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EVALUATION OF TGM2017 FOR HEIGHT SYSTEM USING GNSS/LEVELING DATA IN THAILAND

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ABSTRACT

The Royal Thai Survey Department released the Thailand geoid model of 2017 (TGM2017) for public uses in 2018. The model contains the latest gravity data sets from the terrestrial and airborne gravimetric survey campaigns across the country from April 2015 through June 2016. TGM2017 has been planned to support the height modernization system through the GNSS continuously operating reference station network of Thailand. In this study, TGM2017 was tested using 100 GNSS heights co-located with orthometric heights, referenced in the national Kolak vertical datum of 1915 (Kolak-1915). The testing results showed a 5-cm root mean square (RMS) with a mean offset of +0.011 m. For comparison purposes, EGM2008's had been tested using the same data set. Compared to these models, TGM2017 has a significant improvement of long- and medium-wavelength contents of the geoid.

1. INTRODUCTION

By the contribution of the Global Navigation Satellite System (GNSS), height-system modernization is based on a fundamental equation that connects GNSS-derived heights, h, above World Geodetic System ellipsoid of 1984 (WGS84), and orthometric heights, H, referred to a national vertical datum (i.e., $H = h - N$, where N is the geoid undulation with respect to the ellipsoid) (Jekeli et al., 2009). Such a transformation between two heights through the geoid undulation greatly benefits many engineering applications for several countries having their local geoid models. For those countries lacking the models, a global geoid model, e.g. the Earth Gravity Model of 2008 (EGM2008) (Pavlis et al., 2012), maybe a necessary choice for height determination by GNSS. The accuracy of EGM2008 varies in the range of a few centimeters to decimeters, based on the evaluation of EGM2008 using GPS/leveling data in six different regions (Europe, Germany, USA, Japan, Canada, and Australia) (Gluber, 2009).

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The Royal Thai Survey Department (RTSD) cooperated with Chiang Mai University and Chulalongkorn University constructed THAI12H local geoid model (Dumrongchai et al., 2012) using only 3,979 land gravity points. THAI12H provided potential accuracies as close as 5cm in Bangkok Metropolitan Region. However, larger errors up to 30cm were found in other areas, especially, in the Chao Phraya basin and the northern part of Thailand. These errors were mainly from low intensity of gravity measurements, conducted before 1991, which the earth's surface could vary with respect to time. Furthermore, land relative gravimeters were too old and could falsify gravity values measured.

(a)

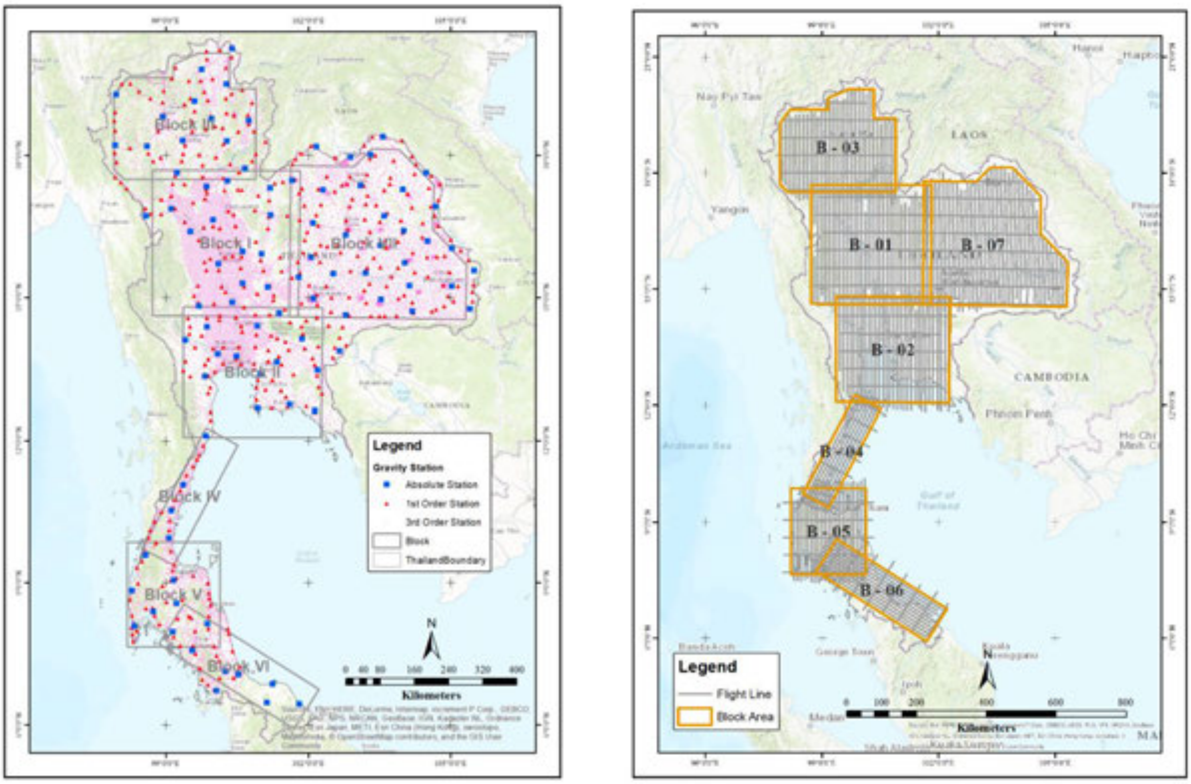
(b)

Figure 1: Natural disasters in Thailand: (a) the earthquake events at Mae Lao, Chiang Rai, in 2014 and (b) floodwaters inundated 90 billion square kilometers of land, more than two-thirds of the country, ranking the natural disaster as the world's fourth costliest disaster as of 2011 (source: www.thairath.co.th, www.oknation.net, and www.gistda.or.th).

The development of a new geoid model for Thailand was conducted in 2015 to support a height modernization system that linked the geoid model to the national real-time kinematic network (RTK GNSS network), expected to complete in 2020. Such a modernized system will quickly provide elevation values when they are needed, anywhere and anytime across the country. It will greatly benefit natural disaster management, which spirit leveling is not able to be used in such severe situations, which occurred in the past. Moreover, it will contribute to decision support data systems for national water resources management and other vertical positioning works. For instance, the earthquake events in the northern part of Thailand in May 2014, had 6.3 magnitudes in Richter scale, and more than 1,000 aftershocks had been reported and damaged utility infrastructures, as shown in Figure 1a. Another natural disaster was the great floodwaters inundated 90 billion square kilometers of land, more than two-thirds of the country, ranking the natural disaster as the world's fourth costliest disaster as of 2011 (Source: http://www.gistda.or.th). If the developed geoid model integrated to the RTK GNSS network were available, it would play an important role in natural disaster management--all these utility infrastructures in the affected areas could be restored as fast as possible. This paper describes the development of TGM2017, GNSS/leveling data, the evaluation approach of TGM2017 including the comparisons with EGM2008, numerical results, and discussion.

2. THAILAND GEOID MODEL OF 2017

TGM2017 was developed between 2015 and 2017 (Dumrongchai and Promtong, 2017) under the Short-Term National Water Strategy Plan (fiscal years 2015 to 2017). TGM2017 was released for public uses in 2018. The model was based on new gravity data sets of more than 10,000 land gravity points and airborne gravity data over Thailand's territory, conducted by RTSD. All gravity measurements followed the federal geodetic control committee of 1984 (FGCC1984) (Bossler, 1984). There were 87 absolute gravity stations (occupied by A10 Micro-g portable absolute gravimeter), their distributions of about 100km spacing, "blue square dots", as shown in Figure2a. The 405 first-order relative gravity stations ("red triangle dots") acquired by Scintrex CG-5 portable relative gravimeter, mostly following existing roads, were extended from the absolute gravity stations. The interval between each relative gravity station was between 30km and 50km. For more than 10,000 second- and third-order gravity data points, the distributions of the data points were uniform, and their resolutions varied from 2 to 10km (1.1 to 5.5 arcminute), see "pink dots" in Figure 2a.



(a) (b)

Figure 2: New gravity data sets: (a) terrestrial gravity data and (b) airborne gravity data

Airborne gravimetry campaigns started from May 2016 to June 2017 to measure the gravity field of Thailand. It was the first-ever airborne gravimetric surveys across the country (Dumrongchai et al., 2018). Due to time constraints for flight operations and seasonal changes in different parts of the country, seven-block areas were defined for conducting airborne surveys, covering all of the land

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areas and shorelines, see Figure 2b. Micro-g TAGS-6 relative gravimeter was mounted in the central area of Beechcraft Super King Air model B200 aircraft. The TAGS-6 recorded gravity data at 20Hz and had Novatel DL-V3 GPS receiver as a timing unit mounted on it. The survey flights were flown in two directions at a nominal height of 4,000 m (above mean sea level) and the speed of 200 knots. The main flight lines, along-tracks, in the north-south direction had 10 km spacing. The supplementary lines, cross-tracks, were in the east-west direction at 50 km spacing to serve as a checking line for monitoring the quality of the main lines. The total flight distances were 65,000 km, and the total number of cross-over points was 999 points. For every line, the aircraft was equipped with TAGS-6 gravimeter and GPS receiver. Post-processing kinematic surveys provided the locations where the gravities were measured. The accuracy of the airborne GPS positioning results was about 10 cm, which agreed with the typical results of around 10 – 30 cm for airborne gravimetry (Dumrongchai et al., 2018; Forsberg et al., 2000; Forsberg et al., 2012, Anantakarn and Witchayangkoon, 2019).

TGM2017 was computed from the available airborne and terrestrial gravity data using remove-restore-technique. For the areas outside Thailand including sea areas where no airborne gravimetric surveys were conducted, we used EGM2008 and DTU13 (Anderson et al., 2015) for data padding in land and sea areas, respectively. All gravimetric data were suitably gridded using least-squares collocation (Moritz, 1980) within the area defined by $3^{\circ} \leq \phi \leq 23^{\circ}$ in latitude and $95^{\circ} \leq \lambda \leq 108^{\circ}$ in longitude. Finally, TGM2017 was computed by the multi-band spherical Fast Fourier Transform (FFT) approach (Forsberg and Sideris, 1993; Forsberg and Tscherning, 2008) with the spatial resolution of one arc-minute regular grid (about 1.8km.).

3. GNSS/LEVELING DATA

In 2002, RTSD completed the adjustment of the national geodetic network in WGS84 (geocentric) datum. The RTSD network was referred to WGS84 ellipsoid, and categorized into three levels as follows: (1) reference frame, (2) primary network, and (3) secondary network. The reference frame (zero-order network) consisted of 7 GPS stations that established every part of Thailand. In 2008, the RTSD network was recomputed to map ITRF2005 after the concurrence of the 9.2 Mw Sumatra-Andaman earthquake on the 26th December of 2004; the previous realizations of the network were tied to ITRF94, ITRF96, and ITRF2000 (Satirapod et al., 2009). There are 18 GPS stations in the primary network with an interval of about 250 km for each station. This network was extended from the zero-order network. For secondary network, more than 690 GPS stations were extended from the primary stations. The station spacing ranged from 20 to 50km, and its accuracy was around 1 ppm. RTSD readjusted the horizontal networks to ITRF2008 at epoch 2013.10 from 2013 to 2017 as well as the re-observations of 412 stations using new GNSS geodetic receivers through more than static 3-hour observation surveys. These 412 GNSS network stations were mostly collocated with the first-order vertical network stations. The errors of the ellipsoid heights were a few centimeters.

For a number of years, the Kolak-1915 vertical datum has remained the official vertical datum in Thailand. The origin of it was realized, based on the tidal observations, which were carried out between 1910 and 1915 at Kolak island using one tide-gauge station located at latitude 11°47'42"N and longitude 99º48'58"E. For vertical control network of the first-order leveling, 357 primary benchmarks with orthometric heights were extended from the origin point to every part of the country under the FGCC standard, i.e. the maximum loop misclosure of 4mm√K (where K is the perimeter loop in km). More than 1,400 secondary benchmarks were tied to the primary control network. However, because the shape of the country looked like an ancient axe or a long trunk, the adjustment of the primary network was separately conducted in two areas—upper and lower areas at the origin point (latitude: 11º47'42"N)—by minimally constrained adjustment (fixed to just one single point). It might cause inconsistencies in the vertical datum over the region besides gross (undetected mistakes) and accumulated errors in spirit-leveling. Due to more thorough investigations for the datum inconsistencies, they were negligible in this study. Therefore, we considered the errors of Kolak-1915 orthometric (or leveled) heights, caused by spirit-leveling, were a few centimeters.

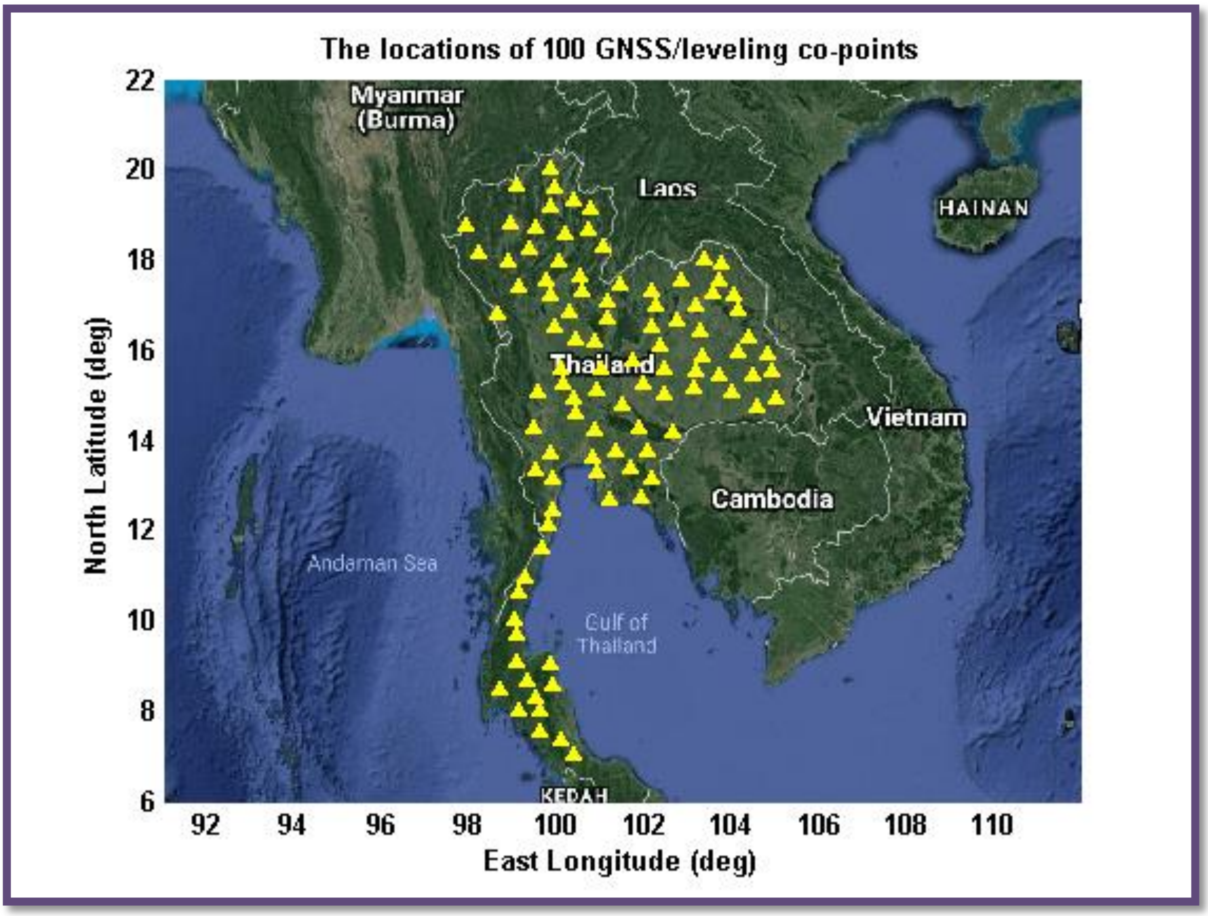

Figure 3: The locations of 100 GNSS/leveling co-points for TGM2017 evaluation.

We used 312 GNSS/leveling co-points, as well as all gravimetric quantities involved, for producing TGM2017. Only 100 GNSS/leveling co-points were used as the checking points to evaluate the geoid, as shown in Figure 3. These stations were rather patchy, and their spacing was variable, ranging from 25 to 100-km spacing. The irregular distribution of these stations occurred in rugged terrains, especially, in the north-western part of the country. Combining the errors of the orthometric (or leveled) and GNSS ellipsoid heights, the accuracy of the geoid heights estimated at the GNSS/leveling co-points could be approximately characterized by the root mean square (RMS) error of sub-decimeter level.

4. COMPARISON RESULTS AND DISCUSSIONS

The TGM2017 geoid undulations, N_{TGM}, was evaluated by comparing with the GNSS/leveling-derived geoid undulations, N_{Kolak}, at 100 checking points, distributed in Thailand's territory (see Figure 3). There were two steps of the geoid evaluation: the assessments of absolute and relative accuracies in the following. The absolute accuracy of TGM2017 was evaluated according to (1)

$$\Delta H^{i}_{abs}=\left(h^{i}_{WGS84}-N^{i}_{TGM}\right)-H^{i}_{Kolak} \quad \text{with } i=1,2,3,\ldots,P \qquad (1),$$

where h^{i}_{WGS84} was the GNSS ellipsoid heights referred to the WGS84 reference ellipsoid. The RMS ΔH^{i}_{abs} was defined by

$$\mathrm{rms}=\sqrt{\frac{\sum_{i=1}^{P}\left(\Delta H^{i}_{abs}\right)^{2}}{P}} \qquad (2),$$

The relative accuracy of TGM2017 was evaluated, according to (3)

$$\delta\Delta H^{ij}=\frac{\left|\Delta H^{ij}_{TGM}-\Delta H^{ij}_{Kolak}\right|}{D^{ij}} \quad \text{with } (i,j)=1,2,3,\ldots,P \text{ and } i\neq j \qquad (3),$$

where D^{ij} was the approximately horizontal distance between the checking points i and j. The TGM2017 and orthometric height differences in (3) were given by

$$\Delta H^{ij}_{TGM}=\left(h^{i}_{WGS84}-N^{i}_{TGM}\right)-\left(h^{j}_{WGS84}-N^{j}_{TGM}\right) \qquad (4),$$

and,

$$\Delta H^{ij}_{Kolak}=\left(H^{i}_{Kolak}-H^{j}_{Kolak}\right) \qquad (5),$$

The relative difference of $\delta\Delta H^{ij}$ in (3) had the unit of ppm (part per million). The relationship between $\delta\Delta H^{ij}$ and D^{ij} revealed the accuracy of height differences, equivalent to the FGCC1984 specification of the 1st, 2nd, and 3rd spirit leveling, i.e., 4mm√K, 8mm√K, and 12mm√K, respectively (Bossler, ibid.; You, 2006), where K = distance in kilometers.

We also evaluated how the new gravity data measured over Thailand improved the long- and medium-wavelengths of TGM2017 by comparing with EGM2008 generated at the maximum degrees 360 and 2190. However, TGM02017 had already been fitted to Kolak-1915 vertical datum, with which EGM2008 was inconsistent. We used THAI17G instead, which was a gravimetric geoid determined, prior to least-squares fitting to obtain TGM2017. Figure 4 showed the distribution of the geoid differences at 100 checkpoints. Table 1 listed the statistics of the differences between the geoid undulations generated from various types of geoid models and the undulations. The values of statistics showed more improvement of TGM2017 than other geoid models—the standard deviation (SD.) of 4.9 cm. The differences between TGM2017 and the derived geoid undulations at the checking points varied in the ranges -10.4 to 1.5 cm. Figure 5 showed TGM2017 differences at the points. The pink circles represented the large differences at four checkpoints, out of the upper and lower bounds of the 95% confidence level. By comparing with EGM2008, THAI17G had the smallest error (SD. = 6.6 cm whereas SD. = 18.4 cm and 13.1 cm for EGM2008(360) and EGM2008(2190), respectively). It was clear that the new gravity data sets significantly improved the accuracies of long- and medium-wavelength contents of the gravimetric geoid by sub-decimeter level.

Table 1: Statistics of geoid differences at 100 GNSS/leveling checkpoints (meters).

Geoid model	min	max	mean	SD.	RMS
EGM2008(360)	0.267	1.391	0.805	0.184	0.826
EGM2008(2190)	0.477	1.249	0.853	0.131	0.862
THAI17G	0.690	1.091	0.918	0.066	0.920
TGM2017	–0.104	0.149	0.011	0.048	0.049

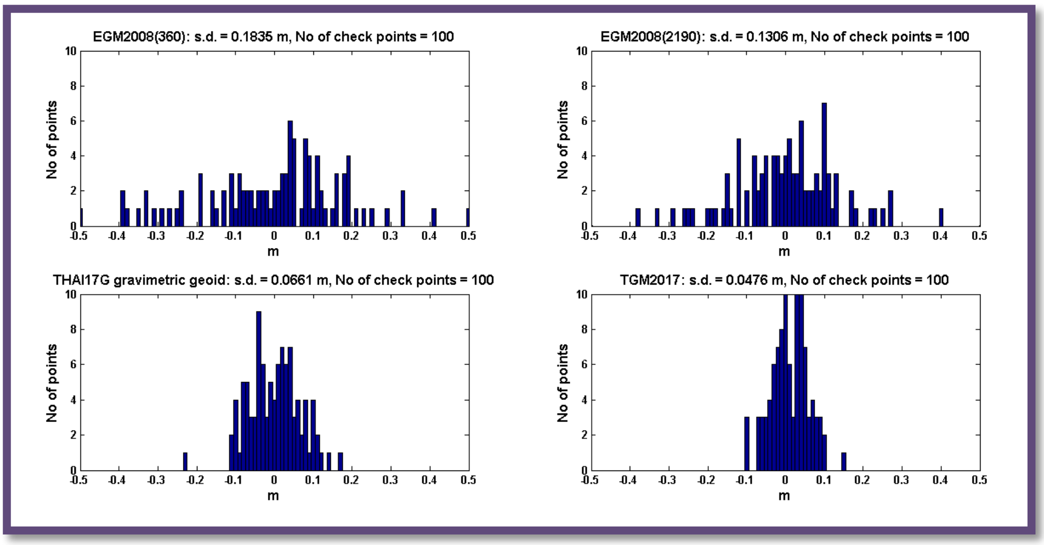

Figure 4: Distribution of the differences of EGM2008(360), EGM2008(2190), THAI17G, and TGM2017 at 100 GNSS/leveling checkpoints.

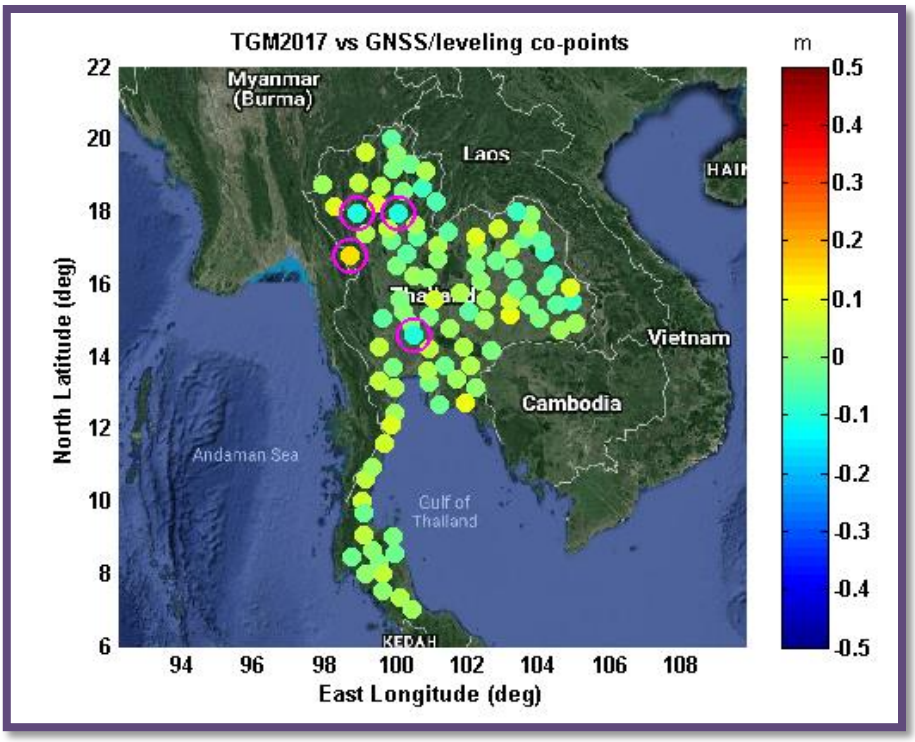

Figure 5: The geoid differences of TGM2017 at 100 GNSS/leveling checkpoints: purple circles indicate large differences, out of the upper and lower bounds at 95% confidence level.

Figure 6 showed the relative accuracy of TGM2017 with respect to 100 GNSS/leveling checkpoints at the distances in the ranges of 30 to 400 km. TGM2017 performed as close as the 3rd order FGCC1984 standard specification (i.e., 12/√K ppm) of spirit leveling, particularly, at farther distances. However, it should be addressed here that the accuracy of the orthometric height differences derived by GNSS, i.e., ΔH^{ij}_{TGM} in (4), depending on the accuracy of ellipsoid heights and geoid undulations. Thus, the longer session of GNSS observation was needed in the field surveys to increase the quality of ellipsoid heights.

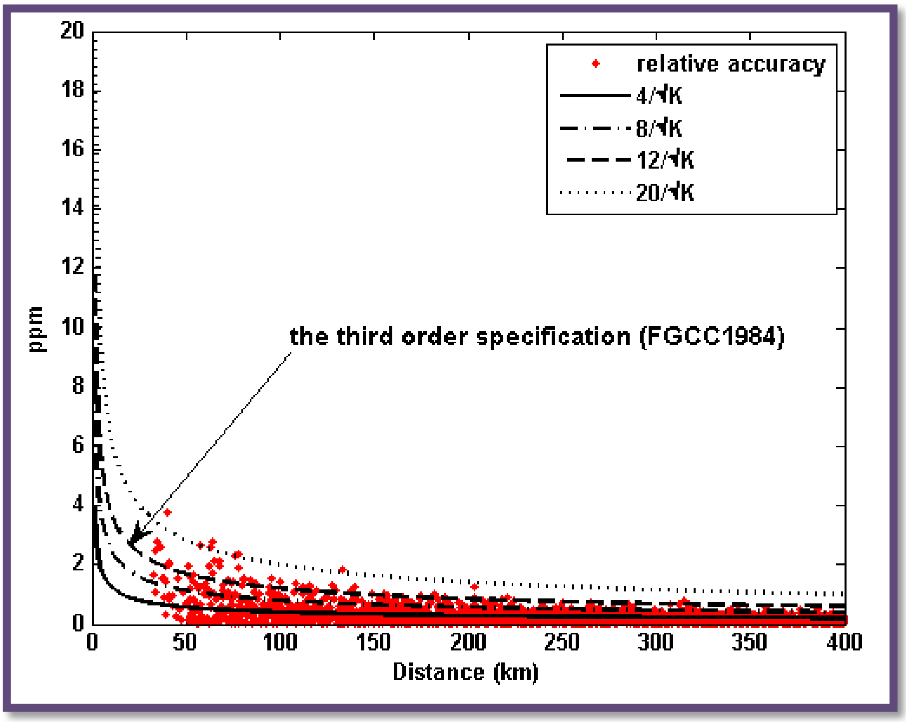

Figure 6: The relative accuracy of Thailand geoid model of 2017 (TGM2017)

5. CONCLUSION

In this paper, the Thailand geoid model of 2017 (TGM2017) was released in 2018. It was a new local geoid model of the country based on the new terrestrial and airborne gravity data sets with robust methods of computations. TGM2017 was planned to be integrated into the national real-time kinematic network (RTK GNSS network), expected to complete in 2020. They are vital to a national height modernization system that permits elevations to be determined with accuracies, and supports such diversified uses, for instance, water resources and floodplain management, disaster preparedness and relief efforts, and engineering works.

TGM2017 was evaluated using a set of 100 high accuracy GNSS/leveling stations as checking points in the mainland area of Thailand. The values of geoid heights (or undulations) from the model were compared with those derived by the combination of Kolak-1915 orthometric (or leveled) heights and GNSS-based geodetic (ellipsoidal) heights. The standard deviation, computed from the obtained differences based on the assessment of absolute accuracy, was equal to 4.8 cm. For comparison purposes, the long-wavelength EGM2008(360) and EGM2008(2190) were tested with the same data set. The results showed TGM performed, at least, two times better to the GNSS/leveling geoid undulations at the checking points. The assessment of relative accuracy revealed that GNSS leveling with TGM2017 satisfied the third-order FGCC1984 standard specification of spirit leveling, particularly, at farther distances. However, the accuracy of orthometric height differences depended not only on the accuracy of TGM2017 geoid heights but also that of GNSS ellipsoid heights.

6. AVAILABILITY OF DATA AND MATERIAL

Data used or generated from this study is available upon request to the corresponding author.

7. ACKNOWLEDGEMENTS

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