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Research paper

Interpretation of residual gravity anomaly caused by simple shaped bodies using very fast simulated annealing global optimization

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ABSTRACT

A very fast simulated annealing (VFSA) global optimization is used to interpret residual gravity anomaly. Since, VFSA optimization yields a large number of best-fitted models in a vast model space; the nature of uncertainty in the interpretation is also examined simultaneously in the present study. The results of VFSA optimization reveal that various parameters show a number of equivalent solutions when shape of the target body is not known and shape factor 'q' is also optimized together with other model parameters. The study reveals that amplitude coefficient k is strongly dependent on shape factor. This shows that there is a multi-model type uncertainty between these two model parameters derived from the analysis of cross-plots. However, the appraised values of shape factor from various VFSA runs clearly indicate whether the subsurface structure is sphere, horizontal or vertical cylinder type structure. Accordingly, the exact shape factor (1.5 for sphere, 1.0 for horizontal cylinder and 0.5 for vertical cylinder) is fixed and optimization process is repeated. After fixing the shape factor, analysis of uncertainty and cross-plots shows a well-defined uni-model characteristic. The mean model computed after fixing the shape factor gives the utmost consistent results. Inversion of noise-free and noisy synthetic data as well as field data demonstrates the efficacy of the approach.

1. Introduction

One of the most imperative purposes in the interpretation of the gravity data is to determine the different types of subsurface structures and the position of the body. Numerous interpretative approaches have been developed in past and also significantly in the present time. Elucidation of the measured gravity anomaly by some idealized bodies such as cylinders and spheres remains an interest in exploration and engineering geophysics (e.g., Grant and West, 1965; Roy, 1966; Nettleton, 1976; Beck and Qureshi, 1989; Hinze, 1990; Lafehr and Nabighian, 2012; Hinze et al., 2013; Long and Kaufmann, 2013). The aim of gravity inversion is to estimate the parameters (depth, amplitude coefficient, location of the body and shape factor) of gravity anomalies produced by simple shaped structures from gravity observations.

Numerous interpretation methods have been developed to interpret gravity field data assuming fixed source geometrical models. In most cases, these methods consider the geometrical shape factor of the buried body being a priori assumed, and the depth variable may thereafter be obtained by different interpretation methods. These techniques include, for example, graphical methods (Nettleton, 1962, 1976), ratio methods (Bowin et al., 1986; Abdelrahman et al., 1989), Fourier transform (Odegard and Berg, 1965; Sharma and Geldart, 1968), Euler deconvolution (Thompson, 1982), neural network (Elawadi et al., 2001), Mellin transform (Mohan et al., 1986), least squares minimization approaches (Gupta, 1983; Lines and Treitel, 1984; Abdelrahman, 1990; Abdelrahman et al., 1991; Abdelrahman and El-Araby, 1993; Abdelrahman and Sharafeldin, 1995a), Werner deconvolution (Hartmann et al., 1971; Jain, 1976; Kilty, 1983), Walsh transformation (Shaw and Agarwal, 1990). Salem and Ravat (2003) presented a new automatic method for the interpretation of magnetic data, called AN-EUL which is a combination of the analytic signal and the Euler deconvolution method. Asfahani and Tlas (2012) developed the fair function minimization procedure. Fedi (2007) proposed a method called depth from extreme points

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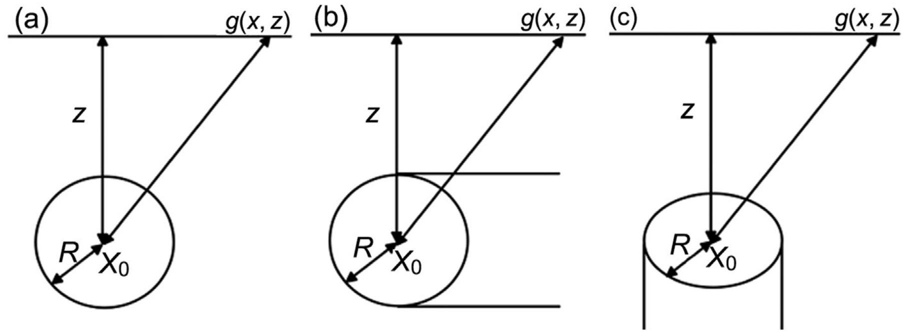

Figure 1. A diagram showing cross-sectional views, geometries and parameters of a sphere (a), an infinitely long horizontal cylinder (b) and a semi-infinite vertical cylinder (c).

(DEXP) to interpret any potential field. Continual least-squares methods (Abdelrahman and Sharafeldin, 1995b; Abdelrahman et al., 2001a, b; Essa, 2012, 2014) have been also developed. Regularized inversion method has also been developed by Mehanee (2014).

In general, the determination of the depth, shape factor, and amplitude coefficient of the buried structure is performed by some of these methods from the residual gravity anomaly. Moreover, location of the exact body is also an important parameter which also needs to be interpreted very precisely. Therefore, the precision of the results obtained by the above mentioned methods depends on the accuracy within which the residual anomaly can be separated from the observed gravity anomaly. Apart from versatile development in interpretation approaches, non-uniqueness of gravity data interpretation has not been addressed in most of the literature. Interpretation of gravity anomaly also suffers from this limitation. Several methods interpret only a few model parameters of the causative body (such as depth, shape factor, and amplitude coefficient). However, a precise interpretation of various parameters needs optimization of all model parameters together. This leads to much more ambiguous interpretation in comparison to finding a few parameters only. Some model parameters could be inter-dependent and estimating their actual values is equally important. Hence, in the present study, uncertainty associated with the interpretation of gravity data over simple shaped bodies (sphere and cylinder) is investigated using VFSA global optimization method. VFSA optimization is able to search a vast model space without compromising the resolution and it had been widely used in many geophysical applications (Sharma and Kaikkonen, 1999a,b; Sharma and Biswas, 2011, 2013; Sharma, 2012; Sen and Stoffa, 2013; Biswas and Sharma, 2015). VFSA's major advantage over other methods is that it has the ability to avoid becoming trapped in local minima. Another feature is that the partial derivatives (Frechet derivatives) and large scale matrix operations are avoided in such operations. Therefore, model parameters of simple bodies are optimized in a vast model space and ambiguities are analysed. Objective of the present study is to find a suitable interpretation steps that produces the utmost consistent model parameters and the slightest uncertainty for simple shaped bodies for gravity anomaly. Moreover, the objective is to invert and interpret the complete observed residual gravity data produced by some body fixed in the subsurface. In most of the cases, authors do not interpret all the model parameters which again lead to some erroneous results. In such case it is highly important to interpret and relevant that more the observed data and model parameter, the better is the inversion results and minimizes the uncertainty in the interpretation. The applicability of the proposed technique is assessed and discussed with the help of synthetic data and field examples taken from different parts of the world. The proposed method can be effectively used to interpret residual gravity anomaly data over simple bodies and can be successfully applied in deciphering subsurface structure and exploration in any area with least uncertainty in the final interpretation.

2. Formulation for forward gravity modelling

The general expression of a gravity anomaly $g(x)$ for a horizontal cylinder, a vertical cylinder, or a sphere-like structure at any point on the free surface along the principal profile in a Cartesian coordinate system (Fig. 1) is given by Gupta (1983), Abdelrahman et al. (2001a,b) and Essa (2007, 2014) as:

$$g(x) = k\left[\frac{z}{\left\{(x-x_0)^2+z^2\right\}^q}\right] \tag{1}$$

where, $q = 1.5$ (sphere), 1 (horizontal cylinder) and 0.5 (vertical cylinder) and $k = \frac{4}{3}\pi G\sigma R^3$ for $q = 1.5$; $k = 2\pi G\sigma R^2$ for $q = 1$ and $k = \frac{\pi G\sigma R^2}{z}$ for $q = 0.5$. k is the amplitude coefficient, z is the depth from the surface to the centre of the body (sphere or horizontal cylinder) or the depth from the surface to the top (vertical cylinder), q is the geometric shape factor, x_0 is the horizontal position coordinate, σ is the density contrast between the source and the host rock, G is the universal gravitational constant, and R is the radius of the buried structure.

3. Very fast simulated annealing global optimization method

3.1. Theoretical concept

Global optimization methods such as Simulated Annealing (SA), Genetic Algorithms (GA), Artificial Neural Networks (ANN) and Particle Swarm Optimization (PSO) have been applied in multi-parametric optimization of various geophysical data sets (Rothman, 1985, 1986; Dosso and Oldenburg, 1991; Sharma and Kaikkonen, 1998, 1999a,b; Juan et al., 2010; Sharma and Biswas, 2011, 2013; Sharma, 2012; Sen and Stoffa, 2013; Biswas and Sharma, 2014a,b, 2015). Simulated annealing is a focused random-search technique which exploits an analogy between the model parameters of an optimization problem and particles in an idealized physical system.

The conventional global optimization techniques (simulated annealing using a heat-bath algorithm or a genetic algorithm) compute the misfit for a large number of models in the model space. Subsequently they compute the probability of each model and try to concentrate in the region of high probability. In the present study, an advanced method of SA known as very fast simulated annealing (VFSA) is used, which does not compute misfit for a large number of models at a time but it moves in the model space randomly. It selects a new model, computes misfit and