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Research on the Use Of Satellite Gravity Data for Gravity Gradients Modeling in The Vietnam Region

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Abstract: Research on gravity gradients holds substantial importance across various scientific and practical domains, particularly in geophysics, geology, resource exploration, and Earth sciences. In addition to traditional gravity measurement techniques using ground-based, marine, or airborne equipment, numerous satellite gravity missions have been launched by agencies such as NASA and ESA. Notable examples include the CHAMP, GRACE, and GOCE missions. This paper investigates the use of several global geopotential models (GGMs), specifically Level 2 data products from the GOCE satellite mission, to determine gravity gradients over a localized region in Vietnam. Open-source software developed in MATLAB is used to process GOCE satellite gravity data and GGMs to compute the gravitational gradient tensor and the disturbing gradient tensor. These values are subsequently transformed into local gravitational gradient models in grid format V_{xx} , V_{xy} , V_{xz} , V_{yy} , V_{yz} , V_{zz} and visualized using the Global Mapper software. The standard deviation of the vertical gravitational component V_{zz} between the measurements at five points and the GGM GOCE model is 0.017 mGal/m. A comparison of the results calculated using the two software programs, GrafLab and Gravsoft, on 961 grid points also shows a high degree of consistency, with a standard deviation of only 0.0000013 mGal/m.

Keywords: Gravity, gravity gradients, GOCE, GrafLab, Gravsoft

1. Introduction

Gravity data play a pivotal role in numerous scientific fields and practical applications, particularly in geodesy, geophysics, and Earth system science. In geodesy, gravity measurements are essential for determining the Earth's figure, defining height and coordinate reference systems, establishing gravity networks, and developing geoid or quasigeoid models. Traditionally, gravity data have been acquired through ground-based, marine, or airborne surveys. However, these methods are constrained by limited spatial coverage, uneven distribution, and high operational costs, especially in remote or inaccessible regions.

The emergence of satellite gravimetry has significantly advanced global gravity field determination. Missions such as CHAMP, GRACE, and especially GOCE have greatly enhanced the resolution, coverage, and accuracy of gravity field models. GOCE (Gravity field and steady-state Ocean Circulation Explorer) was the first mission equipped with a spaceborne gradiometer, capable of directly measuring the second-order derivatives of the gravitational potential known as gravity gradients. This innovation enabled the development of high-resolution global geopotential models (GGMs) and opened new possibilities in geophysical and geological studies.

Internationally, gravity gradient data from the GOCE mission have been extensively applied in a wide range of fields such as lithospheric structure analysis, geoid modeling, earthquake risk assessment, and resource exploration. Numerous studies have demonstrated that gravity gradients provide enhanced spatial sensitivity and resolution compared to conventional gravity anomalies, particularly for detecting small-scale or deeply buried geological features. The six independent gradient components (V_{xx} , V_{xy} , V_{xz} , V_{yy} , V_{yz} , V_{zz}) offer complementary directional information that allows more detailed geophysical

interpretation.

In Vietnam, gravity research has primarily focused on conventional gravity anomalies and geoid determination based on terrestrial measurements and global gravity models. Although the use of satellite data such as EGM2008 and GRACE has become more common in recent years, the exploitation of gravity gradient data-especially from GOCE-remains limited. There is currently a lack of research and tools for processing and interpreting gravity gradients at the regional scale. This creates a gap in fully utilizing the scientific potential of GOCE-derived products in Vietnam's geophysical and geological applications.

Gravity gradients reflect local variations in the mass distribution of the Earth and are more sensitive to short-wavelength features than conventional gravity. They can detect subtle geological structures, such as fault zones, sedimentary basins, or intrusive bodies, which may be overlooked by traditional gravity data. Additionally, gravity gradient data are essential for the downward continuation of satellite data and serve as input for refined regional gravity field modeling. The use of gravity gradients thus provides not only higher-resolution information but also more directional and structural insights, which are vital for advanced applications in resource exploration and crustal studies.

This study aims to apply global geopotential models derived from the GOCE mission to construct gravity gradient models over a selected region in Northern Vietnam. Open-source tools such as GrafLab and Gravsoft are employed to compute the gravitational and disturbing gradient components from spherical harmonic coefficients. The resulting grid-based gradient models are visualized and evaluated to demonstrate their applicability in regional-scale geophysical analysis.

2. Theoretical basis for using satellite gravity data in building gravity gradient models

This section outlines the theoretical formulas used to compute gravitational field components, gravitational gradients, and disturbing gradients using the spherical harmonic coefficients of global gravity field models.

2.1. Gravitational gradients

The Earth's gravity potential at a point is defined as the sum of the gravitational potential V and the centrifugal potential Φ (Hofmann-Wellenhof, 2006; Torge, 1989):

$$W=W(x,y,z) = V + \Phi = G \int_{\Omega} \frac{\delta d\Omega}{r} + \frac{1}{2} \omega^2 (x^2 + y^2) \quad (1)$$

where: (x,y,z) - coordinates in the geocentric coordinate system of the point;
 Ω - Earth's volume
 r - distance from the point to the mass element $\delta d\Omega$.

Due to the lack of precise information on mass density distribution and Earth's exact shape, the gravity potential W is typically approximated using a spherical harmonic expansion (Hofmann-Wellenhof, 2006; Torge, 1989):

$$W(r, \varphi, \lambda) = \frac{GM}{r} \sum_{n=0}^{N_{\max}} \left(\frac{a}{r}\right)^n \sum_{m=0}^n (\bar{C}_{n,m} \cos m \lambda + \bar{S}_{n,m} \sin m \lambda) \bar{P}_{n,m}(\sin \varphi) + \frac{\omega^2 r^2 \cos^2(\varphi)}{2} \quad (2)$$

where: GM - Earth's gravitational constant;
 (r, φ, λ) - coordinates of the point in the spherical coordinate system;
 a - semi-major axis of the reference ellipsoid;
 $\bar{P}_{n,m}(\sin \varphi)$ - normalized associated Legendre function;
 $\bar{C}_{n,m}, \bar{S}_{n,m}$ - spherical harmonic coefficients of the geopotential model;

The formula for calculating the gravitational potential V is as follows:

$$V(r, \varphi, \lambda) = W - \Phi = \frac{GM}{r} \sum_{n=0}^{N_{\max}} \left(\frac{a}{r}\right)^n \sum_{m=0}^n (\bar{C}_{n,m} \cos m \lambda + \bar{S}_{n,m} \sin m \lambda) \bar{P}_{n,m}(\sin \varphi) \quad (3)$$

For practical applications, the gravitational tensor components are often transformed into the Local North-Oriented Reference Frame (LNOF). In the LNOF, the gravitational gradient tensor is expressed as follows (Bucha, 2014):

$$V(r, \varphi, \lambda) = \begin{pmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{yx} & V_{yy} & V_{yz} \\ V_{zx} & V_{zy} & V_{zz} \end{pmatrix} \quad (4)$$

The components of the gravitational tensor in the LNOF are determined by the following formulas (Bucha, 2014):

$$V_{xx} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \bar{C}_{n,m} Q_m(\lambda) (a_{nm} \bar{P}_{n,|m|-2}(\sin \varphi) + [b_{n,m} - (n+1)(n+2)] \bar{P}_{n,|m|}(\sin \varphi) + c_{n,m} \bar{P}_{n,|m|+2}(\cos \theta)) \quad (5)$$

$$V_{xy} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \bar{C}_{n,m} Q_{-m}(\lambda) (d_{nm} \bar{P}_{n-1,|m|-2}(\sin \varphi) + g_{n,m} \bar{P}_{n-1,|m|}(\sin \varphi) + h_{n,m} \bar{P}_{n-1,|m|+2}(\sin \varphi)), m \neq 0 \quad (6)$$

$$V_{xz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \bar{C}_{n,m} Q_m(\lambda) (\beta_{n,m} \bar{P}_{n,|m|-1}(\sin \varphi) + \gamma_{n,m} \bar{P}_{n,|m|+1}(\sin \varphi)) \quad (7)$$

$$V_{yy} = -\frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \bar{C}_{n,m} Q_m(\lambda) (a_{n,m} \bar{P}_{n,|m|-2}(\sin \varphi) + b_{n,m} \bar{P}_{n,|m|}(\sin \varphi) + c_{n,m} \bar{P}_{n,|m|+2}(\sin \varphi)) \quad (8)$$

$$V_{yz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \bar{C}_{n,m} Q_{-m}(\lambda) (\mu_{n,m} \bar{P}_{n-1,|m|-1}(\sin \varphi) + v_{n,m} \bar{P}_{n-1,|m|+1}(\sin \varphi)), m \neq 0 \quad (9)$$

$$V_{zz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n (n+1)(n+2) \sum_{m=-n}^n \bar{C}_{n,m} Q_m(\lambda) \bar{P}_{n,|m|}(\sin \varphi) \quad (10)$$

where:

$$Q(\lambda) = \begin{cases} \cos m\lambda, & m \geq 0 \\ \sin|m|\lambda, & m < 0 \end{cases}$$

2.2. Disturbing gradients

The disturbing potential $T(r, \varphi, \lambda)$ is the difference between the actual gravitational potential of the Earth and the normal reference potential. It is expressed using the differences in spherical harmonic coefficients between the actual and reference models. The disturbing gravity gradient tensor, including T_{xx} , T_{xy} , T_{xz} , T_{yy} , T_{yz} , and T_{zz} , is derived from the second derivatives of T .

$$T(r, \varphi, \lambda) = \frac{GM}{r} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=0}^n (\Delta \bar{C}_{n,m} \cos m\lambda + \Delta \bar{S}_{n,m} \sin m\lambda) \bar{P}_{n,m}(\cos \varphi) \quad (11)$$

The disturbing gradient tensor in the LNOF is expressed as follows (Bucha, 2014):

$$T(r, \varphi, \lambda) = \begin{pmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{pmatrix} \quad (12)$$

The individual components of the tensor in spherical coordinates are defined by the second partial derivatives of the disturbing potential (Bucha, 2014):

$$T_{xx} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_m(\lambda) (a_{n,m} \bar{P}_{n,|m|-2}(\sin \varphi) + [b_{n,m} - (n+1)(n+2)] \bar{P}_{n,|m|}(\sin \varphi) + c_{n,m} \bar{P}_{n,|m|+2}(\sin \varphi)) \quad (13)$$

$$T_{xy} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_{-m}(\lambda) (d_{n,m} \bar{P}_{n-1,|m|-2}(\sin \varphi) + g_{n,m} \bar{P}_{n-1,|m|}(\sin \varphi) + h_{n,m} \bar{P}_{n-1,|m|+2}(\sin \varphi)), m \neq 0 \quad (14)$$

$$T_{xz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_m(\lambda) (\beta_{n,m} \bar{P}_{n,|m|-1}(\sin \varphi) + \gamma_{n,m} \bar{P}_{n,|m|+1}(\sin \varphi)) \quad (15)$$

$$T_{yy} = -\frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_m(\lambda) (a_{n,m} \bar{P}_{n,|m|-2}(\sin \varphi) + b_{n,m} \bar{P}_{n,|m|}(\sin \varphi) + c_{n,m} \bar{P}_{n,|m|+2}(\sin \varphi)) \quad (16)$$

$$T_{yz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_{-m}(\lambda) (\mu_{n,m} \bar{P}_{n-1,|m|-1}(\sin \varphi) + \nu_{n,m} \bar{P}_{n-1,|m|+1}(\sin \varphi)), m \neq 0 \quad (17)$$

$$T_{zz} = \frac{GM}{r^3} \sum_{n=0}^M \left(\frac{a}{r}\right)^n (n+1)(n+2) \sum_{m=-n}^n \Delta \bar{C}_{n,m} Q_m(\lambda) \bar{P}_{n,|m|}(\sin \varphi) \quad (18)$$

3. Experimental area, data and software used

3.1. Experimental area and data

The study area is located in northern Vietnam, between latitudes 21.5°N and 23°N and longitudes 104.5°E to 106°E. Gravity gradient values are calculated at grid points with a resolution of 0.05° x 0.05°.

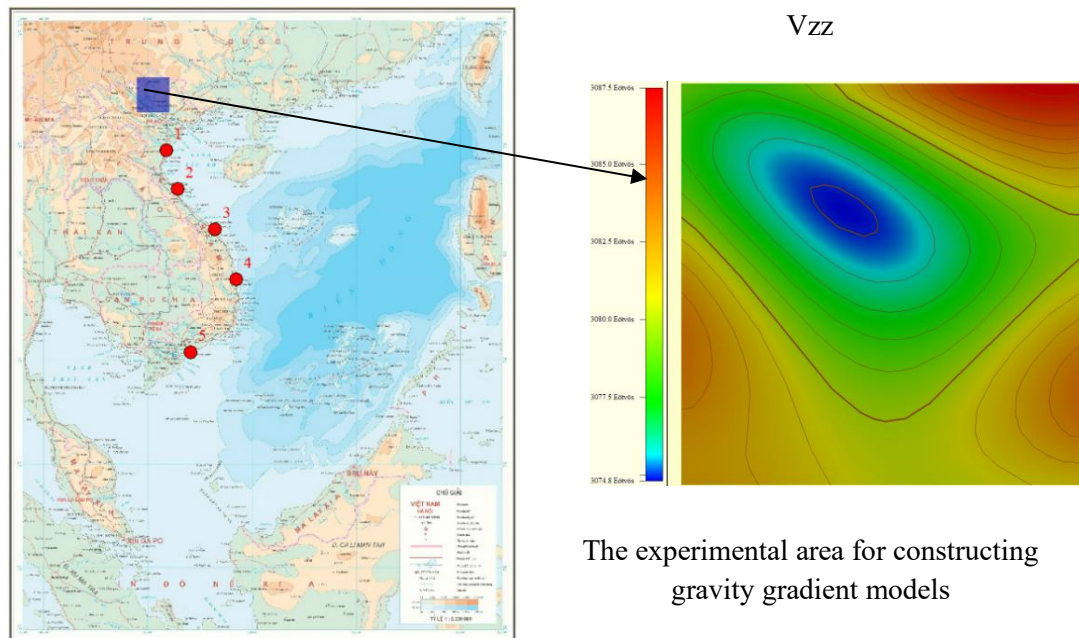


Fig. 1. Location of five comparison points (red) and the experimental area for gravity gradient model construction

Satellite global geopotential models (GGM) are used as the primary data source for calculating gravity gradients. This study uses GOCE GGMs, specifically Level 2 data products from the GOCE satellite mission, as the primary data source for calculating gravity gradient components. The models used include (<https://icgem.gfz-potsdam.de/home>; <https://earth.esa.int/web/guest/missions/esa-operational-eo->

missions/goce):

- GO_CONS_GCF_2_TIM_R6 (abbreviated as GOCE_TIM_R6): This is one of the three official GGM product lines provided by the European Space Agency (ESA) in 2019 from GOCE data analysis, calculated using the "time-wise" method. This model is Level 2 data from the GOCE satellite, comprising a set of spherical harmonic coefficients and the corresponding error covariance matrix. It includes spherical harmonic coefficients and the corresponding full error covariance matrix, with a maximum degree and order of 300.

- GO_CONS_GCF_2_DIR_R6 (abbreviated as GOCE_DIR_R6): This is ESA's GOCE Release 6 gravity field model, provided in 2019, constructed using a direct approach based on improved filtering of reprocessed gradients from the entire mission. GOCE_DIR_R6 is a satellite-only global gravity field model, expressed in spherical harmonics up to a maximum degree and order of 300. The model is calculated from a combination of GOCE gravity gradient data and GRACE data. GOCE_DIR_R6 is considered more accurate than previous GOCE models, especially for medium to high spatial resolutions. This model also belongs to the Level 2 data group of the GOCE satellite gravity mission.

- Ground measurement data: Data from five ground measurement points with information on position and vertical gravity gradient (V_{zz}) values are used. The vertical gradient values were measured in 2018 by the Viet Nam Institute of Surveying and Mapping using the FG5-x absolute gravimeter. The locations of these 5 points are marked in Fig. 1 (Dinh, 2024).

3.2. Software Tools

- GrafLab: MATLAB-based open-source software developed by Dr. Martin J. H. Lees for computing geopotential functionals.

- Gravsoft: A geophysical and gravimetric software package developed in Denmark for regional/local gravity modeling.

- MATLAB: Used for integrating GrafLab and processing data.

- Global Mapper: GIS software used for visualizing model results.

4. Results and Evaluation

4.1. Comparison of V_{zz} values with ground data

Using GrafLab software, V_{zz} values were calculated for 5 points with ground measurement data according to two global gravity field models, GOCE_TIM_R6 and GOCE_DIR_R6. The calculated V_{zz} values at these 5 points were compared with measured data. The deviations between the datasets are presented in Tab. 1.

Tab. 1. Comparison of V_{zz} gravity gradient values calculated by GrafLab and measured data (*Unit: $mGal/m$*)

N ^o	GOCE_DIR_R6	GOCE_TIM_R6	Deviation between Measured Data and GOCE_DIR_R6	Deviation between Measured Data and GOCE_TIM_R6
1	0.308478	0.308527	-0.006978	-0.007027
2	0.307975	0.308015	-0.052675	-0.052715
3	0.307288	0.307311	-0.014688	-0.014711
4	0.308213	0.308260	-0.041013	-0.041060
5	0.308418	0.308395	-0.029618	-0.029595
Standard Deviation (STD)			0.016703	0.016704
Mean Deviation			-0.028994	-0.029022

Vzz values computed using GrafLab and the GOCE_DIR_R6 and GOCE_TIM_R6 models were compared with measured values at 5 ground stations. Both models showed very small deviations from the measurements, with mean errors around -0.029 mGal/m and standard deviations ~0.0167 mGal/m, indicating reliable model performance.

4.2. Comparison between GrafLab and Gravsoft

GrafLab and Gravsoft software packages were used to calculate disturbing potential gradients (Txx, Txy, Txz, Tyy, Tyz, Tzz) at 961 grid points in the study area. To assess the consistency and accuracy of the software tools used, a comparison of the Tzz vertical component of the disturbing potential gradient calculated by both software using the GOCE_DIR_R6 model was conducted. The comparison results are presented in Tab. 2.

The statistical results in Tab. 2 show that the difference between GrafLab and Gravsoft results at each point is very small, ranging from -0.0000020 to +0.0000024 mGal/m, with a mean difference of -0.0000005 mGal/m and a standard deviation of only 0.0000013 mGal/m. These discrepancies lie within the range of numerical noise, likely arising from differences in integration methods, rounding, or spherical harmonic series processing algorithms between the two software. This result indicates that using either software yields equivalently reliable results, and they can be used individually or in combination for subsequent research, depending on specific needs and strengths of each software.

Tab. 2. Statistical comparison of Tzz vertical component of disturbing potential gradient values calculated by GrafLab and Gravsoft at 961 grid points using the GOCE_DIR_R6 model (*Unit: mGal/m*)

Result	Min	Max	Mean Value	Standard Deviation
Calculated by GrafLab	-0.0007798	0.0004837	-0.0002955	0.0002654
Calculated by Gravsoft	-0.0007796	0.0004825	-0.0002949	-0.0002653
Difference GrafLab and Gravsoft	-0.0000020	0.0000024	-0.0000005	0.0000013

4.3. Visualization of gravity gradient models

GrafLab software and global gravity field models GOCE_TIM_R6, GOCE_DIR_R6 were used to calculate the gravitational gradient components (Vxx, Vxy, Vxz, Vyy, Vyz, Vzz) and disturbing gradient components (Txx, Txy, Txz, Tyy, Tyz, Tzz) over the experimental area. The gravitational gradient models and disturbing gradient models calculated based on the GOCE_DIR_R6 model are graphically represented using Global Mapper software in Figs 2 and 3 below.

Using GOCE_DIR_R6, gravity gradient components (Vxx to Vzz and Txx to Tzz) were modeled and visualized. The results showed Vxx and Vyy to be significantly negative, while Vzz was strongly positive, satisfying Laplace's condition ($\nabla^2 V = 0$). Tzz exhibited the highest standard deviation, suggesting sensitivity to subsurface anomalies such as faults or sediment layers. The results demonstrate the effectiveness of the GOCE_DIR_R6 model in resolving regional-scale geological structures.

Gravitational potential gradient components:

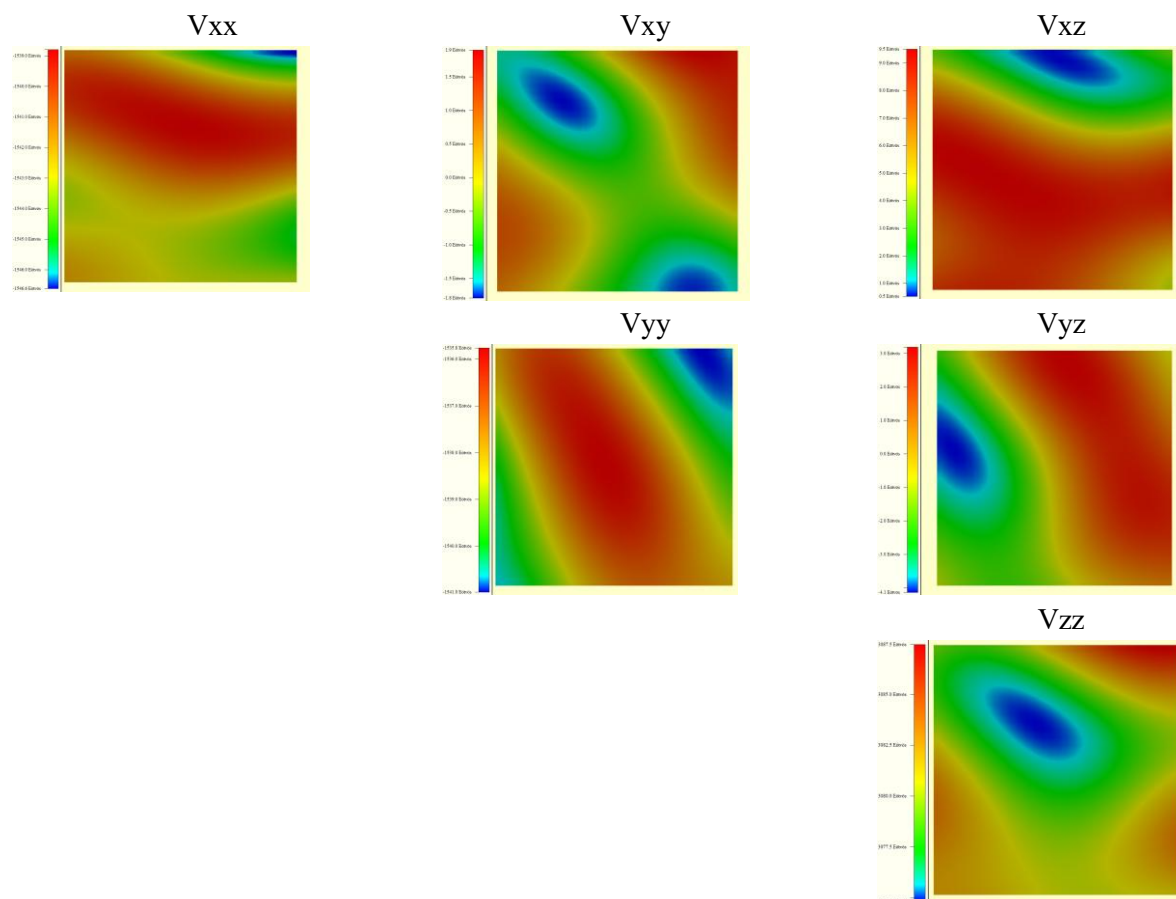


Fig. 2. Gravitational potential gradient models from the GOCE_DIR_R6 model over the experimental area

Statistical values at grid points for gravitational potential gradient components are presented in Tab. 3. The unit is Eötvös (E), where $1 \text{ E} = 10^{-9} \text{ s}^{-2}$ or $1 \text{ E} = 10^{-4} \text{ mGal/m}$.

Tab. 3. Statistical values of gravitational potential gradient components according to the GOCE_DIR_R6 model over the experimental area (Unit: Eötvös (E))

Gradient Model	Min	Max	Mean Value	Standard Deviation
V_{xx}	-1546.6	-1538.8	-1541.8	1.8
V_{xy}	-1.8	1.9	-0.3	0.9
V_{xz}	0.5	9.5	6.5	2.8
V_{yy}	-1541.0	-1535.8	-1537.9	1.5
V_{yz}	-4.1	3.2	0	2.2
V_{zz}	3074.8	3087.5	3079.7	2.7

Disturbing gravity gradient components:

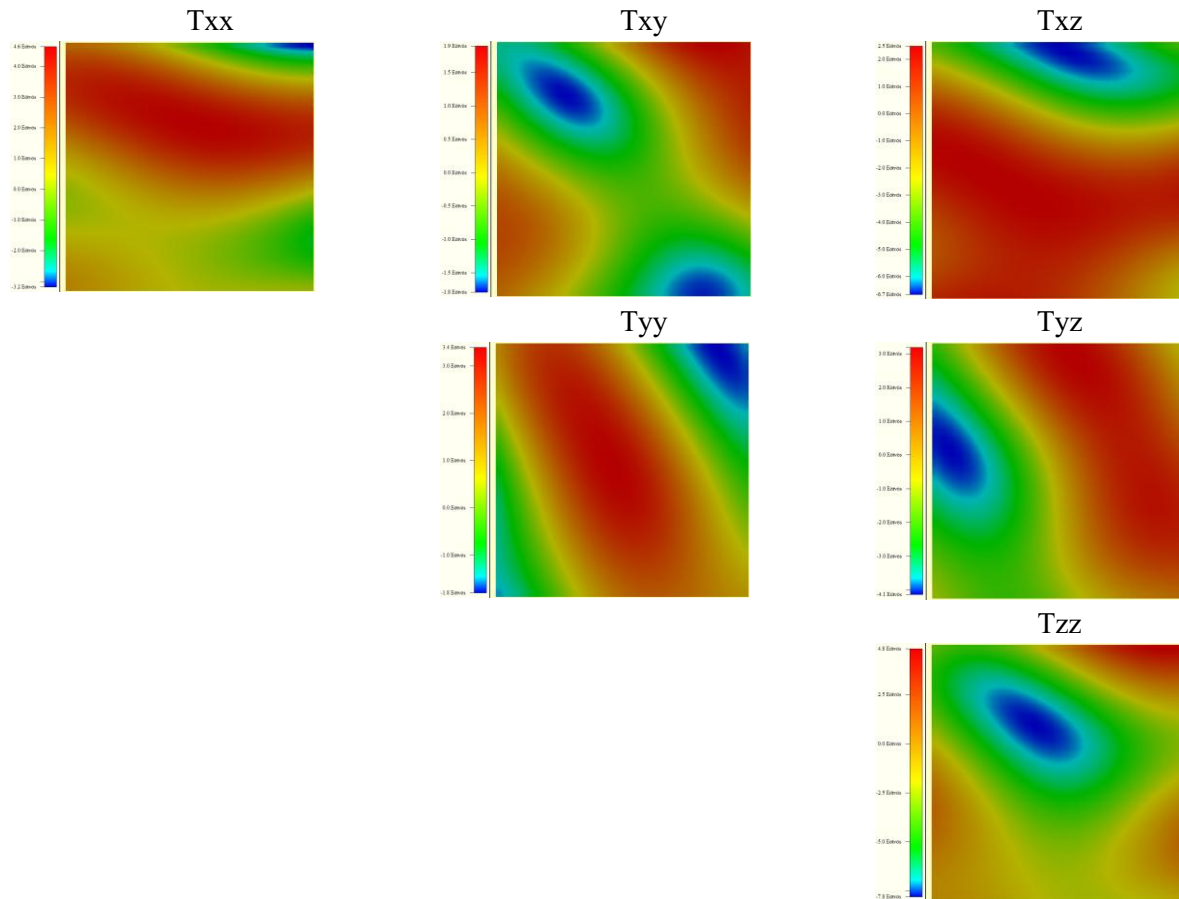


Fig. 3. Disturbing gradient models from the GOCE_DIR_R6 model over the experimental area.

Statistical values of disturbing gradient components are presented in Tab. 4.

Tab. 4. Statistical values of disturbing gradient components according to the GOCE_DIR_R6 model
(Unit: Eötvös (E))

Gradient Model	Min	Max	Mean Value	Standard Deviation
T_{xx}	-3.2	4.6	1.7	1.8
T_{xy}	-1.8	1.9	-0.3	0.9
T_{xz}	-6.7	2.5	-0.5	2.8
T_{yy}	-1.8	3.4	1.3	1.5
T_{yz}	-4.1	3.2	0	2.2
T_{zz}	-7.8	4.8	-2.9	2.7

Visualizing the gravity gradient fields with Global Mapper illustrates the spatial distribution of gravitational gradient tensor components over the experimental area. V_{xx} and V_{yy} values are largely negative (averaging -1541.8 and -1537.9 E, respectively), while V_{zz} is largely positive (averaging 3079.7 E). The sum of the three components $V_{xx}+V_{yy}+V_{zz}$ is approximately 0, which is consistent with Laplace's condition ($\nabla^2 V=0$) in gravity theory. The off-diagonal gradient components (V_{xy}, V_{xz}, V_{yz}) have significantly smaller values, with V_{xz} and V_{yz} showing stronger fluctuations than the other components, reflecting significant vertical variations.

The T_{xx}, T_{yy}, T_{zz} components have small mean values (1.7, 1.3, -2.9 E, respectively), consistent with the fact that gravity anomalies in the experimental area are not excessively large, yet sensitive

enough to distinguish subsurface structures. T_{zz} has a negative mean value and the largest standard deviation (± 2.7 E), indicating the presence of sedimentary bodies or fault zones beneath the survey area. The comparison between V_{xx} – V_{yy} and T_{xx} – T_{yy} shows that the discrepancy between the total gravitational potential and the disturbing potential is real but relatively small. This confirms the quality of the GOCE_DIR_R6 model in studying medium and large-scale geological structures.

5. Conclusion and recommendations

5.1. Conclusion

This study successfully applied Level 2 gravity data from the GOCE mission (GOCE_TIM_R6 and GOCE_DIR_R6) to compute gravitational and disturbing potential gradient models over northern Vietnam. GrafLab and Gravsoft provided reliable and consistent results. The models reflected spatial variability in gravity gradients and showed strong agreement with measured values. GOCE_DIR_R6, with its high resolution, proved effective in simulating deep geological features such as fault zones and sedimentary layers.

The comparison results between the models and field measurement data at 5 points show relatively small error margins, confirming the reliability and applicability of the two global gravity field models and the processing software. The comparison between GrafLab and Gravsoft software on a 961-point grid also showed high consistency in results, with differences within numerical noise limits.

The calculation and graphical representation of gravity gradient components such as T_{xx} , T_{yy} , T_{zz} , as well as off-diagonal components like T_{xz} , T_{yz} , T_{xy} , helped clarify the spatial variation of the gravity field and its ability to reflect subsurface mass anomalies. The GOCE_DIR_R6 model, with a resolution up to degree and order 300, demonstrated its effectiveness in detailed gravity field simulation, particularly its ability to reproduce deep structures such as fault zones, sedimentary layers, or local geological anomalies. The tensor components exhibited adherence to Laplace's condition and accurately reflected local gravity anomalies.

The results achieved in this study not only confirm the practical value of GOCE satellite gravity data but also indicate a feasible direction for constructing gravity gradient models and regional gravity models in Vietnam with low cost, wide coverage, and high accuracy.

5.2. Recommendations

Based on the results obtained in this study, the authors propose several recommendations for applying and developing further research directions on gravity gradients in Vietnam:

- Nationwide application: Extend gravity gradient modeling with GOCE data to the entire territory of Vietnam.
- Model integration: Combine GOCE models with high-resolution GGMs (e.g., EGM2008, EIGEN-6C4) to improve detail in complex terrains.
- Data fusion: Integrate terrestrial gravity measurements, especially in sensitive areas, to enhance the realism and resolution of the gradient models. Future studies should also investigate the direct use of raw GOCE satellite data for higher-accuracy modeling.

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