Comparative study of using different ionosphere models in Thailand for single-frequency GPS users

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Abstract

An Ionosphere layer makes inaccurate GNSS signal. The ionosphere layer contains free electrons delaying the speed of GNSS signals. This problem is solved by using a dual frequency receiver and applied an ionosphere-free linear combination. The delay due to ionosphere still occurs when a single frequency receiver is used. A suitable selection of ionosphere model is actually useful to eliminate this inaccurate GNSS signal. This article presents a comparative study by applying various ionosphere models in Thailand including: Klobuchar model, Global Ionosphere Maps (GIM), Ionosphere Model from QZSS and local ionosphere model. The local ionosphere model is generated from GNSS observations at with the use of locally available GNSS tracking stations by the Bernese GPS software 5.0. Coordinates derived from the above-mentioned models were compared and statistical tests in two observed scenarios; namely, single frequency data and ionosphere-free linear combination from dual frequency data. These experiment results proved that applying the local ionosphere model to the estimation produces the most accurate positioning results. They are similar to the results obtained from an ionosphere-free linear combination, but with significant differences.

KEYWORDS : Ionosphere model, GNSS, Bernese

1. Introduction

Ionosphere is a region of free electrons quantified by the total electron content (TEC); which is the total number of electrons along the signal path, and the frequency of the propagated signal. The TEC depends on time, season and geographic location, with major influencing factors being the solar activity and the geomagnetic field. In extreme cases, the ionospheric delay can range from about 50m for signals at the zenith to as much as 150m for measurements made at the receiver's horizon.

This dependence on the signal frequency allows us to remove its effect of ionosphere delay using two frequency measurements. But, single frequency receivers must apply an ionosphere model to remove this effect, including Klobuchar model, Global Ionospheric Maps (GIM) model and Ionosphere Model from QZSS (Klobuchar, 1987; Schaer et al., 1998; QZSS, 2017). The coefficients of the Klobuchar model are transmitted to users as part of the GPS navigation message. Ionosphere Model from QZSS was proposed for single-frequency QZSS users with performance superior to Klobuchar model at Japan. A widely used ionospheric model is the GIM. GIM are generated by using data from about 200 GNSS station of the IGS and other institutions, contains the vertical TEC (VTEC) in grid map; whereas, areas with a low density of GNSS reference station, GIM may not suitable.

Several local ionosphere models have been proposed by a number of researchers. Todorova et al. (2004) compared local ionosphere model generated by BERNESE with the GIM model. Xiong et al. (2016) and Zhao et al. (2016) created a local ionosphere model for China and compared with the GIM model, which their model provided a better accuracy. Takahashi et al (2014) created TEC map in Brazil to study TEC values in ionosphere on low latitudes. For Thailand, which is in the near equator region, has the highest variability of ionosphere compared to other regions on earth. Thailand should have its own ionosphere model suitable for the area to improve the positioning accuracy within Thailand. (Charoenkalunyuta and Satirapod, 2014)

This paper presents a comparative study of applying various ionosphere models in Thai region including Klobuchar model, Global Ionosphere Maps, Ionosphere Model from QZSS and local ionosphere model. The local ionosphere model is generated with the use of locally available GNSS stations by the Bernese GPS software version 5.0 (Dach et al., 2007). With the use of single frequency data, the coordinates derived from the above-mentioned models were compared with the coordinates obtained from applying an ionosphere-free linear combination from dual frequency receivers.

2. Ionospheric model

Ionospheric model are described in two main cases; namely, for those dual and single frequency GNSS users.

2.1 Option for dual-frequency GNSS users

Dual-Frequency GNSS users can use their combined data called Ionosphere-free Linear Combination. The first order ionospheric effects depend on the inverse of squared signal frequency. This effect can be eliminated through a linear combination of code or carrier measurements, supposing that the expected errors other than ionosphere are eliminated, as shown in equation (1) and (2) (Hofmann et al., 1997):

$$\lambda_1\varphi_1 = \varrho_r^s + c(\Delta\delta_r^s) + \lambda_1 N_1 - \Delta_1^{Iono} \tag{1}$$

$$\lambda_2\varphi_2 = \varrho_r^s + c(\Delta\delta_r^s) + \lambda_2 N_2 - \Delta_2^{Iono} \tag{2}$$

Where φ_1 and φ_2 are the carrier-phase measurements on L1 and L2, respectively; ϱ_r^s is the satellite-receiver true geometric range; c is the speed of light; Δ_r^s is the receiver and satellite clock errors; λ_1 and λ_2 are the wavelength of the L1 and L2 carrier frequencies, respectively; N_1 and N_2 are the non-integer phase ambiguity parameters on L1 and L2, respectively; Δ_1^{iono} and Δ_2^{iono} are the ionospheric delay on L1 and L2, respectively;

Since $C = f\lambda$, the reformatted equation (3) and (4) provides:

$$\varphi_1 = af_1 + N_1 - \frac{b}{f_1} \tag{3}$$

$$\varphi_2 = af_2 + N_2 - \frac{b}{f_2} \tag{4}$$

$$a = \frac{\varrho_r^s}{c} + \Delta\delta_r^s \quad \text{and} \quad b = \frac{f_i^2}{c}\Delta_i^{Iono}$$

Ionosphere-free Linear Combination are used to eliminate ionosphere term (b) by $f_1\varphi_1 - f_2\varphi_2$ and reformatted by multiplying $\frac{f_1}{(f_1^2 - f_2^2)}$ as following, equation (5)

$$[\varphi_1 - \frac{f_2}{f_1}\varphi_2]\frac{f_1^2}{(f_1^2 - f_2^2)} = af_1 + [N_1 - \frac{f_2}{f_1}N_2]\frac{f_1^2}{(f_1^2 - f_2^2)} \tag{5}$$

Although Ionosphere-free Linear Combination can eliminate ionosphere delay but cannot handle all errors because of this error is based on the wave travelling in straightline. In fact, there are other influences that cause distortions (Bassiri and Hajj, 1993).

2.2 Option for single-frequency GNSS users

Most predicted ionosphere models are based on the Single Layer Ionospheric Delay assumption. This is by assuming that ionosphere is a single layer and fixed height above the Earth's surface. This model uses the Zenith (z) angle above the receiver and the Zenith (z ') over the surface of the ionosphere, which is higher than the surface of the Earth (H); whereby both angles are the locations where the satellite signals travel to the receiver (as shown in Figure 1) (Musa, 2007).

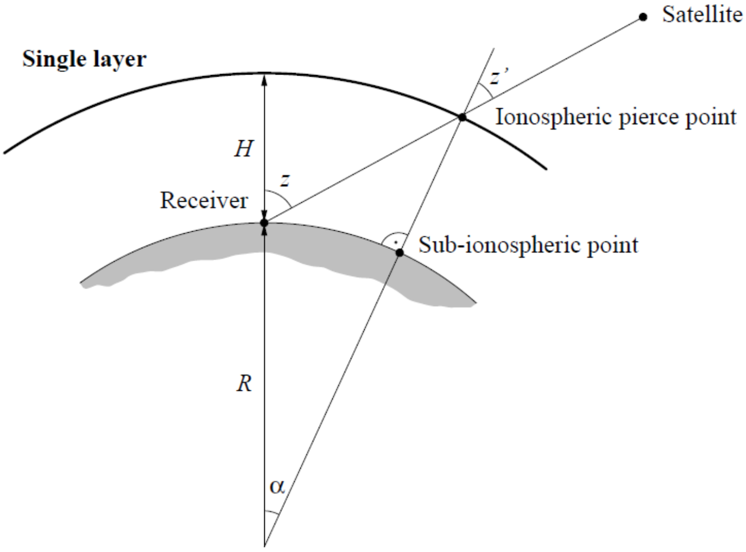

Figure 1. Single Layer Ionospheric Delay

According to this model, latitude and longitude at IPP (Ionospheric Pierce Point) can be calculated according to the equation (6) to (9) as shown below.

$$z' = \sin^{-1}\left(\frac{R_E}{R_E + H}\sin z\right) \tag{6}$$

$$\alpha = z - z' \tag{7}$$

$$\varphi_{IPP} = \sin^{-1}(\cos\alpha\sin\varphi' + \sin\alpha\cos\varphi\cos A') \tag{8}$$

$$\lambda_{IPP} = \lambda' + \frac{\sin\alpha\sin A'}{\cos\varphi} \tag{9}$$

Where φ_{IPP} and $\lambda_{IPP}$are latitude and longitude at IPP (Ionospheric Pierce Point); φ' and λ' are latitude and longitude at a receiver; A' is Azimuth at a receiver; $R_E$is radius of earth (6371 km);

For those Single-Frequency GNSS users, the Ionosphere Model including Klobuchar model, Global Ionospheric Maps (GIM) model, Ionosphere Model from QZSS and the local ionosphere model can be used as elaborated below.

2.2.1 Klobuchar model

GPS satellites broadcast the parameters of the Klobuchar ionospheric model for single frequency users: $\alpha_0,\alpha_1,\alpha_2,\alpha_3,\beta_0,\beta_1,\beta_2,\beta_3$.The Klobuchar model is designed to minimise user computational complexity and user computer storage in order to keep a minimum number of coefficients to transmit on satellite-user. Calculating ionospheric delay is specified as the following equations (10) - (14) (Klobuchar, 1987).

$$\Phi_m = \varphi_{IPP} + 0.064\cos(\lambda_{IPP} - 1.617) \tag{10}$$

$$F = 1 + 16(0.53 - E)^3 \tag{11}$$

$$x = 2\pi \frac{(t - 50400)}{\sum_{n=0}^{3} \beta_n \varphi_m^n} \tag{12}$$

$$t = 4.32x10^4 \lambda_{\mathrm{IPP}} + t_{gps} \tag{13}$$

$$I_r^S = \begin{cases} Fx5x10^{-9}, & |x| > 1.57 \\ Fx(5x10^{-9} + \sum_{n=0}^{3} \alpha_n \varphi_m^n x(1 - \frac{x^2}{2} + \frac{x^4}{24})), & |x| \leq 1.57 \end{cases} \tag{14}$$

Where I_r^s is ionospheric delay; E is elevation angle; t_{gps} is GPS time;

2.2.2 Ionosphere Model from QZSS

The Quasi-Zenith Satellite System (QZSS) is a regional navigation satellite system commissioned by the Japan Aerospace Exploration Agency (JAXA). The QZSS service area covers East Asia and Oceania region. Its platform is multi-constellation GNSS. The QZSS system is not required to work in a stand-alone mode, but needs to work together with data from other GNSS satellites (JAXA 2014).

QZSS sends the ionosphere parameters in the same form as the Klobuchar Model for single-frequency signals. QZSS produces and transmits two types of parameters: parameters for the Southeast Asia and Oceania regions, and parameters for the area near Japan. It is expected that accuracy will be improved as the target regions are made smaller, and that it will be possible to achieve precision of two to three metres in the area near Japan (QZSS, 2017).

2.2.3 Global Ionosphere Maps (GIM) model

A map shows Total Electron Content (TEC) representing within one square metre between two points in terms of VTEC (Vertical Total Electron Content) by using model spherical harmonic expansions and available data in IONEX format. Ionosphere delay from VTEC is calculated using following equation (15) (Takasu, 2013)

$$\mathrm{I}_{\mathrm{r,i}}^{\mathrm{S}} = \frac{1}{\cos z'} \frac{40.3x10^6}{\mathrm{f_i}} \mathrm{VTEC}(\mathrm{t}, \varphi_{\mathrm{IPP}}, \lambda_{\mathrm{IPP}}) \tag{15}$$

At present, the Global Ionosphere Map (GIM) is provided by the Center for Orbit Determination in Europe (CODE) and available on the International GNSS Service (IGS) products (CODE, 2017).

2.2.4 The local ionosphere model

It is generated with the use of locally available GNSS stations by the Bernese GPS Software. This model uses geometry-free linear combinations, which eliminate the geometrical term, receiver and satellite clock errors as previously described in equation (3) and (4). The geometrical term (ϱ_r^s) is removed as specified in equation (16) (Harte and Levitan, 2016).

$$f_2\varphi_1 - f_1\varphi_2 = N_1 f_2 - N_2 f_1 - \frac{f_1 f_2}{c}(\Delta_1^{Iono} + \Delta_2^{Iono}) \tag{16}$$

Term $\Delta_1^{iono} + \Delta_2^{iono}$ is an ionospheric delay. It can be converted into slant TEC (STEC) along the satellite-receiver path. STEC can be converted into VTEC by using the modified single layer ionospheric delay mapping function. as equation (17) and (18) (Dach et al., 2007).

$$STEC = (\frac{f_1^2 f_2^2}{40.3(f_2^2 - f_1^2)})(\Delta_1^{iono} + \Delta_2^{iono}) \tag{17}$$

$$VTEC = STEC \times \cos z' \tag{18}$$

The regional VTEC is expressed as a spherical harmonic expansion. It can be expressed as equation (19) (Dach et al., 2007).

$$VTEC(\varphi, \lambda) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_{nm}(sin\,\varphi)(a_{nm}\,cos\,m\lambda \;+\; b_{nm}\,sin\,m\lambda) \tag{19}$$

Where VTEC(φ,λ) is VTEC at latitude *(φ)* and longitude*(λ)* $\widetilde{P_{nm}}$; are normalized associated Legendre functions of degree n and order m; a_{nm} and$b_{nm}$are the spherical harmonics coefficients.

3. Methodology

A regional network consisting of 11 reference stations in Thailand has been used to develop the proposed regional ionospheric correction model (Figure 2). GNSS observations data will be used between 1 January 2015 and 1 September 2015 (244 days), providing from the Department of Lands (DOL), the Department of Public Works and Town & Country Planning (DPT) and the International GNSS Service (IGS). Each observation file has a 24hours time span and a 30second time interval. These files have been processed using the Bernese GPS Software version 5.0. The final satellite orbit, satellite clock, DCB and earth orientation parameters have been used and converted into the Bernese formats for data processing. In the parameters estimation process, the effective height is selected to be 450 km where a maximum degree and order equal to seven of the spherical harmonic expansion are set. After completed the processing, the VTEC maps are retrieved in the format of IONEX where the spatial resolution is as of 0.5 × 0.5.

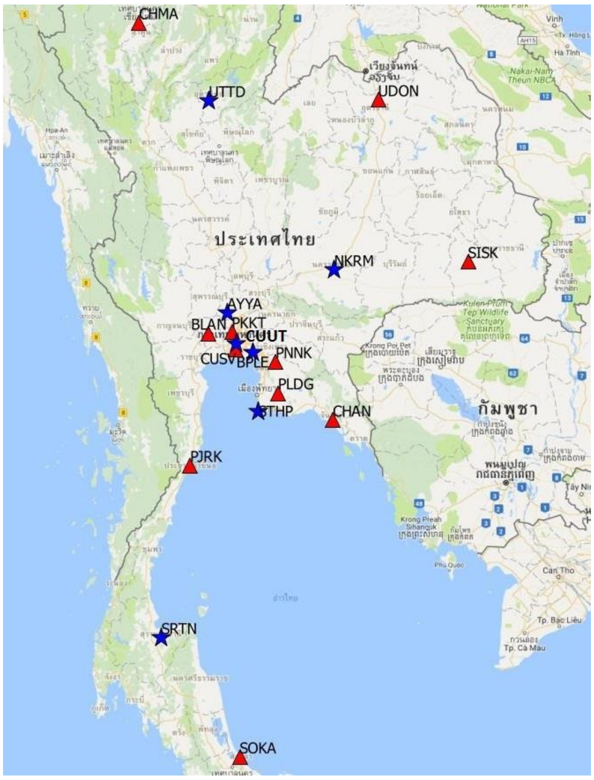

Figure 2. 11 Reference stations (in red triangle) and 7 Examined stations (in blue star)

The examined stations comprised of 7 stations across the countries. They are denoted as AYYA, BPLE, CUUT, NKRM, SRTN, STHP and UTTD. The observed data from these stations are used for evaluate the applied ionosphere models with respected to two main GNSS users.

4. Results and analysis

In order to evaluate the local ionosphere model, GNSS observations from another set of stations (denote as examined stations and pictured as blue stars in Figure 2) have been processed with a single point positioning (SPP) approach using the RTKlib software version 2.4.2. The positioning results and its accuracy are calculated and compared, where observed data are of the dual-frequency ionosphere-free linear combination and the single-frequency users and the Klobuchar model, Global Ionosphere Maps, Ionosphere Model from QZSS and local ionosphere model (THAI) are applied to these estimations. The estimated SPP station coordinates are then compared with the reference coordinates and its corresponding statistical parameters are analysed. The Horizontal and Vertical RMSE at each examined station are as shown in Figure 3– 4.

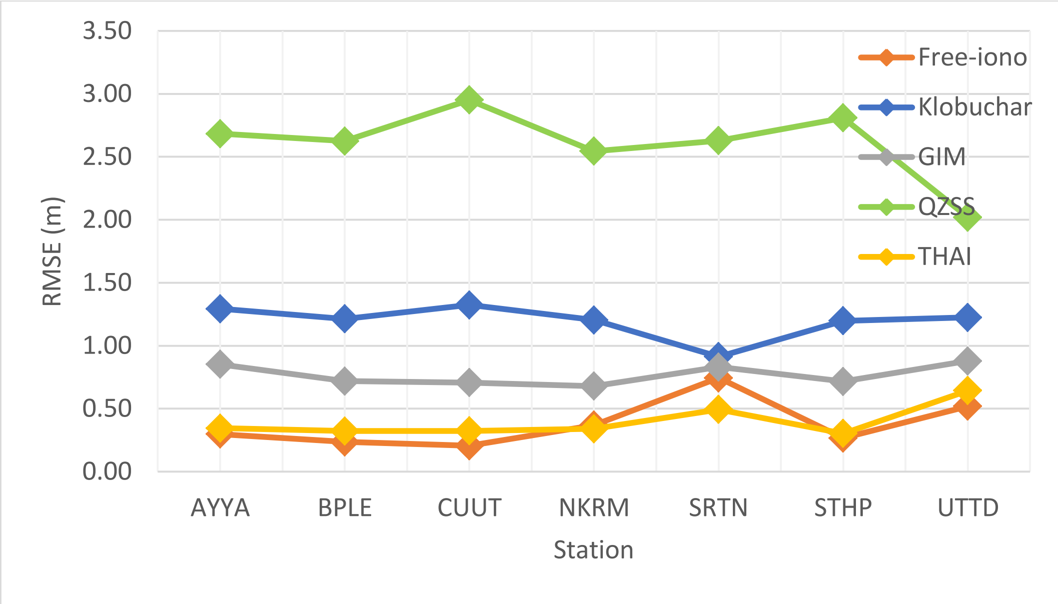

Figure 3. Horizontal RMSE for each station

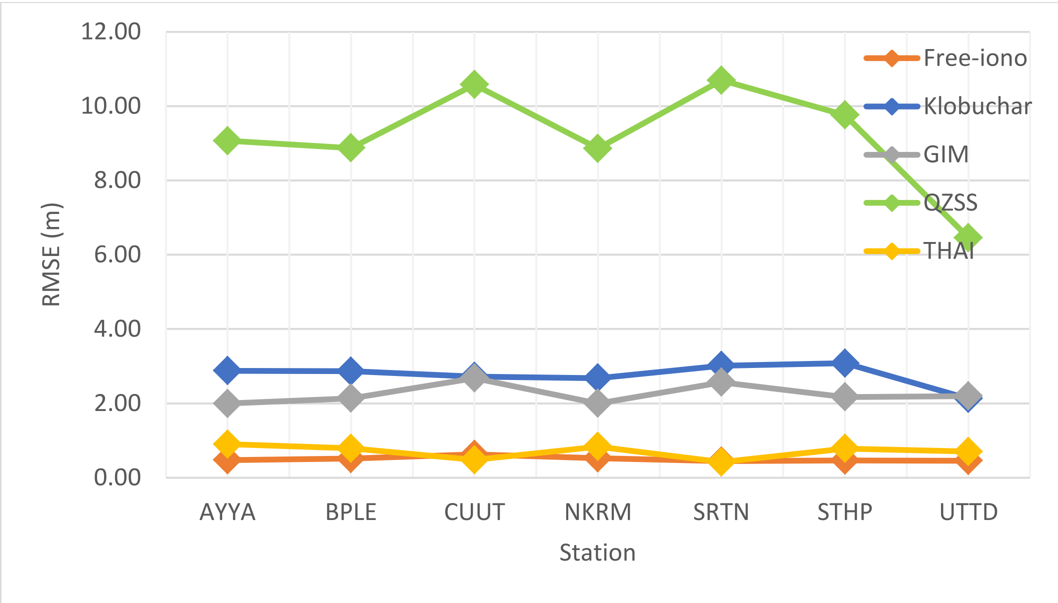

Figure 4. Vertical RMSE for each station

Figures 3 and 4 show Horizontal and Vertical RMSE of each examined station, the RMSEs of each station are similar for each of the ionosphere models.

In terms of the Horizontal RMSEs, it is about 2.02 – 2.95 m when the QZSS model is applied to the estimations, is about 0.91 - 1.32 m with Klobuchar model, and is about 0.68–0.88 m with the GIM model. The horizontal RMSE is the smallest about 0.30 - 0.64 m and similar to value of the ionosphere-free linear combination of dual frequency with the THAI model. In terms of the Vertical RMSEs, it shows that the QZSS model is the largest about 6.46 – 10.70m, Klobuchar model is about 2.13 – 3.08m, the GIM model is about 1.99–2.68 m, and the THAI model is about 0.42 - 0.90 m which is the smallest and similar to value of the ionosphere-free linear combination of dual frequency.

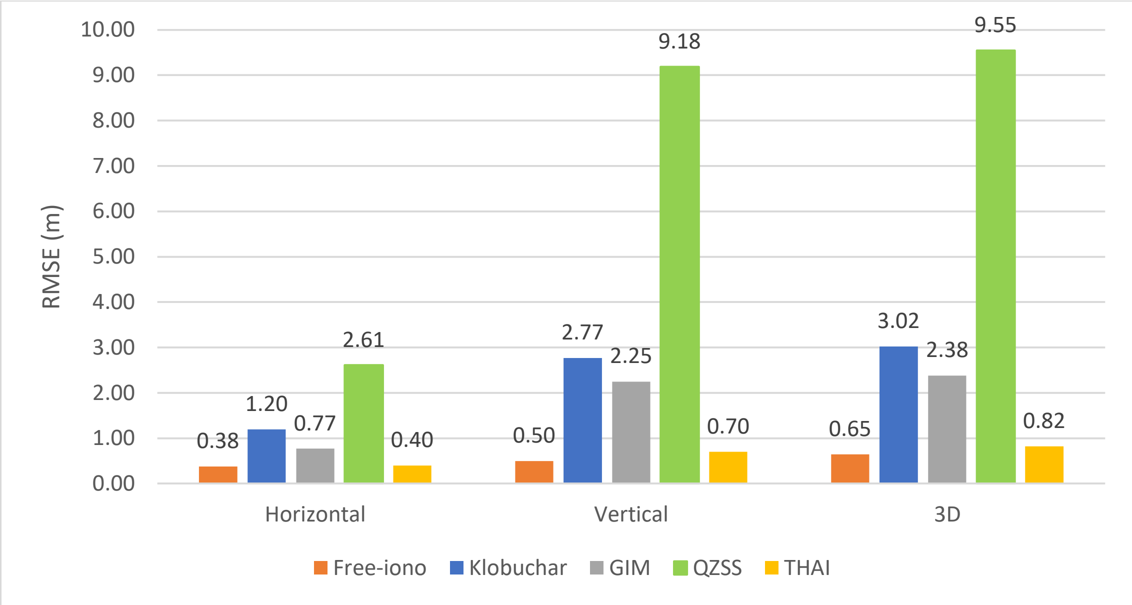

Figure 5. Summary of the statistical results

Figure 5 show statistical summary and comparison results of the Horizontal, Vertical and 3D RMSE obtained when the ionosphere model of the Klobuchar, GIM, QZSS and THAI, and ionosphere-free linear combination of dual frequency are applied in comparisons with the reference coordinates at each station.

In terms of the horizontal RMSEs, it results the largest horizontal RMSE as of 2.61 m when the QZSS model is used in the estimation, followed by 1.20 m with Klobuchar model 0.77 m with GIM model, and 0.40 m with THAI model. This result is the smallest horizontal RMSE of 0.38 m with the Free-iono. In terms of the vertical RMSEs, the application of QZSS model results the highest vertical RMSE of 9.18 m, of 1.20 m with Klobuchar model of 0.77m with GIM model and of 0.40 m with THAI model, whilst the smallest of 0.50 m with the Free-iono combination. In terms of 3D RMSEs, the worse result is as of 9.55 m when the QZSS model is applied, 3.02 m with Klobuchar model, 2.38 m with GIM model and 0.82 m with THAI model whilst the Free-iono will provide the most accurate results as the 3D RMSE is the smallest as of 0.65 m.

Table 1. Summarises the statistical parameters for the positioning accuracy results

Statistical	Klobuchar			Free-iono			GIM			THAI			QZSS		
(m)	2D	H	3D	2D	H	3D	2D	H	3D	2D	H	3D	2D	H	3D
Min	0.02	0.02	0.02	0.05	0.00	0.05	0.01	0.11	0.11	0.00	0.01	0.01	0.04	0.01	0.05
Max	3.14	5.70	6.53	0.87	1.38	1.64	2.46	4.87	5.52	1.66	1.77	2.45	6.79	28.99	29.79
Mean	0.99	2.44	2.64	0.34	0.41	0.55	0.65	2.04	2.14	0.32	0.61	0.71	2.13	6.89	7.22
RMSE	1.20	2.77	3.02	0.38	0.50	0.65	0.77	2.25	2.38	0.40	0.70	0.82	2.61	9.18	9.55

Table 1 summarises the statistical parameters, including the mean, maximum, minimum and RMSEs for the positioning accuracy determination from the single-frequency observations obtained by applying the Klobuchar, GIM, QZSS and THAI, and from ionosphere-free linear combination of dual frequency. They are compared with the positioning determination results from reference coordinates at each examined station. It can be seen that the overall positioning accuracy of THAI model is superior to that other model as of single frequency observations. Comparison of THAI model with Free-iono of dual frequency shows that the positioning accuracy of the two is similar. In case of THAI model, RMSEs is 0.40, 0.70 and 0.82 m in horizontal, Vertical and 3D, respectively. In case of Free-iono, RMSEs is 0.38, 0.50 and 0.65 m in horizontal, Vertical and 3D, respectively. However, in the test of statistical hypothesis, there were significant differences.

5. Conclusion and future works

According to this paper, GPS observations from 11 reference stations across Thailand have been processed using the Bernese GPS software version 5.0 to develop the Ionosphere model (named THAI). In order to validate the developed model, the positioning accuracy for another set of stations (named examined stations) have been estimated and compared with those ionosphere model of the Klobuchar model, Global Ionosphere Maps (GIM), Ionosphere Model from QZSS and ionosphere-free linear combination from dual frequency observations. The result proves that the local ionosphere model produces the most accurate positioning results and they are similar to the results obtained from an ionosphere-free linear combination but with significant differences. This research uses GPS-only data to create ionosphere model for Thailand due to the reference station could only receive data from GPS satellites. Other navigation satellite constellation observed data such as GLONASS, Galileo and BeiDou can also be used to create local ionosphere model. This research could obtain half a year observation data due to the loss of data. It would be more useful if up to one year or several years observed data are available in order to cover different weather conditions and if the number of reference stations are increased in order to have dense area-based observed data to create models to cover more space.

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