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# Development of a local quasigeoid model for Vietnam land area using the global EGM2008 model

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# Development of a local quasigeoid model for Vietnam land area using the global EGM2008 model

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**Abstract**. The article presents the results of research on the development of methods for obtaining normal heights in Vietnam using the global geoid model EGM2008 and software for processing GNSS measurements. The errors between the normal heights computed by the global model of the EGM2008 geoid and the heights found by GNSS measurements and geometric levelling on the territory of Vietnam are determined. The localisation method for the global geoid model EGM2008 for Vietnam's territory is suggested, such a geoid model is practically formed as the EGM2008_ TN file. Tests of the developed technique and the localised model of the EGM2008__TN geoid were carried out, showing the possibility of its application to obtain normal heights from GNSS measurements in Vietnam with the 4th levelling accuracy class.

## 1. Introduction

GNSS technologies allow determining geodetic heights for points on the earth's surface with high accuracy. However, the normal heights are often used in the industry, so the transition from geodetic to normal heights with the accuracy of geometric levelling should be performed by a series of transformations based on the data on anomalies of the height-difference surface of the quasigeoid and ellipsoid. The determination of normal heights from satellite levelling compares favourably with geometric levelling under complicated conditions, such as harsh weather, mountainous swampy areas, rugged terrain, etc. In addition, even if no results of ground geometric levelling are available, GNSS measurements, allow height determination for any point; in this case, a model of height anomalies of the required accuracy is necessary. In this regard, the actual task is to determine the normal heights using GNSS technology without a level run.

Such global geoid models as EGM2008, EIGEN-6C4, GECO and GAO-2012 can be used. The highest degree of geopotential decomposition (2190-degree) has the EGM2008 model with a grid size of 1x1 or 2.5x2.5 minutes of the National Geospatial-Intelligence Agency, NGA of the U.S. Department of Defense. Due to the high level of detail, EGM2008 is widely used in production. However, in mountainous areas, it is necessary to clarify this model because in some cases the result obtained from satellite levelling using the model of height anomalies does not coincide with the results of more reliable geometric levelling.

## 2. Materials and methods

In order to create a local quasigeoid model, more accurate than the global model (EGM2008), it is necessary to use a set of points with known normal heights at which satellite observations were made and geodetic heights were determined.[2, 5-7, 15]. In this case, the constructed model of the local quasigeoid (surface) is applicable to the local area only.

Heights are related by the expression:

$$H = H^g + N = H^\gamma + \zeta, \qquad (1)$$

where: $H$ is for the geodetic height, $H^g$ is for the orthometric (absolute) height (correlates with the geoid), $H^\gamma$ is for the normal height (correlates with quasigeoid), $\zeta$ is for the height anomaly, $N$ is for the geoid height.

According to the work [13], residual and wave methods can be applied for constructing a height anomaly model. The residual method based on the interpolation of the height anomaly from the EGM2008 model is the most common and simpler. It has higher accuracy [4, 8–11, 13, 14], especially at low density of GNSS-levelling points. The residual method gives a better model of elevation anomalies on a local scale (for a small area). This method adjusts the EGM2008 model to the actual values of elevation anomalies.

Knowing the exact model of the height anomaly $\zeta$, it is possible to convert the geodetic height determined by GNSS technology to the normal height. To achieve this goal, a model of height anomalies $\zeta$ with a 1-cm accuracy is required to determine the height with a levelling accuracy of the 3rd or 4th classes [12,16–17].

The wave method is the construction of a local elevation anomaly model without improving the EGM2008 model. The local elevation anomaly model is based on interpolation to compute the $\zeta$ value at an arbitrary point from a set of GNSS points with the known normal heights and to equalise the heights of GNSS levelling points. The wave method is often used under a fairly large density of GNSS measurement points at which normal heights are known.

Model EGM2008 is sufficiently improved and can be used jointly with the data of the GNSS measurements to construct a local height anomaly model for Vietnam.

*2.1. An adjustment algorithm that combines geodesic height, normal height and height anomaly*

For the points of the network by the values of geodetic height, normal height and height anomalies, the deviation vector $\Delta\zeta_i$ can be computed by the formula:

$$\Delta\zeta_i = H_i - h_i - \zeta_i^{2008} = \zeta_i^{ГНСС/Нив} - \zeta_i^{2008} \tag{2}$$

and the equations of adjustment amendments can be drawn:

$$\Delta\zeta_i = f(\phi_i, \lambda_i) + v_i = a_i^T x_i + v_i \tag{3}$$

The elements of the matrix A and the unknown, depending on the model parameters selected to describe the difference between the three elements of the height. In equations (2) and (3), $H_i$, $h_i$, $\zeta_i^{2008}$ are the geodesic height, normal height, and height anomaly, respectively (derived from the EGM2008 model) that correspond to point *i,* and $H_i - h_i = \zeta_i^{ГНСС/Нив}$ is the GNSS-leveling height anomaly.

Accuracy estimation can be performed by 5 types of models: including 4 parameters, 5 parameters, a polynomial of 1st degree, a polynomial of 2nd degree and a polynomial of 3rd degree [3, 14].

In general case

$$a_i^T x_i = \sum_{m=0}^{M}\sum_{n=0}^{N} x_q(\varphi_i - \varphi_0)^n(\lambda_i - \varphi_0)^m \cos^m \varphi_i \tag{4}$$

The system of measurement equations and its solution can be drawn as a matrix:

$$L = Ax + V \tag{5}$$

$$x=-(A^TPA)^{-1}A^TPL=-(A^TA)^{-1}A^TL \tag{6}$$

where P is the weight matrix (the inverse variance matrix, i.e. covariance measurement matrix). We suppose that the measurements and their corresponding errors do not correlate between each other and heights in the same measurement system, i.e. they are independent. On the other hand, we also assume that the heights are measured with the same accuracy; in this case, the weight matrix turns into a unit matrix.

In addition to the above mentioned model, the interpolation method based on the spline function is also widely used in geodetic surveying [1, 3]. Spline interpolation is commonly used in the wave method to construct a local anomaly model.

Let us consider both cases with and without the use of the global EGM2008 model. The height anomaly of a point is interpolated by the points with the use of the spline function according to the following formula:

$$\Delta\zeta\left[P(x,y)\right] = \sum_{i=1}^{n} a_i r_{PP_i}^2 \ln(r_{PP_i}^2) + \tau_1 + \tau_2 x + \tau_3 y, \tag{7}$$

where: $r_{PP_i} = \sqrt{(x-x_i)^2 + (y-y_i)^2}$, $\mathrm{a_i}\,(\mathrm{i}=1\div \mathrm{n});\tau_1,\tau_2,\tau_3$ is the required parameters of the equation system:

$$\left[\begin{array}{cccc|ccc} 0 & g_{1,2} & \cdots & g_{1,n} & 1 & x_1 & y_1 \\ g_{2,1} & 0 & \cdots & g_{2,n} & 1 & x_2 & y_2 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ g_{n,1} & g_{n,2} & \cdots & 0 & 1 & x_n & y_n \\ \hline 1 & 1 & \cdots & 1 & 0 & 0 & 0 \\ x_1 & x_2 & \cdots & x_n & 0 & 0 & 0 \\ y_1 & y_2 & \cdots & y_n & 0 & 0 & 0 \end{array}\right] \times \begin{bmatrix} a_1 \\ a_2 \\ \cdots \\ a_n \\ \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} = \begin{bmatrix} \Delta\zeta_1 \\ \Delta\zeta_2 \\ \cdots \\ \Delta\zeta_n \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{8}$$

where

$$g_{i,j} = g_{j,i} = \begin{cases} r^2_{P_iP_j}\ln(r^2_{P_iP_j}); (i \neq j) \\ 0; (i = j) \end{cases}. \tag{9}$$

By using the above mathematical models, it is possible to compute the height anomalies $\Delta\zeta$ of the points and to move to normal heights by the results of GNSS-positioning:

$$h = H - (\zeta^{2008} + \Delta\zeta) \tag{10}$$

## 3. Results

The geodetic network based on the GNSS technology consists of 180 points (GNSS-levelling) used for the considered (test) territory of the Central Highlands in Vietnam. Measurements were carried out by two-frequency receivers during at least 6 hours for each reception. GNSS levelling points are distributed relatively uniformly across provinces from Quang Nam to Lam Dong, Binh Phuoc, and Ninh Thuan (Fig.1). The research is based on 163 points, the rest 17 control points were used to test the methodology.

### *3.1. Design of a local quasigeoid model using the EGM 2008 model*

With regard to our data (163 points at the Central Highlands) we have the coordinates of the boundaries of the site: Southwest $B_1 = 11^0 41'$, $L_1 = 107^0 00'$; northeast – $B_2 = 15^0 21'$, $L_2 = 109^0 25'$. The region size $\Delta B = 3.67^0$, $\Delta L = 2.52^0$ with a cell size of 2.5' x 2.5', the number of grid points (N) will be 5251 (N = 89x59). At each point of the grid (i), 3 values can be found: latitude$B_i$, longitude $L_i$ and the height anomaly (from the EGM2008 model) $\zeta_i$ ($i$ = 1, 2 ..., 5251).

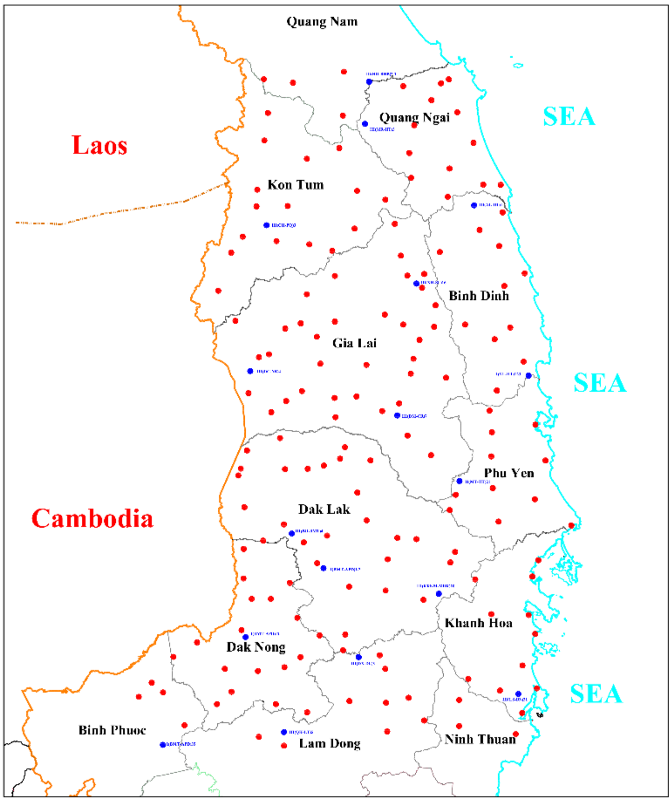


**Figure 1.** GNSS-levelling network (Central Highlands, Vietnam)

Correction computation for the grid points is done using the spline function (8, 10). Height anomalies in the global model EGM2008 are computed by the formula: $\zeta^{TN} = \zeta^{2008} + \delta\zeta$. (where $\zeta^{2008}$ is for the anomalous height, obtained from the EGM2008 model, $\delta\zeta$ is for the anomaly correction obtained by the wave method interpolation (on the basis of the spline function), $\zeta^{TN}$ is for the anomaly height of a continuous model). Height anomaly computation is shown in the flowchart (Fig. 2).

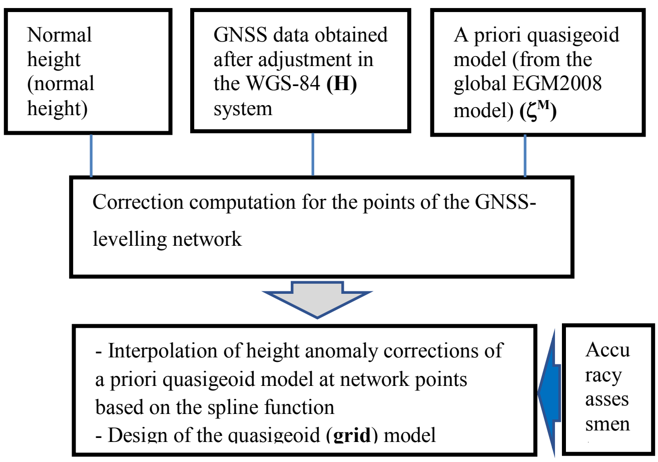


**Figure 2.** Design of a local quasigeoid model according to the global EGM 2008 model

After computation of the height anomaly for the network points ($\zeta^{TN}$), a quasigeoid model of the Central Highlands (and the South Central Coast) has been revised.

The Central Highlands and the South Central Coast quasigeoid models are based on the EGM2008 model, latitude from $11^0 41'$ to $15^0 21'$, longitude from $107^0 00'$ to $109^0 25'$, area of ca. 80 000 km$^2$. A grid model (Table 1) has a cell size of 2.5' × 2.5' (including 5251 points).

**Table 1**. Height anomaly and correction for the grid points (cell model) (part)

| No. | Name | B($^0$) | L($^0$) | $\zeta^{2008}$(m) | $\delta\zeta$ (m) | $\zeta^{TN}$ (m) |
|---|---|---|---|---|---|---|
| 1 | 1 | 15.3500 | 107.0000 | -12.550 | 0.711 | -11.839 |
| 2 | 2 | 15.3500 | 107.0417 | -12.132 | 0.726 | -11.406 |
| 3 | 3 | 15.3500 | 107.0833 | -11.715 | 0.742 | -10.973 |
| … | … | … | … | … | … | … |
| 5250 | 5250 | 11.6833 | 109.3750 | 5.370 | 1.314 | 6.684 |
| 5251 | 5251 | 11.6833 | 109.4167 | 5.519 | 1.364 | 6.883 |
| | | | | Min = -12.55<br>Max = 5.519 | Min = 0.031<br>Max = 1.364 | Min = -11.839<br>Max = 6.883 |

The cell size in the local EGM2008_TN quasigeoid model is 2.5′ × 2.5′, the circle radius is from 6 to 11 km. With this radius, the number of selected points will be between 4 and 13 cell points. Points within this radius will be used as reference points for interpolating GNSS measurement points.

**Accuracy assessment of the interpolation results**

The model was tested on 17 points of the satellite network that are not used for the modelling. First of all, we need to explore and choose the interpolation algorithm of the height anomalies of the EGM2008_TN.

According to the data obtained from 17 points, we calculate the difference in height between these points and then compare them with the tolerances for the 3rd and 4th levelling classes and technical levelling.

In practice, when measuring heights using GNSS technology, at least one point with normal height is needed in the network. For this point, it is necessary to determine the height anomaly $\Delta\zeta$ using the geoid model, then calculate the difference $\Delta h$ using the formula:

$$\Delta h = \Delta H - \Delta\zeta, \tag{12}$$

where $\Delta H$ is the difference of geodetic heights at the considered point.

Let us denote $\Delta H_{i,k}$ as the difference of geodetic heights between two points; $\Delta h_{i,k}$ as the difference of normal heights, and $\Delta\zeta_{i,k}$ as the height anomaly determined by the global model (EGM2008) between two points.

The difference between the normal height of 2 points is computed as follows:

$$\delta_{i,k} = \Delta H_{i,k} - \Delta h_{i,k} - \Delta\zeta_{i,k} \tag{13}$$

Considering the weight measurement, the standard deviation for 1 km is computed using the following formula (17)

$$m_{км} = \pm\sqrt{\frac{[P\delta_i\delta_i]}{m}} \tag{14}$$

The weight is calculated by the formula:

$$P_{i,k} = \frac{1}{D_{i,k}}, \tag{15}$$

where $D_{i,k}$ is the distance between two points in kilometres, $m$ is the number of point pairs to study. In this case, $m$ should be not less than 20, and the distance between the points $D_{i,k}$ should be of different values. The results are shown in Table 2.

**Table 2**. Accuracy assessment for the determined normal heights using EGM2008_TN model

| No. | Factors | EGM 2008 | Weighted average | Polynomial of 1st degree | Polynomial of 2nd degree | Spline function |
|---|---|---|---|---|---|---|
| 1 | Number of points | 136 | 136 | 136 | 136 | 136 |
| 2 | Non-compliance with the technical levelling tolerance | 9 (7%) | 0 (0%) | 0 (0%) | 0 (0%) | 0 (0%) |
| 2 | Compliance with the technical levelling tolerance | 127 (93%) | 136 (100%) | 136 (100%) | 136 (100%) | 136 (100%) |
| 3 | Compliance with the tolerance level of the 4th class | 108 (79%) | 136 (100%) | 136 (100%) | 136 (100%) | 136 (100%) |
| 4 | Compliance with the tolerance level of the 3rd class | 54 (40%) | 94(69%) | 103(76%) | 108(79%) | 115 (85%) |
| 5 | Standard deviation (m) – $m_{km}$ | 0.0244 | 0.0119 | 0.0102 | 0.0096 | 0.0086 |

The interpolation results for 17 control points show that all four interpolation methods provide acceptable results. According to Table 2, ca. 80% of the routes have acceptable accuracy for the 3$^{rd}$ grade levelling under all four interpolation methods, even in the cases of mountain areas. The 100% accuracy is obviously provided for the technical levelling. In practice, we suggest applying the weight-average interpolation method.

## 4. Conclusion

The developed calibration procedure for height anomalies of the EGM2008 is intended for use on a large scale with the large number of points in a network. The computation method is relatively simple and improves the accuracy of height determination based on GNSS measurements.

The network points (GNSS points) should coincide with the level points of the 3rd class and above. The points should be distributed relatively uniformly and fairly densely.

The local EGM2008_TN quasigeoid model based on the local EGM2008 model is of higher accuracy and can be applied for various remote areas. According to the results of the accuracy assessment based on 17 test points, the EGM08_TN model showed an accuracy of 100% corresponding to the 4th levelling class, i.a. for mountainous areas; the 85% level corresponds to the 3rd class. The error in determining the normal height according to GNSS measurements is reduced from 0.0244 m/km to 0.0086 m/km.

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