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Source Location and Depth Estimation Using Normalized Full Gradient of Magnetic Anomalies

Manyetik Anomalilerin Normalize tam Gradyenti ile Kaynak Lokasyon ve Derinlik Kestirimi

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ABSTRACT

The method of the normalized full gradient (NFG) is one of the methods applied for the determination of singular points of potential fields. The NFG method is based on the transformed data and field filtering in downward continuation to the levels below the measuring level. The method was applied to obtain both the horizontal location and depth of the magnetic sources. The feasibility of the proposed method was tested on 2-D synthetic models, such as magnetic horizontal cylinder and vertical dike. The maxima of the NFG field indicate the horizontal locations and depths of the causative. Good results are obtained by using the present method, particularly for depth estimation, which is a primary concern in magnetic prospecting.

The reliability of the NFG method depends mainly on the developed coefficients of the Fourier series in transforming and filtering of magnetic anomalies. The optimum upper harmonic limit of coefficients can be determined from the breaking point on the envelope of the logarithmic spectrum of the Fourier cosine coefficients. In addition, a simple procedure in determining the degree of smoothing factor is also presented to eliminate high-frequency noise resulting from downward continuation process.

The NFG method is applied to magnetic data in the southern Illinois, the USA. The sources' parameters (horizontal location and depth) were compared with results obtained by Euler deconvolution method. The agreement between methods for estimating these parameters is good.

Keywords: Magnetic anomalies, anomalous sources, normalized full gradient

ÖZ

Normalize tam gradient (NTG) yöntemi potansiyel alanların tekil noktalarının belirlenmesi için uygulanan yöntemlerden biridir. NTG yöntemi, ölçüm seviyesinin altındaki aşağı uzanım seviyelerinde veri süzgeçlemesi ve dönüşümüne dayalı bir yöntemdir. Yöntem manyetik anomali kaynaklarının yatay lokasyon ve derinliğinin belirlenmesinde kullanılmıştır. Yöntemin uygulanabilirliği, yatay silindir ve düşey dayk gibi iki boyutlu teorik modeller üzerinde test edilmiştir. NTG alanının maksimumları kaynak kütlelerin yatay lokasyonlarını ve derinliklerini vermektedir. NTG yöntemi manyetik arama yöntemi için önemli bir problem olan derinlik kestiriminde iyi sonuçlar sunmaktadır.

NTG yöntemi manyetik anomalilerin dönüşümünde ve süzgeçlenmesinde, esas olarak Fourier serilerinin katsayılarının hesaplanmasına dayanır. Katsayıların üst harmonik sınırı, Fourier kosinüs katsayılarının logaritmik spektrumunun zarfı üzerindeki kırılma noktasından belirlenebilir. Ayrıca bu çalışmada, aşağı uzanım işlemi sırasında ortaya çıkan yüksek frekanslı gürültüyü yok etmek için kullanılan yuvarlatma faktörünün belirlenmesinde basit bir işlem de sunulmaktadır.

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NTG yöntemi Güney İllinois'deki (ABD) manyetik veriye uygulanmıştır. NTG yöntemiyle elde edilen sonuçlar, diğer yöntemlerle bulunan sonuçlarla uyumludur.

Anahtar Kelimeler: *Manyetik anomaliler, anomali kaynakları, normalize tam gradyent*

INTRODUCTION

Estimation of location and depth of burial bodies from observed magnetic data are some of the primary objectives of interpretation in exploration geophysics. Developing efficient techniques have become particularly important because large volumes of magnetic data are being collected for environmental and geologic applications. For this reason, a variety of semiautomatic methods based on the use of derivatives of the magnetic field have been developed for the determination of magnetic source parameters such as horizontal locations and depths. One of these methods is the approach of the analytic signal of magnetic anomalies. The analytic signal amplitude is defined as the square root of the sum of the squares of the horizontal and vertical derivatives of the magnetic field. The analytic signal for magnetic anomalies was initially developed as a complex field deriving from a complex potential (Nabighian, 1972). Application of analytical signal techniques to 2-D magnetic interpretation was pioneered by Nabighian (1974, 1984), AtchutaRao et al. (1981) and further developed by Thurston and Smith (1997) and Pedersen and Bastani (1997). These attempts are based on the location of the maximum in the NFG sections for determining the source positions.

The analytical downward continuation of the potential fields is widely used for data interpretation (e.g., Fuller 1967; Clarke 1969; Mesko 1984; Pawlowski 1995; Debeglia and Corpel 1997; Xu et al. 2003). The downward continuation of the potential fields from a measured surface is an important method used to amplify certain wavelengths of measured data to enhance the expression of causative bodies. The main problem is that disturbing oscillations occur in the process of downward continuation of a potential field to depths, which are close to the depth of the anomalous sources. The downward continuation procedure was stabilized by means of various approaches (Tikhonov et al. 1968; Fedi and Florio 2002; Trompat et al. 2003; Cooper, 2004).

The NFG method combines both the analytic signal and the downward continuation. This method represents the full gradient (or analytic signal) of the downward continuation of gravity or magnetic data at a point divided by the average of the full gradient at the depth levels. Particularly, it was introduced to detect the oil reservoirs from gravity data (Berezkin and Buketov 1965; Berezkin 1967; Berezkin 1973) and further developed by many authors (Lindner and Scheibe 1977; Strakhov et al. 1977; Mudretsova et al. 1979; Ciancara and Marcak 1979; Elysseieva 1982; Berezkin and Skotarenko 1983; Berezkin 1988; Elysseieva 1995; Pašteka 1996; Zeng et al. 2002).

The first application of NFG method in the interpretation of magnetic data was conducted by Berezkin et al. (1994) without testing it on synthetic models, only applying it on real datasets from oil industry. Xiao (1981) and Xiao and Zhang (1984) have used the method for oil exploration in China. Zeng et al. (2002) published the results of implementing the method for2-D cases sections of anticlines with homogenous density in the Shengli oil field.

The aim of this paper is to present results of the 2-D NFG of magnetic anomalies resulting from causative bodies at datum. The results demonstrate the feasibility and advantages of the usage of NFG maxima in a complementary fashion to obtain geologic information from magnetic data.

THE NFG OPERATOR

The full gradient term means the square root of the sum of the squares of the horizontal and vertical derivatives. The NFG method is very close to the method of analytic signal, introduced by Nabighian (1972), especially to its later modification (Nabighian 1974). The elimination of disturbing oscillations arising during the downward continuation progress is the basic property of the NFG method because the combination of the derivatives into the full gradient reduces the oscillations. This normalization on each depth levels enables us to obtain the relevant extreme of the NFG field close to the source (Berezkin 1988; Pasteka 2000) and eliminates disturbing oscillations which occur near the depths of the anomalous sources during the downward continuation process. The NFG for total field magnetic anomaly T is defined in two dimensions is given as

$$G(x,z)=\frac{\sqrt{T_x(x,z)^2+T_z(x,z)^2}}{\frac{1}{M}\sum_{0}^{M-1}\sqrt{T_x(x,z)^2+T_z(x,z)^2}} \qquad (1)$$

where, T_x and T_z are derivatives of T with respect to *x* and *z*, respectively. *M* is the number of observation points. The denominator of equation (1) is the mean value of full gradient calculated over *M* observation points, and this normalization makes the full gradient value dimensionless.

Computation of the NFG operator is performed using a Fourier series approach in such a way that the $T(x,z)$ function along the x axis can be given as the summation of sine and cosine functions (Bracewell 1984; Blakely 1995). If the data are defined on the (0, L) interval, just the sine or cosine expansions can be used (Rikitake et al. 1976; Elysseieva and Cvetkova 1989). The downward continuation in the wave number domain by Fourier series summation is as follows:

$$T(x,z)=\sum_{n=N_{low}}^{N} A_n \cos\frac{\pi n x}{L} e^{\frac{\pi n z}{L}} \qquad (2)$$

where, A_n is Fourier cosine coefficient, n is the harmonic serial number and z is the plane on which the downward continuation is performed. N_{low} and N are the used lower and upper harmonic limits of Fourier series, respectively. Lower harmonic limit- $N_{low}=1$ is a general convention for the potential data to preserve the lower frequency components (Aydın 1997). N is defined as

$$N \le N, \qquad (3)$$

where $N = M - 1$.

A_n can be calculated by using

$$A_n=\frac{2}{L}\int_0^L T(x,0)\cos\frac{\pi n x}{L}dx. \qquad (4)$$

Therefore, at cosine-decomposition it is possible to use the functions, complicated with a regional component. The numerical methods, such as trapezoidal rule or Filon's method (Filon, 1928), can be used in computing the Eq (4). Aydın (2007) showed that the latter yields more stable results than that of other in computing the coefficients with sine decomposition. Taking the derivatives of equation (2) with respect to the x- and z-direction we get

$$T_x(x,z)=\frac{\pi}{L}\sum_{n=N_{low}}^{N} nA_n \sin\frac{\pi n x}{L} e^{\frac{\pi n z}{L}}, \qquad (5)$$

$$T_z(x,z)=\frac{\pi}{L}\sum_{n=N_{low}}^{N} nA_n \cos\frac{\pi n x}{L} e^{\frac{\pi n z}{L}}. \qquad (6)$$

In order to eliminate high-frequency noise resulting from downward continuation, the following smoothing factor is used:

$$q=\left[\frac{\sin\frac{\pi n}{N}}{\frac{\pi n}{N}}\right]^{\mu}, \qquad (7)$$

where, μ is a positive real number known as the degree of smoothing which controls the curvature of incorporated by the *q* factor. The *q* factor has been incorporated by Berezkin (1967), who used variable value of parameter N and constant value of parameter □ $= 2$. This factor is also known as Lanczos smoothing term and was introduced to eliminate the Gibbs effect. Thus the function $T(x,z)$ and derivatives are given by

$$T(x,z)=\sum_{n=N_{low}}^{N} A_n \cos\frac{\pi nx}{L} e^{\frac{\pi nz}{L}} q, \quad (8)$$

$$T_x(x,z)=\frac{\pi}{L}\sum_{n=N_{low}}^{N} nA_n \sin\frac{\pi nx}{L} e^{\frac{\pi nz}{L}} q, \quad (9)$$

$$T_z(x,z)=\frac{\pi}{L}\sum_{n=N_{low}}^{N} nA_n \cos\frac{\pi nx}{L} e^{\frac{\pi nz}{L}} q. \quad (10)$$

Substituting equations (9) and (10) into equation (1), the NFG is calculated.

APPLICATION TO SYNTHETIC EXAMPLES

To demonstrate the feasibility of the NFG method, some 2-D magnetic bodies with negligible remanent magnetization are considered under the surface. These models are horizontal cylinder with an infinite horizontal extent and vertical dike with infinite depth extent. The theoretical model studies are quite self-explanatory and confirm the efficiency of the method.

Two important parameters in the NFG solutions are the optimum upper harmonic limit N_{opt} and smoothing degree μ. Berezkin (1967) found out that the image of the NFG field with various N will change on model studies and real application. He has developed an empirical rule for the determination of the depths of the sources called Berezkin's criterion of maximum. Elysseieva (1982) enlarged the possibilities of the interpretation of the maximum values and introduced the analysis called "zones of maximum values". This method is based on the connection of the positions of all local maxima, which are situated approximately beneath each other, at every depth levels. Elysseieva (1995) derived analytical expressions, which describe their values and position and developed two criterions for the correspondence between zone characteristics and depth of the singularity. Aydın (1997) suggested that $\mu=1$ or 2 gives reasonable results in the downward continuation. Dondurur (2005) showed N_{low} and N limits are determined by a trial-and-error method. However, the best NFG solutions are characterized by relatively smooth contours between maximum and minimum points, but the method is subjective.

Figure 1 shows the NFG sections which are calculated in the interval of $n=1-16$ for $\mu=1$, 1.5, 2, 2.5 and 3. For $\mu=1$ and 1.5, the NFG maximum is obtained at shallower depths, while the NFG maximum with $\mu=2.5$ and 3 is obtained at deeper depths than actual depth. It is clear that the NFG maximum from $\mu=2$ works well in imaging the center depth to source.

An important property of the method is the fact that the NFG operator is a complicated nonlinear filter with specific spectral characteristics. The frequency filtering function is defined from Eq. (9) and (10) as

$$\Phi_n=\frac{\pi n}{L} e^{\frac{\pi nz}{L}} q. \quad (11)$$

This function determines the frequency characteristic of the NFG operator by transforming into a filter, which is close to a band pass (Berezkin 1988; Aydın 2007). The term $e^{\pi nz/L}$ in Eq. (11) is the spectral characteristic of analytic continuation. Considering that $L=N\ x$, the degree $\pi nz/L$ in this equation can be realized as $R_n \pi n/N$. Thus the parameter R_n is written as

$$R_n=\frac{N}{N}\frac{z}{x}. \quad (12)$$

This parameter represents the equation of a hyperbole, asymptotes of which are axes of coordinates N/N and $z/\Delta x$. This coordinate system is convenient for the analysis of dependence of depth of NFG maximum on N/N (Elysseiva 1995). Equation (12) can be used in the description of the behavior of the center depth (z) of zone maximum point in the computed NFG field. In order to define the relation between parameter μ and z, I have presented two-step procedure. This is similar to a method, based on the criterion α in the Quasi Singular Points (QSP) obtained using method outlined by Elysseiva (1995). At first, the center depths of NFG maxima calculated from μ=0.5,

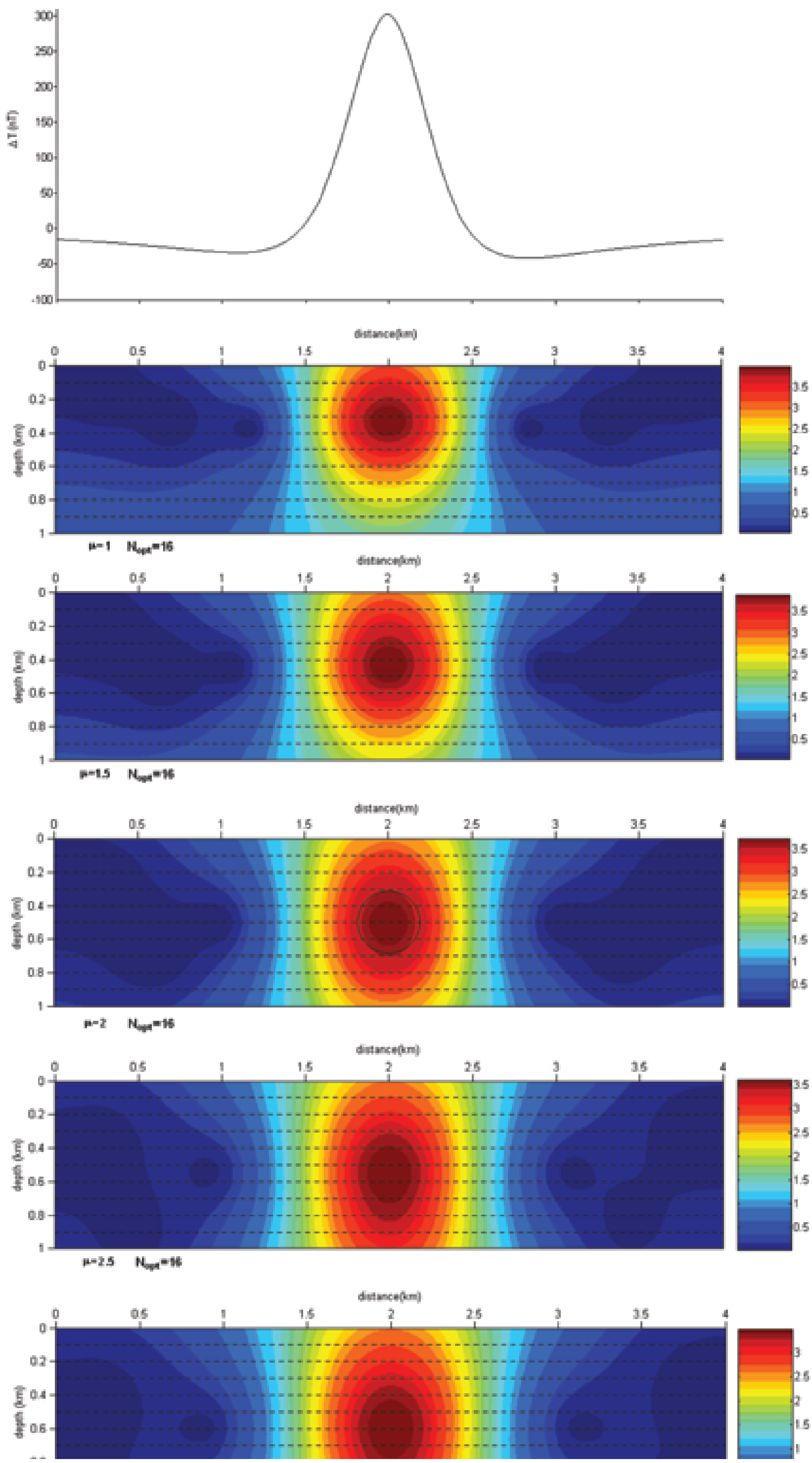

Figure 1. Logarithmic spectral analysis of total-field magnetic anomaly for a long horizontal cylinder model and determination of optimum upper harmonic limit. The spectrum is computed at a smaller sampling interval of 0.05. The vertical arrow marks the breaking point on the envelope of the spectrum and also defines the optimum upper harmonic of $N_{opt} = 16$.

Şekil 1. Uzun yatay silindir modelinin toplam alan manyetik anomalisinin logaritmik spectral analizi. Spektrum 0.05 aralığında hesaplanmıştır. Düşey ok spektrumun zarfının kırılma noktasını işaretler ve aynı zamanda optimum üst harmoniği verir ($N_{opt} = 16$ *)*

1, 1.5, 2, 2.5 and 3 are observed. Further, the depth values from local maximum points of the NFG fields are graphed as a function of N/N values (Figure 2). It can be noted that at low values of the N/N ratio the graph obtained using $\mu = 2$ shows stable depth solutions, and a sudden slope change is present when $N/N = 0.4$ and $z/\Delta x = 5.05$ ($N = 40$, $\Delta x = 0.1$ km). In this case, the NFG maximum practically coincides on depth with the center of the cylinder ($z = 0.5$ km). Thus, this analysis allows obtaining estimates of the optimum upper harmonic limit N_{opt}, smoothing factor μ and depth to source z.

In order to determine optimum upper harmonic limit, I propose a method based on spectral analysis of magnetic anomaly. When logarithmic spectrum of coefficients $|A_n|$ is drawn in function of *n*, a breaking point on the envelope or peaks of spectrum is obtained. This point corresponds to an estimate of the optimum number of Fourier terms (N_{opt}).Figure 3 shows the logarithmic spectrum $|A_n|$ of magnetic anomaly (Figure 1)along a 4 km profile sampled at intervals of 0.1km generated from a long horizontal cylinder which is placed at the depth to the center of 0.5 km. The harmonic limits of spectrum in Fig. 1 are $n = 1-40$. The spectrum is computed at very smaller interval of 0.05 to find a critical point, marking the optimum upper harmonic limit- N_{opt} precisely. Thus the optimum upper harmonic limit- N_{opt} obtained from the breaking point on the envelope of the spectrum is 16 (Figure 3).

Figure 4 and 5 show the results of applying the method to the same anomaly shown in Fig.1 but corrupted with additive, zero-mean, Gaussian noise having standard deviations of 3.88 nT and 5.48 nT, which corresponds to 5 and 10 percent of the maximum of the magnetic anomaly, respectively. When compared with Figure 4, Figure 5 shows the expected increase in the local minima, while the increase of the noise has such small effect that the results are virtually the same as those shown in Figure 3 in determining both the location and depth of the horizontal cylinder.

Figure 6 shows the logarithmic spectrum $|A_n|$ of magnetic anomaly (Fig. 8) along a 4 km profile sampled at intervals of 0.1kmgenerated by an infinite vertical dike model, the top of which is located at 0.5 km depth. The spectrum is computed by sampling interval 0.05 in the harmonic limits of $n = 1-40$. The optimum upper harmonic limit- N_{opt} obtained from the breaking point on the envelope of the spectrum is 10.

Figure 7shows the changes of the depth of the NFG maximum using $\mu = 0.5$, 1, 1.5, 2, 2.5 and 3 vs. N/N ratio. A clear slope change of the graph, obtained from $\mu = 1$, corresponds to values of $N/N = 0.25$ and $z/\Delta x = 6$ ($N = 40$, $\Delta x = 0.1$ km). Therefore, this process also confirms the validity of the optimum upper harmonic limit, obtained from the logarithmic spectrum $|A_n|$ in Fig. 6for definition of body location. In Figure 8, the NFG field has been calculated in the interval of $n = 1-10$ for $\mu = 1$ and imaged the depth to the top of the dike.

FIELD EXAMPLE

In this section, I have tested the validity of the NFG method using a field example. Figure9 shows that the envelope of the logarithmic spectrum $|A_n|$ of the ground magnetic anomaly (Figure 11) measured over an altered peridotitic dike in southern Illinois, USA (Kirkham 2001). The spectrum has a meaningful change of slope, allowing estimating an optimum upper harmonic limit of $N_{opt} = 22$. The spectrum is computed with the interval of 0.05.

The dike strikes northwards and the magnetic profile was obtained in the east-west direction (Kirkham 2001). From closely spaced drilling, it is known that the dike is located at a horizontal distance of 200 m from the origin of the profile with a depth to the top and its width of about 10 m (Kirkham 2001). Salem and Ravat (2003) has developed an analytic signal-Euler (AN-EUL) method based on the derivatives of the analytical signal. Using the same field example, the location and depth of the dike have been estimated as 205.74 m and 9.17 m, respectively. Salem (2005) has also used the same anomaly to detect the source location parameters by using a method based on the first-order analytic signal derivative. Thus the results indicate a causative body, located at a position of

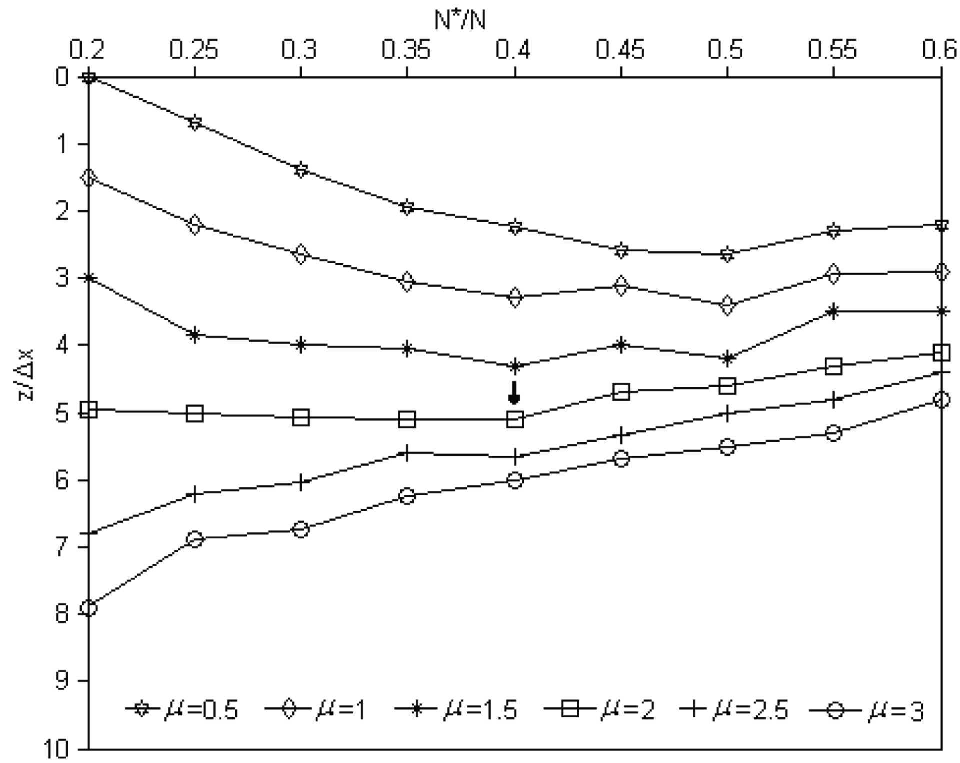

Figure 2. Changes of the depth position of NFG maximum used for the choice of the smoothing parameter μ covering a range from 0.5 up to 3 km in the interval of 0.5. The vertical arrow indicates a change-point on the curve from $\mu = 2$. Note that the curve to this point is almost horizontal. The point confirms the optimum upper harmonic ($N^*_{opt}/N = 0.4$, $N = 40$) from Fig.1. It also defines depth to long horizontal cylinder ($z/\Delta x = 5.05$, $\Delta x = 0.1$ km).

Şekil 2. Yuvarlatma parametresinin (μ) seçimi için kullanılan NTG maksimumlarının derinlik konumlarının değişimleri. Derinlikler 0.5 km den 3 km'ye 0.5 km aralıklarda değiştirilmiştir. Düşey ok $\mu = 2$ 'den elde edilen eğri üzerindeki bir değişim noktasını gösterir. Bu noktaya kadar eğrinin hemen hemen doğrusal olduğuna dikkat edilmelidir. Bu nokta Şekil 1'den elde edilen optimum üst harmoniği ($N^*_{opt}/N = 0.4$, $N = 40$) doğrular ve uzun yatay silindirin derinliğini de belirler.

202.2 ± 0.2 m and at a depth of 9.3 ± 0.2 m.

In Figure 10, following the criterion described in Eq. (12), I selected a μ μ value of 1 and a slope change-point corresponding to the values of $N^*_{opt}/N = 0.2784$ and $z/\Delta x = 1.45$ ($N = 79$, $\Delta x = 5$ m).The anomalous source is positioned at an approximate location of 202 m and in a depth to its top of 7.25 m from the center depth of the NFG maximum (Fig.11). Therefore, NFG image confirms that the positions of the body are close to the horizontal location and depth suggested by Salem and Ravat (2003) and Salem (2005).

DISCUSSION

In this study, the NFG method has provided successful results in the interpretation of magnetic anomalies. The performance and reliability of the NFG method are also tested on the synthetic and field data. As a result of NFG applications to two-dimensional bodies, the method is able to identify for detecting horizontal locations and depths of subsurface features. The method possesses great opportunities at interpretation of magnetic data in conditions of complete absence of a priori information such as depths and locations of the anomalous sources. However,

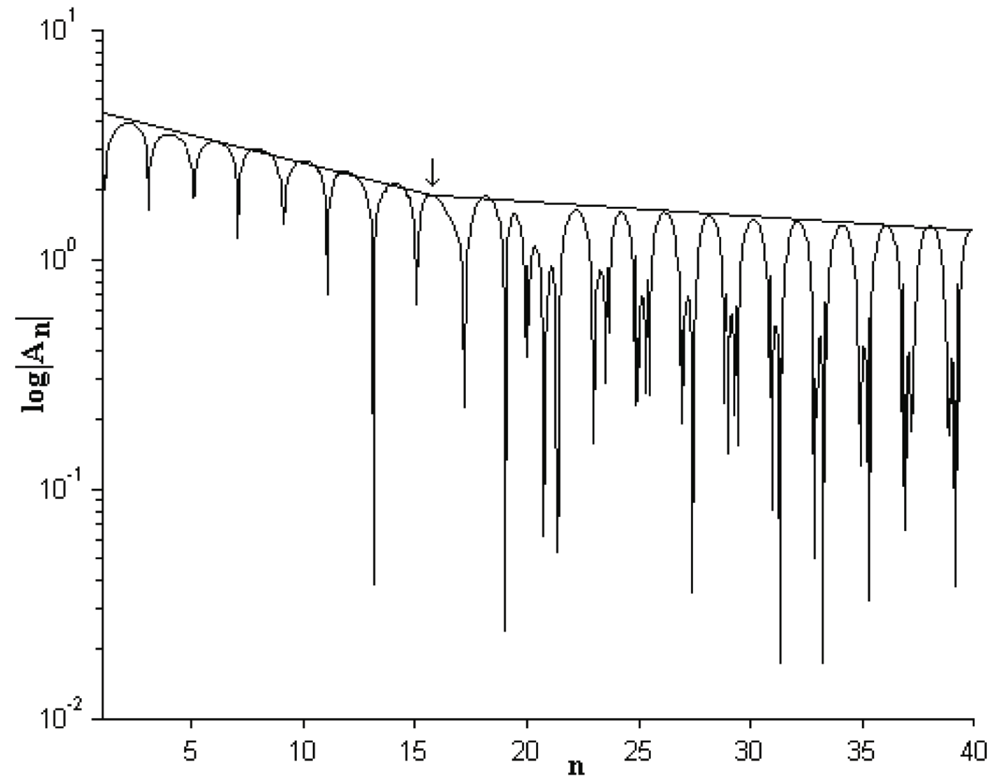

Figure 3. Total-field magnetic anomaly generated by a long horizontal cylinder model with a radius of 0.2 km and the depth to the center of 0.5 km, magnetization vector at 30°. Sampling interval is 0.1 km (M=41). The NFG sections were computed using depth levels of 0.1 km interval. Note that the deeper center depth of the NFG maxima is obtained, the bigger the value of μ. The long horizontal cylinder was illustrated on the panel that the best results were obtained ($\mu = 2$, $N^{\square}_{opt} = 16$). The dashed lines represent the downward continuation levels.

Şekil 3. 0.2 km yarıçaplı, merkez derinliği 0.5 km ve mıknatıslanma vektörünün açısı 30° olan uzun yatay silindir modelinin toplam alan manyetik anomalisi. Örnekleme aralığı 0.1 km dir (M=41). NTG kesitleri 0.1 km aralıklı derinlik seviyelerinde hesaplanmıştır. μ değeri büyüdükçe NTG maksimumlarının da büyüdüğüne dikkat edilmelidir. Uzun yatay silindir, en iyi sonuçların elde edildiği panel üzerinde gösterilmiştir ($\mu = 2$, $N^{\square}_{opt} = 16$). Kesikli çizgiler aşağı uzanım seviyelerini temsil eder.

the method does not does not provide any knowledge on the geometry of the sources. Some semiautomatic techniques such as Euler deconvolution (Thompson, 1982; Reid et al., 1990), local wavenumber (Thurston and Smith, 1997; Salem and Smith, 2005), and continuous wavelet transform (Vallee et.al., 2004). These methods infer the nature of the sources, but the main disadvantages of these methods are that they require a well-founded understanding of a critical parameter, the structural index, which characterizes the source geometry. In addition, these methods are sensitive to noise in the data since they use higher derivatives of magnetic anomalies. In the selection of the parameters to build the NFG operator directly connected with the determination of the source depth. In this study, I have developed two graphs based on the source depth to use upper harmonic and smoothing factor, priori knowledge in the NFG calculations. Some methods, based on the use of this mathematical device, are developed. One of them is the method of quasi singular points (QSP). The QSP is based on the analysis of a peak spectrum, transformations a quantity of fields and their representation by

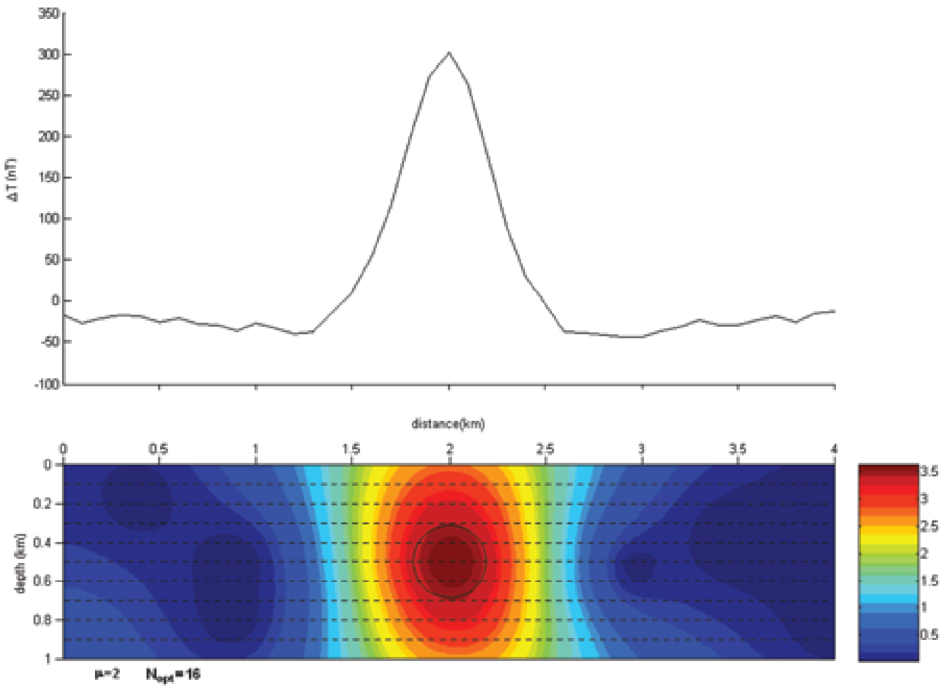

Figure 4. Total-field magnetic anomaly for a long horizontal cylinder model contaminated with Gaussian random noise with standard deviation of 3.88 nT and NFG section. The dashed lines represent the downward continuation levels.

Şekil 4. Uzun yatay silindirin, standart sapması 3.88 nT olan Gauss gürültülü toplam alan manyetik anomalisi ve NTG kesiti. Kesikli çizgiler aşağı uzanım seviyelerini temsil eder.

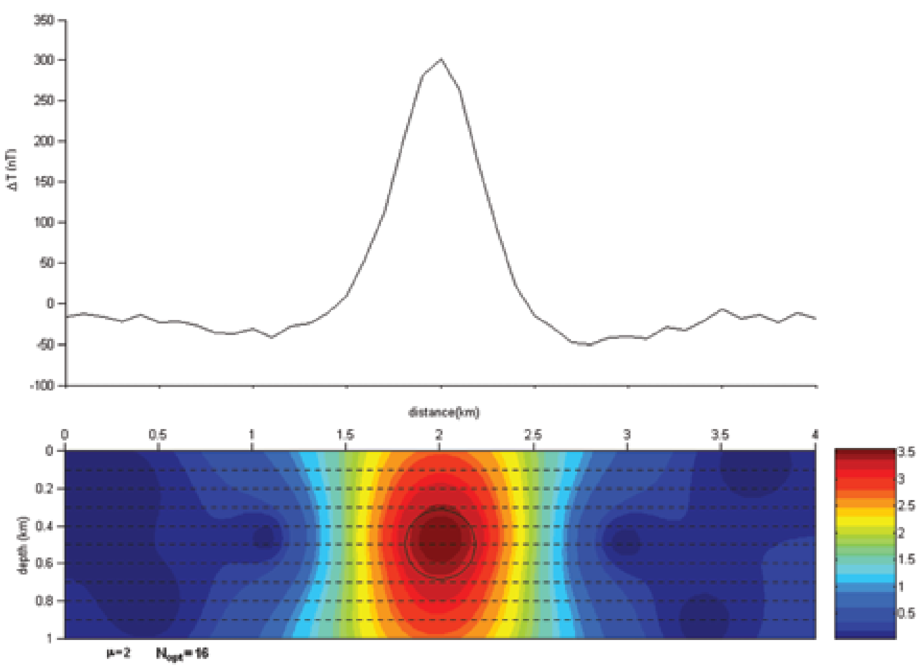

Figure 5. Total-field magnetic anomaly for a horizontal cylinder model contaminated with Gaussian random noise with standard deviation of 5.48 nT and NFG section. The dashed lines represent the downward continuation levels.

Figure 5. Uzun yatay silindirin, standart sapması 5.48 nT olan Gauss gürültülü toplam alan manyetik anomalisi ve NTG kesiti. Kesikli çizgiler aşağı uzanım seviyelerini temsil eder.

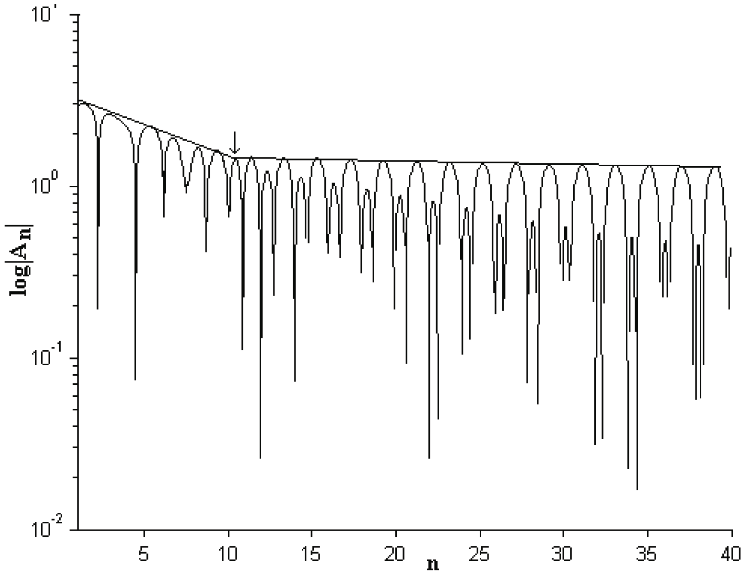

Figure 6. Logarithmic spectral analysis of total-field magnetic anomaly for a semi-infinite vertical dike model and determination of optimum upper harmonic limit. The vertical arrow marks the breaking point on the envelope of the spectrum and also defines the optimum upper harmonic of $N^{*}_{opt} = 10$.

Şekil 6. Yarı sonsuz düşey dayk modelinin toplam alan manyetik anomalisinin logaritmik spectral analizi ve optimum üst harmoniğin belirlenmesi. Düşey ok spektrumun zarfının kırılma noktasını işaretler ve aynı zamanda optimum üst harmoniği verir ($N^{*}_{opt} = 10$*).*

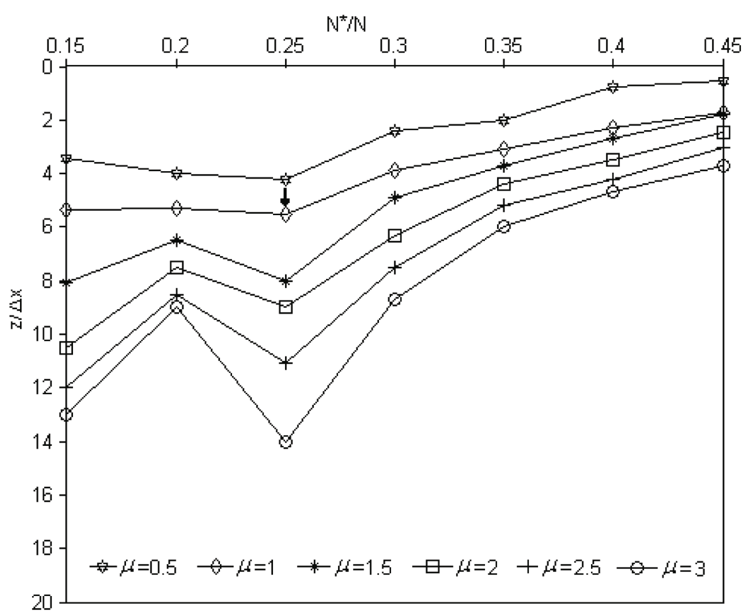

Figure 7. Changes of the depth position of NFG maximum used for the choice of the parameter μ covering a range from 0.5 up to 3 in the interval of 0.5. The vertical arrow indicates a change-point on the curve from $\mu = 1$. Note that the curve to this point is almost horizontal. The point confirms the optimum upper harmonic ($N^{*}_{opt}/N = 0.25$, $N = 40$) from Fig.6. It also defines optimum depth of $z/\Delta x = 6$, $\Delta x = 0.1$ km.

Şekil 7. Yuvarlatma parametresinin (μ *) seçimi için kullanılan NTG maksimumlarının derinlik konumlarının değişimleri. Derinlikler 0.5 km den 3 km'ye 0.5 km aralıklarda değiştirilmiştir. Düşey ok* $\mu = 1$ *'den elde edilen eğri üzerindeki bir değişim noktasını gösterir. Bu noktaya kadar eğrinin hemen hemen doğrusal olduğuna dikkat edilmelidir. Bu nokta Şekil 6'dan elde edilen optimum üst harmoniği (* $N^{*}_{opt}/N = 0.25$, $N = 40$ *) doğrular ve düşey dayk derinliğini de belirler.*

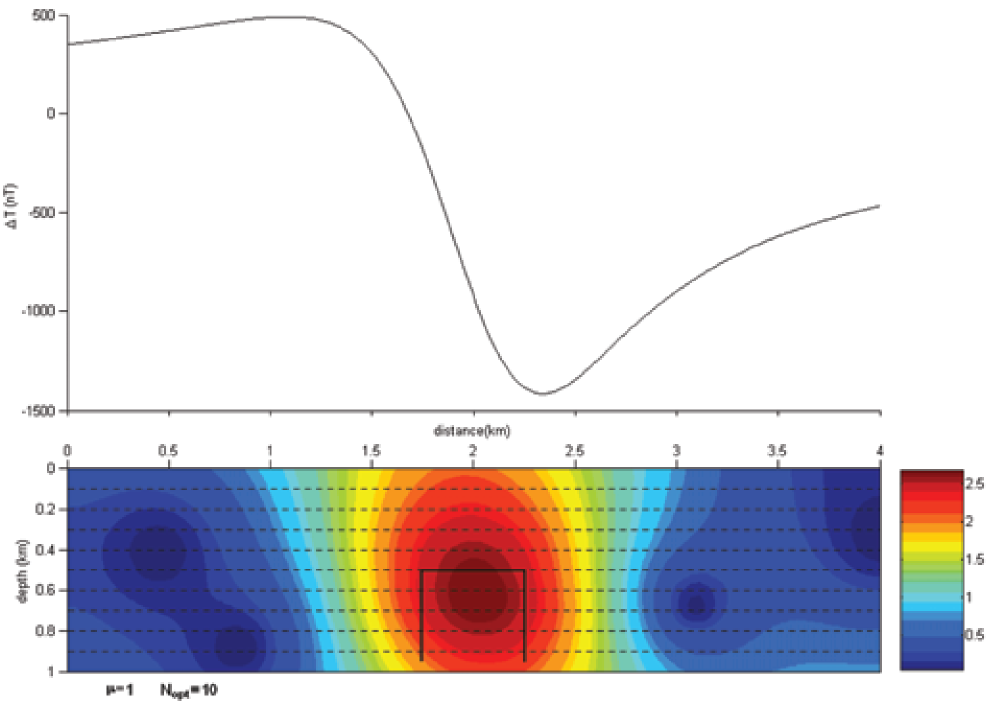

Figure 8. Total-field magnetic anomaly generated by a semi-infinite vertical dike model with a half-width of 0.25 km, a depth to its top of 0.5 km and magnetization vector at 30°. Sampling interval is 0.1 km ($M = 4$). The NFG section was computed using depth levels of 0.1 km interval. The dashed lines represent the downward continuation levels.

Şekil 8. Yarı genişiliği 0.25 km, üst derinliği 0.5 km ve mıknatıslanma vektörünün açısı 30° olan yarı sonsuz düşey dayk modelinin toplam alan manyetik anomalisi. Örnekleme aralığı 0.1 km dir ($M = 4$). NTG kesiti 0.1 km aralıklı derinlik seviyelerinde hesaplanmıştır. Kesikli çizgiler aşağı uzanım seviyelerini temsil eder.

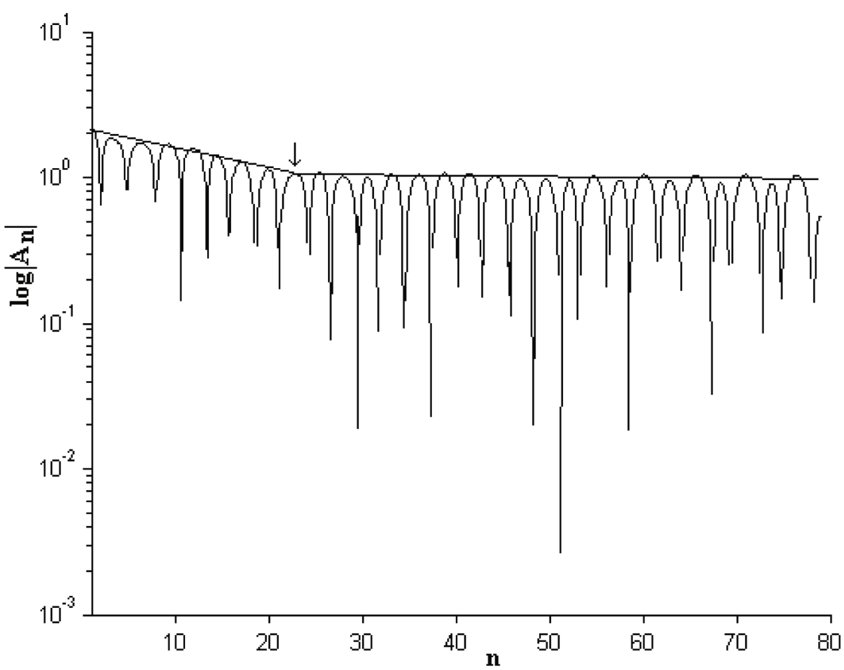

Figure 9. Logarithmic spectral analysis of magnetic anomaly in Figure 11 and determination of optimum upper harmonic limit ($N_{opt}^{\square} = 22$).

Şekil 9. Şekil 11'deki manyetik anomalinin logaritmik spektral analizi ve optimum üst harmoniğin belirlenmesi ($N_{opt}^{\square} = 22$).

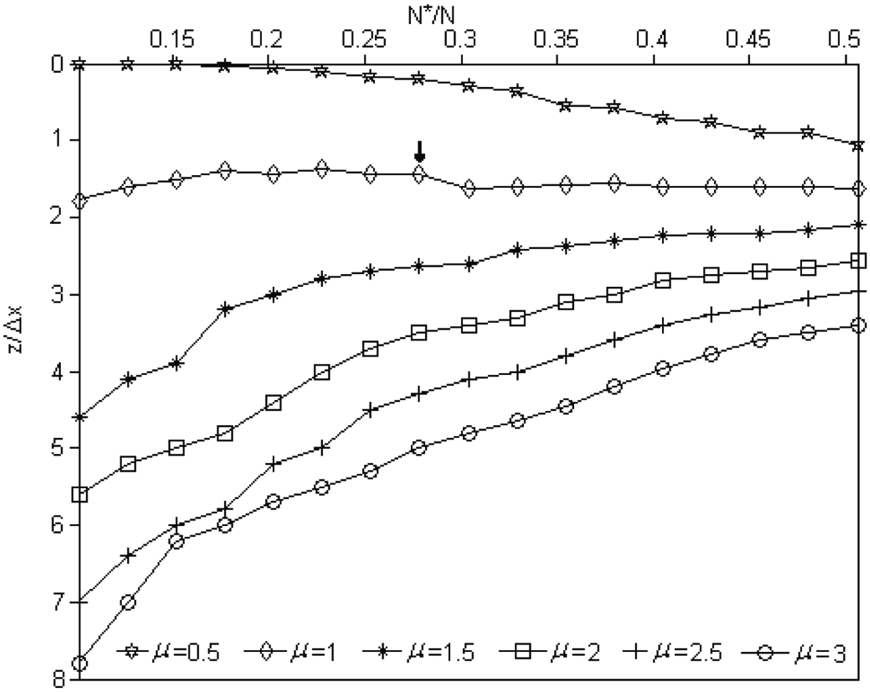

Figure 10. Changes of the depth position of NFG maximum used for the choice of the parameter μ covering a range from 0.5 up to 3 in the interval of 0.5. The vertical arrow indicates a critical change-point on the curve from $\mu = 1$. The point corresponds to the values of $N^{*}_{opt} / N = 0.2784$ ($N = 79$) and confirms the optimum upper harmonic from Fig. 9. It also defines the depth to the top of the semi-infinite vertical dike of $z / \Delta x = 1.45$, $\Delta x = 5$ m.

Şekil 10. Yuvarlatma parametresinin (μ) seçimi için kullanılan NTG maksimumlarının derinlik konumlarının değişimleri. Derinlikler 0.5 km den 3 km'ye 0.5 km aralıklarda değiştirilmiştir. Düşey ok $\mu = 1$ 'den elde edilen eğri üzerindeki bir kritik değişim noktasını gösterir. Bu nokta $N^{*}_{opt} / N = 0.2784$ ($N = 79$) değerine karşılık gelir ve Şekil 9'dan elde edilen optimum üst harmoniği doğrular ve aynı zamanda yarı sonsuz düşey dayk derinliğini de belirler ($z / \Delta x = 1.45$, $\Delta x = 5$ m).

axes of phase's synchronism of increased and lowered values of each field, a choice of these axes (zones) for interpretation, and finding of position of a source of anomaly (Elysseiva 2003). However, this method has only applied for deep research of the Earth crust using gravity data.

CONCLUSION

The main advantage of the NFG method is that it does not produce the oscillations when passing through the depths of anomalous sources. As a result, the downward continuation can be extended to the depths below the anomaly source. Other advantages of this method are that it requires calculation of only first order derivatives of the magnetic field without restricting to data of very high quality.

Tests performed on synthetic sources show a good approximation of the estimated horizontal locations and depths. The method is especially useful for detecting characteristic points of causative bodies because closed maxima of NFG fields correspond to their depths. In particular, the NFG maxima are useful in detecting centers of the compact bodies and the depth to the top of dikes with infinite depth extent. The method is more susceptible to the choice of the upper harmonic limit of Fourier coefficients than to that of the smoothing factor.

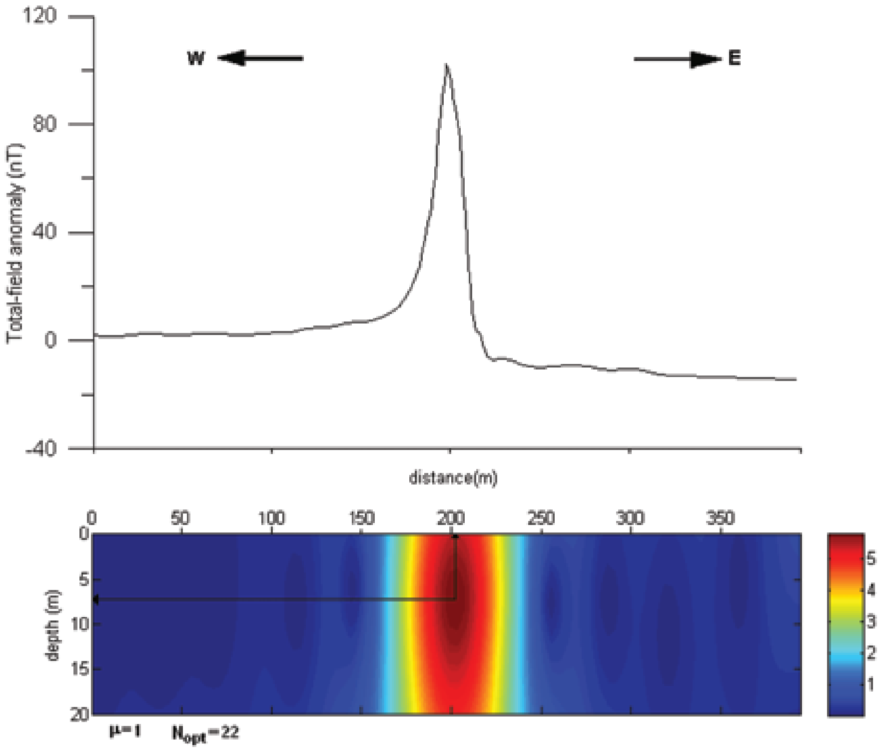

Figure 11. Ground total field magnetic anomaly from an igneous in southern Illinois, USA (Kirkham, 2001) and its NFG section calculated from $\mu = 1$ and $N_{opt} = 22$ using depth levels of 1 m interval. Profile length and sampling interval is 395 m and 5 m, respectively ($M = 80$). The dashed lines represent downward continued levels.

Şekil 11. Güney İllinois'de (ABD) yerden ölçülen ve volkanik kütle üzerinde elde edilen toplam alan manyetik anomali (Kirkham, 2001). NTG kesiti 1 m derinlik seviyelerinde ve $\mu = 1$ ve $N_{opt} = 22$ için hesaplanmıştır. Profil uzunluğu ve örnekleme aralığı sırasıyla 395 m ve 5 m dir ($M = 80$). Kesikli çizgiler aşağı uzanım seviyelerini temsil eder.

I have pointed out that logarithmic spectrum of Fourier cosines coefficients of magnetic anomaly has a marked change of slope at a point corresponding to the optimum upper harmonic limit N_{opt}. Good results have been obtained using this breaking point for theoretical and real applications. This criterion is suitable for situations, when there is only one important source or there are several sources, at approximately equal depth levels. To discern the relation between μ and depth to source z, I have presented a method based on the depth values of maximum or maxima in NFG field calculated by using various smoothing degrees. The NFG solutions show very good accuracy of the estimated depths, since it is possible to make these parameters more exact and proved. The NFG solutions show very good accuracy of estimated depths, compared to the known model depths. In addition, a correlation between the depth to the source and the estimated value of μ was observed, such as the deeper the source, the larger the value of μ.

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