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Normalized full gradient of full tensor gravity gradient based on adaptive iterative Tikhonov regularization downward continuation

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ABSTRACT

Normalized full gradient (NFG) method depends on the downward continuation of NFG values of gravity data. In this paper, I deduce an improved NFG method of full tensor gravity gradient (FTG) data by using *x*-, *y*- and *z*-directional analytic signals of FTG data. During the calculation, I introduce the adaptive iterative Tikhonov regularization downward continuation method in the calculation process to improve the stability of the NFG method. The new approach is tested on various model data with and without noise, and satisfactory results are obtained. It demonstrates that the new NFG method of FTG can improve the lateral resolution and describe the gravity bodies in more detail. In addition, the method is applied to a real field FTG data acquired over the Vinton Salt Dome, Louisiana, USA. All results demonstrate that the new method can accurately detect the depth of the geologic sources while providing enhanced information of the sources simultaneously.

1. Introduction

In ongoing development of the full tensor gradient (FTG) techniques, more and more FTG data are used in resource exploration and geologic structure researches. Various works have demonstrated that FTG data can increase the effective spatial resolution (Pedersen and Rasmussen, 1990; Beiki, 2010; Beiki and Pedersen, 2010; Oruç, 2010; Oruç et al., 2013; Zhou et al., 2013; Pilkington, 2014). It is an effective tool in both oil and gas, and mineral exploration. In addition, FTG measures the derivatives of all the three gravity components in all three directions, and it can provide richer information of sources for defining edges of geologic sources. Therefore, the interpretation methods of the FTG data have been proposed and developed from different ways. Some were proposed by using the characteristics of the FTG data, such as using the invariants or eigenvalues of the FTG (Mataragio and Kieley, 2009; Oruç, 2010; Beiki and Pedersen, 2010). Some were modified from the classic methods, which mainly include the Euler deconvolution (Zhang et al., 2000), analytic signal (Beiki, 2010), and Tilt-depth (Oruç, 2011; Salem et al., 2013).

The normalized full gradient (NFG) method, introduced by Berezkin (1973) and Elysseieva and Pasteka (2009), was subsequently used to locate oil reservoirs from gravity data. The NFG method does not require any geometric input parameters or assumptions regarding geological properties. It can be directly used to obtain the depth of the causative source. In view of these advantages of the method, many researchers have introduced and developed the method to detect various geologic sources from different geophysical data. The theory of the NFG method has been further developed by Zeng et al. (2002). Tremendous progresses have recently been made in the implementation of the NFG technique (Dondurur, 2005; Aydin, 2007; Oruç and Keskinsezer, 2008; Fedi and Florio, 2011; Pamukcu and Akcig, 2011; Aghajani et al., 2011). The NFG method has been applied to self potential data (Sindirgi et al., 2008), electromagnetic data (Dondurur, 2005), and seismic signal data (Karsli and Bayrak, 2010).

The NFG method was mainly used to detect depth and center location of geologic source. In this paper, I focus on improving the lateral resolution and providing more information by using all components of FTG data. I use all of the analytic signal components to establish *x*-, *y*- and *z*-directional NFG method. In addition, in order to incease the stability of NFG method, the adaptive iterative Tikhonov regularization downward continuation method, which was developed by Zeng et al. (2013), is used during the calculation processing. I show the practical utility of the method using model data with and without random noise. The method also is applied to field example of FTG data over the Vinton Salt Dome, USA.

2. NFG method of full tensor gradient

The NFG method combines both the analytic signal and the downward continuation. It was originally implemented using a Fourier series associated with the singular point. The basic concept of NFG method is downward continuation of NFG values of gravity data. The 3-D NFG of

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gravity field data can be defined as:

$$G_H(x,y,z) = \frac{G(x,y,z)}{G_{cp}(z)} = \frac{\sqrt{g_{xz}^2(x,y,z) + g_{yz}^2(x,y,z) + g_{zz}^2(x,y,z)}}{\frac{1}{M}\sum_0^M \sqrt{g_{xz}^2(x,y,z) + g_{yz}^2(x,y,z) + g_{zz}^2(x,y,z)}} \quad (1)$$

where $g_{xz}(x, y, z)$, $g_{yz}(x, y, z)$, and $g_{zz}(x, y, z)$ are the first horizontal and the first vertical derivative of gravity anomalies g_z along the x, y and z directions, respectively. $G(x, y, z)$ is the full gradient of gravity anomalies at point (x, y, z); and $G_{cp}(z)$ is the average of full gradients at depth level z.

In fact, it is easy to see that the amplitude of analytic signal or full gradient is the main function of the method. As Roest et al. (1992) have extended the definition of the analytic signal of the potential field measured on observation plane at the surface ($z = 0$) in 3D, the amplitude is given by:

$$|A(x,y)| = \sqrt{(g_{xz}(x,y))^2 + \left(g_{yz}(x,y)\right)^2 + (g_{zz}(x,y))^2}. \quad (2)$$

As it is well known, the representation of the FTG in the Cartesian coordinate system contains nine components, which is shown in the sketch of Fig. 1. Eq. (2) is one of the components of z-direction. Similar to Eq. (2), x-directional analytic signal can be consisted by g_{xx}, g_{xy} and g_{xz}, the y-directional analytic signal can be consisted by g_{yy}, g_{yx} and g_{yz}.

As Beiki (2010) has introduced, the amplitudes of the directional analytic signals of gravity gradient tensor were defined as:

$$|A_x(x,y,z)| = \sqrt{(g_{xx}(x,y,z))^2 + \left(g_{xy}(x,y,z)\right)^2 + (g_{xz}(x,y,z))^2} \quad (3)$$

$$\left|A_y(x,y,z)\right| = \sqrt{\left(g_{yx}(x,y,z)\right)^2 + \left(g_{yy}(x,y,z)\right)^2 + \left(g_{yz}(x,y,z)\right)^2} \quad (4)$$

and

$$|A_z(x,y,z)| = \sqrt{\left(g_{zx}(x,y,z)\right)^2 + \left(g_{zy}(x,y,z)\right)^2 + \left(g_{zz}(x,y,z)\right)^2}. \quad (5)$$

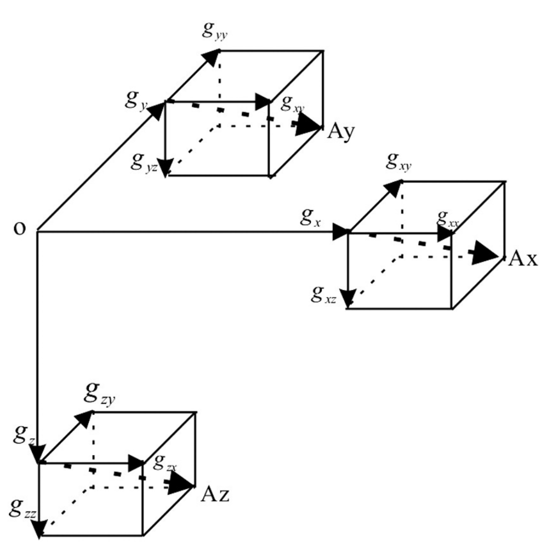

Fig. 1. The sketch of FTG components. g_{xx}, g_{xy}, g_{xz}, g_{yy}, g_{yz} and g_{zz} are the components of FTG. A_x, A_y and A_z are the analytic signal of x-, y- and z-direction.

As shown in Fig. 1, the NFG of FTG components can be shown in x-, y- and z-directions as follows, respectively:

$$G_{Hx}(x,y,z) = \frac{G_x(x,y,z)}{G_{cpx}(z)} = \frac{|A_x(x,y,z)|}{\frac{1}{M}\sum_0^M |A_x(x,y,z)|} \quad (6)$$

$$G_{Hy}(x,y,z) = \frac{G_y(x,y,z)}{G_{cpy}(z)} = \frac{\left|A_y(x,y,z)\right|}{\frac{1}{M}\sum_0^M \left|A_y(x,y,z)\right|} \quad (7)$$

and

$$G_{Hz}(x,y,z) = \frac{G_z(x,y,z)}{G_{cpz}(z)} = \frac{|A_z(x,y,z)|}{\frac{1}{M}\sum_0^M |A_z(x,y,z)|}. \quad (8)$$

These three equations seem to be very simple functions. However, during processing, there are many issues needed to be overcome. The downward continuation plays the key role in the NFG method. The stability of downward continuation method directly determines the accuracy of the NFG method. Therefore, it is necessary to use a stable downward continuation in the calculation process. The classical downward continuation algorithm of NFG method is implemented by using Fourier series with a smoothing filter. In order to simplify the calculation procedure, researchers try to use the stable downward continuation algorithm without resorting to the Fourier series (Fedi and Florio, 2011). The algorithm without Fourier series is used in this paper. There are many new stable algorithms have been introduced to implement the downward continuation method (Fedi and Florio, 2002; Cooper, 2004; Al-Saleh et al., 2009; Li et al., 2013; Ma et al., 2013; Zeng et al., 2013, 2014; Zhang et al., 2013). I choose the adaptive iterative method, which is developed by Zeng et al. (2013). The method is based on the non-stationary iterative Tikhonov regularization method. The authors have introduced the procedure in detail. The method has turned out to be a stable and fast downward continuation method. It can get accurate result without too many iterative numbers and then this enables to have the optimum results avoiding unnecessary iterations.

As Zeng et al. (2013) have introduced, the adaptive iterative Tikhonov regularization method in the frequency domain can be denoted as:

$$\widetilde{U}_n = \widetilde{U}_{n-1} + \left(e^{-h\sqrt{u^2+v^2}} / \left(e^{-h\sqrt{u^2+v^2}} + \mu_* p^{n-1}\right)\right)\widetilde{U}_{n-1} \quad (9)$$

(n = 1, 2, …) until the error level is satisfied the given error level, where $\tilde{U}_n$ is the final downward continuation data in the frequency domain, $1 < p < 2$ is an empirical value, in this paper, 1.5 is used. The regularization parameter μ_* can be chosen based on the L-curve as follow:

$$\Phi(\mu) = \log\left(\left\|\widetilde{U}_\mu\right\|\left\|\widetilde{G} - \Lambda\widetilde{U}_\mu\right\|\right) \quad (10)$$

where $\widetilde{G}$ is the Fourier transform of the observed potential field data G. The detailed calculation steps were described by Zeng et al. (2013).

Therefore, in this paper, the calculation procedures of the NFG method of FTG are:

(1) Calculate the FTG data from the observed gravity data, or obtain from the real measurement.
(2) Set a maximum depth H (the depth that we want to know the maximum range of geologic source) for downward continuation, and underground is divided into n layers (i = 1, 2, 3, …, n).
(3) Calculate FTG data at the different depth levels by using the adaptive iterative Tikhonov regularization downward continuation.
(4) Calculate the NFG of FTG data according to Eqs. (6)–(8).