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An approach for estimating the magnetization direction of magnetic anomalies

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ABSTRACT

An approach for estimating the magnetization direction of magnetic anomalies in the presence of remanent magnetization through correlation between normalized source strength (NSS) and reduced-to-the-pole (RTP) is proposed. The observation region was divided into several calculation areas and the RTP field was transformed using different assumed values of the magnetization directions. Following this, the cross-correlation between NSS and RTP field was calculated, and it was found that the correct magnetization direction was that corresponding to the maximum cross-correlation value. The approach was tested on both simulated and real magnetic data. The results showed that the approach was effective in a variety of situations and considerably reduced the effect of remanent magnetization. Thus, the method using NSS and RTP is more effective compared to other methods such as using the total magnitude anomaly and RTP.

1. Introduction

Magnetic surveys are widely used in different fields, including mining applications, oil and gas exploration, and mapping bedrock topography, among others. In magnetic prospecting, knowledge of the correct magnetization direction of magnetic anomalies is important for calculation of the RTP field, as well as forward calculation and inversion (Li et al., 2010). The total magnetization in a source body is the vector sum of the induced and remanent magnetization. In some cases, the induced magnetization aligns with the direction of earth's ambient field, without remanent magnetization and self-demagnetization effects. However, in most cases, the preexisting remanent magnetization is strong enough to affect the true magnetization direction (Liu et al., 2013, 2015) leading to the erroneous interpretation of magnetic data. Therefore, in recent years, there has been an increasing focus on reducing, or even removing the effects of remanent magnetization in the estimation of magnetization direction.

The problem of determining the total magnetization direction has long been of interest in the field of magnetic interpretation. Roest and Pilkington (1993) estimated the magnetization direction by comparing the amplitude of the analytic and horizontal gradient of pseudogravity. Medeiros and Silva (1995) estimated the total magnetization direction using the source moments up to second order derived from the multipole expansion of the magnetic potential. Phillips (2005) proposed direct and indirect algorithms that implemented Helbig's (1963) integrals for estimating the magnetization direction from the first order magnetic moments. Dannemiller and Li (2006) proposed a method to estimate the magnetization direction of 3-D sources based upon the correlation between the vertical and the total gradients of the reduced-to-the-pole field. A similar method was proposed by Gerovska et al. (2009), based on the correlation between the reduced-to-the-pole field and the total magnitude anomaly. Shi et al. (2014) presented the cross-correlation of magnetic dipole sources for determination of magnetization direction from the total magnetic field anomaly. Oliveira et al. (2015) developed a fast total-field anomaly inversion to estimate the magnetization direction of multiple sources with approximately spherical shapes and known centers. However, the aforementioned techniques all suffer from certain drawbacks which limit their accuracy. These limitations include the results being greatly influenced by noise effects, as well as the total magnitude anomaly being insensitive to the magnetization direction while also influencing the precision of the solution.

In the present study, a correlation coefficient analysis was carried out to estimate the magnetization direction of magnetic anomalies through correlation between NSS data and RTP in the presence of remanent magnetization. We chose to use NSS data as it is less sensitive to the magnetization direction compared to other transforms of the magnetic data and relates well to the location of the magnetic source. Hence, it has a stronger capacity to reduce the remanence effect. Additionally, the NSS shows a strong relationship to horizontal projections

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of the sources, which makes it a more accurate choice for estimating the magnetization direction.

This paper is structured as follows: in Section 2, a new approach for estimating the magnetization direction is described; in Section 3, the results for simulated and real magnetization data are presented. Finally, the conclusions are given in Section 4.

2. Method

2.1. Normalized source strength data

In a Cartesian coordinate system, with the x-axis pointing to the geographical east, the y-axis to the north, and the z-axis vertically downwards, the theoretical magnetic gradient tensor data in the observation plane (x, y, z) can be expressed as follows:

$$G = \begin{bmatrix} B_{xx} & B_{xy} & B_{xz} \\ B_{yx} & B_{yy} & B_{yz} \\ B_{zx} & B_{zy} & B_{zz} \end{bmatrix}, \tag{1}$$

where G is the magnetic gradient tensor matrix and $B_{\alpha\beta}(\alpha,\beta{=}x,y,z)$ are the magnetic gradient tensor components.

If the eigenvalues of the matrix G are arranged in descending order as $\lambda_1 \geq \lambda_2 \geq \lambda_3$. Then the theoretical normalized source strength data may be expressed as (Zhou and Meng, 2015; Guo et al., 2014; Beiki et al., 2012; Pilkington and Beiki, 2013; Wilson, 1985)

$$u(x,y,z) = \sqrt{-{\lambda_2}^2 - \lambda_1\lambda_3}, \tag{2}$$

where $u(x,y,z)$ represents the NSS data at an arbitrary station (x,y,z) on the observational surface.

2.2. Correlation coefficient analysis for choosing optimum magnetization direction

The RTP turns the measured total magnetic field to anomaly at the north magnetic pole, where the magnetization direction points directly downwards; hence, there is a good correlation between the RTP anomaly and the source horizontal projection. In the presence of remanence, the transformation of RTP requires both the geomagnetic field direction (I_0,D_0) and the magnetization direction (I,D). The RTP field may be calculated in the frequency domain using the transfer function (Blakely, 1995)

$$H = \frac{u^2+v^2}{[i(u\cos I_0\cos D_0 + v\cos I_0 \sin D_0) + r\sin I_0][i(u\cos I\cos D + v\cos I\sin D) + r\sin I]}, \tag{3}$$

where u is the angular frequency in the x-direction, v is the angular frequency in the y-direction, and $r = \sqrt{u^2+v^2}$.

The correlation coefficient C between the NSS data and the RTP fields is defined as

$$C = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}\left(\Delta T_{rtp}(i,j) - \overline{\Delta T_{rtp}}\right)\left(T_{nss}(i,j) - \overline{T_{nss}}\right)}{\sqrt{\sum_{i=1}^{M}\left(\Delta T_{rtp}(i,j) - \overline{\Delta T_{rtp}}\right)^2 \sum_{j=1}^{N}\left(T_{nss}(i,j) - \overline{T_{nss}}\right)^2}}, \tag{4}$$

where (M, N) is the grid size, ΔT_{rtp} is the RTP field, T_{nss} is the NSS data, $\overline{\Delta T_{rtp}}$ is mean value of the RTP fields and $\overline{T_{nss}}$ is mean value of the NSS data.

Since the magnetization direction is unknown from the calculations performed using the aforementioned equations, we assumed that the inclination I changed from -90° to 90° and the declination D changed from -180° to 180°, both of which with intervals of 1°. We calculated the RTP field for a series of assumed values of the magnetization direction. Then, using Eq. (4), the correlation coefficient, C, between the NSS and RTP field was calculated. Just as for the NSS, the RTP has a strong relationship to the horizontal projection of the source when the used magnetization and real magnetization directions are aligned. Therefore, the value of C reflects the degree of cross-correlation between the NSS and the RTP and thus is related to the probability of finding the correct magnetization direction of the source. A lower value means lower accuracy of the estimated magnetization direction; therefore, the maximum value of the correlation coefficient indicates the correct magnetization direction.

3. Data experiments

3.1. Test on the synthetic magnetic data

3.1.1. Isolated model

3.1.1.1. The magnetization. The geometric parameters and actual magnetization directions of these models are in Table 1. The direction of the geomagnetic field used for the sources was $I_0 = 60^{\circ}$ and $D_0 = -20^{\circ}$. The observed geometry was a 22×22 regular grid with spacing 0.1 m at an altitude of zero.

The total magnetic field anomalies for the three model sources were forwardly calculated and shown in Fig. 1(a), (e) and (i). The total magnitude anomalies of the three sources roughly corresponded to their real locations, as shown in Fig. 1(b), (f) and (j). The centers of the sphere, horizontal cylinder and rectangular prism were shifted to the south-east, south, and south-east of the real center, respectively. The results show that the total magnitude anomaly was insensitive to the magnetization direction, while also influenced by remanent magnetization; thus the results are not very convincing. The NSS appeared to correspond fairly well to the real positions of the three sources, as shown in Fig. 1(c), (g) and (k). The centers of NSS data were closer to the real centers of the three sources than the centers of the total magnitude anomaly. This shows that the NSS provides more reliable information about the source geometry when the magnetic source contains remanent magnetization with a different direction to that of the inducing field. The results clearly show that while both the NSS data and the total magnitude anomaly are insensitive to the remanent magnetization, the NSS seems to perform better than the total magnitude anomaly. Thus, in theory, using the correlation between NSS and RTP anomaly to estimate the magnetization direction should provide better results than using the correlation between the total magnitude anomaly and RTP anomaly.

Next, we estimated the magnetization directions of the three sources using these two different methods, in order to prove that the NSS is more useful than the total magnitude anomaly. Fig. 1(d), (h) and (l) show the cross-correlation coefficient maps of the three sources using NSS and RTP, and it can be seen that the estimations of

Table 1
The geometric parameters of three sources. *I* and *D*, respectively, represent the actual inclination and declination of each of the sources.

Source	Center coordinates/m	Length in x-direction/m	Length in y-direction/m	Length in z-direction/m	Magnetization direction (I,D)
Sphere	(1,1,0.3)	0.2	0.2	0.2	$(20^{\circ}, -30^{\circ})$
Horizontal Cylinder	(1,1,0.3)	1	0.3	0.3	$(15^{\circ}, 30^{\circ})$
Rectangular	(1,1,0.3)	0.4	0.4	0.2	$(50^{\circ}, -40^{\circ})$