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Magnetic anomaly depth and structural index estimation using different height analytic signals data

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ABSTRACT

This paper proposes a new semi-automatic inversion method for magnetic anomaly data interpretation that uses the combination of analytic signals of the anomaly at different heights to determine the depth and the structural index *N* of the sources. The new method utilizes analytic signals of the original anomaly at different height to effectively suppress the noise contained in the anomaly. Compared with the other high-order derivative calculation methods based on analytic signals, our method only computes first-order derivatives of the anomaly, which can be used to obtain more stable and accurate results. Tests on synthetic noise-free and noise-corrupted magnetic data indicate that the new method can estimate the depth and *N* efficiently. The technique is applied to a real measured magnetic anomaly in Southern Illinois caused by a known dike, and the result is in agreement with the drilling information and inversion results within acceptable calculation error.

1. Introduction

There are a variety of semi-automatic interpretation methods developed for magnetic anomaly data for determining the depth and locations of edges of the source (Reid et al., 1990; Pasteka, 2000; Elysseieva and Pasteka, 2009; Fairhead et al., 2011). The analytic signal method is one commonly used method, and it was initially used to interpret dike-like bodies by Nabighian (1972). The method does not require knowledge of the magnetization direction, and thus it is useful in the presence of remnant magnetization. It is initially applied to estimate the parameters of the causative source assuming that the sources are 2D geological structures, such as contacts, dikes and horizontal cylinders (Roest et al., 1992; Thurston and Smith, 1997; MacLeod et al., 1993; Hsu et al., 1996). Assuming that the source type is known, the depth can be obtained either from the width of the analytic signal anomalies or based on the ratio of the analytic signal to its higher-order derivatives. However, the precision of the depth estimation is dependent on the assumed structural index. Some people have attempted to use the analytic signal method to obtain both the depth and the nature of the magnetic sources (e.g., Debeglia and Corpel, 1997; Hsu et al., 1998; Salem et al., 2004; Salem, 2005; Ma and Du, 2012). The attempts all need to calculate high-order derivatives of the data, which will make the results unstable, especially for the high-order vertical derivative calculation in the frequency domain. Ma and Li (2013a) used the direct analytic signal method to interpret 2D magnetic profile data, which only needs the first-order derivative of the original data and can yield more stable results. However, for severely noise-corrupted data, the method had poor efficacy in estimating source parameters, and it needed filters to suppress the noise. Ma and Li (2013b) presented a method using the correlation coefficient of the analytic signal to obtain the source parameter. Salem and Ravat (2003); Keating and Pilktington (2004) and Wen et al. (2007) combined Euler deconvolution and the analytic signal to estimate source parameters.

Li (2006) illustrated that the analytic signal is sensitive to magnetization direction in three dimensions, so we propose a new method based on analytic signal data of different heights to simultaneously obtain the depth and structural index of two-dimensional profile data for different natural sources. For interpreting data with noise, the method utilizes analytic signals with different upward continuation heights, which can suppress the noise effect in the process of source parameter calculation. Moreover, using the analytic signal directly makes the results more stable because only the first-order derivatives of the data need to be computed. The feasibility of the new method is demonstrated on synthetic noise-free, noisy and measured magnetic anomalies.

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2. The presented method based on analytic signal

The two-dimensional expression of the amplitude of the analytic signal was given by Nabighian (1972):

$$AS(x,z)=\sqrt{\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial z}\right)^2}, \tag{1}$$

where T denotes the magnetic anomaly.

For the 2D magnetic contact, dike and horizontal cylinder models, the analytic signal expressions are written as:

$$AS(x,z)=\begin{cases}\dfrac{\alpha}{\left[(x-x_0)^2+(z-z_0)^2\right]^{1/2}} & \text{contact}\\ \dfrac{\alpha}{\left[(x-x_0)^2+(z-z_0)^2\right]} & \text{dike}\\ \dfrac{\alpha}{\left[(x-x_0)^2+(z-z_0)^2\right]^{3/2}} & \text{horizontal cylinder}\end{cases}, \tag{2}$$

where α is an amplitude factor related to the magnetization of the source, and x_0 and z_0 are the horizontal location and depth of the source, respectively. Salem et al. (2004) generalized Eq. (2) in one form as:

$$AS(x,z)=\frac{\alpha}{\left[(x-x_0)^2+(z-z_0)^2\right]^{(N+1)/2}}, \tag{3}$$

where N is the structural index characterizing the nature of the magnetic source, and different models have different N as shown in Eq. (2).

The analytic signals of different heights h_1, h_2, and h_3 of the original anomaly can be expressed as:

$$\begin{cases}AS(x,-h_1)=\dfrac{\alpha}{\left[(x-x_0)^2+(-h_1-z_0)^2\right]^{(N+1)/2}} & z=-h_1\\ AS(x,-h_2)=\dfrac{\alpha}{\left[(x-x_0)^2+(-h_2-z_0)^2\right]^{(N+1)/2}} & z=-h_2\\ AS(x,-h_3)=\dfrac{\alpha}{\left[(x-x_0)^2+(-h_3-z_0)^2\right]^{(N+1)/2}} & z=-h_3\end{cases} \tag{4}$$

The coordinate system shown in Fig. 1 is established, and the z-axis is defined as positive-downward. For interpretation of two-dimensional data, a profile with a defined y-axis value across the model (a horizontal cylinder in this case) is selected to calculate analytic signals of different height levels. The three height levels h_1, h_2, and h_3 are shown in Fig. 1.

The analytic signal maximum indicates the horizontal location x_0 of the source, and the AS at the horizontal location x_0 can be given by:

$$\begin{cases}AS(x_0,-h_1)=\dfrac{\alpha}{\left[(-h_1-z_0)^2\right]^{(N+1)/2}} & x=x_0,\ z=-h_1\\ AS(x_0,-h_2)=\dfrac{\alpha}{\left[(-h_2-z_0)^2\right]^{(N+1)/2}} & x=x_0,\ z=-h_2\\ AS(x_0,-h_3)=\dfrac{\alpha}{\left[(-h_3-z_0)^2\right]^{(N+1)/2}} & x=x_0,\ z=-h_3\end{cases} \tag{5}$$

We can use the upward continuation method in the frequency domain to compute analytic signals of different heights from the original magnetic data. The h_2 height can be chosen to obtain $AS(x_0,-h_2)$, which are equal to the k multiples of $AS(x_0,-h_1)$, and h_3 can be selected

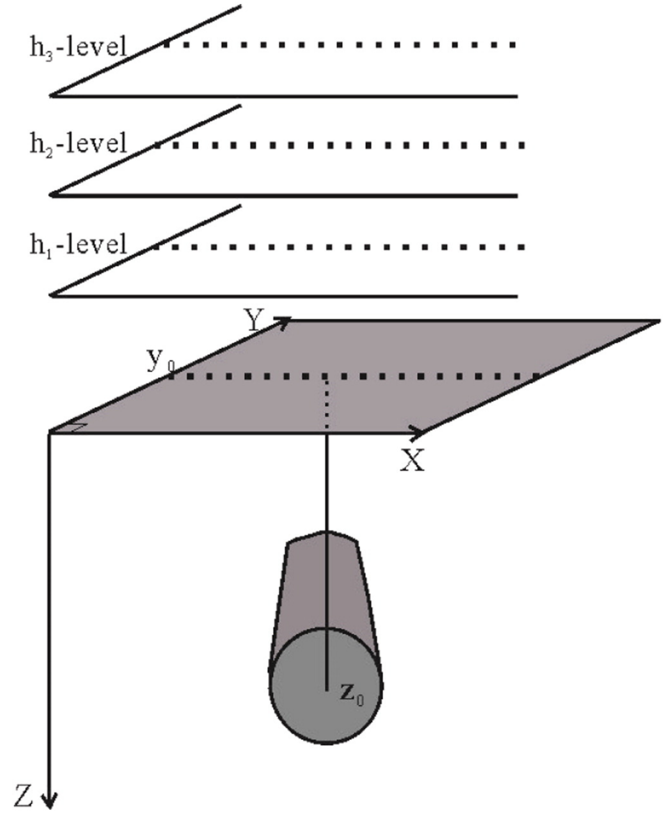

Fig. 1. The established coordinate system with the z-axis defined as downward positive. The dotted lines are the selected 2D interpretation profiles ($y=y_0$) across a horizontal cylinder model, and h_1, h_2, and h_3 are the three selected height levels for interpretation.

to obtain $AS(x_0,-h_3)$, which are equal to the k multiples of $AS(x_0,-h_2)$. The relationship can be expressed as:

$$AS(x_0,-h_3)=\mathrm{k}AS(x_0,-h_2)=\mathrm{k}^2AS(x_0,-h_1), \tag{6}$$

where $h_3>h_2>h_1$ have positive values, and k has a positive value less than one. We can see from Eq. (6) that analytic signals of different heights with the selected upward continuation height have the following relation:

$$[AS(x_0,-h_1)]\times[AS(x_0,-h_3)]=[AS(x_0,-h_2)]^2. \tag{7}$$

Taking Eq. (5) into Eq. (7), we obtain:

$$\frac{\alpha}{\left[(-h_1-z_0)^2\right]^{(N+1)/2}}\times\frac{\alpha}{\left[(-h_3-z_0)^2\right]^{(N+1)/2}}=\frac{\alpha^2}{\left[(-h_2-z_0)^2\right]^{(N+1)}}. \tag{8}$$

Then, we can obtain the source depth:

$$z_0=\frac{{h_2}^2-h_1h_3}{h_1+h_3-2h_2}. \tag{9}$$

After obtaining the depth of the source, we can use the relation of the analytic signals of either of the two heights shown in Eq. (6) to estimate the structural index N. The derived expression for N using the upward continuation analytic signals h_1 and h_2 is:

$$N=-\frac{\ln(\mathrm{k})}{\ln(t)}-1, \tag{10}$$