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# New Methodology in Interpretation of Aeromagnetic Anomalies over Pipe-Like Sources using Analytic Signal Ratio Approach

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**Abstract**

Concepts of signal processing like Fourier transform, filtering, power spectrum, derivatives etc., are widely used in geophysical models in exploring the Earth structures. For example, quantitative interpretation of aeromagnetic maps is based mainly on choosing an appropriate model for evaluating parameters of the causative source. For circular or elliptical anomalies caused by plug-like intrusive sources, the vertical pipe of infinite depth extent (also known as single or mono pole) is most suited. It is also more common to use analytic signal maps in interpretation. For a vertical pipe, the total magnetic intensity (TMI) anomaly is anti-symmetric at the magnetic equator and progressively becomes symmetric at the pole. Based on this property, a new methodology is developed for identifying location and depth of magnetic structures beneath. It is concluded that the analytic signal is almost symmetric for any magnetic latitude and by using both the properties of the anomaly and its analytic signal the location and depth can be evaluated. This new approach is validated by field examples.

**Keywords:** Analytic signal, Aeromagnetic anomaly, Quantitative interpretation

## Introduction

Signal processing techniques are widely used in geophysical models in exploring the Earth structures. Generally analytic signal maps are prepared for ease of interpretation [1-4]. Potential field (gravity and magnetic) anomalies are normally expressed by Fourier series. Often long wavelength data indicate deep structures and short wavelengths shallow structures. When data lengths are limited like in potential field methods, the Discrete Fourier Transform (DFT) is often used. The Fourier transform is represented by a power spectrum. Then procedures like filtering and calculation of derivatives are done to enhance the characteristics of the data. Then follows qualitative and quantitative interpretation of the data [1]. In this study we explain a new procedure for deciphering the Earth structures beneath magnetic profiles. In quantitative interpretation of aeromagnetic data, it is natural to observe several anomalies that are either circular or elliptical in nature. These anomalies can be attributed to 3-D sources such as sphere, vertical prism or plug-like intrusive sources. Interpretation of the magnetic anomaly over plug–like sources are interpreted using the single pole models [5-7] etc. For understanding the nature of anomalies, the total magnetic intensity anomaly shapes at various magnetic latitudes over a vertical pipe, sphere and a vertical prism are prepared and presented here. Especially at low magnetic latitudes, it has become a common practice to prepare analytic signal maps [7-12] to ease interpretation. In a majority of cases, the analytic signal maximum is observed directly over the top of the source. A simple interpretational procedure is suggested to find the parameters of the pipe-like sources in this study.

## Materials and methods

Aeromagnetic maps often contain several circular, elliptic or bipolar anomalies of limited areal extent. These are interpreted using the pipe, sphere or prism model [13]. The anomalies of single pole, sphere and vertical-prism (shown in **Figure 1**) are calculated using the formulas and with help of python code. The results are presented using geosoft software. A comparison of anomalies caused by a vertical pipe (single pole), sphere (dipole) and vertical prism of infinite depth extent are presented here in **Figure 3**. It may be observed from **Figure 2** that the magnetic anomaly over a single pole is anti-symmetric and possess a northern low and southern high of equal magnitude at the magnetic equator (I = 0) whereas the anomaly due to a sphere and the vertical prism are predominant lows with flanking highs on either side. As the

inclination increases, the high towards the south increases with a proportional decrease of the northerly low. This kind of model anomalies are useful in choosing the appropriate model for interpretation. The album of model curves presented by Vacquier *et al.* in 1951 [14] for vertical prisms at different inclinations and various sizes of the prism, and the album of Andreasen and zeith in 1969 [15] for a 4 X 6 model for various directions of magnetization are very useful and serve as a guide for interpretation. In an x, y, z coordinate system, consider a vertical pipe at P (0, 0, z) with its bottom at infinity (very large depth extent) and magnetized in the Earth's magnetic field, the anomaly can be considered as due to a single pole. The expression for the total magnetic intensity anomaly (T) due to a single pole is written as (after [6]),

$$\Delta T = \left(\frac{p}{r^3}\right)(-x\cos(I) + z\sin(I)) \quad (1)$$

where $r^2 = x^2 + y^2 + z^2$

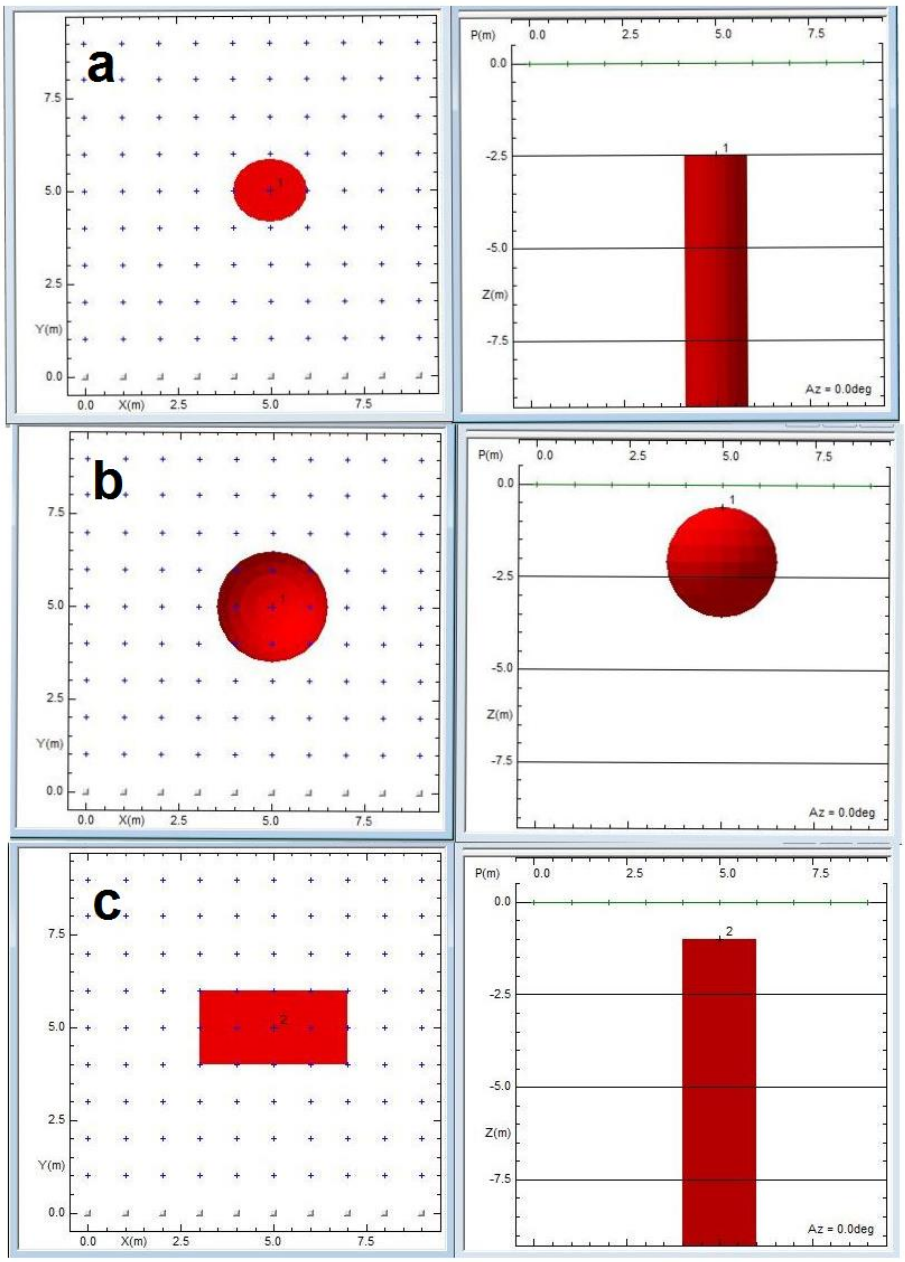


**Figure 1** The top and cross-sectional views of a) vertical pipe b) sphere and c) prism.

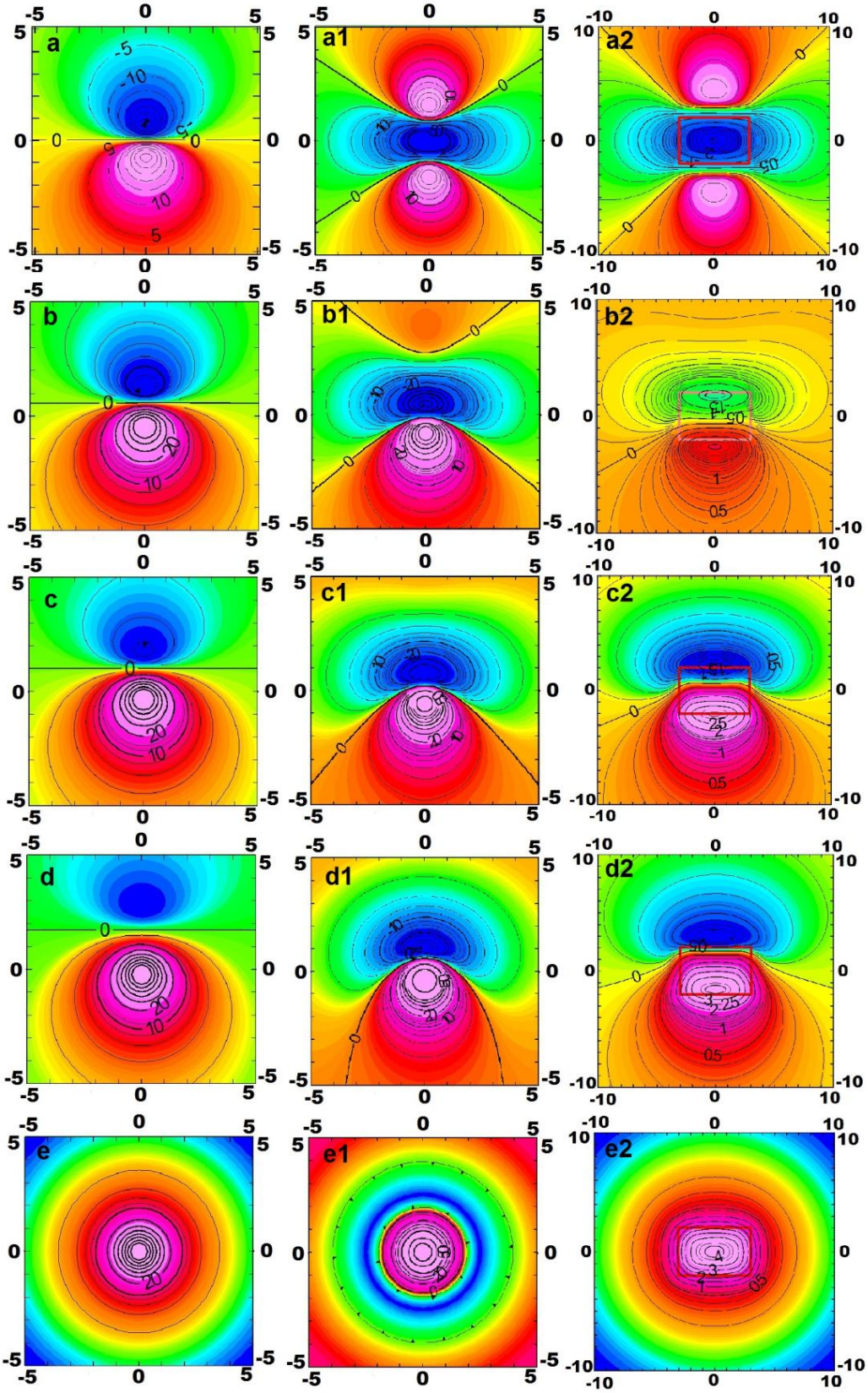


**Figure 2** Total magnetic intensity anomaly maps over a vertical pipe (a - e), sphere (a1 - e1) and verticalprism (a2 - e2) at various inclinations (I). I = 0, 30, 45, 60 and 90 degrees, respectively.

The top of the pipe is at P (0, 0, z) and 'p' is the pole strength, 'I' is the inclination of the Earth's magnetic field and 'z' is the depth. Typical anomaly profiles along the magnetic meridian passing over the top of the pipe are shown in **Figure 2** for various inclinations.

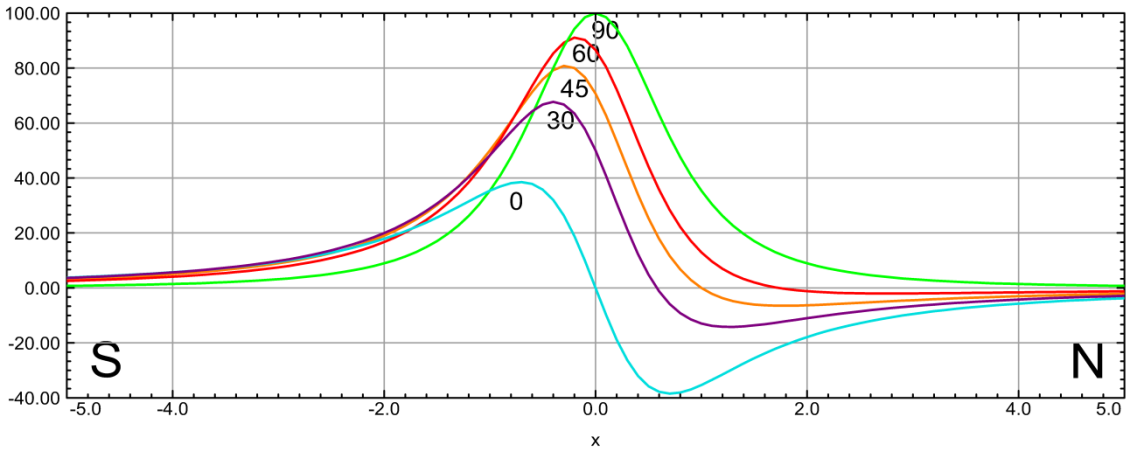


**Figure 3** Total magnetic intensity anomaly at various inclinations along the magnetic meridian passing over a vertical pipe.

From Eq. (1) and **Figure 2**, it may be noted that the anomaly curve is symmetric when I = 90, anti-symmetric when I = 0 and asymmetric in between. The maximum and minimum values of F(x, 0) occur at $X_{max}$, and $X_{min}$, respectively and are given by the expression;

$$x = \left\{3z\tan(I) \pm \sqrt{9z^2\tan^2(I) + 8z^2}\right\}/4 \quad (2)$$

The term with the minus sign gives the $X_{max}$ and that of the plus sign gives $X_{min}$. The distance between $X_{max}$ ($x_1$) and $X_{min}$ ($x_2$) is given by;

$$x_1 - x_2 = \sqrt{9z\tan^2(I) + 8z^2}/2 \quad (3)$$

According to Eq. (3),
When I = 0

$$x_1 - x_2 = \sqrt{2}z = 1.4z \quad (4)$$

Hence,

$$z = 0.71(x_1 - x_2) \quad (5)$$

When I = 90

$$x_1 - x_2 = \infty \quad (6)$$

And when I = 45

$$x_1 - x_2 = \frac{\sqrt{17z^2}}{2} = 2.06z \quad (7)$$

Hence,

$$z = 0.485(x_1 - x_2) \quad (8)$$

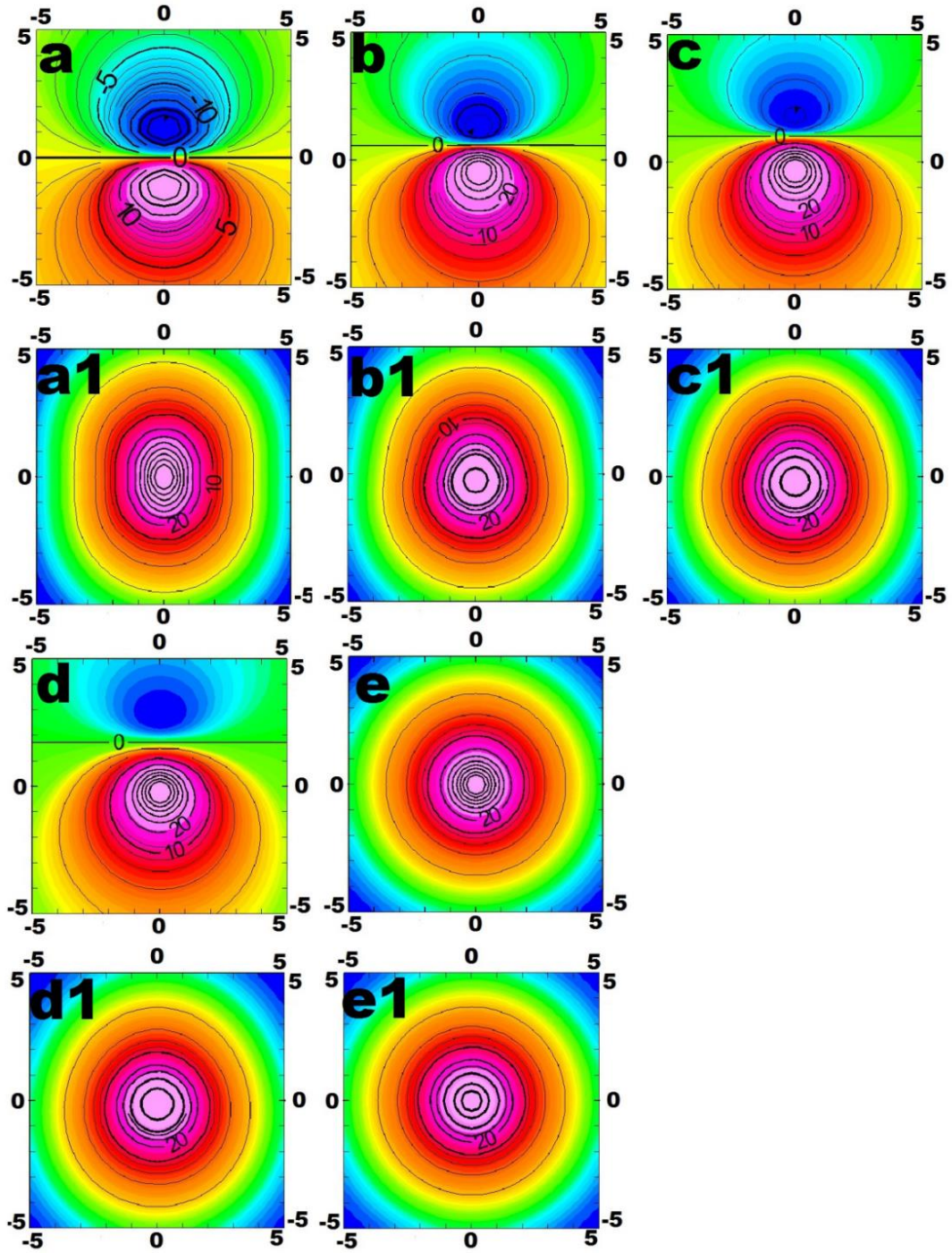


**Figure 4** Total magnetic intensity contour maps of point pole (a, b, c, d, e) and analytical signal maps (a1, b1, c1, d1, e1) at inclination 0, 30,45, 60 and 90 (depth 1 unit, and magnetization 100 units), respectively.

It may be noted from Eqs. (5) and (8) that the depth to top of the pipe varies between 0.5 and 0.7 (approximately) times the distance between the maximum and the minimum, for magnetic latitudes equal to or less than 45 degrees. Now a days, interpretation of aeromagnetic maps is assisted by analytic signal maps [12-14]. Analytic Signal is defined as the square root of the sum of the squares of the vertical and the 2 horizontal derivatives of the total magnetic field and is easy to compute at all latitudes. It is almost but not entirely independent of magnetisation direction. The shape of the analytic signal is almost symmetric as it is nearly independent of the directions of magnetization and of the Earth's field. Hence it is pertinent to examine the anomaly maps vis-a-vis analytic signal maps and profiles are shown in **Figures 4** and **5**. As

expected, it may be observed from the above maps that the shape of the anomaly changes with magnetic inclination whereas the analytic signal map is symmetric and almost circular, with its maximum cantered over the top of the pipe. This property of analytic signal maps helps us to locate the top centre of the pipe in x-y plane. The analytic signal $T_{as}$ is defined as;

$$\mathrm{T_{as}} = (\mathrm{Tx}^2 + \mathrm{Ty}^2 + \mathrm{Tz}^2)^{\frac{1}{2}} \quad (9)$$

From Eq. (1) we obtain the expressions for Tx, Ty and Tz as follows:

$$\frac{d}{dx}\Delta T = \frac{p\{(2\cos(I)x^2 - 3sin(I)xz - \cos(I)z^2 - \cos(I)y^2)\}}{r^{5/2}} \quad (10)$$

$$\frac{d}{dy}\Delta T = -\frac{\{3p(zsin(I) - \cos(I)x)y\}}{r^{5/2}} \quad (11)$$

$$\frac{\mathrm{d}}{\mathrm{dz}}\Delta \mathrm{T} = \frac{\mathrm{p}(-2\sin(\mathrm{I})\mathrm{z}^2 + 3\cos(\mathrm{I})\mathrm{xz} + \sin(\mathrm{I})\mathrm{y}^2 + \sin(\mathrm{I})\mathrm{x}^2)}{\mathrm{r}^{5/2}} \quad (12)$$

$$\Delta T_{as} = p\{sin^2(I)[r^4 - 9z^4 + 3r^2z^2] + cos^2(I)[3x^2r^2 - 9x^2z^2 + r^4] - 3xzr^2\sin(2I) + 9z^4\}^{\frac{1}{2}}/r^5 \quad (13)$$

In calculating the depth by using analytic signal it is assumed that analytic signal maximum over the pipe, x = y = 0. Under this assumption the value of the analytic signal at X = Z and Y = 0 is calculated. Also, the values are calculated at X = Y = 0. In this study the ratios $\frac{(T_{as})_{x=z,y=0}}{(T_{as})_{x=y=0}}$ are taken to define the depth of the bodies causing the anomaly. The following are the ratios at inclination at 0, 45 and 90 degrees.

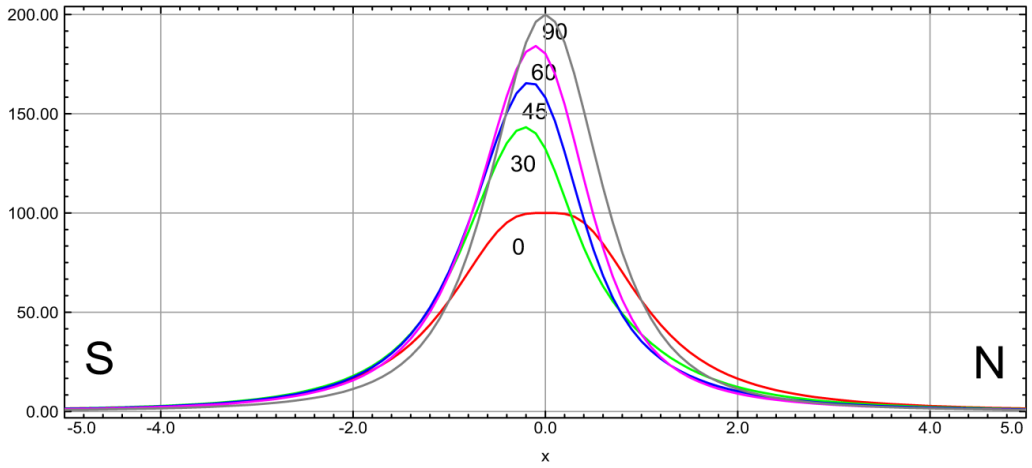


**Figure 5** Analytical signal profiles of single pole at various inclinations.

$$At\ I = 0, \frac{(T_{as})_{x=z,y=0}}{(T_{as})_{x=y=0}} = 0.559 \quad (14)$$

$$At\ I = 45, \frac{(T_{as})_{x=z,y=0}}{(T_{as})_{x=y=0}} = 0.2931 \quad (15)$$

$$At\ I = 90, \frac{(T_{as})_{x=z,y=0}}{(T_{as})_{x=y=0}} = 0.2795 \quad (16)$$

The nature of analytic signal maximums is explained in **Table 1**.

**Table 1** Ratio of where Analytical Signal equals to depth to Analytical signal maximum.

| Inclination | Ratio |
|---|---|
| 0 degree | The analytic signal maximum is at 0 as the curve is symmetric. So, the ratio towards south or north is 0.559 |
| 30 degree | The analytic signal maximum is shifted towards south from 0. So, the ratio towards North is 0.3435 and towards South is 0.3623 |
| 45 degree | The ratio towards North is 0.2931 and towards South is 0.3162 |
| 60 degree | The ratio towards North is 0.253 and towards South is 0.3189 |
| 90 degree | The curve is symmetric and the ratio is 0.2795 |

## Results and discussion

Two examples are presented here to show the approach of interpretation.

**Field example 1**

The 1st example (**Figure 6**) is an aeromagnetic anomaly observed in the Dharwar craton, south India. The area is occupied by granite gneiss with several intrusive in the form of dikes, kimberlites and gabbroic bodies. The amplitude of the anomaly is almost 550nT and it possesses a northern low and southern high of equal magnitude. The anomaly resembles the contour map of a single pole at **Figure 4(a)**. A profile along magnetic meridian (**Figure 7**) is taken and calculated the analytical signal. From **Figure 8** the analytic signal maximum is 2.9.

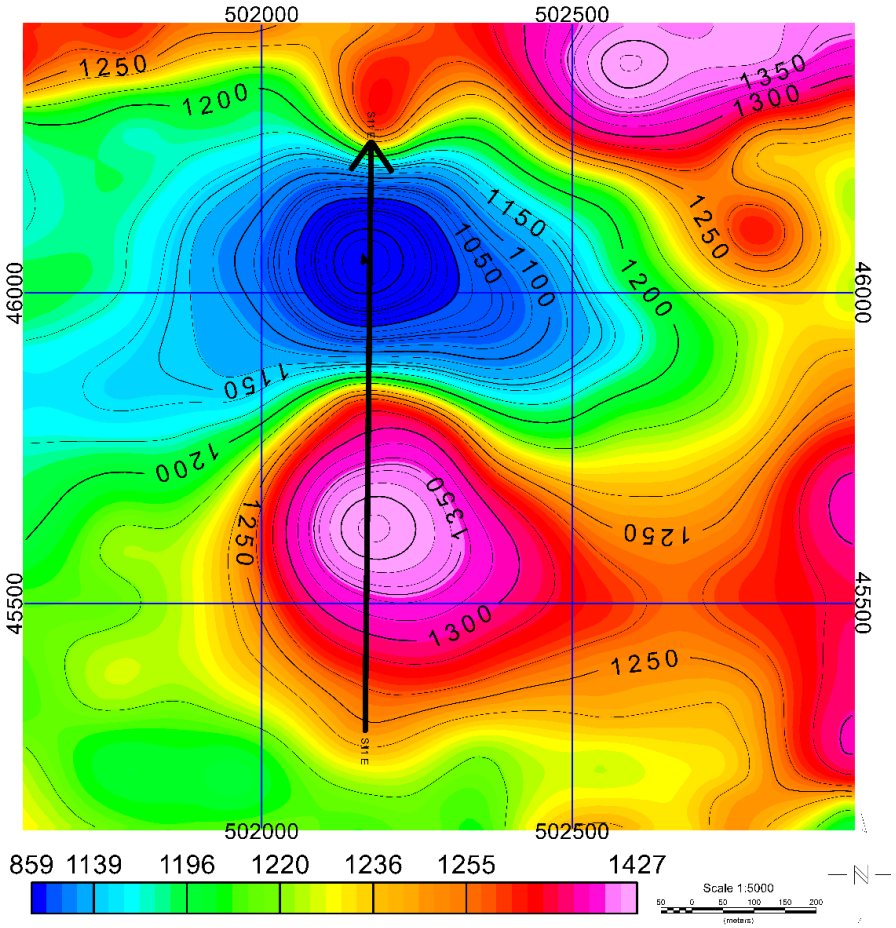


**Figure 6** Total magnetic anomaly intensity map of the study area and a profile is taken along the magnetic meridian (black line).

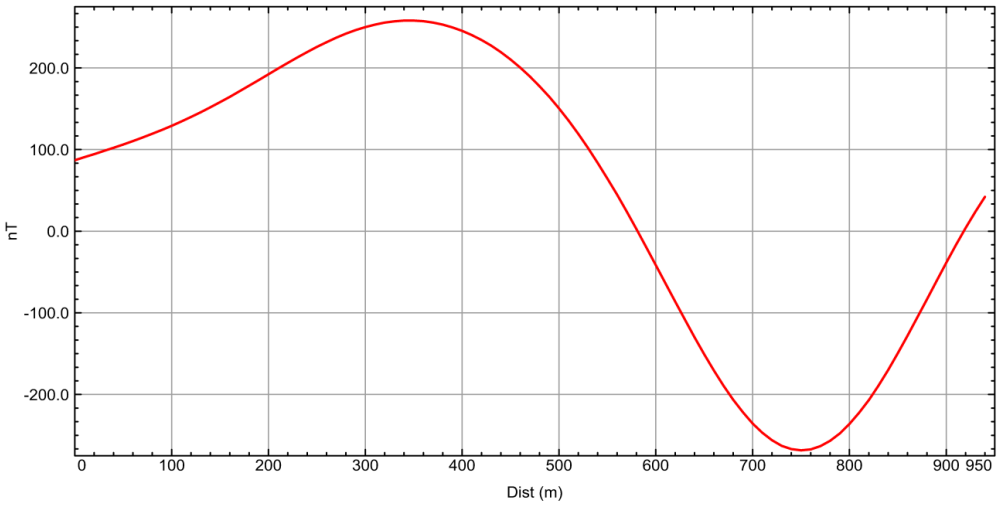


**Figure 7** Anomaly along the profile (black line in **Figure 6**).

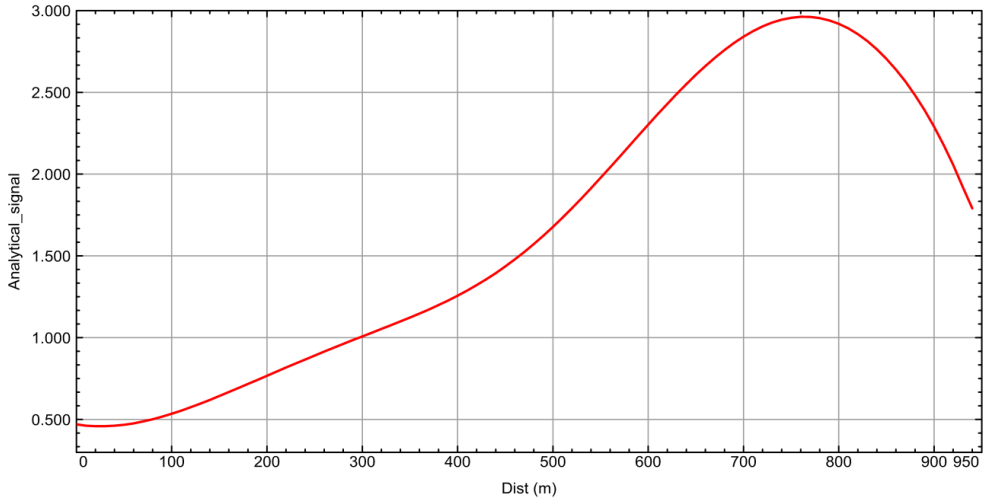


**Figure 8** Analytic signal of the observed profile.

The ratio of the analytic signal maximum to analytic signal at x = z is 0.559. To calculate the depth, simply multiply the analytical signal maximum with the ratio i.e., 2.9×0.559 = 1.6211. The distance between 2.9 and 1.6211 on the x-axis is the depth. The depth to the top from the analytic signal is 300 m. Then Calculated the depth using the work of Smellie [6], i.e., the distance from maximum to half maximum in the profile which is almost 240 m. The total intensity depth factor K (K is calculated by Smellie [6] at various inclinations and various directions) at 0 degree (K) is 1.3 and the angle between x-axis and magnetic meridian (β) is 90. The depth derived is 312 m.

**Field example 2**

The 2nd example is from south-western part of Cuddapah basin near Vempalli (**Figure 9**).

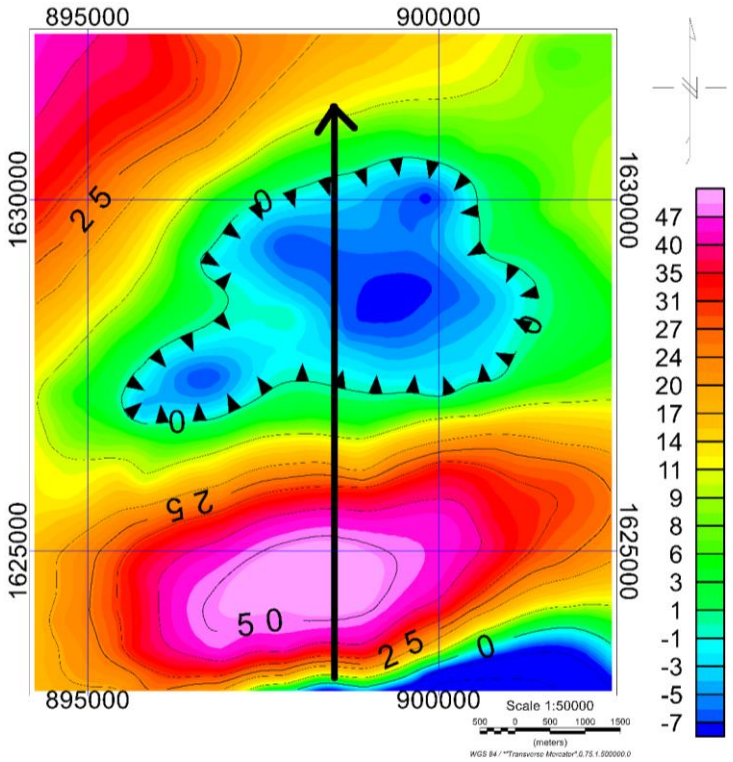


**Figure 9** Total magnetic intensity map of the study area and a profile is taken along the magnetic meridian (black line).

The anomaly is of 70nT and the anomaly minimum is weakly defined (**Figure 9**). The shape of the magnetic profile almost coincides with the profile at inclination 30 degrees (refer **Figure 3**). The analytic signal maximum is 0.08 (**Figure 11**). The ratio of the analytic signal maximum to analytic signal at x = h is 0.3435.

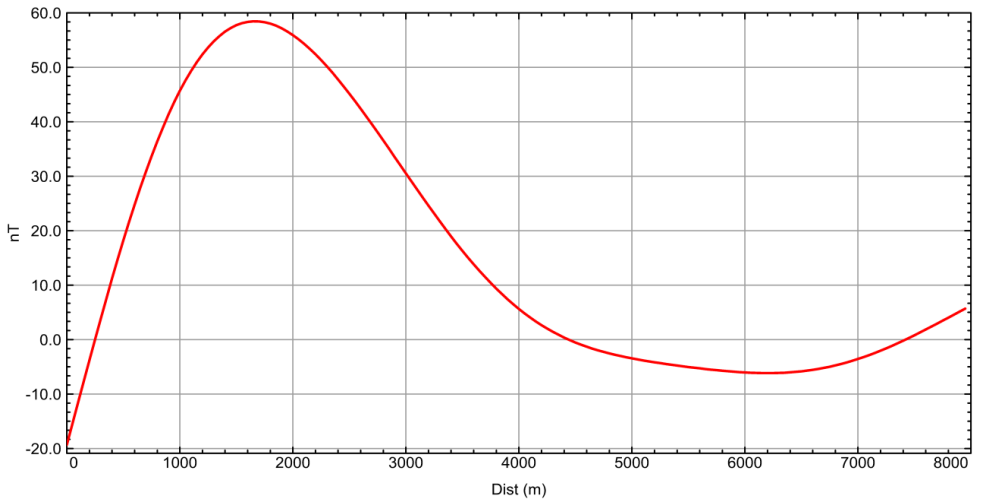


**Figure 10** Anomaly along the profile (black line in **Figure 9**).

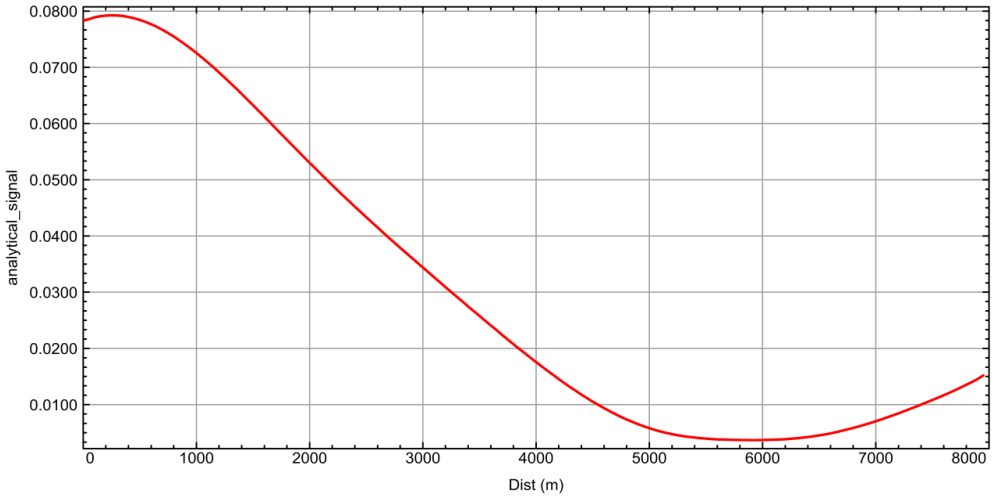


**Figure 11** Analytic Signal of the Magnetic profile of the study area.

The depth to the top is almost 3,200 m. To get an estimate of depth from [6], with I = 30 degrees and 'β' is 90 degrees as arguments, K value becomes 1.8. The value of distance at half maximum is 1,650 m from the profile (**Figure 10**). So, the depth is 1.8×1,650 = 2,970 m. The results obtained in this study are compared with other works [2,6] and are presented in **Table 2**.

**Table 2** Depths calculated from different methods.

| Field examples | Smellie's formula [6] | Telford *et al.*'s work [2] | Analytic signal ratio (proposed method) |
|---|---|---|---|
| Field example 1 | 306 | 312 | 300 |
| Field example 2 | 2,970 | 3,120 | 3,200 |

## Conclusions

The theory and application of using analytic signal to determine the location and depth to the point pole is described in this study. The method is useful in locating pipe-like (vertical cylinder, kimberlite pipes) structures. The shape of the magnetic anomaly changes with magnetic inclination whereas the analytic signal map is symmetric and almost circular, with its maximum centred over the top of the pipe. This property of analytic signal maps helps us to locate the top centre of the pipe in a horizontal plane. The analytic signal is almost symmetric for any magnetic latitude and by using both the properties of the anomaly and its analytic signal, the location and depth to the top can be evaluated. Thus, the study provides a new methodology by extensively using signal processing concepts. Further developments of this method include the extension of the theory to different kinds of geologic sources.

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