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ASSESSMENT OF THE ACCURACY OF THE GLOBAL GRAVITY FIELD MODEL GAO 2012 ON THE TERRITORY OF VIETNAM

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Abstract

The accuracy of GAO 2012 model on the Vietnamese territory is evaluated using 819 GNSS/levelling points of the national levelling networks by comparing the height anomaly of the point was calculated from the field measurement results with the height anomaly of that point was exploited from the GAO 2012 model and the difference in the height anomaly of pairs of points. The results show that the average height anomaly deviation compared to height anomalies exploited from GAO 2012 model is 0.3974 meters. The highest accuracy of GAO 2012 model is in Southwest region, the lowest one is in the Northwest region. The Southeast region and the Red River Delta give a higher accuracy than the Northeast, North Central, South Central and Central Highlands region. In addition, 1804 levelling routes in 8 experimental areas throughout Vietnam have been evaluated for accuracy. It is the first time the accuracy of the GAO 2012 model has been determined in Vietnam. These are useful information for the conversion from ellipsoidal height to normal height as well as for the purpose of building a local geoid.

Keywords: *GAO 2012; EGM; Evaluate accuracy; Geoid; GNSS/levelling.*

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1. Introduction

A global gravity model is a mathematical function which describing the gravity field of the Earth. Nowadays, along with the development of science and technology, many global earth gravity models have been proposed such as EGM96, EGM2008 (Nikolaos K. Pavlis et al., 2008, 2012; Thomas Gruber, 2009) [22, 31]; EIGEN - 6C4, GAO 2012, SGG - UGM - 1 (E. Sinem Ince et al., 2019) [8]; GECO, XGM2019e (P. Zingerle et al., 2020) [24]; SGG - UGM - 2 (W. Liang et al., 2020) [32]; EIGEN - CG01C (Ch. Reigber et al., 2014) [4]; GGM02 (Tham Bui Thi Hong, 2019) [29]; GOCE (Yi W. et al., 2014) [35]. In the area, the accuracy of the model needs to be determined in the application of the Earth gravity field model.

The gravity data were used to evaluate the accuracy of global gravity models such as GOCE in West Siberia and Kazakhstan (Alexander P. Karpik et al., 2016) [2]; GGM05G, EIGEN - 6C4, ITU_GRACE16, ITU_GGC16, GECO in Nigeria (Apeh et al., 2018) [3]; GECO, EGM2008, EIGEN - 6C4 in Antarctica (Gilardoni et al., 2016) [12]; EIGEN - 6C4, EGM2008, DIR - R5 GOCE in Iran (Ismael Foroughi et al., 2017) [16]; EGM2008, EIGEN6C4, GECO in Turkey (M. Yilmaz et al., 2018) [19].

The GNSS/levelling data were used to evaluate the accuracy of global gravity models such as EIGEN-6C4 (Hoa Thi Pham et al., 2019) [14]; EGM2008 (Nguyen Duy Do, 2011, 2012; Sang Nguyen Van, 2006; Tham Bui Thi Hong, et al. 2015) [6, 21, 27]; GECO (Tham Bui Thi Hong, 2019) [29] in Vietnam; EIGEN-6C4, EGM 2008 in Europe, USA, Canada, Brazil, Japan, Czech Republic and Slovakia (Förste et al., 2014) [11]; EIGEN - 4C, EGM2008, CHAMP, GRACE in Fennoscandia (Jan Kostelecký et al., 2015; M. Bilker, 2005) [17, 18]; EGM96, EIGEN-5C, GGM03C, EGM2008 (A Ustun et al., 2010) [1]; EIGEN - CG03C, EIGEN - GL04C, EGM96 (Erol, B. et al., 2009) [9]; EIGEN - 6C4, GECO, EGM96, EIGEN - 5C, EGM 2008 Ibrahim Yilmaz et al., 2010; Mustafa Yılmaz et al., 2017) in Turkey [15, 20]; EGM2008, EIGEN - 5C, EIGEN - 5S in Austria (Foerste, C. et al., 2009) [10]; GOCE in Poland (Walyeldeen Godah et al., 2015) [33]; EGM 2008, EIGEN - 6C4, GOCE, EGM 2008 combined model (GECO) in the Internal Aegean Region (Walyeldeen Godah et al., 2016).

The topographic data were used to evaluate the accuracy of global gravity models such as EGM2008 and GOCE models in Amazon Basin, Brazil (E. P. Bomfim et al., 2013) [7]. The mixed data were used to evaluate the accuracy of the global gravity model such as GOCE in the Mediterranean area and in particular, the Italian and Greek (Daniela Carrion et al., 2015) [5], in parts of Asia, Africa, South America and Antarctica (Hirt, C. et al., 2011) [13].

These studies show the assessment of the accuracy of global gravitational models has been done with different data. Studies on the accuracy of the global gravity models involve in identifying the best-fitting model to the local gravity field for geodetic and geophysical applications. The development of GNSS technology has allowed the problem solving to determine the coordinates of points with the required accuracy. However, the point height problem is challenging and needs to be solved. The height of the point determined by GNSS technology is the ellipsoidal height (h), while the national height in Vietnam is the normal height (H). So far, Vietnam has not published a highprecision local geoid model throughout the territory yet. Therefore, finding the global gravity model most suitable for the Vietnamese territory is interested in this research.

The Russian global gravity model GAO 2012 with a degree of 360 established based on high altimetry data, ground data and GOCE satellite data (Gravity Field and Steady - State Ocean Circulation Explorer) and GRACE (Gravity Recovery and Climate Experiment) satellites. Currently, recent studies have not published the accuracy of GAO 2012 on the territory of Vietnam yet. The accuracy of the model should be identified and evaluated to make it possible to apply GAO 2012 in Vietnam. Therefore, the height anomaly value of GAO 2012 was used in this study. The accuracy of height anomalies of GAO 2012 all over Vietnam was evaluated on the basis of the national GNSS/levelling points (the point has two heights: ellipsoidal height and normal height). The results of this study are the basis for the use of GAO 2012 in Vietnam.

2. Data and research methods

2.1. Theoretical basis

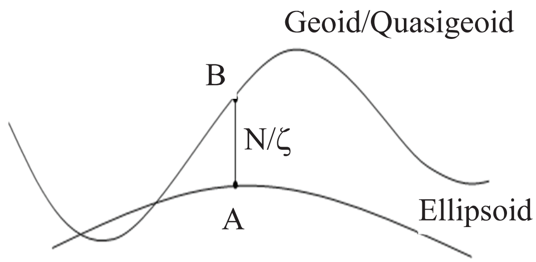

Figure 1: The geoid height/the height anomaly

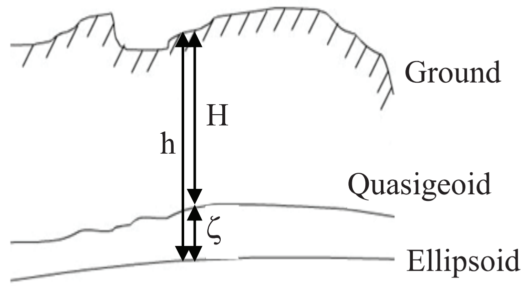

Figure 2: Relationship among H, h, ζ

To set up the elevation system, one of the important tasks is to select the starting surface. According to Stokes theory, the selected surface is a calm water surface unaffected by noise (causes other than gravity) in rivers, lakes and on the surface of the ocean. This surface is also known as the geoid surface. To define the geoid, it is necessary to determine the distance between the ellipsoid and the geoid surface (is called the geoid height and symbolized as N) (Fig. 1). The determination of the geoid surface is not easy because of the structure of the Earth's surface. Therefore, the average sea level in a certain area is set as a starting point for elevation for a region, a country, a group of countries and so on.

As the geoid surface cannot be closely and precisely defined, according to the Molodenxki theory, the quasigeoid surface is used as a substitute for the geoid. The quasigeoid surface is built on the principle that points from the ground place straight lines with a length equal to the normal height downwards linearly with the ellipsoid surface. The series of endpoints of those segments will form the quasigeoid surface. The difference between the quasigeoid surface and the ellipsoid surface is called the quasigeoid height or height anomaly, denoted by ζ. We have the following formula (Fig. 2):

$$H = h - \zeta \qquad (1)$$

The geoid height and height anomaly have different meanings, but in terms of value, both are nearly equal. They vary from 2 to 3 meters in mountainous areas, approximately equal in deltas and equally in the seas and oceans. Therefore, in terms of the magnitude, these two quantities are called height anomaly.

Based on the scope of the building, the geoid model can be divided into global geoid or local geoid. The global geoid is built for the entire Earth. The local geoid is built for a specific area. The global geoid is the gravitational equipotential, which is close to the average sea surface at some point. The global geoid model is usually built on the basis of combining data, such as gravity, altimetry satellites, GNSS/levelling, etc. The model is presented in digital form and published on the website. Users can easily access and exploit data for use.

2.2. Data resources for the research

Two data sources were used in this study:

- The data of the 819 GNSS/levelling points on Vietnamese territory (Tham Bui

Thi Hong, et al, 2015) (Fig. 3). Among these points, 234 points are the first - order (the red points), 199 points are the second - order (the yellow points) and 386 points are the third - order (the green points) of the national levelling networks. First - order, second - order and third - order levelling in Vietnam allows misclosure of $3\sqrt{L}$, $5\sqrt{L}$, $12\sqrt{L}$ mm over a distance of L km, respectively.

- The height anomalous data of the abovementioned 819 GNSS/levelling points were exploited from the GAO2012 model. The data of these points are extracted from the website of the International Center for Global Earth Models (ICGEM) (http://icgem.gfz-potsdam.de/home).

2.3. Research Methods

The height anomaly accuracy of the GAO 2012 model in the territory of Vietnam was assessed by two methods:

The first method: Comparing the height anomaly of the points was calculated from the field measurement results with the height anomaly of that point was exploited from the GAO 2012 model.

The second method: Comparing the difference in the height anomaly of pairs of points.

- The first method:

The process sequence for assessing model accuracy is performed as follows:

Calculate the height anomaly (denoted by ζ_{do}) of GNSS/levelling points using formula (1).

Calculate the height anomaly (denoted by $\Delta\zeta$) of the GNSS/levelling points using the following formula:

$$\Delta\zeta_i = \zeta_{mh} - \zeta_{do} \qquad (2)$$

Where:

ζ_{mh} is the height anomaly determined from the model;

ζ_{do} is the height anomaly determined from the field surveying.

Calculate the average value of the height anomaly (denoted by $\Delta\zeta_{tb}$) using the formula:

$$\Delta\zeta_{tb} = \sum_{i=1}^{n} \Delta\zeta_i / n \qquad (3)$$

Where n is the GNSS/levelling points.

The average value of the absolute value of the height anomaly (denoted by $|\Delta\zeta|_{tb}$ is calculated using the formula:

$$|\Delta\zeta|_{tb} = \sum_{i=1}^{n} |\Delta\zeta_i| / n \qquad (4)$$

Eliminate GNSS levelling points that are unsatisfactory if:

$$|\Delta\zeta_i| > 3|\Delta\zeta|_{tb} \qquad (5)$$

Rejected points are excluded in the GAO 2012 model's anomaly accuracy evaluation process in the next steps, the square deviation of the height anomaly (denoted by M) is calculated by the formula:

$$M = \pm\sqrt{[\Delta\zeta\Delta\zeta]/q} \qquad (6)$$

Where, q is the number of GNSS levelling points that it participates in evaluating model accuracy. The root mean square from is calculated using the following formula:

$$m = \pm\sqrt{[\Delta\zeta'\Delta\zeta']/(q-1)} \qquad (7)$$

Where:

$$\Delta\zeta_i' = \zeta_i - \zeta_{tb} \qquad (8)$$

- The second method.

This method uses the difference in height anomalies $\Delta\zeta$. The ellipsoidal height difference value (Δh) is calculated on the normal height value according to the following formula:

$$\Delta H = \Delta h - \Delta \zeta_i \quad (8)$$

Where: the symbol Δh_{ij} is the ellipsoidal height difference, ΔH_{ij} is the normal height difference and $\Delta \zeta_{ij}$ is the height anomaly difference, which is determined from the global gravity model GAO 2012 between two points i and j. The value of this height anomaly is determined by the formula:

$$\Delta \delta_{ij} = \Delta h_{ij} - \Delta H_{ij} - \Delta \zeta_{ij} \quad (9)$$

Factors affecting the accuracy of $\Delta \zeta_{ij}$ are GNSS measurement errors, levelling errors and error of the geoid model.

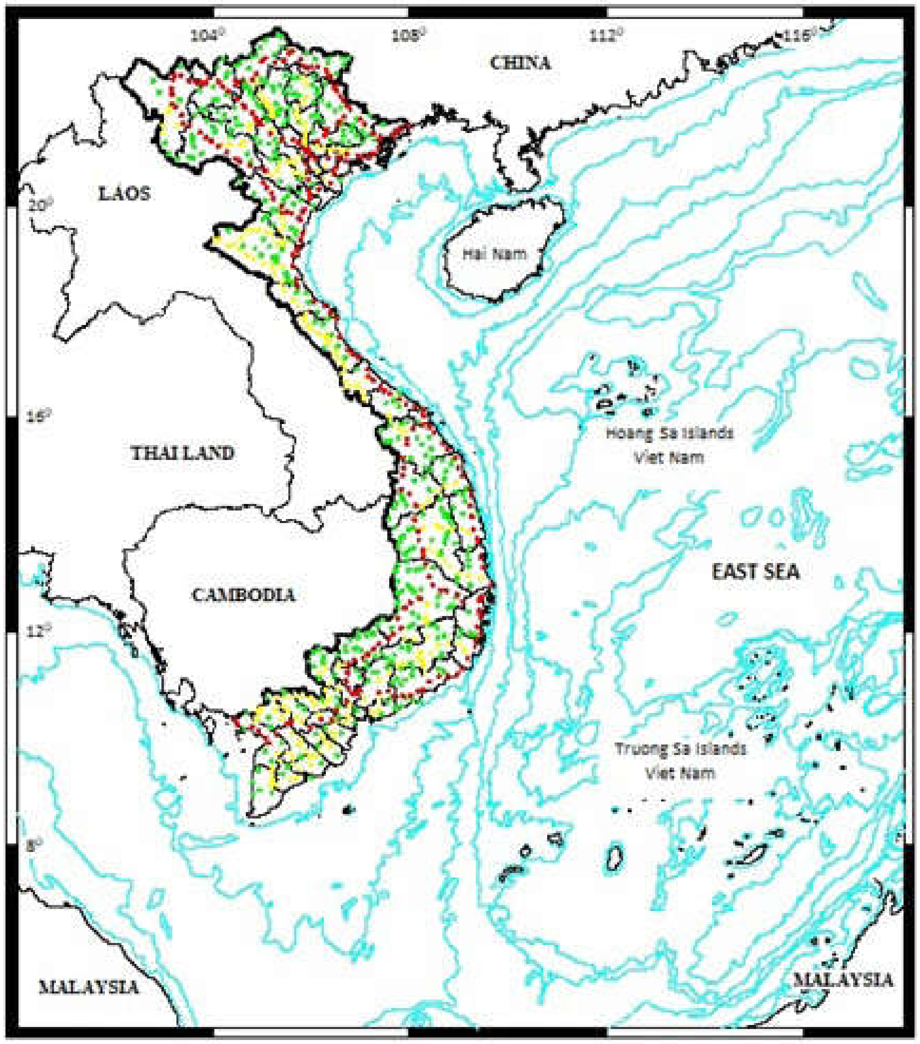

Figure 3: The GNSS/levelling points of the national levelling networks

The root mean square error (aggregate) of height difference over 1 km is calculated using the following formula:

$$m_{km} = \pm\sqrt{[P\Delta\delta\Delta\delta]/q} \quad (11)$$

Where:

$$P_{ij} = 1/S_{ij} \quad (12)$$

In equation (11), q is the number of pairs of points used for the survey, these values should not be less than 20. S_{ij} is the distance between pairs of points used for the survey.

If the normal height error of 1 km is known ($m_{\Delta H}$), ellipsoidal height error of GNSS per 1 km using the geoid model will be calculated using the formula:

$$m_o = \pm\sqrt{m_{km}^2 - m_{\Delta H}^2} \quad (13)$$

If the estimation of the ellipsoidal height difference is over 1km ($m_{\Delta h}$), the geoid model error is calculated using the following formula:

$$m_{km} = \pm\sqrt{[P\Delta\delta\Delta\delta]/q} \quad (14)$$

According to the formula (14), m_{lkm-mh} is the root mean square error of the difference in height anomaly over 1 km. This value is considered the typical value for the accuracy of the Geoid model.

Comparing the root mean square error of height difference over 1 km calculated using formula (11) with the permissible error of each class, we will evaluate the accuracy of the Geoid model that needs to be investigated.

To determine the class of a levelling route, the root mean square error of height difference over 1 km is compared with the allowableroot mean square error. The error for first-order, second-order and third-order levelling are presented in section 2.2. For fourth-order levelling, technical levelling, the accuracies are 25 $\sqrt{L}$, 50$\sqrt{L}$, respectively.

In addition, if the root mean square error of height difference over 1 km is bigger than 50$\sqrt{L}$, the levelling is unsatisfactory.

3. Results and discussion

3.1. Accuracy of height anomaly of the GAO 2012 model by the first method

The measured height anomaly values calculated from the ellipsoidal height and levelling height of the GNSS/levelling points and the value in the difference in height anomaly between the measured height anomaly and elevation anomalies which is exploited from GAO 2012 model are shown in Table 1.

Table 1. Values ζ_{do} and $\Delta\zeta$ of GNSS/leveling points

No	Name	ζ_{do} (m)	$\Delta\zeta$ (m)	No	Name	ζ_{do} (m)	$\Delta\zeta$ (m)
1	I(BH - HN)13	-29.403	-0.4036	…	…	…	…
2	I(BH - HN)17	-29.212	-0.3414	806	III(XL - TS)8	0.896	-0.4329
3	I(BH - HN)19 - 1	-28.938	-0.3877	807	III(XT - NQ)5	-25.915	-0.4570
4	I(BH - HN)20 - 1	-28.860	-0.3145	808	III(YB - AN)3	-30.148	-0.6620
5	I(BH - HN)26	-28.270	-0.1895	809	III(YB - AN)5	-30.017	-0.7084
6	I(BH - HN)33	-27.732	-0.2515	810	III(YL - CQ)4	-24.810	-0.3337
7	I(BH - HN)39	-27.419	-0.5113	811	III(YL - HB)11	-26.862	0.2958
8	I(BH - HN)4 - 1	-29.968	-0.4299	812	III(YL - HB)3	-26.972	0.0657
9	I(BH - HN)42	-27.193	-0.5604	813	III(YM - ND)10	-29.501	0.0422
10	I(BH - HN)48	-26.734	-0.6796	814	III(YM - ND)3	-29.299	0.1292
11	I(BH - HN)8	-29.753	-0.4458	815	III(YM - NK)12	-28.260	-0.5204
12	I(BH - HN)9 - 1	-29.604	-0.4622	816	III(YM - NK)18	-28.906	-0.0002
13	I(BH - LS)11 - 1	-30.386	-0.5009	817	III(YM - NK)22	-28.646	-0.2066
14	I(BH - LS)16A	-30.150	-0.5614	818	III(YM - NK)8	-28.270	-0.5959
15	I(BH -LS)21	-30.372	-0.1603	819	III(YM - YD)11	-29.299	-0.0374

The average value of the absolute value of height anomalies:

$$|\Delta\zeta|_{tb} = 0.4803 \text{ (m)}$$

Comparing the absolute value of the height anomaly of points with 3 times the average of the absolute value of the height anomaly shows that 4 of 819 points are unsatisfactory for GAO 2012 model accuracy assessment. These are points: II (BN-QT) 14, II (XM-HN) 8, III (NT-HH) 8 and III (PD-NR) 11. Thus, after eliminating these points, 815 GNSS/levelling points will be used to evaluate the accuracy of GAO 2012 model.

Average value of height anomaly:

$$\Delta\zeta_{tb} = \sum_{i=1}^{n} \Delta\zeta_i / n = -0.3974 \text{ (m)}$$

The mean deviation value of the height anomaly M:

$$M = \pm\sqrt{[\Delta\zeta\Delta\zeta]/q} = \pm 0.5186 \text{ (m)}$$

The root mean square error:

$$m = \pm\sqrt{[\Delta\zeta'\Delta\zeta']/(q-1)} = \pm 0.3334 \text{ (m)}$$

3.2. Accuracy of height anomaly of the GAO 2012 model by the second method

To assess the accuracy of height anomalies of GAO 2012 model, according to the second method, based on the terrain, Vietnamese territory is divided into 8 areas for research, which are the Northwest (1), Northeast (2), Delta Red River (3), North Central (4), South Central (5), Central Highlands (6), Southeast (7) and Southwest (8) (Fig. 4).

On each experimental area, based on the GNSS/levelling points, the levelling lines were set up to evaluate the accuracy of GAO 2012 model. According to the theory presented in section 2, the results of the implementation steps are presented for each area. Summarizing the results, we have data that are shown in Table 2 and Table 3.

Table 2. Summary of levelling routes in experimental areas

Nº	Area	Classes			
		III	IV	Technical levelling	Unsatisfactory
1	Northwest	33	32	56	68
2	Northeast	88	101	127	54
3	Delta Red River	23	19	32	18
4	North Central	61	70	108	57
5	South Central	57	38	76	56
6	Central Highlands	61	48	108	77
7	Southeast	51	40	38	4
8	Southwest	58	47	78	20
Summary of levelling routes		432	395	623	354

Table 3. Summary of the root mean square error of the height difference over 1 km

Nº	Area	m_{km} (m)	Nº	Area	m_{km} (m)
1	Northwest	± 0.0852	5	South Central	± 0.0616
2	Northeast	± 0.0514	6	Central Highlands	± 0.0667
3	Delta Red River	± 0.0364	7	Southeast	± 0.0310
4	North Central	± 0.0525	8	Southwest	± 0.0163

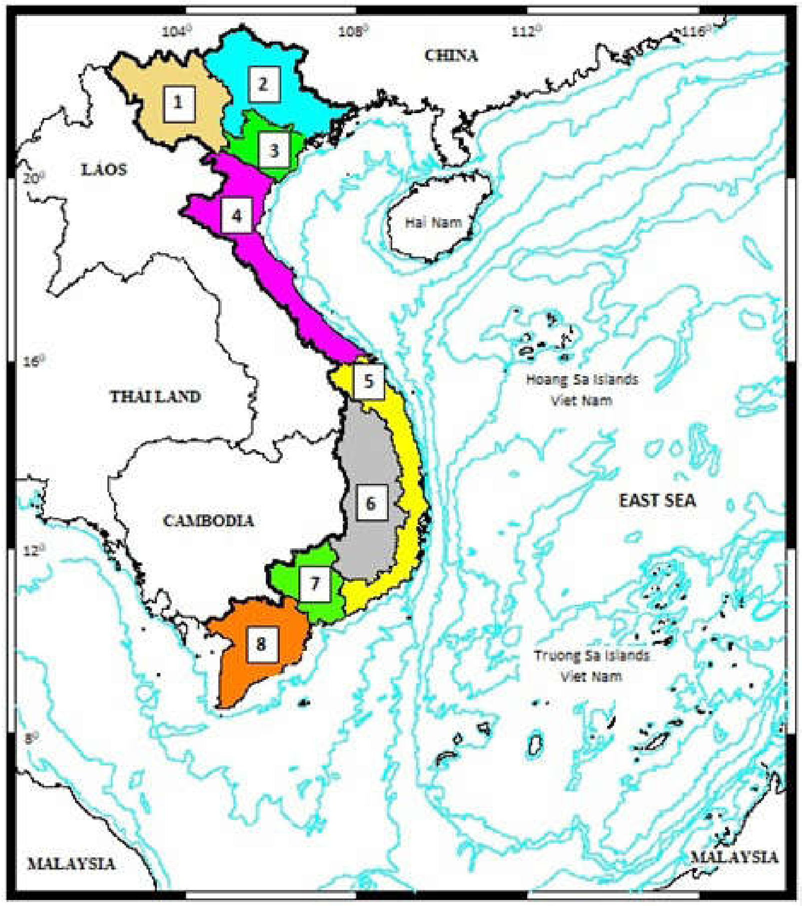

Figure 4: The experimental areas

In 8 experimental areas, 1804 levelling routes have been evaluated for accuracy. Research results have shown that the accuracy of the GAO 2012 model is the highest in the Southwest region, the worst in the Northwest region. In the Southeast region and the Red River Delta, GAO 2012 model has higher accuracy than the remainregions.

On Vietnamese territory, there are 354 levelling routes that are unsatisfactory, it accounts for 19.6 % of the 1804 levelling routes used for the survey. Thus, the number of unsatisfactory levelling routes is large.

4. Conclusion

The accuracy of the GAO 2012 model obtained from this research is completely reliable because the evaluation process is based on the accurate and rigorous theoretical basis, the source of the data used is clear.

Before assessing the accuracy of the model, the quality of the GNSS/levelling points for the calculation was checked. The results showed that 4 of 819 GNSS/levelling points were unsatisfactory. These points were excluded which were not involved in the accurate evaluation process of the model.

The process of evaluating the accuracy of the GAO 2012 model is conducted by the two methods. The average deviation of height anomalies between measuring height anomaly and modeling height anomaly is 0.3974 meters.

The accuracy of the GAO 2012 model for 8 experimental areas was determined. The accuracy of the GAO 2012 model is not much different from other models like EGM 2008, EIGEN - 6C4, GECO, XGM 2019. The information on the accuracy of GAO 2012 model in this study is a reference data source to build a high - precision geoid model in the territory of Vietnam. In addition, when exploiting the height anomaly of GAO 2012 model on Vietnamese territory, users can base on this study to estimate the accuracy achieved when converting ellipsoidal height to levelling height. Especially, if the levelling routes do not meet the requirements, users should have appropriate solutions to get accuracy to meet the job.

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