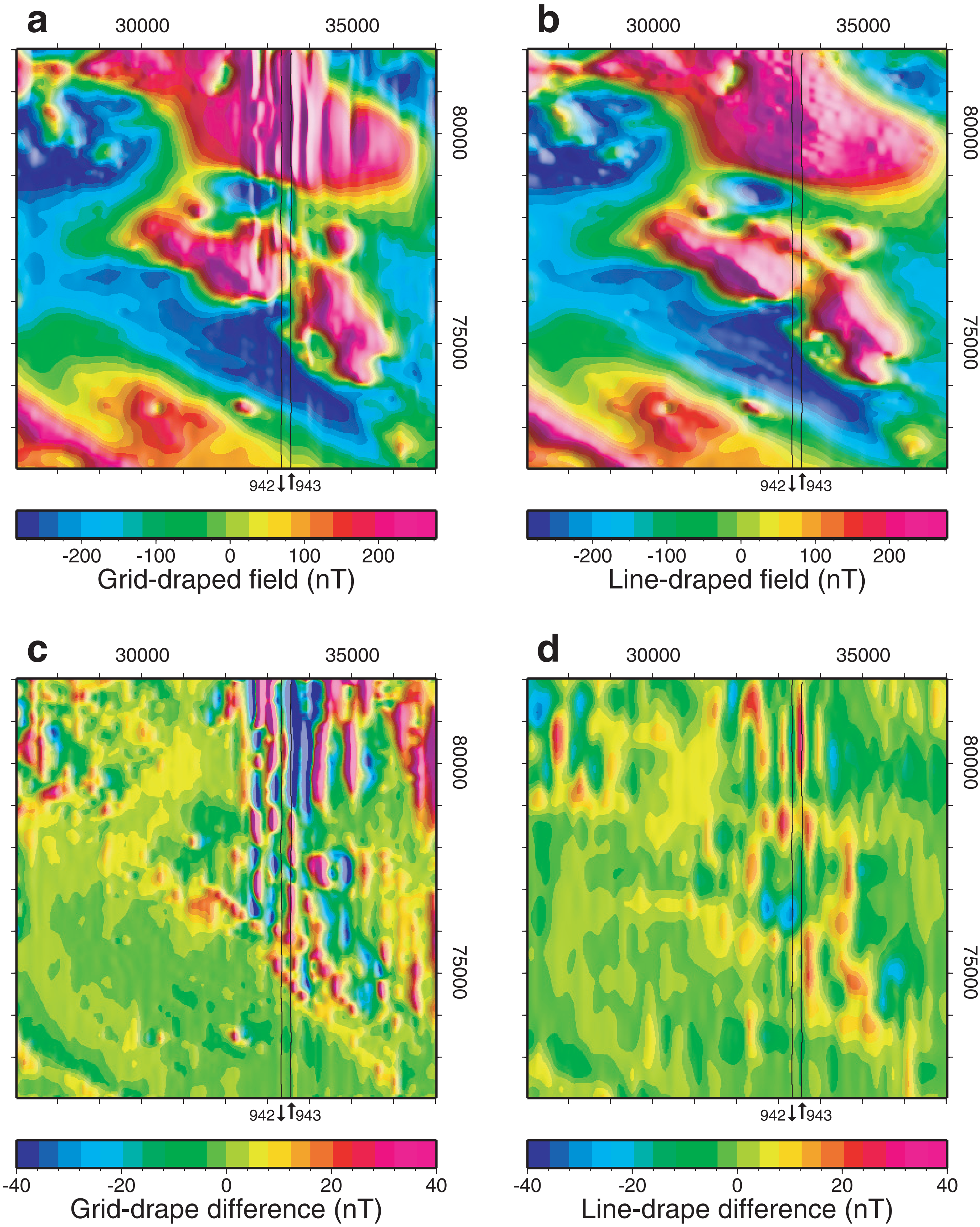

Fig. 3. (a) Total-field image from Figure 1d after the grid-based drape correction and standard microlevelling. (b) Total-field image from Figure 1d after the line-based drape correction and standard microlevelling. (c) Difference between grid-based draped data in a. and original magnetic field of Figure 1d. (d) Difference between line-based draped data in b. and original magnetic field of Figure 1d. Images in a-d are all illuminated from the east.

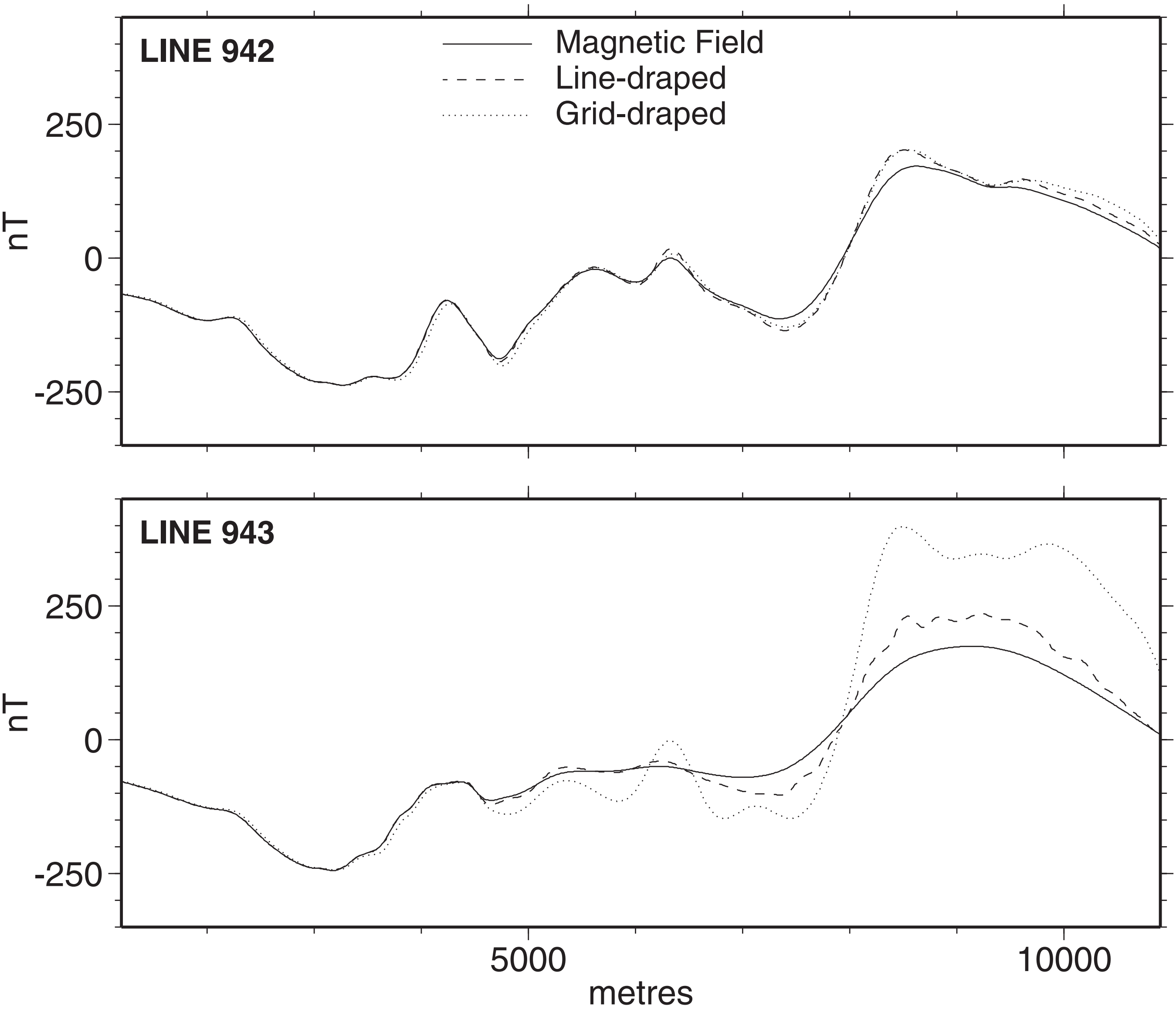

Fig. 4. Comparison between line- and grid-based draping along adjacent lines 942 and 943. Line locations are shown in Figures 1 and 3. Ground elevation and flight height for each line are given in Figure 2.

method on a single data set from Pilkington and Roest (1992). They showed superior resolution from the wavelet method but pointed out that results from the other approaches could be improved by optimum tuning of the (low-pass) filtering involved. We expect that results of all the methods discussed to be similar, with differences only in the resolution of the computed fields related to the filter parameters used to guarantee a stable solution. In the following, we use the Taylor series approach to carry out the draping corrections in the study area.

DRAPING WITH TAYLOR SERIES

The field ($\mathbf{B}_{surf}$) on the surface h(x,y) is given by a Taylor series expansion as

$$B_{surf}(x,y) = \sum_{n=0}^{\infty} \frac{h^n(x,y)}{n!} \frac{\partial^n}{\partial z^n} B_{level}(x,y) \tag{1}$$

or equivalently as

$$B_{surf}(x,y) = \sum_{n=0}^{\infty} \frac{h^n(x,y)}{n!} \mathcal{F}^{-1}\{\left|k\right|^n \mathcal{F}[B_{level}(x,y)]\}, \tag{2}$$

where $\mathbf{B}_{level}$ is the field as observed on a plane, **k** is the wavenumber, and $\mathcal{F}$ and $\mathcal{F}^{-1}$ denote forward and inverse Fourier transformation. Equation (2) provides the most efficient way of evaluating the series by calculating vertical derivatives in the frequency domain. The calculation of n^{th} order derivatives leads to magnification of the high frequency content (including noise and gridding artefacts) of the data which may obscure meaningful geological signals. Large amplitude terms in the series will also result from large gradients in the data (usually due to magnetic source body edges) and large downward continuation distances. Therefore, low-pass filtering must be incorporated into each term of the Taylor series. Convergence of the series is dependent on the frequency content of the measured field and the continuation distance and has been discussed for a number of source geometries by Roy (1967) and Negi (1967). They point out that the Taylor series method allows continuation to points below the source level at locations that have sufficient horizontal separation from the source. Since the aim is to achieve the greatest possible resolution of geologic signals in the draped data, as much high wavenumber information as possible is retained without overamplifying any noise present. This usually involves draping with a range of filter parameters followed by inspection of the calculated field to determine whether or not the corrections are acceptable. If grid sizes are large, filter parameters can be determined using the radially-averaged power spectrum of the data (Pilkington and Roest, 1992).

GRID- AND LINE-BASED DRAPING

Draping was first attempted using the gridded magnetic (Figure 1d) and radar altimeter data (Figure 1c). Low-pass filtering was set to a cut-off wavelength of 500 m (with a cosine roll-off to 1000 m) after some trials and the results of draping shown in Figure 3a. For comparative purposes, the draped data were microlevelled using the same parameters as for the observed field (Figure 1d). The grid-based draping performs poorly, with areas of significant line-to-line flight-height variation showing worse corrugation effects. The failure of the Taylor series approach on this data set is mainly due to errors in the vertical gradient calculation. The vertical gradient is a combination of the two orthogonal horizontal gradients through Hilbert transformation. The along-line gradients are acceptable but in the cross-line direction, the gradients are incorrect because they are based on field values not measured on a horizontal plane (for which the Taylor series is only strictly valid). The flight-height variation along lines is smooth enough not to degrade the gradient calculation, but adjacent line height changes of >200 m, i.e., >45° slope renders the resulting cross-line gradient values invalid. The process of gridding exacerbates the problem since the interpolated altimeter values between lines with large height variations are not reliable. Similarly, interpolated magnetic field values between lines will be corrupted by the unrepresentative values measured on the higher lines. Hence, even the gradients calculated on lines flown at the nominal flight height are affected, but to a lesser degree than the higher lines.

To reduce the errors introduced by gridding, and more importantly, the dependence of calculated gradients on magnetic field values on adjacent lines, we drape the data line by line. If the data can be successfully draped in this way to remove line-to-line height changes, subsequent gridding (interpolating between flight lines) will not degrade the results since the magnetic field and altimeter values are now at the nominal (constant) flight height. The high resolution of the measurements along lines is also preserved after the draping correction. A disadvantage of line-based processing is the inherent 2-D source assumption. However, this effect is reduced by flying lines perpendicular to the dominant geologic strike, as was the case for this survey. Furthermore, treating each line independently ensures that lines with significantly different average heights have no influence on the gradients computed on adjacent lines. Line draping also has the advantage that it can be applied before tie-line levelling. This ensures that levelling can proceed with tie lines and traverse lines at least nominally at the same height. Otherwise, arbitrary levelling corrections will be applied to any poorly draped survey data having large height differences at traverse-tie line intersections.

Before draping of the complete survey data, low-pass filter parameters for the corrections were chosen based on test draping of lines with the greatest elevations, thus ensuring that the remaining lines would not be under-filtered (leading to ringing, etc.). A cosine-taper roll-off passing wavelengths greater than 500 m and suppressing those below 250 m was deemed sufficient. This filter was initially applied to lines flown at the nominal terrain clearance to determine the effect of applying essentially no draping correction. Maximum differences of <5 nT resulted from the low-pass filtering. Since the along-line Nyquist frequency is larger than for the gridded data, the line-based low-pass filtering is not as severe as for grid-based draping.

Figure 3b shows the line-draped and gridded data, microlevelled with the same parameters as those used in Figure 1d. The corrugation effects are almost entirely removed; revealing greater continuity of anomalies, particularly along strike, and highlighting previously unresolved features. The difference between the two approaches along the two adjacent flight lines (Figure 4) indicates that the grid method overcorrects for height effects along the higher lines but is reasonably stable for lines closer to the mean survey height. Comparison of the grid- and line-based draping corrections for our study area (Figures 3c,d) shows that the former clearly removes much more signal in directions not parallel to the flight line direction, e.g., the trend extending from the centre to the southeastern corner of the grid. This is a consequence of the cross-line derivatives effectively "spreading" the erroneous corrections between the flight lines. For both approaches, in the southwestern quadrant of the area, where the nominal terrain clearance was maintained (Figure 1c), corrections are generally <5 nT.

CONCLUSIONS

Aeromagnetic survey lines flown at average heights substantially different from the nominal terrain clearance are often unavoidable due to operational factors such as weather and rugged ground topography. To correct for the effects of the height differences, the data are draped onto a surface equal to the mean terrain clearance. If height differences are large between adjacent lines, this leads to errors in the computed gradients perpendicular to the lines, and a grid-based approach to draping is likely to fail. Gridding of the altimeter and magnetic field data prior to draping also tends to add to the errors by interpolating values between lines that are corrupted by the unrepresentative values measured on the anomalously higher lines.

Draping of the line data, however, leads to acceptable results. The corrections are applied independently to the lines and gridding therefore takes place on the draped data, so that field values are already at the nominal terrain clearance. The deleterious effects of across-line gradients are avoided since gradients are only calculated along lines. The example of a recent survey flown in Namibia, where high wind conditions led to some lines flown much higher than the mean survey height, illustrates the superior results gained from a line-based draping approach.

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