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# A comparison of aeromagnetic levelling techniques with an introduction to median levelling

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**ABSTRACT**
Aeromagnetic data collected in areas with severe diurnal magnetic variations (auroral zones) are difficult to level. This paper describes levelling of an aeromagnetic survey where such conditions prevail, and where sophisticated levelling techniques are needed. Corrections based on piecewise low-order polynomial functions are often used to minimize mis-ties in aeromagnetic data. We review this technique and describe similar mis-tie fitting methods based on low-pass filter levelling, tensioned B-spline levelling and median levelling. It is demonstrated that polynomial levelling, low-pass filter levelling and tensioned B-spline levelling depend on the careful editing of outlying mis-ties to avoid the introduction of false anomalies. These three techniques are equally efficient at removing level errors. Median levelling also removes level errors efficiently, but it is more robust in the sense that mis-tie editing is not required. This is due to the inherent noise-removal capabilities of the median filter. After mis-tie editing, the total field anomalies of the other three techniques closely resemble the unedited median-levelled total field anomaly.

## INTRODUCTION

Variations in the earth's magnetic field with time can pose severe problems in magnetic surveying. These are mainly caused by the solar wind (charged particles from the sun) impinging on the earth's magnetosphere and ionosphere, giving rise to variations in the magnetic field. At any location, the magnitude of the magnetic field has temporal variations. These variations are short compared with the time it takes to carry out an aeromagnetic survey (Luyendyk 1997). Variations are most severe in the auroral zones centred on magnetic latitudes 70°N and 70°S. Variations in diurnal patterns of more than 100 nT during a period of 32 days in a polar region survey have been reported. The most severe variations reached amplitudes of nearly 600 nT recorded over a period of 30 minutes (Maslanyj and Damaske 1986). While carrying out magnetic surveying, it is usual to monitor diurnal variations using a base station magnetometer. Data from this magnetometer can be used directly to correct magnetic readings if the survey area is close to the base station. According to Reeves (1993), the most remote part of the survey area should be within 50 km distance of the base station for the base station readings to be used in this way. This criterion is rarely met for large surveys. Routinely, tie-lines are used to level surveys, even when base station corrections are also applied. In large-scale surveys, tie-lines are often measured orthogonal to survey lines to produce a set of intersection points with duplicate magnetic readings, one from the survey line and one from the tie-line. Differences in the readings at intersection points (mis-ties) are mainly due to diurnal variations in the earth's magnetic field. Other sources of mis-ties are navigational errors, variations in flight altitude, transient anomalies from ships, magnetometer drift and random noise. Levelling is the process that seeks to remove short-period magnetic variations from the data by minimizing mis-tie values. Levelling is carried out without regard to the causes of the mis-ties. The sensitivity of modern surveys is $\pm 0.1$ nT or less, while mis-tie values can be of the

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order of 10–100 nT. Therefore, in order to resolve anomalies with amplitudes in the range 0.1–1 nT, such as those caused by intrasedimentary susceptibility contrasts, the levelling process must be given careful attention.

A common technique for levelling is minimizing mis-ties by least-squares polynomial fitting for each flight line (Foster, Jines and van der Weg 1970; Yarger, Robertson and Wentland 1978; Bandy, Gangi and Morgan 1990; Luyendyk 1997). The polynomial levelling technique is described in detail in this paper and compared with related levelling techniques.

The following techniques for obtaining levelling corrections from mis-ties are discussed.

**1** Fitting of piecewise low-order polynomial functions to mis-ties.
**2** Low-pass filtering of mis-ties.
**3** Tensioned B-spline fitting of mis-ties.
**4** Median filtering of mis-ties.

We demonstrate that levelling using the first three techniques gives almost identical results. However, these techniques usually require careful editing of mis-ties before they can be applied. Median levelling stands out as a particularly robust technique in that mis-tie editing is seldom necessary.

## DESCRIPTION OF LEVELLING FILTERS

This section briefly describes the theoretical background for the filters and operators used in the different levelling techniques. These filters and operators are used to obtain smooth mis-ties. The levelling corrections are then applied through the application of interpolation between the crossover points.

### Polynomial functions

Minimizing mis-ties can be carried out by fitting low-order polynomials to the mis-ties using the least-squares method. A polynomial of order $n$ is expressed as

$$f(x) = ax^n + bx^{n-1} + \cdots + cx + d.$$

In order to fit a second-order polynomial to mis-ties using the least-squares method, the following function must be minimized:

$$q = \sum_{j=1}^{n} (g_j - ax_j^2 - bx_j - c)^2,$$

where $q$ is the sum of the squares of differences between the mis-ties ($g$) and the polynomial function values. The $x_j$ represent distance of time (fiducial) along the line. The minimum value of $q$ can be found by taking the partial derivatives of $q$ with respect to $a$, $b$ and $c$ and solving the three linear equations:

$$\frac{\partial q}{\partial a} = 0, \quad \frac{\partial q}{\partial b} = 0, \quad \frac{\partial q}{\partial c} = 0.$$

This can be expressed as

$$cn + b\sum_{j=1}^{n} x_j + a\sum_{j=1}^{n} x_j^2 = \sum_{j=1}^{n} g_j,$$

$$c\sum_{j=1}^{n} x_j + b\sum_{j=1}^{n} x_j^2 + a\sum_{j=1}^{n} x_j^3 = \sum_{j=1}^{n} g_j x_j,$$

$$c\sum_{j=1}^{n} x_j^2 + b\sum_{j=1}^{n} x_j^3 + a\sum_{j=1}^{n} x_j^4 = \sum_{j=1}^{n} g_j x_j^2.$$

Because the $x_j$ and $g_j$ are known, we can solve for the polynomial coefficients $a$, $b$ and $c$ in the above equations. Such polynomial functions are calculated piecewise for mis-ties along each flight line to be levelled. The lines are levelled by subtracting the value of the polynomials at each point along the lines.

### Low-pass filter

Low-pass filtering of mis-ties can be carried out using a convolution filter. The implementation of the filter used here is described in detail by Fraser, Fuller and Ward (1966). The convolution operation can be discretized by

$$g(x) = \sum_{n=-T/\Delta x}^{T/\Delta x} W(n) f(x - n\Delta x),$$

where $T$ is half the desired filter length and $\Delta x$ is the spatial sampling interval. $g(x)$ is the output value, $f(x - n\Delta x)$ are input values and $W(n)$ is the series of filter coefficients. $W(n)$ can be expressed by

$$W(n) = h(n\Delta x)s(n\Delta x)\Delta x.$$

$h(n\Delta x)$ is the inverse Fourier transform of the ideal wave number response expressed by

$$h(n\Delta x) = \frac{2}{\pi n\Delta x}\sin(2\pi\Delta k n\Delta x)\cos(2\pi k_0 n\Delta x),$$

where $\Delta k$ is half the bandwidth and $k_0$ is the centre wave number.

$h(n\Delta x)$ is infinite in length and must be shortened. This is done by applying the Hanning function (Blackman and Tukey 1958) which is expressed as

$$s(n\Delta x) = \frac{1}{2}\left(1 + \cos\frac{\pi n\Delta x}{T}\right), \quad |n\Delta x| < T.$$

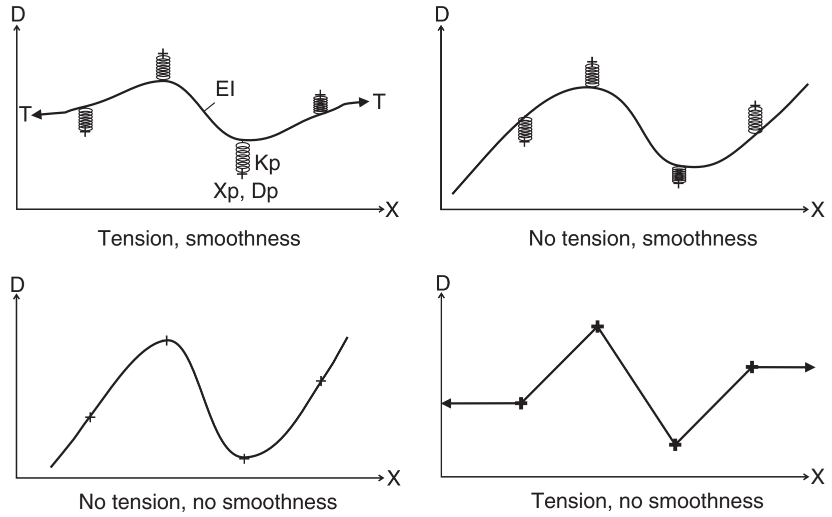



**Figure 1** Deformation of a thin elastic bar using different values for smoothness (*EI*) and tension (*T*) (after Inoue 1986).

**B-splines in tension**

The physical analogy of 1D tensioned B-splines can be visualized by the deformation of a thin elastic bar under tension (stretch), which is pulled by springs perpendicular to the bar (Fig. 1). In the figure, *T* denotes the tension applied to the bar, *EI* is the flexural rigidity, while $K_p$ is the spring stiffness for point ($X_p$, $D_p$). The function representing the shape of the deformed bar can be found by minimizing the energy of the static system in Fig. 1. The function is composed of a running series of cubic splines (Inoue 1986).

In the levelling problem, *EI* represents the smoothness of the function. The higher the value, the smoother the function. *T* denotes tension. The function's approximation to the mis-ties becomes poorer and the fitted line becomes straighter when the tension is increased. The effects of varying *EI* and *T* are shown in Fig. 1.

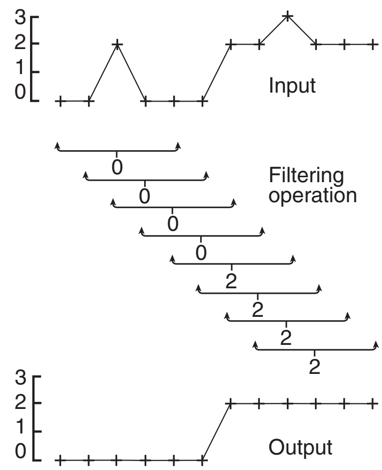



**Figure 2** Median filtering of a sequence of numbers using a 5-point filter (modified after Stewart 1985). Note the removal of spikes and the preservation of edges.

**Median filter**

The median is the middle value in an array of numbers sorted in ascending order. The median is denoted by

$\mathrm{Median}(X_1, X_2, \ldots, X_n)$.

The median filter of size $n$ (odd) in the sequence $\{x_i, i \in Z\}$ is defined as (Justusson 1981)

$$y_i = \mathrm{Median}\; x_i \triangleq \underset{n}{\mathrm{Median}}\,(x_{i-v}, \ldots, x_i, \ldots, x_{i+v}), \quad i \in Z,$$

where $v = (n - 1)/2$ and $Z$ denotes all natural numbers.

The median filter is a non-linear filter, which has two important properties. It acts as a noise filter and is particularly efficient at removing spikes. Although it is a smoothing filter, it preserves sharp edges in a data set (Justusson 1981; Stewart 1985). Both these properties are illustrated in Fig. 2 (after Stewart 1985), which also outlines the procedure for 1D median filtering.

## PRELEVELLING PROCESSING

All the levelling methods discussed in this paper, including median levelling, require the same preprocessing steps. Raw data are edited either manually or using a non-linear filter (Naudy and Dreyer 1968) to remove spikes due to lightning strikes or other non-geological sources. A model of the field due to the earth's geodynamo – the International Geomagnetic Reference Field (IGRF) – is removed, and a parallax (or lag) correction is applied to correct for the sensor offset as the plane flies in alternating directions. For various reasons, it may be necessary to fly long lines in multiple segments. These segments may be shifted and joined prior to levelling. If deemed beneficial, a base station correction is applied. However, for the survey described in this paper, the area covered was large and the base station was of necessity located outside the survey area, so the correction was not applied. Base station magnetometer data were used only for the purpose of assessing periods of high diurnal activity. After all the pre-levelling corrections are applied, the data are resampled at uniform spatial intervals to improve the effectiveness of subsequent filters applied during the levelling procedure. The sampling interval must be smaller than half the distance between possible magnetic sources and the sensor to avoid aliasing (Reid 1980).

## OVERVIEW OF THE LEVELLING PROCEDURE

Regional aeromagnetic surveys are usually flown in a grid pattern. Lines are flown across the dominant geological strike direction and cover the whole survey area. Tie-lines are flown perpendicular to the lines and are used for levelling purposes. The distance between tie-lines is usually 2–5 times the distance between lines.

Traditionally, levelling is performed using one of two different methods (Green 1983; Luyendyk 1997):

1 Minimizing closure errors in a network of intersection loops by a least-squares fitting method (Cowles 1938; Gibson 1941; Green 1983). This method often needs correction of navigational errors before it can be applied. The method is used in areas with low magnetic gradient where the range of intersection errors is small (Green 1983; Luyendyk 1997).

2 Linewise fitting of smooth functions to mis-tie values. The most frequently used technique in this category is fitting by piecewise least-squares low-order polynomials (Foster *et al.* 1970; Yarger *et al.* 1978; Bandy *et al.* 1990; Luyendyk 1997).

The latter suite of techniques are described in detail in this paper. Fitting of low-order polynomials is a technique which is included in the processing programs of major software vendors, such as Geosoft and DFA/Intrepid.

The first step is to perform a zero-order network adjustment in which data along lines and tie-lines are shifted up and down linewise to minimize mis-tie values. The average mis-tie for the whole survey should then be close to zero. The second step is to level each tie-line by subtracting a smooth function fitted to the mis-tie values. After recalculating mis-ties, lines are levelled to the tie-lines in the same way.

## ZERO-ORDER NETWORK ADJUSTMENT

If a tie-line is flown during quiet diurnal conditions, it can be used as the basis for levelling of all other lines and tie-lines (Luyendyk 1997). In this case the tie-line is considered to be level. In surveys where the diurnal variations are severe and parts of tie-lines are recorded during different flights, a zero-order network adjustment is performed as the basis for further levelling. This is done to bring the lines and tie-lines into approximately level positions. In this step, levelling is carried out by calculating the arithmetic mean of the mis-ties for tie-lines and lines. First, all the tie-lines are levelled to the lines. Then, new mis-ties are calculated and lines are levelled to tie-lines that are already levelled. The levelling procedure only introduces constant shifts to the lines and tie-lines and therefore it does not distort the original data. However, this levelling procedure is rarely sufficient to remove all line errors, and maps produced from zero-order network adjusted data usually show these errors as narrow bands along the flight lines.

## HIGHER-ORDER LEVELLING TECHNIQUES

This section describes the advantages and disadvantages of using the different operators in the levelling techniques.

### Polynomial levelling

Levelling by polynomials is a common technique used for aeromagnetic data (Foster *et al.* 1970; Yarger *et al.* 1978; Bandy *et al.* 1990; Luyendyk 1997). Usually, the order of the polynomial is low (1–3). There are some problems involved in using polynomial functions to reduce mis-ties. The order of the polynomial should be low compared with the number of mis-ties in order to get a smooth trend line through the mis-ties. Usually, the order of the polynomial should be less than $(t - 1)/2$, where $t$ is the number of mis-ties (Luyendyk 1997). Another weakness is that a low number of mis-ties will better fit the polynomial than will a large number of mis-ties, resulting in variable smoothing. Figure 3 shows an example of fitting a third-order polynomial to 5 and 10 mis-ties. Note that 10 mis-ties yield a smoother polynomial than 5 mis-ties.

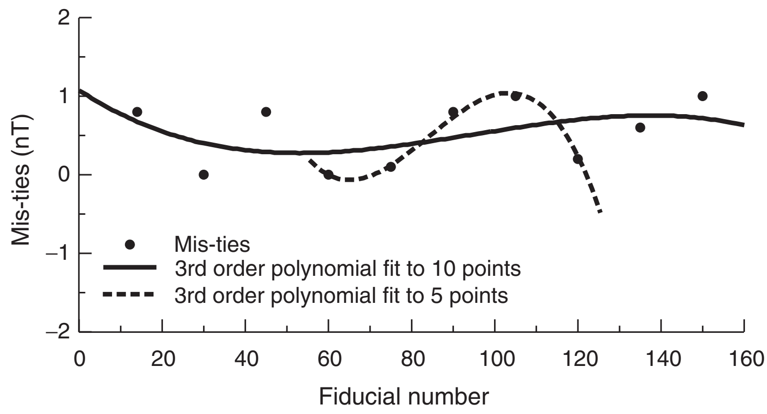



**Figure 3** Third-order polynomial fitting to 5 and 10 points.

In high-latitude survey areas, high-order polynomials may be needed to obtain an acceptable fit to mis-ties. Unfortunately, fitting of high-order polynomials can give unstable solutions, especially at the ends of lines where there are no data constraints. This may lead to severe corrugations and anomaly distortion. All mis-ties in polynomial fitting are weighted equally, so the fitting is sensitive to outlying mis-ties.

The above-mentioned shortcomings of polynomial fitting can be reduced by using piecewise low-order polynomials with smoothing (Luyendyk 1997). This is implemented by moving a window over the mis-ties and calculating a least-squares polynomial function for the window based on the mis-ties within it. The calculated value of the polynomial function for the centre point of the window is then taken to be the value of the final fitted curve for that position. After the window has been moved along the entire line to be processed, the calculated values are interpolated to give a continuous correction vector. This technique eliminates the need for high-order polynomials while still obtaining a close fit to the mis-ties. A disadvantage of this technique is that a varying density of mis-ties along a line leads to a varying degree of smoothness of the fitted line, as demonstrated in Fig. 4. The problem becomes less prominent if the fitted line is subsequently smoothed (see Fig. 4). An approach for reducing the influence of outlying mis-ties is discussed later.

## Low-pass filter levelling

In this technique, a convolution operator is used to filter the mis-ties. To find an appropriate filter length, the variations on the readings of the base magnetometer can be examined. Ideally, a small cut-off wave number should be chosen.

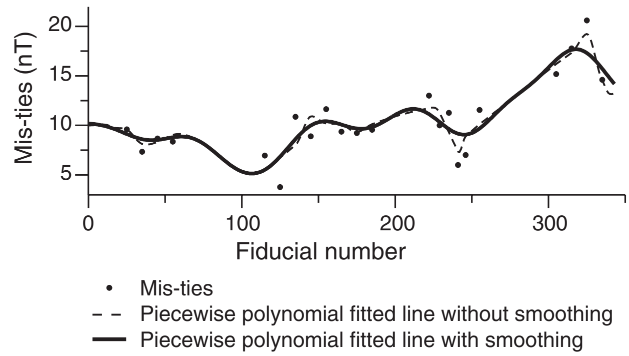



**Figure 4** Piecewise polynomial fitting (second-order) to mis-ties, with and without smoothing.

A large cut-off wave number results in a closer fit to the outlying mis-ties, making anomaly distortion conspicuous. The degree of smoothing is not sensitive to the number of mis-ties along a line. This is illustrated in Fig. 5 (compare with polynomial fitting in Fig. 3). Neither is it necessary to adjust the filter according to the density of mis-ties. This is demonstrated in Fig. 6, which shows the fitting techniques applied to an irregularly sampled sine wave. The low-pass filter technique is thus convenient when mis-ties are distributed unevenly.

Low-pass filtering is sensitive to outlying mis-ties, especially if several mis-ties are spatially gathered.

## B-spline levelling

In order to avoid unwanted distortion of anomalies, the fitting of mis-ties with B-splines should be carried out with tension and relatively high smoothness. With high values for tension and smoothness, the technique has low sensitivity for isolated, outlying mis-ties. However, some mis-tie editing

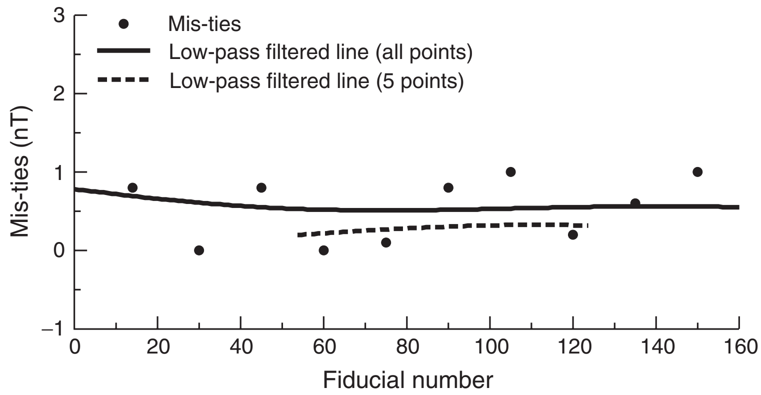



**Figure 5** Low-pass filtering of 5 and 10 points. The points are the same as in Fig. 3.

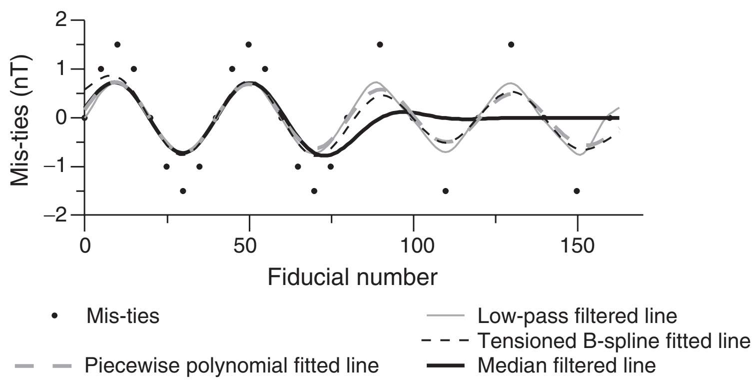



**Figure 6** Variations in the degree of trend line smoothing depending on the density of mis-ties for different filtering operators.

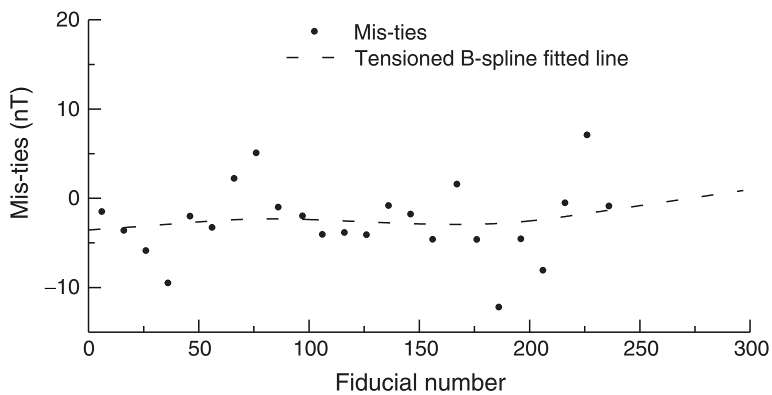



**Figure 7** Curve-fitting by B-splines in tension showing low sensitivity to outlying mis-ties and high stability at the ends of lines.

usually has to be carried out. Using tension, the curve-fitting is stable at the ends of lines. Both these properties are demonstrated in Fig. 7.

This technique can yield a varying degree of smoothing depending on the density of mis-ties to be fitted (Inoue 1986). A high density of mis-ties gives less smoothing than a low density for fixed values of smoothness and tension. This is illustrated in Fig. 6, which shows a changing density of mis-ties along a line. The left half of the figure has twice the density of mis-ties compared with the right half.

Using tension values that are too high leads to a sequence of piecewise near-linear curve segments which bend sharply at the mis-tie values, thus leading to undesirably rough curve-fitting (see Fig. 1). A tension value has to be found which is low enough to fit a smooth curve while preserving the stability at the ends of lines.

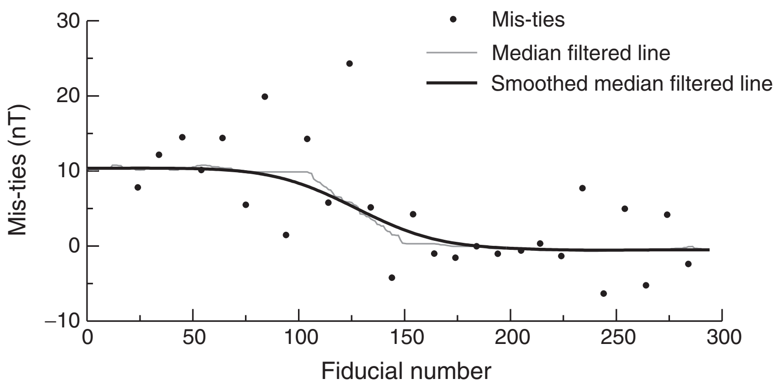



**Figure 8** Example of median filtering of mis-ties. For the thick, black line, a low-pass filter has been applied after median filtering in order to yield a smooth transition between ramps in the data set.

**Median levelling**

The median filter is especially suited for the removal of random noise. Applying a median operator to the filtering of mis-ties is insensitive to outlying values. This reduces the need for automatic and manual editing of outlying mis-ties before levelling is carried out. The smoothing of the mis-ties increases with the operator length. Figure 8 (thin line) shows an example of median filtering of mis-ties along a line. The smoothness of the median-filtered trend line also depends on the density of mis-ties, which is apparent from Fig. 6, which shows a 3-point median filter run through an unevenly sampled sine function. Because of the low sample density in the right half of the figure, the median operator treats the extreme points as outliers.

Applying the median filter yields stable values at the ends of lines. Figure 8 shows abrupt level shifts in the filtered curve where there are changes in the level of the mis-tie values. This is one of the properties of the median filter (Justusson 1981) which, in this case, is unfortunate since a smooth filtered curve is required to avoid anomaly distortion. This can easily be overcome by applying a smoothing filter to the median-filtered mis-ties (see Fig. 8, thick line). Smoothing is also used to accommodate an uneven distribution of mis-ties.

The stability of the filter, and the notion that mis-tie editing can be omitted, make median filtering of mis-ties a robust and practical technique.

**Mis-tie editing**

Noisy and outlying mis-ties are included in the calculation of the trend vector, which is further used to correct magnetic total field values. Including outlying mis-ties can then add artefacts/distortions to the total field values. Relatively high wave-number trend lines may be necessary to accommodate severe diurnal variations. This may require that the levelling techniques use short operator lengths in the calculation of trend values. Outlying mis-ties typically have more impact on the calculated trend values when the operator length decreases. This is demonstrated for piecewise polynomial levelling in Fig. 9. Therefore, the quality and reliability of levelling may improve considerably if mis-ties can be weighted or selectively removed. Three methods of mis-tie editing are in use (Luyendyk 1997) and are outlined below.

**1** Manual rejection of mis-ties. By this method, mis-ties are visually inspected after preliminary fitting or filtering of mis-ties. Mis-ties which are suspected of having a degradational impact on the levelling are rejected, and new fitting/filtering is performed on the remaining mis-ties.

**2** Automatic rejection of mis-ties. Manual rejection of mis-ties is a rather tedious and time-consuming process, and automatic rejection may be preferred. This can be performed by excluding all mis-ties at points where the horizontal magnetic gradient exceeds some threshold value (the method preferred by Geosoft). Another way of performing automatic rejection is by means of statistical evaluation after preliminary fitting or filtering of mis-ties. If the absolute difference between the fitted/filtered trend line and a mis-tie is greater than a few standard deviations, the mis-tie is rejected. The standard deviation is dynamic in the sense that it is determined from a moving window centred around the point to be evaluated. This prevents excess rejection of mis-ties in areas where they are highly scattered (increased standard deviation) but still not obviously outlying.

**3** Weighting of mis-ties. Instead of either keeping or rejecting mis-ties, they can be weighted during fitting/filtering, based on the magnitude of the horizontal magnetic gradient at the crossover point (the method preferred by Intrepid). If the gradient is high, navigational errors lead to large mis-tie

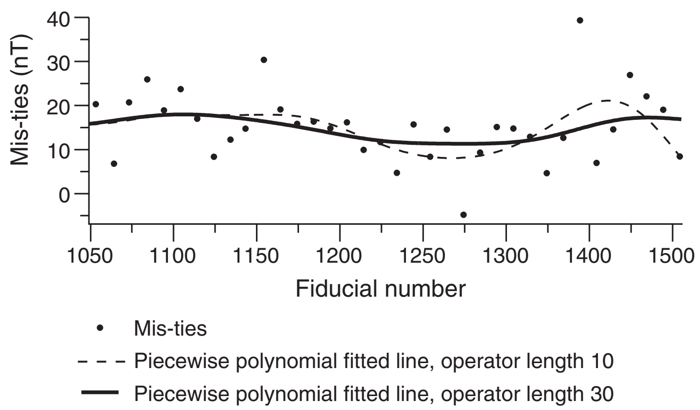



**Figure 9** Outlier mis-tie impact on the trend line for different operator lengths (second-order piecewise polynomial).

values (Luyendyk 1997). Mis-ties are often weighted according to the inverse of the gradient amplitude or to the inverse of the gradient amplitude squared.

## COMPARISON OF LEVELLING TECHNIQUES

In order to evaluate the usefulness of different techniques, levelling is carried out using magnetic data recorded during a period of severe temporal variations in the earth's magnetic field. The present survey area lies within the auroral zone. Readings from the base magnetometer were not used directly to correct survey readings because the survey area is too large and situated too far from the base station. At the time of data acquisition, these readings were used only for quality checking to evaluate which portions of flights should be reflown. The large diurnal changes led to large line-level errors.

The survey was carried out with a fixed-wing aircraft using a line spacing of 1 km and a tie-line spacing of 5 km (a subset of the survey lines is shown in Fig. 12a). The nominal aircraft and sensor altitudes were 200 m and 130 m, respectively. The aircraft speed was approximately 200 km/h. Data were collected at 0.2 s intervals, equivalent to a spatial sampling interval of approximately 12 m, but were resampled at a constant spacing of 100 m after preprocessing. A thick water column (100–1000 m) above any outcropping sources justifies the use of a sampling interval larger than half the sensor altitude (65 m).

Preprocessing included spike removal and subtraction of the IGRF. A minimum curvature routine (Briggs 1974) using a grid cell size of 250 m was employed in the gridding of data. Gridded raw data of a selected part of the survey area are shown in Fig. 12(b). Severe line-level differences (corrugations) are evident. The average absolute mis-tie is 17.3 nT.

### Zero-order network adjustment

After preprocessing, zero-order network adjustment (constant shift) was performed on all tie-lines and lines. The resulting levelled data were gridded and are shown in Fig. 12(c). Only minor differences can be noticed compared with the raw data. The zero-order network adjusted data are the basis for later levelling using piecewise low-order polynomials, low-pass filtering, tensioned B-splines and median filtering.

### Mis-tie editing and higher-order levelling

Mis-tie editing is not used in the median-levelling technique, because of its inherent noise-removing property. For the other techniques, the method of automatic rejection was used in mis-tie editing with a threshold of 1.5 standard deviations. Weighting of mis-ties using the magnitude of horizontal gradients was not successful due to the lack of correlation between mis-ties (calculated after preliminary levelling) and horizontal gradient. The average correlation coefficient for all lines was 0.034. This lack of correlation suggests that the navigational data are of high quality.

Figures 10 and 11 show levelling results for two lines using all the different techniques mentioned above. For all techniques, we have aimed at obtaining equally smooth trend lines through the mis-ties to be able to compare the techniques. For polynomial levelling, piecewise second-order functions are used. Figures 10(a) and 11(a) show calculated trend lines through unedited mis-ties, while Figs 10(c) and 11(c) show trend lines after mis-tie editing. Figures 10(b), 11(b), 10(d) and 11(d) show total field anomalies after subtraction of the trend lines, before and after mis-tie editing. The zero-order network adjusted total field anomaly is also shown. Note that the vertical scales are different for mis-ties and total field anomalies.

Figures 10(a) and 11(a) show that the shape and magnitudes of the trend lines for piecewise polynomial fitting, B-spline fitting and low-pass filtering are similar. However, these techniques diverge from the median-filtered trend line at positions where there are outlying mis-ties (positions 900, 1000 and 1150 in Fig. 10 and positions 950 and 1050 in Fig. 11). After subtracting the trend lines from the zero-order adjusted total field anomaly, we get the total field anomalies shown in Figs 10(b) and 11(b). There are differences between the median-levelled total field anomaly and the total field anomalies levelled with the other techniques due to the outliers included in the levelling. The most significant discrepancies can be seen between positions 900 and 1200 in Fig. 10 and positions 850 and 1150 in Fig. 11. In the same areas, the median-levelled total field anomaly shows less distortion and a higher semblance to the zero-order adjusted total field

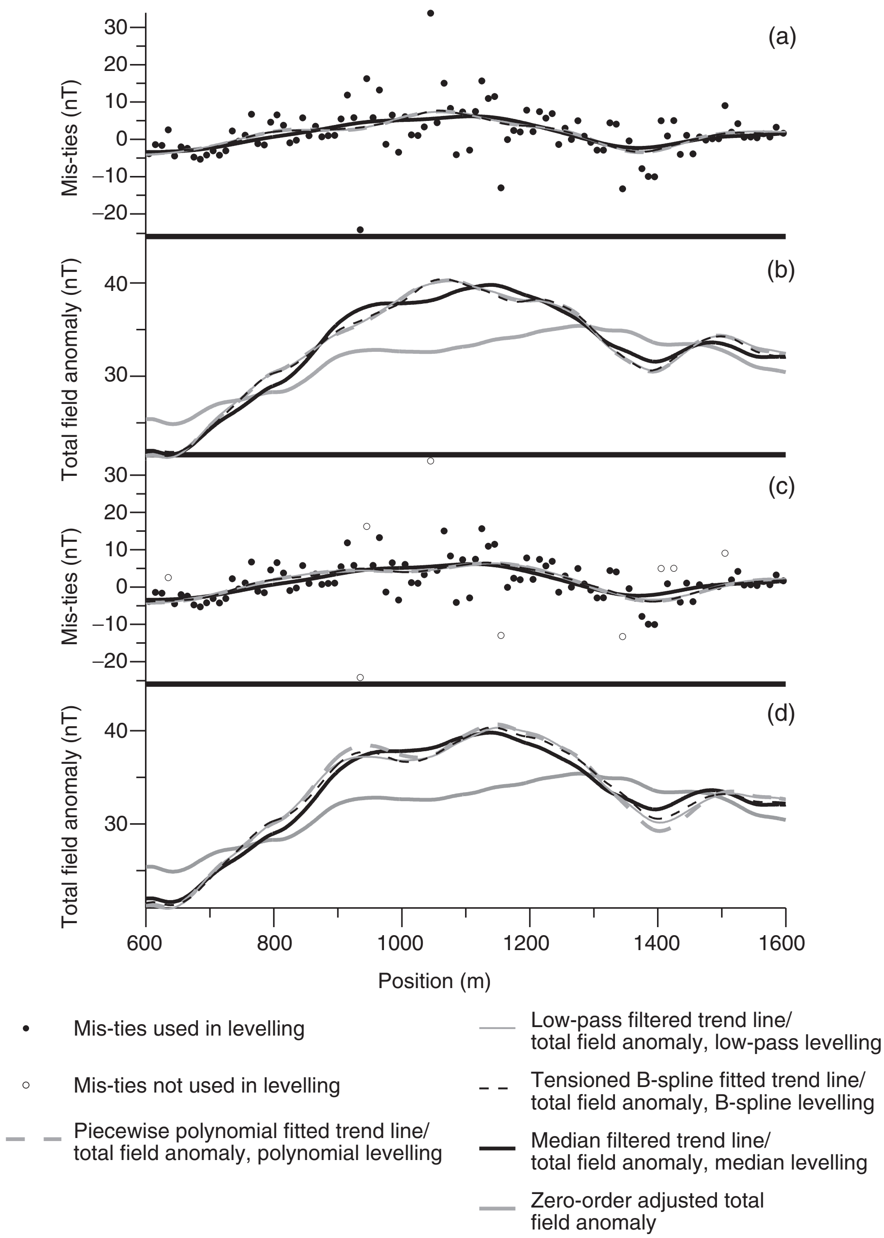



**Figure 10** Trend lines and magnetic total field anomalies: (a) and (b) before, (c) and (d) after, mis-tie editing. Line example 1.

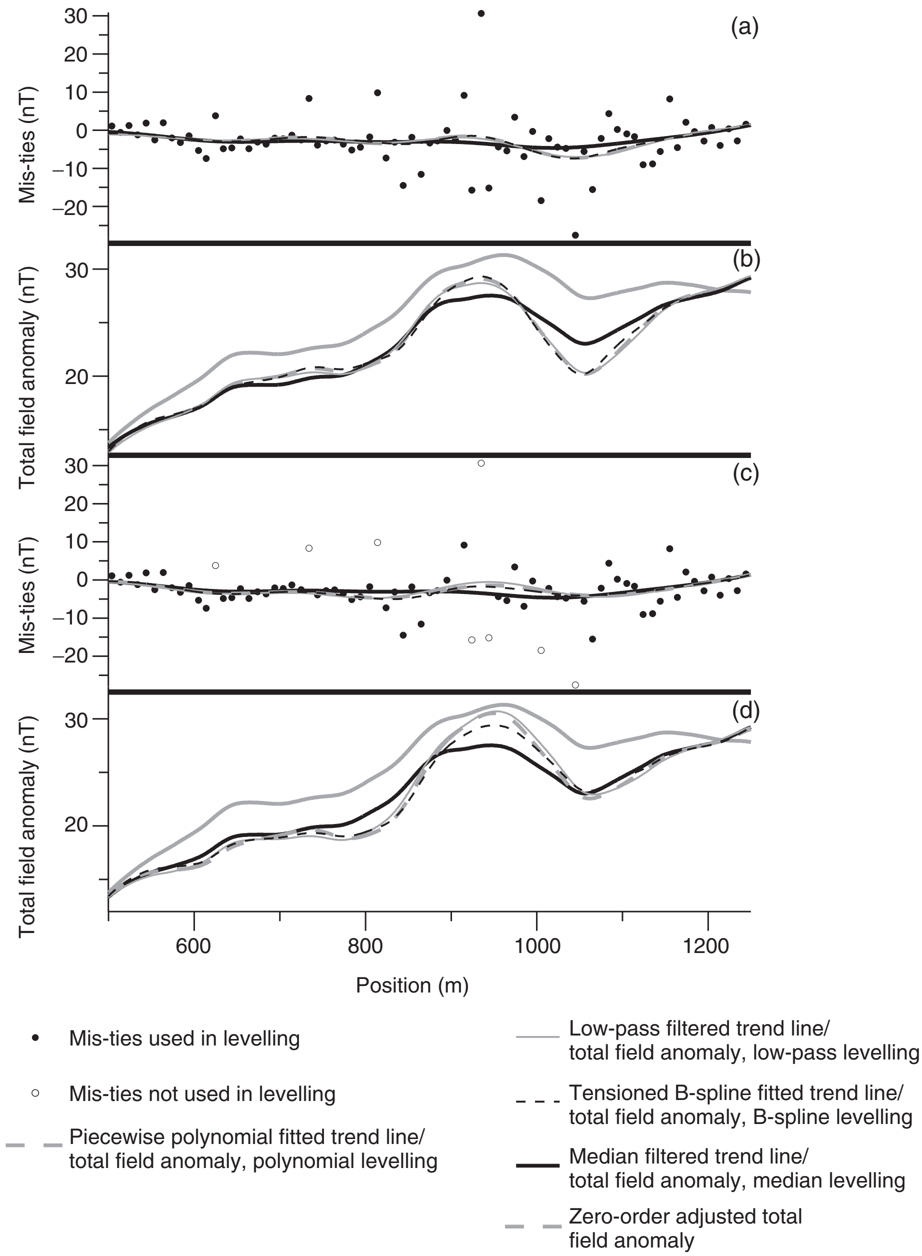
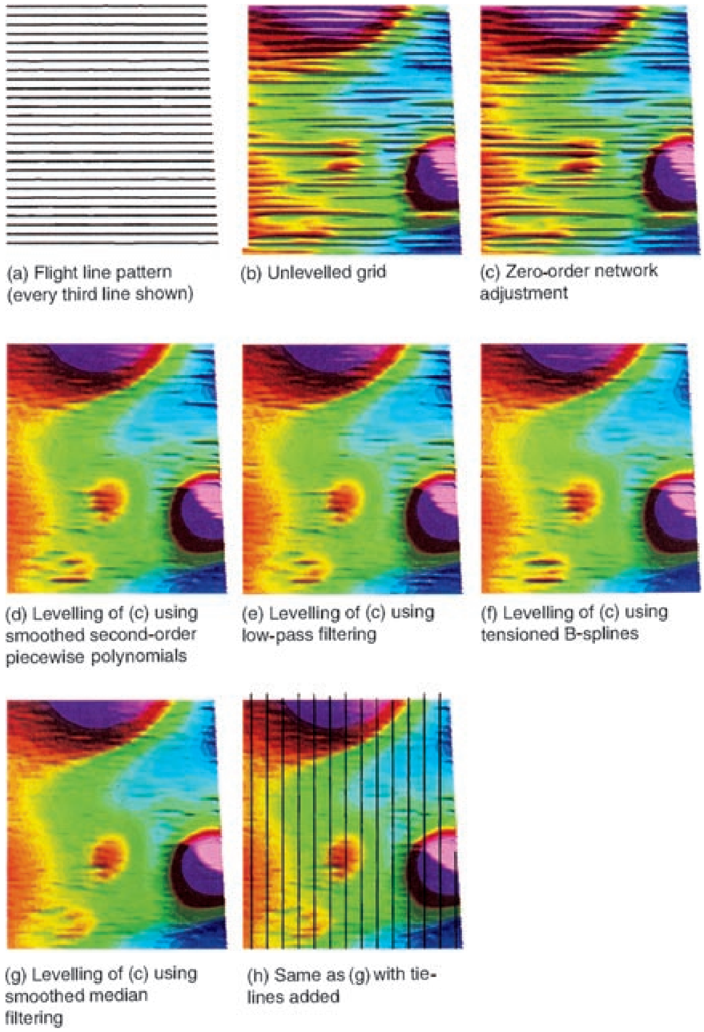



**Figure 11** Trend lines and magnetic total field anomalies: (a) and (b) before, (c) and (d) after, mis-tie editing. Line example 2.

anomaly than the data levelled by the other techniques. These techniques have introduced overcorrection due to the outlying mis-ties.

After mis-tie editing and subtraction of the trend lines (Fig. 10c) from the zero-order adjusted total field anomaly, there is a higher semblance between the median-levelled total field anomaly and the total field anomalies levelled with the other techniques (Fig. 10d), indicating that the mis-tie editing led to improved levelling. The same cannot be said about the levelling example in Fig. 11. While levelling has improved the total field anomalies between positions 1050 and 1150, it has introduced unacceptable levels of distortion to the anomalies between positions 850 and 1050. Overcorrection is introduced between positions 750 and 850. Thus, outlier mis-tie rejection has not been effective in improving levelling for this line. This can be explained by considering Fig. 11(c), which shows the mis-ties that remain after editing. The distortion is introduced because two outlying mis-ties below the trend line

**Figure 12** Images of gridded magnetic total field anomalies based on different levelling techniques.




are not balanced by outliers on the opposite side. This can be improved by manual editing or by changing the mis-tie rejection threshold. A better solution may be to introduce a type of mis-tie editing in which mis-ties are weighted according to their difference from a preliminary fitted trend line. Still, a threshold value (e.g. 1.5 standard deviations) can be set, above which mis-ties are rejected.

Data from a small part of the survey area are shown in Fig. 12, gridded after levelling, using the techniques discussed. The unlevelled grid is shown in Fig. 12(b). Line-to-line corrugation is severe. Although it is difficult to see any significant improvement in the grid after zero-order network adjustment (Fig. 12c), the average absolute mis-tie has been reduced from 17.3 nT to 5.0 nT. Figure 12(d–g) show grids of total field anomalies after piecewise polynomial levelling, low-pass filter levelling, tensioned B-spline levelling and median-filter levelling, respectively. After levelling, the absolute average mis-tie values for these techniques are 0.7, 0.7, 0.6 and 0.6 nT, respectively. Corrugation is still evident in these grids, although dramatically reduced. Grids after tensioned B-spline and median levelling show less corrugation at the right edge of the grid, indicating that B-spline and median operators are more stable at the ends of lines. Otherwise, there are only small differences between the grids.

Figure 12(h) shows the grid of median-levelled data with tie-lines plotted. It appears that the lengths of most of the remaining corrugations are less than twice the tie-line spacing, which means that further tie-line levelling will have little effect on the remaining line-level errors.

The remaining corrugations can be reduced by microlevelling techniques (e.g. Mauring and Kihle 2000). As a rule, the average value of microlevelling adjustments should not exceed 1 nT. The average absolute mis-tie remaining after ordinary levelling is no more than 0.7 nT for this survey, and microlevelling can safely be used to make average adjustments up to 1 nT.

## CONCLUSIONS

Four techniques used for tie-line levelling of aeromagnetic data have been compared in order to test their ability to remove level errors in a survey area with severe diurnal variations. Three of the techniques require mis-tie editing prior to final levelling to avoid the introduction of false anomalies. These are piecewise polynomial levelling, low-pass filter levelling and tensioned B-spline levelling. These techniques are equally efficient at removing level errors. The mis-tie editing method used was automatic rejection of mis-ties based on a standard deviation threshold.

Even though median levelling cannot be seen to improve levelling beyond that of the above-mentioned techniques, it has the advantage of needing no mis-tie editing. It is shown that the other levelling techniques, after mis-tie editing, yield total field anomalies that closely resemble the median-levelled total field anomaly. This is not surprising, since the median levelling has inherent mis-tie editing capabilities.

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