Paper Title：

Leveling airborne geophysical data using a unidirectional variational model

Response to Referee 1:

Many thanks for your significant comments on our paper. We have revised the manuscript according to your comments. The response to each revision is listed as following:

1. Comment 1:

The quality of English language is very low, so in many cases it makes it difficult to understand what authors mean.

Response: A native speaker has helped us to modify the grammar and expression of the manuscript. We will carefully and repeatedly check the manuscript to improve the quality of English language.

2. Comment 2:

Introduction is too long and does not explain in clear form what is advantage of proposed method over existing variety of techniques.

Response: As the referee suggested, we have modified the introduction in the manuscript. We summed up the published methods in a more efficient way and supplied the advantage of proposed method. The supplied introductions are given as below shown. A revised manuscript with the red marked correction in Lines 63-83 was attached as the supplemental material entitled by “track-changes-file”.

> This paper describes a new leveling technique based on image space properties of leveling error. 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. A smooth field is constructed to obtain the real data level of the nonanomalous area in advance. Based on the directional distribution property, the leveling method extracts the leveling errors by combining unidirectional variational model with spatially adaptive multi-scale model.
>
> The leveling method can protect the integrity of anomaly data by separating the potential anomaly points and constructed smooth field. More importantly, the geophysical area data are leveled as a whole which avoids the possible error transfer. The method is adaptive and automatic without parameter setting. The technology is applied to three types of field datasets to show the stability and robustness of the method.

3. Comment 3:

There is complete misunderstanding what are the gradients. Gradients are measured in nT/m and not in nT as, for instance, in Figure 2. These incorrect terms are found all over the text.

Response: In the manuscript, we leveled the geophysical data based on image space properties. The leveling errors are often visible as stripe patterns (Huang, 2008; Fan, 2016). When we studied the data leveling, we found that the stripe noise effects severely degrade the image quality in similar way. And the variety of destriping algorithms are proposed in the literature (Bouali and Ladjal, 2011; Zhou et al., 2014; Guan et al., 2019). Then we tried to consider the properties of leveling errors in the image space. In the manuscript, the gradient is calculated and understood from the point of image processing.

Mathematically, the gradient is defined as vector and only applicable to continuous functions. In digital image processing, image is deemed as two-dimensional discrete function. The image gradient is approximately calculated by the finite difference method. The gradient image shows the difference between adjacent pixels. So the unit of gradient is nT in Fig. 2.

4. Comment 4:

In Figure 1 we see that x and y axes are horizontal axes of the survey area. However, in line 177 it is written that TVx anTVy are horizontal and vertical variations.

Response: In Fig.1, x axe is the horizontal axe. Let **D** be the survey area data, the corresponding horizontal gradient $\mathbf{DX}$ is

$$\mathbf{DX} = \mathbf{D}(i+1,j) - \mathbf{D}(i+1,j).$$

That is, the horizontal gradient is equivalent to difference data between the adjacent flight lines. The vertical gradient is equivalent to difference data between the adjacent pseudo tie lines. In line 177, TVx and TVy are defined as horizontal and vertical variations for consistency. The similar definition is given in Reference [3]. The Reference firstly proposed unidirectional variational model to remove stripe noise in moderate resolution imaging spectroradiometer data.

We have supplied the calculation formulas of horizontal gradient and vertical gradient to better explain the method. The supplied introductions are given as below shown. A revised manuscript with the red marked correction in Lines 98-104 was attached as the supplemental material entitled by “track-changes-file”.

> Here, the gradients are calculated by the finite difference method following the gradient definition in the image space. Assuming there are L flight lines and N survey points in each line, expressed as $\mathbf{D}(N \times L)$,
>
> $$\mathbf{D} = \begin{bmatrix} d_1^1 & d_1^2 & \cdots & d_1^L \\ d_2^1 & d_2^2 & \cdots & d_2^L \\ \vdots & \vdots & \ddots & \vdots \\ d_N^1 & d_N^2 & \cdots & d_N^L \end{bmatrix} = \begin{bmatrix} \mathbf{D}_1 \\ \mathbf{D}_2 \\ \vdots \\ \mathbf{D}_N \end{bmatrix} = [\mathbf{D}^1 \quad \mathbf{D}^2 \quad \cdots \quad \mathbf{D}^L]$$
>
> whered_N^L is the Nth survey data in the Lth flight line, $\mathbf{D}_N = (d_N^1, d_N^2, \ldots, d_N^L)$ are the Nth pseudo tie-line data, and $\mathbf{D}^L = (d_1^L, d_2^L, \ldots, d_N^L)^T$ are the Lth flight line data, T abbreviates transpose. The horizontal gradient data are expressed

as $\mathbf{DX} = [\mathbf{0} \quad \mathbf{D}^2 - \mathbf{D}^1 \quad \cdots \quad \mathbf{D}^L - \mathbf{D}^{L-1}]$. The vertical gradient data are expressed as $\mathbf{DY} = [\mathbf{0} \quad \mathbf{D}_2 - \mathbf{D}_1 \quad \cdots \quad \mathbf{D}_N - \mathbf{D}_{N-1}]^T$.

5. Comment 5:
Given examples of levelling do not convince me of the advantage of the proposed method over existing ones.
Response: There are three advantages of proposed method compared with existing leveling methods.
(a). The manuscript proposed a general model for leveling preprocessing. The leveling preprocessing has important significances. A synthetic model is established in **Appendix** to state why we need a leveling preprocessing model to separate the anomalous and nonanomalous data. The Appendix part explains the necessity of moving anomalous area data before leveling. The details have been published in another paper of mine in Reference [6].
In the manuscript, the leveling preprocessing model is constructed based on characteristic analysis of leveling errors. It is available and general for airborne geophysical data leveling.
(b). In the leveling method, the survey data are leveled as a whole. The leveling errors are extract at once rather than block processing. The integrated processing avoids the regional error caused by strong noise, missing data, or error transfer in the common leveling process.
(c). Many leveling methods perform the correction process with the assistance of extra tie-line data, a selected standard level, or configured filter parameters. The proposed leveling method is an adaptive and automatic correction without tie-line data. There are massive data collected in geophysical exploration. It is important to maintain the data processing efficiency.
We will sum up and supply the advantages of proposed method in the revised manuscript (Lines 348-352).

6. Comment 6:
Probably, modeled magnetic map with artificial anomalies and leveling errors would provide more persuasive arguments in the favor of suggested method.
Response: As the referee suggested, a reasonable simulation model can help to validate the efficiency of a new algorithm. Thank you for your comments. This opinion is of great value for our future research.

We tried our best to improve the manuscript and made some revisions in the manuscript. These revisions will not influence the content and framework of the paper. Once again, thank you very much for your comments and suggestions.

Appendix
Synthetic model
Huang (2008) proposed an effective leveling method based on line-to-line correlations

that has been tested on airborne geophysical data without tie-lines. By selecting a reference line, the level errors in the adjacent line are determined from the differences between the line data and the reference line data in a least-squares sense. Leveled line serves as new reference line to level its adjacent line until all lines are leveled. However, the leveling process may be influenced by anomalies along tie-line direction. In addition, the single-channel leveling algorithm might cause channel data distortion in some cases. Figure 1 shows a synthetic airborne time-domain electromagnetic (ATEM) model with a rectangular anomaly and no level error is added to the synthetic ATEM data. We apply line-to-line correlation leveling on the synthetic data, selecting Line 3 as the reference line and the first order polynomial as the level error function.

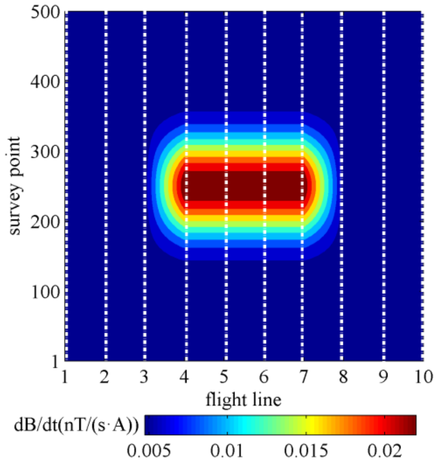

Fig. 1. The synthetic ATEM model without level errors.

Figure 2 shows the leveling results of Line 4, including channel 14 and channel 15. We expect the fitted level errors are approximately zero, however, fake level problem is caused in the fitted level errors as Fig. 2 shown. More importantly, the leveling results are distorting at channel 14 and channel 15 (marked by the dashed black circle in Fig. 2). As shown in Fig. 1, Line 4 is located on the edge of the anomaly that has gradient variation with Line 3. The difference data (see Fig. 2) between Line 4 and its reference line (Line 3) are dominated by the sharp anomaly variation, as well as the fitted level errors in Line 4. The between-line differences of anomaly area lead to fake level in the fitted level errors. Moreover, because the differences between the fitted level errors at the adjacent channels are bigger than the differences that of the raw data at the adjacent channels, the leveling results between channels are distorting. Therefore, we deem it is necessary to separate the smooth nonanomalous data from the anomalous areas data in advance.

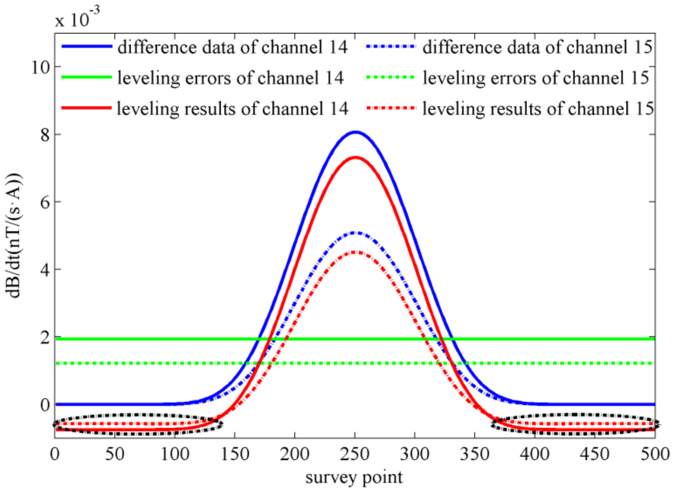

Fig. 2. The data from Line 4 in Fig. 1. The difference data between Line 4 and the reference line of channel 14 (solid blue) and channel 15 (dashed blue), the level errors of channel 14 (solid green) and channel 15 (dashed green), and the leveling results of channel 14 (solid red) and channel 15 (dashed red).

References

[1] Huang, H. P.: Airborne geophysical data leveling based on line-to-line correlations, Geophysics, 73, 83-89, doi:10.1190/1.2836674, 2008.

[2] Fan, Z. F., Huang, L., Zhang, X. J., and Fang, G. Y.: An elaborately designed virtual frame to level aeromagnetic data, IEEE Geoscience and Remote Sensing Letters, 13, 1153-1157, doi:10.1109/LGRS.2016.2574750, 2016.

[3] Bouali, M. and Ladjal, S.: Toward optimal destriping of MODIS data using a unidirectional variational model, IEEE Transactions on Geoscience & Remote Sensing, 49, 2924-2935, doi:10.1109/TGRS.2011.2119399, 2011.

[4] Zhou, G., Fang, H. Z., Yan, L. X., Zhang, T. X., and Hu, J.: Removal of stripe noise with spatially adaptive unidirectional total variation, Optik, 125, 2756-2762, doi:10.1016/j.ijleo.2013.11.031, 2014.

[5] Guan, J. T., Lai, R., Xiong, A.: Wavelet Deep Neural Network for Stripe Noise Removal, IEEE Access, 7, 44544-44554, doi:10.1109/ACCESS.2019.2908720, 2019.

[6] Zhu, K. G., Zhang, Q., Peng, C., Wang, H., Lu, Y. M: Airborne electromagnetic data levelling based on inequality-constrained polynomial fitting, Exploration Geophysics, 51, 600-608, doi:10.1080/08123985.2020.1798923, 2020.

Response to Referee 2:

Many thanks for your significant comments on our paper. We have revised the manuscript according to your comments. The response to each revision is listed as following:

1. Comment 1:

First of all, please clarify the word "gradient" in Section 2, Is it a spatial derivative or (I guess) is it simply a difference or an anomalous component of a total field? Anyway, this should be clarified (defined), so that most readers could understand it clearly at once before they see the maps with the "nT" labels at color bars.

Response: In the manuscript, we leveled the geophysical data based on image space properties. The gradient is calculated and understood from the point of image processing. In digital image processing, image is deemed as two-dimensional discrete function. The image gradient is approximately calculated by the finite difference method (Bouali and Ladjal, 2011).

As the referee suggested, we have supplied the calculation formulas of horizontal gradient and vertical gradient to better explain the method. The supplied introductions are given as below shown. A revised manuscript with the red marked correction in Lines 98-104 was attached as the supplemental material entitled by “track-changes-file”.

> Here, the gradients are calculated by the finite difference method following the gradient definition in the image space. Assuming there are L flight lines and N survey points in each line, expressed as $\mathbf{D}(N \times L)$,
>
> $$\mathbf{D} = \begin{bmatrix} d_1^1 & d_1^2 & \cdots & d_1^L \\ d_2^1 & d_2^2 & \cdots & d_2^L \\ \vdots & \vdots & \ddots & \vdots \\ d_N^1 & d_N^2 & \cdots & d_N^L \end{bmatrix} = \begin{bmatrix} \mathbf{D}_1 \\ \mathbf{D}_2 \\ \vdots \\ \mathbf{D}_N \end{bmatrix} = [\mathbf{D}^1 \quad \mathbf{D}^2 \quad \cdots \quad \mathbf{D}^L]$$
>
> whered_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. The horizontal gradient data are expressed as $\mathbf{DX} = [\mathbf{0} \quad \mathbf{D}^2 - \mathbf{D}^1 \quad \cdots \quad \mathbf{D}^L - \mathbf{D}^{L-1}]$. The vertical gradient data are expressed as $\mathbf{DY} = [\mathbf{0} \quad \mathbf{D}_2 - \mathbf{D}_1 \quad \cdots \quad \mathbf{D}_N - \mathbf{D}_{N-1}]^T$.

2. Comment 2: Next, in the Discussion section where the results are discussed and compared to the similar leveling results obtained by other methods, it is recommended to add some quantitative estimates for the comparison (RMS, for instance) to fully display the advantages of the new method.

Response: As the referee suggested, a reasonable and quantitative estimate can help to validate the efficiency of proposed algorithm. However, it is hard to set up an evaluation criterion by accurate calculation formulas. There are two reasons for missing quantitative comparison.

(1) As introduced in the manuscript, there are a variety of unmeasurable factors

contributing to the leveling errors in the geophysical surveys. The leveling errors are difficult to analysis quantitatively in forward modeling.

Some published papers display the advantages of the proposed leveling algorithm by synthetic data examples. Geophysicists add generated leveling errors on the field data to conduct synthetic experiments (Davydenko and Grayver, 2014; Fan et al., 2016). Beiki et al. (2009) numerically calculate the magnetic field and illustrate a realistic case by adding diurnal variations from a real data set. In addition, the statistical data of the crossover differences are used to compare results in magnetic data leveling (Quesnel et al., 2009; Ishihara, 2015) and frequency-domain electromagnetic data leveling (Siemon, 2009). There are no available evaluation parameters to compare various leveling algorithms in multi-type geophysical data.

(2) In our manuscript, we compared the leveling results with the processed data published by the geophysical companies. In the leveling example of airborne electromagnetic data, we compared the leveling results with the data processed by Fugro Airborne Surveys. Based on the data report, the personnel process the airborne electromagnetic data through multiple steps, including lag adjustment, drift adjustments, spike editing for spheric events, the correction for coherent noise, and adaptive filtering (Ontario Geological Survey 2007). To present the leveling effects, we only conduct the data leveling algorithm on the raw data. So the leveling results are hardly to be quantitatively compared.

The similar situation occurs with the leveling example of airborne magnetic data. The manuscript compared the leveled data in tie-line leveling method performed by the Geophysics Leveling module of Oasis montaj software. The main data processing includes lag correction, heading correction, statistical leveling, and tie-line leveling. When we showed the leveled data in the manuscript, the raw data are processed by single leveling algorithm.

In the next work, we will build synthetic model to validate the efficiency of a new algorithm. Thank you for your comments.

3. Comment 3: Specific comments:

Line 26: "... temperature has seasonal fluctuations even regional fluctuations" should be changed to "... temperature has seasonal fluctuations and even regional fluctuations"

"Temperature variations can change the configuration of used survey aircraft, and the collected data as well..."

I recommend rewriting this statement, for example: "Temperature variations can change the configuration of the used survey aircraft, affect its measuring hardware and the collected data".

Other corrections (some of them are recommendatory):

Line 33: "are also happened" should be changed to "also take place"

Line 37-38: it is better to say "... relatively more sensitive"

Line 41: It's better to rewrite it: "...it is hard to quantitatively calculate..."

Line 120: "which has" should be changed to "which have"

Line 137: "greater" should be changed to "is greater"

Line 145: "...and spatially..." should be changed to "... and the spatially..."

Line 168-169: "proposed a unidirectional variational..." ... model?

Line 185: "In unidirectional variational method,..." Should be changed to "In the unidirectional variational method,..."

Line 194: "result" should be changed to "resulting"

Line 215: "data.Figure 3" should be changed to "data. Figure 3" (a space is missing)

Line 228: "Both the methods" should be changed to "Both methods"

Line 241: "the parameters of unidirectional variational model algorithm" should be changed to "the parameters of the unidirectional variational model algorithm"

Line 266: "presented" should be changed to "presents"

Line 291-292: "Then unidirectional variational model is applied on the smooth field, considering that the directional distribution property discussed above."
Possibly this should be rewritten this way: "Then the unidirectional variational model is applied to the smooth field, taking into account the directional distribution property discussed above."

Response: We have modified the manuscript as the referee suggested. The detailed changes are listed as following. A native speaker is helping us to modify the grammar and expression of the manuscript. We will carefully and repeatedly check the manuscript to improve the quality of English language.
(1) Line 26: "... temperature has seasonal fluctuations even regional fluctuations" has been replaced as "... temperature has seasonal fluctuations and even regional fluctuations". A revised manuscript with the red marked correction in Line 26 was attached as the supplemental material entitled by "track-changes-file".
(2) Thank you for your revisions to the manuscript again.
Line 26: "Temperature variations can change the configuration of used survey aircraft, and the collected data as well..." has been changed to "Temperature variations can change the configuration of the used survey aircraft, affect its measuring hardware and the collected data". A revised manuscript with the red marked correction in Line 27 was

attached as the supplemental material entitled by “track-changes-file”.
(3) Line 33: “The temperature fluctuations are also happened” has been replaced as “The temperature fluctuations also take place”. A revised manuscript with the red marked correction in Line 33 was attached as the supplemental material entitled by “track-changes-file”.
(4) Line 39: “AEM data are relatively sensitive to altitude” has been replaced as “AEM data are relatively more sensitive to altitude”. A revised manuscript with the red marked correction in Line 39 was attached as the supplemental material entitled by “track-changes-file”.
(5) Line 41: “the leveling errors are difficulty to quantitatively calculate in accurate error equations” has been rewritten as “it is hard to quantitatively calculate the leveling errors in accurate error equations”. A revised manuscript with the red marked correction in Line 41 was attached as the supplemental material entitled by “track-changes-file”.
(6) Line 120: “the discontinuity of anomaly may be regarded as leveling errors which has considerable impact on the data leveling” has been rewritten as “the discontinuity of anomaly may be regarded as leveling errors which have considerable impact on the data leveling”. A revised manuscript with the red marked correction in Line 132 was attached as the supplemental material entitled by “track-changes-file”.
(7) Line 137: “If the vertical gradient of the survey point data greater than the average values of its horizontal or vertical directions” has been rewritten as “If the vertical gradient of the survey point data is greater than the average values of its horizontal or vertical directions”. A revised manuscript with the red marked correction in Line 148 was attached as the supplemental material entitled by “track-changes-file”.
(8) Line 146: “the unidirectional variational model and spatially adaptive multi-scale model” has been rewritten as “the unidirectional variational model and the spatially adaptive multi-scale model”. A revised manuscript with the red marked correction in Line 158 was attached as the supplemental material entitled by “track-changes-file”.
(9) Line 168-169: “Bouali and Ladjal (2011) proposed the unidirectional variational” has been replaced as “Bouali and Ladjal (2011) proposed the unidirectional variational model”. A revised manuscript with the red marked correction in Line 180 was attached as the supplemental material entitled by “track-changes-file”.
(10) Line 185: “In unidirectional variational method” has been changed to “In the unidirectional variational method”. A revised manuscript with the red marked correction in Line 196 was attached as the supplemental material entitled by “track-changes-file”.
(11) Line 194: “The calculated result data” has been changed to “The calculated resulting data”. A revised manuscript with the red marked correction in Line 205 was attached as the supplemental material entitled by “track-changes-file”.
(12) Line 215: “data.Figure 3” has been changed to “data. Figure 3”. A revised manuscript with the red marked correction in Line 226 was attached as the supplemental material entitled by “track-changes-file”.
(13) Line 228: “Both the leveling methods” has been rewritten as “Both leveling methods”. A revised manuscript with the red marked correction in Line 239 was attached as the supplemental material entitled by “track-changes-file”.

(14) Line 241: “the parameters of unidirectional variational model algorithm” has been rewritten as “the parameters of the unidirectional variational model algorithm”. A revised manuscript with the red marked correction in Line 252 was attached as the supplemental material entitled by “track-changes-file”.
(15) Line 266: “Figure 7(a) presented” has been changed to “Figure 7(a) presents”. A revised manuscript with the red marked correction in Line 277 was attached as the supplemental material entitled by “track-changes-file”.
(16) Line 291-292: “Then unidirectional variational model is applied on the smooth field, considering that the directional distribution property discussed above” has been rewritten as “Then the unidirectional variational model is applied to the smooth field, taking into account the directional distribution property discussed above”. A revised manuscript with the red marked correction in Line 302 was attached as the supplemental material entitled by “track-changes-file”.

We tried our best to improve the manuscript and made some revisions in the manuscript. These revisions will not influence the content and framework of the paper. And here we did not list the changes but marked in red in revised manuscript.
Experienced Editors and Referees really help to improve the manuscript. We appreciate for Editors and Referees’ warm work earnestly, and hope that the correction will meet with approval. Once again, thank you very much for your comments and suggestions.

References
[1] Bouali, M. and Ladjal, S.: Toward optimal destriping of MODIS data using a unidirectional variational model, IEEE Transactions on Geoscience & Remote Sensing, 49, 2924-2935, doi:10.1109/TGRS.2011.2119399, 2011.
[2] Davydenko, A. Y. and Grayver, A. V.: Principal component analysis for filtering and leveling of geophysical data, Journal of Applied Geophysics, 109, 266-280, doi:10.1016/j.jappgeo.2014.08.006, 2014.
[3] Fan, Z. F., Huang, L., Zhang, X. J., and Fang, G. Y.: An elaborately designed virtual frame to level aeromagnetic data, IEEE Geoscience and Remote Sensing Letters, 13, 1153-1157, doi:10.1109/LGRS.2016.2574750, 2016.
[4] Beiki, M., Bastani, M., and Pedersen, L. B.: Leveling HEM and aeromagnetic data using differential polynomial fitting, Geophysics, 75, 13-23, doi:10.1190/1.3279792, 2010.
[5] Quesnel, Y., Catalán, M., Ishihara, T.: A new global marine anomaly dataset, Journal of Geophysical Research, 114, doi:10.1029/2008JB006144, 2009.
[6] Ishihara, T.: A new leveling method without the direct use of crossover data and its application in marine magnetic surveys, weighted spatial averaging and temporal filtering, Earth, Planets and Space, 67, doi:10.1186/s40623-015-0181-7, 2015.
[7] Siemon, B.: Levelling of helicopter-borne frequency-domain electromagnetic data, Journal of Applied Geophysics, 67, 206-218, doi:10.1016/j.jappgeo.2007.11.001, 2009.
[8] Ontario Geological Survey 2007. Ontario airborne geophysical surveys, magnetic and electromagnetic data, North Spirit Lake area; Ontario Geological Survey, Geophysical Data Set 1056.