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THE ROLE OF THE TIDAL SYSTEMS OF GLOBAL GEOID MODELS IN THE DETERMINATION OF HEIGHTS USING THE GNSS LEVELING METHOD

A number of factors can significantly affect the accuracy of height determination when applying the GNSS leveling method. In general, it is possible to distinguish those related to the process of GNSS observations and their post-processing, and those related to the selection of the geoid/quasi-geoid height model. This work focuses on aspects of GNSS leveling accuracy when choosing global geoid models. In particular, to better ensure accuracy, it is important to understand the significance of the heights tidal system selection of global geoid models. The purpose of the work is to analyze the influence of different tide systems of global geoid models on the accuracy of height determination by the GNSS leveling method. This paper considers the heights of global geoid models EGM08, EIGEN-6C4, GECO, and XGM2019e_2159 of high degree and order calculated in the tide systems of “tide-free”, “mean-tide”, “zero-tide”. The analysis of the actual accuracy of the geoid heights was carried out on the basis of the standard and root mean square deviations of the heights differences of global geoid models in the corresponding tidal systems in relation to the GNSS leveling data. GNSS leveling data were obtained at 14 high-precision geometric leveling points of accuracy class 1–2, covering the central part of the Lviv region. Similarly, the accuracy of the geoid models was analyzed taking into account the differences of gravity anomalies concerning the high-resolution anomalies of the WGM2012 model. Data presenting differences of height and gravitational anomalies allowed us to correct the height of the models according to the weighted average principle. In addition, corresponding statistics were calculated for them. The conducted analysis shows that for the EGM08 model, the system of “mean-tide” is optimal with an accuracy assessment at the level of σ = 2–3 cm and m = 4 cm. For the EIGEN-6C4 model, it is best to use the “zero-tide” system which will ensure accuracy up to 4–5 cm. The accuracy of the EGM08 and EIGEN-6C4 models is confirmed by the statistical characteristics analysis results of the gravity anomaly differences. The GECO and XGM2019e_2159 models give ambiguous results within 3–9 cm by both parameters and in all tidal systems. Only after correction of the heights, their accuracy is 2–5 cm. Considering the optimal tidal system, the heights of the EGM08 and EIGEN-6C4 models can provide an accuracy of 1–3 cm after the correction by weighting coefficients.

Key words: GNSS leveling; global geoid model; tidal system; gravity anomalies; accuracy; correction.

Introduction

The modern approach to determining the heights of the Earth’s surface is mostly based on the GNSS leveling method. Despite the fact that this method has many advantages and is a good alternative to the classic ground-based methods of determining heights, it still has some disadvantages regarding its application. This is primarily due to the fact that for its implementation, it is necessary to have known heights of the geoid or quasi-geoid which are usually obtained from global or regional models. The main advantage of using regional models is that they are actually fully adapted for their direct use in height determination by the GNSS leveling method [Denker, 2015]. However, the disadvantage of these models is that they are created for a certain part of the Earth’s surface, usually within one or more countries [Reguzzoni, 2021]. The use of global models for the GNSS leveling method makes it possible to avoid this drawback, since they are created on a global scale.

Today, the International Centre for Global Earth Models (ICGEM) website presents 177 geoid models from 8 to 2190 degree and order. For GNSS leveling purposes, the following models of the highest degrees and orders should be used: EGM08 [Pavlis et al., 2012], EIGEN-6C4 [Ch et al., 2014], GECO [Gilardoni et al., 2016], XGM2019e_2159 [Zingerle et al., 2020]. In this case, for some regions of the planet, global geoid models can demonstrate even better accuracy than the regional ones. The accuracy of the models is evaluated at the bench-marks of high-precision geometric leveling. As research practice shows, the accuracy can vary from a few to tens of centimeters within a relatively small area. This is due to many factors that should be taken into account when choosing a global model for determining heights using the GNSS leveling method.

One of the important factors is the system of tides which is chosen to calculate geoid heights (or height anomalies) from one or another model. In general, there are three main tidal systems [Vatrt, 1999; Mäkinen, Ihde, 2009; Mäkinen, 2021]:

1) "tide-free" – the system is free of tides, where the influence of the attraction potential of the Moon and the Sun (direct effect) and the influence of the potential of permanent deformation of the Earth (indirect effect) are removed;

2) "mean-tide" – the tidal system of the "middle Earth", where the influence of direct and indirect effects is preserved;

3) "zero-tide" – system of zero-tides, where the influence of the direct effect is eliminated, and the indirect effect is preserved.

When determining heights by the GNSS leveling method using Global Earth Models, the correct choice of the tide system can significantly affect their accuracy.

Analysis of recent research and publications

On the territory of Poland, the EGM08 model was tested at points of normal heights of the first and second order (class) using the tidal system "tide-free" [Krynski J. et al., 2009]. The consistency of the model with the GNSS leveling data at these points is estimated at the level of standard deviation of 0.020 m (43 points of the first class) and 0.023 m (184 points of the first and second class).

In the study [Ellmann et al., 2009], the EGM08 model in the "tide-free" system was tested against GNSS leveling data at geometric leveling points (system of normal heights) in the Baltic countries, such as Estonia (26 points), Latvia (53 points), and Lithuania (110 points). The standard deviations of the obtained differences were 4.8 cm, 6.3 cm, and 4.8 cm, respectively. Joint processing of 189 points gave a result of 6 cm. The authors concluded that the overall accuracy of height anomalies obtained from the EGM08 model is at the level of accuracy of the Baltic gravimetric geoid – BALTgeoid-04.

Scientists from the Czech Republic, Germany and Slovakia [Kostelecký et al., 2015] published a study of joint testing of geoid models EIGEN-6C4 and EGM2008 ("tide-free" tide system) for the territory of Europe, the USA, Canada, Brazil, Japan, Australia, the Czech Republic and Slovakia. An accuracy assessment was performed for each region separately and with a different number of involved points. For Slovakia 64 values were used, 1020 values for the Czech Republic, and 166 values for Europe as a whole. The root mean square deviations for the EGM08 model in these territories were 5 cm, 3.3 cm, 9 cm, and for the EIGEN-6C4 model – 4.2 cm, 4.0 cm and 8.6 cm. Such results indicate some improvement of EIGEN-6C4 over EGM08 for these areas.

The study [Kim et al., 2020] conducted the accuracy assessment of the heights of the GECO, EIGEN-6C4 and EGM08 geoid models in the "zero-tide" system with respect to GNSS leveling data. It was based on 1182 points of the South Korea national network – UCP (Unified Control Point). GECO's root mean square deviation was 0.236 m, EIGEN 6C4's was 0.221 m, and EGM08's was 0.216 m. The best agreement between the data was for the EGM08 model, although in theory, the other two models should show better accuracy as they are supplemented with new satellite and ground-based data.

In December 2019, at the annual SIRGAS symposium, a study on the geoid models accuracy for different regions of the planet was presented [Gruber T. et al., 2019]. The XGM2019e_2159 model in the "zero-tide" system was taken into account in addition to the EGM2008 and EIGEN-6C4 models in the "tide-free" tide system. According to the data of this study, the root mean square deviations of the XGM2019e_2159 model from the GNSS leveling data were the following: for Germany – 2.6 cm; for Great Britain – 4.6 cm; for Japan – 7.8 cm; for Greece – 13.7 cm, etc.

The analysis of publications shows that the height characteristics of global geoid models have quite different statistical properties.

Purpose

The purpose of this work is to highlight the influence of different tidal systems of global geoid models on the accuracy of height determination by the GNSS leveling method.

Methodology

The research territory of this work covers part of the Lviv region around the permanent station SULP, as shown in Fig. 1. As can be seen from Fig. 1, the studied area (T) is also conventionally divided into the northern (N) and southern (S) parts relative to the SULP station.

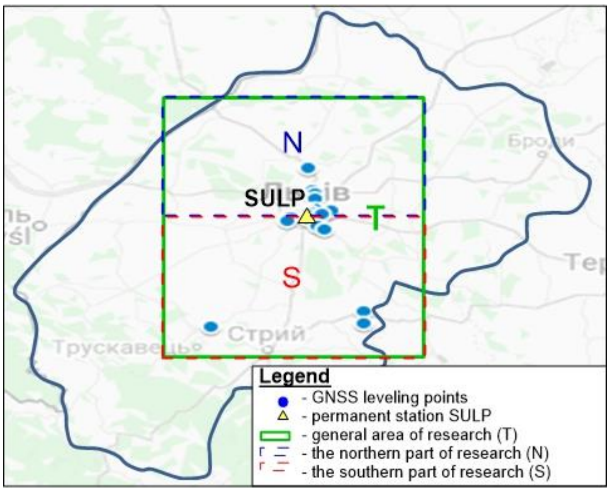

Fig. 1. Territory of research

To realize the set goal, this work uses the data of 14 height points of the I–II class of geometric leveling accuracy, on which GNSS leveling was performed. According to these data, the heights of the so-called "real" geoid and the difference in heights with respect to the values obtained from global models were determined:

$$N_{(o)} = H - H^{\gamma}_{(\kappa)}, \quad (1)$$

$$\Delta N = N_{(o)} - N_m, \quad (2)$$

where $N_{(o)}$ are the heights of the geometric ("real") geoid/quasi-geoid, calculated from GNSS leveling data; ΔN – height differences between geometric geoid/quasi-geoid values and model heights; N_m – geoid heights obtained from the global model as a function of height anomalies; H – ellipsoidal height obtained by converting spatial geocentric coordinates X, Y, Z into ellipsoidal (B, L, H) from processing GNSS measurements in professional software; $H^{\gamma}_{(\kappa)}$ is the normal height determined by the method of high-precision geometric leveling and is taken from the class I–II height catalogs. At the same time, the average accuracy of obtaining *X, Y, Z* coordinates based on GNSS measurements in static mode is 1–2 cm [Savchuk et al., 2022]. The accuracy of determining normal heights by the method of high-precision geometric leveling is equal to zero because the "real" geoid/quasi-geoid obtained on their basis sets the zero reference surfaces of heights.

Since the heights of geoid or quasi-geoid models are calculated on the basis of gravity anomalies (Δg), the values of anomaly differences were also used to analyze their accuracy:

$$\delta\Delta g = \Delta g_{WGM2012} - \Delta g_m, \quad (3)$$

where $\Delta g_{WGM2012}$ – gravity anomalies in free air obtained from the WGM2012 (Word Gravity Map) model with a resolution of 2'×2' [BGI, 2012]; Δg_m – gravity anomalies of global geoid models.

To analyze the possibility of increasing the accuracy of the heights of global geoid models, the corrected values of the differences were found:

$$\Delta N(P) = \frac{\Delta N \times P}{2P}, \quad (4)$$

where $P = 1/(\delta\Delta g)^2$ are weighting coefficients of heights differences calculated on the basis of gravity anomalies.

All geoid heights and gravity anomalies are obtained through the ICGEM site utility /User-Defined Points/, taking into account the /height anomaly/ function and the tide systems "tide-free", "zero-tide" and "mean-tide" for the models EGM08, EIGEN-6C4, GECO and XGM2019e_2159 [ICGEM, 2022]. At the same time, the GRS80 system is taken as the reference surface [Moritz, 1980]. To convert the heights of the geoid models obtained in this way to the scale of the "real" geoid, all values should be increased by 52 cm, which corresponds to the undulation of the zero-order geoid for the GRS80 system [Odumosu et al., 2017; Fedorchuk, 2022].

The methodology of this work is based on the analysis of the root mean square deviations (m) and standard deviations (σ) of global geoid models for: 1) heights differences of global geoid models (ΔN); 2) differences in gravity anomalies ($\delta\Delta g$); 3) corrected heights differences ($\Delta N(P)$) by weighting coefficients.

At the same time, the statistics for height differences are calculated according to the principle:

$$m_{\Delta N} = \sqrt{\frac{\sum \Delta N_m^{\,2}}{2}}, \quad (5)$$

$$\sigma_{\Delta N} = \sqrt{\frac{\sum \overline{\Delta N_m}^{\,2}}{2}}, \quad (6)$$

where ΔN_m – height differences obtained by formula (2); $\overline{\Delta N_m} = N_0 - \left(\frac{(N_0 + N_m)}{2}\right)$ – height differences without a systematic component. Similarly, statistics were calculated for differences in gravity anomalies and adjusted differences in heights.

The values of $\sigma_{\Delta N}$, $\sigma_{\delta\Delta g}$ and $m_{\Delta N}$, $m_{\delta\Delta g}$ are calculated to study the character of the changes in the actual accuracy of the geoid heights of each global model in different tidal systems. The values of $\sigma_{\Delta N(P)}$ and $m_{\Delta N(P)}$ represent the a priori accuracy of height correction of geoid models based on the weighted average principle.

Results

Standard deviations of heights differences and gravity anomalies of global geoid models EGM08, EIGEN-6C4, GECO and XGM2019e_2159 in three tidal systems for the entire research area (T) and for its northern (N) and southern (S) parts are shown in Table 1, and the root mean square deviations in Table 2.

From Table 1, we see that the standard deviations of heights differences and gravity anomalies are practically the same for geoid models of the same name, regardless of tidal systems. However, the difference in values between the northern and southern parts of the surveys can be up to 1.6 cm and 0.6 mGal, respectively.

Table 1

Standard deviations of differences of height and gravity anomalies

Tidal system		Tide-free				Mean-tide				Zero-tide			
Model name and territory		egm	eigen	geco	xgm	egm	eigen	geco	xgm	egm	eigen	geco	xgm
$\sigma_{\Delta N}$, cm	T	2.0	2.3	3.1	2.5	2.1	2.3	3.2	2.5	2.1	2.3	3.2	2.5
	N	2.7	3.0	3.1	3.0	2.6	3.0	3.1	3.0	2.7	3.0	3.1	3.0
	S	1.4	1.4	3.3	1.5	1.5	1.6	3.5	1.6	1.4	1.5	3.4	1.5
$\sigma_{\delta\Delta g}$, mGal	T	0.1	0.1	0.7	1.4	0.1	0.1	0.7	1.4	0.1	0.1	0.7	1.4
	N	0.1	0.2	0.3	1.1	0.1	0.2	0.3	1.1	0.1	0.2	0.3	1.1
	S	0.1	0.1	0.9	1.0	0.1	0.1	0.9	1.0	0.1	0.1	0.9	1.0

Table 2

Root mean square deviations of differences of height and gravity anomalies

Tidal system		Tide-free				Mean-tide				Zero-tide			
Model name and territory		egm	eigen	geco	xgm	egm	eigen	geco	xgm	egm	eigen	geco	xgm
$m_{\Delta N}$, cm	T	9.3	5.1	4.5	4.3	2.9	6.9	8.6	8.1	6.9	3.2	3.5	2.9
	N	11.4	6.9	4.7	6.4	3.7	7.8	10.7	8.4	8.6	4.7	3.8	4.3
	S	10.4	4.7	5.8	3.0	3.0	8.4	9.5	10.4	7.5	2.3	4.3	1.9
$m_{\delta\Delta g}$, mGal	T	0.2	0.8	1.8	2.1	0.2	0.8	1.8	2.1	0.2	0.8	1.8	2.1
	N	0.2	0.8	2.4	1.4	0.2	0.9	2.4	1.4	0.2	0.9	2.4	1.4
	S	0.2	1.0	1.8	3.3	0.2	1.0	1.8	3.3	0.2	1.0	1.8	3.3

According to the results of Table 2, the root mean square deviations of the heights differences of the geoid models differ significantly for various tidal systems. For example, for the EGM08 model, the error difference between tidal systems is 2.4–6.4 cm, for EIGEN-6C4 1.9 cm, for GECO 1–4.1 cm, and for XGM2019e_2159 1.4–3.8 cm. In addition, there is some discrepancy between the values of the northern part and the southern part for each model, which can be 0.8–1.1 cm, 0.6–2.4 cm, 0.5–1.2 cm, and 1.9–3.4 cm for the corresponding models. The root mean square deviations of gravity anomalies are the same for models of the same name in all three tidal systems. However, the difference between the values of the northern and southern parts of the EIGEN-6C4 model is 0.1 mGal, GECO is 0.6 mGal, and the XGM2019e_2159 model is 1.9 mGal.

The results given in Table 1, 2 demonstrate generalized information on the accuracy of global geoid models in various tidal systems. Therefore, this work conducted an accuracy analysis based on the principle of the quantitative ratio of standard deviations and root mean square deviations with respect to accuracy parameters with a change in the limits of 1 cm and 0.1 mGal. Fig. 2, 3 show the quantitative distribution of standard deviations and root mean square deviations of heights differences of global geoid models in tide systems “tide-free”, “mean-tide” and “zero-tide”. A graphic representation of the quantitative distribution of gravity anomalies statistical characteristics is presented in Fig. 2–5.

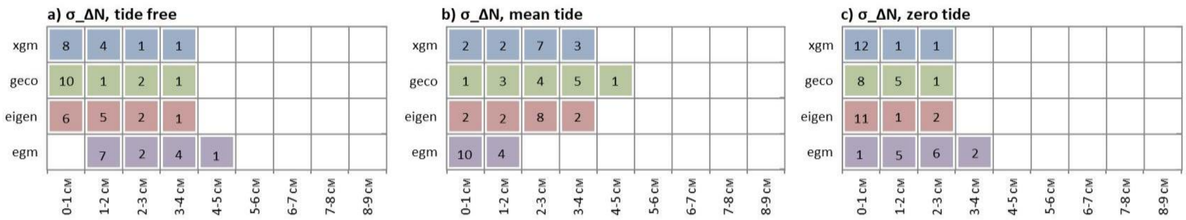

Fig. 2. Quantitative distribution of standard deviations of heights differences of global geoid models for tidal systems: a – “tide-free”; b – “mean-tide”; c – “zero-tide”

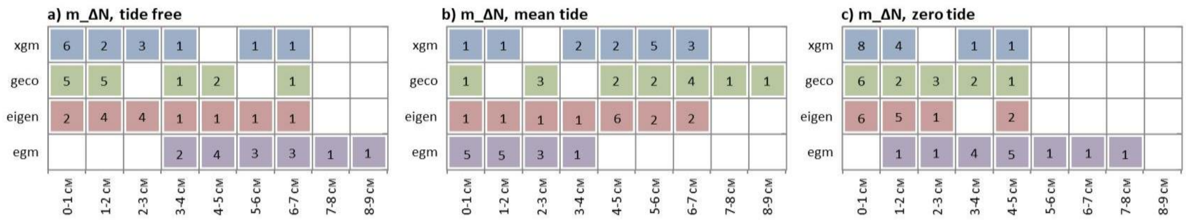

Fig. 3. Quantitative distribution of root mean square deviations of heights differences of global geoid models for tidal systems: a – “tide-free”; b – “mean-tide”; c – “zero-tide”

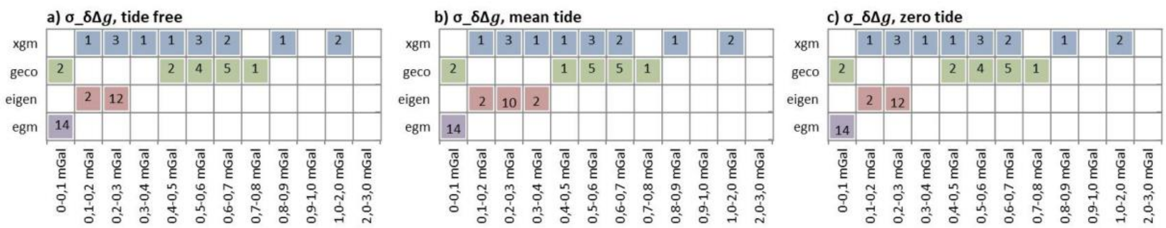

Fig. 4. Quantitative distribution of standard deviations of gravity anomaly differences of global geoid models for tidal systems: a – “tide-free”; b – “mean-tide”; c – “zero-tide”

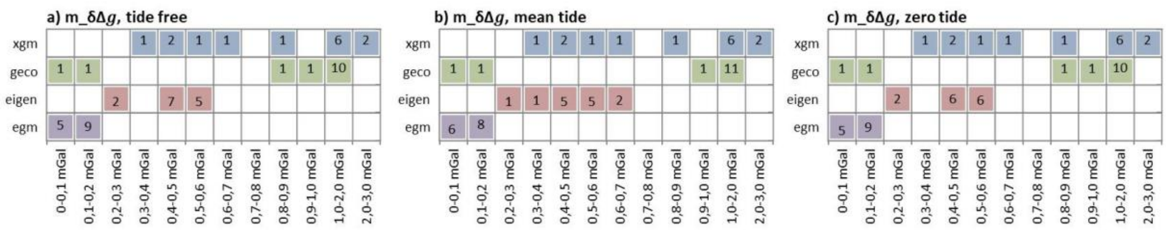

Fig. 5. Quantitative distribution of root mean square deviations of gravity anomaly differences of global geoid models for tidal systems: a – “tide-free”; b – “mean-tide”; c – “zero-tide

Fig. 2 shows that in the case of standard deviations, the values for the EGM08 model are within 5/2/4 cm in the "free/mean/zero-tide" system, respectively. For the EIGEN-6C4 and XGM2019e_ 2159 models, this result can reach 4/4/3 cm, and for the GECO model – 4/5/3 cm. The values of root mean square deviations (see Fig. 3) generally have a scattered nature of change. More grouped values can be highlighted: 1) for the EGM08 model in the "mean-tide" system within the range of up to 4 cm; 2) for models EIGEN-6C4, GECO and XGM2019e_ 2159 in the "zero-tide" system with a maximum value of up to 5 cm.

For the standard deviation values of gravity anomalies (see Fig. 4), only the EGM08 model has reliable accuracy limits within 0.1 mGal for all tidal systems, as well as EIGEN-6C4 within 0.3–0.4 mGal. Fig. 5 shows that based on the root mean square deviations, the differences in gravity anomalies can range from 0.3 mGal to 0.7 mGal for the EIGEN-6C4 model, from 0.4 mGal to 3 mGal for the XGM2019e_2159 model, and within 0–2 mGal for GECO. Only the errors of the EGM08 model can be considered as lying within a reliable interval of up to 0.2 mGal.

To the analysis of the results of Fig. 2–5, it must be added that each global geoid model is initially built in a specific tidal system. For example, models EGM08, EIGEN-6C4 and GECO are defined in the "tide-free" system, and model XGM2019e_2159 as a "zero-tide" system.

According to the IAG (International Association of Geodesy) resolution of 1983, it is recommended to use the "zero tide" system for values related to the geopotential of the Earth, that is, in fact, for gravity field models [IAG, 1984]. The "mean tide" system should be used for geodetic quantities related to measurements on the Earth's surface, such as geometric and GNSS leveling. In addition, when determining geoid heights from global models, there is another important parameter – the choice of reference ellipsoid, relative to which these heights will be determined. The official website of the ICGEM service suggests the list of reference ellipsoids. It also allows entering the custom parameters of the ellipsoid. However, once again, the IAG association recommends using the global ellipsoid GRS80 (Geodetic Reference System 1980) [Moritz, 2000] which uses the "zero tide" system to process geodetic data.

In particular, on the territory of Ukraine, the heights of geometric leveling points are determined by the average level of the Baltic Sea. Theoretically, to use the GNSS leveling method, the geoid model should be based on a system of mean-tides to ensure the best consistency and accuracy. Fig. 2–5 shows that for the research area, only the EGM08 geoid model falls under this criterion. The other three models present ambiguous results. To some extent, the EIGEN-6C4 model in the "zero-tide" system demonstrates slightly better results than GECO and XGM2019e_2159.

Summarizing the obtained results of Fig. 2–5, we see that the character of the change in standard deviations for the models of the same name is more uniform and does not depend on the choice of the tidal system. As for the root mean square deviations, they change quite ambiguously. This situation indicates that the choice of a specific system of tides when calculating geoid heights from global models has a significant impact on the accuracy of height determination by the GNSS leveling method. Therefore, for the research area, the accuracy of GNSS leveling as root mean square deviations can be corrected to the level of 4–5 cm, provided that the correct system of tides of the geoid models EGM08 and EIGEN-6C4 is taken into account, and the standard deviations are at the level of 2–4 cm.

Table 3 gives statistical characteristics of heights differences after correction according to formula (4), and Fig. 6 presents their quantitative distribution.

Table 3

Statistics of corrected height differences

Model name	Tidal system	$\sigma_{\Delta N(P)}$, cm			$m_{\Delta N(P)}$, cm		
		T	N	S	T	N	S
egm	tide-free	1.0	1.3	0.7	4.7	5.7	5.2
	mean-tide				1.4	1.9	1.5
	zero-tide				3.5	4.3	3.8
eigen	tide-free	1.2	1.5	0.7	2.5	3.5	2.4
	mean-tide				3.5	3.9	4.2
	zero-tide				1.6	2.3	1.2
geco	tide-free	1.6	1.6	1.7	2.3	2.4	2.9
	mean-tide				4.3	5.3	4.8
	zero-tide				1.7	1.9	2.2
xgm	tide-free	1.3	1.5	0.7	2.1	3.2	1.5
	mean-tide				4.0	4.2	5.2
	zero-tide				1.4	2.2	0.9

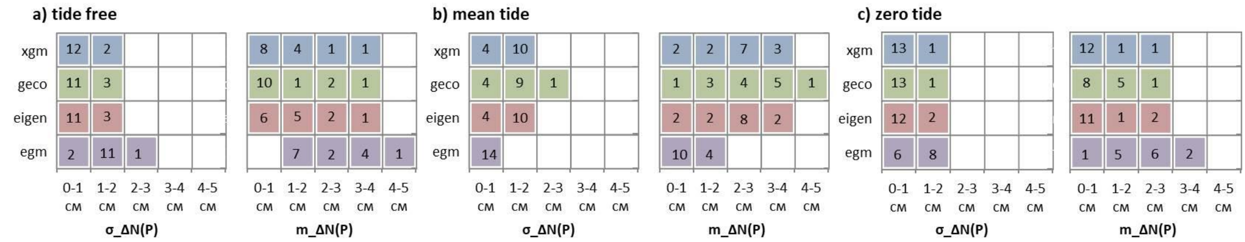

Fig. 6. Quantitative distribution of statistics of corrected heights differences of global geoid models for tidal systems: a – "tide-free"; b – "mean-tide"; c – "zero-tide"

According to the results of Table 3, it can be seen that the standard deviations do not exceed 2 cm for all models, and the difference between the north and south points is up to 1 cm. In general, the smallest standard and root mean square deviations of the EGM08 model in the "mean-tide" system are 1 and 1.4 cm, respectively. For the EIGEN-6C4, GECO and XGM2019e_2159 models, the smallest statistics were obtained for the "zero-tide" system in the range of 1–3 cm. Such data confirm the results regarding the optimal choice of the tidal system (see Fig. 2–3).

Fig. 6 shows that the root mean square deviations of the corrected heights of the models do not exceed 5 cm, and the standard deviations do not exceed 3 cm. Height correction by weighting coefficients enables a 50 % reduction in errors and eliminates the effect of dispersed variations.

Scientific novelty and practical significance

It is shown that the correct choice of the tide system allows optimizing the actual height accuracy of global geoid models for the implementation of the GNSS leveling method. A priori accuracy was found for the first time for the corrected heights of global models EGM08, EIGEN-6C4, GECO and XGM2019e_2159 based on weighting coefficients of gravity anomaly differences, taking into account the tide systems of the "tide-free", "mean-tide", and "zero-tide". The characteristics of the selection are given for the optimal tidal system to ensure better accuracy of height determination by the GNSS leveling method using global geoid models. It was established that even for the local area, the accuracy of the heights of the selected global model is changing and depends on the accuracy of the particular tidal system data.

Conclusions

The results obtained in this work give reason to believe that for the implementation of the GNSS leveling method, the correct choice of the tide system of the selected global geoid model plays an important role in terms of accuracy.

The greatest impact is observed in relation to root mean square deviations, the range of which can fluctuate up to 6.4 cm between tidal systems. Considering the standard deviations, the accuracy of the geoid models heights has more constant values and is practically the same in all three tidal systems for the models of the same name. In general, the difference in values between the northern and southern parts of the research is up to 1.6 cm. The difference in corrected heights does not exceed 1 cm. Such an effect is rather related to the fact that the research area encompasses a flat relief in the north and foothills in the south. For more flat areas, this difference will be minimal.

From the analysis of the statistical characteristics of heights differences and gravity anomalies, it can be concluded that the actual heights differences of the geoid models GECO and XGM2019e_2159 have ambiguous properties. This effect is eliminated by correcting the heights of the models by weighting coefficients.

For the considered area of research, EGM08 height models in the "mean-tide" system, and EIGEN-6C4 models in the "zero-tide" system can ensure the accuracy of root mean square deviations in relation to GNSS leveling at the level of 4–5 cm. And accuracy of standard deviations is within 2–3 cm without taking into account additional calculations. By correcting the heights of these models, you can get accuracy at the level of 1–2 cm and 2–3 cm, respectively.

To implement the GNSS leveling method of higher accuracy classes, it is necessary to correct the heights of global geoid models for local areas.

Completing this type of task can be reduced to modeling the differences in the heights of the geoid obtained from GNSS leveling and the corresponding global model based on weighting coefficients. The results of this study show that when modeling such quantities, an important parameter is the selection of the tidal system of the selected global geoid model. On the other hand, the results can be interpreted as the need to model heights differences for each tidal system and geoid model individually, depending on the relief of the studied area. Taking into account the optimal tide system of global models, a priori estimation of such an approach reveals that the accuracy can be expected to be 1–3 cm.

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РОЛЬ СИСТЕМ ПРИПЛИВІВ ГЛОБАЛЬНИХ МОДЕЛЕЙ ГЕОЇДА У ВИЗНАЧЕННІ ВИСОТ МЕТОДОМ GNSS-НІВЕЛЮВАННЯ

На застосування методу GNSS-нівелювання впливає багато чинників, які можуть істотно позначитися на точності визначення висот. Загалом можна виділити чинники, пов’язані з процесом GNSS-спостережень та їх опрацюванням, та чинники, пов’язані з вибором моделі висот геоїда/квазігеоїда. В цій роботі увагу зосереджено на аспектах точності GNSS-нівелювання під час вибору глобальних моделей геоїда. Зокрема, для кращого забезпечення точності важливо розуміти, яку роль відіграє вибір системи припливів висот глобальних моделей геоїда. Мета роботи – проаналізувати вплив різних систем припливів глобальних моделей геоїда на точність визначення висот методом GNSS-нівелювання. У роботі розглянуто висоти глобальних моделей геоїда EGM08, EIGEN-6C4, GECO та XGM2019e_2159 високого ступеня/порядку, обчислені у системах припливів “tide free”, “mean tide”, “zero tide”. Аналіз фактичної точності висот геоїда здійснено на основі стандартних та середніх квадратичних відхилень різниць висот глобальних моделей геоїда у відповідних припливних системах щодо даних GNSS-нівелювання. Дані GNSS-нівелювання отримано на 14 пунктах високоточного геометричного нівелювання 1–2 класів точності, що охоплюють центральну частину Львівської області. Аналогічно точність проаналізовано на основі різниць гравітаційних аномалій моделей геоїда щодо аномалій високої роздільної здатності моделі WGM2012. За даними різниць висот та гравітаційних аномалій здійснено коригування висот моделей за принципом середнього вагового та розраховано для них відповідні статистики. Аналіз показує, що для моделі EGM08 оптимальною є система припливів “mean tide” із оцінкою точності на рівні σ = 2–3 см та m = 4 см. Для моделі EIGEN-6C4 найдоцільніше використовувати систему “zero tide”, що забезпечить точність до 4–5 см. Точність моделей EGM08 та EIGEN-6C4 підтверджують результати аналізу статистичних характеристик різниць гравітаційних аномалій. Моделі GECO та XGM2019e_2159 дають неоднозначні результати – 3–9 см точності за обома параметрами та у всіх системах припливів. Лише після коригування висот їх точність досягає 2–5 см. З урахуванням оптимальної системи припливів та після коригування за ваговими коефіцієнтами висоти моделі EGM08 та EIGEN-6C4 можуть забезпечити точність на рівні 1–3 см.

Ключові слова: GNSS-нівелювання; глобальна модель геоїда; система припливів; гравітаційні аномалії; точність; коригування.

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