Aeromagnetic anomalies interpretation based on improved bi-dimensional empirical mode decomposition (BEMD) and RGB composition

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Abstract. In this study, the bi-dimensional empirical mode decomposition (BEMD) technique is improved by morphological extrema reconstruction, kriging in terpolation and self-adaptive termination condition to make the decomposed components more robust. The decomposed components is a self-adaptive and data-driven dyadic filter bank. The high pass filter BIMF1 is about shallow or subsurface faults, it is an indirect indication to polymetallic deposits, especially tectonic-hydrothermal ones. The band pass filter BIMF2 is about regional anomalies from the middle-shallow or mantle-crustal, it is especially indicative to contact-metasomatic deposits. The low pass filter BIMF3+Residue is the shape of deep source trend of mantle magmatic crystalline basement. As they are independent and the original magnetic data can be reconstructed by their summation, they are taken as R, G, and B component and composited as an image, which retains all characters of the filters and shows ore-prospecting areas. The BEMD-RGB algorithm in this way makes aeromagnetic anomalies easier to interpret and more geologically meaningful. The whole process is performed on MATLAB 2010b platform automatically.

1. Introduction
The geological and metallogenic process is a typical nonstationary multifactor and multiscale random process. When different metallogenic prediction targets exist, the data must be decomposed on different scales in space (Zhao et al., 2016). Aeromagnetic anomaly separation into the regional and residual is considered very essential before any qualitative and quantitative interpretation process. The reason is because the observed aeromagnetic anomalies represent the combined effects of sources under different depth, density or magnetic variation, especially the metallic deposits (Al-Rahim, 2016). The scale of aeromagnetic anomalies is related not only to the size, but also to the depth of geological bodies. The same scale and type of anomaly might be produced by different lithological units located at different depths. These complexities and difficulties mean that new information decomposition techniques are required to identify possible ore-bearing locations from huge amounts of geosciences data. Decomposition of aeromagnetic fields is crucial for investigation of specific geological structures such as faults, concealed granites and the Moho discontinuity (Chen et al., 2017). Fortunately, empirical mode decomposition (EMD) is exactly a method of decomposing stationary, nonstationary, and nonlinear data. Since invented by Huang et al.(1998), it was soon expanded to bidimensional empirical mode decomposition and used in image texture analysis (Nunes et al., 2003, 2005), image feature extraction (An and Zhou, 2017; Molinari et al., 2018), image classification (He et al., 2013),
image watermarking (Abbas et al., 2018), image fusion (Liu et al., 2017), and the like. It has been one of the most important methods in geophysics and geochemical anomalies extraction due to its fully data-driven and self-adaptive nature (Al-Rahim, 2016; Chen et al., 2017; Hou et al., 2012; Xu et al., 2016; Zhao et al., 2016). While one of its essential drawbacks is the boundary effect caused by lacking extrema near the boundaries of the middle images generated in the iterations, and associated mode mixing or aliasing, excessive or incomplete decomposition problems. So morphological extrema reconstruction, kriging interpolation, and a self-adaptive termination condition are applied to improve its robustness in this study. RGB is a color space for human perception of nature, the R, G, and B components of a natural optic image are usually highly correlated, which means much redundant information in the image. So if some specific components that are unrelated are composited as a RGB image, more information can be visualized and make it easier to interpret. The decomposed components by BEMD method is exactly a self-adaptive dyadic filter bank, in which a series of bi-dimensional intrinsic mode functions(BIMFs) ranging from high frequency to low frequency are retrieved and can be categorized into a high-pass, band-pass, and low pass filter(Chen and Jeng, 2014; Chen et al., 2017; Flandrin et al., 2004; Wu and Huang, 2004, 2009; Xu et al., 2016). The additivity and orthogonality of the algorithm make it available that the original data can be reconstructed by the summation of these filters that are independent with one another.

2. Methodology

2.1 Empirical mode decomposition (EMD)

Empirical mode decomposition (EMD) is a kind of signal processing method suitable for analysing nonlinear and non-stationary signal sequence, with high signal-to-noise ratio. The principle is to extract variations from the data by separating the fluctuations from the mean (Chen et al., 2006). The key point of this method is to obtain the intrinsic mode function (IMF), a complicated signal is decomposed into a finite set of IMFs and a Residue, each component contains some kind of local characteristics of different scales from high to low frequency, the residual component is monotonic. Take a synthesized signal \( y = \sin(2\pi f_{\text{low}} t) + \sin(2\pi f_{\text{high}} t) \) of low frequency \( f_{\text{low}} = 1 \) and high frequency \( f_{\text{high}} = 10 \) as an example, then the algorithm can be divided into three steps: (1) Extrema searching, building upper, lower and mean envelopes (figure 1a); (2) Setting an experimental threshold SD between 0.2 and 0.3 (Chen et al., 2006; Huang et al., 1998; Nunes et al., 2003, 2005), screening out each IMF in turn, IMF1 is the \( f_{\text{high}} \) signal and IMF2 is the \( f_{\text{low}} \) signal; (3) The algorithm termination condition is suggested to be improved in this paper when the amount of extreme points is less than 3 or the envelopes are near collinear, then all IMFs and a Residue are screened out (figure 1b,c,d).
The algorithm has two special characteristics. The first one is orthogonality, which means the decomposed results are independent and uncorrelated. Another one is additivity, which means the original signal is the sum of all IMFs and a Residue in equation (1), \( N \) is the number of IMFs. Until now EMD algorithm lacks a precise mathematical definition that would allow the determination of its properties and its suitability for the analysis of signals produced by a specific situation, while it has been found to be useful in a variety of situations. Our main objective is to find whether this procedure, can be helpful in the analysis of other application fields (Ortega and Smith, 2009).

\[ y = \sum_{i=1}^{N} IMF_i + \text{Residue}, \quad i = 1, 2, ..., N. \]  

**2.2 Bi-dimensional empirical mode decomposition (BEMD)**

Most of the published BEMD algorithms are actually one dimensional or pseudo-two-dimensional (pseudo-2D), which manages 2D data as a set of one dimensional traces, and analyses each trace using conventional one dimensional (1D) EMD algorithm. After decomposing each trace of the data, the components of the same sifting level in each trace are sorted out to one gather to construct a pseudo-2D EMD component (Rojas et al., 2013). In this paper, the BEMD algorithm is also divided into three steps (figure 2) and is improved by morphological extrema reconstruction, kriging interpolation, and self-adaptive termination condition. It inherits the advantages of orthogonality and additivity from EMD, data-driven and self-adaptive. In addition, a series of BIMFs ranging from high frequency to low frequency are retrieved to achieve a dyadic filter bank (Chen and Jeng, 2014; Chen et al., 2017; Flandrin et al., 2004; Wu and Huang, 2004, 2009; Xu et al., 2016), suitable for processing stationary, nonstationary and nonlinear data. Assuming that the original aeromagnetic data set \( A \) can be decomposed into a finite number of BIMFs and a residue showing the information of different scales from high to low frequency, \( A \) can be divided into various types of filters and grouped into high-pass (FHP), band-pass (FBP) and low-pass (FLP) filter (equation 2-4). As is shown in figure 2, BIMF \( 1 \) is a high-pass filter, BIMF \( (k+1) \) is a band-pass filter, BIMF \( (m+1) \) and Residue are low-pass filters, each of them contains useful geological information and shows some specific geological characters, and \( A \) is the summation of these filters that are independent with one another.

![Figure 2. Schematic diagram of improved BEMD algorithm](image)

\[ F_{HP} = \sum_{i=1}^{k} BIMF_i, \quad i = 1, 2, ..., k, \]  
\[ F_{BP} = \sum_{i=k+1}^{m} BIMF_i, \quad i = k + 1, 2, ..., m, \]  
\[ F_{LP} = \sum_{i=m+1}^{N} BIMF_i + \text{Residue}, \quad i = m + 1, 2, ..., N. \]
results are incredible. Another kind can be called interpolation or surface fitting, the extrema are searched in two dimensional morphological space and then interpolated or fitted into an envelope, such as the commonly used sliding window method based on a statistical filter to fit the envelope, which is called Fast adaptive empirical mode decomposition (FAEMD) (Bhuiyan et al., 2008), using mean or median filter as a moving average window to fit the envelope (Chen et al., 2014), or using interpolation methods to interpolate the envelope, namely spline interpolation (Zhao et al., 2016), RBF interpolation (Bajaj et al., 2017; Huang et al., 2010; Molinari et al., 2018; Nunes et al., 2003, 2005), triangle mesh interpolation (Chen et al., 2014; Liu et al., 2017), multiquadric interpolation (Chen et al., 2017) and ordinary kriging interpolation (Xu et al., 2016), and the like, of which the ordinary kriging interpolation is most applicable to geological data processing. Meanwhile, we have to take the boundary effect into consideration while interpolation, as the boundary points are hard to estimate accurately and most of them are not extrema really, the error of the boundary effect will spread into the inner, thus causing mode mixing or aliasing. The easy way out is to apply a window and masking the influence of the boundary points (Chen et al., 2006), and fortunately, the kriging interpolation is an auto correlated interpolation method with the auto correlated distance $h$ as a self-adaptive window overcoming the boundary effect (equation 5-6).

Thus in this paper, we use morphological method to search extrema (figure 3, L is minimum and N is maximum, $L<M<N$) and ordinary kriging interpolation method that is revoked from Golden Software Surfer 10.0 to interpolate the enveloping surfaces. The principle of kriging interpolation is on condition that the mean and variance do not change with lag $h$ that is usually consistent with the aeromagnetic data. It has three advantages: (1) Linear, which means the unobserved data points $Z_i^*$ can be predicted by the weighted linear sum of the neighboring observed points $Z_i$ (equation 5); (2) Unbiased, which means the sum of weights $\lambda_i$ of the neighboring points is 1 (equation 6); (3) Optimal estimation, which means the fitting error $\delta_E^2$ (equation 7) is the smallest obtained by Lagrange’s equation (equation 8), $u$ is a Lagrange variable, $\gamma(h)$ is the semi-variogram (equation 9), $N(h)$ is the quantity of observed points within the lag $h$.

$$Z^*(x_i) = \sum_{i=1}^{N(h)} \lambda_i Z(x_i), \quad (5)$$
$$\sum_{i=1}^{N(h)} \lambda_i = 1, \quad (6)$$
$$\delta_E^2 = 2\mu(\sum_{i=1}^{N(h)} \lambda_i - 1), \quad (7)$$
$$\sum_{i=1}^{N(h)} \lambda_i \gamma(x_i, x_j) + \mu = \gamma(x_i, x_h), \quad (8)$$
$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - \bar{Z}(x_i + h)]^2. \quad (9)$$

2.2.2 The self-adaptive termination condition to screen out BIMFs and Residue

The most commonly used termination methods are based on the monotonicity of the residual component (Abbas et al., 2018; Al-Rahim, 2016; Chen et al., 2014; He et al., 2013; Huang et al., 1998; Wu and Huang, 2009), or applying a fixed number of screening to obtain the IMF (Xu et al., 2012), which cannot avoid the excessive or incomplete decomposition problems. In this paper, the termination condition is decided upon the quantity of upper or lower extrema, all BIMFs and a Residue are screened out when it is less than 4, which is originated from Nunes et al. (2003, 2005) in
1D EMD. This will restrain the excessive or incomplete decomposition, mode mixing and associated problems to some extent.

2.3 Orthogonality verification

The orthogonality is often verified by orthogonality index (OI) that is originated from 1D EMD and usually less than 1% to show the degree of independence among the BIMFs and Residue (Bhuiany et al., 2008; Chen et al., 2017; Huang et al., 1998; Huang et al., 2010; Xu et al., 2016). A low value of OI (equation 10) indicates good decomposition results and means independent correlation between BIMFs and Residue, \((x, y)\) is the spatial coordinates of original aeromagnetic data with its size \((m, n)\), \(K\) is the number of components, \(C_i\) and \(C_j\) is a BIMF or a Residue, \(\sum C\) is the sum of decomposed components. Furthermore, the orthogonality can be verified by correlation coefficient, the smaller the better either, statistically it is considered that the decomposed components have weak or no correlation when the absolute value of their correlation coefficients is less than 0.3.

\[
OI = \frac{\sum_{x=1}^{m} \sum_{y=1}^{n} \left( \sum_{i=1}^{K} \sum_{j=1}^{K} \frac{C_i(x,y)C_j(x,y)}{\sum C^2(x,y)} \right)}{} .
\]

(10)

3. Application

3.1 Aeromagnetic anomalies and geology overview

The aeromagnetic data is surveyed in a polymetallic ore field in Inner Mongolia, northwest China, longitude \([101°0'E, 101°30'E]\), latitude \([39°20'N, 39°40'N]\), at a scale of 1:50 000. As it is located at a low latitude, the aeromagnetic data is processed by reduction to the pole via standardized polar transform with a declination value of -1.81° and an inclination value of 59.48°, figure. 4a is the image after reduction to the pole.

The study area is located on the joint of the orogenic belt between Tarim plate and Tianshan Mountains-Junggar Basin-North Mountains plate, the belt of ophiolite tectonic mélanges is taken as a boundary between the North Mountains back-arc basin on its north and Tarim continental plate on its south (figure 4b). The aeromagnetic anomalies are mainly distributed along the Nuergai-Kewula-Wutongou reverse fault that is northeast oriented and inclined to north about 60°, where exposed Proterozoic stratum that consists of biotite-quartz schist and amphibolite face gneisses, Cambrian gabbro and serpentinized peridotite, Silurian quartz diorite and Permian quartz diorite. The anomalies in the north of the study area are mainly induced by the ophiolite tectonic mélanges and Carboniferous stratum. The belt of ophiolite tectonic mélanges was formed in the late Ordovician when the Paleo-Asian oceanic plate subducted from north to south, and is distributed along the Asilen-Tebai reverse fault, northwest oriented, inclined to north about 30°. The mélanges are composed of a set of Ordovician sandy slate, siliceous slate, sandstone and basalt, Cambrian gabbro and serpentinized peridotite. The gabbro in the mélanges measured about 514 Ma is an N-MORB type (figure 5) according to Meschede (1986) and Saccani (2015). The Carboniferous stratum is mainly composed of basic volcanic rocks in a mid-oceanic-ridge volcanic environment. While other strata are regionally of weak or negative magnetism, the Permian stratum is composed of clasolite and a few acid volcanic intercalations, the Cretaceous stratum is a set of sandstones and conglomerates, and the Quaternary stratum is a set of migratory dunes and flood alluvial layer. The metallogenesis of the study area is mainly concentrated in the Paleozoic and is in the Alashan Au-Cu-Fe-Ni polymetallic belt. There are magmatic-liquated nickel deposits and contact metasomatic gold deposit in Cambrian, tectonic hydrothermal hematite deposits in Silurian, post-magmatic hydrothermal alteration related gold deposit, tectonic hydrothermal gold deposit, tectonic volcanogenic gold deposit, contact metasomatic-hydrothermal copper deposit, and tectonic hydrothermal copper deposit, which are formed between late Carboniferous and early Permian period. These deposits are the important reason for aeromagnetic anomalies.
Figure 4. Aeromagnetic anomalies and geology overview of the study area: (a. the aeromagnetic data after reduction to pole; b. geology map, 1 Quaternary desert, 2 Quaternary sandy conglomerate, 3 Cretaceous stratum, 4 Permian stratum, 5 Carboniferous stratum, 6 Proterozoic stratum, 7 Permian monzonitic granite, 8 Permian diorite, 9 Permian syengranite, 10 Carboniferous monzonitic granite, 11 Carboniferous diorite, 12 Devonian syengranite, 13 Devonian monzonitic granite, 14 Devonian diorite, 15 Silurian monzonitic granite, 16 Silurian diorite, 17 Ophiolitic mélanges, 18 Cambrian gabbro, 19 Cambrian peridotite, 20 small gold occurrence, 21 medium-sized gold occurrence, 22 big gold occurrence, 23 copper occurrence, 24 hematite occurrence, 25 nickel occurrence, 26 fault).

Therefore there are magnetic bodies at different depth and in different geological process associated with tectonics and the deposits, which could be divided into different scales and decomposed into different levels of layers to interpret.

Figure 5. Tectonic discrimination diagrams (the gabbro in the mélanges)

### 3.2 Aeromagnetic anomalies decomposition by improved BEMD

In the decomposed results some local anomalies correspond to the geology background, while others might not meet that requirements caused by mode mixing (Hou et al., 2012). We cannot give a direct answer to mode mixing problem, which might be due to the way of detecting the extrema, the method of interpolation, the sifting process, or the termination condition, especially the mixing in the last BIMF and Residue, and the associated excessive or incomplete decomposition problems. Some specific BIMF components that contain useful geological information are chosen as the filtering result to interpret geological features (Hou et al., 2012; Huang et al., 2010; Xu et al., 2016; Zhao et al., 2016), while others that are uncertain and may have no geological meaning are not. Those components of no use actually may have potential information to be investigated, which are hard to interpret because we
just didn’t find a proper way out or didn’t have enough known knowledge to interpret them. If we neglect these components, much information will be lost, the self-adaptive and additive advantages of the algorithm will not be able to be taken.

The anomalies as shape of strings and beads in BIMF1 are signs of faults where the high magnetic material concentrates and most of the polymetallic deposits located on them. As is interpreted in figure 6(a) and listed in table 1, the gold deposit (Number 2) and the nickel deposit (Number 3) are controlled by the northwest oriented fault, the gold deposit (Number 1) is volcanogenic and enriches in northeast oriented fractures. The gold deposit (Number 5) is tectonic hydrothermal related and controlled by a northeast oriented right-lateral fault with its ore body enriching in fractured altered rocks and quartz veins. The copper deposits (Number 8, 9, 11) are all tectonic hydrothermal related and controlled by the faults with its ore bodies enriching in quartz veins of Permian quartz diorites. Therefore, BIMF1 is a high pass filter that indicates to the faults of shallow or subsurface geological architecture where polymetallic deposits enrich and occur, especially tectonic-hydrothermal ones.

BIMF2 in figure 6(b) is a band pass filter that shows the middle-shallow or mantle-crustal anomalies, in which many polymetallic deposits enrich, while it is especially indicative to contact metasomatic related deposits because the gold deposit (Number 4) is contact metasomatic related and it occurs between the boundary of Proterozoic stratum and Silurian granite with its ore body enriching in the altered rocks of silication and skarn along a northeast oriented fault. The copper deposit (Number 10) is also contact metasomatic-hydrothermal related with its ore body enriching in the quartz veins along a nearly East-West oriented fault. The mode mixing problem is severe between BIMF3 and Residue as is shown that they are visually similar to each other, however, they are both low pass filters, so we apply the summation of BIMF3 and Residue as a low pass filter in figure 6(e), showing the mantle crystalline basement consisting of Proterozoic biotite-quartz schist, Cambrian gabbro and peridotite.

Table 1. Mineral deposits in the study area

| Ore-prospecting areas | Number | Deposit type | Latitude | Longitude | Deposit genesis                                      |
|-----------------------|--------|--------------|----------|-----------|-----------------------------------------------------|
| I1-3                  | 1      | Au           | 39°38'31''  | 101°00'52'' | tectonic volcanogenic post-magmatic hydrothermal alteration related magmatic-liquated |
|                       | 2      | Au           | 39°36'00''  | 101°22'50'' |                                                     |
|                       | 3      | Ni           | 39°35'27''  | 101°24'50'' |                                                     |
| II                    | 4      | Au           | 39°30'53''  | 101°15'33'' | contact metasomatic hydrothermal                     |
|                       | 5      | Au           | 39°28'42''  | 101°06'30'' | tectonic hydrothermal                               |
|                       | 6      | Fe           | 39°32'43''  | 101°06'40'' | hydrothermal                                       |
|                       | 7      | Fe           | 39°32'29''  | 101°12'40'' | tectonic hydrothermal                               |
|                       | 8      | Cu           | 39°28'40''  | 101°11'30'' | tectonic hydrothermal                               |
|                       | 9      | Cu           | 39°29'46''  | 101°13'40'' | tectonic hydrothermal                               |
|                       | 10     | Cu           | 39°30'01''  | 101°20'02'' | contact metasomatic-hydrothermal                     |
|                       | 11     | Cu           | 39°30'45''  | 101°20'27'' | tectonic hydrothermal                               |
|                       | 12     | Ni           | 39°28'17''  | 101°15'12'' | magmatic-liquated                                   |
Figure 6. BEMD results and RGB composition show
From the subjective visualization in figure 6, it is clear that the filters are more geologically meaningful, as a dyadic filter bank, data-driven and self-adaptive, orthogonal and additive, every one of them has its own geological meaning without losing any information.

3.3 Orthogonality verification
The OI obtained by equation 10 is $1.54 \times 10^{-8}$, much less than 1%, which means the decomposed components are independent. Furthermore, the orthogonality is verified by correlation coefficient (table 2), if there are similar frequencies in the decomposed components, the correlation coefficient would be greater than the value without mode mixing, which can be explicitly depicted by the correlation coefficient between BIMF3 and Residue whose absolute value is much bigger than 0.4 due to the mode mixing problem. Meanwhile those correlation coefficients between BIMF3+Residue and the other BIMFs are all less than 0.3, which means they are uncorrelated and independent.

|               | BIMF1 | BIMF2 | BIMF3 | Residue | BIMF3+Residue |
|---------------|-------|-------|-------|---------|---------------|
| BIMF1         | 1.00  | 0.10  | -0.12 | -0.25   | -0.18         |
| BIMF2         | -     | 1.00  | 0.13  | -0.01   | 0.10          |
| BIMF3         | -     | -     | 1.00  | 0.56    | 0.96          |
| Residue       | -     | -     | -     | 1.00    | 0.78          |
| BIMF3+Residue | -     | -     | -     | -       | 1.00          |

3.4 RGB composition of the filters
The decomposed high-pass, band-pass and low-pass filter is assigned as R, G and B component respectively to be composited as figure 6(f). It retains all the information of those filters and shows some kinds of ore-prospecting areas, of which the first one I 1-3 is associated with the subduction movement and distributed along the Asilen-Tebai reverse fault where the anomalies are due to the ophiolitic tectonic mélanges and Carboniferous mid-oceanic-ridge basic volcanic rocks, and where tectonic volcanogenic gold deposit, post-magmatic hydrothermal alteration related gold deposit and magmatic-liquated nickel deposit enrich, on the north of these anomalies is the Northern Mountain back-arc basin. Another one II is distributed along the Nuergai-Kewula-Wutongou reverse fault, it is strictly associated with tectonic hydrothermal and contact metasomatic deposits that were mainly formed between late Carboniferous and early Permian. This region is a continental arc in the Tarim block, where the anomalies are due to the Proterozoic biotite-quartz schist and amphibolite face gneisses, Cambrian gabbro and serpentinitized peridotite, and Permian basic biotite quartz diorite. There is also a famous big magnetite iron deposit of skarn type called Kexiutata on the east and outside of the study area, which was formed in early Permian and is in the intersection between the Asilen-Tebai reverse fault and the Nuergai-Kewula-Wutongou reverse fault.

4. Conclusions and discussion
Firstly, every component of the decomposed results has its own geological meaning, and no one should be neglected, for only in this way can the whole information be retained. Otherwise, some information will be lost, the data-driven and self-adaptive, additive and orthogonal advantages of the algorithm could not be taken. As a self-adaptive dyadic filter bank, BIMF1 is a high pass filter applicable to interpreting the shallow or subsurface tectonic structures and is an indirect indicator to polymetallic deposits, especially tectonic-hydrothermal related ones. BIMF2 is a band pass filter showing the middle-shallow or mantle-crust information, it is especially indicative of contact metasomatic deposits. BIMF3+Residue is a low pass filter showing the deep source trend of mantle crystalline basement. These filters are independent with one another and the original aeromagnetic data can be reconstructed by their summation. Secondly, the orthogonality of the algorithm can be evaluated by correlation coefficient to show the independent relationship between the decomposed components, which is clearer than orthogonal index, and shows the underlying principle of the data-
driven and self-adaptive, additive and orthogonal advantages of the algorithm. Thirdly, RGB composition is a good method in integrating and enhancing characters of the filters, and it is applicable to prospecting metallogenic areas.

Generally speaking, the filters are additive and orthogonal, from high pass to low pass, showing the geological information from the shallow to the deep on different scales. BEMD and RGB composition is a data-driven and self-adaptive method and an effective way in aeromagnetic interpretation. The method also can be used in gravity and geochemical anomalies interpretation, and other polymetallic districts in the world.

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