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

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Summary

A new technique removes the leveling errors in airborne geophysical data based on the 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 adjacent line to be leveled. Tie lines used in conventional leveling techniques are not needed. The technique produces a marked improvement in the quality of the unleveled raw data.

Introduction

Airborne geophysical data leveling is a critical step of the data processing and interpretation. In terms of leveling, one may group airborne geophysical data into two types. One is flight altitude-insensitive, including the potential field data, radiometric, VLF, and AFMAG measurements. These data are measured with passive sensors. The other is altitude-sensitive data. This type of data are measured with active sensors which transmit an artificial magnetic field to excite the targets of interest and record the secondary magnetic field, for example, conventional frequency- or time-domain helicopter electromagnetic (HEM) systems. I refer to the former as "altitude-insensitive data", and to the latter as "altitude-sensitive data". Based on this definition, the airborne resistivity (or its reciprocal, conductivity) data, computed from active EM data, may be classified as altitude-insensitive data. This is because the transformed resistivity or conductivity is virtually altitude-independent, in spite of the fact that the measured data is altitude-sensitive. Figure 1 presents the in-phase and quadrature data at 7 kHz and the total magnetic field, as well as the altitude of the sensors. We see that the HEM data rapidly decrease in amplitude as the altitude increases in the 5000 – 6000 m region of the flight path, while the magnetic data are not affected by the variations in the altitude.

There are a number of references on leveling techniques for the altitude-insensitive data. The standard leveling techniques comprise tie-line leveling for large error corrections and micro-leveling for small error corrections after tie-line leveling (Urquhart, 1988; Minty, 1991; Luyendyk, 1997; Ferraccioli et al., 1998; Huang and Fraser, 1999). The 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 may themselves not be time-stable. The micro-leveling techniques are based on combination of directional 2-D and 1-D filters. Alternatively, some authors have reported other techniques used to level altitude-insensitive data. Green (1987) uses the between-channel correlation in airborne gamma-ray data to remove leveling errors that exists 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 data collected along regular and irregular line patterns.

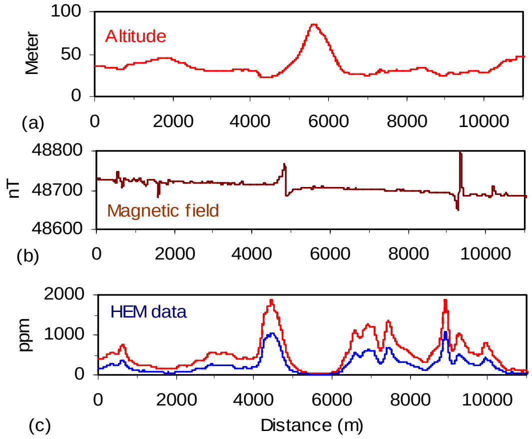

Figure 1: Data from an HEM/magnetic survey. (a) altitude, (b) total magnetic field, and (c) HEM data at 25 kHz, the in-phase component in red and quadrature component in blue.

Compared with the altitude-insensitive data leveling, the altitude-sensitive data leveling is much more difficult. The conventional tie-line leveling used for altitude-insensitive data is generally not very useful for altitude-sensitive data leveling because the altitude of the tie line, at its intersection with the flight line, may be different from that of the flight line. Nonlinear short wavelength errors also may 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 correctly leveled from one frequency/time to the next, as well as leveled correctly for a given single channel across the entire map. Valleau (2000) reviewed the leveling procedures for frequency-domain HEM data used by HEM survey contractors. Green (2003) developed an algorithm to level frequency-domain HEM data by minimizing the between-line differences using weighted, damped least squares.

This paper describes a technique for geophysical data leveling based on line-to-line correlations. The method will be introduced briefly, and then field examples from a variety of airborne data will be presented.

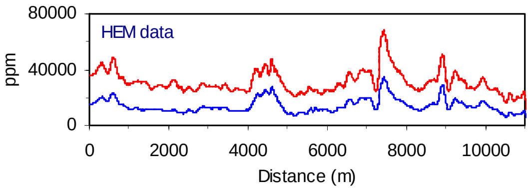

Figure 2: The HEM data transformed from those in Figure 1c. The in-phase component in red and quadrature component in blue.

Method

The leveling technique is based on the fact that the geophysical field is continuous from line to line, even though the geology could be suddenly changed. Therefore, the observed data show great correlations between flight lines.

First, a flight line is selected, which is believed to be free of leveling errors. Alternatively, one can manually level a flight line based on prior information. If multi-channel data are involved, all channel data need to be well leveled to yield a suitable starting reference line. Data in the adjacent line will be leveled based on the reference line. Alternatively, the reference line can be selected automatically based on some measure of the character (e.g., the roughness) of the data.

Let $\mathbf{d}^0$ be data in the reference line, which is leveling-error-free and $\mathbf{d}^1$ the data in the adjacent line which contains leveling errors. 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., difference between $\mathbf{d}^1$ and $f(\mathbf{x})$, is

$$\mathbf{d}^{1L}=\mathbf{d}^0 - f(\mathbf{x}) \qquad (1)$$

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

$$R^2=||\Delta\mathbf{d}- f(\mathbf{x})|||^2 = \text{min.} \qquad (2)$$

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 (1), the leveled data $\mathbf{d}^{1L}$ severs as a new reference line to level the next line. This procedure is repeated until all flight lines are leveled.

The key to a successful leveling is choosing a model of 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 (2) fits $\Delta\mathbf{d}$ perfectly, the corrected data $\mathbf{d}^{1L}$ would be identical to $\mathbf{d}^0$. Obviously, this is not correct. 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, we need to think about how the leveling errors behave, and decide whether some of the parameters should be constrained.

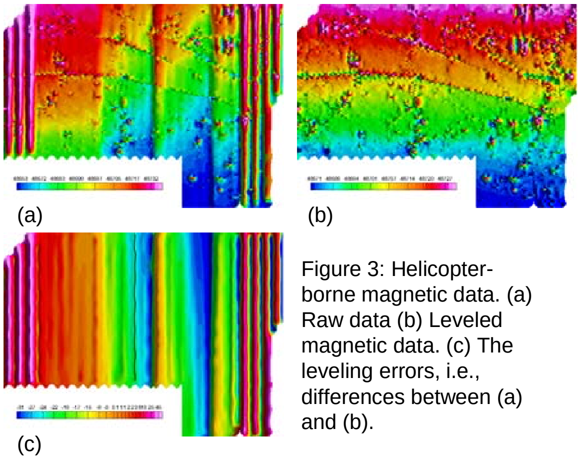

Figure 3: Helicopter-borne magnetic data. (a) Raw data (b) Leveled magnetic data. (c) The leveling errors, i.e., differences between (a) and (b).

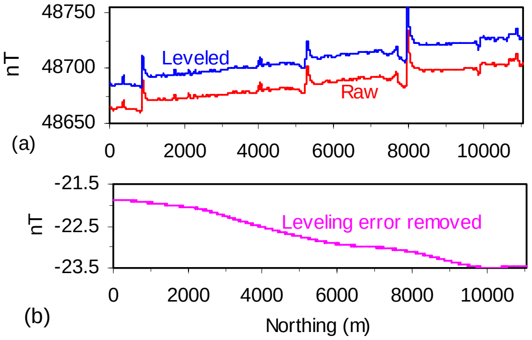

Figure 4: Data from a flight line in Figure 3. (a) Raw and leveled data and (b) leveling errors.

The leveling technique can be directly applied to altitude-insensitive data. 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 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 which 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.

The HEM data in Figure 1c are transformed into the response parameter as shown in Figure 2. The altitude sensitivity is significantly reduced in the response parameter domain. Thus, the level technique may be applied to the response parameter data. Then, the leveled data may be transformed back.

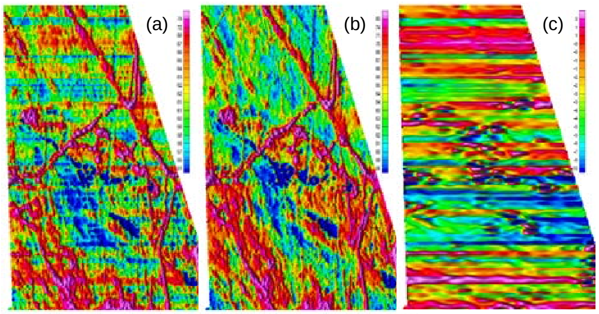

Figure 5: (a) Apparent conductivity data computed from frequency-domain HEM data. (b) Leveled apparent conductivity. (c) The leveling errors.

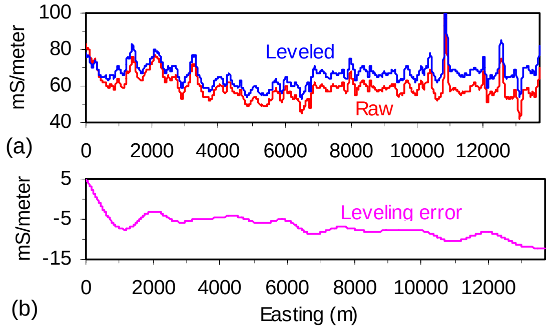

Figure 6: Data from a flight line in Figure 5. (a) Raw and leveled data and (b) leveling errors.

Examples

The leveling techniques have been tested on a variety of real datasets which 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 lots of culture noise in this area as shown by many isolated anomalies. The line-based leveling errors appear clearly in the east and west parts on the map, and the flight-based leveling errors in the mid of the map. Figures 3b and 3c depict the leveled data and the leveling errors removed. Figure 4 shows a magnetic data profile before and after the leveling, as well as the leveling errors for a flight line whose line path is plotted on Figure 3c. The amount of correction for this specific line varies from 22 nT to 23.5 nT, with a dynamic range of about 1.5 nT. All the slowly varying leveling errors have been removed without the localized anomalies being trimmed.

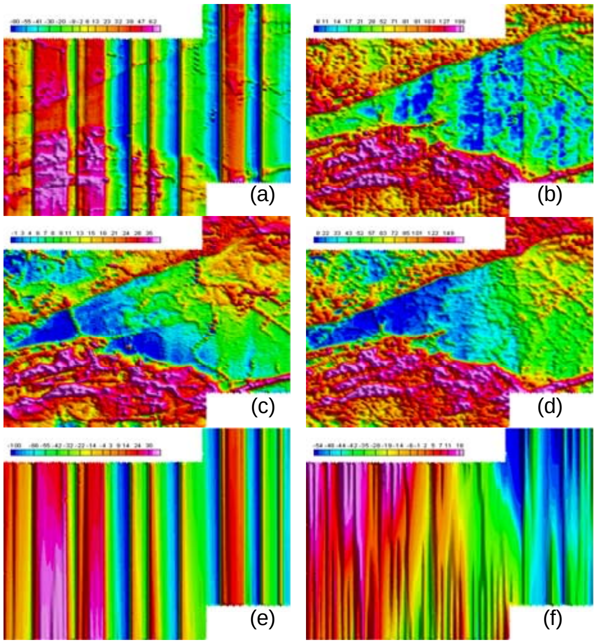

Figure 7: Leveling results for altitude-sensitive data. The in-phase (a) and quadrature (b) HEM data at 400 Hz before leveling, the in-phase (c) and quadrature (d) after leveling, and the leveling errors removed (e) in-phase and (f) quadrature.

The second example shows the leveling results of apparent conductivity that is transformed from frequency-domain HEM data. Since the altitude-effects have been removed through the conductivity transformation, the conductivity belongs to the altitude-insensitive data. As illustrated in Figure 5a, a lot of leveling errors associated with flying direction are shown on the conductivity map, even thought the HEM data were leveled before the transformation was made. After applying the technique to the data, the leveled map is obtained as shown in Figure 5b. The continuity of linear features that strike at oblique angles to the flight lines has been improved. Compared to the magnetic data in Figures 3 and 4, the conductivity data behaves variably, and contains more short-wavelength leveling errors (Figures 4 and 6). Still, Figure 4c does not appear to contain any geological signal, implying that geological information was not noticeably impaired by the leveling operations.

The third example is from an HEM survey using 5 coplanar frequencies ranged from 400 Hz to 100 kHz. Figure 7 illustrates the in-phase and quadrature data at 400 Hz before and after the leveling, as well as the errors removed. The EM data are first transformed into response parameters and then the technique is applied to the response parameters. Finally, the leveled data are inversely transformed to the in-phase and quadrature components. Figure 8 is a profile of the in-phase and quadrature data, and the removed leveling errors.

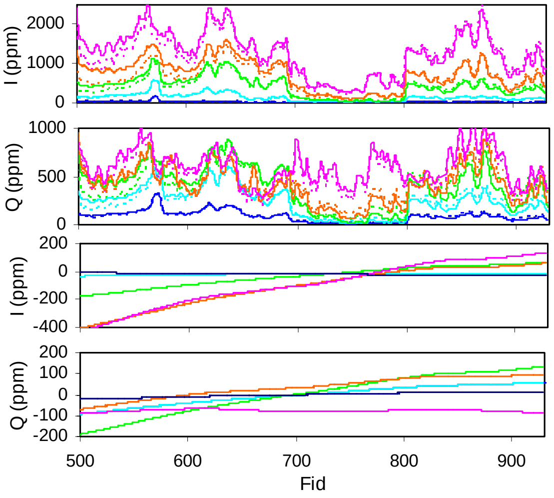

Figure 8: The in-phase and quadrature responses at 5 frequencies before (dotted curves) and after (solid curves) the leveling, and the removed leveling errors. The warm color stands for the higher frequency and the cool color for the lower.

The last example is from a time-domain HEM survey in a resistive area. Figure 9 demonstrates the leveling results from two channels. One is at mid time and the other at late time. The starting reference line is selected automatically based on roughness of the data perpendicular to the direction of flight line. Figure 10 is the leveling result from a flight line, showing 12-channel data before and after the leveling and the removed leveling errors.

Conclusions

A new approach to leveling airborne geophysical data has been developed based on between-line correlations. Since 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 at all. This may save about 10% of the operational cost. Furthermore, a cost savings for frequency-domain HEM surveys may also be made by reducing the high-altitude zero-level observations that is needed for conventional leveling. As shown in the examples, the technique produces a marked improvement in the quality of the unleveled raw data.

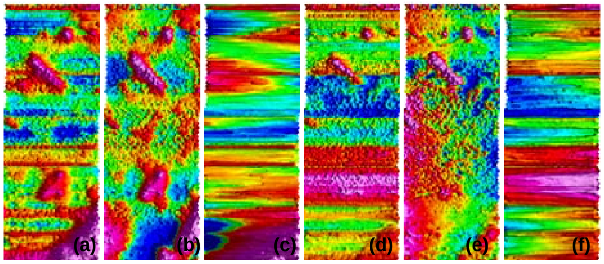

Figure 9: Two channel time-domain HEM data (a) before and (b) after the leveling and (c) the removed leveling errors for early time channel, and (d), (e) and (f) for late time channel.

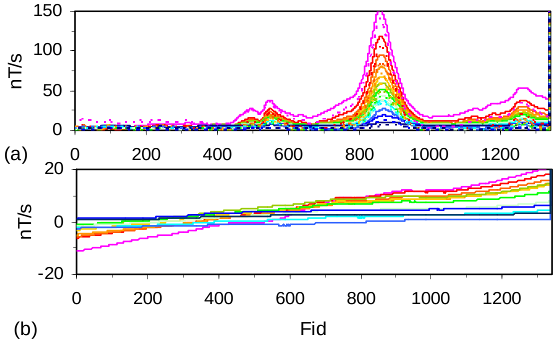

Figure 10: (a) 12 channel time-domain HEM responses before (dotted curves) and after (solid curves) the leveling, and (b) the leveling errors removed.

Acknowledgments

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EDITED REFERENCES

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