Decomposing Worldwide Complete Spherical Bouguer Gravity Anomaly Using 2-D Empirical Method

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Abstract. Currently available worldwide gravity anomaly data provides a high-resolution (2' x 2') of Complete Spherical Bouguer Anomaly (CSBA) based on the available information of the Earth gravity field from surface and satellite measurements. The data has not only been provided and processed thoroughly but it also has been claimed to be appropriate for various geophysical applications. Therefore, the analysis of gravity anomaly is becoming increasingly significant for the earth sciences as a whole and assisting both shallow and deep geological problems. Earth gravity anomaly has to be analyzed carefully as it has very complex data due to anomaly mixing of the density masses spread over the Earth horizontally and vertically. The bigger the spatial coverage of data (e.g. global scale data), the more severe the data from anomaly mixing due to various wavelength. BEMD is an empirical method supposedly suitable with highly oscillation-mixing data. It can effectively isolate each local anomaly in details and is analogized as successively reverse moving average with local windowing. BEMD is designed to reduce multi-component, non-linear gravity field data to a series of single local anomaly contributions. Anomaly from a single body was assumed as a mono-component signal. The main advantage of BEMD processing techniques is to present the subtle details in the data which are not clearly identified in anomaly maps, without specifying any prior information about the nature of the source bodies. As the result, we have identified regional anomalies due to the drift of continental and oceanic masses considered as crust-regional anomaly (CRA). We remove the CRA from the CBA to provide surface-residual anomaly (SRA) where shallow geologic bodies reveal. Meanwhile, the CRA itself can be used as reference to reduce this high magnitude anomaly from any measurement data to exhibit only shallow body anomaly. Further analysis can be carried out to build a general understanding of the details and parameters of the shallower or deeper causative body distributions.

1. Introduction

The gravity method involves measurement of very small variations in the Earth’s gravitational field, of the order of a few parts per million or lower, caused by lateral variation in density. The gravity anomaly is the contrast of gravitational acceleration between Earth’s masses and that of a reference mass distribution. It has a wide variety of applications in the Earth sciences, especially in geophysics. Gravity variations over thousands of kilometres can be used for studies of mantle convection, variations over hundreds and tens of kilometres are relevant for studies such as lithospheric flexure, plate tectonics, crustal structure, sedimentary basin development, hydrocarbon and mineral exploration, while gravity variations over tens of metres can be used in civil engineering applications.
[1]. The potentially broad range of contrasting densities in the near-surface, in the crust, and in subcrustal rock materials leads to the wide range of applications of the gravity method [2]. Depth of the source anomaly relates to its wavelength in the surface due to potential field expansion. While the amplitude is proportional to the lateral density contrast, it follows the rule of Newton’s inverse square of mass distance. Therefore, measurement of the Earth gravity field is a useful tool for investigating the sub-surface because mass variations below the surface cause variations in the gravity field.

Separation of gravity anomaly is considered as an important step for interpreting and modeling subsurface condition related to density contrast. Observed gravity data is a resultant from entire sub-surface bodies which one type of them might be considered as target anomaly (the residual). The idea of such separation process relies on different scale of the wavelength between shallow-small bodies and deep-regional bodies. Several techniques have been developed and applied to do anomaly separation graphically and mathematically. The graphical method is not used these days anymore but it has historical importance [3]. Among the distinguished analytical methods are polynomial fitting, moving average, upward and downward continuation and wavelength filtering [3],[5]. Complexity of geological structure and mass body distribution derives multi-component, non-stationary, and non-linear gravity anomaly [4],[5],[6]. These facts lead to some difficulties in identification, localizing and examination the anomalous suspected body using the gravity field anomaly. The drawback of all of the existing methods is, when the gravity bodies extracted by averaging the anomalous target zone, some residual still remains mixed with the regional [2]. BEMD of gravity field can get more information and richer physical geographical (geological) meaning than the previous analytic continuation and other traditional field decomposition methods [6].

There are now many ways to acquire gravity data on land, sea, air, and from space. These data play important role in gravity studies in many scales. The World Gravity Map (WGM) is a set of high-resolution (2’x2’) gravity anomaly maps at global scale. This is the first dataset that take into account a realistic Earth model and that consider the contribution of most surface masses (atmosphere, land, oceans, inland seas, lakes, ice caps, and ice shelves) [7]. One of the data contained in WGM is Complete Spherical Bouguer Anomaly (CSBA) which is provided to meet the definition of gravity anomaly in geophysics. The source of data is taken from surface gravity measurements (from land, marine or airborne surveys), satellite altimetry and satellite gravimetry (GRACE mission) measurements. Availability of this data has increased the interest to study the Earth’s gravitational field on local and global scale.

2. Methodology
The geophysical potential data are nonlinear and nonstationary. A relatively new technique named empirical mode decomposition (EMD) has been developed to deal with such type of data. EMD is developed by Huang et al. (1998) to establish a multi-resolution decomposition technique[8]. EMD is an adaptive decomposition of one-dimensional data and widely used to analyze different variety of signals. In geophysical field, EMD has been applied to seismic data [9],[10] and log evaluation [11]. EMD gives the decomposition result in small number of what so called intrinsic mode functions (IMFs). EMD works efficiently and it decomposes the input signal completely. There is no information loss, i.e., the original signal is reconstructed by summing all IMFs. The result is excellent in resolution and separation between details so we can get multi-resolution signal separated each other entirely. It is a quasi-orthogonal decomposition in that the cross-correlation coefficients between the different IMFs are always close to zero. This minimizes energy leakage between the IMFs[12]. The residual mixing within regional can be handled using this methodology.

EMD is one-dimensional data analysis while WGM is two-dimensional. The concept of EMD was implemented to analyze two-dimensional signal (image or map) that is called Bidimensional Empirical Mode Decomposition (BEMD) [[13],[14],[15]]. This method has been successfully applied to examine gravity map and shows good conformity with geological environment by Hasan (2008) [9], Huang et al. (2010) [16], Morris et al. (2010) [17], Firdaus et al. (2012) [5], Rahim (2015) [4]. The fundamental
principle of BEMD is to extract mono-component image from multi-component image by removing local trends. The BEMD results are Bidimensional IMF (BIMF) which are a set of mono-component multi-resolution image arranged by the order of detail component. It is designed to reduce a complex gravity field data to a series of single local anomaly contributions. The highest detail appears as the first BIMF and than come BIMFs with less and less detail until the last one called residual component coming out bringing global trend for the entire map. This methodology somewhat is in kind with successively reverse moving average with local windowing. We use this kind of image analysis to isolate every single body anomaly contained in WGM data.

3. Data
CSBA has a very highly non-linear and non-stationary data as it represent global and local anomalies. It contains very wide information about earth gravitational field. Figure 1 presents several features brought by the data. Negative anomalies (greenish to purple) occur on regions associated with very thick continental crust where the dominant part of continental crust is reflected by relatively low anomaly (< 250 mGal, yellow to greenish). Oceanic crust has higher anomaly (> 400 mGal, shining red) which can be divided into two parts. The first part has lower anomaly than the second part. The first part is more likely associated with younger oceanic crust while the second part represents more mature oceanic crust. Plate boundaries also can be observed directly by their distinguished anomalous value between 250 mGal to 400 mGal (darker red). Such kind of information is very valuable to understand the Earth through gravity anomaly. Higher resolution data contain much more detail informations thus more local which permit us to interpret and model a very specific part of the Earth using gravity anomaly. However, these details are hardly to be observed in the original map. Hence the anomalies appear in different level of details, BEMD technique can be used to automatically gives us multi-resolution results separated by order of detail.

4. Results
Applying BEMD to CSBA data generates nine BIMF extractions which are each of them gather all local oscillations. Assuming the CSBA generated by a superposition of their local oscillations, BIMF could be considered as a bidimensional monocomponent representation of gravity anomalies resulted from removing the local trend. Figure 2 shows different scale of detail and complete separation of anomaly mixing into each single local body anomaly without specifying any prior information about the nature of the source bodies. It could be considered as an anomaly from a single source body under assumption that a body anomaly like point mass approximately contribute only one single oscillation to the data. Each BIMF carries intense physical meaning from the original data. It brings out of each anomaly and places them in the order of local frequency. A wide range of densities occurs within the
crust, from the essentially zero density of air-filled voids in near-surface formations, to density of unconsolidated sediments with their interstitial openings filled with either air or water, to the highest densities related to Fe/Mg-rich crystalline rocks and metallic ores. Even higher densities are associated with the radial shells that make up the mantle and the core of the Earth [2].

**Figure 2.** Bidimensional IMFs (BIMFs) expose the relative local gravity anomaly in the order of detail. The higher to lower order of detail anomalies is shown as BIMF1 to BIMF9 successively. Relative residual anomalies appear in BIMF1 to BIMF3, whereas the relative regional anomalies appear in BIMF4 to BIMF9. BIMF9 could also be considered as an absolute regional of the Earth gravity field.

The first three BIMFs contain the majority of body anomaly yet less dominant in the original data (CSBA). They reflect a great detail of gravity anomalies around the earth. Hydrocarbon and mineral exploration are strongly related to these scale of anomaly, especially BIMF1. The next BIMFs exhibit less and less detail anomaly. BIMF4 to BIMF5 might be suited for basin and tectonic analysis. They have wider wavelength and the amplitude is relatively increasing. The longer-wavelength anomalies, related to deeper and larger sources, typically have greater amplitudes than the local anomalies of interest thus distort the target anomalies [18]. This explains why it is so hard to notice very small anomalous magnitude in the order of less than 50 mGal in the original data which has amplitude range from -600 to +600 mGal. BEMD analogous to microscope instrument in physical optics. BIMF1 to BIMF3 might be considered as the type of residual anomaly. These residuals often mixed together into a single map so we never have noticed them in such detail and fully understand what the physical and the geological meaning of them directly without further interpretation. The next BIMFs would be the regional anomalies for them all. The last BIMF is global trend of entire earth gravity field in the shape of monotonic signal. It is the most regional of all regional anomalies. Looking at the amplitude and the size of the anomaly, it is truly the most dominant contributor of observable Earth gravity field magnitude. It is tough to explain what physical earth yields such anomaly however all geophysicist believe that what we measure on the surface must have some relation to that of the sub-surface.

The edge of body anomaly is can also be determined sharply as it falls on zero crossings of BIMF. Therefore, one can make geometrical and structural interpretation using these results. BIMF1, for instance, can be used for near-surface structure mapping especially at the location where surface covered by alluvial deposits at land or deep water at sea, on such condition where we can not get direct
observation either on the ground or up from the space. Also, these set of anomalies particularly give insight about gravity field stratification from surface to the deeper part of the Earth. This anomaly stratification represents structure, dimension and mass body distribution from the surface to the mantle or even deeper.

The ambiguity of gravity interpretation can be suppressed by using auxiliary geophysical and geological data [18]. Although non-uniqueness is an overriding concern in all gravity interpretation, the availability of appropriate constrains surely can limit these ambiguities [2]. BEMD reduces some amounts of ambiguity inherited in gravity method by separating oscillation redundancy at local points, giving monocomponent which equal to single body anomaly respon of lateral density contrast. The relevant and appropriate constrains expressed by BIMFs could be inferred by integrating them with geological and other geophysical constrains. We would like to consider these results as a pseudo-inverted body anomaly by means that we can delineate source bodies and get the density contrast place to place relatively using the results. The relative depth and geometry of the body anomaly is also can be inferred and it is might be more useful to make it as an initial model for estimating anomalous density by gravity inversion techniques.

Figure 3. Crust-Regional Anomaly (CRA) extracts major informations that are easily observable e.g. lithospheric structures and plate boundaries. CRA is generated from BIMF5-BIMF9.

BEMD isolates and enhances gravity anomaly for helping the interpretation of the data. BEMD facilitates other method to isolate gravity anomalies by separating the gravity effects of known or hypothesized geological sources. From the results, for instance, it can be identified some anomalous bodies which have very wide wavelength but still associated with noticeable structure from surface (BIMF5-BIMF7). Those BIMFs reconstruction together with BIMF8 and BIMF9 resemble major Earth structures such as oceanic – continental crust boundaries, thicker regions of continental crust, some varieties in oceanic crust density, main lithospheric and mantle structures, and divergent plate boundary regions. In short, the resultant of BIMF5-BIMF9 extracts major informations that are observable from the original data. These groups of anomalies are suitable for deep and major Earth’s structure interpretations. As we just notice, the term of regional anomaly is not always about the related depth of source body but it might be in the size of some form of density basins or containers where smaller bodies assemble within. It must be recognized that some anomalies that are broad and with relatively low curvature values may also be related to shallow geological features that are themselves broad and without abrupt changes of slope [19]. Generally we know two obvious density containers; continental and oceanic crust. We notify them as Crust Regional Anomaly (Figure 3).

Smaller bodies jostle inside the CRA. BIMF5-BIMF9 from which CRA was generated are analogue to the reference of any body smaller than them as in BIMF1-BIMF4. Smaller anomalies we usually consider as residual certainly have smaller body, restricted in dimension at some locals. We typically use this kind of anomalies in much of our practical works. The residuals have smaller ambiguity than those of regional anomalies. BIMF1-4 show most of the residual anomalies around the globe. IMF1 is the most detail and the nearest to the surface. Next come BIMF2, 3 and 4 bringing less detail compared to BIMF1. This kind of body anomalies collections surely can help us in interpreting
and modeling earth subsurface in different scales. CRA can effectively be used as practical tool to quickly extract surface-residual anomaly (SRA) from any CBA data, providing higher resolution data, only by using formulae: SRA = CBA - CRA. Surface-residual anomaly (SRA) stands for CBA anomalies separated from CRA. After such separation between CRA and SRA, one can do simple and robust BEMD technique to the SRA so BIMF1-4 can be obtained.

Figure 4. Surface-Residual Anomaly SRA (left) compared to CBA (right). SRA = CBA – CRA.

Dealing with data in the size of WGM is clearly not easy. Meanwhile, reducing the size of WGM data to get smaller data to process is unbearable as it will fail to give complete decomposition results. BIMF will come up with fewer amount. For the size of WGM data, it could take several weeks and great amount of memories to decompose the data completely, though it also depends on utilized computational framework. To make it efficient, we keep the CRA to all new measurement data so the further processing and modeling stage can be performed to give good interpretation of new data. Demonstrating the result of removing CRA from the new higher resolution data is given in Figure 4. Simple matrices subtraction could reveal the surface-residual anomaly. It gives the detail insight to our data with ease.

SRA has the preserving amplitude without any distortion, implying that the SRA can savey be used as modeling input. True residual of our target anomaly can be extracted from SRA using BEMD or other anomaly separation methods. SRA is not a type of residual anomaly and CRA not the regional one according to common terminology. Based on our experience, residual resulted from exploration scaled measurements using spectral analysis is comparable to the BIMF1, while the rest is considered as regional. Rarely we found the BIMF2 or above representable enough to our residual results. Nevertheless other author using polynomial separation method found residual as somehow similar to the resultant of BIMF1 to BIMF3 [4]. It does not matter, the most important thing for interpreting the data is we have to be sure what we keep inside our data and which part we put away. That way, we can build and interpret better geological models. The comparison between SRA and BIMF1 (the most shallow and local residuals) is given in Figure 5.
Figure 5. Comparison between SRA (left and right edges) with BIMF1 (centered)

5. Conclusions
BEMD resolve all the anomalies contained in WGM data in a few number of BIMFs with excellent resolution in separating one anomaly from others. BEMD reveals those physical structure and groups them together so we can make hypotheses of the geological bodies from only gravity anomaly. One of those earth physical structure is crust-regional anomaly (CRA). CRA due to the gravity anomaly drifts is caused by continental and oceanic masses. Removing CRA from any measurement data will reveal surface-residual anomaly (SRA). Therefore, the CRA can be used as reference to inspect shallow body anomaly from any new measurement data. Each BIMF or a resultant of a few selected of their combinations provides us a very good understanding to hypothesize geological structure and mass bodies distribution. They are better input for qualitative interpretation, quantitative analysis, inversion and modeling. That is because we have dealt with a great amount of ambiguity in gravity method caused by anomaly mixing which hides true physical structure of geological matters.

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