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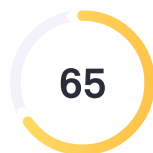
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11

Mixed dialects of english



16

Wrong or missing prepositions



1

Conjunction use



7

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13	Incorrect noun number	<div><div></div></div>
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1

APPLICATION OF GENERALIZED DERIVATIVE OPERATOR ON BOUGUER
ANOMALY FOR DETECTING GEOLOGICAL STRUCTURES

APLIKASI OPERATOR TURUNAN UMUM PADA ANOMALI BOUGUER UNTUK
MENDETEKSI STRUKTUR GEOLOGI

Dicky Ahmad Zaky^{1,2*}, Alissa Bilqis¹

¹Geophysical Engineering Department, Universitas Pertamina

²Center for Geosciences Artificial Intelligence and Advanced Computing,
Universitas Pertamina

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Correspondent Email:

dicky.az@universitas
pertamina.ac.id

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Abstract. Generalized Derivative Operator (GDO) is one of the first-order derivative filters that could control the derivative's direction by modifying the value of azimuth (θ) and dip (ϕ) parameters. This study aims to examine those GDO parameters on synthetic Bouguer anomaly and apply them to field data of the Silver Peak geothermal field to identify the geological structures. We use Python programs to conduct the GDO and other derivative operators such as horizontal gradient (HG), analytic signal amplitude (AS), as well Second Vertical Derivative (SVD) for comparison. The derivative operators are performed in the Fourier domain and spatial domain. The results from synthetic data show that

GDO can amplify the response both on local and regional anomalies.

Nevertheless, enhanced local and regional anomaly might be shown as the same maximum value of GDO, it appears that GDO disregard the influence of density contrast and depth variation of the anomalous body. Subsequently, anomaly enhancement of Silver Peak area shows that GDO anomaly concurred with geological map. GDO and SVD could amplify the response of geological structures such as intrusive granite, fault lineaments, and lithological contact, as well as the horst-graben structure, as mentioned in previous studies, that might be acting as fluid pathways for the Silver Peak geothermal system.

Abstrak. Operator Turunan Umum atau Generalized Derivative Operator (GDO) merupakan salah satu filter turunan orde pertama yang mampu mengontrol arah turunan dengan memodifikasi nilai parameter sudut azimuth (θ) dan kemiringan (ϕ). Penelitian ini bertujuan untuk menguji parameter GDO pada anomali Bouguer sintetik dan mengaplikasikannya pada data di lapangan panasbumi Silver Peak untuk mengidentifikasi struktur geologi. Kami menggunakan program Python untuk menerapkan GDO dan operator turunan lainnya seperti, horizontal gradient (HG), analytic signal amplitude (AS) serta Second Vertical Derivative (SVD) sebagai pembanding. Operator turunan dilakukan dalam domain Fourier dan domain spasial. Hasil dari pengujian data sintetik menunjukkan bahwa GDO mampu untuk meningkatkan respon baik dari anomali lokal maupun regional. Namun demikian, anomali lokal dan regional yang ditingkatkan mungkin saja menunjukkan nilai maksimum GDO yang sama, tampaknya GDO mengabaikan pengaruh dari variasi kontras densitas dan kedalaman dari sumber anomali. Selanjutnya, peningkatan anomali di area Silver Peak menunjukkan bahwa anomali GDO sesuai dengan peta geologi. GDO dan SVD dapat meningkatkan respon dari struktur geologi

seperti, intrusi granit, kemenerusan sesar, dan kontak litologi, serta struktur horst-graben yang disebutkan dalam studi terdahulu, yang mungkin berperan sebagai jalur fluida sistem panasbumi Silver Peak.

INTRODUCTION

Anomaly enhancement and isolation using the derivative of potential field data such as gravity data is generally used in almost all geophysical exploration.

Most of them are intended to understand the geological features and structures around the surveyed area which are often covered by regional responses and noisy data. Either first or second derivatives help to give a general image of those features and structures.

Numerous methods were developed and frequently used among geophysicists to isolate and enhance gravity anomaly using its derivatives, such as horizontal gradient, analytic signal amplitude, and second vertical derivative.

Another anomaly enhancement method is the Generalized Derivative Operator (GDO) introduced by Cooper & Cowan (2011). It is a combination of first horizontal and vertical directional derivatives which are controlled by two angles, azimuth, and dip, and later divided by analytic signal amplitude. Cooper (2017; 2018), Cooper & Cowan (2011), and Khalil et al. (2015) show promising results of GDO to identify small and linear geological features.

Nevertheless, it is possible to perform derivation of potential field data on both spatial and frequency domains by mathematical approach. We use finite¹

difference (FD) for derivation in the spatial domain and fast Fourier transform (FFT) for derivation in the frequency domain. In this study, we adopt the Python package developed by Uieda et al. (2013) and Melo & Barbosa (2020) to perform the routine derivative and develop the GDO Python program.

Furthermore, this study is intended to recognize how to determine the appropriate angles of GDO and interpret the result of GDO which is later compared to analytic signal amplitude, horizontal gradient, and second vertical derivative. The other three derivative filters are used because all methods are widely applied to potential field data and are considered to be quite powerful to detect edges and anomalous bodies.

Various synthetic data and the Complete Bouguer Anomaly of Silver Peak are used to test GDO parameters. The CBA is filtered out from Alum and Silver Peak Complete Bouguer Anomaly data points using Verde (Uieda, 2018) module for acquiring only gravity data points around the Silver Peak area.

LITERATURE REVIEW

Silver Peak Geothermal Area

Silver Peak area is part of the geothermal explorations in Esmeralda County, where the trans-tensional Walker Lane belt structure zone separates the Sierra Nevada block on the west and extensional Basin-Range on the east. According to the G&G report by Practical Geophysics (2008) and (Hulen, 2008) in Figure 1, there lays Goat Island horst-graben from Clayton Valley to Mineral Ridge. This feature acts as a hot fluid path for Silver Peak geothermal system.

Silver Peak geothermal system is a heat-sweep system, where a geothermal system is formed from hot deep fluid circulation in an active tectonic environment (continental rifting (Hochstein & Browne, 2000) and does not associate with volcanism. Surface manifestation presence, Quaternary hot-spring sinter, points out the existence of this feature. The existence of horst-

graben, high-angle fault, and granite in the Silver Peak geothermal area was identified from a previous gravity study (Figure 1). It is intriguing to inquire how GDO will enhance and isolate the anomaly of horst-graben, high-angle fault, and granite.

Figure 1. (a) Complete Bouguer Anomaly Map of Silver Peak Area with interpreted High-Angle Fault. (b) Cross Section of C-C' showing anomaly of gravity profile and schematic interpretation of High-Angle Fault (Practical Geophysics, 2008b). (c) Conceptual model of Silver Peak geothermal system which is controlled by complex fault system (Hulen, 2008).

Derivative of Gravity Data

The derivative filters are based on the horizontal and vertical derivation of gravity data. The derivation is performed on the frequency and spatial domain using Fast Fourier Transform (FFT) and the central finite difference (FD) approach defined by Blakely (1995). For derivation on the frequency domain, the n-order derivatives of gridded gravity anomaly (gz) on x , y , and z -axis were described by the equations as follows,

$$\frac{\partial^4 gz}{\partial x^n} = F^{-1} i k_x^n F(gz) \quad (1)$$

$$\frac{\partial^6 gz}{\partial y^n} = F^{-1} i k_y^n F(gz) \quad (2)$$

$$\frac{\partial^8 gz}{\partial z^n} = F^{-1} k_z^n F(gz) \quad (3)$$

where,

$$k_z^n = k_x^2 + k_y^2 \quad (4)$$

F is the FFT operator to transform spatial domain data (gz) to the frequency domain and will be inverted back to the spatial domain using IFFT operator F^{-1} .

The n is the derivation order while k is the wavenumber.

Padding and tapering were applied to the data before derivation using FFT to add extra columns and rows around the interpolated data matrix so that the grid dimensions would become even powers of two and also add artificial values on the padded area to preserve the edges of the data matrix (Khalil et al., 2015).

Subsequently, the first derivative on the spatial domain was performed using finite difference¹¹ which is described by the equation as follows,

$$\frac{\partial g_{z,i,j}}{\partial x} = \frac{g_{z,i+1,j} - g_{z,i-1,j}}{2\Delta x} \quad (5)$$

$$\frac{\partial g_{z,i,j}}{\partial y} = \frac{g_{z,i,j+1} - g_{z,i,j-1}}{2\Delta y} \quad (6)$$

the i and j are indices of 2D matrix g_z ¹⁶ which correspond with x and y -direction. Δx and Δy ¹⁷ is the distance of grid points.

DATA AND METHODS

Derivative Operator

The derivative operator is developed based on variation and association between derivatives of the potential field in x , y , and z axes which is already described in Section 2.2.

The derivative operator such as horizontal gradient, analytic signal amplitude, and second vertical derivative will result in a higher frequency response that enhances and localises¹⁹ the response of the source.

In this paper, the results from GDO and common derivative operator, are compared by applying them to the synthetic data and field data. Table 1 shows the equation of Generalized Derivative Operator (GDO) and derivative operator that is used in this paper.

Table 1. Derivative operator equation.

Derivative Operator

Formula

Horizontal gradient (HG)

$$H = \partial f / \partial x^2 + \partial f / \partial y^2 \quad (7)$$

Analytic Signal Amplitude (AS)

$$AS = \partial f / \partial x^2 + \partial f / \partial y^2 + \partial f / \partial z^2 \quad (8)$$

Second Vertical Derivative (SVD)

$$\partial^2 g_z / \partial z^2 = -\partial^2 g_z / \partial x^2 - \partial^2 g_z / \partial y^2 \quad (9)$$

Generalized Derivative Operator (GDO)

$$GDO = \partial f / \partial \theta \partial \phi \quad AS = \partial f / \partial x \sin \theta + \partial f / \partial y \cos \theta \cos \phi + \partial f / \partial z \sin \phi \partial f / \partial x^2 + \partial f / \partial y^2 + \partial f / \partial z^2 \quad (10)$$

Generalized Derivative Operator

Generalized²⁰ Derivative Operator (GDO) is defined as a directional derivative filter. Mlsna and Rodríguez (2009) defines "2D directional derivative" by,

$$\partial f / \partial \theta = \partial f / \partial x \cos \theta + \partial f / \partial y \sin \theta \quad (11)$$

with θ as an angle to the horizontal x-axis, assuming the axis has an east-west orientation. Cooper and Cowan (2011) reverses²¹ its angle to follow the azimuth of the geographic coordinates, changing equation (11) to be,

$$\partial f / \partial \theta = \partial f / \partial x \sin \theta + \partial f / \partial y \cos \theta \quad (12)$$

To derive the function on a 3D vector, "3D directional derivative" can be defined as equation (13) by following equation (12) to derive the function between the horizontal plane and vertical z-axis.

$$\partial f / \partial \theta \partial \phi = \partial f / \partial x \sin \theta + \partial f / \partial y \cos \theta \cos \phi + \partial f / \partial z \sin \phi \quad (13)$$

$$\partial f / \partial \theta \partial \phi = \partial f / \partial x \sin \theta + \partial f / \partial y \cos \theta \cos \phi + \partial f / \partial z \sin \phi \quad (14)$$

ϕ is an angle between horizontal²² plane and vertical²³ z-axis. If equation (13) is normalised²⁴ by analytic signal, equation (8), then the formula of GDO is obtained, equation (10). Following Cooper (2018), choosing θ follows the orthogonal of the structure strike.

The direction of various derivative operators in 3D space is illustrated in Figure 2. Note that, the potential field f for gravity data is Bouguer anomaly which is the gravity field in the z-direction.

Figure 2. The direction of various derivative operators in 3D space.

GDO which is based on "3D²⁵ directional derivative" will give the flexibility to control the direction of the derivative. Subsequently, the enhanced anomaly will be maximized and correspond with the desired orientation of the anomalous body.

GDO is also normalized with AS which will return a value between -1 to 1. As seen in Figure 2, if the "3D directional derivative" is aligned and has the same direction with²⁶ AS so that²⁷ the GDO will return value 1. Conversely, if the "3D directional derivative" has the opposite direction with²⁸ AS, the GDO value will be -1. The opposite direction means a negative value which could be obtained from the derivative of the potential field in the horizontal direction of x and y.

Synthetic Data

This study uses Bouguer anomaly synthetic data which is obtained from forward²⁹ modelling³⁰ of simple prisms. We utilise³¹ Harmonica by Soler et al. (2021) which is a Python package that provides forward³² modelling³³ function of a simple geometry shape. The boundary and density contrast of the prism model are varied to obtain different responses. Figure 3 shows the map of gravity anomaly

response from 3 models and Table 2 shows the detail parameter of the synthetic model.

Model A is only 1 simple prism with a density contrast of 1000 kg/m³ which is buried at a depth of 500 m (Upper Boundary). This model is set such that has an N-S strike. Model A is expected to denote local response.

Figure 3. Bouguer anomaly map of synthetic data of 3 model, the label model corresponds with detail parameter in Table 2. Solid lines denote the edges of the model prisms.

Table 2. Parameter of ³⁴synthetic model.

Parameter

Model A

Model B

Density Contrast

1000 kg/m³

Prism 1: 1000 kg/m³

Prism 2: 2000 kg/m³

Upper boundaries

-500 m

Prism 1: -1000 m

Prism 2: -1000 m

Lower boundaries

-700 m

Prism 1: -1500 m

Prism 2: -2000 m

Grid Size

100 m x 100 m

Area size

20 km x 20 km

Conversely, Model B consists of 2 prisms that are varied in strike orientation. Prism 1 with E-W strike and 1000 kg/m³ density contrast, as well as prism 2 with N-S strike and 2000 kg/m³ density contrast. Furthermore, the prisms have deeper³⁵ depth at 1000 m. Model B represents the regional anomaly response.

Silver Peak Gravity Data

In this paper, we use gravity field data of Silver Peak which is generated from the Silver Peak Innovative Exploration Project (Ram Power Inc, 2013). The data is publicly accessible in Geothermal Data Repository (<http://gdr.openei.org/submissions/268>).

The Complete Bouguer Anomaly (CBA) data of Silver Peak is covering a 12 km x 14 km area with grid spacings of 0.25 km to 1.6 km (0.5 mi). The Bouguer density is 2.35 g/cc with NAD83 datum (Magee, 2009). The CBA map described in Figure 4a is interpolated data field by using the Kriging method with 100 m x 100 m grid sizes. Additionally, the geological map of Silver Peak is shown in Figure 4b.

Figure 4. (a) Complete Bouguer Anomaly map of Silver Peak area. (b) Geological Map of Silver Peak area, modified from Hulen (2008) and Western Geothermal

Partners LLC (2006). Note that the dashed-line rectangular on the CBA map denotes the covered area of the geological map.

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The Silver Peak area lithologies consist of Cambrian dolomitized-marble (Cr), Proterozoic Wyman formation (pCw³⁶), Cambrian Deep Spring formation (Cds), Cambrian Poleta formation (Cp), Mesozoic granitoid intrusive rocks (Ig), Quaternary playa deposits (Qp), Quaternary/Tertiary basalt (Qlb) and Quaternary alluvial deposits (Qaf). Quaternary hot-spring sinter is present which consists of travertine and tuff (Qs). Lithologies older than Quaternary deposits are known as Mineral Ridge in the Silver Peak, which deforms by cross-central faults.

It can be understood that the CBA anomaly is highly related to the response of the lithological contact, as seen by comparing between CBA map and geological³⁷ map. The pattern of relatively high CBA anomaly (red - yellowish) is similar to the existence of Cr, pCw³⁸, and IG lithology. The medium CBA anomaly (greenish) also occurs with the existence of alluvial deposits (Qaf).

Conversely, the existence of structures such as graben, high-angle fault, and granite is hardly detected on the CBA map. Subsequently, anomaly enhancement with derivative operator might be interesting to be carried out.

RESULTS AND DISCUSSION

GDO of Synthetic Data

Essentially, the test on synthetic data will provide an understanding of GDO behaviour³⁹ as performed by Cooper & Cowan (2011) and Cooper (2018).

Consequently, we attempt the GDO on synthetic Bouguer anomaly from the prism model described in Table 2, which is generated using Harmonica⁴⁰ Python package by Soler et al. (2021). In this attempt, we compare GDO with its underlying formula, which is 2D and 3D directional derivatives.

Figure 5 describes the 2D directional derivative, 3D directional derivative, and GDO anomaly map of the synthetic Model A. The 2D directional derivative with $\theta = 45^\circ$ results in both high (red) and low (blue) anomalies which are concurred with the edges of the prism model (Figure 5a).

Furthermore, the 3D directional derivative will amplify the response of the geometry body from the prism model (Figure 7b), which is quite similar to the response of AS. High anomalies appear to be the geometry of its source with low anomalies surrounding the source.

Moreover, GDO is the ratio of 3D directional derivative and AS. If we use $\theta = 90^\circ$ and $\phi = 0^\circ$, the east edge of the source shows high anomalies (red) and the west edge of the source shows low anomalies (blue) as shown in Figure 5c. On the other hand, Figure 5d shows if we use $\theta = 0^\circ$ and $\phi = 0^\circ$, the north edge of the source shows low anomalies (blue) and the south edge of the source shows high anomalies (red). From these trials, we can understand that $\phi = 0^\circ$ only leaves the horizontal derivatives (x and x) that follows the direction of the azimuth (θ).

Figure 5e shows the GDO response where $\theta = 0^\circ$ and $\phi = 90^\circ$. According to equation (10) of GDO, the use of $\phi = 90^\circ$ only leaves the vertical derivative and won't respond to any horizontal derivatives with different azimuth.⁴¹

Last, Figure 5f shows the GDO response where $\theta = 30^\circ$ and $\phi = 60^\circ$. We can see that the response of GDO follows the direction of the azimuth (θ). Yet the

enhanced anomaly slightly misses the actual location of the prism.

As suggested by Cooper (2018) the value of azimuth (θ) of the GDO parameters should follow the orthogonal direction of the structure strike. In this research, we have a limitation on the prism model which only could have N-S or W-E strike orientation. Consequently, the attempt on GDO using $\theta = 30^\circ$ (Figure 5f) will be more suitable if the prism model used has a strike with azimuth 120° .

Figure 5. (a) 2D directional derivative with $\theta = 45^\circ$; (b) 3D directional derivative with $\theta = 45^\circ$, $\phi = 90^\circ$; (c) GDO with $\theta = 90^\circ$, $\phi = 0^\circ$; (d) GDO $\theta = 90^\circ$, $\phi = 90^\circ$; (e) GDO $\theta = 0^\circ$, $\phi = 90^\circ$; (f) GDO $\theta = 30^\circ$, $\phi = 60^\circ$.

Comparing GDO with SA, HG, and SVD

We compare the result from GDO with common derivative operators such as SA, HG, and SVD. Figure 6 shows the results of GDO, SA, HG, and SVD based on synthetic Bouguer anomaly from Model A.

As seen in Figure 6, all derivative operators have successfully enhanced the response anomaly of the shallow depth prism (Model A). It is denoted by the anomaly pattern that concurs with the edges of the prism. Anomaly profiles from all derivative operators are also exhibited to obtain detailed perspectives between edges response and the anomaly pattern.

The GDO anomaly of $\theta = 0^\circ$ and $\phi = 90^\circ$ shows maximum values concurring with the prism geometry (Figure 8a). It is observed from the GDO profile that a significant decreasing value occurred near the edges of the prism (red-dashed line).

Nevertheless, analytic signal amplitude returns a ridge-like response where high⁴² value is near the edges of the prism and slightly decreases at centre^{43,44} of the prism (Figure 6b). Meanwhile, the horizontal gradient shows maximum values at the edges of the prism and zero values at the centre⁴⁵ of prism⁴⁶ (Figure 6c). HG and 2D directional derivative⁴⁷ with $\theta = 45^\circ$ are derivative operators in the horizontal plane which return similar patterns (Figure 5a and Figure 6c), though the 2D directional derivative has positive and negative values that concur with the edges of the prism.

Figure 6. Results comparison of (a) GDO $\theta=0^\circ$ and $\phi=90^\circ$, (b) Analytic Signal Amplitude (AS), (C) Horizontal Gradient (HG), (D) Second Vertical Derivative (SVD) based on local⁴⁸ anomaly of synthetic model A. On the profile, red-dashed lines denote the edge of the prism and black-dashed⁴⁹ line is zero value level.

Besides, the Second Vertical Derivative (SVD) anomaly is estimated from the second derivative in x⁵⁰ and y⁵¹ direction (Equation 9). The SVD operator will return the curvature of the Bouguer anomaly, means⁵² the changes of⁵³ the dip direction of the anomaly. As seen in Figure 6d, the edge of prism⁵⁴ (red-dashed line) is⁵⁵ concurrent⁵⁵ with zero value between maximum⁵⁶ and minimum value of SVD (Sumintadireja et al., 2018).

Equally important, the comparison between derivative operators is carried out for regional anomaly. We use synthetic Bouguer anomaly from Model B (Figure 3b) consisting 2⁵⁷ prisms with deeper depth.

As observed in Figure 3b, the Bouguer anomaly response of prism 1 is lower than prism 2 due to smaller density contrast. The Bouguer map indicate⁵⁸ two sources of anomaly although the geometry of the sources is hardly identified.

Figure 7 shows the result of different derivative filters on synthetic regional anomaly from Model B. Unequal with the derivative result of local anomaly from Model A, which is concurred with the prism geometry, the anomaly of deeper⁵⁹ source from Model B fails to be amplified with operator AS, HG, and SVD, especially for the response of prism 1.

It appears that the anomaly response of prism 2 with higher contrast density is enhanced by AS, HG and⁶⁰ SVD. Nevertheless, the pattern of enhanced anomaly is not match⁶¹ with⁶² the edges of the prism. Yet SVD anomaly able⁶³ to elucidate the boundary.

Conversely, GDO able⁶⁴ to amplify the response of deeper⁶⁵ source body which is described by high⁶⁶ anomaly with value⁶⁷ 0.7⁶⁸ higher (red colour⁶⁹). If we compare the result of GDO between local⁷⁰ anomaly of model A and regional⁷¹ anomaly of model B, it appears that enhanced anomalies are slightly not match⁷² with geometry⁷³ of the prisms. Nonetheless⁷⁴ the response from prism 1 is successfully enhanced by GDO.

From several tests of synthetic data, we conclude that GDO tends to amplify the anomaly, regardless of the value of the Bouguer anomaly, as well as the medium value which could be caused by lower density contrast or deeper location of the anomalous source. Thus, we should be cautious when interpreting GDO⁷⁵ anomaly and should compare the result with Bouguer⁷⁶ anomaly and geological map.

GDO of Silver Peak Area

Various derivative operators are applied to the Complete Bouguer Anomaly from the Silver Peak area. We try GDO by varying the azimuth (θ) & dip (ϕ), and another derivative operator of AS, HG, and SVD as well, the results are described in Figure 8.

We reconcile on the geological map (Figure 4b) to interpret the enhanced anomaly from the derivative operators. The structure of horst-graben plays an important role in geothermal fluid pathway on Silver Peak geothermal system as well as the intrusive granite at Mineral Ridge area. To interpret the GDO anomaly, we try to follow the suggestion of Cooper (2018) where $\pm 1/2$ GDO might be a contact and zero GDO appears to be dykes.

It appears that AS and HG fail to enhance the anomaly at the Silver Peak area (Figure 8a and 8b). The expected response from horst-graben and intrusive granite are not revealed from AS and HG results.

Conversely, SVD and GDO are able to amplify the response of possible horst-graben and intrusive granite (Figure 8c and 8d). It appears that the potential field responses of those geological structures are more sensitive with the changes in vertical direction (vertical derivative). Consequently, we deduce that this might be related with the geometry of high-angle fault including horst-graben structure in Silver Peak Area (Hulen, 2008).

Furthermore, by referring the geological map, there lays a cross-central fault system that separate Clayton Valley and Mineral Ridge. This fault might extend to the south across the horst-graben from GDO and SVD results.

Comparing the GDO results of Figure 8d, 8e, and 8f, it appears that varying the dip parameter (ϕ) of the GDO will enhanced the anomaly in certain ways. For instance, in Figure 8f we use $\phi=30^\circ$ and the horst anomaly appears as narrow closure. Nevertheless, in Figure 8d and 8e, the horst anomaly become more extensive.

Subsequently, opposite behaviour is observed for intrusive granite structure in Mineral Ridge area. Granite anomaly appears extensively in lower dip GDO (Figure 8f) rather than in higher dip GDO (Figure 8d and 8e). Meanwhile, the

response from lithology of basalt strongly appears in GDO $\theta=45^\circ$ and $\phi=75^\circ$ (Figure 8e) rather than others⁹⁹ (Figure 8d and 8f).

Consequently, we could conclude that GDO¹⁰⁰ able to enhance the anomaly of potential¹⁰¹ field with several possibilities by varying its parameters of azimuth (θ) and dip (ϕ). Tuning the GDO parameters in certain ways might reveal the edge response of complex geological structure¹⁰² which might not appear in ordinary derivative operators. Examining the correlation between θ and ϕ of GDO with the various orientation and dip of know source anomaly might be intriguing to be validated in the future¹⁰³ work.

Figure 7. Results comparison of (a) GDO $\theta=0^\circ$ and $\phi=90^\circ$, (b) Analytic Signal Amplitude (AS), (C) Horizontal Gradient (HG), (D) Second Vertical Derivative (SVD) based on regional¹⁰⁴ anomaly of synthetic model B.

Figure 8. Interpreted of enhanced anomaly from (a) Analytic Signal Amplitude (AS), (b) Horizontal Gradient (HG), (c) Second Vertical Derivative (SVD), (d) GDO $\theta=45^\circ$ and $\phi=45^\circ$, (e) GDO $\theta=45^\circ$ and $\phi=75^\circ$, (f) GDO $\theta=90^\circ$ and $\phi=30^\circ$.

CONCLUSION

In this study, we examine GDO parameters and compare it with another¹⁰⁵
derivative operators¹⁰⁶, both on synthetic and field Bouguer anomaly¹⁰⁷. Thus, we
conclude that,

The results from synthetic data show that GDO can amplify the response both
on local and regional anomalies. The enhancement anomaly of GDO apparently¹⁰⁸
disregards the influence of density contrast and depth of the anomalous body.
This is a consequence of normalization¹⁰⁹ factor where GDO is basically, 3D¹¹⁰
directional derivative that normalize¹¹¹ with Analytic Signal Amplitude (Equation
10). Thus, we should cautious when interpreting GDO¹¹² anomaly and should
comparing¹¹³ the result with the Bouguer anomaly and geological map.

The anomaly enhancement of Silver¹¹⁴ Peak area elucidates the GDO anomaly
concurrent with the geological map. It appears that the response from horst-
graben structure¹¹⁵ and intrusive granite are managed to be amplified by GDO. The
SVD can amplify the response of horst-graben as well, though AS and HG does¹¹⁶
not show the same results.

GDO can enhance the anomaly of potential fields which could reveal the edge
response of complex geological structures that might not appear in ordinary
derivative operators.

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1.	the finite	Determiner use (a/an/the/this, etc.)	Correctness
2.	gz → X	Misspelled words	Correctness
3.	the x	Determiner use (a/an/the/this, etc.)	Correctness
4.	ngz	Unknown words	Correctness
5.	gz	Unknown words	Correctness
6.	ngz	Unknown words	Correctness
7.	gz	Unknown words	Correctness
8.	ngz	Unknown words	Correctness
9.	gz	Unknown words	Correctness
10.	gz → X	Misspelled words	Correctness
11.	finite-difference	Misspelled words	Correctness
12.	gz → X	Misspelled words	Correctness
13.	gzi	Unknown words	Correctness
14.	gz → X	Misspelled words	Correctness
15.	gzi	Unknown words	Correctness
16.	gz → X	Misspelled words	Correctness
17.	is → are	Faulty subject-verb agreement	Correctness
18.	the x	Determiner use (a/an/the/this, etc.)	Correctness
19.	localises → localizes	Mixed dialects of English	Correctness

20.	A generalized	Determiner use (a/an/the/this, etc.)	Correctness
21.	reverses → reverse	Faulty subject-verb agreement	Correctness
22.	the horizontal, or a horizontal	Determiner use (a/an/the/this, etc.)	Correctness
23.	the vertical	Determiner use (a/an/the/this, etc.)	Correctness
24.	normalised → normalized	Mixed dialects of English	Correctness
25.	a "3D	Determiner use (a/an/the/this, etc.)	Correctness
26.	with → as	Wrong or missing prepositions	Correctness
27.	so that	Conjunction use	Correctness
28.	with → to	Wrong or missing prepositions	Correctness
29.	forward → forwarding	Incorrect verb forms	Correctness
30.	modelling → modeling	Mixed dialects of English	Correctness
31.	utilise → utilize	Mixed dialects of English	Correctness
32.	a forward	Determiner use (a/an/the/this, etc.)	Correctness
33.	modelling → modeling	Mixed dialects of English	Correctness
34.	the synthetic, or a synthetic	Determiner use (a/an/the/this, etc.)	Correctness
35.	a deeper	Determiner use (a/an/the/this, etc.)	Correctness
36.	pCw → PCW	Misspelled words	Correctness

37.	the geological	Determiner use (a/an/the/this, etc.)	Correctness
38.	pCw → PCW	Misspelled words	Correctness
39.	behaviour → behavior	Mixed dialects of English	Correctness
40.	the Harmonica	Determiner use (a/an/the/this, etc.)	Correctness
41.	azimuth → azimuths	Incorrect noun number	Correctness
42.	a high	Determiner use (a/an/the/this, etc.)	Correctness
43.	the centre	Determiner use (a/an/the/this, etc.)	Correctness
44.	centre → center	Mixed dialects of English	Correctness
45.	centre → center	Mixed dialects of English	Correctness
46.	the prism, or a prism	Determiner use (a/an/the/this, etc.)	Correctness
47.	derivative → derivatives	Incorrect noun number	Correctness
48.	the local	Determiner use (a/an/the/this, etc.)	Correctness
49.	the black-dashed, or a black-dashed	Determiner use (a/an/the/this, etc.)	Correctness
50.	the x	Determiner use (a/an/the/this, etc.)	Correctness
51.	direction → directions	Incorrect noun number	Correctness
52.	which means	Pronoun use	Correctness
53.	ef → in	Wrong or missing prepositions	Correctness

54.	the prism, or a prism	Determiner use (a/an/the/this, etc.)	Correctness
55.	is concurred → concurs, has concurred	Incorrect verb forms	Correctness
56.	the maximum	Determiner use (a/an/the/this, etc.)	Correctness
57.	of 2	Wrong or missing prepositions	Correctness
58.	indicate → indicates	Faulty subject-verb agreement	Correctness
59.	the deeper	Determiner use (a/an/the/this, etc.)	Correctness
60.	, and	Comma misuse within clauses	Correctness
61.	is not match → is not matched	Incorrect verb forms	Correctness
62.	with	Wrong or missing prepositions	Correctness
63.	is able	Incorrect verb forms	Correctness
64.	is able	Incorrect verb forms	Correctness
65.	the deeper	Determiner use (a/an/the/this, etc.)	Correctness
66.	a high	Determiner use (a/an/the/this, etc.)	Correctness
67.	a value	Determiner use (a/an/the/this, etc.)	Correctness
68.	of 0.7	Wrong or missing prepositions	Correctness
69.	colour → color	Mixed dialects of English	Correctness

70.	the local	Determiner use (a/an/the/this, etc.)	Correctness
71.	the regional	Determiner use (a/an/the/this, etc.)	Correctness
72.	are slightly not matched, are slightly not matching	Incorrect verb forms	Correctness
73.	the geometry	Determiner use (a/an/the/this, etc.)	Correctness
74.	Nonetheless,	Comma misuse within clauses	Correctness
75.	the GDO	Determiner use (a/an/the/this, etc.)	Correctness
76.	the Bouguer	Determiner use (a/an/the/this, etc.)	Correctness
77.	the geothermal	Determiner use (a/an/the/this, etc.)	Correctness
78.	at → in	Wrong or missing prepositions	Correctness
79.	the Mineral	Determiner use (a/an/the/this, etc.)	Correctness
80.	a contact	Determiner use (a/an/the/this, etc.)	Correctness
81.	Figure → Figures	Incorrect noun number	Correctness
82.	are → is	Faulty subject-verb agreement	Correctness
83.	are able to → can	Wordy sentences	Clarity
84.	Figure → Figures	Incorrect noun number	Correctness
85.	with → to	Wrong or missing prepositions	Correctness

86.	the vertical, or a vertical	Determiner use (a/an/the/this, etc.)	Correctness
87.	with → to	Wrong or missing prepositions	Correctness
88.	fault → faults	Incorrect noun number	Correctness
89.	structure → structures	Incorrect noun number	Correctness
90.	the Silver	Determiner use (a/an/the/this, etc.)	Correctness
91.	to the	Wrong or missing prepositions	Correctness
92.	separate → separates	Faulty subject-verb agreement	Correctness
93.	Figure → Figures	Incorrect noun number	Correctness
94.	enhanced → enhance	Modal verbs	Correctness
95.	behaviour → behavior	Mixed dialects of English	Correctness
96.	structure → structures	Incorrect noun number	Correctness
97.	the Mineral	Determiner use (a/an/the/this, etc.)	Correctness
98.	Figure → Figures	Incorrect noun number	Correctness
99.	in others	Wrong or missing prepositions	Correctness
100.	GDO is, or GDO was	Incorrect verb forms	Correctness
101.	the potential, or a potential	Determiner use (a/an/the/this, etc.)	Correctness
102.	structure → structures	Incorrect noun number	Correctness

103.	the future	Determiner use (a/an/the/this, etc.)	Correctness
104.	the regional	Determiner use (a/an/the/this, etc.)	Correctness
105.	it → them	Pronoun use	Correctness
106.	another derivative operator, other derivative operators	Determiner use (a/an/the/this, etc.)	Correctness
107.	anomaly → anomalies	Incorrect noun number	Correctness
108.	apparently	Wordy sentences	Clarity
109.	the normalization	Determiner use (a/an/the/this, etc.)	Correctness
110.	a 3D	Determiner use (a/an/the/this, etc.)	Correctness
111.	normalize → normalizes	Faulty subject-verb agreement	Correctness
112.	the GDO	Determiner use (a/an/the/this, etc.)	Correctness
113.	comparing → compare, be comparing	Modal verbs	Correctness
114.	the Silver	Determiner use (a/an/the/this, etc.)	Correctness
115.	the horst-graben	Determiner use (a/an/the/this, etc.)	Correctness
116.	structure → structures	Incorrect noun number	Correctness
117.	does → do	Faulty subject-verb agreement	Correctness
118.	to	Wrong or missing prepositions	Correctness

119.	the advice → their advice	Determiner use (a/an/the/this, etc.)	Correctness
120.	to → on	Wrong or missing prepositions	Correctness
121.	to	Wrong or missing prepositions	Correctness
122.	to	Wrong or missing prepositions	Correctness
123.	to → of	Wrong or missing prepositions	Correctness
124.	Generalising → Generalizing	Mixed dialects of English	Correctness
125.	... → ., ...	Closing punctuation	Correctness
126.	with Reference to → concerning, regarding, about	Wordy sentences	Clarity