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Airborne electromagnetic data levelling using principal component analysis based on flight line difference

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ABSTRACT

A novel technique is developed to level airborne geophysical data using principal component analysis based on flight line difference. In the paper, flight line difference is introduced to enhance the features of levelling error for airborne electromagnetic (AEM) data and improve the correlation between pseudo tie lines. Thus we conduct levelling to the flight line difference data instead of to the original AEM data directly. Pseudo tie lines are selected distributively cross profile direction, avoiding the anomalous regions. Since the levelling errors of selective pseudo tie lines show high correlations, principal component analysis is applied to extract the local levelling errors by low-order principal components reconstruction. Furthermore, we can obtain the levelling errors of original AEM data through inverse difference after spatial interpolation. This levelling method does not need to fly tie lines and design the levelling fitting function. The effectiveness of this method is demonstrated by the levelling results of survey data, comparing with the results from tie-line levelling and flight-line correlation levelling.

1. Introduction

Airborne electromagnetic survey has been widely applied in geological mapping, mineral exploration and groundwater search, while the proper levelling of AEM data remains a challenge and is still an active research area (Huang, 2008). Levelling errors can be easily recognized as the striping pattern along survey profile direction and significantly affect data quality. In the airborne survey, flight altitude variations (Huang, 2008; Beiki et al., 2010), flight direction changes (Huang and Fraser, 1999) and temperature variations (Valleau, 2000; Siemon, 2009) are main sources of levelling errors.

Airborne geophysical data levelling can be achieved in both tie-line direction (perpendicular to flight-line direction) and the flight-line direction. Early airborne geophysical data are levelled using tie lines which are flown cross profiles. Tie-line levelling deems the differences at the crossover points of the tie lines and the flight lines as levelling errors (Nelson, 1994). Unlike airborne magnetic data, AEM data are sensitive to the flight altitude. The fluctuation of flight altitude leads to residual corrugation in the tie-line levelling results of AEM data (Huang, 2008). Foster et al. (1970), Yarger et al. (1978) and Bandy et al. (1990) use the differences at the crossover points to fit and calculate the levelling errors, which improves the tie-line levelling method. Analysing the data features of levelling error, pseudo tie lines have also been used to level data without the need for tie lines. Huang and Fraser (1999) set the endpoints of the pseudo tie line in region without levelling errors and perform levelling through interpolation along the pseudo tie line. Davydenko and Grayver (2014) design a directional filter using principal component analysis (PCA) to levelling, considering that levelling error in the tie-line direction has a larger difference than that in the flight-line direction.

As for flight-line direction, Green (2003), Huang (2008), White and Beamish (2015) pre-set the error function to fit levelling errors using least-squared method. The levelling results are closely related to the selected error function. Beiki et al. (2010) design differential polynomial fitting levelling that avoids the selection of error function. However when the levelling errors of adjacent flight lines are similar, this algorithm cannot effectively remove the levelling errors (Davydenko and Grayver, 2014). Furthermore, median filtering (Huang and Fraser, 1999; Mauring et al., 2002; Mauring and Kihle, 2006), temporal filtering (Ishihara, 2015) and mean filtering (Li, 2007) have also been applied to level airborne data. These levelling methods generally need to configure the filter parameters.

This paper describes a method to level airborne geophysical data by analysing the characteristics of levelling error in tie-line direction and flight-line direction. Flight line difference is used to highlight the features of levelling error. Instead of levelling AEM data as usual, levelling

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is conducted to the difference data. Principal component analysis is applied to pseudo tie lines of the difference data to obtain the levelling error. To confirm the reliability of the method, we apply the method to airborne time-domain electromagnetic (TDEM) data and magnetic data acquired by Geotech Limited. Meanwhile, the levelled data are compared with results of tie-line levelling and flight-line correlation levelling for further analysis.

2. Methodology

2.1. Flight line difference

We assume there are L flight lines in the survey area after preliminary processing, expressed as $\mathbf{D} = [\mathbf{d}^0, \mathbf{d}^1, \cdots, \mathbf{d}^L]$. A flight line is selected as the reference line deemed without levelling errors (Huang, 2008). Let the data in the reference line and its adjacent flight line be expressed as $\mathbf{d}^0$ and $\mathbf{d}^1$, respectively,

$$\mathbf{d}^0 = \mathbf{d}^{0\_\mathrm{response}} + \mathbf{d}^{0\_\mathrm{error}}, \tag{1}$$

$$\mathbf{d}^1 = \mathbf{d}^{1\_\mathrm{response}} + \mathbf{d}^{1\_\mathrm{error}}, \tag{2}$$

where $\mathbf{d}^{0\_\mathrm{response}}$ and $\mathbf{d}^{1\_\mathrm{response}}$ are the pure responses in AEM data, $\mathbf{d}^{0\_\mathrm{error}}$ and $\mathbf{d}^{1\_\mathrm{error}}$ are the levelling errors. Typically, there are $\mathbf{d}^{\mathrm{response}} > \mathbf{d}^{\mathrm{error}}$ for airborne geophysical data.

Because the conductivity of earth model contains smaller differences between adjacent flight lines, the corresponding airborne electromagnetic responses are approximately equal, namely, $\mathbf{d}^{0\_\mathrm{response}} \approx \mathbf{d}^{1\_\mathrm{response}}$. Therefore, the differences between adjacent flight-line data are as follows,

$$\begin{aligned}\Delta \mathbf{d} = \mathbf{d}^0 - \mathbf{d}^1 &= \left(\mathbf{d}^{0\_\mathrm{response}} - \mathbf{d}^{1\_\mathrm{response}}\right) \\ &+ \left(\mathbf{d}^{0\_\mathrm{error}} - \mathbf{d}^{1\_\mathrm{error}}\right) \approx \mathbf{d}^{0\_\mathrm{error}} - \mathbf{d}^{1\_\mathrm{error}}.\end{aligned} \tag{3}$$

Eq. (3) shows that the flight line difference eliminates the electromagnetic response portion in the data. However, in some cases the conductivity of earth model contains large differences in the tie-line direction and the electromagnetic responses of adjacent flight lines are not approximately equal. The differences between adjacent flight line data are

$$\Delta \mathbf{d} = \mathbf{d}^0 - \mathbf{d}^1 = \left(\mathbf{d}^{0\_\mathrm{response}} - \mathbf{d}^{1\_\mathrm{response}}\right) + \left(\mathbf{d}^{0\_\mathrm{error}} - \mathbf{d}^{1\_\mathrm{error}}\right). \tag{4}$$

In this case, the difference data $\Delta \mathbf{d}$ cannot be used to approximate the levelling error differences between the adjacent flight lines. In conclusion, flight line difference improves the ratio of levelling error to AEM data which enhances the features of levelling error. Based on the analysis, we decide to conduct levelling to the difference data instead of to airborne geophysical data directly.

2.2. Principal component analysis levelling principle

The survey AEM data $\mathbf{D}$ are transformed into the difference data $\Delta \mathbf{D}$ through flight line difference. According to Eqs. (3) and (4), we select n distributive pseudo tie lines avoiding the anomalous regions and construct a pseudo tie-line data set $\Delta \mathbf{D}_{\mathrm{tie}}$. Since the pseudo tie lines are selected in distributive way along survey profile direction, the electromagnetic responses of each pseudo tie line have smaller correlations. While there are high correlations between selective pseudo tie lines for the levelling errors, principal component analysis is introduced to extract the levelling error differences from the data set.

Firstly, we calculate co-variance matrix $\mathbf{C}_X$ of the data set $\Delta \mathbf{D}_{\mathrm{tie}}$ and perform eigenvalue decomposition using the co-variance matrix,

$$\mathbf{C}_X = \mathbf{R} \boldsymbol{\Lambda} \mathbf{R}^{\mathrm{T}}, \tag{5}$$

where $\boldsymbol{\Lambda}$ is eigenvalue matrix of the pseudo tie-line data set and $\mathbf{R}$ is eigenvector matrix of the data set. The rotational matrix $\mathbf{R}^{\mathrm{T}}$ is used to linearly map data set $\Delta \mathbf{D}_{\mathrm{tie}}$ as the principal components Ψ,

$$\Psi = \mathbf{R}^{\mathrm{T}} \cdot \Delta \mathbf{D}_{\mathrm{tie}} = \begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \\ \Psi_n \end{bmatrix}, \tag{6}$$

where $\Psi_1, \Psi_2, \ldots, \Psi_n$ are the 1st to nth principal component. The cumulative contribution rate of the principal components is

$$\delta_m = \sum_{j=1}^{m} \boldsymbol{\Lambda}_{j,j} \Big/ \sum_{i=1}^{n} \boldsymbol{\Lambda}_{i,i}. \tag{7}$$

When the cumulative contribution rate of the principal components δ_m reaches 85%, the first m low-order components represent the main features of the levelling error difference. We use the m low-order components to reconstruct the difference data,

$$\widehat{\Delta \mathbf{D}}_{\mathrm{tie}} = \mathbf{R} \begin{bmatrix} \Psi_1 \\ \Psi_2 \\ \vdots \\ \Psi_{\mathrm{m}} \end{bmatrix}. \tag{8}$$

The reconstructed results express the levelling error differences in the pseudo tie-line data set. Then we perform a spatial interpolation of $\widehat{\Delta \mathbf{D}}_{\mathrm{tie}}$ in the survey profile direction and obtain the levelling error differences of the survey area, $\widehat{\Delta \mathbf{D}} = [\widehat{\Delta \mathbf{D}}^0, \widehat{\Delta \mathbf{D}}^1, \cdots, \widehat{\Delta \mathbf{D}}^L]$.

The levelling errors of original AEM data can be obtained by inverse difference, for example, the levelling errors $\mathbf{d}^{1\_\mathrm{error}}$ in the flight line data $\mathbf{d}^1$ are

$$\mathbf{d}^{1\_\mathrm{error}} = \mathbf{d}^{0\_\mathrm{error}} + \widehat{\Delta \mathbf{D}}^1, \tag{9}$$

where $\mathbf{d}^{0\_\mathrm{error}}$ are the levelling errors in the flight line data $\mathbf{d}^0$. The corresponding levelling results are given by Eq. (10):

$$\mathbf{dl}^1 = \mathbf{d}^1 + \mathbf{d}^{1\_\mathrm{error}}. \tag{10}$$

The levelling errors and the levelling results of the AEM data can be derived from line to line.

3. Field examples

3.1. Airborne magnetic data levelling

The levelling method has been tested on field magnetic data obtained by Geotech Limited. As seen in Fig. 1a, the raw data contain clear striped levelling errors. The survey area includes 40 flight lines (denoted L10160-L10550) with a line spacing of 200 m. According to the flight log, 6 tie lines were flown in this survey area with a spacing of approximately 2500 m.

We select flight line L10300 (shown by the black dashed line in Fig. 1a) as the reference line. Based on this reference line, the flight line difference data are calculated and shown in Fig. 1b. A comparison of Fig. 1a and b shows the striped feature of levelling error is significantly enhanced, especially at the regions without anomalous features, such as the regions around y(6,858,900 m, 6,861,300 m) and y (6,868,200 m, 6,873,400 m). Based on Eq. (3), flight line difference eliminates a large portion of airborne magnetic response, and the difference data in these regions are approximately equal to the levelling error differences. However the difference data contain part of magnetic response differences at the regions with anomalous features along tie-line direction, for example, the region around y(6,861,300 m, 6,868,200 m). We also analyse the correlations between the pseudo tie lines before and after flight line difference. The correlation