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Leveling airborne geophysical data using a unidirectional variational model

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Abstract. Airborne geophysical data leveling is an indispensable step to the conventional data processing. Traditional data leveling methods mainly explore the leveling error properties in the time and frequency domain. A new technique is proposed to level airborne geophysical data in view of the image space properties of leveling error, including directional distribution property and amplitude variety property. This work applied unidirectional variational model on entire survey data based on the gradient difference between the leveling errors in flight line direction and the tie-line direction. Then spatially adaptive multi-scale model is introduced to iteratively decompose the leveling errors which effectively avoid the difficulty on the parameter selection. Considering the anomaly data with large amplitude may hide the real data level, a leveling preprocessing method is given to construct a smooth field based on the gradient data. The leveling method can automatically extract the leveling errors of the entire survey area simultaneously without the participation of staff members or tie-line control. We have applied the method to the airborne electromagnetic, magnetic data, and apparent conductivity data collected by Ontario Geological Survey to confirm its validity and robustness by comparing the results with the published data.

1 Introduction

Airborne geophysical surveys are widely used to produce geological mapping and mineral exploration that commonly adopt continuous “S-type” flight mode under the certain elevation (Hood, 2007). In airborne survey, the dynamic flight conditions cause the unequal data levels which defined as leveling errors and showed as the striping pattern along the flight direction. Leveling errors have serious impact on airborne geophysical data analysis and interpretation.

A variety of factors contribute to the leveling errors, classified as the uncontrollable external environment and routine measuring mode. Airborne surveys in one measuring area usually have to last certain months or so, and the environmental temperature has seasonal fluctuations even regional fluctuations. Temperature variations can change the configuration of used survey aircraft, and the collected data as well (Huang and Fraser, 1999; Valleau, 2000; Siemon, 2009). Also worth noting is that the solar wind gives rise to the geomagnetic diurnal variations in the earth’s magnetic field (Yarger et al., 1978; Mauring et al., 2002). This is also considered as leveling errors in airborne magnetic data.

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The continuous "S-type" flight mode in measuring area brings the opposite directions between adjacent lines which lead to the survey aircraft affected by different surrounding environment (Luyendyk, 1997; Gao et al., 2021). When the survey aircraft is blown by the wind in the opposite directions, the flight attitude angle may have minor difference, particularly for hanging bird (Yin and Fraser, 2004; Huang, 2008). The temperature fluctuations are also happened if the sun strikes the survey aircraft in the different directions (Huang and Fraser, 1999). The fluctuations are uncontrollable and hard to compensate which contribute to leveling errors.

In addition, altitude variation is the source of the leveling errors in airborne electromagnetic (AEM) data. Although the drape flying used in the unmanned aircraft systems has allowed to collect data at constant terrain clearance (Tezkan et al., 2011; Eppelbaum and Mishne, 2011), it is still a test to keep a fixed flying altitude in most airborne geophysical systems. Unlike airborne magnetic data, AEM data are relatively sensitive to altitude. The inconsistent altitude leads to the change of collected data (Huang and Fraser 1999; Huang, 2008; Beiki et al., 2010) and external temperature (Siemon, 2009).

As the source analysis, the leveling errors are difficulty to quantitatively calculated in accurate error equations. In order to correct leveling errors, certain supplementary data are used as a comparison inspection. Tie-line leveling is a classic method based on an assumption that leveling errors are varying slowly along flight lines (Foster et al., 1970). The survey data are corrected using the differences at the crossover points of the tie lines and flight lines. Then geophysicists have improved the tie-line leveling to better match the leveling errors with the differences at the crossover points (Foster et al., 1970; Yarger et al., 1978; Bandy et al., 1990; Mauring et al., 2002; Srimanee et al., 2020).

In practice, it is hard to keep the same survey aircraft configuration and external environment when the survey flew the flight line data and the tie line data. The differences at the crossover points can also be caused by magnetic storms, or variations in navigation and flight altitude (Urquhart, 1988; Nelson, 1994). The data leveling no longer regarded tie-line data as the absolute standard but constructed a smooth representation of the regional field. Urquhart (1988) separated and filtered the long-wavelength components in the gridded data to reduce the leveling errors on apparent susceptibility maps. Based on the reconstruction method of the total field, Nelson (1994) used horizontal gradients to generate a gridded total field, followed by the compensation of the long-wavelength components in the anomaly field. Then more geophysicists focused on using long-wavelength components to level airborne magnetic data (Luo et al., 2012; White et al., 2015). Furthermore, virtual tie lines (Huang and Fraser, 1999; Zhang et al., 2018) and cross-line frame (Fan et al., 2016) are skilfully constructed to level geophysical data instead of tie lines.

Another important basis of data leveling is that the geophysical field is continuous, but the leveling errors are not continuous between adjacent flight lines (Huang, 2008). Based on the point, Green (2003) minimised the between-line differences over the whole survey area to reduce the effect of the drift errors. Huang (2008) chose a reference flight line as the standard of the survey area. The adjacent flight line data are leveled by minimising the differences with its reference flight line (Huang, 2008; Zhu et al., 2020). Furthermore, certain geophysicists proposed to construct one-dimensional (1D) and two-dimensional (2D) sliding windows based on the continuity difference between geophysical field data and leveling errors (Mauring, 2006; Beiki, 2010; Ishihara, 2015). The 1D window value at each survey point is determined by the survey point along the flight line within the window. The 2D window value is determined from nearby data values in the current line and neighbouring lines. The geophysical data are leveled by the difference between the 1D and 2D window values, namely the difference with its neighbouring points. Moreover, the aerophysical data can be microleveled using the statistical approach in designed moving window (Groune et al., 2018).

Leveling errors show as the striping pattern along survey profile direction, namely, there are spatially directional distribution characteristic. The directional filters are designed and leveled the geophysical data (Minty, 1991; Ferraccioli et al., 1998; Siemon, 2009; Davydenko and Grayver, 2014; Gao et al., 2021). Furthermore, there are some leveling methods are proposed in the response-parameter domain, considering the altitude-sensitive characteristic of AEM data (Huang and Fraser, 1999; Huang, 2008; Siemon, 2009).

This paper describes a new leveling technique based on image space properties of leveling error. The technique integrates the directional distribution characteristic and the data continuity difference between the geophysical field and the leveling errors. Firstly, we studied the leveling error characteristic, including directional distribution property and amplitude variety property. Then the proposed leveling method is described based on the property analysis. The technology is applied to three types of field datasets to show the stability and robustness of the method. Field examples shown in this paper suggest that the method can be used to level a variety of airborne geophysics without tie-line data.

2 Image Space Property Analysis of Leveling Errors

In order to extract the leveling error of the geophysical data preciously, it is necessary to assess the properties of the leveling error components. Here we mainly analyse the directional distribution property and amplitude variety property based on the gradient data of leveling error.

2.1 Directional distribution property

As related research work mentioned, the leveling errors present a significant directional property (Minty, 1991; Ferraccioli et al., 1998; Siemon, 2009; Davydenko and Grayver, 2014; Gao et al., 2021). Figure 1 shows the gradient of magnetic data in horizontal and vertical direction which is corrupted by the leveling errors. As seen in Fig. 1(a), the raw magnetic field data, obtained by Ontario Airborne Geophysical Survey, contain striped leveling errors. The survey area measured in the 29.02 km×23.59 km area and has been grided as 117 flight lines (denoted as L10160-L11320) with 733 points for each line.

According to the flight log, there are 10 tie lines flown in this survey area with a spacing of approximately 2,500 m. Figure 1(d) shows the leveled data in tie-line leveling method performed by the Geophysics Leveling module of Oasis montaj software, which is developed by Geotech Limited. The main data processing includes lag correction, heading correction, statistical leveling, and tie-line leveling.

The horizontal gradients of raw data and leveled data are presented in Figs 1(b) and (e). Through comparison the horizontal gradients with and without leveling errors, we can see that the leveling errors show dense response in horizontal gradient and

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cause the discontinuity between flight lines. The discontinuity seriously affects the anomaly distributed along vertical direction. The vertical gradient of the corrupted magnetic data and leveled data exhibit good smoothness and similarity in Figs. 1(c) and (f). The leveling error is a smoothly varying drift along survey profile direction (Foster et al., 1970; Yarger et al., 1978; Luo et al., 2012). That is, the leveling errors can be regarded as continuous between the adjacent survey points for a given flight line. Based on the above analysis, the horizontal gradient more reflects the leveling error distribution and the vertical gradient outputs the discontinuous and rapidly variable anomaly in the area. It is feasible to remove the leveling errors and retain the structures of the magnetic data from the directional gradient perspective.

2.2 Amplitude variety property

Another consideration is the clearly larger amplitude of the horizontal gradients (Figs. 1(b) and (e)) compared with the vertical gradients (Figs. 1(c) and (f)). The horizontal gradients reflect the differences between the adjacent flight lines, but the vertical gradients are the differences between the adjacent survey points. Generally, the average distance between flight lines is 100 times bigger than that in survey points after resampling processing, so the horizontal direction has bigger amplitude variety.

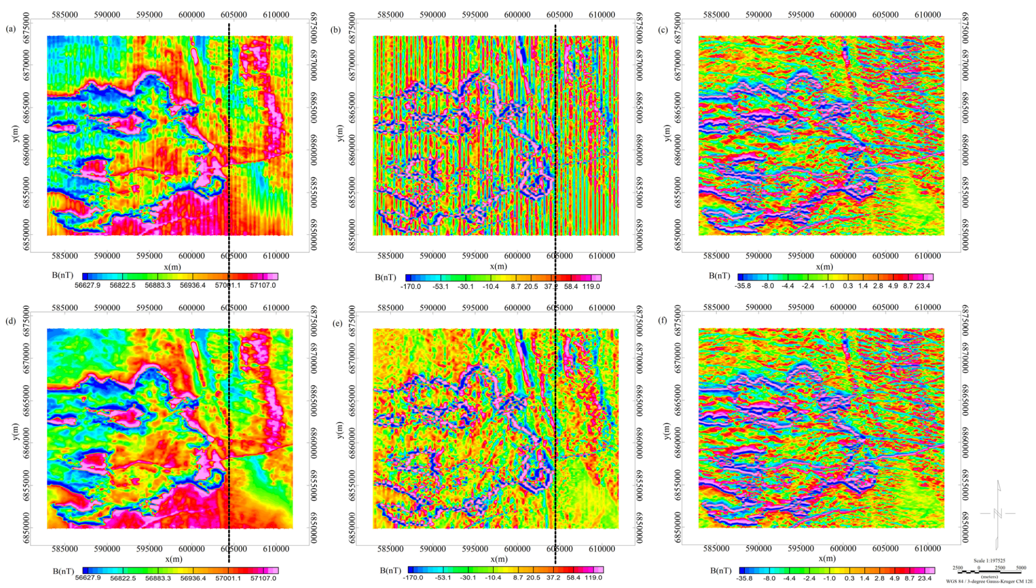

Figure 1. The directional property of leveling error. (a) The raw magnetic data. (b) The horizontal gradients of the raw magnetic data. (c) The vertical gradients of the raw magnetic data. (d) The leveled magnetic data. (e) The horizontal gradients of the leveled magnetic data. (f) The vertical gradients of the leveled magnetic data.

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Figure 2 depicts the maximum values of the horizontal gradients and the vertical gradients. We find the horizontal gradients are not smooth trend which have an amplitude jump at the black dotted line in Fig. 2(a). To analyse the amplitude variety, two black dotted lines are given at the corresponding position in Fig. 1. The comprehensive analysis indicates that the larger amplitudes in the horizontal gradients are caused by the discontinuous abnormal distribution in the left side of the survey area. The vertical gradient amplitudes are affected by the same reason as shown in Fig. 2(b). That is to say, the anomaly data show a non-negligible discontinuity in flight line direction and the tie-line direction.

As mentioned in Introduction, many previous papers study the assumption that the geophysical field is continuous, but the leveling errors are not continuous between adjacent flight lines. The leveling errors contribute to the difference between adjacent flight lines. However a neglected issue is that the discontinuity of anomaly may be regarded as leveling errors which has considerable impact on the data leveling. Corresponding simulation experiment has proved the thought and publish in our papers (Zhu et al., 2020; Zhang et al., 2021). Therefore reasonable leveling preprocessing is need to filter anomaly data and construct a smooth field which is helpful to level data accurately.

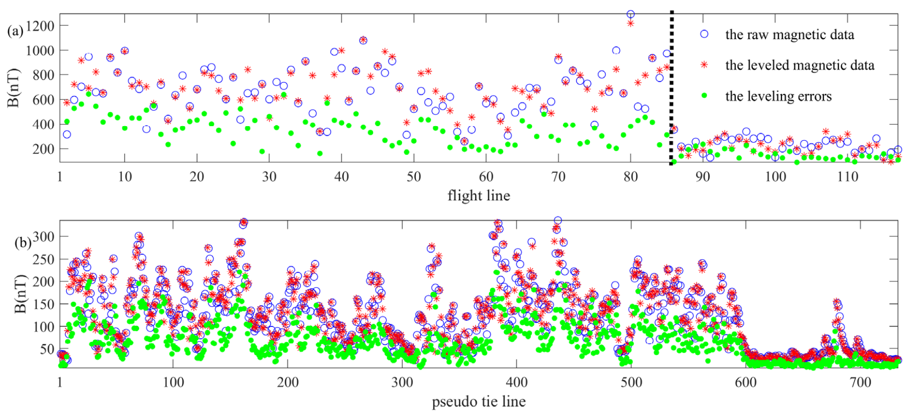

Figure 2. The maximum values of the gradients. (a) The horizontal gradients. (b) The vertical gradients.

3 Proposed Method

3.1 Leveling preprocessing

As the property analysis of leveling errors, leveling preprocessing is needed to avoid the interference of survey anomaly in the leveling processing. We try to construct a smooth field based on the vertical gradient of the raw data which could better represent the anomaly distribution as shown in Fig. 1(c). Assuming there are L flight lines and N survey points in each line, expressed as $\mathbf{D}(N \times L)$,

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$$\mathbf{D} = \begin{bmatrix} d_1^1 & d_1^2 & \cdots & d_1^L \\ d_2^1 & d_2^2 & \cdots & d_2^L \\ \vdots & \vdots & \ddots & \vdots \\ d_N^1 & d_N^2 & \cdots & d_N^L \end{bmatrix} = \begin{bmatrix} \mathbf{D}_1 \\ \mathbf{D}_2 \\ \vdots \\ \mathbf{D}_N \end{bmatrix} = [\mathbf{D}^1 \quad \mathbf{D}^2 \quad \cdots \quad \mathbf{D}^L]. \tag{1}$$

where d_N^L is the Nth survey data in the Lth flight line, $\mathbf{D}_N = (d_N^1, d_N^2, \dots, d_N^L)$ are the Nth pseudo tie-line data, and $\mathbf{D}^L = (d_1^L, d_2^L, \dots, d_N^L)^T$ are the Lth flight line data, T abbreviates transpose. Based on the vertical gradient of the survey area **DX**, we distinguish the anomaly points by the comprehensive comparison from the horizontal and vertical directions. If the vertical gradient of the survey point data greater than the average values of its horizontal or vertical directions following Eq. (2), the survey point is deemed as a potential anomaly.

$$\begin{cases} dx_i^j > average\left(dx_1^j, dx_2^j, \dots, dx_N^j\right)^T \\ dx_i^j > average\left(dx_i^1, dx_i^2, \dots, dx_i^L\right) \end{cases}, i = 1,2,\cdots,N; j = 1,2,\cdots,L. \tag{2}$$

where dx_i^j is the vertical gradient of the ith survey data in the jth flight line. Then the potential anomaly point is replaced by the average level of the flight line following Eq. (3).

$$dp_i^j = average\left(d_1^j, d_2^j, \dots, d_N^j\right)^T, i = 1,2,\cdots,N; j = 1,2,\cdots,L. \tag{3}$$

After processing the area by point-to-point, a smooth field **DP** is constructed to avoid the potential anomaly point. The smooth dataset can better display the real data level compared with the raw data.

3.2 Unidirectional Variational Model

Following the leveling preprocessing, a new leveling method is proposed based on the unidirectional variational model and spatially adaptive multi-scale model. As the leveling error property discussed above, the leveling error shows the similar directional distribution property with the striping noise in imaging systems which conduces to separate the leveling error components and the pure geophysical data in the destriping process.

In the image processing field, geometric variation method and partial differential equation (PDE) display excellent results which make comprehensive use of functional analysis, variation calculation, partial differential equations, differential geometry, vector and tensor analysis, bounded variation space, and viscosity solution theory (Osher and Rudin, 1990; Liu et al., 2016). Here we consider the survey data to be a 2D function defined in a bounded domain Ω and the leveling error is an additive drift formulated as,

$$\mathbf{DP}(i,j) = \mathbf{E}(i,j) + \mathbf{R}(i,j), \tag{4}$$

where $\mathbf{DP}(i,j)$ is the preprocessed data of the ith survey data in the jth flight line, $\mathbf{E}(i,j)$ is the leveling error trend of the survey point, $\mathbf{R}(i,j)$ is the residual data. The ill-posed problems require to introduce a regularizing constraint on the solution. Combining with prior information, an estimate of the leveling error trend can be computed by minimizing an energy functional that includes a penalty term and a regularization term. The penalty term is used to keep the fidelity of the estimated solution to the preprocessed data. And the regularization term could regulate the smoothness of the solution.

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In energy functional framework, Rudin, Osher, and Fatem (1992) introduced total variation (TV) norm and proposed ROF total variation model which has been widely used in image-denoising applications. The energy functional is defined as,

$$F(\mathbf{E}) = \int_{\Omega} \|\mathbf{E}\|^2 + \lambda TV(\mathbf{DP} - \mathbf{E}), \tag{5}$$

where λ is the regularization coefficient that quantifies the degree of smoothness, $TV(\mathbf{E})$ is the total variation of the estimated solution **E** expressed as,

$$TV(\mathbf{E}) = \int_{\Omega} |\nabla \mathbf{E}| = \int_{\Omega} \sqrt{\left(\frac{d\mathbf{E}}{dx}\right)^2 + \left(\frac{d\mathbf{E}}{dy}\right)^2}\, dxdy. \tag{6}$$

The ROF model can better preserve discontinuities in the solution which is important for geophysical data processing. By exploiting the unidirectional signature of stripes in the TV framework, Bouali and Ladjal (2011) proposed the unidirectional variational which provides optimal qualitative and quantitative results on images contaminated with severe stripes. The scholars have deeply studied the algorithm and applied it on the striping noise removal (Huang et al., 2016; Zhang and Zhang, 2016; Liu et al., 2019). Based on directional distribution property, leveling error trend **E** can be viewed as a similar structured variable, of which variations are mainly concentrated along the *x*-axis. In mathematical words, the leveling errors of the most survey points hold the following property,

$$\left|\frac{\partial \mathbf{E}(i,j)}{\partial x}\right| \gg \left|\frac{\partial \mathbf{E}(i,j)}{\partial y}\right|. \tag{7}$$

Integration of Eq. (7) over the survey area leads the inequality to a characteristic of the leveling error,

$$TV_x(\mathbf{E}) \gg TV_y(\mathbf{E}), \tag{8}$$

where TV_x and TV_y are horizontal and vertical variations. To obtain a robust leveling error removal, the leveling error characteristic is introduced into the energy functional in Eq. (5),

$$F(\mathbf{E}) = TV_y(\mathbf{E}) + \lambda TV_x(\mathbf{DP} - \mathbf{E}). \tag{9}$$

Then the minimization of unidirectional variational model in Eq. (9) is calculated by alternating direction method of multipliers (ADMM) in a sequence of iterative sub-optimizations (Bertsekas, 1982). Based on the directional distribution of leveling error, the unidirectional variational model separates the leveling error trend and the residual data into the penalty term and the regularization term which could better constraint the decomposition results.

3.3 Spatially Adaptive Multi-Scale Variation

In unidirectional variational method, the regularization coefficient λ has be carefully assigned because of deciding effect on the smoothness of the results. A large value of regularization coefficient will induce excessive geologic information into leveling error trend. If regularization coefficient is too small, the stripes could not be completely extracted. Based on the multiscale hierarchical decomposition theory (Tadmor, 2003), we add the spatially adaptive multi-scale model into the energy functional to avoid the difficulty on the selection of regularization coefficient. While the preprocessed data are decomposed as leveling errors **E** and residual data **R**, the algorithm loops through multiple iterations in multiscale regularization coefficients to retain more useful details. In the kth iteration, the energy functional is expressed as,

$$\begin{cases} F_k(\mathbf{E}_k) = TV_y(\mathbf{E}_k) + \lambda_k TV_x(\mathbf{DP}_k - \mathbf{E}_k) \\ \lambda_k = \lambda_0 * 2^{-k} \\ \mathbf{DP}_k = \mathbf{E}_{k-1} \end{cases}. \quad (10)$$

In order to accurately decompose leveling errors, the regularization coefficient is updated with spatially adaptive strategy. The calculated result data at each iteration are further decomposed in smaller regularization coefficient. When the iteration has been convergence as Eq. (11) shown, the algorithm terminates the iterative decomposition.

$$\|\mathbf{E}_{k-1}\|_2^2 - \|\mathbf{E}_k\|_2^2 < \varepsilon. \quad (11)$$

The raw input data are decomposed as multi residual dataset and a leveling error trend in Eq. (12),

$$\mathbf{DP} = \mathbf{R}_1 + \cdots + \mathbf{R}_k + \mathbf{E}_k = \sum_{j=1}^{k} \mathbf{R}_j + \mathbf{E}_k. \quad (12)$$

The leveled data **Dl** are calculate by removing the directional striping trend $\mathbf{E}_k$ from the geophysical data **D**.

$$\mathbf{Dl} = \mathbf{D} - \mathbf{E}_k + \frac{\sum_{j=1}^{L}\sum_{i=1}^{N} \mathbf{E}_{k}{}_i^j}{N*L}. \quad (13)$$

The spatially adaptive multi-scale model can level geophysical data automatically and avoid the unfavourable over-smoothing effect.

4 Results

4.1 Airborne electromagnetic data leveling

We have tested the proposed leveling method on the AEM data collected by Ontario Geological Survey, Ministry of Northern Development and Mines (MNDM). The survey was carried out in North Spirit Lake area using the time-domain GEOTEM® 1000 electromagnetic system mounted on a fixed wing platform (Ontario Geological Survey 2007). The area data named Geophysical Data Set 1056 were flown with 200 m flight line spacing in 40°-220° flight line direction. The B-field data of serial flight lines L10510-L11150 at the 9*th* channel are shown in Fig.3 (a) affected by the obviously inconsistent data level among the flight lines.

After leveling preprocessing, Fig.3 (b) presents the constructed smooth field which has filtered most of the potential anomaly points. It is worth mentioning that the altitude sensitivity in the AEM data should be reduced before leveling (Huang 2008). Based on the superposed dipole assumption (Fraser, 1972), Huang (2008) proposed to transform the altitude-sensitive AEM data into the response-parameter domain. Follow the opinion of Huang, the AEM data used in the paper have been transformed into response-parameter domain data.Figure 3(c) depicts the processed data by the unidirectional variational model algorithm in which the initial regularization coefficient λ_0 is fixed to 50 and updated with $\lambda_k = \lambda_0 * 2^{-k}$ in iteration. The proposed leveling processing can be completed automatically without professional geophysicists.

In contrast, Fig.3 (d) presents the data processed by Fugro Airborne Surveys through multiple steps, including lag adjustment, drift adjustments, spike editing for spheric events, the correction for coherent noise, and adaptive filtering. The used drift

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adjustment is in flight form based on the baseline minima rule along each channel (Ontario Geological Survey 2007). Through a graphic screen display, the flight lines are passed a low order polynomial function to correct drift.

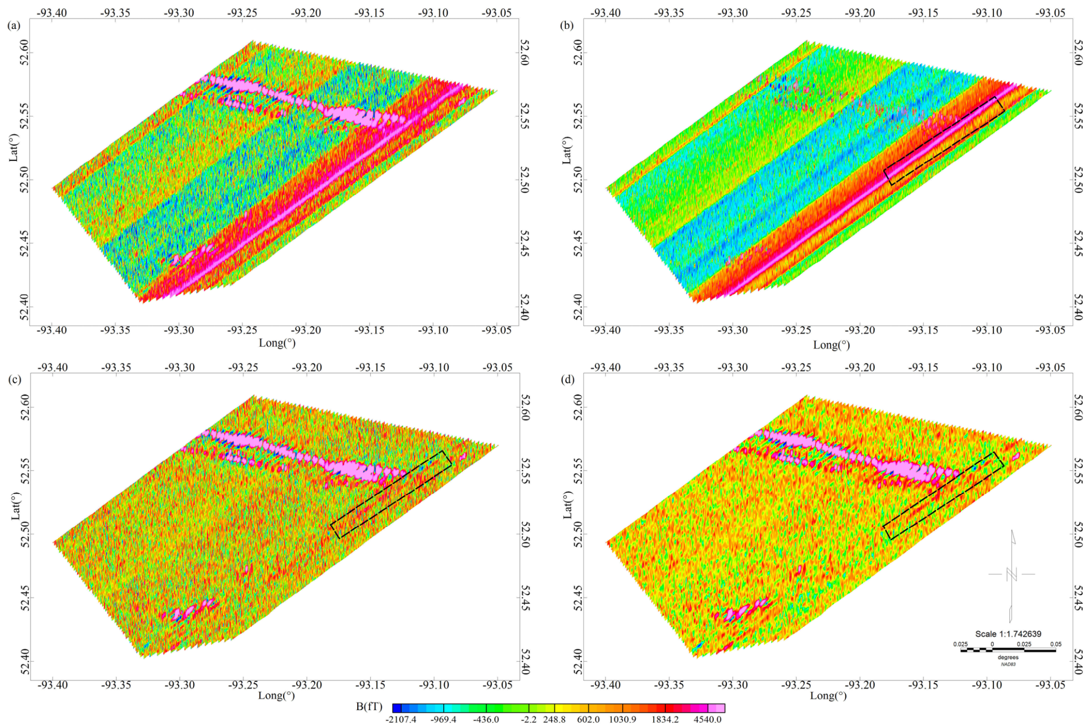

Figure 3. The AEM data leveling. (a) Raw AEM data. (b) The preprocessed smooth field. (c) Leveled data by the unidirectional variational model algorithm. (d) The data processed by Fugro Airborne Surveys.

Figure 4 shows the leveled transient data to compare the results in greater detail. Two flight lines are selected and locally enlarged to show leveling errors in different degrees, as Figs. 4 (b) and (c) shown. The leveling errors are approximately zero in the 25*th* flight line, and the level errors are larger in the 50*th* flight line. Both the leveling methods can remove the leveling errors in the area. Because of extra denoising by Fugro Airborne Surveys, the processed data show some differences, especially in the spike of anomaly points.

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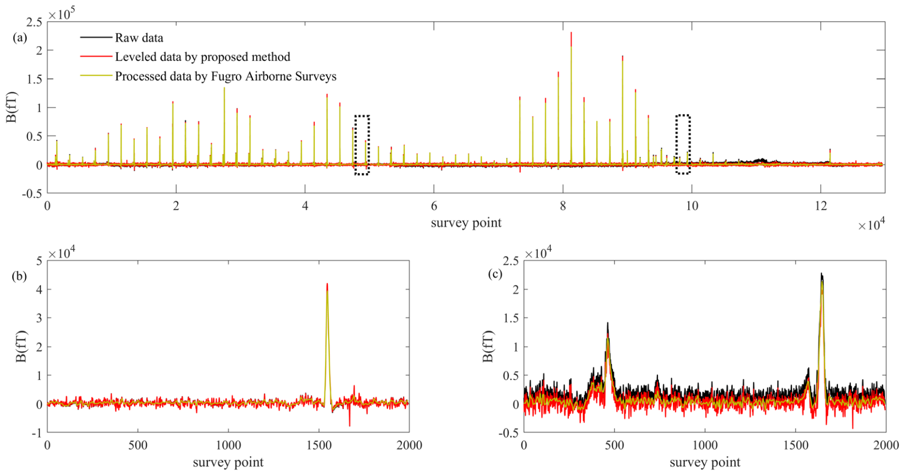

Figure 4. The result comparison analysis between the unidirectional variational model algorithm and Fugro Airborne Surveys. (a) All flight line data. (b) The 25*th* flight line data, corresponding to the first black dotted rectangle in Fig. (a). (c) The 50*th* flight line data, corresponding to the second black dotted rectangle in Fig. (a).

4.2 Airborne magnetic data leveling

We have tested the proposed leveling method on the magnetic data collected by Ontario Airborne Geophysical Survey as shown in Fig. 1(a). The dataset information has been provided in the Image Space Property Analysis that are no longer to introduce. Based on the vertical gradient of the survey area, we removed the anomaly points that may interfere the leveling. As Fig.5 (a) shown, the constructed smooth field could better represent the data level of the measuring area. In the leveling process, the parameters of unidirectional variational model algorithm are set in the same way as AEM data leveling example. That is the initial regularization coefficient λ_0 is fixed to 50 and reduced by half in iterations. The leveled data and decomposed leveling errors are shown in Figs. 5 (b) and (c).

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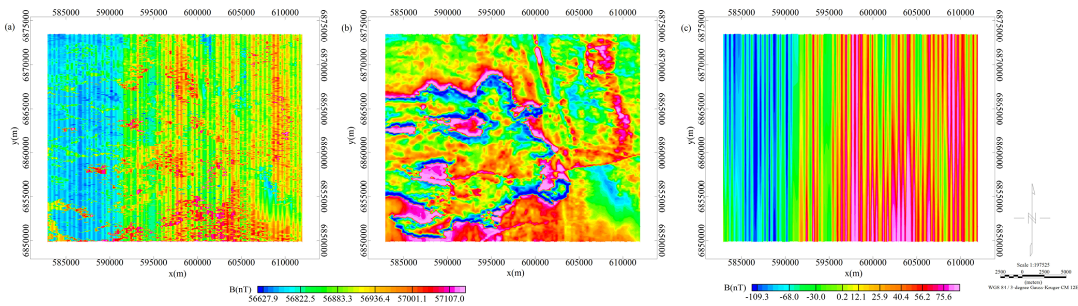

Figure 5. The leveling of the magnetic data. (a) The preprocessed smooth field. (b) Leveled data by the unidirectional variational model algorithm. The figure is shown under the same colorbar with the leveling results in Fig. 1(d). (c) Decomposed leveling errors.

The leveled data by tie-line leveling method are used as comparative data which have been given in Fig. 1(d). Then contrasts of the corrected transient data are presented in Fig. 6. Similarly, we enlarged two flight lines in different error degrees as the samples, as Figs. 6 (b) and (c) shown. The leveling errors are larger in the 44*th* flight line, and that are approximately zero in the 112*nd* flight line.

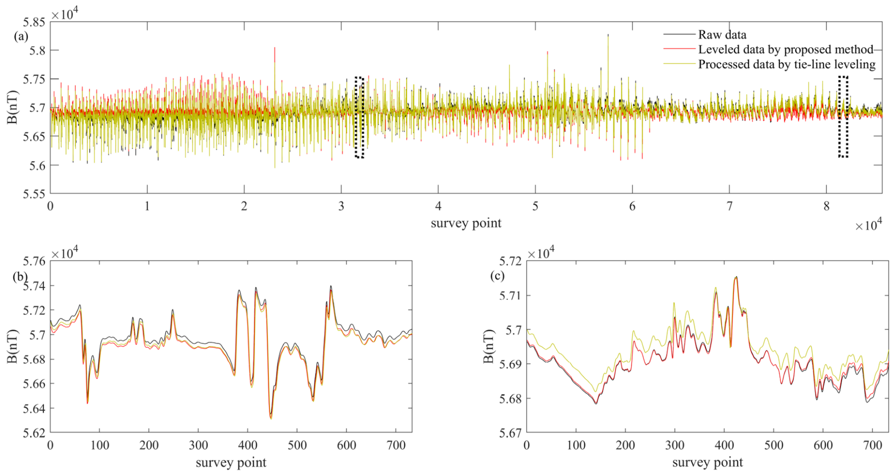

Figure 6. Leveled magnetic data. (a) All flight line data. (b) The 44*th* flight line data, corresponding to the first black dotted rectangle in Fig. (a). (c) The 112*nd* flight line data, corresponding to the second black dotted rectangle in Fig. (a).

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4.3 Apparent conductivity data leveling

The third example shows leveling results for apparent conductivity. Geotech Limited carried out a helicopter-borne combined aeromagnetic and electromagnetic survey for the Ministry of Northern Development and Mines in 2014 which is performed as part of the Ontario Geological Survey geoscience program in the Nestor Falls area in north-western Ontario. In the helicopter-borne electromagnetic survey, the geophysical surveys used the versatile time-domain electromagnetic (VTEM®Plus) system with Z-component measurements. Based on Resistivity depth imaging (RDI) technique (Meju, 1998), Geotech Limited converted the EM profile decay data into an equivalent resistivity versus depth cross-section, by deconvolution of the measured TEM data. Data compilation and processing were carried out using Geosoft® OASIS montaj™ and programs proprietary to Geotech Ltd (Ontario Geological Survey 2014).

The dataset used in the paper is formed by 71 flight lines named L310-L1000 as a part of Geophysical Data Set 1076 measured in the surveys. Figure 7(a) presented the apparent conductivity calculated from dBz/dt response at 97 m average depth from the surface. There are obvious striped errors along the flight line direction.

According to the length of flight lines, the survey area data are divides two parts in the leveling example. We applied the same parameters to test the robustness of the unidirectional variational model algorithm. The regularization coefficient is fixed to 50 in the initial iteration and reduced by half at each iteration. The leveled data and decomposed leveling errors are shown in Figs. 7 (b) and (c). The contrast of the corrected transient data is presented in Fig. 8. We selected and enlarged two flight lines in different error degrees as the samples, as Figs. 8 (b) and (c) shown. The leveling errors are larger in the 6*th* flight line and approximately zero in the 71*st* flight line.

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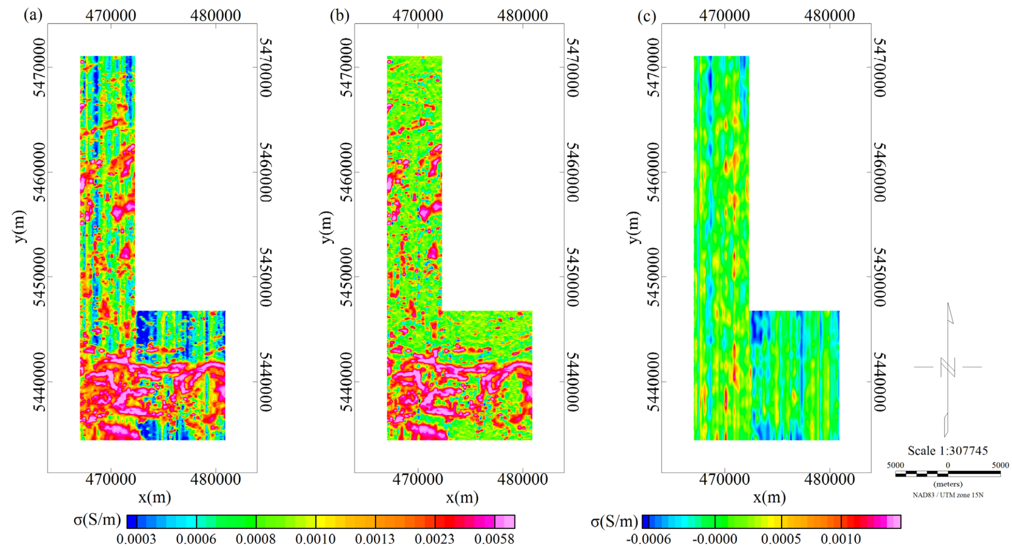

Figure 7. The leveling of the apparent conductivity data. (a) The raw data. (b) Leveled data by the unidirectional variational model algorithm. (c) Decomposed leveling errors.

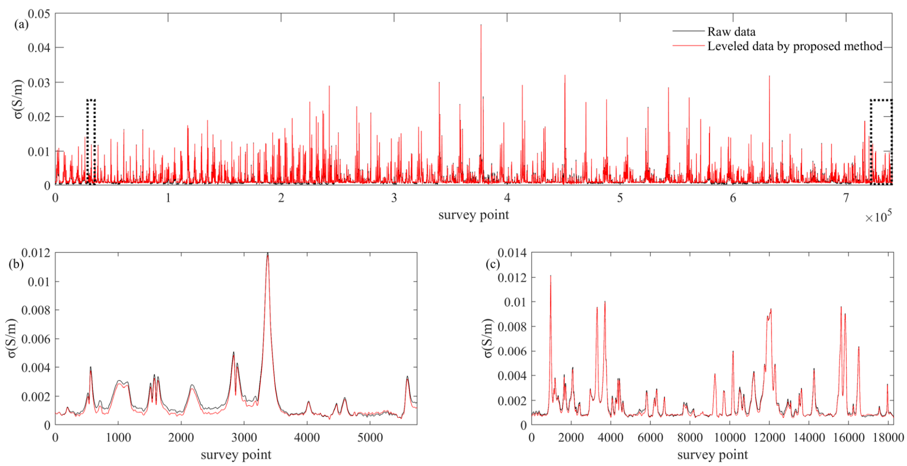

Figure 8. Leveled apparent conductivity data. (a) All flight line data. (b) The 6*th* flight line data, corresponding to the first black dotted rectangle in Fig. (a). (c) The 71*st* flight line data, corresponding to the second black dotted rectangle in Fig. (a).

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5 Discussions

Firstly, we analysed and discussed the leveling results in AEM example. As shown in Fig. 3, the leveling errors in the AEM data are associated with a block of flight lines and presented as block distribution. Based on the proposed leveling method, the first step is leveling preprocessing to filter the survey anomaly in the field. The preprocessing is essential for accurately distinguish the data level in the following processing. As shown in Fig. 9(a), a common phenomenon is that the maximum value in one flight line is greater than the median value and average value in the flight line. For certain flight lines, the maximum value is even thousands of times greater than the median value and average value which have been tested in Fig. 9(b). The anomaly data with large amplitude may hide the real data level. The leveling preprocessing solved the problem by removing the potential anomaly point and constructing a smooth field. And the smooth field can better reflect the real data level by comparing the data in Figs. 3(a) and (b).

Then unidirectional variational model is applied on the smooth field, considering that the directional distribution property discussed above. The variations of leveling errors are mainly concentrated along the tie-line direction compared with the flight line direction. Meanwhile, spatially adaptive multi-scale variation is introduced to assist the parameter selection. This is very important for the massive data processing in geophysical exploration. Fully automatic data processing not only accelerates the processing speed, but also reduces the process steps of data processors.

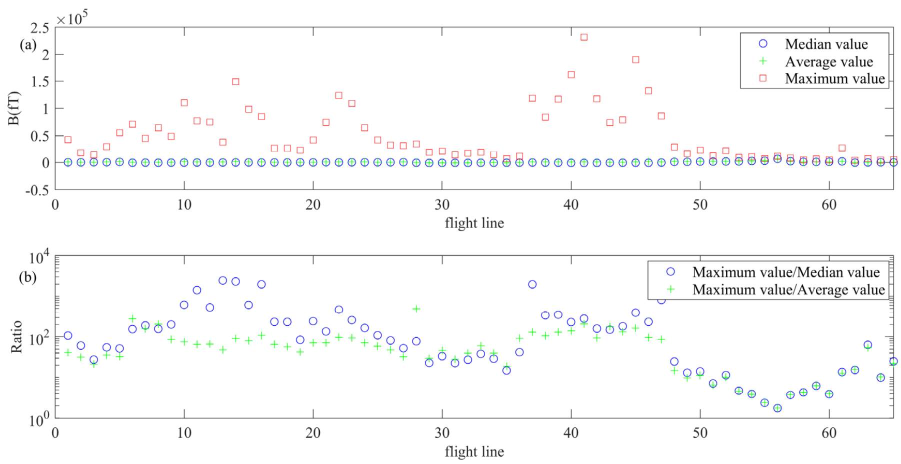

Figure 9. Statistical values of the raw AEM data. (a) The median value, average value, and maximum value of each flight line in the field. (b) The ratio of the maximum value to the median value, the maximum value to the average value. For a better visualization effect, the ratio curves are shown in logarithmic form.

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Figures 3 and 4 compare the leveling results of the proposed method and Fugro Airborne Surveys. Both leveling methods can remove the leveling errors and get the smooth leveled data. Meanwhile, the amplitude and area of anomaly data were almost unchanged as the transient data curves shown in Fig. 4. That is, the proposed leveling method can reach an ideal process result in a relatively simple and completely automated way.

It is worth noting that most leveling method cannot distinguish the leveling errors and the anomaly throughout the flight lines. As Fig. 3(c) shown, there is a narrow strip of anomaly in the black dotted rectangle. If the narrow strip is long enough to throughout the flight line, it will be misjudged as leveling errors. The problem may appear in most leveling methods. The leveling preprocessing used in the paper can avoid the problem because the anomaly data are separated in advance. The anomaly data are not involved the leveling process which protect the integrity of the anomaly data to the most extent.

We analysed the leveled results in the leveling examples of magnetic data and apparent conductivity data in a similar way. Compared with AEM data example, there are more anomaly areas in a scattered or continuous distribution form as Figs. 1(a) and 7(a) shown. When we applied leveling preprocessing on the datasets and removed suspected anomaly points, the leveling errors are underlined in the constructed smooth field as shown in Fig. 5(a). This is helpful to check and operate the inconsistent data levels, the leveling errors. In the following leveling steps, we used the fixed algorithm parameters in the unidirectional variational model and spatially adaptive multi-scale variation algorithms. Figures 5-8 intuitively show the leveled data in maps and transient data curves.

In the airborne magnetic example, the comparison intuitively shows both tie-line leveling method and the proposed leveling method work well in removing leveling errors as Figs. 1(d) and 5(b) shown. In reality, tie-line leveling method regards tie-line data as standard and highly depends on the data quality of measured tie lines. There are usually uncontrollable differences in measurement environment when flew flight lines and tie lines which increases the disturbing in tie-line leveling. The related professionals are needed to operate the leveling steps. However, the proposed leveling method can achieve an expected result in a relatively general way, despite the data type and the source of leveling errors.

The leveled date of apparent conductivity example are given in Fig. 7. In the survey area, the length of flight line has larger difference. In order to decompose the survey data, an extra division is needed according to the length of flight line so that the leveled areas are relatively regularly in the image space domain. From the points of leveled data in Figs. 7(b) and 8(a), we can roughly deem the leveled data can reach a consistent data level.

6 Conclusions

In this paper, we proposed a leveling method based on unidirectional variational model and spatially adaptive multi-scale model. A reasonable leveling preprocessing is introduced to highlight the real difference of data level which helps to extract the leveling error component. Based on the vertical gradient data, a simple filtering is used to remove the large amplitude anomaly data. As the field examples presented, leveling preprocessing has two advantages in the leveling method. One, the leveling preprocessing reduces the obstacle to distinguish leveling errors. Second, it is helpful to ensures the integrity of anomaly data, including the amplitude and area of the anomaly data.

Then a general leveling method is proposed considering the directional distribution property and amplitude variety property of leveling error. The leveling method combines unidirectional variational model with spatially adaptive multi-scale model which can produce desired results with the stability and robustness. For the vast amounts of measured data in geophysical exploration, it has become increasingly important as the requirements for automatic processing method. We have confirmed the reliability of the method by applying it to the AEM, magnetic data, and apparent conductivity data with fixed parameters and without tie-line control.

Code/Data availability

The data used in the paper have been opened by Ontario Geological Survey. The more information can be found in the official website (https://www.mndm.gov.on.ca/en).

Author contribution

The manuscript is approved by all authors for publication. Zhang and Sun developed the algorithm model and performed the simulations. Yan designed the experiments and Lv carried them out. Liu prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest. I declare on behalf of my co-authors that the work described was original research that has not been published previously and is not under consideration for publication elsewhere, in whole or in part.

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