Testing Horizontal Coordinate Correction Model Used for Transformation from PPP GNSS Technique to Thai GNSS CORS Network Based on ITRF2014

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Abstract
The movement of tectonic plates directly affects the coordinates of geolocation and reference frame at the same position over time. Many international organizations and agencies have attempted to improve the reference frame to be more consistent with the current plate movements. In this study, a horizontal coordinates correction model based on the International Terrestrial Reference Frame 2014 (ITRF2014) in Thailand is tested by applying the Precise Point Positioning (PPP) technique computed by the GipsyX software. Coordinates of the points from some Continuously Operating Reference Stations (CORS) distributed over the country are used in the test. These points are observed twice. They are divided into two groups: training points and check points. GNSS observations from these points are processed with the PPP techniques to get 3D coordinates of all the points. The coordinates of the training point are used to compute the shift rates between the two epochs. Then, the surfaces are constructed by interpolation of the shift rates at the training points. The testing is based on four types of the interpolation: Inverse Distance Weighted (IDW), Kriging, Natural Neighbor, and Spline. In addition, vertical values often have problems with different types and heights of various kinds of antennas from the CORS stations and vertical values are mainly based on field work form leveling survey. This paper will focus on only the horizontal coordinates for grid transformation. Each of the surfaces is sampled into a grid which is used to compute correction for the coordinates of the check points. The differences between the two versions of the coordinates of check points (the coordinates directly obtained from observations and the coordinates, from the other epoch, corrected to the same epoch as the former) becomes errors. The root mean square errors (RMSEs) of horizontal coordinates are computed based on 149 checkpoints scattered throughout the country. The findings indicates that the correction models of IDW, Kriging, Natural Neighbor, and Spline method give horizontal coordinate accuracies of 0.011, 0.010, 0.017, and 0.017 meters, respectively. Thus, this can improve the accuracy of horizontal coordinates for the ITRF2014 in Thailand to less than 2 cm. The result is equivalent to less than 3 cm and 4 cm for the confidence level of 95% and 99.7%, respectively.

1. Introduction

In Thailand, collaborations have been established between Thai government agencies to plan and share GNSS CORS observation data under the guidance of the GNSS infrastructure management subcommittee. The national geospatial committee has approved the establishment of the National CORS Data Center (NCDC) responsible for integrating a huge GNSS observation data into a unified system throughout the country based on ITRF2014 at the incoming epoch 2021.93 (Epoch 2021.93 corresponds to the 340th day of the year or December 6, 2021). The NCDC provides data and product support to various applications such as surveying and mapping, tectonic plate movement, atmospheric science, cadastral surveying, precise timing, robotic and autonomous vehicle (Bresson et al., 2017, Charoenkalunyuta et al., 2019, Charoenphon and Satirapod, 2019, 2022, Panumastrakul et al., 2012, Park et al., 2021, Pothikunkupatarak et al., 2019, Satirapod and Homniam, 2006, Trakolkul and Satirapod, 2020, 2021 and Thongtan et al., 2017).

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In the past, a service of the first-order cadastral survey, using GNSS CORS Network Real-Time Kinematic (NRTK) positioning, was provided by the Department of Lands (DOL) whose coordinates were based on ITRF2005 at epoch 2008.87 and the Royal Thai Survey Department (RTSD) (the appointed agency to set up a zero-order geodetic control network of Thailand) whose coordinates were based on ITRF2008 at epoch 2013.81. Both the DOL and the RTSD have a plan on updating and unifying horizontal datum transforms to the latest version of the reference frame; ITRF2014. More details, on calculating the advanced coordinate adjustment of the GNSS CORS network in Thailand can be found from Kriengkraiwasin et al., (2021). The seven parameters with the grid residual corrections enhance the accuracy of the coordinate transformation between the geodetic network from ITRF2005 to ITRF2014, ITRF2005 to ITRF2008, and ITRF2008 to ITRF2014 at approximately 1–2 cm and the accuracy of the coordinate transformations can be achieved at 3-4 cm horizontally.

The movement of tectonic plates continuously occurs over time. Hence, many international organizations and mapping agencies are trying to update their reference frames to be more consistent with the movements. Especially, Thailand when starts to officially use the ITRF2014 at epoch 2021.93. General users who take advantage of surveying and mapping with the PPP technique may neglect inaccuracies in the coordinate that are settled in the exact time frame. The difference in coordinates at epoch may be accumulated over time due to the tectonic plates.

This study focuses on testing the horizontal coordinates transformation model to be used_with the PPP technique in order to be compatible with the incoming ITRF 2014 at the defined reference frame in Thailand.

2. Methodology

2.1 Data Acquisition

The coordinates of the points used in the testing were obtained from 229 GNSS CORS stations consisting of 134 stations from the DOL, 80 stations from the RTSD, and 15 stations from the Department of Public Works and Town & Country Planning (DPT). These stations were scattered throughout the country as seen from Figure 1. The GNSS (GPS, GLONASS, Beidou, and Galileo) signals were collected during the years 2020 and 2021. Each data collection session took 7 days.

The first observations in 2020 were acquired between March 1 - 7, 2021 and based on ITRF 2014 epoch 2021.17. The later observations in 2021 were acquired between February 29 - March 6, 2020 and based on ITRF 2014 epoch 2020.17. The data were divided into 2 sets. The first set consisted of the data from 80 RTSD stations to be used to compute coordinates of training points. The second set consisted of the data from 134 DOL stations and 15 DPT stations to be used to compute coordinates of check points.

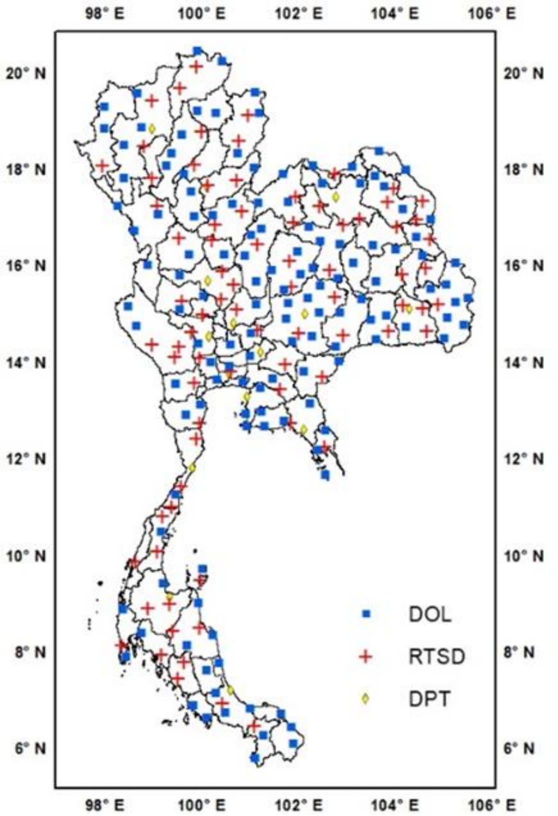

Figure 1: Location of Nationally well-distributed 229 GNSS CORS stations

2.2 Data Processing

According to some technical difficulties, only the signal from GPS is used for the processing by the software package, GipsyX, broadly recognized as efficient and highly accurate software for geodetic applications (Bertiger et al., 2020). Multi-GNSS constellations technique is applied to compute station coordinates with PCV/PCO, ocean loading, precise orbit, and clock corrections. The NUVEL 1A plate motion model is then applied to station velocity estimations (UNAVCO, 2022).

2.3 Computing Rates of Shifting and Surface Interpolation

The differences in coordinates of the training points from each epoch are obtained by subtracting the ITRF2014 frame coordinates at epoch 2020.17 with the coordinates at epoch 2021.17. Since the observations were made one year apart, the differences can be interpreted as shifting per year or rates of shifting, each of which consist of 3 elements (ΔX, ΔY, ΔZ) in the unit of millimeters per year for each CORS station. For the rates of shifting to conveniently be applied as corrections in the testing, they need to be rearranged into a regular grid. The construction of the grid takes two steps. First, the rates of shifting, from all the training points, in each axis (X, Y, and Z) are used to construct a surface by interpolation (Ajvazi and Czimber, 2019). Second, each of the surfaces is sampled into the grid (this will be cover in the next section). The first step is accomplished through the use of ArcMap software (ArcGIS Desktop 10.8, 2022). In this work, 4 methods of interpolation are employed including Inverse Distance Weighted (IDW), Kriging, Natural Neighbor, and Spline. In the case of IDW, the method is subdivided into 3 cases: power 1, 2 and 3. In the case of Kriging, the method is subdivided into 5 cases: Spherical, Circular, Exponential, Gaussian, and Linear. Finally in the case of IDW, the method is subdivided into 2 cases: Regularized and Tension. Thus, there are a total of 11 interpolation cases for constructing the surfaces for each axis, as illustrated in Figure 2. Each of the surface, covering the whole country, extends from 97°-106°E and 5°-21°N (Dumrongchai and Duangdee, 2019).

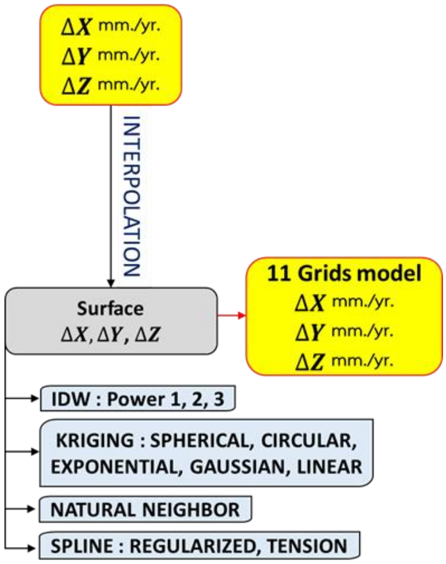

Figure 2: Interval estimation procedure

2.4 Correction Grid Construction

The total of 33 correction grids are constructed by Leica Infinity software (LEICA Geosystems AG, 2014) and stored using the country specific coordinate system (CSCS) model. Each of them covers the same area as the surfaces. The cell size of the grid is 1 minute, or approximately 1.85 km. The value of the point in a grid cell is calculated by the bilinear interpolation method. Figure 3 illustrates, for each cell, the positions of the variables used in the following equations.

$$s = \frac{x-x_0}{x_1-x_0} \text{ and } t = \frac{y-y_0}{y_1-y_0}$$

Equation 1

Here, x_0, x_1, and y_0, y_1 represent the longitude and latitude each corner of grid cell, and x and y represent the longitude and latitude of finding value in grid cell (Z). The calculation of a parameter Z (in our instance both differences in the coordinate directions) results from:

$$Z = f(x) = (1-s)(1-t)z_{00} + (1-s)tz_{01} + s(1-t)z_{10} + stz_{11}$$

Equation 2

More details about the bilinear interpolation can be found in (Press et al., 1988 and Garnero, 2014). The position of the project area starts at the lower-left corner (5° N, 97° E) and ends at the upper-right (21°N, 106° E) and Reading direction from west to east (WE) and south to north (SN) respectively as shown in Figure 4. Figure 5 gives an example of cells for the 1-minute area covering Bangkok, Thailand.

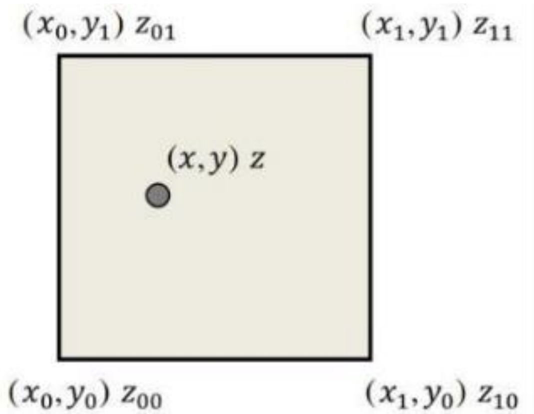

Figure 3: Bi-linear interpolation parameters (Garnero, 2014)

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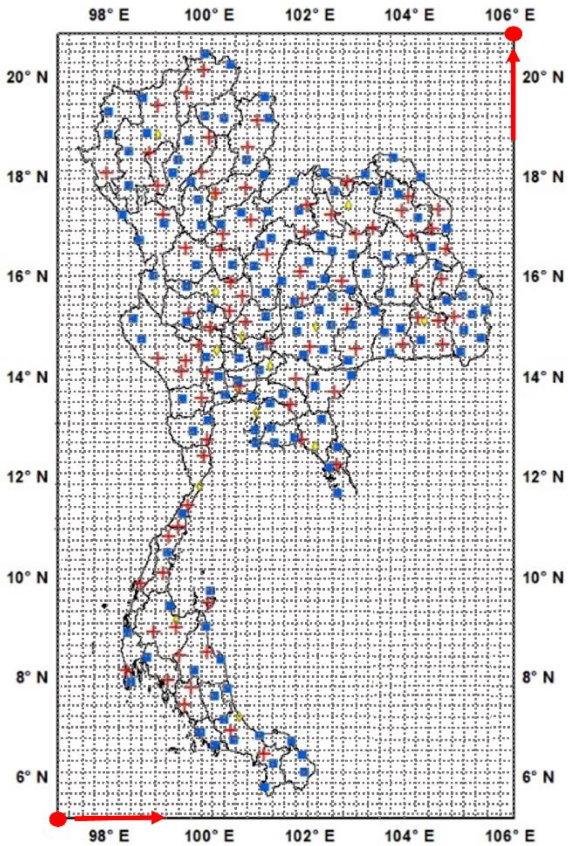

Figure 4: Example bilinear reading direction

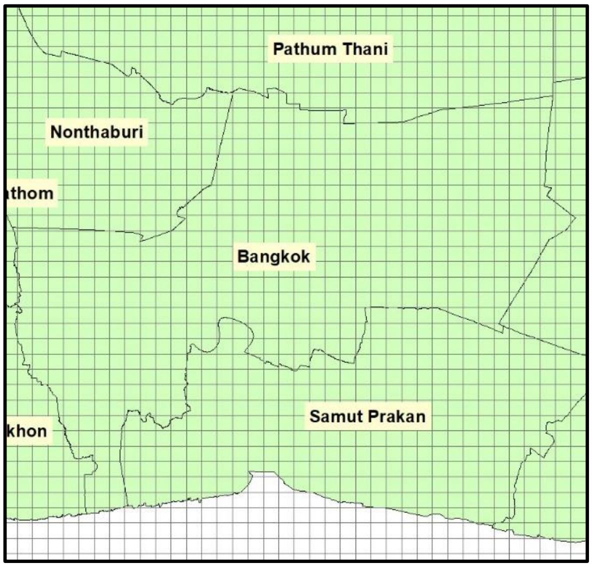

Figure 5: Example of cells for the 1-minute area covering Bangkok, Thailand

3. Results and Discussion

3.1 Surface of Corrections

As stated earlier, the total of 33 different surfaces of correction are generated using the ArcMap software. Examples of the surfaces created from the Kriging Gaussian interpolation method, in the X, Y, and Z axes, are plotted in Figure 6. Since the corrections for each of the axis have different ranges, a colour representing a correction value interval in Figure (a) may represent different correction value intervals in Figures (b) and (c).

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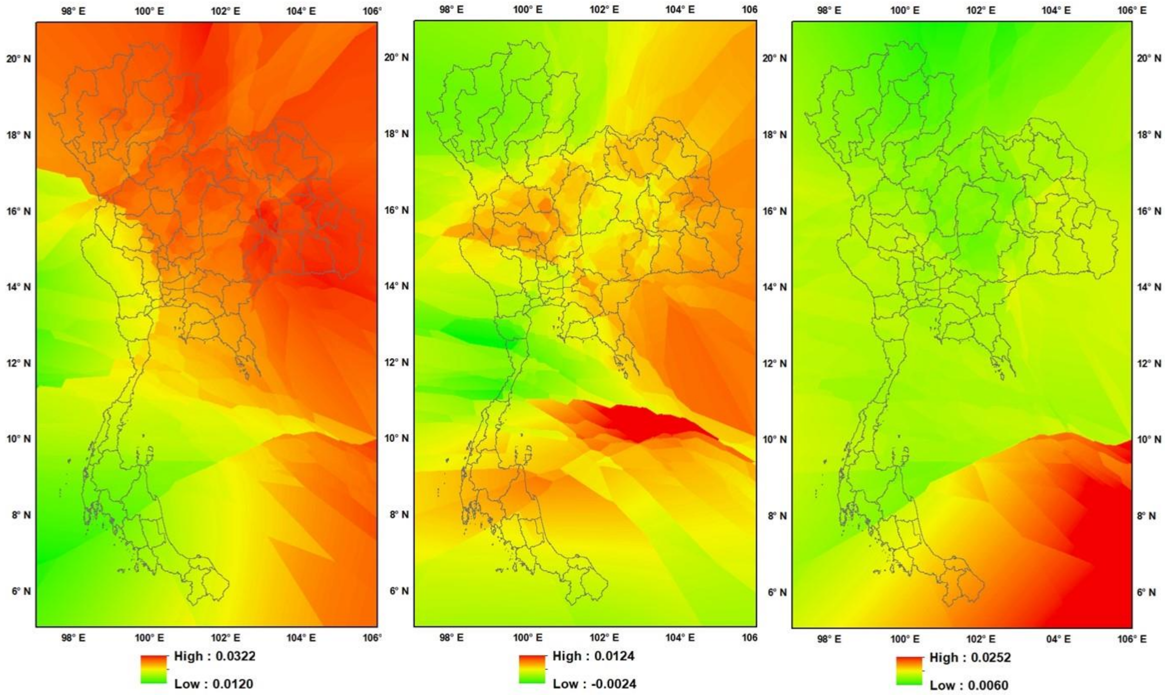


(a) (b) (c)

Figure 6: Example surfaces of grid corrections resulting from applying the Kriging Gaussian method: (a) X corrections, (b) Y corrections, and (c) Z corrections

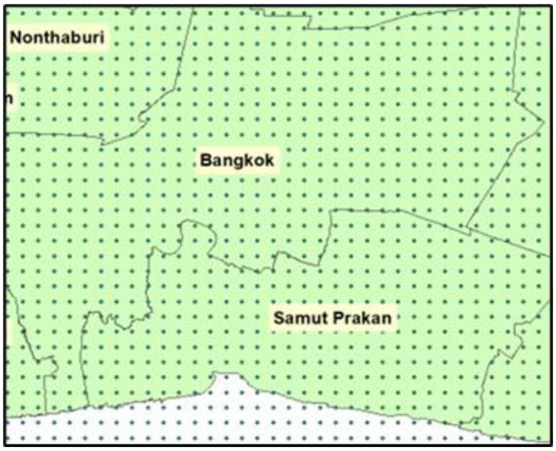


Figure 7: Correction grid over an area of Bangkok, Thailand

3.2 Correction Grids

The surfaces created in 3.1 are used to construct the correction grids using bilinear interpolation. Each of the grids, as mentioned before, consists of 1-minute cells (approximately 1.85 km by 1.85 km). Since each of them extends from 97° - 106°E and 5° - 21°N, there are 961 rows and 541 columns leading to 519,901 grid points. Figure 7 depicts part of a grid over an area of Bangkok, Thailand.

3.3 Accuracy Determinations on Correction Grids

Once the correction grids have been created, the coordinate of a point based on ITRF2014 at epoch 2021.17 can be transformed to a coordinate based on ITRF2014 at epoch 2020.17. In our study, the coordinates of 149 check points are transformed with all 33 correction grids. Then, the X, Y, Z coordinates of each point on both epochs are converted to a UTM (easting, northing) coordinate. The differences between the UTM coordinates of the two epochs represent horizontal accuracies (or errors).

Table 1: Horizontal coordinate differences when applied correction grid models with check points

Grid Model	Horizontal Accuracies (m)				
	Min	**Max**	**Avg**	**SD**	**RMSE**
IDW-1	0.001	0.089	0.005	0.009	0.010
IDW-2	0.001	0.089	0.006	0.009	0.011
IDW-3	0.001	0.089	0.007	0.010	0.012
Kriging Spherical	0.001	0.086	0.006	0.009	0.010
Kriging Circular	0.001	0.086	0.006	0.009	0.010
Kriging Exponential	0.001	0.086	0.006	0.009	0.010
Kriging Gaussian	0.001	0.087	0.005	0.008	0.010
Kriging Linear	0.001	0.086	0.006	0.009	0.010
Natural Neighbor	0.001	0.080	0.011	0.013	0.017
Spline Regularized	0.001	0.079	0.012	0.015	0.019
Spline Tension	0.001	0.086	0.009	0.012	0.015

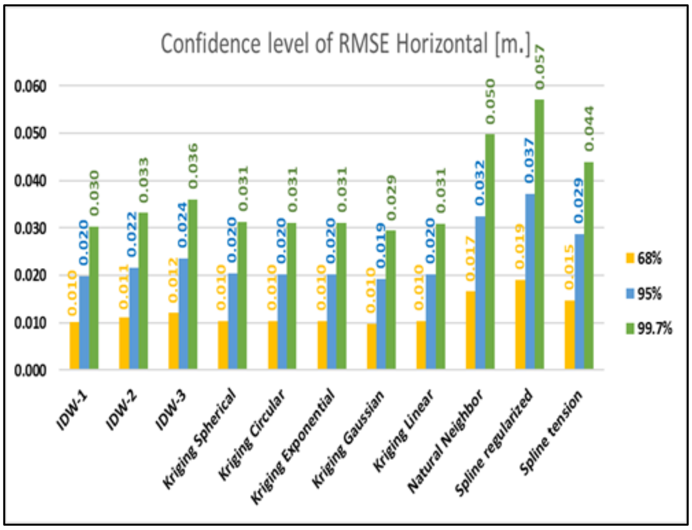


Figure 8: Confidence level of RMSE horizontal

Table 1 lists the values of the minimum (Min), maximum (Max), average (Avg), standard deviation (SD), and root mean square error (RMSE), in meters, computed from all the check points for each of the 11 methods of interpolation. Based on t-test statistic, the confidence levels of the RMSEs are constructed. They are shown in Figure 8. It can be seen from the figure that the Kriging models yield the highest accuracies. Thus, this can improve the accuracy of horizontal coordinates for the ITRF2014 in Thailand by less than 2 cm which is equivalent to less than 3 cm for the 95% confidence level and less than 4 cm for the 99.7% confidence level. Figure 9 plotted the horizontal differences for all the check points in northings (blue) and eastings (red) from the Kriging Gaussian method.

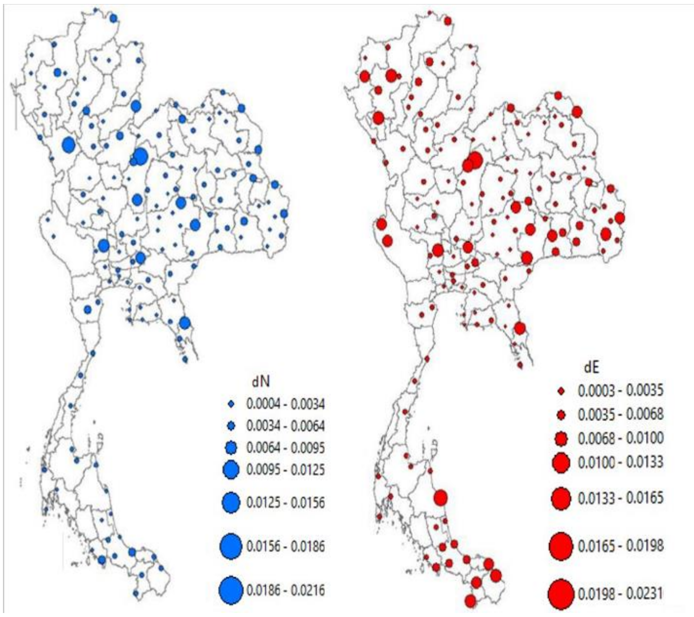


Figure 9: Horizontal differences (Northing and Easting) with Kriging correction grid

Table 2: Horizontal coordinate differences with ITRF2014 Epoch 2020.17 when applied the grid corrections with other epochs checking points

EPOCH	Horizontal Accuracy (m.)				
	Min	Max	Avg	SD	RMSE
2020.66	0.000	0.022	0.005	0.003	0.006
2021.66	0.000	0.023	0.006	0.004	0.007

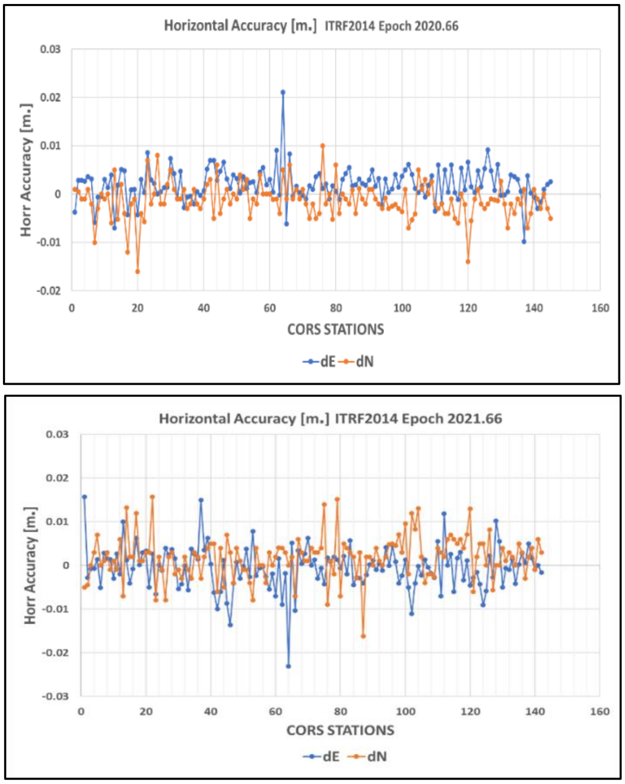
3.4 Additional Testing of the Accuracy of Horizontal Coordinates

Additional testing of the accuracy of horizontal coordinates in the UTM coordinate system by shifting in easting (ΔE) and northing (ΔN) with a comparison of horizontal coordinates on the ITRF2014 Epoch 2020.66 and Epoch.2021.66 through a set of coordinate transformations back at the ITRF2014 Epoch 2020.17 (fixed reference frame). The horizontal accuracy of both ITRF2014 Epoch 2020.66 and Epoch.2021.66 are shown in Figure 10. The coordinates at any other epochs can be calculated by a linear regression formula. For example, the coordinates at epoch 2020.66 can be calculated through the following equation (Wang, 2013).

$$\begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} = \begin{bmatrix} X_j \\ Y_j \\ Z_j \end{bmatrix} - [2020.17 - t_i] * \begin{bmatrix} V(\Delta X) \\ V(\Delta Y) \\ V(\Delta Z) \end{bmatrix}$$

Equation 3

Here, X_i, Y_i, and Z_i represent coordinates in the ITRF2014 Epoch 2020.17 frame, and X_j, Y_j, and Z_j represent coordinates in ITRF2014 with any epochs frame; t_i represents any other epoch at that time; $V(\Delta X, \Delta Y, \Delta Z)$ can be obtained from Kriging correction model including correction millimetres per year (mm/year) related to latitude and longitude coordinate system. Table 2 indicated testing the accuracy of horizontal coordinates for both ITRF2014 Epoch 2020.66 and Epoch.2021.66 about 0.006 and 0.007 meters, respectively and mean error of about 0.005 ± 0.003 and 0.006 ± 0.004 meters. It can be further developed in the part of the program to support the instruction set by inputting the PPP coordinates on the ITRF2014 at any epoch to convert the coordinates become the reference coordinates of Thailand by assuming to be the ITRF2014 at Epoch 2020.17, which is the corresponding reference coordinates. The reference coordinates for each organization or general user can take the resulting coordinates in the same direction. The advantage of the proposed model is that users can expect very high accuracy positioning results at any location in Thailand. However, the proposed model requires GNSS CORS data to keep track of coordinate changes. In addition, the proposed model would work well under the normal situation (only tectonic plate motion).



(a)

(b)

Figure 10: The horizontal accuracy of both ITRF2014 (a) Epoch 2020.66 and (b) Epoch.2021.66

If any big earthquake occurs, a modelling of co-seismic and post-seismic displacements is needed. An example on how co-seismic and post-seismic displacements are modelled can be found in Panumastrakul et al., (2012).

4. **Conclusion**

The DOL 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. Additionally, The RTSD has continued to develop the International Terrestrial Reference Frame based on WGS84/ITRF2008 at epoch 2013.81. Even so, tectonic plates constantly move and tend to change over time. Moreover, each coordinate always changes due to the earth's crust movements and the mass transition of the earth's inner core and surface. Many international organizations and agencies have attempted to improve the reference frame to WGS84/ITRF2014 to be more consistent with the current plate. This study computes the correction grid models based on WGS84/ITRF2014 at epoch 2020.17 in Thailand which models 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 correction grid model is formed to improve the accuracy of horizontal coordinate transformation from ITRF2014 at any epochs to ITRF2014 epoch 2020.17, consistent with the study by Kriengkraiwasin et al., (2021) focuses on applying both Molodensky-Badekas transformation and grid residual correction.

The findings indicated that the correction grid model of horizontal coordinates by applying difference coordinates of IDW, Kriging, Natural Neighbor, and Spline method give horizontal coordinates accuracy of about 0.011, 0.010, 0.017, and 0.017 meters respectively, the mean error of about 0.006 ± 0.010, 0.006 ± 0.009, 0.011 ± 0.013 and 0.011 ± 0.014 meters respectively, the Kriging method gives the highest horizontal coordinate accuracy. Thus, this can improve the accuracy of horizontal coordinates for the ITRF2014 in Thailand by less than 2 cm. The result is equivalent to less than 3 cm and 4 cm for the confidence level of 95% and 99.7%, respectively.

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 utilizing 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 by increasing the period for more observation data every week to process the coordinates (weekly solution) to track the rate of positioning movement for further study and become as a local velocity of Thailand.

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