EVALUATION OF EGM2008 USING GPS/LEVELING DATA IN THAILAND

Puttipol DUMRONGCHAI[a,*], Chaiwat PROMTONG[b] and Santipong WITHIYAPHAN[c]

[a,c]Assistant Professor, Dept. of Civil Engineering, Chiang Mai University 50200, Thailand;
Tel: +6653-944156-9; Fax: +6653-892376;
E-mail: puttipol.d@cmu.ac.th
[b]Director of Geodesy Division, Royal Thai Survey Department, Royal Thai Armed Forces Headquarters,
Ministry of Defense, 10200 Thailand; Tel: +662-2223045

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Abstract: The non-tidal EGM2008 geopotential geoid model has been compared with 258 GPS heights co-located with orthometric heights in Thailand (in the ITRF2005(2008) and the national Kolak vertical datum of 1915 (Kolak-1915)). The comparisons show a 1.012-m root mean square (rms) with a mean offset of +0.997m. A north-south tilted plane of about 0.135 ppm [or mm/km] is also evident in the differences in the whole area of the country, whereas there is no appreciable east-west tilted plane. Considering separated north and south areas reveals the tilts of about 0.136 ppm and 0.352 ppm. Importantly, because of good quality of GPS heights, these disagreements (assumed to be errors) are possibly in one or all of EGM2008 and Kolak-1915 datum deficiencies.

INTRODUCTION

With the aid of the Global Positioning System (GPS), height-system modernization is based on a fundamental equation that connects GPS-derived heights, h, above World Geodetic System (WGS) ellipsoid, 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 at al. 2009). Such a transformation between two heights through the geoid undulation greatly benefits many engineering and geodetic applications for several countries having their own local geoid models. For those countries lacking of the models, a global geoid model, e.g. the Earth Gravity Model of 2008 (EGM2008), may be a necessary choice for height determination by GPS, though with uncertainties of up to a decimeter level.

EGM2008 is the latest version of geopotential model, officially released by National Geospatial-intelligence Agency (NGA) in April 2008 (Pavlis et al. 2012), following EGM96 (Lemoine et al.1998) that utilizes world gravity data at a 30 arcminute resolution. The model is more ambitious, and has maximum resolution of 5 arcminute, based on improved long wavelength information from GRACE, improved terrain data and altimetry data, and reliable and updated surface gravity database (Kenyon et al. 2007). EGM2008 is complete to spherical harmonic degree and order 2159, and contains additional coefficients extending to degree 2190 and order 2159, which corresponds to a minimum spatial resolution of about 5 km (wavelength of 10 km). 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).

Since a local geoid model for Thailand has not yet been available, the knowledge of the accuracy of EGM2008 and its problem areas over the country is necessary for obtaining orthometric heights using GPS technology. One feasible method to evaluate the global geoid model is through comparisons with geoid undulations derived from GPS heights co-located with leveling stations, which are referred to Kolak-1915. The numerical finding in this study reveals a north-south tilt between Kolak-1915 and EGM2008.

GPS/LEVELING DATA

In 2002, the RTSD completed the adjustment of national geodetic network in WGS84 (geocentric) datum (RTSD 2003) in accordance with the standard of Federal Geodetic Control Committee (FGCC) (Bossler 1984). The RTSD network is referred to WGS84(G1150) ellipsoid, and categorized into three levels as follows: (1) reference frame, (2) primary network, and (3) secondary network. The reference frame (zero order network) consists of 7 GPS stations established every part of Thailand. In 2008, the 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 (first order) network with the interval of about 250km for each station. This network was extended from the zero order network. For secondary (second order) network, more than 690 GPS stations were extended from the primary stations. The station spacing ranges from 20 to 50km, and its accuracy is around 1 ppm.

For a number of years, Kolak-1915 vertical datum has still remained the official vertical datum in Thailand. The origin of it was realized based on tidal observations carried out between 1910 and 1915 at Kolak island using one tide-gauge station located at latitude 11º47'42"N and longitude 99º48'58"E. For vertical control network of the

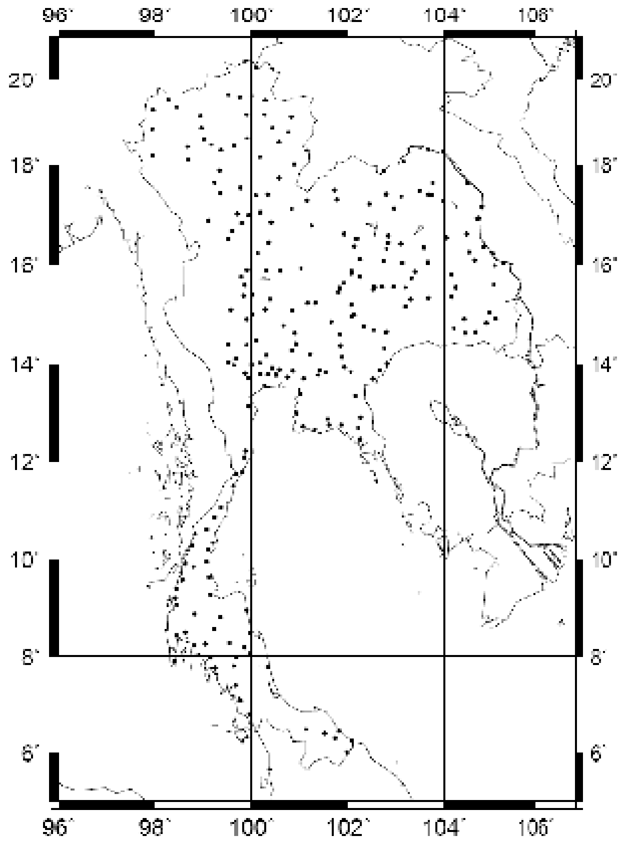


Figure 1: Points where GPS/leveling data are available.

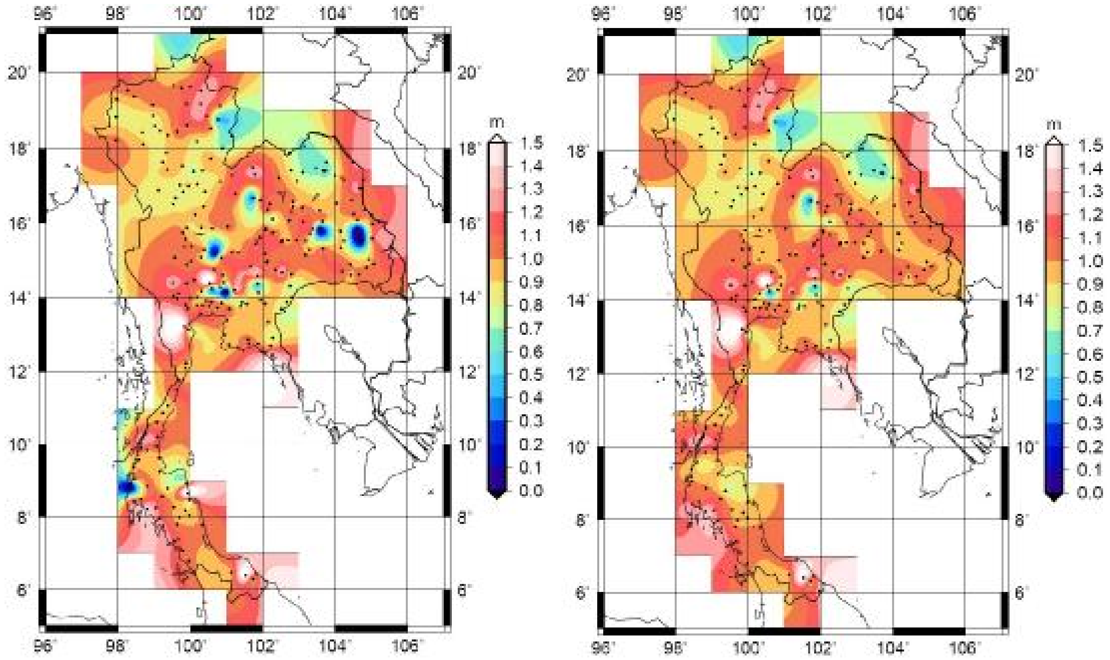
first order leveling, 333 primary benchmarks with orthometric heights were extended from the origin point to every part of the country under the FGCC standard, i.e. 3-4mm-square-root-km allowable misclosure. More than 1,600 secondary benchmarks were tied to the primary control network. However, because 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). This may cause inconsistencies in the vertical datum over the region besides gross (undetected mistakes) and accumulated errors in spirit-leveling.

In this study, only 265 leveling stations co-located with the GPS heights on the horizontal network stations were available, and used for datum investigation. Figure 1 shows the distribution of 265 GPS/leveling reference stations. These stations are rather patchy, and their spacing is variable, ranging from 25 to 100-km spacing. The irregular distribution of these stations occurs in rugged terrains, especially, in the north-western part of the country. The quality of the leveling stations is ambiguous and difficult to identify because they come from different orders of spirit-leveling, i.e. first, second, and third orders. It must be emphasized that the accuracy of these heights may not be equally accurate as one would expect, but the spirit-leveling should not exceed 12mm-square-root-km allowable misclosure (the third order).

RESULTS AND DISCUSSIONS

The EGM2008 geoid undulations were computed at the geodetic coordinates of 265 GPS/leveling stations using the hsynth_WGS84.f FORTRAN program from http://earthinfo.nga.mil/GandG/wgs84/gravitymod/egm2008/ egm08_wgs84.html. We assumed that all quantities were in tide-free (or non-tidal) system. All parameters of WGS84(G1150) ellipsoid were set in the program. The geoid undulations were generated using spherical harmonic coefficients from degree 2 to 2190, and the zero-degree term of −41 cm was included. Then, the geoid undulations were compared with the GPS/leveling-derived geoid undulations in absolute and relative senses (Featherstone et al. 2001; Featherstone and Filmer 2008; Abeyratne at al. 2009, p. 284-316). These absolute and relative comparisons signify an offset and a tilt between EGM2008 and Kolak-1915, respectively.

Figure 2a shows the differences between 265 GPS/leveling-derived geoid undulations minus EGM2008, interpolated to grid points using a method of continuous curvature spines in tension in the Generic Mapping Tools (GMT) (Smith and Wessel 1990; Wessel 2009). Table 1 summarizes the statistics of the differences between 265 GPS/leveling data and EGM2008, which cover two areas, upper and lower the origin point of Kolak-1915 ($\phi =$



(a) (b)

Figure 2 Difference between GPS/leveling-derived geoid undulations minus EGM2008 (a) before and (b) after outlier detection ; units in metres.

(ϕ = 11º47'42"N), and the whole area of Thailand. The mean offset is +0.978 m with the standard deviation (σ) of ±0.232 m. The large differences appear in middle-east area (14º-16ºN and 100º-105ºE) and southern area (centered at ~9.0ºN and 95.5ºE). After the outlier detection with ±3σ threshold, seven points were removed; only 258 points were used. The mean offset is +0.997 m with the standard deviation of ±0.174 m. For the lower area, the standard deviation significantly decreases to ±0.1667 m (±0.2589 m prior to outlier detection). From Figure 2b, some spurious points were not rejected by the ±3σ threshold, and remain in eastern and southern areas. The largest differences appear in the southernmost area (centered at ~6.5ºN, ~101.5ºE) and the middle west area (centered at ~13.0ºN and 99.5ºE). This may indicate local distortions (short-wavelength errors) in either Kolak-1915 or EGM2008, where apparent tilts will be different in different areas (Featherstone 2008). These would be most probably due to spirit-leveling errors if short-wavelength errors in EGM2008 were not significant and the accuracy of the leveling had been verified. Unfortunately, these are accounted for inseparable problem between Kolak-1915 and EGM2008. A potential method that one can further investigate the problem is to re-do the minimally constrained adjustment of the leveling network for the entire area (fixed just to the origin point of Kolak-1915). Then, one determines the new orthometric heights, repeats the earlier experiments using these heights, and then compares the results with those in Table 1 and Figure 1. If the numerical comparisons reveal significant differences, the spirit-leveling will affect Kolak-1915. Another method is to use the combined satellite-only global gravity field model, e.g. GOCO03S (Mayer-Gürr T. et al. 2012), to estimate the long-wavelength errors (tilts) of Kolak-1915 datum. This method also provides more insight into the remaining short to intermediate wavelength errors in the vertical datum with the removal of long-wavelength errors (Wang et al. 2012). These are beyond the scope of this work, and thus are left for future study.

Table 1 Statistics of the absolute differences between 265 GPS/leveling data and EGM2008 (including zero-degree term of –0.41 m) before and after outlier detection (parentheses); units in metres.

Area	No. of Points	Min	Max	Mean	S.D.	RMS
Upper area	218 (213)	–0.1022 (+0.3689)	+1.5782 (+1.5782)	+0.9590 (+0.9809)	±0.2225 (±0.1716)	±0.9844 (±0.9958)
Lower area	47 (45)	–0.0650 (+0.8134)	+1.8272 (+1.6193)	+1.0656 (+1.0738)	±0.2589 (±0.1667)	±1.0960 (±1.0864)
Total area	265 (258)	–0.1022 (+0.3689)	+1.8272 (+1.6193)	+0.9779 (+0.9971)	±0.2325 (±0.1741)	±1.0050 (±1.0122)

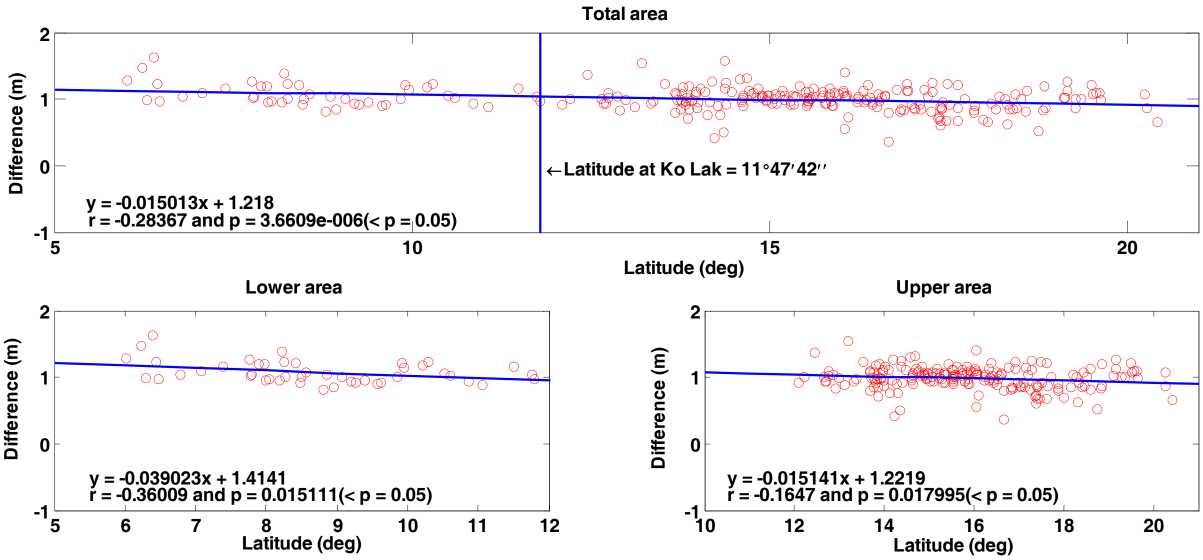


Figure 2 Linear regression of 258 GPS/leveling geoid minus EGM2008 versus latitude in degrees. Under t hypothesis testing at the significant level of 0.05, there exist the significant tilts of about –0.135, –0.352, and –0.136 mm/km [or ppm] over total, lower, and upper areas, respectively.

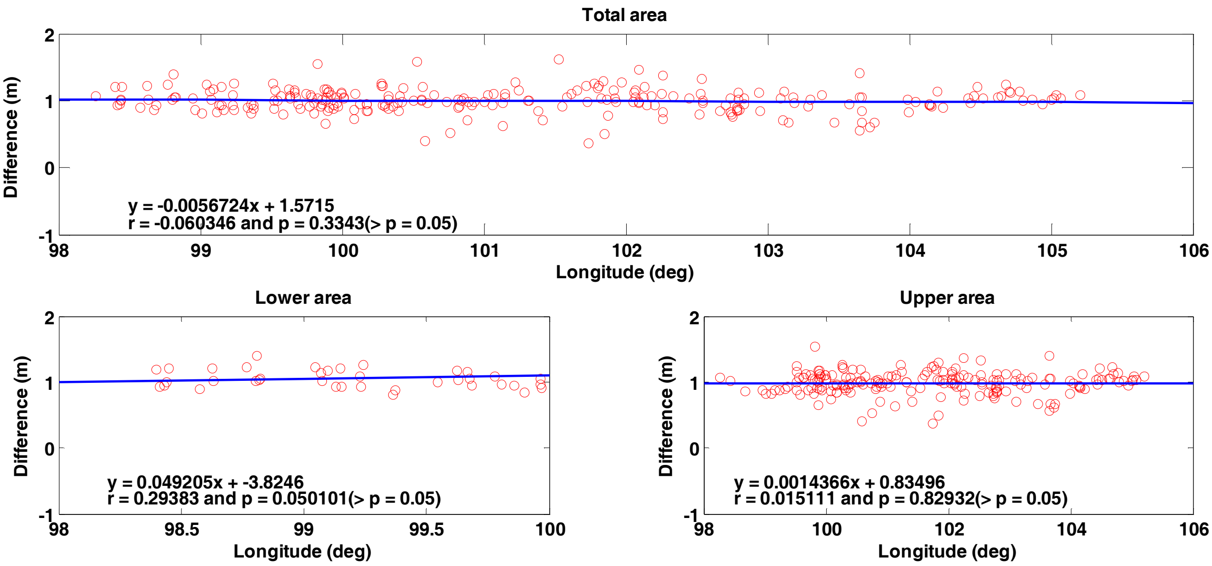


Figure 3 Linear regression of 258 GPS/leveling geoid minus EGM2008 versus longitude in degrees. Under t hypothesis testing at the significant level of 0.05, there exist no significant tilts for all areas.

Figure 2 shows linear regressions of 258 GPS/leveling-derived geoid undulations minus EGM2008 versus latitude and longitude in degrees. We used corrcoef function in MATLAB for correlation analysis. Table 2 summarizes latitudinal and longitudinal tilts of the differences and their significances by means of the "r" correlation coefficient, and hypothesis testing using t-test at the significant level of 0.05; for the large number of data points, one may use Z-test under the assumption of normal distribution. If a p(probability)-value is less than 0.05, the correlation between height difference and latitude/longitude is significant. Based on the numerical results in Table 2, there exists significant tilts (after converting degrees to kilometers) of about –0.136 mm/km [or ppm] (r = –0.284 and p = 0.00), (one degree is ~111 km) across the country. When considering two areas separately, upper and lower the origin point, the tilt across the lower area changes to –0.352 mm/km (r = –0.360 and p = 0.02) whereas –0.136 mm/km (r = –0.165 and p = 0.02) over the upper area. However, no east-west tilts are significant. These (latitudinal tilts) may be due to the adjustment of the primary network, separately conducted in two areas as well as the aftermath of the 9.2 Mw Sumatra-Andaman earthquake on the 26th December of 2004.; further investigation will be needed.

Table 2 Summary of latitudinal and longitudinal tilts of the differences between 258 GPS/leveling data and EGM2008 and their significances by means of the "r" correlation coefficient and t-test (p-value <0.05)*.

Tilt	North-south (mm/km)	r	t-test (p-value)	East-west (mm/km)	r	t-test (p-value)
Upper area	–0.135	–0.165	0.02*	+0.013	+0.015	0.83
Lower area	–0.352	–0.360	0.02*	+0.443	+0.294	0.05
Total area	–0.136	–0.284	0.00*	–0.051	–0.060	0.33

CONCLUSIONS & RECOMMENDATIONS

This study has compared EGM2008 geoid undulations with 265 GPS heights co-located with leveled Kolak-1915 heights over Thailand. After outlier detection with ±σ threshold, only 258 GPS/leveling points were used to assess differences of Kolak-1915 minus EGM2008. The difference shows the rms of ±1.012 m, therefore suggesting the bias between the Kolak-1915 GPS/leveling data and EGM2008. The north-south significant tilts with respect to latitudes are about –0.135, –0.352, and –0.136 mm/km [or ppm] over total, lower, and upper areas, respectively under hypothesis testing with the 0.05 level of significance. There is no significant tilt in east-west direction. These results may be due to long-wavelength errors in either Kolak-1915 or EGM2008. In addition, the larger value of tilt in the lower area than that of the upper area reveals vertical datum inconsistency. This is probably due to encapsulating the separation of vertical network adjustments over both areas and the post-seismic deformation in the southern part of Thailand after the 9.2Mw Sumatra-Andaman earthquake on 24th December 2004. Although the tilt is seemingly small (about 0.26 m trend from north to south across the country) and can be corrected for the conversion between Kolak-1915 and EGM2008 geoid undulations, high-order distortions (cf. figure 1b) remain, which may be due to other errors in the spirit-leveling data and/or EGM2008, which we are currently investigating.

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