Assessment of the performance of EIGEN-6C4 via GNSS/leveling data over Vietnam

Hoa PHAM THI, Thang NGUYEN VIET, Thu TRINH THI HOAI and Bac NGUYEN XUAN, Vietnam

Keywords: EGM2008, EIGEN-6C4, GNSS/leveling, height anomalies, Vietnam

SUMMARY

EIGEN-6C4, up to maximum spherical degree and order 2190, is a global combined gravity field model of GFZ Potsdam and GRGS Toulouse. The satellite gravity gradiometry data of the entire GOCE mission along with more terrestrial gravity data obviously contribute to an improvement of the EIGEN-6C4 interpretation. This paper uses the GNSS/leveling data over the mainland part of Vietnam as independent source for investigating the performance of EIGEN-6C4 with respect to EGM2008 which is commonly used in Vietnam. The evaluation was done in both absolute and relative approaches. The result reveals that compatibility of EIGEN-6C4 and EGM2008 derived values and the GNSS/leveling observation are not stable. It also provides an improvement for EIGEN-6C4 compared to EGM2008 in term of height anomaly at a particular point as well as the discrepancy of height anomalies for baseline across Vietnam. In addition, the better performance of EIGEN-6C4 over EGM2008 is dependent on terrain characteristics in study area.

TÓM TẮT

EIGEN-6C4 là mô hình trọng trường có bậc và hạng đạt mức 2190, ra đời dựa trên sự hợp tác của hai cơ quan GFZ Potsdam và GRGS Toulouse. Ngoài các nguồn dữ liệu tham gia xây dựng mô hình EGM2008, mô hình EIGEN-6C4 còn được bổ sung thêm toàn bộ dữ liệu của dự án GOCE cùng với các số liệu trọng lực mặt đất. Nghiên cứu này sử dụng số liệu GNSS/Thủy chuẩn để đánh giá hiệu quả của mô hình EIGEN-6C4 so với EGM2008 (mô hình đang sử dụng phổ biến ở Việt nam) trên phạm vi lãnh thổ Việt nam. Quá trình đánh giá được thực hiện theo cả phương pháp tuyệt đối và tương đối. Kết quả đạt được cho thấy sự tương thích của dữ liệu mô hình EIGEN-6C4 và EGM2008 so với số liệu GNSS/thủy chuẩn thay đổi theo vùng xét. Sô liệu tính toán cũng cho thấy mô hình EIGEN-6C4 tốt hơn mô hình EGM2008 khi xét dị thường độ cao cũng như hiệu dị thường độ cao trên tuyến. Thêm nữa, mức cải thiện về chất lượng của EIGEN-6C4 so với EGM2008 phụ thuộc vào đặc điểm địa hình tại vùng nghiên cứu.

Assessment of the performance of EIGEN-6C4 via GNSS/leveling data over Vietnam

Hoa PHAM THI, Thang NGUYEN VIET, Thu TRINH THI HOAI and Bac NGUYEN XUAN, Vietnam

Keywords: EGM2008, EIGEN-6C4, GNSS/leveling, height anomalies, Vietnam

1. INTRODUCTION

Earth Gravitational Models (EGMs) are commonly divided into two different types**:** 1) The Satellite-only models and combined. Satellite-only models are derived from the artificial earth satellite data such as CHAMP, GRACE, GOCE (Balmino, 2009) and Lageos. They are independent from any terrestrial data and their degree is low. 2) The combined models are generated through merging/combining satellite data, airborne gravimetry with ground-based observation data over the continental areas and altimetry data over the ocean areas (Rapp, 1997). The combined EGMs have much higher degrees and more accurate data compared to satellite-only models.

The first high resolution global combined gravity field model which was integrated with the information of the GRACE gravity mission, the Earth Gravitational Model 2008 (EGM2008) (Pavlis *et al. 2008)*, has been publicly released since 2008. It is complete to degree and order 2159 and contains additional spherical harmonic coefficients extending up to degree 2190 and order 2159 (Pavlis *et al.* 2012). In 2014, not only GRACE but the GOCE and Lageos data along with more terrestrial gravity data were integrated to develop the European Improved Gravity model of the Earth by New techniques (EIGEN-6C4) described by spherical harmonic expansion up to the order 2190 (Förste et al., 2014).

Both above-mentioned models are now among the highest accuracy ones. However, it is not guaranteed that these models produce the same accurate results universally. In other words, the publications of accuracy estimates for GGMs are commonly not used to choose which GGM is best for a certain region. Because the published error estimates are determined as global averages and thus they do not stand for the quality of the GGM in a particular region. Therefore, there is a need to be locally investigated before they are used for practical purposes. Many researchers have investigated the performance of the two models for various areas of the earth by analyzing the differences between model-derived values and independent datasets such as GNSS/ leveling, airborne and terrestrial gravity data.

For instance, the geoid heights generated from EIGEN-6C4 and EGM2008 has compared with GNSS/Leveling source in many areas such as Canada, USA, Australia, Japan, Brazil, Europe, Czech Republic and Slovakia (Kostelecky, et al. 2015). The results showed that EIGEN-6C4 fits GPS/Levelling data slight better than EGM2008 for Canada, USA, Australia, Japan, Brazil, Europe and Slovakia, which could be caused by the contribution of the GOCE satellite data in EIGEN-6C4. In contrast, EIGEN-6C4 provided less accurate result than EGM2008 for the Czech Republic. To verify the high-degree geopotential global model that is the best for precise regional geoid model determination, the GNSS/levelling data in the

internal Aegean region of Turkey has been used as the independent data source to evaluate EGM2008 and EIGEN-6C4 (Yılmaz, 2017). These results denoted that EGM2008 has the best agreement with the GPS/leveling data. Investigation of the performance of EGM2008 and EIGEN-6C4 also was done by GNSS/leveling geoid height and terrestrial gravity anomalies in Iran (Ismael, et al., 2007). In general, those models provide similar results in terms of validation against both geoid undulation and gravity anomalies. However, in particular, the EIGEN-6C4 is slight better for estimating the geoid heights and EGM2008 achieves the closest results respective to terrestrial gravity anomalies. EGM2008 and EIGEN-6C4 are also evaluated by GPS-leveling data in China (Wei et al., 2018). The results indicated that the error level of EIGEN-6C4 derived geoid height is smaller than EGM2008.
EIGEN-6C4 and EGM2008 model was also validated by airborne gravity disturbance in Maowusu area and the results revealed that all of them provide the same accuracy level of gravity disturbance (Wei et al., 2018). According (Huang and Véronneau), over the Canadian land, because EGM2008 and EIGEN-6C4 are based on the same terrestrial gravity data so that both of them have similar level of statistical comparison with regard to the ground-based gravity data. The result represented that the GOCE data in EIGEN-6C4 agree with the corresponding land components in EGM2008 to the accuracy level of the land gravity data.
The above-metioned results showed the performance EIGEN-6C4 is slight better than EGM2008 with regard to GNSS/leveling data validation in most surveying regions, except the Czech Republic and the internal Aegean region where the spatial extend is not very large compared to the spatial resolution of GOCE data. This confirms the contribution of the novel GOCE data in EIGEN-6C4. However, the outstanding of EIGEN-6C4 over EGM2008 in term of gravity data is not clearly because of quite less researches published and both models might be dependent on terrestrial gravity data in study area. To verify an improvement from EIGEN-6C4 over EGM2008 in term of gravity anomalies or gravity disturbance, there is a need to investigate in areas where land gravity data or airborne gravity data are not used to generate those models.
Evaluation EGMs has never been performed via terrestrial gravity observations but GNSS/Leveling data in mainland of Vietnam. Investigation of the compatibility of some early combined models such as OSU91A, EGM96, EGM2008 with GNSS/leveling data has inplemented by statistical value of the differences between geoid/quasigeoid heights obtained by GGMs and GNSS/leveling datasets (Hoa and Lan, 2015). It resulted that EGM08 is the best performance of global gravity model over Vietnam. Similar study for EIGEN-6C4 has never been done for territory of Vietnam. Thus, there is a need to valuation for EIGEN-6C4 in Vietnam, especially for further geoid determination at local scale. This paper aims to investigate the performance of EIGEN-6C4 with respect to EGM2008 via GNSS/leveling data. This study differs from (Hoa and Lan, 2015) in that not only adding the new EIGEN-6C4 but also the new way to evaluate EGMs. Beside the comparison the quasigeoid heights created by EGM and GNSS/leveling data for points (absolute comparision), which is similar to ((Hoa and Lan, 2015), this study compares the difference of quasigeoid heights for baseline (relative comparison) as well.

2. THEORY BACKGROUND

2.1. The height anomaly derived from EGMs

EGMs represent globally the potential field of the Earth through spherical harmonics (SH) coefficients. According to this the height anomaly (ζ) can be calculated as follows (Hofmann Wellenhof, Moritz, 2005):

$$\zeta(\lambda, \phi) = \frac{GM}{r\gamma(r\phi)} \sum_{l=0}^{l_{max}} \left(\frac{R}{r}\right)^{l} \sum_{m=0}^{l} \overline{R}_{lm} \overline{Y}_{lm}(\lambda, \phi) \quad (1)$$

where, $$\overline{R}_{lm} = \begin{cases} C_{lm}^{T} & m \geq 0 \\ S_{lm}^{T} & m < 0 \end{cases} \quad (2)$$

and: $$\overline{Y}_{lm} = \begin{cases} \overline{P}_{lm}(\cos\phi)\cos m\lambda & m \geq 0 \\ \overline{P}_{lm}(\cos\phi)\sin |m|\lambda & m < 0 \end{cases} \quad (3)$$

$$C_{lm}^{T} = C_{lm}^{W} - C_{lm}^{U};$$
$$S_{lm}^{T} = S_{lm}^{W} - C_{lm}^{U}; \quad (4)$$

where, GM is the product of Newtonian gravitational constant G and the Earth's mass M. $\overline{P}_{lm}$ reprerents the fully normalized associated Legendre polynomial function of degree l and order m; lmax is the maximum degree of the SH expansion; r is distance from the center of the Earth to the point where the heigh anomaly is determined. C_{lm}^{T} T and S_{lm}^{T} are the spherical harmonic coefficients of the disturbing potential: $C_{lm}^{U}$and C_{lm}^{U} are the ellipsoidal normal potential coefficients; C_{lm}^{W} and S_{lm}^{W} are the ellipsoidal actual potential coefficients. By subtracting the coefficients of the normal ellipsoid, the disturbing potential field is derived which could be used to compute height anomalies (for more detail Hofmann Wellenhof, Moritz 2005).

2.2 GNSS/Leveling

GNSS-derived geodetic heights refer to a reference ellipsoid, while normal heights determined through EIGEN-6C4 refer to a quasigeoid. When these heights are derived at the same point, height anomaly can be determined through a geometrical approach. GNSS/levelling quasigeoid height are computed by (Hofmann Wellenhof and Moritz,2005):

$$\zeta_{\text{GNSS/leveling}} = h - H \quad (5)$$

Here $\zeta_{\text{GNSS/leveling}}$ stands for height anomaly, *h* denotes for ellipsoidal height obtained from GNSS measurements, and *H is* normal height derived from EIGEN-6C4 measurements. For a baseline generated from point A and point B, the difference of height anomalies are calculated as follows:

$$\Delta\zeta_{GNSS/levelling} = \zeta_{GNSS/levelling,B} - \zeta_{GNSS/levelling,A} \quad (6)$$

$$\Delta\zeta_{model} = \zeta_{model,B} - \zeta_{model,A} \quad (7)$$

uhere $\zeta_{GNSS/levelling,B}$ *and* $\zeta_{GNSS/levelling,A}$ are height anomalies derived from GNSS/leveling at point A and point B, respectively; $\zeta_{model,B}$ *and* $\zeta_{model,A}$ are height anomalies derived EGM at point A and point B, respectively.

3. EVALUATION PROCEDURE

3.1 Absolute evaluation (point evaluation)

The performance of EGMs focuses on the correspondent height anomaly differences which could be determined as following equation:

$$\Delta\zeta = \zeta_{\text{GNSS/leveling}} - \zeta_{\text{model}} \quad (8)$$

where $\Delta\zeta$ is the quasigeoid height residual, $\zeta_{GNSS/leveling}$ is the quasigeoid height estimated from GNSS/levelling, and ζ_{model} is the quasigeoid height generated from EGMs. The $\Delta\zeta$ includes random and systematic components. The random part comprises the error of GNSS/leveling measurements and GGM data. The other one comes from the reference systems of GGMs differs from GNSS/leveling ones. For the statistical analysis of quasigeoid height differences for points, the root mean square of $\Delta\zeta$ is determined as follows:

$$m_{\Delta\zeta} = \pm\sqrt{\frac{[\Delta\zeta'\Delta\zeta']}{n-1}} \tag{9}$$

where *n* is the number of the points used for the comparison, and:

$$\Delta\zeta_{TB} = \frac{1}{n}\sum_{j=1}^{n}\Delta\zeta_j \tag{10}$$

$$\Delta\zeta_j^{/} = \Delta\zeta_j - \Delta\zeta_{TB} \tag{11}$$

3.2. Relative evaluation (Baseline evaluation)

The quasigeoid height differences for baseline are determined as follows:

$$\delta/_{baseline} = \Delta\zeta_{GNSS/levelling} - \Delta\zeta_{model} \tag{12}$$

The value of $\delta_{/baseline}$ represents the error of GNSS data, levelling data and GGM data. The root mean square per 1km is determined as :

$$\delta_{/1km} = \pm\sqrt{\frac{P\delta\delta}{n-1}} \tag{13}$$

Where P is the weight of $\delta_{/baseline}$ and could be calculated as:

$$P = \frac{1}{D} \tag{14}$$

with D stands for baseline length.

4. STUDY AREA AND DATASETS

This study has been done in the territory of Vietnam.The datasets consist of GPS/leveling, EIGEN-6C4 and EGM2008 data. The GNSS/levelling networks, containing 818 points regularly covering in different regions of Vienam, has been surveyed by Department of Surveying, Mapping and Geoinformation of Vietnam with the aim to build local quasigeoid. The GNSS observations and the normal heights were tied to the World Geodetic System 1984 (WGS84) and the Vietnamese vertical datum, respectively. For all 818 points, quasigeoid heights were derived using Eq. (8)

The sets of grid model of height anomalies based on EGM2008, EIGEN-6C4 were computed from the International Centre for Global Earth Models *(ICGEM)* web, http://icgem.gfz-potsdam.de/ICGEM, and respect to the reference system WGS84 system. The grid model covers the whole of Vietnam territory with parts of the neighbouring countries. The "zero-degree" parameter based on difference between the *GM* value estimated for the Earth and the *GM* value for WGS84 ellipsoid was considered in quasigeoid height computation. From the *EGM* grid net established, height anomalies of 818 GNSS/levelling points were interpolated using a Collocation method.

5. RESULTS AND DISCUSSION

5.1. Absolute evaluation

Absolute assessment was performed for all GNSS/leveling networks in the entire mainland of VietNam as well as in distinct parts (northern, middle and southern) with different terrain characteristics. Specifically, the complexity of the terrain decreases sharply from northern area to southern area. The statistics of the differences between the GNSS/leveling based and the GGM-based geoid undulations are given in Table 1.

Table 1. Root mean square (m) about the mean of GNSS/levelling minus model-derived geoid heights for EGM2008 and EIGEN-6C4

Areas	GGMs	Root mean square ($m_{\Delta\zeta}$)
Entire mainland of Vietnam	EGM2008	0.2867
	EIGEN-6C4	0.1895
Northern area of Vietnam	EGM2008	0.3731
	EIGEN-6C4	0.2461
Central area of Vietnam	EGM2008	0.2456
	EIGEN-6C4	0.1778
Southern area of Vietnam	EGM2008	0.1842
	EIGEN-6C4	0.1137

The data in table 1 reveals that root mean square values for EGM2008 is larger than those ones for EIGEN-6C4. In means EIGEN-6C4 outperform EGM2008 in term of height anomaly in mainland Vietnam. It can be explain by adding of GOCE mission data and Lageo data in the EIGEN-6C4 model. Furthermore, the outstanding of EIGEN-6C4 reduces from northern to southern area and it is remarkable in northern part which is the highest and roughest area in Vietnam. It could be concluded that the improvement of the EIGEN-6C4 over EGM2008 related to characteristics of topography in surveying areas.

5.2. Baseline evaluation

Baseline assessment was also performed for all GNSS/levelling networks in the entire territory of VietNam as well as in three regions. The baselines is divided into different groups which their lengths varies from 0 to 5km, from 5km to 10km,..., and from 1495 to 1500km. The computed results corresponding baseline lengths is given in the following chart (fig., fig.2, fig.3, fig.4).

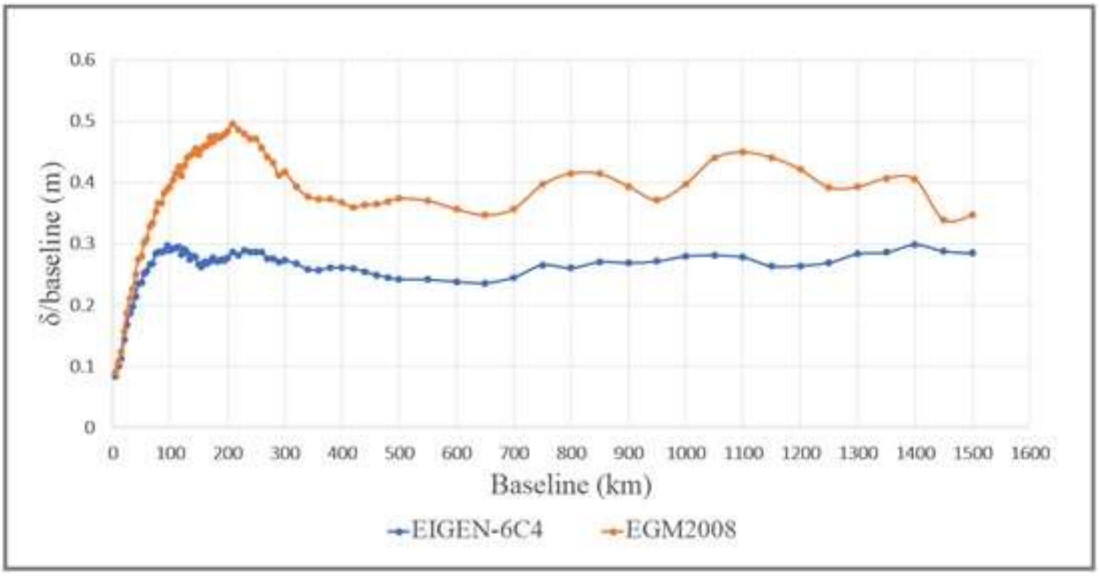

Figure 1: The values of $\delta/_{baseline}$ for the entire mainland of VietNam

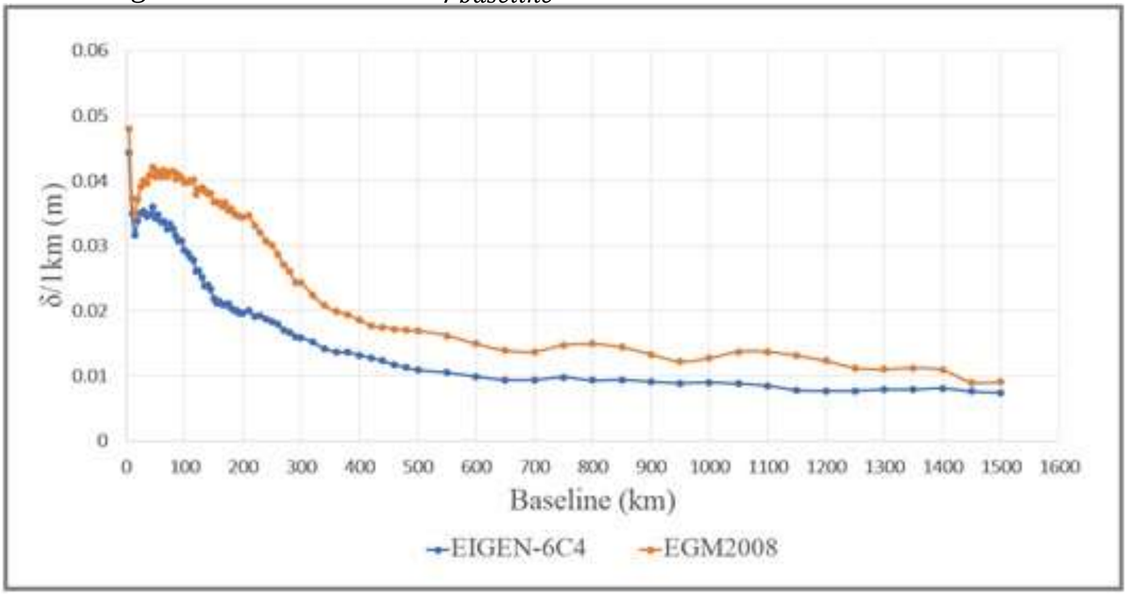

Figure 2. The values of $\delta/_{1km}$ for the entire mainland of VietNam

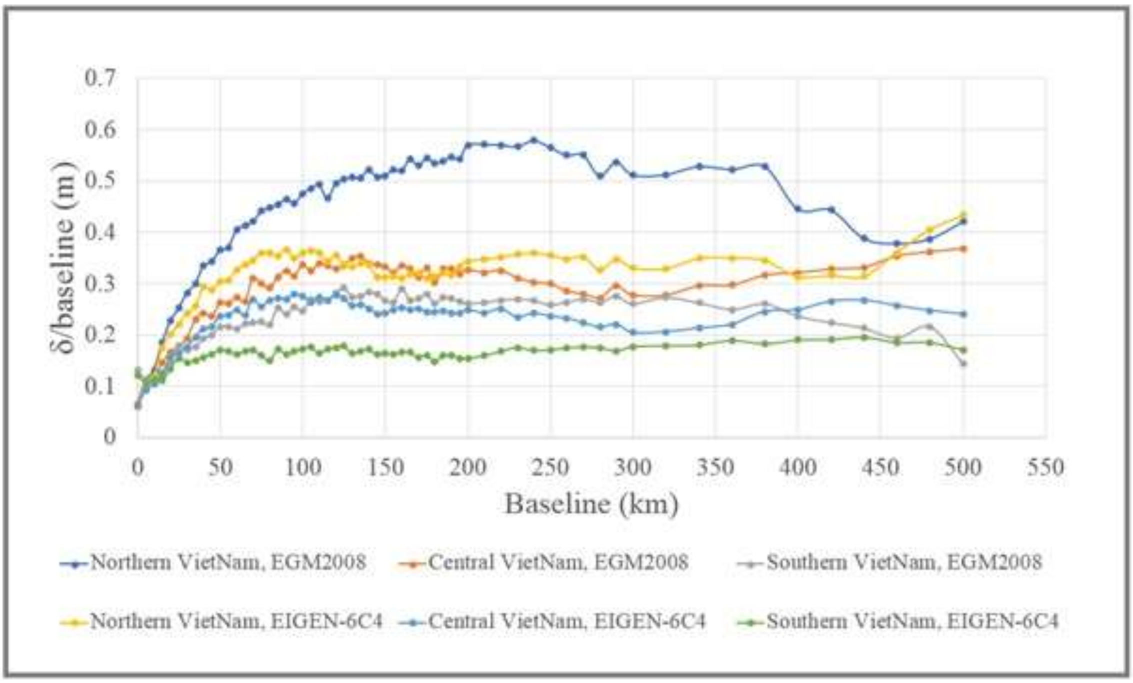

Figure 3. The values of $\delta/_{baseline}$ for separate areas in VietNam

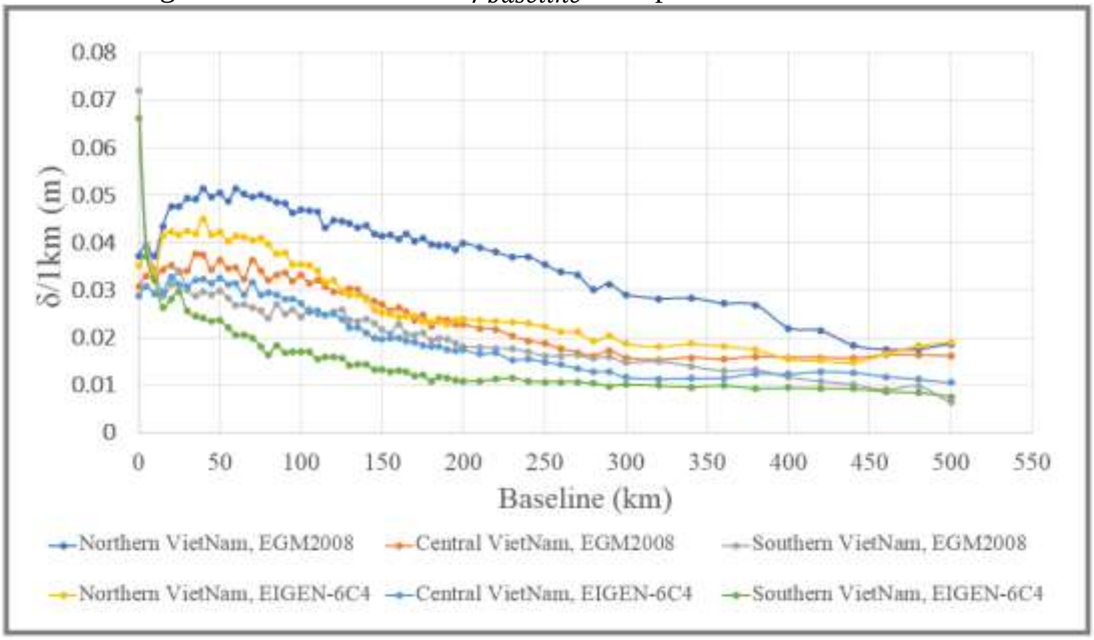

Figure 4: The values of $\delta/_{1km}$ for separate areas in VietNam

In general, the δ/baseline respect to EIGEN-6C4 is smaller and more stable than the corresponding one for EGM2008. The value of δ/baseline increases dramatically with baselines shorter than 100 km and 200km for Eigen 6c4 and EGM2008, respectively. For the left baseline lengths, δ/baseline fluctuates slightly for EGM2008 but remain stable for EIGEN-6C4.

The δ/baseline is the same value of +0.09m at the beginning for both models but increases dramatically to +0.5m at corresponding baseline of 200km for EGM2008 and +0.3m at baseline lengths of 100km for EIGEN-6C4. The values of δ/baseline is stable with remain distances for EIGEN-6C4. However, for EGM2008, it decreases gradually to +0.41m at baseline length of 300 km and then fluctuates.

Overall, the value of δ/1km regard to EIGEN-6C4 is smaller and more stable than EGM2008. The difference in δ/1km of the two models is almost negligible at a distance of less than 10km but quite large at a distance of from 30km to 300km. The parameter of δ/1km decreases dramatically from 0.045m to 0.032m with baselines shorter than 10 km for both EIGEN-6C4 and EGM2008, then gets bigger and reach 0.042m at distance of 50km and 0.035m at distance of 30km for EGM2008 and EIGEN-6C4, respectively. The component of δ/1km reduces gradually to 0.017m for EGM2008 and 0.010m for EIGEN-6C4 at the baseline shorter than 500km and be stable with left distances.

The result of ralative evaluation is consistent with absolute evaluation outcome. EIGEN-6C4 outperform EGM2008 in all study areas. The statistical indicators, δ/baseline and δ/1km, for both models also decline from northern region to southern region and the values in northern area are quite large compare to corresponding components in the other regions. It can be explained by the fact that the terrain complexity increase dramatically from the southern area to the northern area.

6. CONCLUSION

GNSS/levelling datasets have been used to evaluate EIGEN-6C4 and EGM2008 on mainland of Vietnam by absolute approach as well as relative approach. This states a better performance of EIGEN-6C4, when compared to the older one - EGM2008, in term of height anomaly as well as the discrepancy of height anomalies of baseline across Vietnam. It can be explain that there are some new input sources in EIGEN-6C4 such as Goce and Lageo data.

The improvement of EIGEN-6C4 over EGM2008 reduces from northern to southern region, which consistent with the decline of the surface complication. In particular, the better performance of EIGEN-6C4 in northern which is the most complex level of terrain is remarkable compare to the other regions. It is possible to verify that the improvement of the EIGEN-6C4 with regard to EGM2008 related to topography condition in study areas.

It is recommended to use EIGEN-6C4 model to replace EGM2008 model for practical purposes related to height anomaly within the territory of Vietnam.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by a research grant from the Natural Resources and Environment of the Socialist Republic of Vietnam (Project “The science research in building marine geoid for Vietnam, testing for a typical area”. No: TNMT.2018.07.08).

RREFERENCES

Balmino, G. et al (2009). CHAMP, GRACE and GOCE: mission concepts and simulations. Bollettino di geofisica teorica ed applecata. Vol. 40, N. 3-4, pp. 309-319;

Förste, C. et al (2014) “The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse”. In: 5th GOCE User Workshop, Paris. 25–28 November 2014. *url*: http://icgem.gfz-potsdam.de/ICGEM/documents/Foerste-et-al-EIGEN-6C4.pdf

Hoa, P., Lan, P. (2015). Determining the separation between global and local quasigeoid at HonDau tidal station in Vietnam. Journal of Natural Resources and Environment, 2015, 23(277)

Huang, J. and Véronneau, M. Assessments of Recent GRACE and GOCE Release 5 Global Geopotential Models in Canada

Hofmann Wellenhof, B.; Moritz, H. (2005). *Physical Geodesy*.Wien: Springer

Ismael, F., Yosra, A., Sabah, R., Abdolreza, S. (2007). Local evaluation of earth gravitational models, case study: Iran. Geodesy and Cartography. Vol 43(1): 1–13. https://doi.org/10.3846/20296991.2017.1299839

Kostelecky, J.; Klokocnik, J.; Bucha, B.; Bezdek, A.; Förste, C. (2015) . Evaluation of the Gravity fIeld model EIGEN-6C4 in comparison with EGM08 by means of various functions of the gravity potetnial and by GNSS/Leveling, Geoinformatics 14(1): 7–28.

Pavlis, N.; Holmes, S.; Kenyon, S.; Factor, J. (2008). "An Earth gravitational model to degree 2160: EGM 2008," Presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, pp. 13-18, April 2008.

Pavlis, N.; Holmes, S.; Kenyon, S.; Factor, J. 2012. Te development and evaluation of the Earth Gravitional Model 2008 (EGM08), Journal of Geophysical research 117(B4): 1–38. https://doi.org/10.1029/2011jB008916 Rapp, R.H. (1997). Past and future developments in geopotential modelling, in: Forsberg, R, Feissl, M., Dietrich, R. (Eds.) Geodesy on the Move, Springer, Berlin, pp. 58-78.

Yılmaz, M., Turgut, B. , Güllü, M. , Yılmaz, I. (2017). The Evaluation of High-Degree Geopotential Models for Regional Geoid Determination in Turkey. AKU J. Sci. Eng. 17 (2017) 015501 (147-153)

Wei, L., Xinyu, U., Jiancheng,L. et al (2018). The Determination of an Ultra high Gravity Field Model SGG-UGM-1 by Combining EGM2008 Gravity Anomaly and GOCE Observation Data[J] . Acta Geodaetica Cartographica Sinica, Vol (4): 425-434 .

BIOGRAPHICAL NOTES

- graduated bacholer degree at Hanoi University of Mining and Geology in 2000
- graduated master degree at Hanoi University of Mining and Geology in 2004
- graduated PhD degree at Hanoi University of Mining and Geology in 2012

PAST EXPERIENCES

-Some requirements of terrain elevation data for calculating the terrain effect on height anomaly in Vietnam

-Some requirements of terrain elevation data for calculating the terrain effect on height anomaly in Vietnam

-Investigation the relationship between terrain effect in height anomaly and calculated radius in Lai Châu- Sơn La

-Determination of the elevations based on national vertical datum with the same accuracy as 3rd order levellingon large islands near the coast of Vietnam

-Determining dynamic connections between Vietnamese geodetic datum VN2000 and international terrestrial reference systems

CONTACTS

Title Given name and family name: Hoa Pham Thi
Institution: Hanoi University of Natural resources and environment
Address: No 41A, Phu Dien Street, Bac Tu Liem District, Hanoi
City: Hanoi
COUNTRY: Vietnam
Tel. + 84 984 867 372
Email: pthoa.tdbd@hunre.edu.vn