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Airborne geophysical data leveling based on line-to-line correlations

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ABSTRACT

A new technique removes the leveling errors in airborne geophysical data based on an assumption that the data are continuous (i.e., not renulled or recalibrated) from line to line. A single flight line is selected as a reference to level and tie all survey lines to this continuously varying datum. The leveling errors are determined in a least-squares sense from the reference line and the adjacent line to be leveled. The technique markedly improves the quality of the unleveled, raw data and works best if the reference line overlaps most of the line being leveled. This method cannot distinguish a linear geologic feature in the direction of flight lines from a leveling error. The technique initially was developed for airborne electromagnetic (EM) data in cases where tie-line leveling works poorly. However, it may also be used for airborne-magnetic and other data, in which case tie-lines used in conventional leveling techniques are not needed.

INTRODUCTION

Airborne geophysical data leveling is a critical step in data processing and interpretation. In the case of total-field magnetometer measurements, it is safe to assume that the regional field is invariant within the altitude variations of the survey aircraft. Thus, tie-line intersections can be used to level the data. This is feasible because the measured data from tie-line and flight line, where these lines cross, should have the same value inasmuch as there is no altitude sensitivity or directional dependence to the total magnetic field in the absence of local sources. This favorable situation is not present for frequency or time-domain-airborne electromagnetic (AEM) surveys, the data leveling of which forms an important part of this paper.

The data from AEM surveys are measured with active sensors that transmit a primary magnetic field to the targets of interest and record the secondary magnetic field. In contrast to the general insensitivity of magnetometer data to altitude variations, AEM data are extremely altitude sensitive. Figure 1 presents the in-phase and quadrature data at 7 kHz from a frequency-domain, helicopter-towed EM (HEM) system, as well as the total magnetic field and the sensor altitude. The HEM data rapidly decrease in amplitude as the altitude increases from 30 to 90 m in the 5000–6000-m region of the flight path, although the magnetic data are virtually not affected by the variations in altitude. I loosely refer to EM as altitude-sensitive data and to magnetic as altitude-insensitive data.

HEM data typically are transformed into a resistivity (or its reciprocal, conductivity) parameter. Although derived from altitude-sensitive data, the transformed parameter may be classified as altitude-insensitive data. This is because the transformed resistivity or conductivity is virtually altitude independent (Fraser, 1978; Huang and Fraser, 1999), a fact that renders this parameter of significant value in interpretation.

There are a number of references on leveling techniques for altitude-insensitive data. The standard leveling techniques comprise tie-line leveling for large error corrections, followed by microleveling for the remaining small error corrections (Urquhart, 1988; Minty, 1991; Luyendyk, 1997; Ferraccioli et al., 1998; Huang and Fraser, 1999). Tie-line leveling requires flying several tie-lines perpendicular to the original survey lines. Differences in the data measured, where the tie-lines intersect the flight lines are attributed to leveling errors in the flight lines, notwithstanding the fact that the data of the tie-lines themselves may not be time stable.

Microleveling techniques are based on a combination of directional filters. Some authors report techniques to level altitude-insensitive data. Among them, Green (1987) uses the between-channel correlation in airborne gamma-ray data to remove leveling errors that exist only in the uranium channel. Nelson (1994) proposes a technique to level total magnetic field data using horizontal gradient measurements. Fedi and Florio (2003) use the wavelet transform to remove directional trends of magnetic fields. Mauring and Kihle (2006) describe a technique that can be used to level magnetic data collected along regular and irregular line patterns.

Compared with the altitude-insensitive magnetic data leveling, the altitude-sensitive AEM data leveling technique is much more difficult. Conventional tie-line leveling used for altitude-insensitive data is generally not useful for altitude-sensitive data leveling because the altitude of the tie-line, at its intersection with the flight line,

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often differs from that of the flight line. Nonlinear, short-wavelength errors may also exist, again mitigating against the effectiveness of tie-line leveling. Additionally, in producing maps and sections of apparent conductivity, the EM data need to be leveled correctly from one frequency/time to the next, as well as leveled correctly for a given single channel across the entire map.

Valleau (2000) reviews the leveling procedures for frequency-domain HEM data used by survey contractors. Green (2003) develops an algorithm to level frequency-domain HEM data by minimizing the between-line differences using weighted, damped least squares. Siemon (2007) proposes a technique to level the secondary-field components using leveled values of apparent resistivity and apparent depth. These values are computed from frequency-domain HEM data using a half-space model. After recalculating the secondary-field components based on the half-space parameters leveled, the long-wavelength portion of the differences of measured and recalculated secondary-fields value are assumed to describe the leveling error and thus are subtracted from the measured HEM data.

This paper describes a technique for geophysical data leveling based on line-to-line correlations. After a brief introduction to the method, field examples from a variety of airborne data sets are presented.

LEVELING ERRORS IN AIRBORNE GEOPHYSICAL DATA

In general, leveling errors in airborne geophysical data can be grouped into three types: flight-based leveling errors, flight-direction-based leveling errors, and a variety of leveling errors of smaller spatial wavelength.

Flight-based leveling errors are associated with a block of flight lines, which may cause a broad constant offset in the data of a block of flight lines or an entire flight. It is often easy to recognize this problem visually on the imaged maps. The width of the affected block of flight lines usually varies from several hundred meters to several kilometers, depending on the survey. Flight-direction-based leveling errors show up with every other flight line because of changes in flying direction. The amount of shift of the zero level on a flight line may be primarily constant or may comprise a slow drift. In both cases, the leveling errors can be recognized by a striping pattern parallel to the flight lines. The flight-based and flight-direction-based leveling errors may be present on both altitude-sensitive and altitude-insensitive data.

In addition to the low-frequency flight-based and direction-based leveling errors, there may be a number of minor leveling errors of higher frequency, which are often seen in airborne EM data. The reasons for this could be nonlinear drifting from thermal variations; variations in sensor attitude, such as yaw, pitch, and roll in flight; variable calibration errors; errors in navigation; and the residual primary magnetic fields that are not bucked out and varying with time. Some of the errors may be reduced if proper consideration is given to these factors (Holladay et al., 1997; Deszcz-Pan et al., 1998; Fitterman, 1998; Fitterman and Yin, 2004; Yin and Fraser, 2004). The leveling errors shown in geophysical data are often a combination of the three types. Examples of these leveling errors in airborne resistivity data can be found in Huang and Fraser (1999).

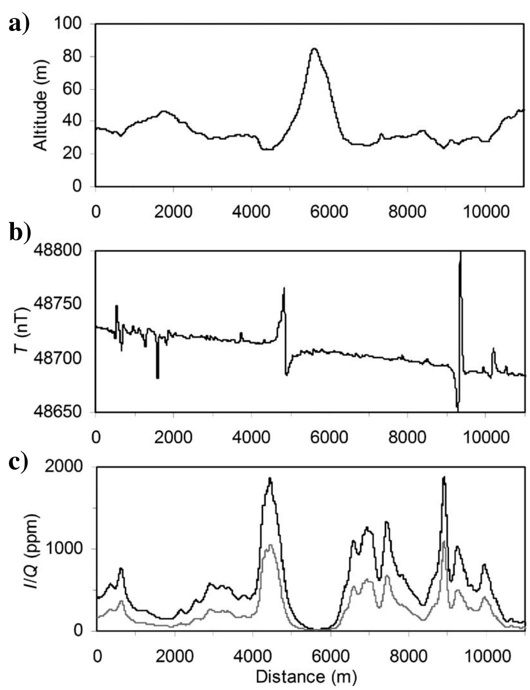

Figure 1. Data from an HEM/magnetic survey. (a) Altitude, (b) total magnetic field T, and (c) HEM data at 7 kHz. The in-phase I component is black; the quadrature component Q is gray.

METHOD

The leveling technique is based on an assumption that the geophysical field is continuous from line to line (i.e., neither releveled nor recalibrated in flight). Even though the geology may be variable, the observed data will tend to show significant correlations between flight lines, as is commonly seen in practice.

First, we visually examine the imaged data and select a flight line that is believed to be free of leveling errors for the reference flight line. Alternatively, one can manually level a flight line based on prior information, which serves as the reference line. If multichannel data are involved, all channel data for that line need to be well leveled to yield a suitable starting reference line. Data in the adjacent line will be leveled based on this reference line.

Let $\mathbf{d}^0$ be the data in the reference line, which is deemed to be free of leveling error, and $\mathbf{d}^1$ be the data in the adjacent line that contains leveling errors. The two lines may not be the same length in general, and so we consider only overlapped segments of the two lines. Data may be resampled over the overlapped segments to obtain equal-spaced data against distance $\mathbf{x}$. The number of data in the overlapped portions is N. Thus, I can write

$$\mathbf{d}^0 = (d_1^0, d_2^0, \ldots, d_N^0)^T, \tag{1}$$

$$\mathbf{d}^1 = (d_1^1, d_2^1, \ldots, d_N^1)^T, \tag{2}$$

and

$$\mathbf{x} = (x_1, x_2, \ldots, x_N), \tag{3}$$

where T stands for transpose. The leveling errors in $\mathbf{d}^1$ can be expressed as a function of distance $\mathbf{x}$, $f(\mathbf{x})$. The leveled data, i.e., the difference between $\mathbf{d}^1$ and $f(\mathbf{x})$, are

$$\mathbf{d}^{1L} = \mathbf{d}^1 - f(\mathbf{x}). \tag{4}$$

Because the geophysical field is continuous and correlated line to line, the leveled data $\mathbf{d}^{1L}$ should best match $\mathbf{d}^0$, i.e., the difference between the two data series should be minimal,

$$R^2 = \|\Delta\mathbf{d} - f(\mathbf{x})\|^2 = \min, \tag{5}$$

where $\Delta\mathbf{d}$ is $\mathbf{d}^1 - \mathbf{d}^0$. Thus, once a model for $f(\mathbf{x})$ is selected, the error function $f(\mathbf{x})$ can be determined from $\mathbf{d}^0$ and $\mathbf{d}^1$ in a least-squares sense. After the data $\mathbf{d}^1$ are corrected using equation 4, the leveled data $\mathbf{d}^{1L}$ serve as a new reference line to level the next line. This procedure is repeated until all flight lines are leveled.

The key to successful leveling is choosing a model for the leveling error, which should be based on our understanding of leveling errors. A leveling error model that fits the $\Delta\mathbf{d}$ best is unlikely to correspond to a scientifically meaningful model. For example, if $f(\mathbf{x})$ in equation 5 fits $\Delta\mathbf{d}$ perfectly, the corrected data $\mathbf{d}^{1L}$ will be identical to $\mathbf{d}^0$. Obviously, this is incorrect. In practice, a number of models are selected based on the features of the leveling errors encountered. The program fits data to these models and then chooses the model that defines the leveling error best. Also, when performing the leveling, one needs to think about how the leveling errors behave and decide whether some of the parameters should be constrained.

For simplicity, we discuss the simple model of error function $f(\mathbf{x})$ of a polynomial. We have

$$f(\mathbf{x}) = a_0 + a_1 x + a_2 x^2 + \cdots + a_k x^k, \tag{6}$$

where k is the degree of polynomial and a_k is the coefficient. The residual is given by

$$R^2 = \sum_{i=1}^{N} [\Delta d_i - (a_0 + a_1 x_i^1 + a_2 x_i^2 + \cdots + a_k x_i^k)]^2. \tag{7}$$

The coefficients $\boldsymbol{a} = (a_0, a_1, \ldots, a_k)^{\mathrm{T}}$ can be resolved easily in a least-squares sense. Setting $k = 1$ in the above equations reduces to the linear solution (first-degree polynomial). In this case, we assume the leveling errors are linear, and the correction involves only a DC shift and tilt. In general, higher degrees must be used to remove nonlinear leveling errors.

Obviously, the method works best if the reference line overlaps most of the line being leveled. Otherwise, some leveling extrapolation may be applied in the general case. In some cases, one must divide one survey block into two or more where the overlapped segments of two adjacent lines are much shorter than the not-overlapped segments. Then, the subblocks are leveled separately using the lines that join the subblocks as the reference lines.

ALTITUDE-SENSITIVE DATA LEVELING

For altitude-sensitive data such as HEM, the amplitudes vary approximately as the inverse cube of the sensor-source distance. The altitude sensitivity in the data should be reduced before performing the leveling. One way to do this is to transform the data into the response-parameter domain based on the superposed dipole assumption (Grant and West, 1965; Fraser, 1972). The term *superposed dipole* refers to a transmitter-receiver coil separation that is so small in comparison with the flight height that, for practical purposes, the coils may be considered to lie at the same point. In the analysis of the data, it is assumed that the bird-earth system acts as if the coil separation were zero (e.g., Fraser, 1978; Yin and Fraser, 2004). The superposed dipole model is valid for most frequency-domain HEM systems and for some time-domain HEM systems.

When the superposed dipole assumption is valid, the observed inphase I and quadrature Q components in the frequency domain may be transformed into the response parameters M and N, which depend only upon the induction number, $\theta = (\sigma\mu\omega)^{1/2}h$, where σ is the conductivity, μ is the magnetic permeability, ω is the angular frequency, and h is the sensor altitude (Huang and Fraser, 2001). Thus, we have

$$M = I \times \left(\frac{h}{s}\right)^3 \text{ and } N = Q \times \left(\frac{h}{s}\right)^3, \tag{8}$$

where s is the coil separation.

The M and N are much less sensitive to altitude. For instance, the HEM data (I and Q) in Figure 1c are transformed into the response parameters (M, N) as shown in Figure 2. The altitude sensitivity is significantly reduced in the response-parameter domain. Thus, the leveling technique can be applied to the response parameter data. Then, the leveled I and Q data can be obtained from the leveled M and N from equation 8 when using an observed height h. This approach is strictly correct for surveys flown over ground that is highly conductive to the frequency in question. For a more resistive earth, the cubic power in equation 8 would be replaced by a (generally smaller) number that is correct for the resistivity of the ground.

In time-domain HEM surveys, the transient data, e.g., from a concentric system, can be transformed into the response parameter by multiplying $(h/r)^3$, where r is the radius of the transmitter loop of the HEM system.

FIELD EXAMPLES

The leveling techniques have been tested on a variety of real data sets that are contaminated seriously by leveling errors. Some results are shown for both altitude-insensitive and altitude-sensitive data.

Figure 3a illustrates the raw magnetic data obtained using a helicopter-borne sensor. There is abundant cultural noise in this area, as shown by many isolated anomalies. Flight-direction-based leveling errors appear clearly in the eastern and western parts on the map, and flight-based leveling errors appear in the middle of the map. Figure 3b and c, respectively, depicts the leveled data and the leveling errors removed. Figure 4 shows a magnetic data profile before and after leveling, as well as the leveling errors for a flight line whose line path is plotted on Figure 3b (A–A′). The amount of correction for this specific line varies from 22 to 23.5 nT, with a dynamic range of about 1.5 nT. All of the slowly varying leveling errors have been removed without the localized anomalies being trimmed.

The second example shows leveling results for apparent conductivity transformed from frequency-domain HEM data using the

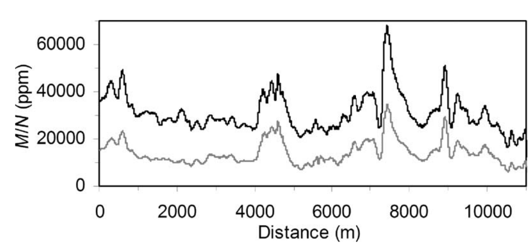

Figure 2. The HEM data transformed from those in Figure 1c. The in-phase component M is black and the quadrature component N is gray.

pseudo-layer model (Fraser, 1978). Because the altitude effects have been removed through the conductivity transformation, the conductivity belongs to the altitude-insensitive class of data. As seen in Figure 5a, many leveling errors associated with flying direction occur on the conductivity map, despite the fact that the HEM data were leveled using the traditional method before the transformation was made. After applying the technique to the data, the leveled map is shown in Figure 5b. The continuity of linear features that strike at oblique angles to the flight lines has improved. Compared to the

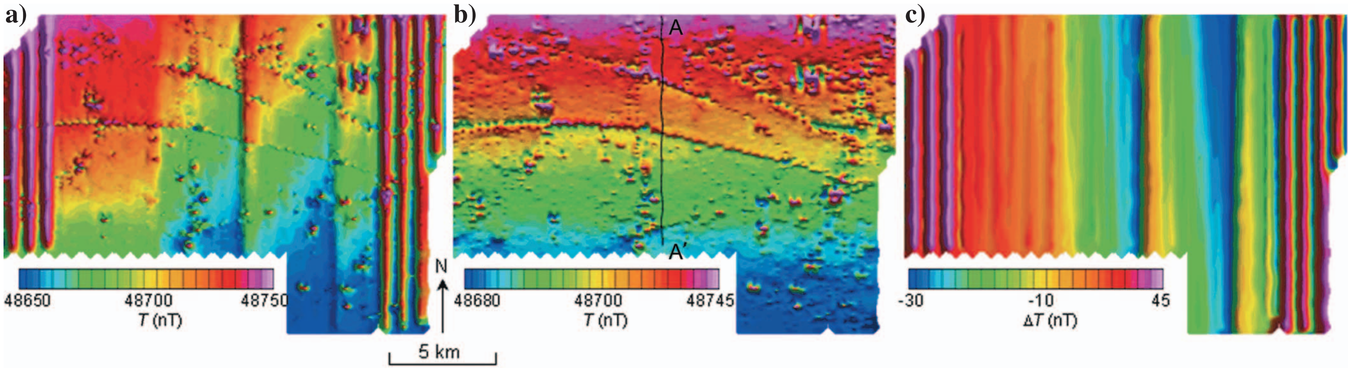

Figure 3. Helicopter-borne magnetic data T. (a) Raw data; (b) leveled magnetic data. (c) The leveling errors, i.e., differences ΔT between (a) and (b).

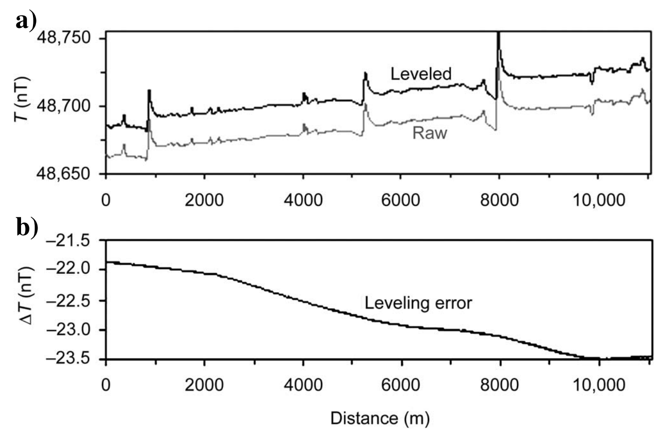

Figure 4. Data from a flight line marked in Figure 3b (A–A′). (a) Raw and leveled data; (b) leveling errors.

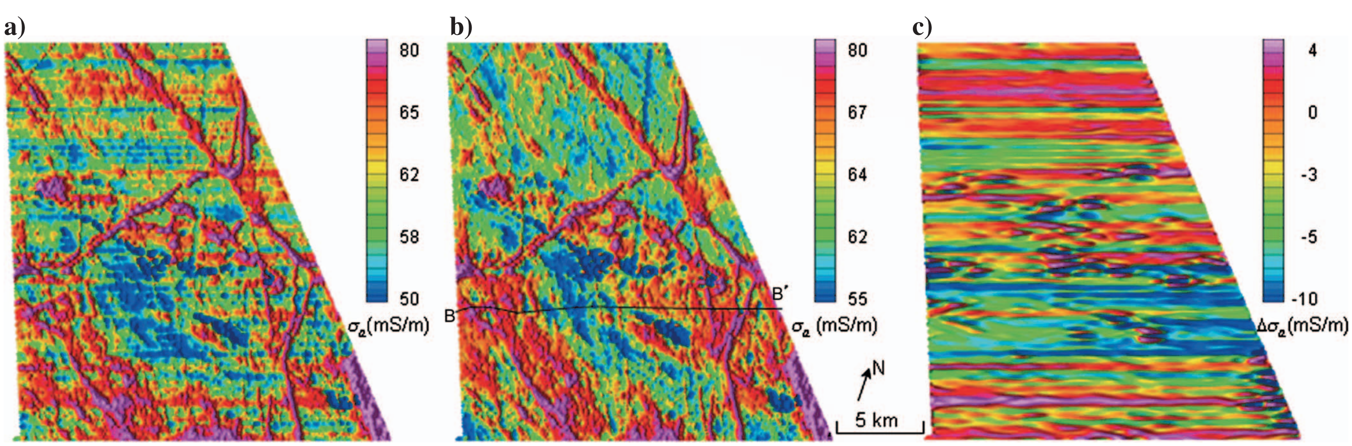

Figure 5. (a) Apparent conductivity σ_a computed from frequency-domain HEM data at 7 kHz. (b) Leveled apparent conductivity. (c) The leveling errors $\Delta\sigma_a$.

magnetic data in Figures 3 and 4, the conductivity data behave variably and contain more short-wavelength leveling errors (compare with Figures 4 and 6). Still, Figure 5c does not appear to contain any geologic signal, implying that geologic information was not noticeably impaired by the leveling operations.

The third example is from an HEM survey using five coplanar frequencies that ranged from 400 Hz to 100 kHz. Figure 7 illustrates the in-phase and quadrature data at 400 Hz before and after leveling, as well as the errors removed. The altitude-sensitive data are first transformed into response parameters; then the technique is applied to the response parameters. Finally, the leveled data are inversely transformed to the in-phase and quadrature components. This method cannot distinguish a linear geologic feature in the direction of flight lines from leveling errors. If such a feature is removed by the leveling process, the geologic feature can be retrieved by applying a high-pass filter to the removed leveling errors and adding them back to the leveled data. Figure 8 is a profile of the in-phase and quadrature data and the removed leveling errors.

The last example is from a time-domain HEM survey in a resistive area. Figure 9 demonstrates the leveling results from two channels: one middle-time and one late-time channel. The leveling errors in the time-domain AEM data are similar to those of frequency-domain AEM data. For example, there are flight-based and flight direction-based leveling errors as in Figure 9a and d. Figure 10 is the leveling result from a flight line, showing 10-channel data before and after the leveling and the removed leveling errors.

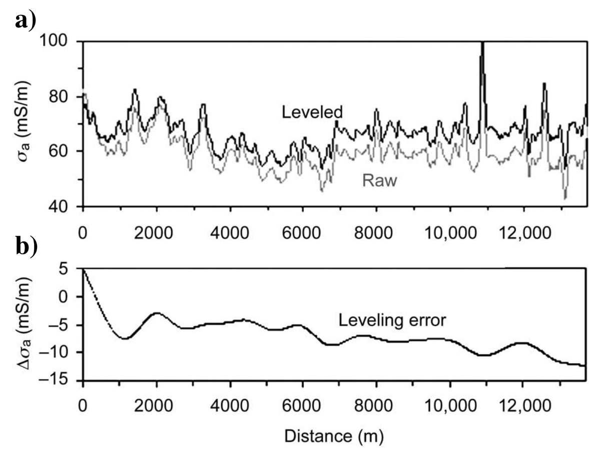

Figure 6. Data from a flight line marked in Figure 5b (B–B′). (a) Raw and leveled conductivity σ_a and (b) leveling errors $\Delta\sigma_a$.

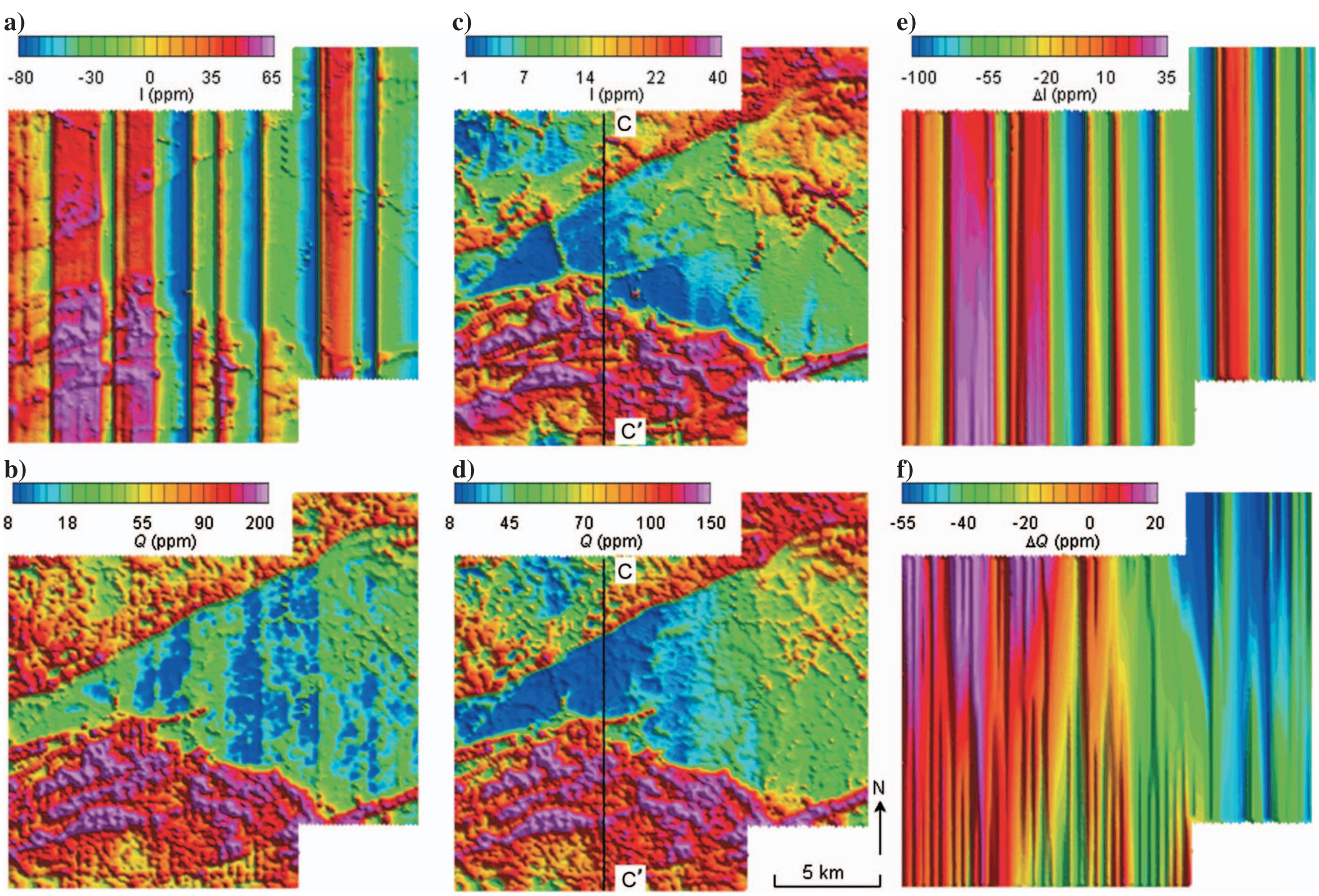

Figure 7. Leveling results for altitude-sensitive data. (a) The in-phase I and (b) quadrature Q components of HEM data at 400 Hz before leveling. (c) The in-phase I and (d) quadrature Q after leveling. The leveling errors removed from (e) ΔI and (f) ΔQ data.

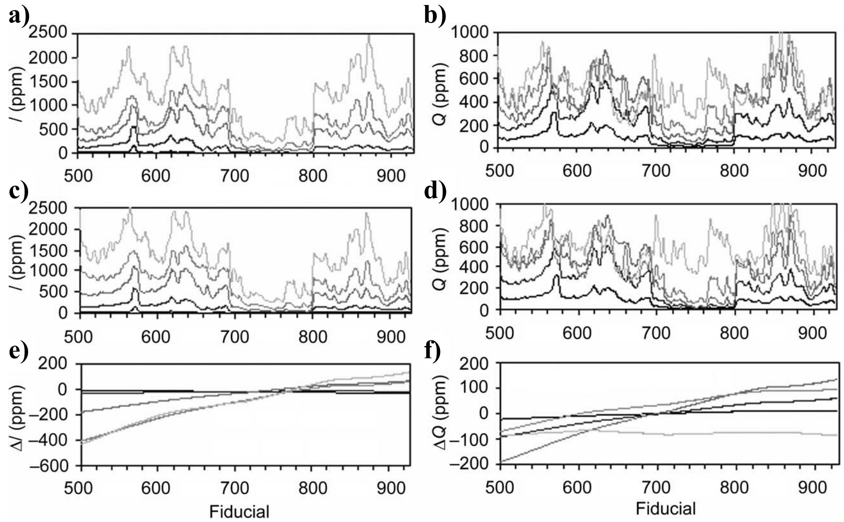

Figure 8. Data from a flight line marked in Figure 7c and d (C–C′). The I and Q responses at five frequencies before (a, b) and after (c, d) leveling, and the removed leveling errors (e, f). Gray tones darken as frequencies become lower (100 kHz, 25 kHz, 6 kHz, 1.5 kHz, and 400 Hz).

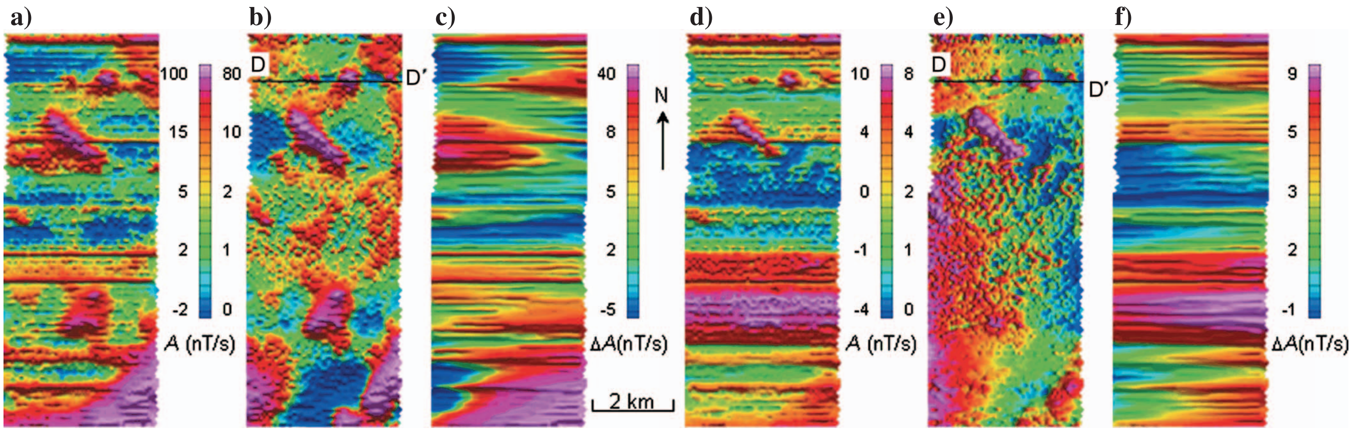

Figure 9. Two-channel time-domain HEM data A (a,d) before and (b,e) after leveling. (c) The removed leveling errors ΔA for the midtime channel and (f) for the late-time channel.

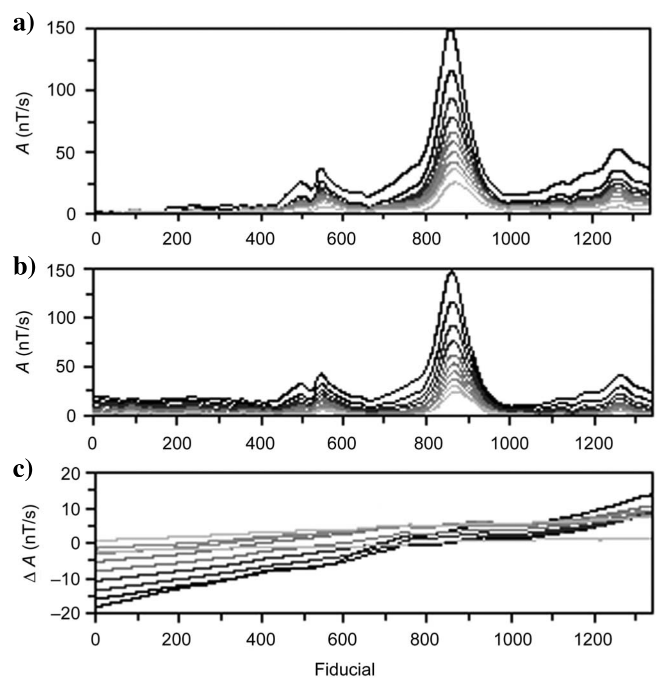

Figure 10. Ten-channel time-domain HEM data A from a flight line marked in Figure 9b and e (D–D′). (a) Before leveling; (b) after leveling; (c) the leveling errors ΔA. Gray tones darken as time delays increase.

CONCLUSIONS

A new approach to leveling airborne geophysical data has been developed based on line-to-line correlations. Because the geophysical data are continuous from line to line, a single flight line is used as a reference to tie all survey lines to this continuously varying datum. Tie-lines used in conventional leveling techniques are not needed. This may save about 10% of the operational cost. As shown in the examples, the technique markedly improves the quality of the unleveled raw data. This method cannot distinguish a linear geologic feature in the direction of flight lines from leveling errors. If such a feature is removed by the leveling process, the feature can be added back to the leveled data because the technique is flight-line based.

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