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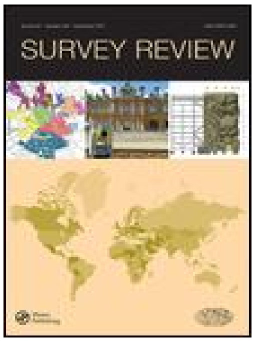

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Unification of GNSS CORS coordinates in Thailand

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This study estimates station coordinates of GNSS CORS networks in Thailand, based on ITRF2014, by applying the Precise Point Positioning (PPP) technique computed by the GipsyX software. Datum transformation parameters between ITRF2005 and ITRF2014 were investigated to transform station coordinates from ITRF2005 to ITRF2014. The Molodensky-Badekas model provides more reliable results than the Bursa-Wolf model on these transformations. The accuracy of coordinate transformations can be increased by interpolating the remained residuals from transformed coordinates into grid residual corrections. The analyses show that the seven parameters with the grid residual corrections can significantly improve the accuracy of the coordinate transformation.

Keywords: Datum transformation, PPP, GNSS, Grid residual corrections

1. Introduction

Collaborations amongst Thai government agencies have been currently established in Thailand to plan and share GNSS CORS observations, steered by the GNSS infrastructure management subcommittee. Its ensures maximum values from the existing and emerging GNSS technologies, by providing data and product supports towards various applications, such as surveying and mapping, tectonic plate motion, atmospheric science, cadastral surveying and precise timing (Satirapod and Homniam 2006, Panumastrakul *et al.* 2012, Mustafar *et al.* 2017, Thongtan *et al.* 2017, Pothikunkupatarak *et al.* 2018, Prakanrattana and Satirapod 2018, Charoenkalunyuta *et al.* 2019, Charoenphon and Satirapod 2020, Trakolkul and Satirapod 2020, Trakolkul and Satirapod 2021). The Department of Lands has adopted the GNSS Network Real-Time Kinematic (NRTK) surveying technique in first- and second-order survey controls since 2011 as part of enhancing their cadastral surveys. The GNSS NRTK positioning mainly helps to resolve the existing problems of cadastral surveys as parcel mapping tools. In the past, issued land parcel possessory right documents were believed to be inaccurate and did not comply with international standards in terms of geographic coordinates and parcel boundary marks. The parcel position depicted in a cadastral map sheet used to be unclear. Nowadays, a service of first-order cadastral survey, using GNSS NRTK positioning, is provided. It directly brings accurate coordinates, based on International Terrestrial Reference Frame 2005 (ITRF2005), at epoch 2008.87. Tectonic plates tend to continuously move and change over time; hence, many international organisations and mapping agencies have to update their reference frames to be more consistent with the plate movements.

Currently, many land surveying and mapping agencies in Thailand have already adopted the ITRF2005 at epoch 2008.87 and have a plan on updating and unifying horizontal datum transforms to the ITRF2014; particularly the Royal Thai Survey Department (RTSD) – the main department to set up a zero-order geodetic control network across the nation. More details, on the historical development of the geodetic network in Thailand, can be found in Satirapod *et al.* (2013). Figure 1 illustrates the magnitudes of horizontal position shifts based on reference frame transitions between ITRF2005 and ITRF2014 for the first-order geodetic control network across the nation. Table 1 shows comparison results of preliminarily determined station coordinates, estimated by the post-processing static method and obtained from 18 RTSD GNSS CORSs employed to support the first-order geodetic control network. The results show that mean horizontal position differences in the ITRF2005 and ITRF2008, ITRF2005 and ITRF2014, and ITRF2008 and ITRF2014 are 11.6, 32.7, and 21.1 cm, respectively. Determined coordinate differences are referred to the most recent versions of ITRF consisting of ITRF2005, ITRF2008, and the ITRF2014. The Department of Lands plans to implement updated station coordinates within the GNSS CORS network to the latest reference frame versions to be compatible with the RTSD and other agencies. This research focuses on coordinate determinations of currently existing GNSS

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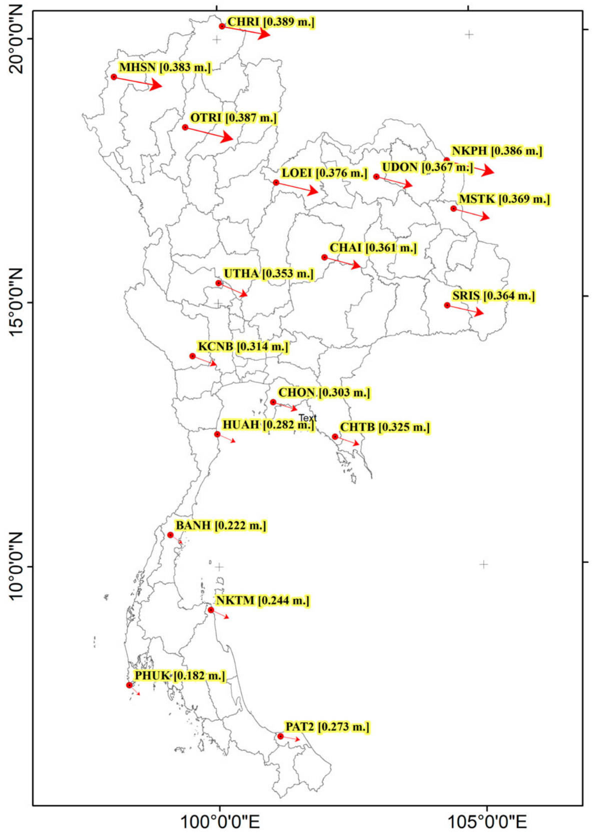


1 Magnitudes of horizontal position shifting between ITRF2005 and ITRF2014 reference frames.

CORS. In addition, their transformation parameters are realised and validated amongst various geodetic networks.

2. Data processing strategy

The Department of Lands' GNSS CORS coordinates are aligned to the ITRF2005 at epoch 2008.87. GNSS observations, obtained from 1 to 7 March 2020, were used to estimate station coordinates with respect to ITRF2008 and ITRF2014. Figure 2 shows distributions of a total of 229 GNSS CORSs nationwide. A daily data processing was carried out using the software package, GipsyX, recognised to be efficient and high accurate software for geodetic applications and is also internationally acclaimed (Satirapod *et al*. 2013, Bertiger *et al*. 2020). Multi-GNSS constellations (comprising GPS, Glonass, Beidou and Galileo) were applied in these station coordinate estimations.

Formerly, primarily due to the lack of GNSS observation data, estimated station coordinates, based on ITRF2008, were performed by transforming the coordinates from ITRF2014 at epoch 2020.17 to ITRF2008 at epoch 2013.81 (these coordinates are set to be at the exact time frame of the ones currently provided by RTSD) and used 14 transformation parameters, determined by the Institut Géographique National (IGN) in France with its station velocity obtained from a NUVEL 1A tectonic plate motion model (Demets *et al.* 1994) expressed in ITRF2014. These 14 parameters consist of 3 translation parameters, 3 rotation parameters and one scale factor with their time derivatives (Soler and Marshall 2003, Zuheir 2018). Figure 3 illustrates a station coordinate determining process at a different time frame in as follows: In the first step, the station coordinate estimations based on ITRF2014 at epoch 2020.17 are generated using the GipsyX by Precise Point Positioning (PPP) technique with PCV/PCO, Ocean loading, precise orbit and clock corrections. The NUVEL 1A plate motion model is then applied to station velocity estimations (UNAVCO 2021). The station coordinates and velocities are transformed from ITRF2014 at epoch 2020.17 into ITRF2008 at epoch 2020.17 involving the 14 parameters. The station coordinates from ITRF2008 at epoch 2020.17 are later transformed into epoch 2013.81 by applying their station velocities. The final solution of the station coordinates is based on ITRF2008 at epoch 2013.81. More detailed mathematical relationship determinations between the two geodetic networks based on ITRF2005, ITRF2008, and ITRF2014 will be explained in the following session.

3. Determinations on datum transformation parameters between coordinate frames: ITRF2005, ITRF2008 and ITRF2014

A mathematical relationship between the two geodetic networks lying on ITRF2005, ITRF2008 and ITRF2014 can be calculated by selecting common points in pairs (within two frames), from available 229 stations distributed throughout the country. Two well-known mathematic models used for the coordinate transformation between geodetic datums are Bursa-Wolf (B-W) and Molodensky-Badekas (M-B), as shown in Equation (1) (Závoti and Kalmár 2015) and Equation (2) (Deakin 2006), respectively. Investigations are on the assigned data that are well fitted to both models. The least-squares adjustment is used to predict the behaviour of dependent variables. Share common pairs of points, where predicted residuals are greater than 3-Sigma are eliminated. The station height is referred to as an ellipsoidal height. The transformation model is defined by three parameters in translation vectors (t_x, t_y, t_z), three rotation parameters (R_x, R_y, R_z), and one scale factor (Δs) (Kutoglu *et al.* 2012).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = (1+\Delta s)\begin{bmatrix} 1 & R_Z & -R_Y \\ -R_Z & 1 & R_X \\ R_Y & -R_X & 1 \end{bmatrix} \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_1 + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_2 = (1+\Delta s)\begin{bmatrix} 1 & R_Z & -R_Y \\ -R_Z & 1 & R_X \\ R_Y & -R_X & 1 \end{bmatrix} \times \begin{bmatrix} X-X_G \\ Y-Y_G \\ Z-Z_G \end{bmatrix}_1 + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix}_2 \tag{2}$$

when $X_i, Y_i, Z_i, \ \ i = 1, 2$ are the common pairs of points. X_G, Y_G, Z_G are the centroid points.

Table 1 GNSS CORS horizontal and vertical coordinate differences in Thailand with respect to reference frame versions are calculated from plane coordinates (dE and dN)

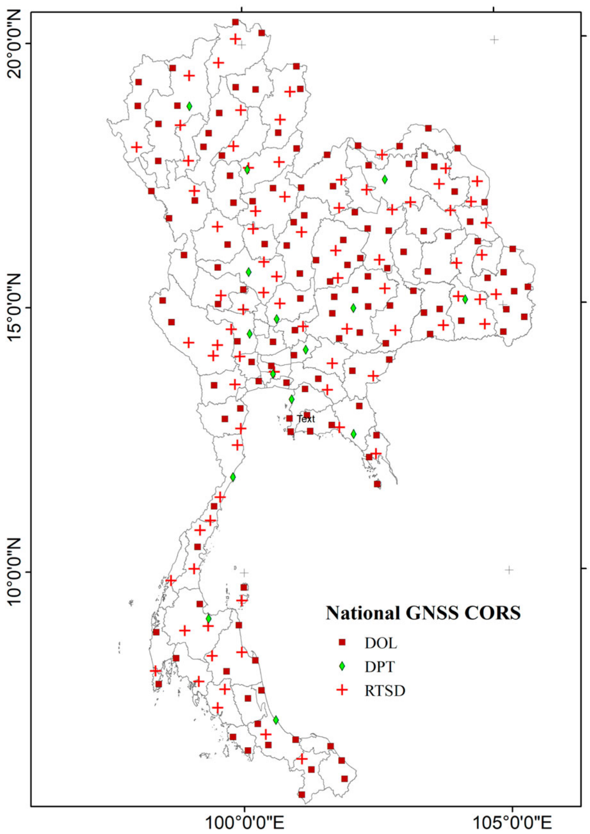
	ITRF2005 and ITRF2008		ITRF2005 and ITRF2014		ITRF2008 and ITRF2014	
Coordinate Differences [cm]	dHor	dVer	dHor	dVer	dHor	dVer
Min	4.2	0.4	18.2	2.0	12.2	1.1
Max	16.3	3.9	38.9	109.8	34.9	112.4
Mean	11.6	1.8	32.7	15.3	21.2	15.1
SD	3.5	1.2	6.3	25.4	5.2	26.1

4. Datum transformation model validation

Background on datum transformation model validations that is directly applicable to this research is given throughout this section as they comprise a large body of research starting from transformation parameters, datum transformation residuals and grid residual corrections to accuracy validations on the determined model and their solutions.

4.1 Transformation parameters

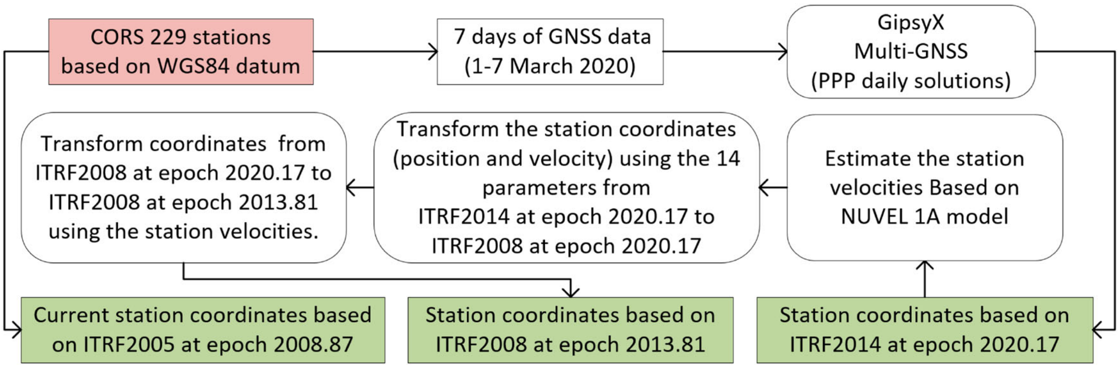
B-W and M-B models are evaluated on transforming station coordinates in the ITRF versions of ITRF2005, ITRF2008 and ITRF2014. Their standard deviations are determined to define their accuracy. The result of the least-squares adjustment, after the calculated transformation parameters, shows that the common pairs of points (229 stations) for each case of transformation have a residual of less than 3-Sigma in the X, Y, and Z components. Thus, none of the stations are eliminated. Moreover, the standard deviation obtained from the M-B model is smaller than from the B-W model, as shown in Table 2. This indicates that the M-B model provides better compatibility with common pairs of points than the B-W model which corresponded to studies described by both Kutoglu *et al.* (2012) and Hassan *et al.* (2019). Both models give identical solutions on rotation parameter accuracies, as shown in Table 2. These consider that the appropriate coordinate transform model between the geodetic datums in Thailand is the M-B model. Moreover, standard deviations of the determined parameters indicate unreliability if they are greater than the assigned value (0.0) and considered not to be used for the coordinate transformations. The computed parameters and their standard deviations are as shown in Table 2.



2 Nationally well-distributed 229 GNSS CORS from different departments.

4.2 Datum transformation residuals

Residuals produced from the M-B model in the coordinate transformation, along with E, N and U components, between the geodetic networks as of ITRF2005 to ITRF2008 and ITRF2008 to ITRF2014 transformations are ±3.2, ±2.6, and ±50.8 cm, respectively, as presented in Table 3. Figure 4 illustrates that larger residuals occur in northern, eastern and southern Thailand because these CORSs were previously installed based on WGS84/ITRF2005 at epoch 2008.87; which was determined at a different time frame and applied a different data processing method. Figure 5 illustrates the residuals of transformed coordinates between the geodetic networks. Recently, the national CORS network was further expanded. It started in the central region before extended installations to other regions across the country, including northern, eastern and southern areas, following the national network expansion plans. Different assigned station coordinate time frames and data processing methods lead to the accumulation of various systematic and random errors after the network became larger. However, the computed transformed coordinates, along with E, N and U components, provided by the M-B model between the geodetic networks as of ITRF2008 to ITRF2014 are described in Table 3 where their corresponding residuals along these axes are ±0.3, ±0.1, ±0.1 cm, respectively. The results show that the coordinates with common pairs of points are perfectly compatible because these station coordinates are based on ITRF2008 and ITRF2014 retrieved from the coordinate transformation by applying the 14 parameters and their velocities, as previously explained in Section 2.



3 Station coordinates' determining process based on ITRF2005, ITRF2008 and ITRF2014.

Table 2 Datum transformation parameters between two geodetic datums deployed in the B-W and the M-B models

	ITRF2005 epoch 2008.87 to ITRF2008 epoch 2013.81		ITRF2005 epoch 2008.87 to -ITRF2014 epoch 2020.17		ITRF2008 epoch 2013.81 to ITRF2014 epoch 2020.17	
Parameter	B-W	M-B	B-W	M-B	B-W	M-B
t_x (m.)	−2.0532 ± 0.6283	−0.2582 ± 0.0195	−2.0502 ± 0.6283	−0.4020 ± 0.0195	0.0030 ± 0.0031	−0.1438 ± 0.0001
t_y (m.)	−0.5350 ± 0.3056	0.5405 ± 0.0195	−0.5324 ± 0.3056	0.5289 ± 0.0195	0.0026 ± 0.0015	−0.0116 ± 0.0001
t_z (m.)	0.1144 ± 0.3295	0.0999 ± 0.0195	0.1166 ± 0.3295	0.0462 ± 0.0195	0.0022 ± 0.0016	−0.0537 ± 0.0001
R_X (″)	0.0	0.0	0.0	0.0	0.00127 ± 0.00005	0.00127 ± 0.00005
R_Y (″)	0.0	0.0	0.0	0.0	0.00321 ± 0.00005	0.00321 ± 0.00005
R_Z (″)	0.06529 ± 0.02015	0.06529 ± 0.02015	0.06113 ± 0.02015	0.06113 ± 0.02015	−0.00417 ± 0.00001	−0.00417 ± 0.00001
Δs (ppm)	0.1068 ± 0.0453	0.1068 ± 0.0453	0.1069 ± 0.0453	0.1069 ± 0.0453	0.0	0.0
X_G (m.)	0.0	−1198142.3550	0.0	−1198142.3550	0.0	−1198142.6133
Y_G (m.)	0.0	6042212.6473	0.0	6042212.6473	0.0	6042213.1878
Z_G (m.)	0.0	1592438.3497	0.0	1592438.3497	0.0	1592438.4496

Table 3 Residuals of horizontal differences obtained from the M-B model when the seven parameters are applied

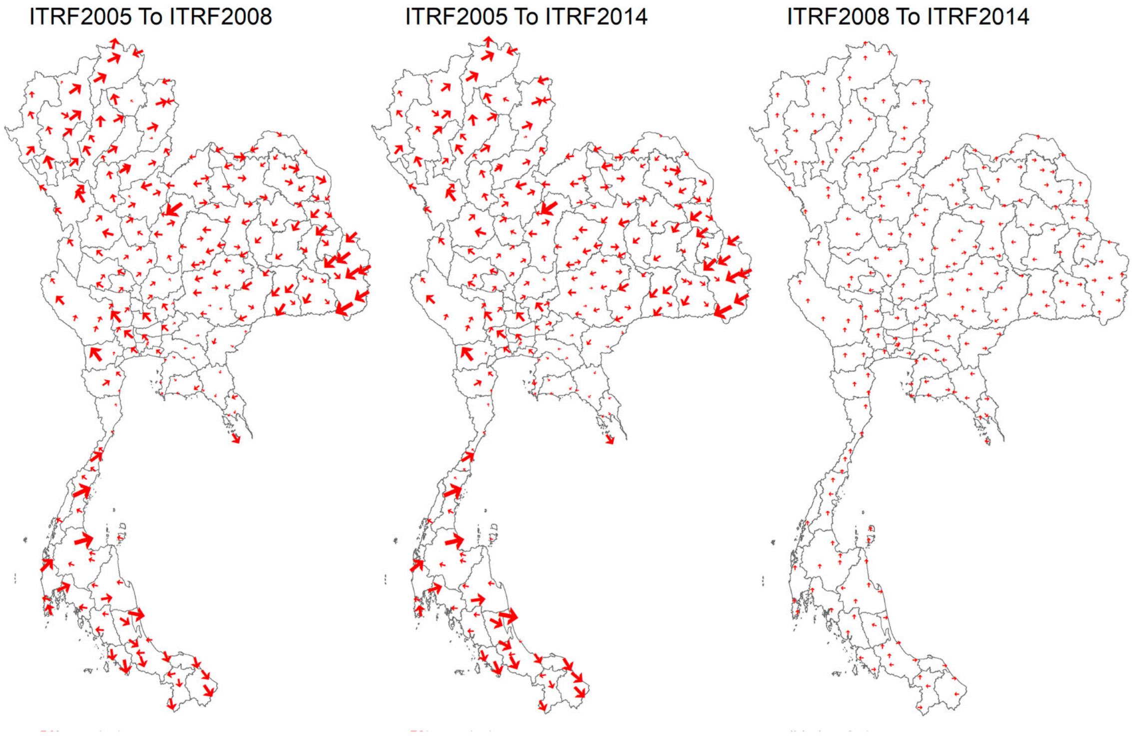
	ITRF2005–ITRF2008 (cm)			ITRF2005–ITRF2014 (cm)			ITRF2008–ITRF2014 (cm)		
Statistic	dE	dN	dU	dE	dN	dU	dE	dN	dU
Max	8.8	6.1	72.6	9.9	5.9	72.5	0.6	0.1	0.1
Min	−8.0	−6.4	−97.3	−8.1	−6.5	−97.0	−0.6	−0.2	−0.2
Mean	−0.2	0.1	0.6	−0.2	0.1	0.6	0.0	0.0	0.0
SD	3.2	2.6	50.8	3.2	2.4	50.8	0.3	0.1	0.1
3*SD	9.5	7.7	152.4	9.7	7.2	152.4	0.9	0.3	0.3

4.3. Grid residual corrections

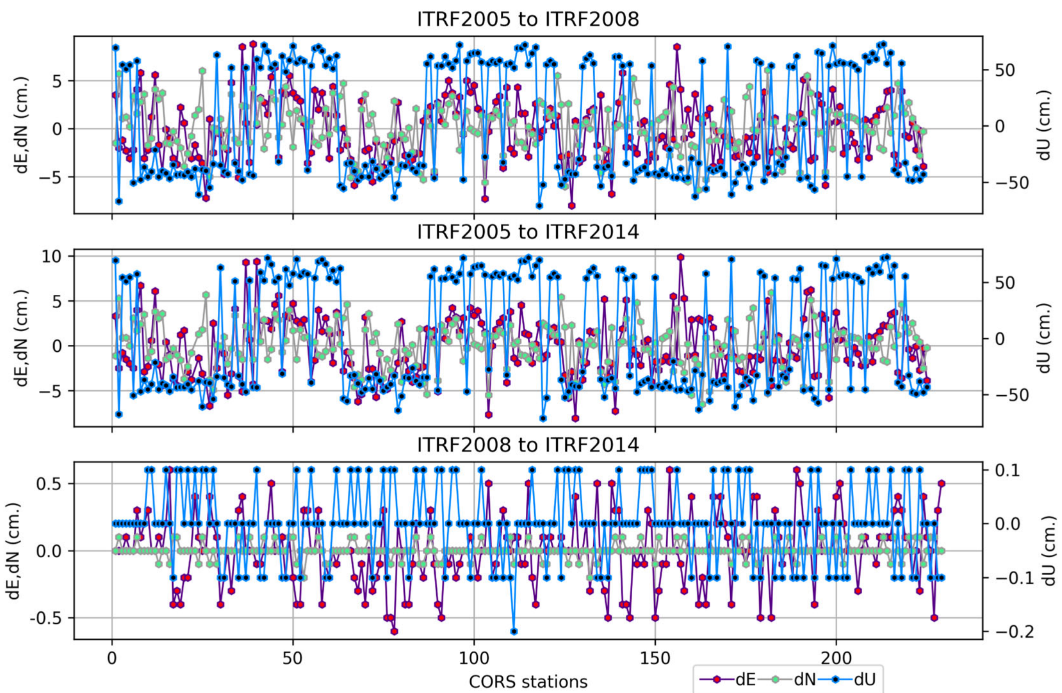
The accuracy of the coordinate transformations between the geodetic networks can be improved by interpolating residuals into grid residual corrections. These grid residual corrections consist of latitude and longitude corrections. Positioning residuals, as shown in Figure 4, of control points measured in both coordinate reference systems are selected to create the grid residual corrections (where their pixel size is 2 × 2 km and later illustrated in Figure 7). They can be interpolated by various methods, such as IDW (Invert Distance Weight), Kriging, Natural Neighbor and Spline. The process of creating grid residual corrections is shown in Figure 6. The method that gives the best result will be explained in the next section.

4.4. Accuracy determinations on datum transformation parameters and grid residual corrections

It is found that the M-B model is more compatible with the common pairs of point dataset in coordinate transformations between the geodetic networks in Thailand. However, after applying the seven parameters into the model, large residuals are in certain areas because of systematic and random errors due to some station coordinate determinations that are based on the previous reference frame version of WGS84/ITRF2005. They are ground stations installed earlier and their station coordinates were computed using different data processing methods; hence, coordinates may be inconsistent.



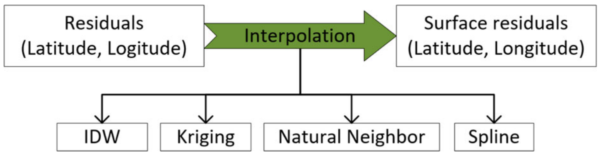
4 Magnitudes of horizontal differences between the set of control points from plane coordinates measured in both coordinate reference systems where the seven parameters are applied in the M-B model.



5 Residuals of transformed coordinates when the seven parameters are introduced in the M-B model (Unit: m.)

To validate the accuracy for both the seven parameters and the grid residual corrections, a GNSS static positioning, through field surveys, was carried out and defined as a checking point. Observation data were collected from about 445 locations with appropriate positions across the country at a 1-second sampling rate for 30 min at each observed station. These checking points were implemented in the baseline post-processing method. The obtained results from both the seven parameters and the grid residual corrections are compared and analysed. The analytical procedure is provided in Figure 8.

After the coordinate transformation between the geodetic networks, using a large number of the checkpoints, was tested in twofold when only seven parameters and both parameters and grid corrections are applied. The grid residual correction at each point can be simply

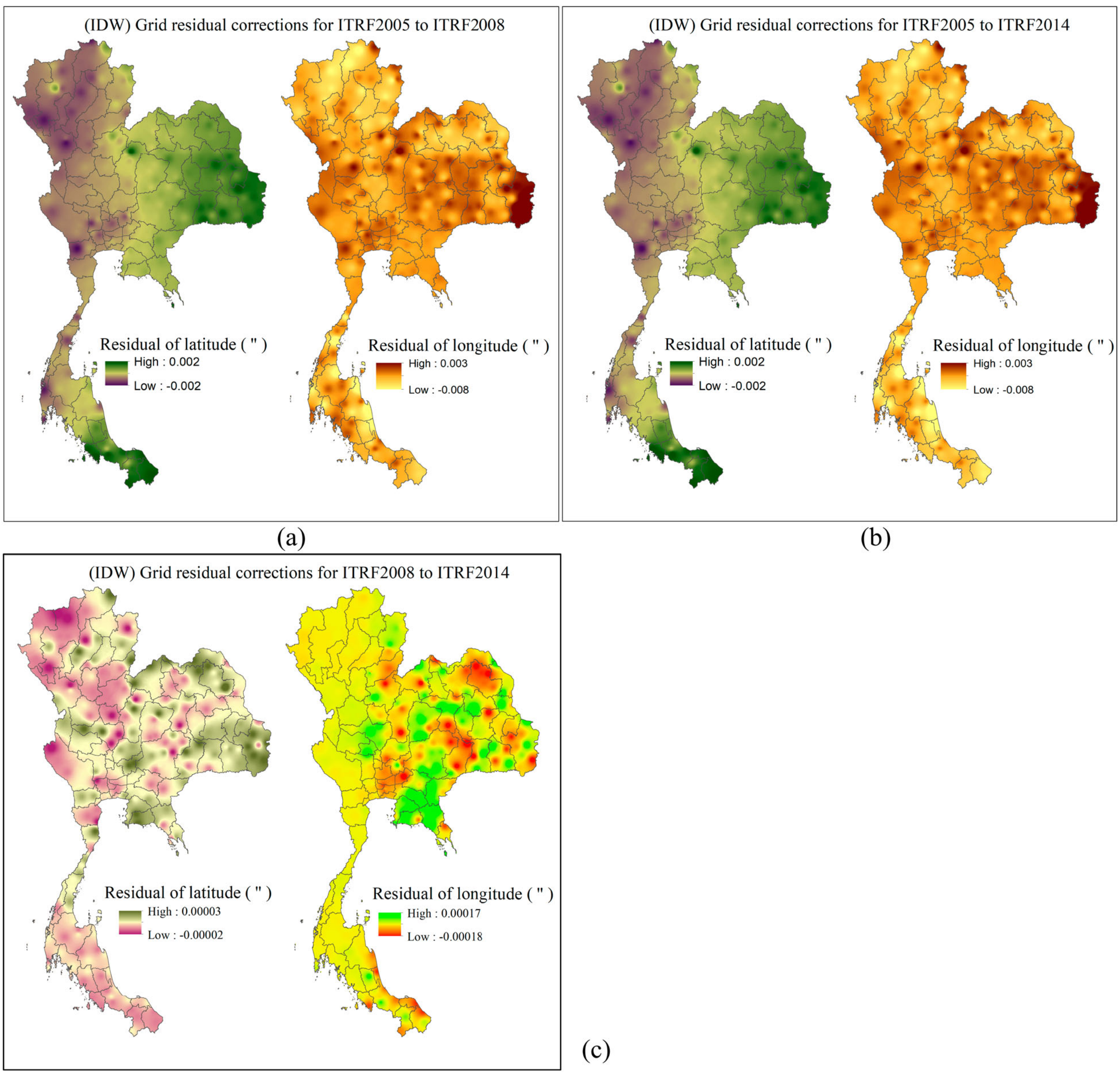


6 Processing technique on grid residual correction determinations.

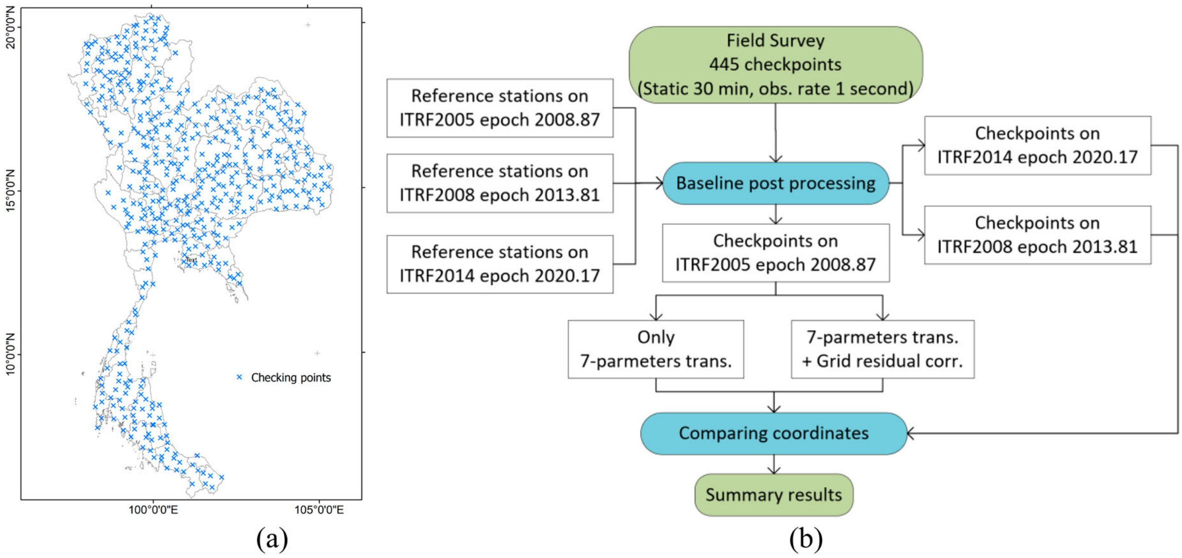
interpolated by the bilinear method. More details about the bilinear interpolation can be found at Press *et al.* (1988). Table 4 shows averaged horizontal accuracies of the coordinate transformation between ITRF2005 to ITRF2008 and ITRF2005 to ITRF2014 when only seven parameters are applied are 4.9 and 4.7 cm, respectively and when both the seven parameters and the grid residual corrections of each case of interpolation methods are applied. Averaged horizontal accuracy ranges from 3.0 to 3.3 cm. Figure 9 shows the magnitudes and directions of horizontal coordinate differences of checking points when applying M-B + IDW. Four interpolation methods share almost identical accuracy and no significant differences. Therefore, the experimental results indicate that the seven parameters and the grid residual corrections can improve the precision of the transformation to about 1–2 cm. On the contrary, the grid residual corrections do not improve the accuracy, when they transform the station coordinates from ITRF2008 to ITRF2014.

5. Conclusions and recommendations

The Department of Lands has adopted a Network RTK positioning to enhance cadastral surveys from Second Order to First Order with a high-accuracy GPS/GNSS positioning based on WGS84/ITRF2005 at epoch 2008.87. Even so, tectonic plates constantly move and tend to change over time. Many international organisations and agencies have attempted to improve the reference frame to be more consistent with the current plate



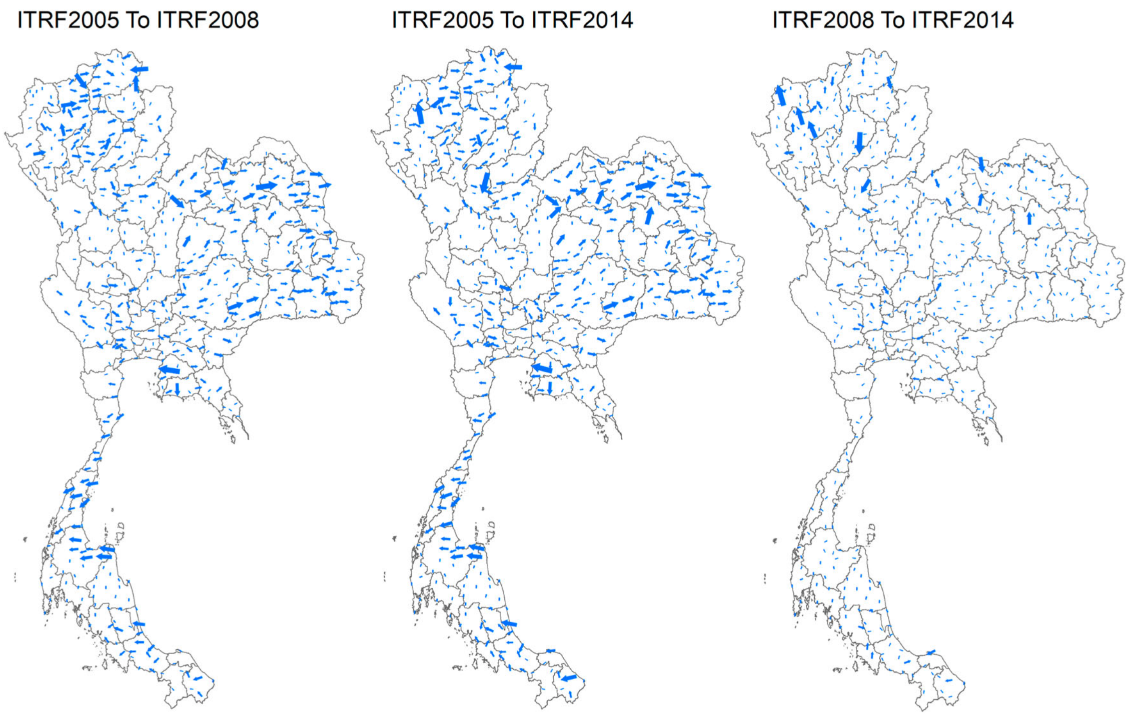
7 Example of grid residual corrections on coordinate transformation from (a) ITRF2005 to ITRF2008, (b) ITRF2005 to ITRF2014, and (c) ITRF2008 to ITRF2014 by applying the IDW method.



8 (a) Positions of checking points, (b) Data analysis procedure to test the accuracy of the transformation parameters and the grid residual corrections for a coordinate transformation between two geodetic networks.

Table 4 Horizontal coordinate differences when applied the seven parameters and the grid residual corrections

	ITRF2005–ITRF2008 (cm)				ITRF2005–ITRF2014 (cm)				ITRF2008–ITRF2014 (cm)			
Statistic	Max	Min	Avg	SD	Max	Min	Avg	SD	Max	Min	Avg	SD
Only M-B	32.0	0.2	4.9	6.3	31.0	0.2	4.7	5.5	34.5	0.0	0.9	4.4
M-B + IDW	30.7	0.1	3.2	4.9	30.8	0.1	3.0	4.0	34.7	0.0	0.9	4.4
M-B + Kriging	31.2	0.1	3.3	4.8	31.5	0.3	3.1	3.9	34.7	0.0	0.9	4.4
M-B + Natural Bk.	30.1	0.1	3.2	4.9	30.7	0.1	3.0	4.0	34.7	0.0	0.9	4.4
M-B + Spline	29.5	0.1	3.2	4.9	30.1	0.0	3.0	4.1	34.7	0.0	0.8	4.4



9 Example of horizontal coordinate differences of checking points when applying M-B + IDW.

movements. This study computes the GNSS CORS coordinates based on WGS84/ITRF2014 at epoch 2020.17 in Thailand. Solutions are generated from the high accuracy GNSS processing software, GipsyX where daily GNSS observations are applied and PPP results are obtained; hence the coordinates of the CORS network become very precise and united. On coordinate transformation parameters, the M-B model provides better reliable parameter solutions than the B-W model, consistent with the study by Kutoglu *et al.* (2012) and Hassan *et al.* (2019). On frame transformation from ITRF2005 to ITRF2014, large residuals show poor compatibility of parameters in some areas because, during the initial CORS installations, station coordinates are based on WGS84/ITRF2005 at epoch 2008.87, accumulating both systematic and random errors. Owing to station network expansion, the different installation periods of the referent stations and different processing methods at the coordinated station, coordinates are inconsistent. To resolve this problem, grid residual corrections are formed to improve the accuracy obtained solely from the seven parameters.

The analyses show that combining the seven parameters with the grid residual corrections helps to enhance the accuracy of the coordinate transformation between the geodetic network from ITRF2005 to ITRF2008 and ITRF2005 to ITRF2014 at approximately 1–2 cm. The accuracy of the coordinate transformations for both systems can be achieved at 3-4 cm horizontally; sufficient for the Department of Lands' uses on revising pin coordinates and land boundary marks. Moreover, the coordinate transformations particularly from ITRF2008 to ITRF2014 are compatible with using only the seven parameters as the results provide sufficient positioning accuracy. Nevertheless, each station coordinate always changes due to the earth's crust movements and the mass transition of the earth's inner core and surface. Moreover, the newly invented version of the terrestrial reference frame, ITRF2020, which shall be introduced soon, should be implemented in future studies to keep track of coordinate changes caused by these stated factors. Effective tools to pursue further studies are utilising data from the GNSS CORS in the network and a high accuracy positioning technique, such as PPP to anticipate the situations and keep tracking changes.

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