

Levelling aeromagnetic survey data without the need for tie-lines

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ABSTRACT

A new methodology that levels airborne magnetic data without orthogonal tie-lines is presented in this study. The technique utilizes the low-wavenumber content of the flight-line data to construct a smooth representation of the regional field at a scale appropriate to the line lengths of the survey. Levelling errors are then calculated between the raw flight-line data and the derived regional field through a least squares approach. Minimizing the magnitude of the error, with a first-degree error function, results in significant improvements to the unlevelled data. The technique is tested and demonstrated using three recent airborne surveys.

Key words: Magnetics, Data processing, Levelling, Aeromagnetic.

INTRODUCTION

The accurate levelling of airborne geophysical data is necessary prior to the application of any interpretation procedures. This study proposes a methodology for levelling aeromagnetic data without the need for tie-lines. The acquisition of orthogonal tie-line data is expensive and can add up to 10%–20% of the total flight-line distance when generating the technical specification for a survey.

A standard aeromagnetic data processing sequence involves: (i) base station (diurnal) subtraction, (ii) tie-line correction, and (iii) microlevelling (e.g., Reeves 1993). The element reconsidered here is that of tie-line processing, which performs the main initial spatial levelling of the survey data. Due to the statistical and iterative nature of the procedure (e.g., Luyendyk 1997, Appendix 1), it is normally applied when all the survey data have been acquired.

Tie-line processing (Urquhart 1988; Luyendyk 1997) relies on the fact that the total field (total magnetic intensity) aeromagnetic data are directionally invariant. As such, at crossover points, the flight and tie-lines should record equivalent values. The flight-lines are then levelled to the tie-line data using the intersection points and a series of conditional tests. Most laterally extensive airborne surveys operate under this acquisition methodology, yet tie-line

corrections are often ineffective due to strong gradients in the anomaly field and the low flight altitude at which modern surveys may operate. Errors at intersection points are commonly larger, by a significant degree, than the potential accuracy of modern high-resolution aeromagnetic surveys (e.g., < 1 nT). This finding is often overlooked during levelling, and the use of tie-line levelling methodologies continues unabated.

An available levelling approach for data acquired without tie-lines is to generate synthetic 'virtual' tie-lines, from the flight-line data, by extracting profiles at right angles to the primary flight-line direction (Hautaniemi *et al.* 2005). By taking two or more 'virtual' lines, offset by reasonable distances, the entire line lengths can be levelled by shifting the points on the tie-line in order to create a smooth cross-section. This technique relies on the continuity of features at the location of the 'virtual' tie-lines and is generally undertaken where the total field displays low gradients. Further techniques to level aeromagnetic data in the absence of tie-line data have been published and employ different strategies to solve the problem. For example, Nelson (1994) utilized the horizontal gradients to level the total magnetic field, whereas Fedi and Florio (2003) decorrugated magnetic data using the wavelet transform to isolate and remove directional trends in the data. Beiki, Bastani, and Pedersen (2010) developed a scheme applicable to airborne electromagnetic and magnetic data. Their approach determined levelling errors by fitting polynomials

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to the data in both one and two dimensions and comparing the results.

One levelling procedure that uses only flight-line data is the 'line-to-line' correlation technique developed by Huang (2008). This approach is primarily utilized for airborne electromagnetic data and minimizes the difference between data acquired on adjacent lines. The method requires the selection of an initial reference line from which all the remaining lines are progressively referenced and corrected. Several problems are introduced by this approach, namely, that errors are propagated from one line to the next such that the lines at the limits of the survey are most affected. The choice of the initial 'level' line is often arbitrary, and there are clear stability issues in the minimization as a single poor solution will result in all subsequent lines being incorrectly levelled. The scheme also introduces further steps to the levelling workflow as the regional trend is removed from the data and should be restored following levelling.

The original premise of this study was to remove the requirement for tie-lines by levelling the recorded flight-line data directly to the International Geomagnetic Reference Field (IGRF), i.e., the very long wavelength magnetic field observed above the Earth's surface (International Association of Geomagnetism and Aeronomy, Working Group V-MOD 2010). At the scale of the aeromagnetic surveys considered here, the IGRF can be assumed to vary linearly along the acquired line lengths. Variations observed from the IGRF are likely to be caused by magnetized rocks in the crust (or high-frequency components of the field generated in the Earth's core). However, the practicalities of real-world airborne surveying decreed that this approach was unsuitable for levelling the majority of aeromagnetic data sets. Problems arise for a number of reasons, most attributable to the fact that the IGRF is not a suitable representation of the recorded data due to the differing wavenumber components. Furthermore, single-survey lines are often, for reasons associated with weather, time, availability, equipment, and optimal flight plans, split between different flights. The partial sections of the line are then levelled individually, and the joint between the two (or more) sections acts as a hinge that exacerbates the levelling errors.

This study aims to build on this premise of the 'virtual' tie-line and 'line-to-line' correlation techniques that there is a continuation of recorded features orthogonal to the flight-line direction; however, this study also extends the technique to utilize a much greater proportion of the data. The methodology presented relies upon the assumption that the entire recorded data set can adequately replicate the regional field,

with wavenumber components relevant to the survey size, when subjected to appropriate smoothing algorithms, i.e., the long-wavelength component of the aeromagnetic data represents the regional field. The individual flight-lines are then levelled to this regional baseline. Any poor solutions are obvious and stand alone, meaning subsequent lines are unaffected.

As a further levelling step, a two-dimensional (2D) minimization of the difference between the smooth regional field and the IGRF may also be applied. This step produces zero- and first-degree polynomial coefficients that can be applied directly to the levelled flight-line data. This additional procedure produces a levelled, IGRF-corrected, local anomaly field.

Unlike other levelling methodologies, this entire approach is computationally, rather than manually, intensive. Entire large data sets can be automatically levelled with minimal user input. As such, the approach is an excellent quality control (QC) tool for use throughout the acquisition stage. Furthermore, two overlapping data sets can be levelled to the same regional grid to enable comparison and interpretation.

Three recent airborne geophysical surveys are considered here, two of which were flown without tie-lines as part of the high-resolution airborne resource and environmental surveys (HiRES) programme established by the British Geological Survey (Lee *et al.* 2001) to generate, in part, a modern U.K. magnetic baseline data set. The third is a project where the publicly available contractor-levelled data are compared with the equivalent data, levelled using the new approach. All three surveys acquired magnetic, radiometric, and electromagnetic data, and only the magnetic data are considered here.

METHODOLOGY

Aeromagnetic survey data generally follow a standard processing flow (Luyendyk 1997) with common corrections necessary on all surveys. A complete description of the normal processing flow undertaken on HiRES surveys was given by Hautaniemi *et al.* (2005). The corrections can be broadly divided into distinct categories.

1. The first category includes those developed as a consequence of a magnetized metal body moving through the Earth's magnetic field. These are generally compensated for in real time following a calibration procedure at the start of the survey and depend on flight direction and aircraft movement (pitch, roll, and yaw).
2. The second category includes those caused by short-term (tens of seconds to several hours) fluctuations in the Earth's magnetic field. These diurnal corrections are removed using

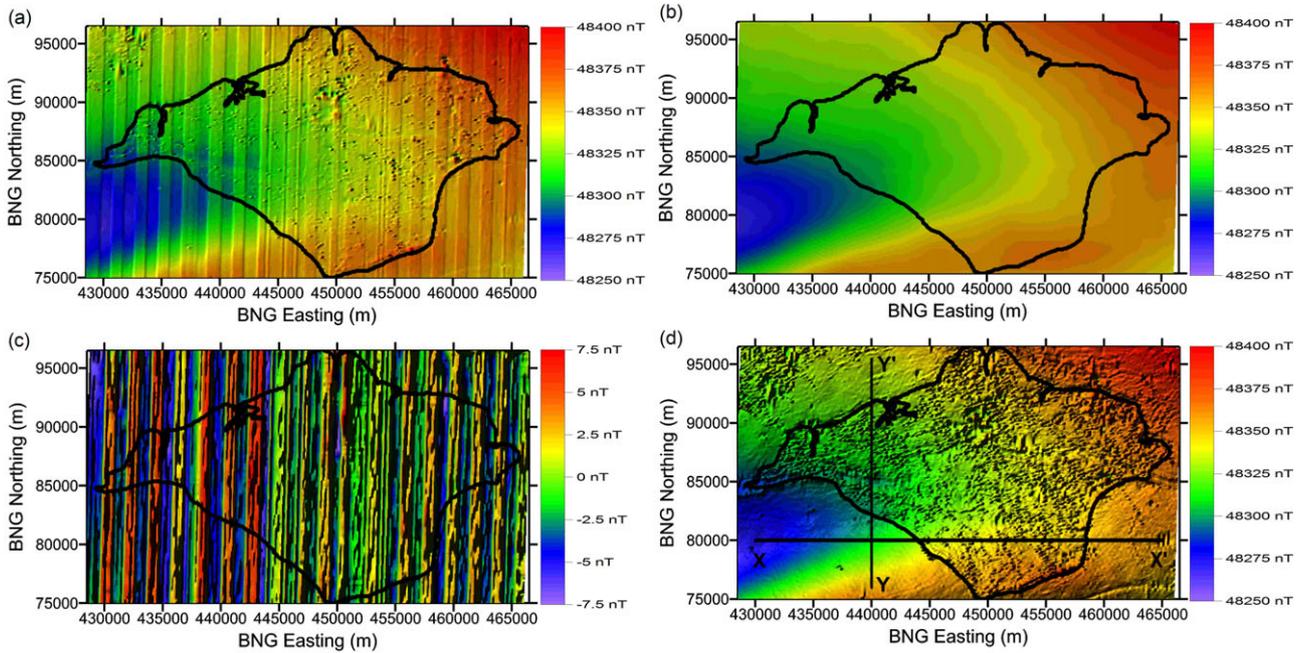


Figure 1 Aeromagnetic data from the Isle of Wight HiRES survey as illuminated 3D surfaces with a linear colour scale. Shading from the NW. Outline of Isle of Wight highlighted with black polygon. (a) The pre-levellled data; (b) the long-wavelength regional field derived from filtered bi-directional gridding technique; (c) the levelling corrections; and (d) the levelled data set.

a magnetic base station established within, or close to, the survey area.

3. The final category includes those caused by a small lag (time delay) in the recording of the data and confirmed as appropriate by continuation of cross-cutting magnetic features.

Most survey workflows undertake initial processing steps to correct for the aforementioned errors then perform a QC and spike removal operation, especially if flown over urban areas, since significant cultural noise can mask the signal from the subsurface; this is particularly the case for U.K. survey data (Cuss 2003; Lahti *et al.* 2007). It is at this stage that tie-line levelling is normally performed to remove residual errors from incomplete diurnal, compensation, or heading corrections. This study proposes the use of the partially processed data, prior to tie-line levelling, to derive the regional field using a filtered bi-directional gridding scheme under the assumption that the individual lines will capture the long-wavelength component of the total field. The bi-directional gridding method initially interpolates data values to the desired grid spacing in the flight-line direction, nominally 40 m for surveys flown with 200-m flight-line spacing. These points are then interpolated in the perpendicular, tie-line direction to produce values at the required grid points. A low-pass filter with a cut-off between eight and ten times the line spacing is applied in each

direction during gridding. Finally a nine-point Hanning filter, consisting of a 3×3 convolution matrix, is utilized to remove any residual high-frequency noise.

The derived regional magnetic field data, \mathbf{mr} , are then sampled at coincident locations, \mathbf{x} , to the unlevelled magnetic line data, \mathbf{md} . Each line of data consists of N points as follows:

$$\mathbf{mr} = (mr_1, mr_2, \dots, mr_N)^T, \quad (1)$$

$$\mathbf{md} = (md_1, md_2, \dots, md_N)^T, \quad (2)$$

$$\mathbf{x} = (x_1, x_2, \dots, x_N). \quad (3)$$

The error between the fields at equivalent locations, $\mathbf{md} - \mathbf{mr}$, is termed $\Delta\mathbf{d}$. The statistical distributions of values in $\Delta\mathbf{d}$ have a general tendency to be normally distributed. A least squares minimization is undertaken on a line-by-line basis, along the entire line length, to calculate the optimal error function, $\mathbf{f}(\mathbf{x})$, such that,

$$|\Delta\mathbf{d} - \mathbf{f}(\mathbf{x})|^2 = \min, \quad (4)$$

where $\mathbf{f}(\mathbf{x})$ is normally defined as a first-degree polynomial.

Unfortunately, utilizing this approach with every data point on a single line inadvertently gives undesirable weighting to short-wavelength high-amplitude features that are often

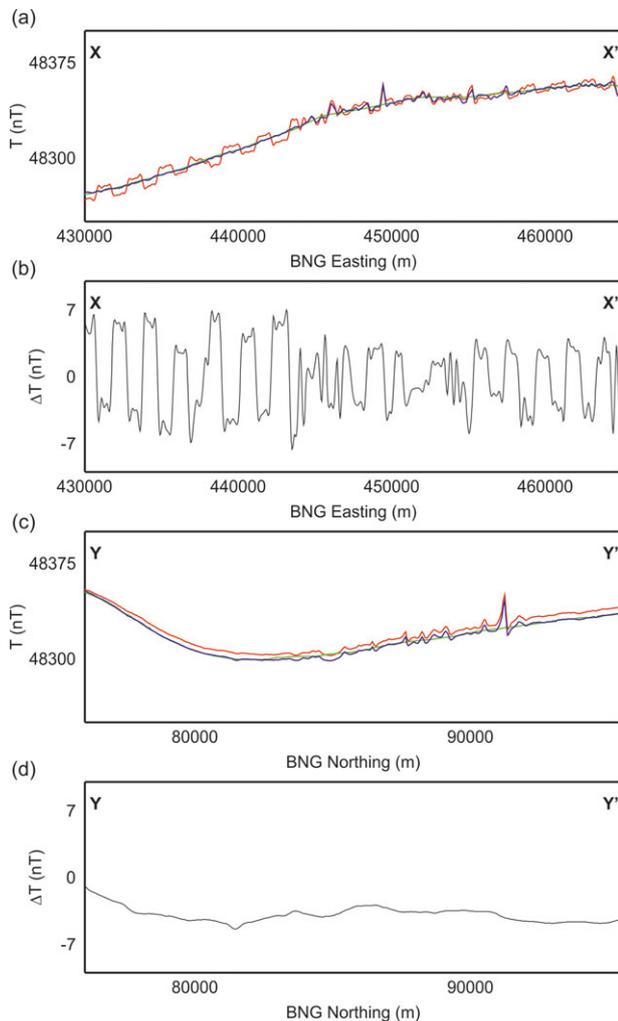


Figure 2 Data extracted from cross-sections X–X' and Y–Y' in Fig. 1(a) and (c) show the raw (red), regional (green), and corrected (blue) aeromagnetic data, and (b) and (d) display the levelling corrections.

associated with cultural interference. These values can skew the levelling of the entire line. To minimize this drawback, only a statistically derived subset of the data from each flight-line is used. The minimization, as defined in equation (4), uses only the values in Δd , which fall between the 20th and 80th percentiles of the distribution. The minimization is performed with a simulated annealing scheme. The levelling proceeds from one line to the next, generating a levelled line as the output in each case. This levelling methodology is referred to as 'mag-to-regional' levelling.

The 'mag-to-regional' levelling step may then be followed by a 2D minimization of the smooth regional field to the IGRF. A reduced, sparsely sampled data set is used to perform the

minimization with operator input required to select the optimum along- and cross-line spacing. The minimization proceeds in a similar manner as before. The error function is again defined as a first-degree polynomial but has orthogonal first-degree terms. As such, a single set of coefficients defines the entire correction, and these are applied to the levelled (mag-to-regional) line data, rather than the smoothed regional field. This second step is referred to as 'mag-to-IGRF' levelling and is only undertaken where the IGRF-corrected local anomaly field is desired.

A microlevelling procedure is usually employed as the final step to remove small remnant errors (Minty 1991; Fedi and Florio 2003; Ferraccioli, Gambetta, and Bozzo 1998) and results in a final magnetic anomaly data set ready for interpretation.

DATA EXAMPLES

In order to verify the methodology developed for this submission, the approach has been tested on three aeromagnetic surveys that suffer varying degrees of levelling errors. The first two surveys were undertaken by the British Geological Survey as part of the multi-sensor HiRES programme. These surveys were flown without tie-lines and levelled using the 'mag-to-regional' approach.

The first survey, flown during September and October 2008 over the Isle of Wight, U.K., covered an onshore and offshore area of 36 km x 22 km with flight-lines spaced every 200 m in an approximately north–south (N–S) direction. This study considered 4391 line km of data and survey heights ranged from 23.2 m to 247.1 m with a mean altitude of 63.3 m and a standard deviation of 26.9 m. Magnetic data were acquired with two sensors, one in the left wing tip and the other in the nose of the plane. Levelling problems were observed in both data sets, most significantly with the nose data presented here, and White, Beamish, and Cuss (2009) described the processing in detail. White and Beamish (2011) then used the final levelled magnetic data to classify the magnetic structural information contained within a high-resolution airborne survey. The region was of particular interest since the thick and relatively young, sedimentary succession displayed little significant shallow magnetic structure pushing the limits of the achievable resolution. The survey has not been systematically decultured (e.g., Lahti *et al.* 2007) but has been subjected to a deculturing procedure (White *et al.* 2009). All images are displayed in British National Grid (BNG).

Figure 1 shows the developments made during the processing sequence with pre-levelled data shown in Fig. 1(a).

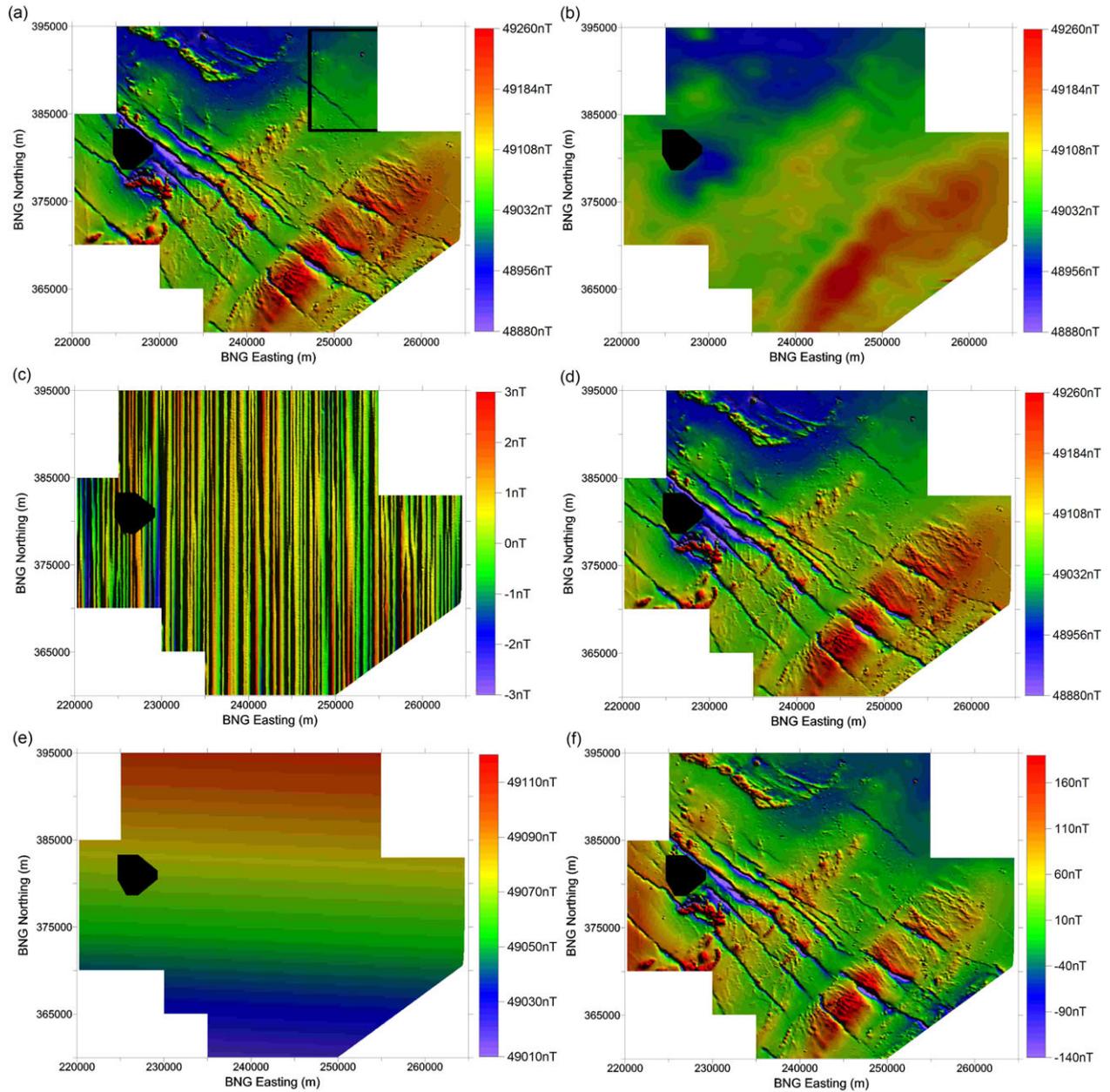


Figure 3 Aeromagnetic data from the Anglesey HiRES survey as illuminated 3D surfaces with linear colour scale. Shading from the NW. (a) The pre-levelled data; (b) the long-wavelength regional field derived from filtered bi-directional gridding technique; (c) the levelling corrections; (d) the data set levelled to the regional field; (e) the IGRF; and (f) the final magnetic anomaly data set levelled to the IGRF.

The stripy nature of the image highlights the levelling issues encountered, and the high-amplitude short-wavelength anomalies show up the substantial cultural noise prevalent in the data. The regional field, Fig. 1(b), is generated with a low-pass filter wavelength of 2000 m utilizing a two-step bi-directional gridding algorithm. The mag-to-regional levelling corrections, displayed in Fig. 1(c), are limited to less than 10

nT across the survey. Figure 1(d) shows the corrected data using the same linear scale as Fig. 1(a). The low amplitudes resulting from the largely non-magnetic sedimentary structure are evident, along with many cultural sources, which give rise to shadows on the illuminated 3D surface. The regional field is clearly, and smoothly, imaged, and the significant corrugation displayed in the raw data has been removed.

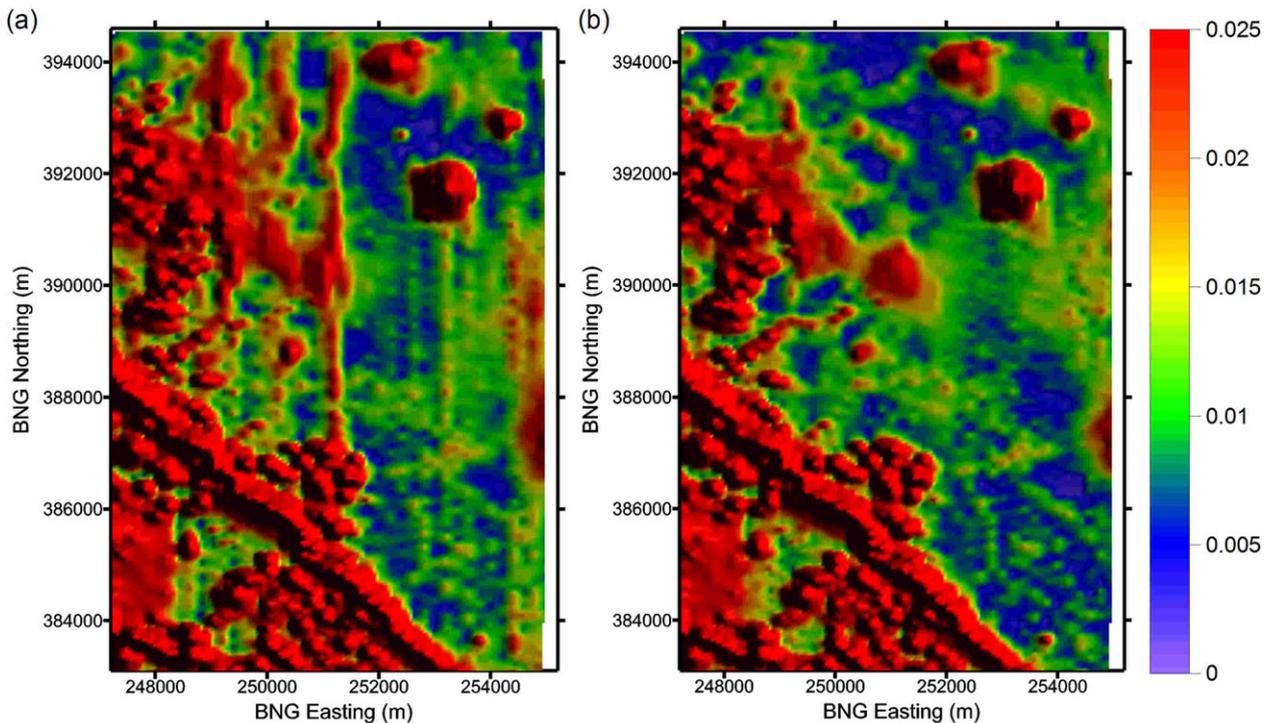


Figure 4 The AS of the total field data from an 8 km x 11.5 km portion of the HiRES Anglesey data displayed as a shaded relief image with illumination from the NE. (a) The AS from the pre-levelled magnetic data set and (b) the AS following ‘mag-to-regional’ levelling. Units are nT/m.

The corrections are further summarized in Fig. 2 through a pair of orthogonal cross-sections taken from the survey region and defined as X–X’ and Y–Y’ in Fig. 1(d). The cross-sections are 35 km and 19.5 km long in the X- and Y-directions, respectively. The cross-sections reveal the improvements made to the data and underline the degree to which intelligent levelling is necessary. The raw data, highly corrugated in the cross-line direction, are successfully levelled to the regional trend. The localized geological signals, and/or cultural artefacts, are preserved in the levelled data and have not hindered the levelling.

The second survey considered in this study was flown in the summer of 2009 and covered an irregular area of 1200 km² over the Isle of Anglesey (Ynys Môn) and the Northwest Wales coast. Lines were flown N–S in BNG at a flight-line spacing of 200 m. During the survey, 6302.7 line km of data were processed, and survey heights ranged from 25.4 m to 232.1 m with a mean altitude of 58.2 m and a standard deviation of 17.0 m. White and Beamish (2010) described the geophysical processing in detail; the data were noticeably less noisy than those from the Isle of Wight survey, and the root-mean-square misfits of the levelling corrections were smaller. The levelled

data were used alongside the U.K. national baseline magnetic survey data set acquired in the late 1950s and early 1960s to compare the data content in modern and previous generation aeromagnetic surveys (Beamish and White 2011).

Figure 3 shows the developments made during the processing sequence with pre-levelled data shown in Fig. 3(a), gridded at a spacing of 50 m. The data are dominated by high-amplitude, NW–SE trending, negative anomalies associated with largely concealed Palaeogene dykes. The region blanked by the in-filled black polygon throughout Fig. 3 masks the response of an aluminium smelting works on the island over which some of the largest total magnetic field readings encountered during the HiRES programme were observed. Figure 3(b) displays the filtered regional field following a bi-directional filtering process employing a low-pass filter wavelength of 1800 m. Fig. 3(c) and (d) shows the ‘mag-to-regional’ levelling correction and the corrected data, respectively. The amplitudes of the corrections are small relative to the variable response of the near surface, and the effect is difficult to visualize on the levelled total field data. Magnetic interpretation is normally undertaken using first- and second-order derivatives, and the accurate levelling of the data is essential

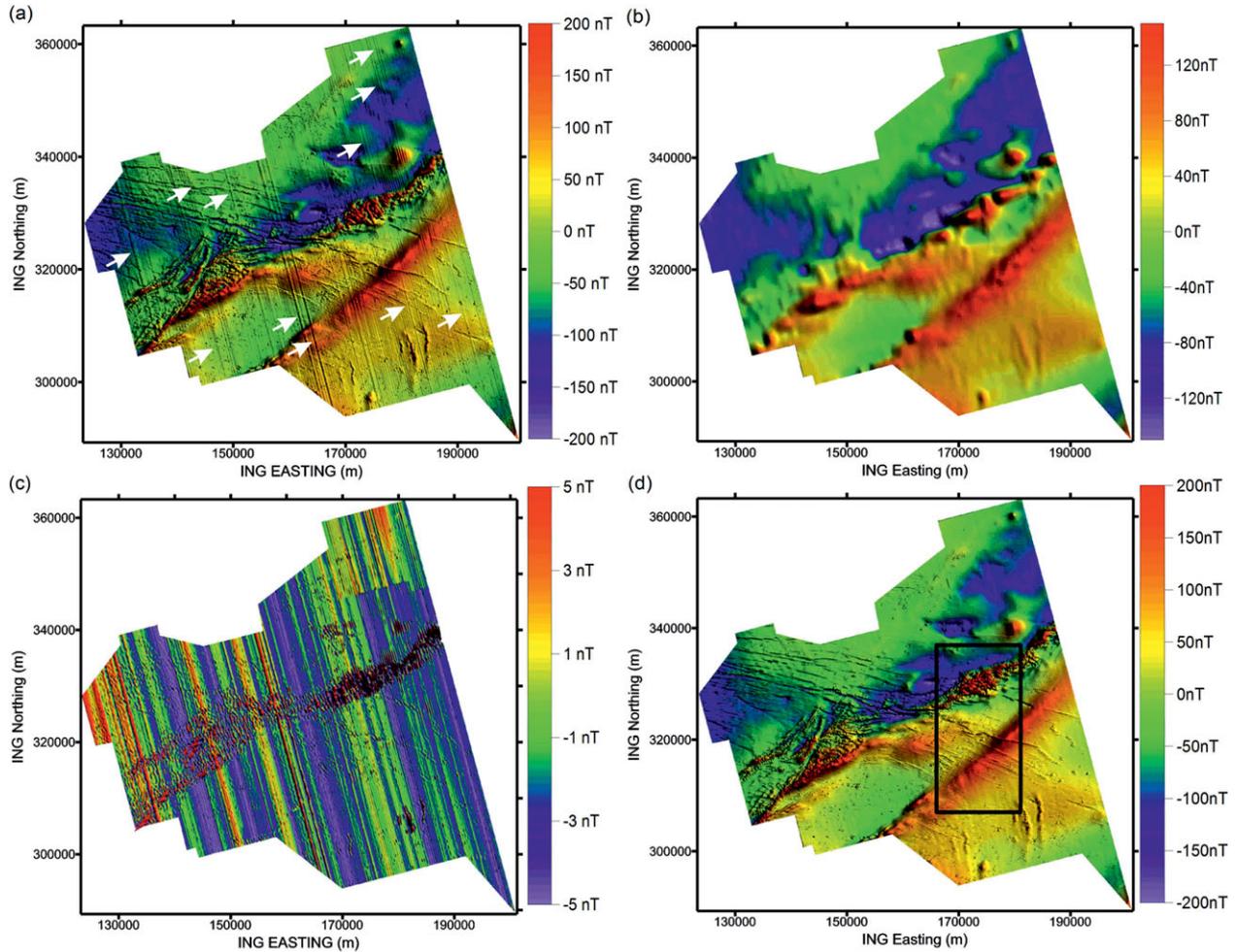


Figure 5 Aeromagnetic data from the Tellus Border survey as illuminated 3D surfaces with colour scale. Shading from the NE. (a) The pre-levelled data; (b) the long-wavelength filtered regional field; (c) the levelling corrections; and (d) the data set levelled to the regional field where the black box highlights a region for further analysis.

as low-level noise will significantly affect the quality of the results. Figure 3(e) displays the IGRF across Anglesey and the North West Wales coast and is seen to vary linearly along the N–S survey lines. The final magnetic anomaly data set, levelled with the ‘mag-to-IGRF’ scheme, is shown in Fig. 3(f).

Since the extent of the line-to-line corrugation is hard to appreciate in the Anglesey HiRES data, one approach to assess the success of the levelling scheme is an analysis of the analytic signal (AS) of the pre- and post-levelled data sets. Here, an 8 km × 11.5 km region displayed with a black rectangle in NE of Fig. 3(a) is studied since the area has little high-amplitude geological signal. When applied to gridded measurements of the total field (T), the AS amplitude is defined as

$$AS = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2}. \quad (5)$$

The AS amplitude is the total gradient, defined by derivatives in all three directions, and is sensitive to high-wavenumber gradients in the observed data. While it is commonly used as a tool for assessing cultural interference in aeromagnetic data (Roest, Verhoef, and Pilkington 1992; Beamish and White 2011; White and Beamish 2011), it is clearly useful for highlighting corrugation between poorly levelled lines. Figure 4 displays the AS from the pre- and post-levelled data, and the effect of the levelling algorithm is immediately apparent. The first-order derivatives have highlighted the stripy nature of the data prior to levelling. Continuous N–S trending anomalies linked to poorly levelled line data are observed in the gridded AS. The levelled data are much cleaner and ready for further interpretation procedures (see Beamish and White 2011).

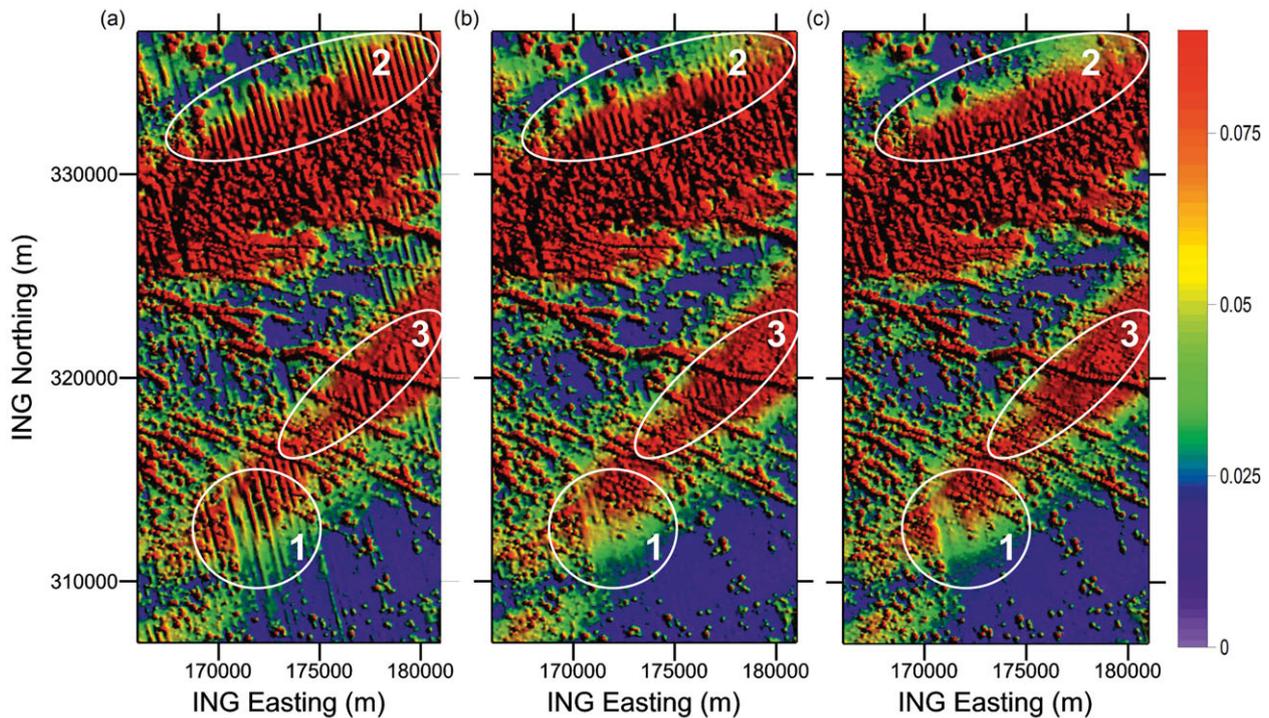


Figure 6 The AS of the total field data from a 15 km x 30 km portion of Tellus Border data displayed as a shaded relief image with illumination from the NE. (a) The AS from the pre-levelled magnetic data set; (b) the AS of the contractor-supplied levelled data set; and (c) the AS following 'mag-to-regional' levelling. Units are nT/m.

The final data set considered here is the Tellus Border survey, an EU INTERREG IV-funded regional mapping project, flown over the border counties of the Republic of Ireland, adjacent to Northern Ireland. The primary aims of the survey were to generate an accurate baseline data set and stimulate interest and investment in mineral exploration in the region. The survey, completed in July 2012, was flown with 200-m line spacing and has significantly longer line lengths than the previous examples. Unfortunately this results in a significant number of partial lines (data from the same line split between different days and flights), which makes levelling more complicated. From a processing perspective, the complete survey covers a non-ideal footprint since it comprises a highly irregular area adjacent to previous airborne surveys (Beamish and Young 2009). The subsection chosen for analysis in this study contains 15816 line-kilometres of data with line lengths of between 8 km and 100 km. The data were acquired across a broad distribution of altitudes with a mean flying height of 86.4 m, a standard deviation of 61.6 m, and a range from 28.8 m to 619.2 m. The region is primarily located over the counties of Sligo and Leitrim and is approximately equivalent to section 1 of the released data (from www.tellusborder.eu).

The data were delivered in the Irish National Grid coordinate system and were flown at a flight-line orientation of 345° from geographical north. Orthogonal tie-lines were flown as part of the Tellus Border survey at 1000-m separations. In-field, diurnal, and IGRF corrections had already been applied to the data prior to delivery. Figure 5(a) shows a section from the pre-levelled data where significant levelling issues are highlighted with white arrows. Processing, in this study, was undertaken in a rotated coordinate system to simulate N-S flight-lines then returned to the Irish National Grid prior to imaging.

A filtered regional field was created (Fig. 5(b)) from the raw data using a bi-directional gridding algorithm with a 1600-m low-pass filter. An alternative approach using the tie-line data to generate the regional field was also tested, and it produced comparable results. This additional development may be a useful tool to utilize the tie-line responses in a less manually intensive way.

The flight-line data were subjected to the 'mag-to-regional' levelling correction, and a standard microlevelling procedure was applied. The levelling corrections are shown in Fig. 5(c) and reveal that the 'mag-to-regional' algorithm

is responsible for the majority of the correction magnitude across a large amount of the survey extent while the short-wavelength microlevelling adjustments primarily occur near high-amplitude geological signal. The levelled data are displayed in Fig. 5(d). The improvement from the raw data is clear. However, a truer test of the quality of the levelling of airborne magnetic data is through derivatives of the gridded data, which are commonly employed during data interpretation. Figure 6 shows the analytical signal of three complimentary grids: the raw pre-levelled data; the final contractor-levelled data set; and the data levelled with the 'mag-to-regional' algorithm. The contractor-levelled comparison data set was processed using a proprietary levelling methodology that utilizes the orthogonal tie-lines flown during the survey. In their workflow, the unlevelled magnetic field values were extracted at intersection points, and the data from each flight-line were adjusted by a constant amount to minimize the intersection differences. Additional local corrections were then employed to further reduce the crossover errors. Finally, a microlevelling procedure, which used a combination of a directional cosine filter and a high-pass Butterworth filter, was applied to strip out any remaining artefacts. The data used in the comparisons cover a 15 km x 30 km region highlighted by the black box in Fig. 5(d), and the results, displayed in Fig. 6, clearly highlight the different degrees of corrugation seen in the three data sets.

The pre-levelled data are evidently influenced by line-to-line levelling errors as the AS has a stripy nature throughout. In order to compare the two levelled data sets, three regions of interest are selected. Region 1 demonstrates that the substantial improvements levelling can bring about in data quality. The two levelling techniques have removed the line-to-line mismatches and produced an enhanced data set without spurious anomalies in the magnetic gradients.

Region 2 is on the edge of a continuous zone of high magnetic amplitude, which cross-cuts the flight-line direction. A change from high to low AS is observed at this location. Both levelled data sets offer improvement from the unlevelled data, but the 'mag-to-regional' approach has better defined the edge of the anomaly and has significantly less corrugation in the flight-line direction at the frequency of the line spacing. A similar effect is seen in region 3, which covers the peak of a high-amplitude response. The raw data are stripy, but a significant proportion of the high-frequency noise is still contained in the contractor-released data. Greater continuity of cross-cutting features, a smoother anomaly field, and an absence of flight-line orientated stripes are observed in the 'mag-to-regional' levelled data.

CONCLUSIONS

A new approach for levelling aeromagnetic data has been described. The technique relies on the long-wavelength component of the flight-line data accurately sampling the regional field. The data can then be levelled to the regional grid without the need for tie-lines. In an additional development, the data can be further levelled to the IGRF to derive the anomaly field using a 2D minimization based on similar principles. The method currently uses a first-degree polynomial to define the error function for each line, but higher degree polynomials can be applied where necessary.

The examples shown in this study highlight the degree of improvement that the technique offers compared with the unlevelled data. It is suggested that one primary benefit of the technique is in the QC of aeromagnetic data during the survey. Once enough lines are flown to generate a regional field, the automated scheme proposed here would allow a levelled partial survey to be produced with little user input.

The scheme was shown to outperform other levelling strategies and has the major advantage of being computationally, not manually, intensive, levelling large data sets in under an hour. The method appears to work at a range of scales and with data sets that display high- and low-magnitude geological signals. Furthermore, cultural noise does not seem to unduly hinder the levelling algorithm.

A possible simplification of the technique, where lines are long and flown without breaks, is the one-step levelling of the flight-line data to the IGRF. Further work continues in this regard.

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