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LEVELLING OF AEROMAGNETIC DATA

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ABSTRACT

The current demands of image processing and display technologies require that aeromagnetic data must resolve anomalies with amplitudes significantly less than one nanotesla. For this reason, accurate levelling of the magnetic data is more important than ever.

We will present some fundamental considerations and techniques used to level magnetic data to very tight tolerances while maintaining data integrity across the full range of frequencies in the data.

INTRODUCTION

Aeromagnetic surveys have benefited greatly from recent advances in acquisition and processing technologies. Noise levels are much lower and spatial resolution has improved considerably compared to surveys of just 10 years ago. To take full advantage of the low amplitude anomalies now discernible within these data sets we must correct for effects that previously could only be handled crudely and were often even ignored.

The essence of the problem is that, no matter how free of noise the line data are and no matter how small the anomalies resolved, if there is limited coherence between lines, grids of the data will be dominated by cross-line variations at the expense of detail along line. These cross-line variations or levelling errors are inevitable in any aeromagnetic survey.

The procedure of "levelling" the data by the use of magnetic base station/s and additional "tie" lines flown at an angle to the survey direction have long been used to adjust the measured values for the following three main reasons:

1) **Diurnal** – in addition to varying from location to location, the magnetic field of the earth varies with time. The main variation follows a daily cycle and is known as the diurnal variation of the field. However, solar activity, atmospheric effects and sometimes geology cause variations in the field over a wide range of frequencies. For the purposes of aeromagnetic data analysis, these variations are all equally undesirable and are collectively dubbed "diurnal". The goal of aeromagnetic surveying is to obtain the magnetic signature of an area independent of time variations. Since surveys are flown over a finite period, all temporal variations must be removed to provide a time-independent "snapshot" of the field.
2) **Position** – it is not operationally possible to fly the aircraft at the exact same height at corresponding points on adjacent lines. Because magnetic intensity varies with height above the surface, this will introduce errors in intensity from line to line. Figure 1 illustrates the difficult case of flying in mountainous terrain. The arrows indicate the height difference between adjacent lines flown in opposite directions. Although this effect can be reduced by attempting to match climb and descent rates it cannot be eliminated. Even if all lines were flown in the same direction, a similar but reduced effect would occur. This is partly because topographic shape changes from line to line. Height differences also occur because weather conditions and other factors will prevent the pilot from maintaining an exact height. The accuracy of the recorded position of the aircraft is also important in a minor way. Although positioning methods are now very accurate there will always be a small error in the computed position and therefore a corresponding error in the magnetic intensity value assigned to a given location.
3) **Aircraft Signatures** – despite concerted efforts to minimize the effects, every survey aircraft displays a different magnetic "signature". Any survey flown using two or more aircraft will exhibit a level shift between lines flown by different aircraft.

The levelling procedures used to handle these effects must reduce the introduced errors without affecting the subtle but valuable information contained in the high resolution line data.

METHOD

Levelling of aeromagnetic data can be carried out using two principal methods. The first is subtraction of the time-based variations measured at a base station (referred to as diurnal correction). The second is correction of flight lines using a series of "tie" lines flown at a steep angle to the survey lines, providing a regularly spaced network of tie line

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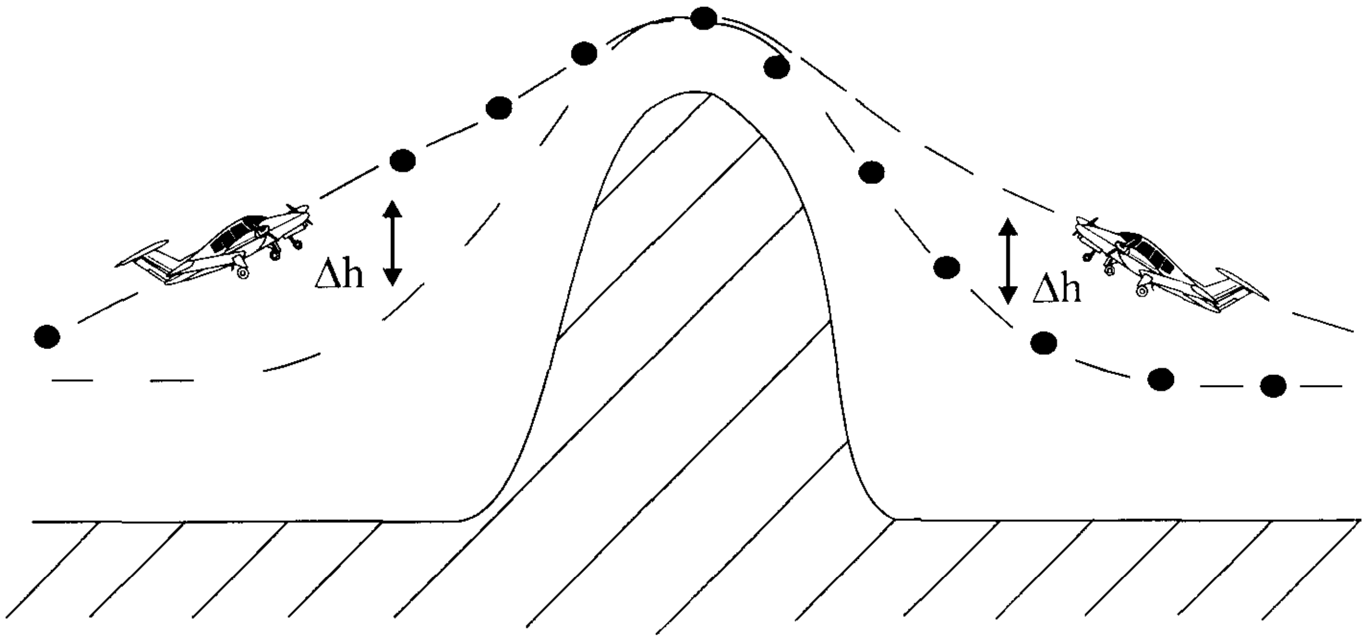

Fig. 1. Effect of flying height on acquired magnetic data. In a field with vertical gradient ΔB, the magnetic error between these lines is ΔB*Δh.

crossover points (tie line levelling). The diurnal levelling method will have no effect on errors caused by aircraft position or varying aircraft signatures. Similarly, although tie line levelling can correct for all three types of error, it cannot correct perfectly for diurnal variations occurring between tie lines. Instead, corrections at each line intersection must be interpolated to approximate the variation between tie lines. Consequently, the method described here combines both levelling techniques to derive maximum benefit from both.

To ensure the effectiveness of the levelling procedures the survey must be prepared, flown and processed using the following guidelines:

1) **Flight planning** – the survey must be planned so that there are enough tie lines to adequately determine the shape of the corrections to be applied to each survey line. Any variation with a wavelength less than the tie line spacing will not be correctable. For example, a tie line spacing of one kilometre will "see" diurnal variations with a wavelength of two kilometres or more. At an aircraft speed of 80 metres per second, this corresponds to a period of 25 seconds.
2) **Survey Flying** – the survey lines must be flown well with careful attention paid to maintaining a constant height above ground level.
3) **Culture** – if the survey area contains significant "culture" such as well casings, pipelines, buildings, etc. the levelling will be compromised by the large magnetic responses usually associated with such features. To improve the levelling these magnetic responses should first be suppressed or removed.
4) **Diurnal** – the removal of diurnal activity as measured by the base station is very important as a correction for medium and long wavelength, large amplitude variations from line to line. It must be understood that the only way to completely remove diurnal variations is to have a base station at the location of every survey data point (i.e., at survey height). This is because the time-varying field is different at every point in space, particularly at ground level where the effects of geology are significant. Features of all frequencies in the diurnal field will have different amplitude at different locations. Therefore, the diurnal variations measured by the base station will not exactly match those at the aircraft. The long wavelength errors that result from this can be removed by the use of tie lines. However, short wavelength variations are difficult to correct for and flying during periods of high diurnal activity is to be avoided. Any lines that are flown during such periods should be reflown.

The variation of base station response between two locations in Western Canada is shown in Figure 2. This example depicts the magnetic response of base stations several hundred kilometres apart, a distance comparable to the size of some large surveys and smaller than the distance from base to survey area in some cases. Similar variations have been noted between base stations separated by kilometres to tens of kilometres (less than the size of a typical survey). Clearly, all wavelengths are affected by differing amounts and differently at different times.

The above considerations lead to the conclusion that the most important useable information in diurnal base station data is at medium and long wavelengths (minutes to hours). Therefore, filtering of the base station data to remove low-amplitude, high frequency noise will not reduce its effectiveness and is actually recommended.

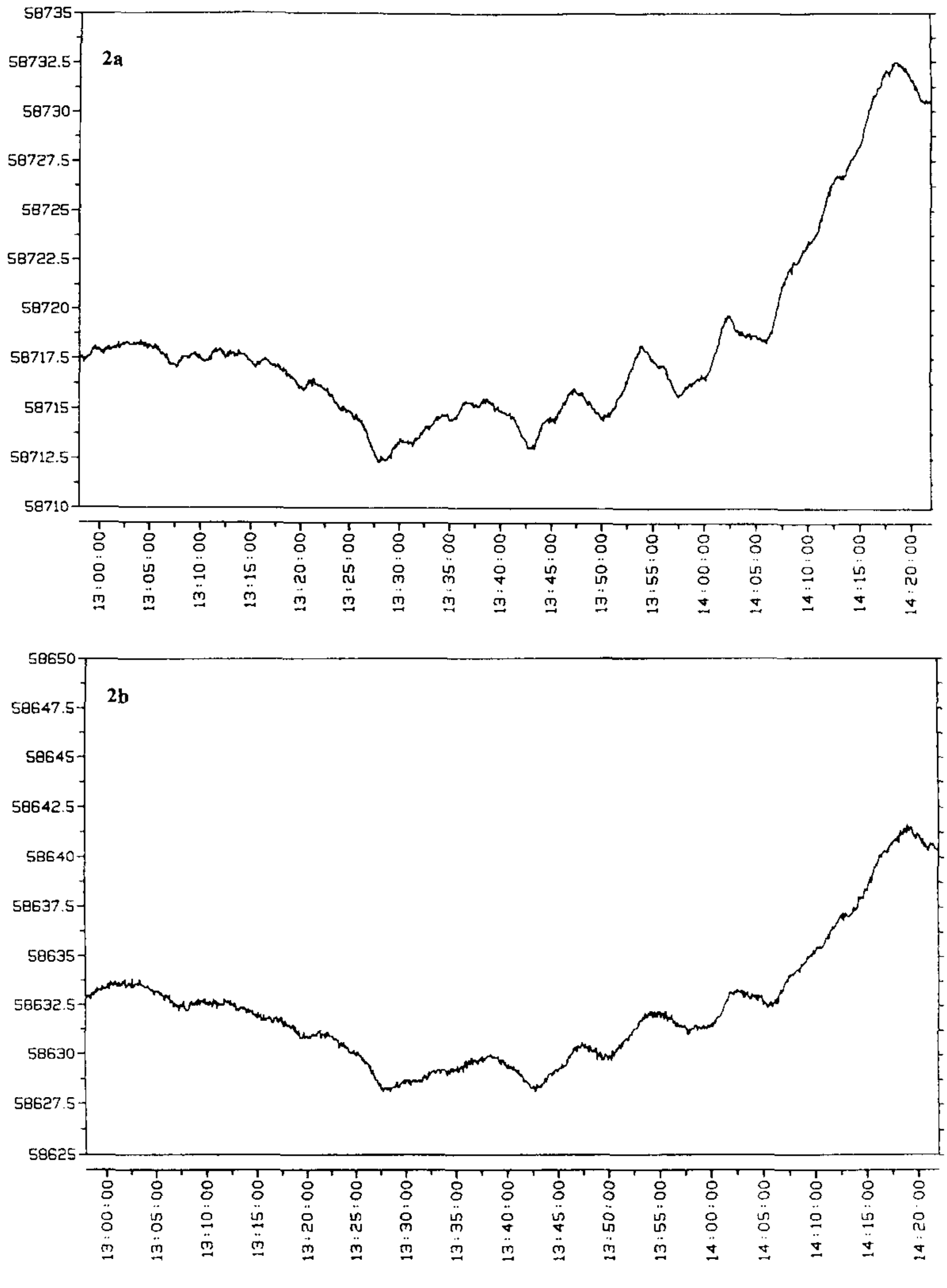

Fig. 2. Variability of the diurnal magnetic field at two locations in Western Canada. 2a: Fort Nelson. 2b : Fort St. John. Note that corresponding features differ in amplitude in a completely non-systematic way, independent of time or frequency.

Once the data have been acquired properly the levelling is carried out in three main steps: diurnal removal, tie line levelling and "microlevelling".

Diurnal removal simply involves the point for point subtraction of the diurnal base station values from the collected airborne magnetic values. The raw diurnal base values are collected at intervals typically between one and five seconds, filtered lightly and interpolated to match the aircraft sample interval. Diurnal is both acquired and applied by synchronizing its time base with that of the aircraft.

Since it is the diurnal variation about the local mean field value that is of interest, it is recommended that this mean value be adjusted for secular variation before it is removed. A simple way of doing this is to remove the IGRF modelled field (including secular variation) from the base station readings. This technique is especially important for surveys flown over a long period.

High frequencies in the diurnal base station data that do not accurately reflect diurnal activity at the aircraft will cause spurious anomalies in the aircraft data. These anomalies show no correlation with features on adjacent survey lines. In the worst case of rapidly varying diurnal at high amplitudes (magnetic storms) or low amplitudes (micropulsations), no levelling procedure can adequately remove these spurious anomalies. Affected data must be reflown. Long wavelength diurnal discrepancies of virtually any amplitude can be corrected by tie line levelling if the procedure is applied with care. This is because the tie line intersections can easily be used to construct the true diurnal variation curve.

Tie line levelling is the key step in the procedure and has the largest bearing on the result. It is critical to preserve geological information at both short and long wavelengths during this procedure. The introduction of tilts and warps into the data is likely if proper procedures are not followed.

Tie line levelling involves deriving a correction function by computing the difference between survey lines and tie lines at the intersection points ("crossovers") of each set of lines. Under no circumstances are the positions of these intersections modified. Because tie lines and survey lines sometimes cross at significantly different altitudes and because residual diurnal effects may exist at isolated crossover points, it is necessary to reject some crossover values. For this reason it is important to plan a survey network containing a large number of crossover points.

Tie lines must be flown at times when diurnal activity is very low since the tie lines will form the reference geomagnetic "surface" for levelling the survey lines. Because diurnal correction cannot perfectly remove all medium and long wavelength levelling errors, tie lines flown over a significant period of time will never exactly represent this reference surface. For this reason the tie lines are first coarsely levelled using the survey lines. Since the survey lines are still unlevelled these corrections can only be applied loosely, usually by heavily smoothing the corrections. This technique relies on a large number of crossover points to provide statistical confidence. Only the very long wavelength components of the levelling correction function are applied in this case. The method works best if each tie line crosses the same set of survey lines. The larger this set of survey lines is, the more confidence can be placed on the results obtained.

Once tie lines have been levelled to remove long wavelength errors the survey lines are corrected using the levelled tie lines. As with the preliminary levelling of the tie lines, spurious corrections caused by major height variations or residual diurnal effects are rejected.

After rejection of the spurious correction values, those remaining are very lightly smoothed to minimize the smaller deviations caused by minor height variations, diurnal errors and slight positional errors. Our objective is not to remove every last trace of levelling error but to minimize the remaining errors to the order of one or two nanoteslas. These residual errors will be removed in the next step.

The lightly smoothed level corrections are applied to the survey line data and gridded. This grid is then checked to verify the quality of the tie line levelling. Once verified, the grid is "microlevelled". Microlevelling is a popular term applied to a variety of methods, usually grid based, which remove the remaining residual levelling errors in the magnetic data. The strength of the various techniques is in their ability to remove high frequency, cross-line "noise" caused by levelling errors but leave high frequency along-line detail untouched. Effective microlevelling clarifies detail in the data that would not otherwise be readily apparent. An accurately levelled magnetic intensity grid can reveal details with amplitudes less than 0.1 nanotesla while preserving long wavelength and large amplitude features.

Case Study: Fort Nelson, British Columbia

In 1997 a large, high-resolution survey was flown in the Fort Nelson region of the Rocky Mountains Foothills. Flight lines were spaced at 400 metres and tie lines at 1200 metres to ensure sufficient crossover points for tie line levelling. As is typical for surveys flown at these latitudes in Canada, diurnal magnetic variations were significant at most times. Active to stormy magnetic conditions prevailed on many days during survey flying. Figures 3 and 4 illustrate a 7114 square kilometre portion of the final data set obtained from this survey, depicting the stages of levelling described in this paper. The grids used in these figures are high frequency enhancements that highlight cross-line errors caused by line levelling problems.

In Figures 3a and 4a, the aeromagnetic line data have been corrected only for parallax error[1] and removal of the Earth's modelled regional magnetic field (IGRF95 in this case). The gridded data are obviously dominated by large amplitude cross-line variations, causing individual survey lines to stand out dramatically and obscure fine geological detail.

The effect of removing diurnal variation as measured at a base station is shown in Figures 3b and 4b. Clearly, more subtle spatial detail is emerging. However, several significant areas of cross-line variation remain. These can be

[1]Parallax error, or system parallax, refers to the time lag between recording of position and recording of geophysical data. This must be corrected for in data processing so that magnetic data values can be ascribed to their actual geographic positions.

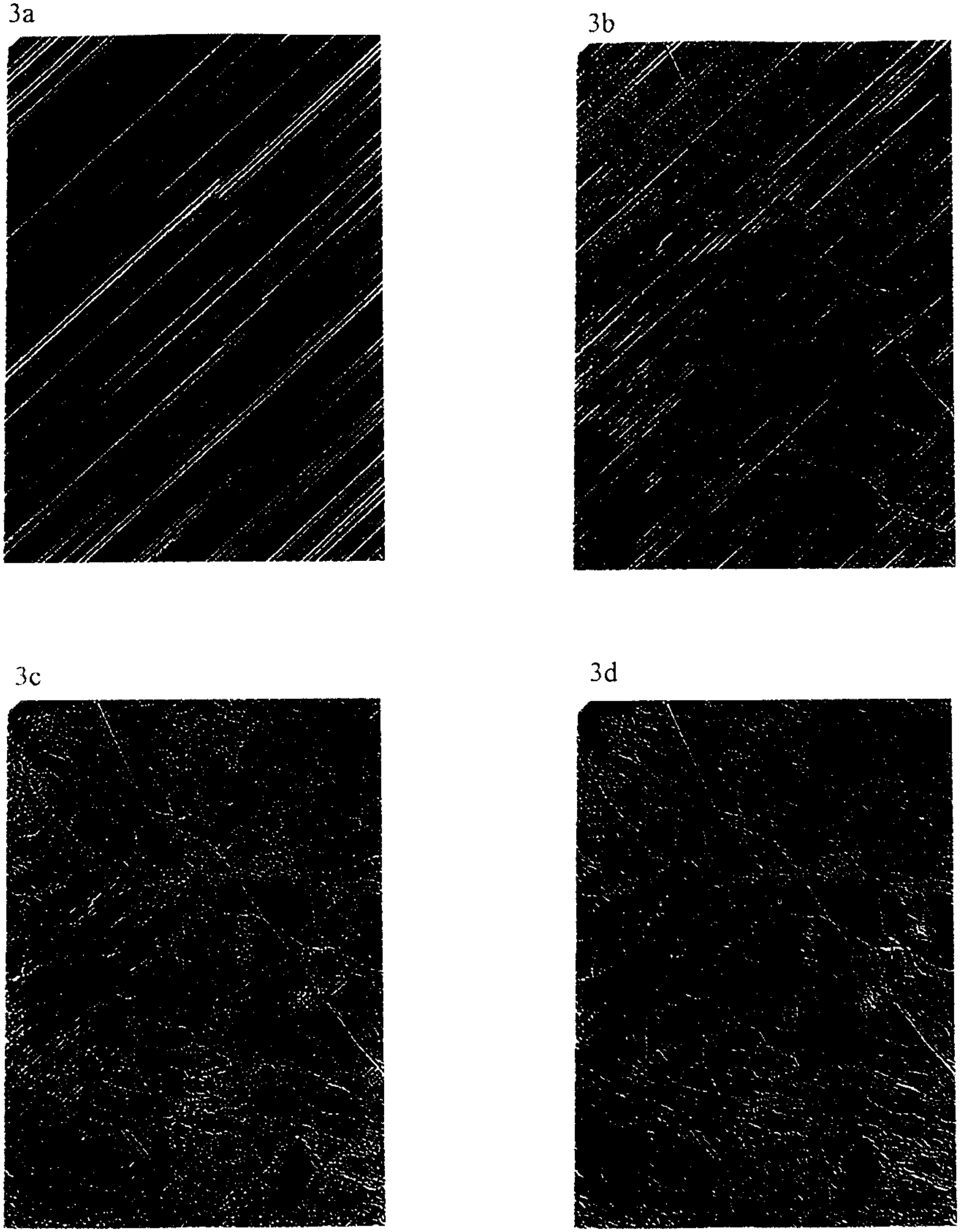

Fig. 3. Second vertical derivative images of a magnetic grid at four stages of the levelling procedure. 3a: No levelling applied. 3b: Diurnal variations removed. 3c: Tie line levelling applied. 3d: Microlevelling applied.

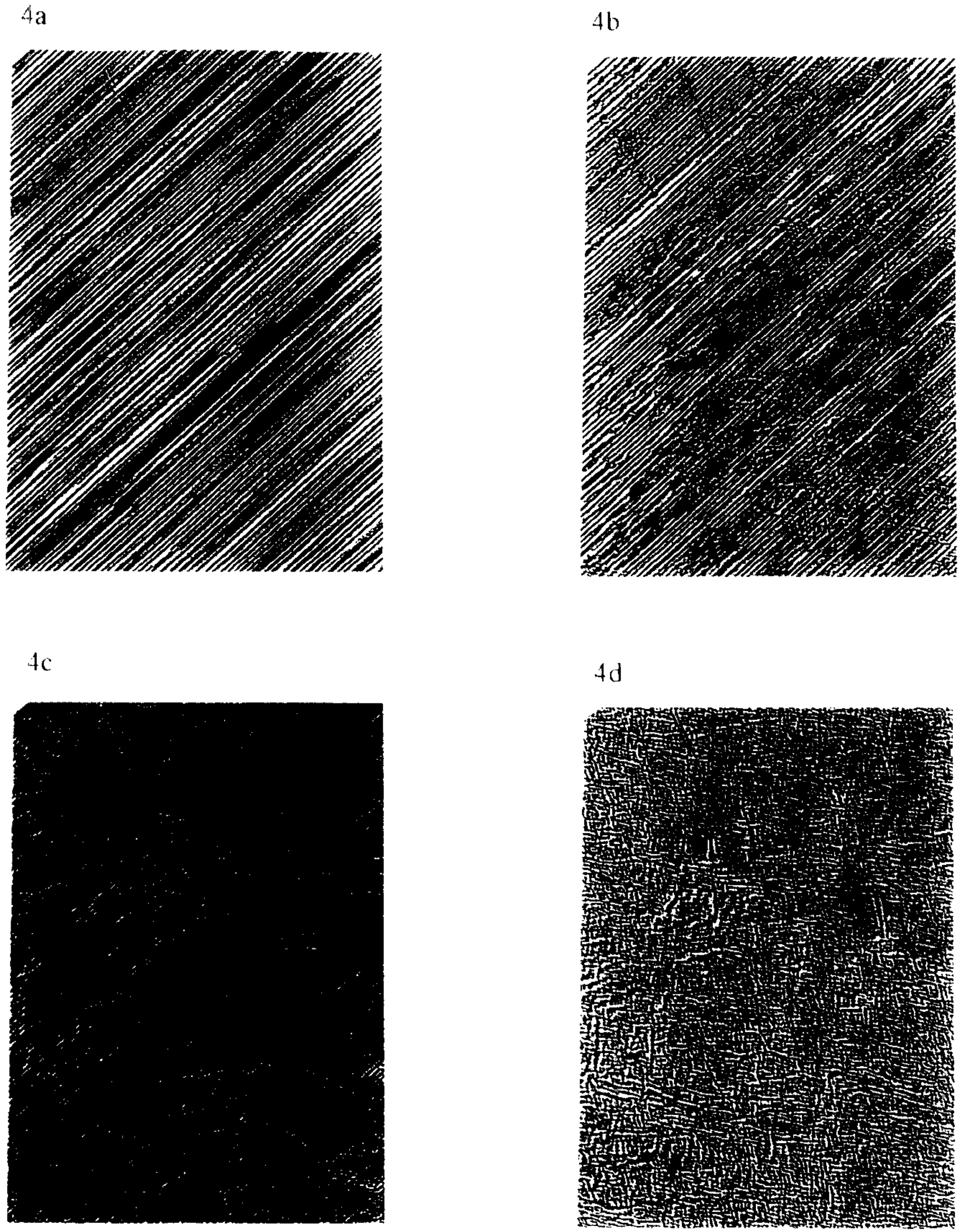

Fig. 4. Northwest sun angle illumination images of a magnetic grid at four stages of the levelling procedure. 4a: No levelling applied. 4b: Diurnal variations removed. 4c: Tie line levelling applied. 4d: Microlevelling applied.

attributed to days of higher diurnal activity, at which times the base station less accurately reflected variations at the aircraft. However, the high-amplitude, long wavelength variations between lines have been reduced. This will assist the tie-line levelling procedure to follow.

After the full tie-line levelling procedure, the gridded data begin to display their full resolution, as seen in Figures 3c and 4c. Spatial detail is now considerably enhanced and anomalies of the order of one nanotesla can be detected. However, there still exist some subtle along-line features caused by residual errors in tie line levelling.

The final procedure – microlevelling – yields the data set shown in Figures 3d and 4d. Comparison of these images with those preceding them shows that large and small levelling variations from line to line have been eliminated, leaving a very detailed, highly useful exploration tool. The geological information at all frequencies has been preserved through all stages of the levelling procedure. In this final data set, features with amplitudes significantly less than one nanotesla have been delineated.

Conclusion

To achieve maximum results from an aeromagnetic data set, a rigorous and thorough approach must be taken to remove levelling errors. This approach extends from careful survey preparation through collection of high quality base and aircraft data to a careful and rigorous multi-step levelling procedure. If the techniques are applied correctly, image and line data products of high integrity and usefulness will be obtained. This is illustrated by the example from the Fort Nelson high-resolution survey, in which features with amplitudes of a few tenths of nanoteslas are clearly mapped.

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