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Original article

Improved Height Determination Using a Correction Surface by Combining GNSS/Leveling Co-points and Thailand Geoid Model 2017

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Abstract

The evolution of the GNSS (Global Navigation Satellite System) technology has enhanced positioning performance in terms of positioning accuracy and time efficiency. The technology makes it possible to determine orthometric heights at a few centimeter accuracies by transforming accurate ellipsoid heights if an accurate geoid model has been employed. This study aims to generate a correction surface using GNSS/leveling co-points and a local geoid model, Thailand Geoid Model 2017 (TGM2017), through the Kriging interpolation method in a small local area. Combining the surface and TGM2017 significantly improves height transformation with the 1-cm RMSE (Root Mean Square Error) fit of 10 GNSS/leveling reference points and a mean offset of +0.1 cm. The evaluation of the correction surface at 5 GNSS/leveling checkpoints shows the RMSE of 1.0 cm, which is 82.6 percent of accuracy improvements. The GNSS leveling method can possibly be used to replace a conventional leveling technique at a few centimeter uncertainties in the case of small areas with clear-sky and high satellite visibility environments.

Keywords : Geoid, Thailand Geoid Model 2017, Orthometric Height, Correction Surface, Kriging

1. Introduction

The GNSS is used to measure coordinates due to its convenience and rapidity. It does not require a line of sight, which has the advantage of positioning in any accessible area. There was widespread use of GNSS technology for practical surveying and geodetic applications (Panumastrakul *et al*., 2012; Sun *et al*., 2016; Featherstone *et al*., 2018). The geodetic surveys, especially the control survey, play an essential role in mappings, such as aerial mapping, three-dimensional mapping, and the works related to laser scanning, by providing precise horizontal and vertical locations. The horizontal control points are commonly measured by GNSS surveying with achievable accuracy of millimeter levels. GNSS measures geometric heights related to a reference ellipsoid, regarded as ellipsoid heights, with an accuracy of a few centimeters or better. However, many applications require orthometric heights that are the nature heights above a meaningful physical surface as the geoid or, at least, a realized surface relating to the geoid, i.e., local mean sea level, or specifically a local vertical datum. Converting the ellipsoidal heights derived from GNSS to orthometric heights

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requires a geoid height(or geoid undulation) model. This height transformation procedure has become important since the emergence of the RNSSs (Regional Navigation Satellite Systems), such as the Japanese QZSS (Quasi-Zenith Satellite System) and the SBAS (Satellite-Based Augmentation Systems) (Hein, 2020). The RNSS provide accurate position information and time services, enhancing reliable positioning solutions. Such a modern height determination method utilizing the GNSS positioning technique is faster and more economical than spirit leveling. In Thailand, the usage of the method has increased after the operation of CORSs (Continuously Operating Reference Stations) for the Network-Based Real Time Kinematic (NRTK) GNSS positioning(Rizos and Satirapod, 2011; Charoenkalunyuta *et al*., 2019; Jongrujinan and Satirapod, 2020; Kriengkraiwasin *et al*., 2021; Thongtan *et al*., 2022). Obtaining accurate orthometric heights at centimeter levels requires an accurate geoid model. However, TGM2017(Dumrongchai *et al*., 2021) provides height solutions with a 10-centimeter accuracy that may limit construction and engineering works requiring more accurate height information.

For many years, the determination of GNSS-derived orthometric heights with a few centimeter levels of accuracy has been studied in several countries(Jung *et al*., 2018; Erol and Çelik, 2004; Li and Ning, 2019; Nahavandchi and Soltanpour, 2006; Soycan, 2013). The height differences derived from GNSS and leveling as an additional source of geoid data are employed to improve the(orthometric) height determination through a new correction(or conversion) surface. The differences indicate that a geoid model does not coincide with a mean sea level vertical datum due to possible errors in, for instance, geoid computations, GNSS, and leveling. Thus, it is necessary to determine the correction surface, which improves the transformation of ellipsoid heights to orthometric heights. The differences can be modeled to obtain the surface using interpolation methods such as inverse distance weighting, bilinear interpolation, polynomial regression, least-squares collocation, and geostatistical Kriging. The outcomes of these methods can differ when considering the application area, surface features, data, accuracy, and ease of calculation(Soycan, 2013). The last two methods rely on stochastic approaches that can not only interpolate values(or create surfaces) but also assess the uncertainties of those values. The primary purpose of this study is to emphasize the necessity of the correction surface to improve orthometric height determination for construction and engineering works. Since it is easier to use and more available in several software tools than the least-squares collocation, the kriging interpolation method is used in this study. A small local area, e.g., Pathum Thani suburb, is chosen as a testing area with a clear sky and high satellite availability to verify the achievable accuracy of the orthometric height transformation of GNSS ellipsoid height data. In this paper, Sec. 2 discusses the steps of acquiring the correction surface and accuracy assessments. Sec. 3 describes GNSS surveying, precise spirit leveling, and TGM2017. The results are discussed in Sec. 4, and the conclusions are summarized in Sec. 5.

2. Methodology

TGM2017 satisfied the necessary accuracy for the GNSS-derived orthometric height determination across Thailand. However, some parts of the model were contaminated with significant errors which were not applicable for such a modern height determination. Improving the geoid of a limited area using more intensive data was required to serve the practical engineering and construction applications. For generating a correction surface, the first step was calculating the residuals of TGM2017 geoid undulations and the undulations determined at a set of leveled GNSS control points. These points should be homogeneously distributed with appropriate density to improve the accuracy of the geoid in the study area. We constructed the correction surface using kriging interpolation and then added the surface in TGM2017 to obtain the improved geoid model. Finally, we evaluated the accuracy of the improved model by comparison with an independent set of GNSS/leveling geoid undulations that were not included in the surface computations.

2.1 Geoid undulations of co-stations

The co-stations were the points where orthometric heights and ellipsoidal heights were observed to obtain geoid undulations. The co-station data sets were used to generate the correction surface by kriging interpolation. These stations should be well-distributed over the study area to increase the surface quality. Most co-stations were used as control points to generate the correction surface, while the remaining points were used as checkpoints. The geoid undulation of a co-station, N_{obs}, was defined as the fundamental expression as follows(Heiskanen and Moritz, 1967).

$$N_{obs} = h_{obs} - H_{obs} \tag{1}$$

where h_{obs} was the ellipsoidal height derived from the processing of GNSS observations and H_{obs} was the orthometric height obtained by precise spirit leveling in Kolak-1915 vertical datum.

2.2 Geoid undulation residuals

Modeling the improved or combined geoid, GNSS, and leveling begins by forming the residual, e, as follows

$$e = N_{obs} - N_{TGM} \tag{2}$$

where N_{TGM} is TGM2017 geoid undulation. This residual corresponds to the accumulated errors of the undulations assumed to be in a random field. Thus, applying a suitable interpolation method yields the interpolated conversion surface values fitting TGM2017 to Kolak-1915 vertical datum.

2.3 Kriging interpolation

Kriging is a geostatistical method that interpolates spatial data based on the stochastic nature of the data set. This interpolator provides accurate prediction results depending on an appropriate variogram model specifying the spatial continuity of the data. The method has been commonly employed in, for instance, geodesy and geophysics applications(Erol and Çelik, 2004; Daya and Bejari, 2013; Soycan, 2013). The ordinary kriging method was commonly in favor of spatial interpolation methods because it was simple to use and available in many geospatial processing tools, e.g., ArcGIS. The method relied on the assumptions of unknown mean, stationarity, and isotropy, i.e., the constants of mean and variance throughout the spatial data field and uniformity in all directions. For simplicity, we thus chose the ordinary kriging method with the Gaussian semi-variogram model in this study. Section 4 discussed the results of the study.

2.4 Geoid evaluation

For evaluating the improved geoid model in this study, the RMSE of the orthometric height values is given by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(H_{obs} - H_{model})^2}{n}} \tag{3}$$

where H_{model} is the orthometric height determined using the improved geoid and GNSS ellipsoidal height, and n is the number of GNSS/leveling co-points.

3. The Study Area and Data Acquisition

In this study, we emphasized that the improved geoid model possibly maximized its accuracy to serve practical purposes of construction and engineering works. We chose Pathum Thani suburb as a study area having a size of about 11×11 km^2, as shown in Fig. 1. The area was in the central part of Thailand at the latitude of 14°02.6′N and the longitude of 100°42.8′E. The topographic terrain was flat and had the mean, minimum, and maximum elevations of about 3.826 m, 2.400 m, and 5.368 m above Kolak-1915 mean sea level, respectively, and the standard deviation of 1.022 m. In accordance with this area, TGM2017 geoid undulations varied from -30.446 to -30.072 m, with the mean of -30.242 m and the standard deviation of 0.140 m. Most of the area was in a clear sky with high GNSS satellite visibility. There was THAI CORS operated by the NIMT (National Institute of Metrology) in the area. Furthermore, 10 GNSS/leveling co-points were decided to use as control points for combining TGM2017 and GNSS/leveling geoids resulting in the correction surface. The remaining 5 GNSS/leveling co-points(checkpoints) were used to assess the accuracy of the improved geoid; one point was located near THAI CORS, while the others approximately differed from the base station every 1 km. More details are as the followings.

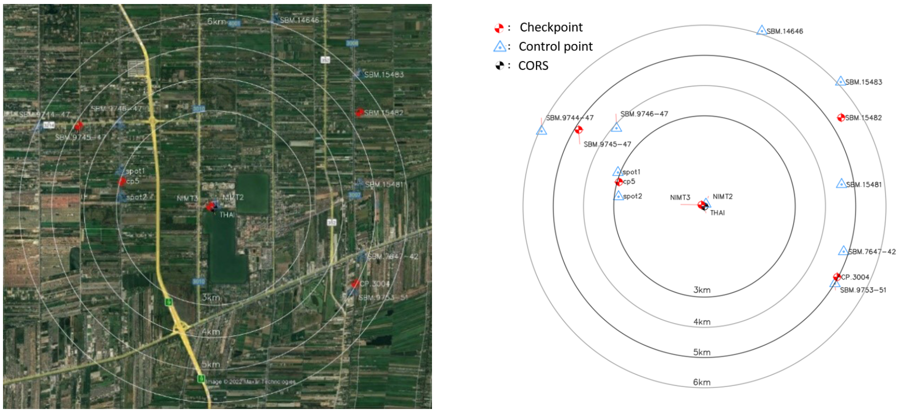

Fig. 1. Study area and locations of THAI CORS, GNSS/leveling control points and GNSS/leveling checkpoints


(a) (b) (c)

Fig. 2. The GNSS static surveying and precise spirit leveling: (a) THAI CORS and (b) GNSS observations using CHC i80 geodetic receiver, and (c) the barcode rod installed at an RTSD leveling benchmark

3.1 GNSS measurements

The GNSS observation data of points obtained from GNSS surveying were necessary to determine their latitude and longitude geodetic coordinates and ellipsoidal heights. The GNSS measurements were conducted in a static mode referenced to THAI CORS from February to March 2021, as shown in FigS. 2(a) and 2(b). Each rover station was occupied for more than 25 minutes with a 1Hz measuring rate (one-second epoch interval) using CHC i80 geodetic receiver. Processing the short-baseline GNSS observations using TBC (Trimble Bussiness Center) commercial software resulted in an average ellipsoidal height accuracy of about ±1.0 cm, reliable for this study. All GNSS observations were referred to the International Terrestrial Reference Frame 2014 (ITRF2014) at epoch 2020.17.

3.2 Precise spirit leveling

As mentioned before, 15 accurate orthometric heights were employed in this study. There were 9 first-order orthometric heights of the RTSD (Royal Thai Survey Department), available in the area with a few centimeter accuracies. However, one benchmark was under trees, as shown in Fig. 2(c). We thus relocated it to an open space area 50m away suitable for GNSS observations. These heights were referred to Kolak-1915 vertical datum. The leveling surveys of three loops were carried out using Topcon DL-501 precise digital leveling instruments equipped with barcode rods over a 6-km leveling loop distance in April 2021. Each loop misclosure was less than 1.0 cm satisfying the first-order maximum allowable criteria of 4mm√K, where K was a loop leveling distance in km unit. We neglected gravity measurements along the leveling surveying lines because the area was small and, seemingly, homogenous mass. For simplicity, no orthometric corrections and adjustments were applied to the levelings. However, due to the Coronavirus disease(COVID-19) pandemic in 2021, we experienced a very time constraint in conducting the leveling. Thus, only 6 orthometric heights were obtained. Although our intention to establish a well-distribution of GNSS/leveling co-points over the study area was unsuccess, the GNSS, leveling data, and the reliable orthometric heights sufficiently contributed to our study.

3.3 Thailand Geoid Model 2017

The TGM2017 was released for public use in 2018(Dumrongchai *et al*., 2021). It was the first hybrid geoid model for Thailand territory, computed based on the Molodensky approach (Heiskanen and Moritz, 1967) and the Wong and Gore modification of the Stokes's kernel function(Forsberg and Tscerning, 2014). The long wavelength structures of the model relied on GOCE-EGM2008 combined model (GECO) (Gilardoni *et al*., 2016) and the Technical University of Denmark's global marine gravity model 2013 (DTU13) (Anderson *et al*., 2015). Over 10,000 terrestrial gravity data points and airborne gravity data sets were used in the gravimetric geoid computation along with a one-arcsecond digital elevation model. The combined 299 GNSS/leveling co-points and the gravimetric geoid model through least-squares collocation (Moritz, 1980) resulted in the hybrid geoid model, TGM2017, transferring Kolak-1915 across the country. However, TGM2017 possibly contained local bias and distortions due to, for instance, accumulated errors in leveling networks, land uplifts of benchmarks, datum distortions, ellipsoid errors, and commission and omission errors in geoid computations. Consequently, the model provided the orthometric heights derived from GNSS ellipsoid heights at a 10-cm accuracy or better. The model was based on the Geodetic Reference System 1980 (GRS80) reference ellipsoid and ITRF2008 at epoch 2013.81. Further details on TGM2017 computations can be found in Dumrongchai *et al*. (2021).

4. Results and Discussions

The study was carried out in an 11x11 km^2 Pathum Thani suburb using GNSS/leveling data and TGM2017. We computed the geoid undulation residuals according to Eqs. (1) and (2) using 10 GNSS/leveling co-points used as control points. The ordinary kriging interpolation method was applied to the residuals using ArcGIS geostatistical tool for correction surface modeling. Our significant and time-consuming task at this step was to determine an optimal Gaussian-semi-variogram model. We repeated parameter computations for several models by trial and error to achieve the best fit model to the empirical semi-variogram. Adding the correction surface to TGM2017 produced the improved geoid.

Fig. 3 showed the conversion surface was smooth with a few concave and convex parts around the west-southern part and the boundary of the area. Such curve characteristics reflected local distortions caused by accumulated errors of leveling, GNSS data, and mainly, TGM2017. The datum inconsistency of ITRF datums also could cause the error due to TGM2017 based on ITRF2008, whereas all GNSS data set in this study referred to ITRF2014. Furthermore, the discrepancy error associated with extrapolation increased due to inadequate data points available, especially in the lower left part of the area, see also Fig. 3. The statistics results in Table 1 implied

Table 1. The differences among the GNSS-derived geoid undulations, TGM2017, and the improved geoid model at control points (unit: cm)

Discrepancy	Min.	Max.	Mean	Abs. Mean	S.D.	RMSE
$N_{obs} - N_{TGM}$	-12.7	1.2	-7.2	7.5	5.5	8.9
$N_{obs} - N_{model}$	-0.1	0.0	0.0	0.0	0.1	0.1

that all these errors possibly ranged from -12.7 to 1.2 cm.

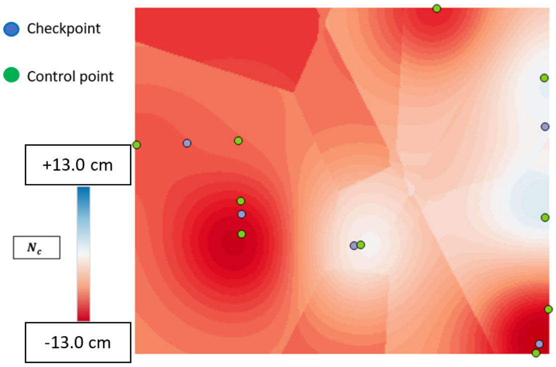

Fig. 3. Geoid correction surface with the location of control points in green dots and checkpoints in blue dots (unit: cm)

As listed in Table 1, it was seen that the improved model fitted the control point data with ±0.1 cm RMSE with 0.0 mean bias. These statistic values implied that the kriging method was well performed to model the error quantities from all data sources. Thus, the correction surface modeling was successful, which resulted in the usability for predicting new points. Table 2 and Fig. 4 summarize the effectiveness of the improved model on the accuracy of GNSS-derived orthometric heights as compared with TGM2017 at 5 checkpoints. After applying the correction surface to TGM2017, the RMSE value was of ±1.0 cm as compared with ±6.0 cm RMSE of TGM2017. The error reduction of 82.6 percent indicated a significant improvement in height determination. TGM2017 could determine the GNSS-derived orthometric height with the maximum error of 13.3 cm at CP3004 checkpoint (see Fig. 4). The differences(between the orthometric heights from leveling and TGM2017), ranging from -1.5 to 13.3 cm, were mainly due to errors in TGM2017. When the improved model was applied, the maximum error was 1.6 cm at CP5. Unlike other checkpoints, which showed positive differences, SBM15482 showed a negative value of -1.5 cm that reflected a lower local consistency of TGM2017. However, the -1.5 cm RMSE still remained at this point after applying the improved model. It meant that the ordinary kriging method could not model the uncertainties associated with the data along the boundary. Overall, after removing such a local distortion existing in the study area, the differences significantly decreased and then ranged from -1.5 cm to 1.6 cm for using the improved model, as seen in Table 2.

Therefore, the implementation of the correction surface using the ordinary kriging interpolation provided reasonable results for the study area. It was applicable for modeling the geoid of this area to serve construction and engineering works. However, the improvement of the geoid model highly depended on the topographic characteristics of the study areas. The well-distribution of GNSS/leveling data points was necessary for geoid determination with accuracy requirements in the range of one decimeter down to a few centimeters.

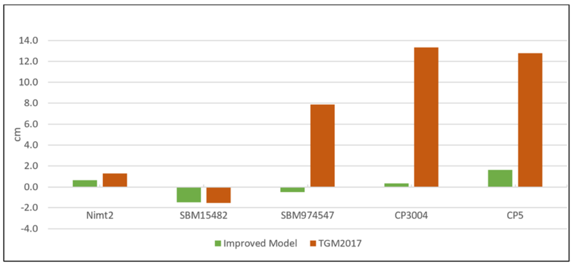

Fig. 4. Orthometric height differences from the improved model (green) and TGM2017 (brown) compared with 5 GNSS/leveling checkpoints (unit: cm)

Thailand has different topographies with heights ranging from 0 to 2,565 m above Kolak-1915 mean sea level. The rough terrains reflect more variation surface of TGM2017 than the

Table 2. The differences among the orthometric heights from leveling, GNSS, TGM2017, and the improved geoid model (unit: cm)

Difference	Min.	Max.	Mean	Abs. Mean	S.D.	RMSE
H_{obs} - H_{TGM}	-1.5	13.3	6.7	7.4	10.1	6.0
H_{obs} - H_{model}	-1.5	1.6	0.1	0.9	1.0	1.0
error reduction	-	-	-	-	88.4%	82.6%

flat areas, which means shorter wavelength components of the geoid exist in the terrains. These areas can locally affect the accuracy of TGM2017. According to Dumrongchai *et al*. (2021), TGM2017 errors increased over the roughness areas up to 15 cm, mainly in the northwest part of the country. The least-squares collocations could not model the short wavelength components of the geoid in those roughness areas. Thus, more GNSS/leveling control points were needed to improve the geoid accuracy, and selecting control points by considering topography should be done. Similar to our case study, there was a lack of control points over the western part of the study area, causing a large discrepancy of about 13 cm (see Fig. 3).

The accuracy of the improved geoid model depends on the available GNSS/leveling data, their accuracy, and their spatial distribution. However, this study focused only on a flat terrain area with a clear sky and high satellite availability. A few centimeter accuracies were achievable for height transformation. It would not be the case in rough areas where the number of GNSS/leveling points is limited. For this case, several important factors, which affect the accuracy of GNSS-derived orthometric height determination, for instance, the distribution and number of GNSS/leveling co-points, the accuracy of GNSS ellipsoidal heights, the use of interpolation methods, and characteristics of geoid surface in the area, should be investigated. Considering these factors would be in our future study. Multi-path reception could be a vulnerability to the accuracy of the ellipsoid height in high-multipath environments such as urban areas and tree-covering areas. Furthermore, the ordinary kriging interpolation method may not be suitable for rough terrains and large areas. There are several methods for scattered data interpolation, such as inverse distance weighting, bilinear interpolation, polynomial regression, triangulation, radial basis functions, nearest-neighbor interpolation, and least-squares collocation(Dumrongchai *et al*., 2021; Nahavandchi and Soltanpour, 2006; Soycon, 2013). However, no methods provide better or worse solutions than others, depending on topographic features, data availability, distribution, and accuracy. Further studies are needed on whether an interpolation method is appropriate for correction surface modeling of an area for engineering and construction purposes. In summary, modeling an improved geoid to provide a few centimeter accuracies of GNSS-derived orthometric heights is an unfinished task in the Thai geodetic community. After all, the results of the studies lead to practical guidelines on modern height determination in Thailand.

5. Conclusions

The height determination using satellite techniques has been widely used after the evolution of GNSS and RTSS occurrences. It gains higher time and cost efficiency than spirit leveling. We require a local geoid model to transform the GNSS ellipsoid height to obtain the orthometric height. This study aimed to produce a transformation solution to practical surveying and geodetic applications in a small area where a few centimeter accuracies in the GNSS-derived orthometric height determination were achievable based on an accurate geoid model. However, TGM2017 could not meet this requirement since it provided the orthometric heights derived from GNSS ellipsoid heights at a 10-cm accuracy. We constructed the correction surface by means of the kriging interpolation method to obtain the improved geoid model. In this study, we emphasized that the improved geoid model possibly maximized its accuracy to serve practical purposes of construction and engineering applications. We chose Pathum Thani suburb as a study area having a size of about 11×11 km^2, open sky, and high satellite visibility. By applying the ordinary kriging interpolation method, 10 GNSS/leveling co-points were used as control points for generating the correction surface, and another 5 GNSS/leveling points as checkpoints were used for geoid evaluation.

In the results, the correction surface modeling was successful, which resulted in the usability for predicting new points with ±0.1 cm RMSE fit with 0.0 mean bias. These statistic values implied that the kriging method was well performed to model the error quantities from all data sources with an 82.6-percent reduction. By comparison with 5 GNSS/leveling checkpoints, the orthometric differences significantly decreased and ranged from -1.5 cm to 1.6 cm for using the improved model. Therefore, implementing the correction surface using the ordinary kriging interpolation provided reasonable results for the study area. Implementing the correction surface using the ordinary kriging interpolation provided reasonable results for the study area. However, this study focused only on a small flat area with a limited number of GNSS/leveling co-points used for creating the correction surface, and no suitable pattern locations of the points were considered. The accuracy of a correction surface depends on not only the number of GNSS/leveling co-points but also their spatial distribution along with topographic terrains and area sizes. Furthermore, one interpolation method may provide better or worse solutions than the other, depending on topographic features, data availability, distribution, and accuracy. For future study, these mentions will be thoroughly investigated using several interpolation methods to obtain the desired accuracy of GNSS-derived orthometric height determination as well as economic feasibility for engineering and construction purposes.

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