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A new edge detection method based on the analytic signal of tilt angle (ASTA) for magnetic and gravity anomalies

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Abstract

In order to obtain maximum information from magnetic and gravity anomaly maps, application of an edge detection method is necessary. In this regard two commonly used methods are derivative filters and local phase filters. In this paper, a MATLAB code is expanded to combine an analytic signal filter and a tilt angle filter as a new edge detection filter called ASTA filter. This method was demonstrated on synthetic magnetic data from 3 models and also on real magnetic and gravity data from southwest England. Findings show that the boundaries of a causative body are enhanced more accurately using this new filter, compared with other edge detection filters. The source code in MATLAB format is available from the authors on request.

Keywords: Magnetic anomaly; gravity anomaly; edge detection; derivative filters; local phase; ASTA; southwest England

1. Introduction

Magnetic and gravity imaging is a commonly used geophysical technique to identify and image subsurface targets. Interpretation of magnetic and gravity anomalies is a complex process due to superposition of multiple sources, the presence of geologic and cultural noise, and acquisition and positioning error [1]. Therefore, the results in the form of maps, etc that are obtained from magnetic and gravity surveys are influenced by noises that require application of different edge detection filters for potential field anomalies in order to enhance different features of magnetic and gravity maps and bring out subtle information [2]. In this regard there are different filters for edge detection, such as derivative-based filters and local phase filters that employ a variation of a quantity over magnetic and gravity anomalies. Both vertical and horizontal derivatives of potential field data are useful; horizontal derivative enhances edges, whereas vertical derivative narrows the width of the anomaly, thereby locating source bodies more accurately [3]. It is possible to combine vertical and horizontal derivatives of the magnetic field to achieve an analytic signal that is independent from body magnetization direction and its maximum value lies directly over the edges of the body.

However, interference effects limit its application in many cases, since detected edges from different bodies are not sharp enough to distinguish them from adjacent causative bodies. Hsu *et al* (1996) used a second order vertical derivative of the analytic signal to overcome this problem [4]. Other filters are local phase filters [4]. There are several variations of local phase filters in use, such as tilt angle, tilt derivative map and the Theta map [5]. Fundamental to these filters is local phase measuring of the potential field data over the imaged area. The disadvantage of this filter is that when deep sources are encountered, detected edges are blurred in the form of a halo. To overcome this problem, several authors have introduced new filters. Verduzco et al. (2004) suggested using the total horizontal derivative of the tilt angle (THDR) as an edge detector [6]. Cooper and Cowan (2006) introduced new phase-based filters such as hyperbolic tilt angle and second order vertical derivative of the tilt angle [5].

We expanded a MATLAB code in order to combine analytic signal and tilt angle as a new edge detection method in magnetic and gravity anomalies which removes the problems of tilt angle and analytic signal. Our method was implemented on synthetic magnetic data from 3 models and also on real magnetic and gravity data from southwest England.

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2. Analytic signal filter

There are a number of approaches that involve working with quantities that are calculated from the observed magnetic and gravity data and have minimal dependence on the magnetization direction [7, 8]. The best-known approach of this type involves the analytic signal concept introduced in 1972 [8]. It can be shown that by using the Hilbert transform, denoted as H, the vertical derivative of the magnetic and gravity field can be calculated from the horizontal derivative, allowing for a fast and accurate method of computing the vertical derivative from a given magnetic or gravity profile.

$$\partial M/\partial z = H\left[\partial M/\partial x\right] \quad (1)$$

where M is the magnetic or gravity anomaly data**.**

Further, these two quantities can be combined into a two-dimensional quantity known as the analytic signal (AS),

$$AS(x,z) = \partial M/\partial x + i\,\partial M/\partial z \quad (2)$$

where *i* denotes imaginary number.

The amplitude of the analytic signal is defined as

$$|AS(z)| = \sqrt{\left(\partial M/\partial x\right)^2 + \left(\partial M/\partial z\right)^2} \quad (3)$$

The amplitude of the analytic signal is a symmetric bell-shaped function [9, 10]. By examining its profile across a magnetic source, the analytic signal can be used in interpretation to provide an indication of the edges of the causative body.

Similarly for the three dimensional case, the analytic signal is given by [11]:

$$AS(x,y) = (\partial M/\partial x) + (\partial M/\partial y) + (i\,\partial M/\partial z) \quad (4)$$

where its amplitude is defined as

$$|AS(x,y)| = \sqrt{\left(\partial M/\partial x\right)^2 + \left(\partial M/\partial y\right)^2 + \left(\partial M/\partial z\right)^2} \quad (5)$$

As mentioned above, the maximum value of the analytic signal determines the edges of a magnetic or gravity body. However because of the interference effects from different adjacent causative bodies, the use of analytic signal in the 3-D case seems insufficient to detect geologic boundaries. Under these conditions the detected edges from different bodies are not detachable [9, 10]. Because the existing interference condition in many cases is not negligible, enhancement of its resolution or using other replacement techniques becomes important.

3. Tilt angle filter

One of the conventional local phase filters for enhancing features and causative body edge detection in potential field images is tilt angle. This filter was first developed by Miller and Singh (1994). Tilt angle is the ratio of the vertical derivative to the absolute amplitude of the total horizontal derivative, which is defined as [12]:

$$T = \tan^{-1}\left(\frac{\partial M/\partial z}{\sqrt{\left(\partial M/\partial x\right)^2 + \left(\partial M/\partial y\right)^2}}\right) \quad (6)$$

Where, M is the magnetic or gravity field. The tilt angle is positive over the source and passes through zero when over or near the edge (where the vertical derivative is zero). The horizontal derivative is maximum and negative outside the source region. The tilt angle has a range of -90 to +90 degrees and is much simpler to interpret than the analytic signal. Figure1 shows the tilt angle geometrically.

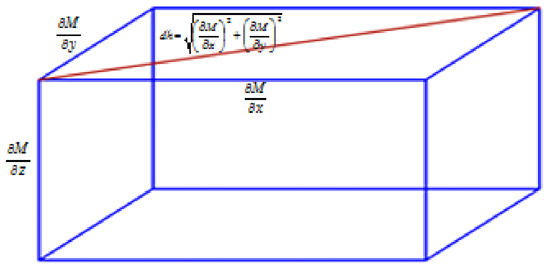

Fig. 1. Schematic diagram to illustrate the tilt angle filter

4. New edge detection filter

As mentioned above, the tilt angle filter is not applicable in deep sources because the detected edges are blurred. To overcome this problem, the analytic signal and a tilt angle filter, were combined to producing a new filter termed “ASTA[1]”, which yields more accurate results than the two separate original filters. The idea in producing this new filter is that a zero value in the tilt angle filter determines body edges that lay the between the maximum and minimum values and complicate delineation of the body edges from its map, whereas the maximum value of the analytic signal lies over body edges. Computing an analytic signal of the tilt angle produces a new filter that has its maximum value over body edges, thereby sharply enhancing the edge of the causative body without the complications of the analytic signal and tilt angle filters that were mentioned above.

[1] - Analytic Signal of Tilt Angle (ASTA).

If T implies the tilt angle of the magnetic or gravity data, the ASTA filter can be defined as follows:

$$ASTA = \sqrt{\left(\partial T / \partial x\right)^2 + \left(\partial T / \partial y\right)^2 + \left(\partial T / \partial z\right)^2} \quad (7)$$

Where, *T* is tilt angle and *ASTA* is the analytic signal of tilt angle as a new edge detection filter.

5. Application to the synthetic model

Figure 2 shows the application of the conventional and new edge detection filters on synthetic magnetic data from a vertical cylinder. The model lies at 1000m depth, its radius is 1500m, and the ambient magnetic field inclination and declination are supposed as 60 and 15 degrees, respectively. Magnetization contrast is assumed to be 3 A/m. Figure 2a shows the magnetic response of the model.

Figure 2b and 2c show the analytic signal map and tilt angle filter of the magnetic data in Fig. 2a, showing that their maximum and zero values lay on the model edge, respectively.

In these images, diagnostic interpretations of the model boundaries are difficult. Figure 2d shows the application of the new filter ASTA, which more clearly enhances the model outlines, compared to its vicinity.

Another model is magnetic prismatic body, as shown in Fig. 3. Model parameters are: 80 m width in the east-west direction, 160 m length in the north-south direction, and a burial depth of 500m. It is also assumed that the magnetization intensity is 5 A/m^{-1}, the magnetic inclination and declination of the model are 45 and 30 degrees, and the inclination and declination of the ambient geomagnetic field are 50 and 5 degrees, respectively.

Figure 3a is the total magnetic response of the body. Figure 3 b is the analytic signal map of the data from Fig. 3a. Figure 3c is the tilt angle map of the data from Fig. 3a, and Fig. 3d is a map of the ASTA filter as a new edge detection filter. From Figures 3b, 3c and 3d, it can be seen that the ASTA filter has the best results relative to the other edge recognition methods.

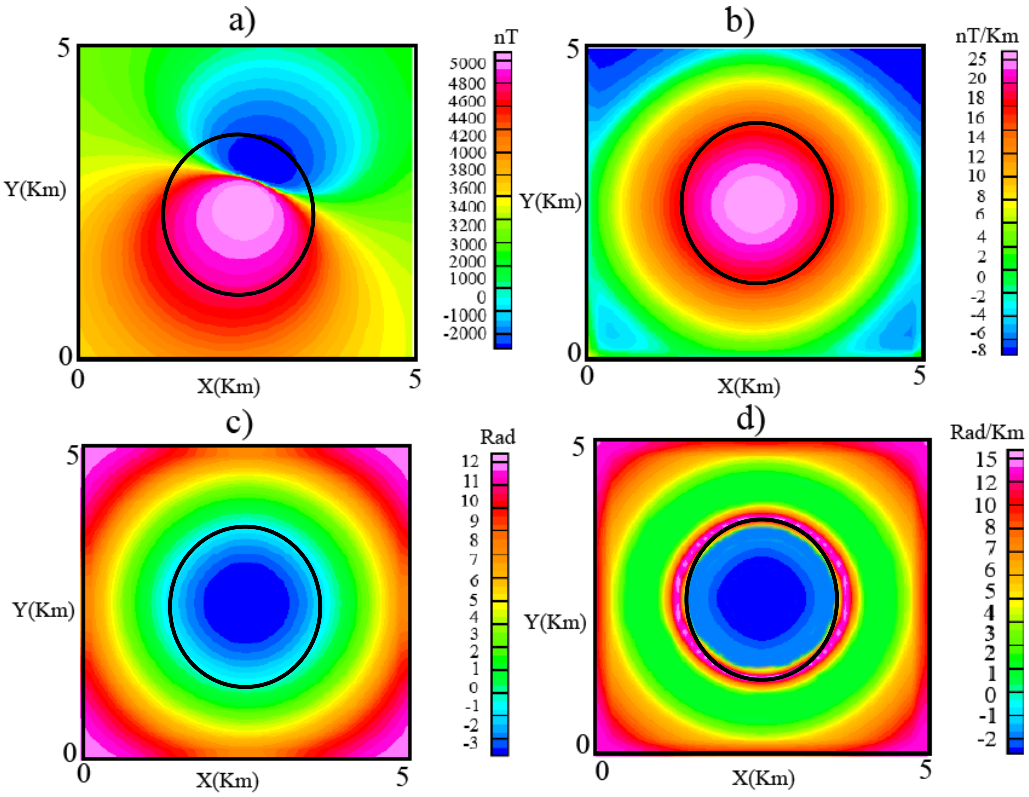

Fig. 2. Application to synthetic magnetic data from a vertical cylinder body. The magnetic response has been produced for an inclination and declination of 60 and 15 degrees, respectively. (a) Total magnetic response of the model. (b) Analytic signal map of the data in (a). (c) Tilt angle filter of the data in (a). (d) ASTA filter of the data in (a), which sharply enhances body outlines. The black circle represents the cross-sectional boundaries of the vertical cylinder.

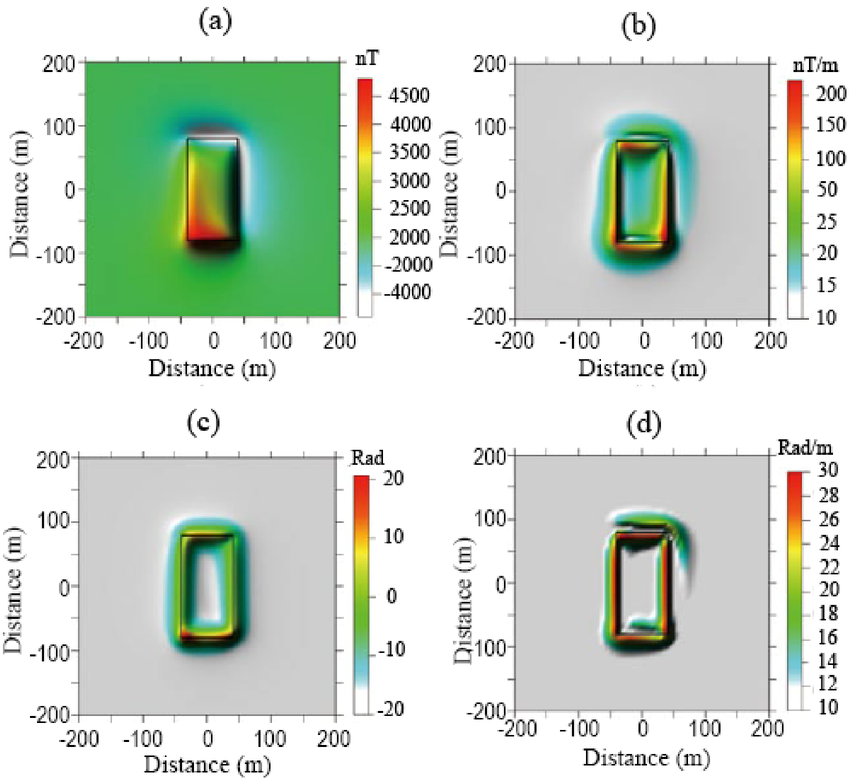

Fig. 3. Application of edge recognition filters to synthetic magnetic data from a prismatic model. (a) total magnetic response of the model with magnetization intensity equal to $5A/m^{-1}$. (b) analytic signal map of the data in Fig. 3a. (c) tilt angle map of the data in Fig. 3a. (d) Application of the ASTA filter of the data in Fig. 3a.

Model 3 is a combination of three same-sized but different depth magnetic vertical prismatic models (Fig. 4). The magnetization intensities of each model are 2.1 A/m^{-1} and each is 40 m wide in the east-west direction, 160 m long in the north south direction, and buried at 50 m, 65 m, and 80 m depth, respectively. The three prisms are separated by a 90 m horizontal distance in east-west direction. The magnetic inclination and declination of the both model and the ambient geomagnetic field, are 90 and 0 degrees respectively.

The objective of such a model is to test the ability of this new method to recognize the edges of deep geological bodies at different depths. Figure 4a is the magnetic anomaly map of the model. Figure 4b shows the results calculated by the analytic signal method and Fig. 4c is the results from the application of the ASTA filter. As can be seen from Fig. 4, the edges of the bodies at different depths are enhanced more sharply by the ASTA filter than by the analytic signal or tilt angle filters applied separately.

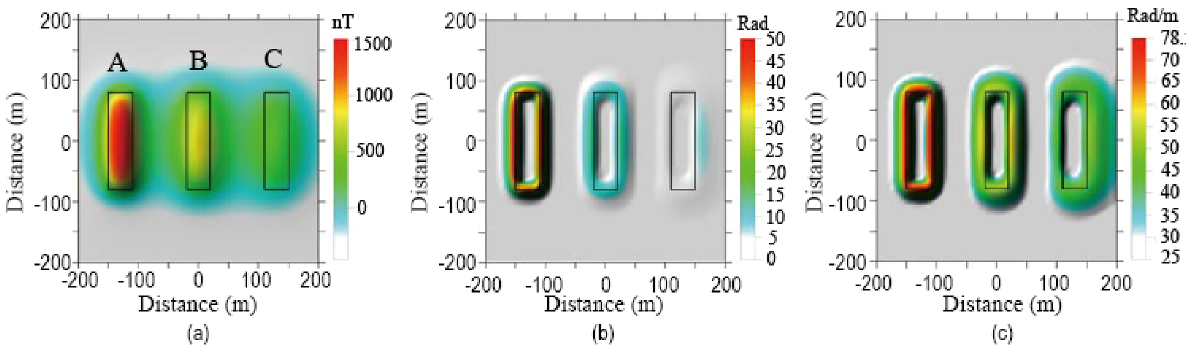

Fig. 4. Application of the edge recognition filters on three similar prismatic models. The buried depths of prisms A, B and C are 50, 65 and 80 m, respectively. (a). total magnetic response of the models. (b). analytic signal map of the data in Fig. 3a. (c) ASTA map of the data in Fig. a

6. Application to real magnetic and gravity data

The Cornubian Batholith of southwest England underlies the counties of Cornwall and Devon, running down the axis of the peninsula for in excess of 200 km. It is exposed onshore in five major plutons (east to west: Dartmoor, Bodmin Moor, St Austell, Carnmenellis and Land's End) [10, 13]. It outcrops further west at the Scilly Isles (28 km west of Land's End) and beyond (gravity surveys in 1963-65 by the Bedford Institute of Oceanography indicated a 100 mile seaward extension of the batholith). The Haig Fras granite bosses, 95 km WNW of the Scilly Isles, out in the Western Approaches are also of Variscan age [14] though appear to represent a separate plutonic body. The batholith intrudes a succession of deformed, low-grade, regionally metamorphosed sediments and igneous rocks of Devonian and Lower Carboniferous age (Fig. 5). The rocks of the batholith are granitic [10, 13] in nature and their origin is related to the later stages of the Variscan Orogeny (late Carboniferous) that had previously deformed [14] and metamorphosed the sedimentary pile. The batholith is also highly mineralized and this mineralization has been exploited by deep mining continuously for the last 400 years within local records, and for some 2000 years prior to that by shallow surface mining and working placer deposits. This area has been used as a model for vein mineralization and contributed significantly to the understanding of ore forming processes. South-west England has undergone major thrusting and faulting during the Variscan orogeny and consequently there are a large number of structural lineaments present in both study areas. The identification of basement lineaments, that represent deep faults that may have acted as a conduit for mineralizing fluids, is important in the definition of the prospective areas [14, 15 and 16].

The first substantial geophysical work to be undertaken across Cornwall was a pendulum gravity survey by Bullard & Jolly (1936). This survey established the pattern of bouguer anomalies (with pronounced negative anomalies over the granite outcrops) across the peninsula, but made no interpretation of the results. This work was followed up by a major survey (acquiring gravity and magnetic data) in the late 1950's covering Cornwall, Devon and Somerset. The results of this survey were published in 1958 [14] and this seminal work has formed the basis of the gravity interpretation of the batholith to the present day. Regional gravity data collected as part of a national survey by the BGS have a distribution of about one station per km^2.

Regional reconnaissance magnetic surveys carried out by (British Geological Surveys (BGS)) in the 1950s identified a prominent high frequency aeromagnetic anomaly in the central area of Devon and east Cornwall which approximately follows the mapped outcrop of Lower Carboniferous strata along the northern margins of the Dartmoor and Bodmin Moor granites. The form of the magnetic anomaly indicates that its source has a strong Natural Remnant Magnetisation (NRM) vector. The most important ferromagnetic mineral in the area was shown to be pyrrhotite, which has a Curie temperature in the range 270-330° C. The pyrrhotite appears to have been formed at about the time of granite intrusion, either by metasomatism or by recrystallisation of syngenetic pyrite [14, 15 and 16].

The present investigation concerns both the gravity and magnetic dataset in order to enhance Cornwall structure from magnetic data and the gravity body’s locations and their separating faults from gravity data. Figure 6a shows the aeromagnetic data set from the study area, and Fig. 6b shows its first order vertical derivative. Figure 6c is the total horizontal derivative filter of magnetic data. Both images are dominated by the high-amplitude anomalies. Since the aeromagnetic data often contain anomalies with a large range in amplitude (for example the data from southwest England) then the processed aeromagnetic images, such as horizontal and vertical derivatives, similarly contain features with large and small amplitudes. It is possible that the smaller amplitude anomalies might be of considerable geologic interest, but they can be hard to delineate among those of larger amplitude. Figure 6d is the analytic signal of the data in Fig. 6a. In this image the maximum values are located over causative bodies, similar to vertical and horizontal derivative filters, and the results dominated by large magnetic amplitude in the northern part. In other words there is no balance between the output results. Figure 6e shows the tilt angle map of the aeromagnetic data in Fig. 6a. In this image the Cornwall structure enhanced truncated, so there is no connectivity between different features. Figure 6f is the ASTA filter, which provides the best resolution of the magnetic markers in the Cornwall structure.

Fig. 7a shows a gravity map of southwest England, displaying intense low gravity with NE-SW trends, corresponding to Cornubian granite batholith. This batholith has previously been modeled using gravity data [16]. It has been shown that the batholith widens from about 10 km near the surface to between 30 and 50 km at the base, which is at a depth of between 10 and 12 km [14, 15 and 16]. In order to enhance the boundaries of the granite batholith and to separate faults the analytic signal of the gravity data was computed, as shown in Fig. 7b. Due to the interference effects of granite batholiths the detected boundaries are blurred, showing no detachment between granite bodies. In Figure7c the tilt angle filter is displayed. Figure 7d is the ASTA filter. its maximum lies over granite batholiths, and the separating faults and margin of the granite bodies are enhanced with respect to the surroundings.

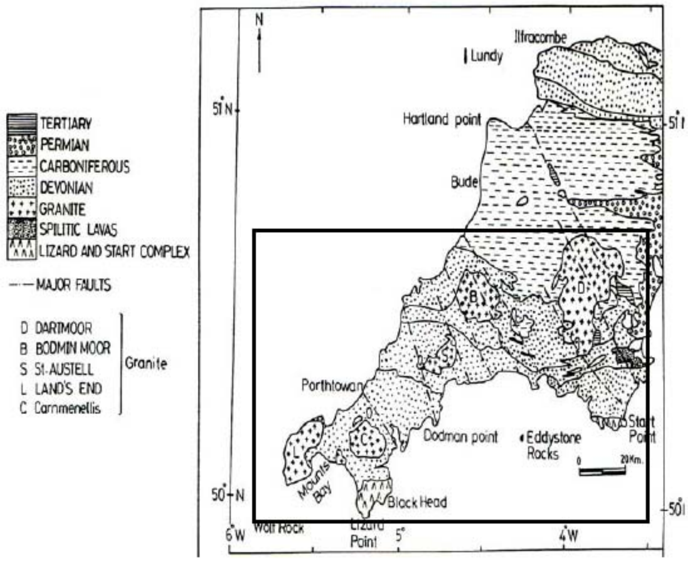

Fig. 5. A simplified geological map of the Cornubian massif in southwest England [13]. The black rectangle shows the area covering magnetic and gravity surveys which maps represented in Figs 6 and 7.

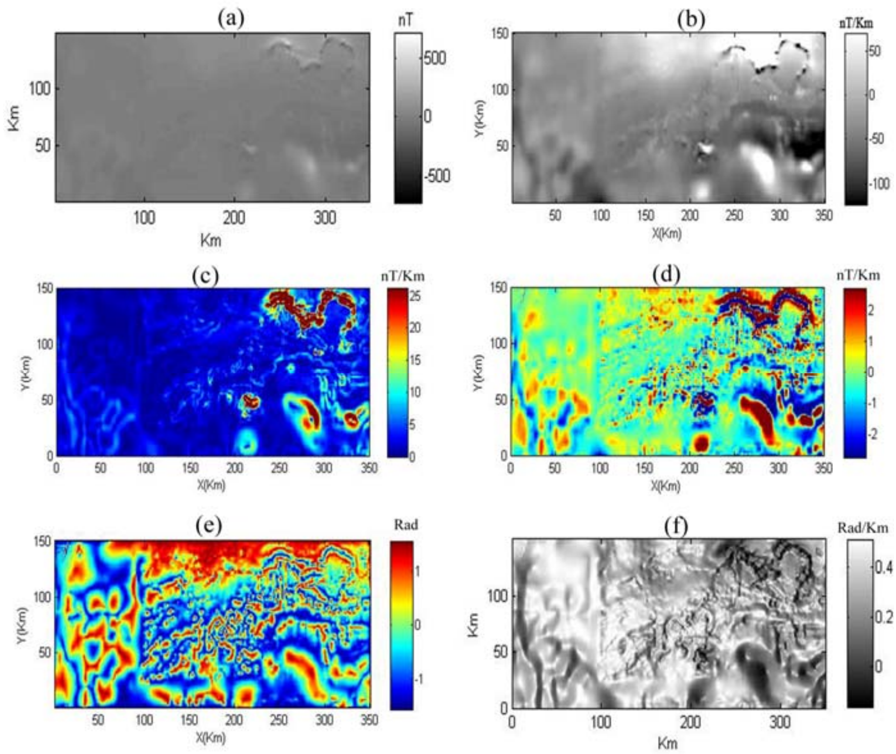

Fig. 6. Application of the proposed filters on aeromagnetic data from southwest England. a) aeromagnetic map of the study area. b) Vertical derivative map of the magnetic data in Fig. 6a. c) Total horizontal derivative map of the magnetic data in

Fig. 6a. d) Analytic signal map of the magnetic data in Fig. 6a. e) Tilt angle map of the data in Fig. 6a. f) ASTA filter map of the magnetic data in Fig. 6a.

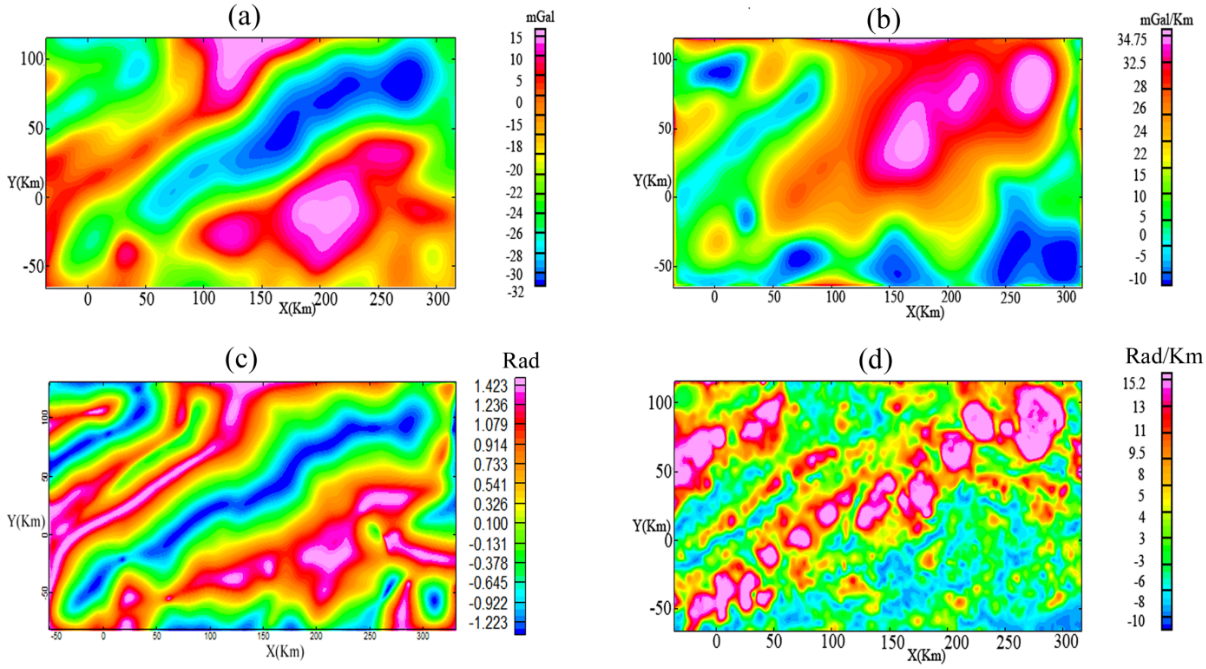

Fig. 7. Application of the proposed filters on gravity data, southwest England. a) Bougeur gravity map of the study area. b) Analytic signal map of the gravity in Fig. 7a. c) Tilt angle map of the data in Fig. 7a. d) ASTA filter map of the gravity data in Fig. 7a.

7. Conclusion

Since a magnetic or gravity anomaly map can be considered as an image, various filters can be used to reduce noise and enhance the signal-to-noise ratio. The analytic signal, or total gradient filter, is a combination of horizontal and vertical derivatives. The tilt angle filter is a conventional phase-based filter defined as a ratio of the vertical derivative to the absolute value of the total horizontal derivative. In this paper a new filter was defined that was produced by a combination of the analytic signal and the tilt angle filters, which has greater applicability and accuracy in edge detection and image processing than the original filters separately.

We studied the performance of the proposed method relative to other filters on synthetic models in different circumstances, including single and multiple bodies located at different depths. From the results of the edge recognition of the new filter, it is concluded that the ASTA filter is insensitive to superficial noises and its results are adequately stable even in the case of interference from neighboring sources. Unlike other edge detection methods for which the magnetic data must be converted into pseudo-gravity images or RTP prior to application, the ASTA filter can be applied to the magnetic dataset directly.

This method also was tested on aeromagnetic and gravity data from the Cornubian Batholith in southwest England in order to investigate its capabilities for real potential field data. In this regard, the analytic signal, tilt angle, and new ASTA filters were used and their results were compared with each other. Findings show that the ASTA filter has some advantages in comparison to other filters in determining the Cornwall structures from magnetic and gravity data.

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