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Comparison of GPS Positioning Accuracy UsingKlobucharModel andIGS TEC Modelin Thailand

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Abstract

In global positioning system (GPS), ionospheric delay is a dominant source of errors causing degradation in positioning accuracy. To compensate for the ionospheric delay, Klobuchar model is a well-known model which is currently used for civilian single-frequency GPS receiver. The coefficients of the model are broadcast daily in the GPS satellite navigation message for worldwide users. However, its accuracy can be alternatively improved by the total electron content (TEC) data provided by the International GNSS Service (IGS).In this work, we compare the ionospheric delays from the Klobuchar model with the TEC IGS modelat Chiang Mai, KMITL and SuratThani stations in Thailand during 2014.The results show that the maximum difference of about 6.25 meters occurs at Chiang Mai station. We then compare the receiver positioning errors when these two ionospheric delay compensations are applied at various seasons. The results show that the IGS TEC compensation gives more improvement than the Klobuchar compensation. The maximum percentage reduction of 95% error is 42.311% with IGS TEC compensation. The accuracy in June and December solstice is lower than March and September equinox. The positioning errors at the low-latitude stationarefound to be lower than the high-latitude station.

Keywords: Positioning accuracy, Ionospheric delay, Global positioning system.

1. Introduction

Global Positioning System (GPS) is the satellite based radio navigation system with32 satellites orbiting at the altitudes of about 20,000 km from the Earth [1]. GPS is widely available for various civilian applications such as aeronautical navigation, transportation tracking, surveying, meteorology and others. The GPS signals provide the navigation data, time correction and broadcast parameters. Since GPS applications are mostly related to position estimation, the accuracy and precision are important parameters. The GPS signals are transmitted from GPS satellites through the atmosphere to an antenna causing delays.

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To estimate the position of GPS receiver, we need to know the code measurements between satellites and a receiver computed from the GPS signals. It requires that at least four GPS satellites be visible to the receiver. The three-dimensional receiver position is computed by the iterative least square method [2-3]. The measurement errors depend on observation errors, receiver errors and satellite errors [4]. Theobservation errors are related to pseudorange and signal delay. The receiver errors, on the other hand, are related to receiver clock, receiver bias, and others, while the satellite errors are from satellite clock, satellite orbit.The GPS signals are refracted and propagated by atmosphere introducing inaccurate pseudo range measurement [5]. The ionospheric delay is a dominant source of errors in GPS positioning. The ionosphere is an ionized region of the upper layer of the earth's atmosphere. The ionosphere delay depends on total electron content (TEC) during the GPS signal passing through this region to a receiver. Thailand is located in the EIA (Equatorial Ionospheric Anomaly) region at ±15˚ latitude from the magnetic equator where ionospheric disturbance often occurs. The International GNSS Service (IGS) generates the TEC maps in the Ionosphere map Exchange (IONEX) format. The vertical TEC data cover area from ±87.5° latitude and ±180° longitude. The IGS provides the highest quality data from over 400 permanent GNSS station network [6]. The empirical TEC models: Neustrelitz TEC Model (NTCM) and Klobuchar model in comparison with IGS TECare the best models with low solar flux values above Europe and North America [7], however, the ionospheric delay is compensated using the model. The ionospheric delay can be estimated by the Klobuchar model using parameters broadcast by GPS satellites [8]. It is a simple empirical model for single-frequency GPS receiver. The delay of each satellite depends on GPS receiver positions, elevation angles, azimuths and local times [9]. The estimated ionospheric delay from GPS signals are compared with Klobuchar and IRI-2007 model in India during 2006 and found that the IRI-2007 model gives closer estimates to the delays from observed data [10]. Nevertheless, the Klobuchar model has been used to compensate for the ionospheric errors [11,12]. It is shown that, after applying the Klobuchar model to GPS positioning analysis in Japan, the vertical accuracy is improved for about 4 to 5 meters, but the horizontal positioning errors are hardly changed [11]. The horizontal errors with the applied Klobuchar model during high solar activity periods are larger than low solaractivity periods. Furthermore, the forecasting ionospheric delay by Winter's method provides the highly correlated value with observation data in Chiang Mai province [12]. Thus it is possible to use ionospheric correction for single GPS receiver in Thailand [13].

In this work, we estimate ionospheric delay which is obtained from the Klobuchar model and IGS TEC data at Chiang Mai, KMITL and SuratThani stations in Thailand. Then, we compute the position errors with and without ionospheric delay and compare receiver position errors. The theoretical background on pseudorange equation to estimate the GPS receiver position is described in Section 2. In Section 3, we explain methodology and models. The results and discussions are in section 4. Finally, the conclusions are made in the last section.

2. Theoretical Background and Methods

2.1 Pseudorange equation

A simple model for the pseudorange (P^k) measurement between the k^{th}satellite and a receiver is [14]

$$P^k = \rho^k + c(dt_i - dT^k) + I^k + T^k + S^k + \varepsilon^k \tag{1}$$

where$c$isvelocity of light, dt_i and dT^k are thei^{th} receiver and the k^{th} satellite clock errors, respectively, I^k is ionospheric delay, T^k is tropospheric delay, S^k is the Sagnac effect, ε^k is multipath and noise which are not considered because the antenna is situated on the rooftop of a tall building. The true range (ρ^k) between the k^{th} satellite and a receiver can be computedm

$$\rho_i^k = \sqrt{(x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2} \tag{2}$$

Where(x^k, y^k, z^k) is the position of the k^{th} satellite and (x_i, y_i, z_i) is the estimated receiver position.

2.2Position estimation

There are 4 unknowns, i.e. x_i, y_i, z_i and dt_i in Eq. (2). We estimate the receiver position and receiver clock error by using the least square method. Therefore, Eq. (2) needs to be expressed in the linear equation. Assuming the initial receiver position (x_0, y_0, z_0) at the center of the earth (0, 0, 0),let i be the iteration number, the position estimation can be computed iteratively from

$$\begin{aligned} x_{i+1} &= x_i + \Delta x_i \\ y_{i+1} &= y_i + \Delta y_i \\ z_{i+1} &= z_i + \Delta z_i \end{aligned} \tag{3}$$

The terms $\Delta x_i, \Delta y_i, \Delta z_i$ are unknowns. The Taylor's series of $f(x_i + \Delta x_i, y_i + \Delta y_i, z_i + \Delta z_i)$ [4] can be expanded as

$$\begin{aligned} f(x_{i+1}, y_{i+1}, z_{i+1}) = f(x_i, y_i, z_i) + \frac{\partial f(x_i, y_i, z_i)}{\partial x_i}\Delta x_i + \frac{\partial f(x_i, y_i, z_i)}{\partial y_i}\Delta y_i + \\ \frac{\partial f(x_i, y_i, z_i)}{\partial z_i}\Delta z_i + \frac{1}{2!}\frac{\partial^2 f(x_i, y_i, z_i)}{\partial x_i^2}\Delta x_i^2 + \ldots \end{aligned} \tag{4}$$

We truncate the Taylor's series after the first order term, so the partial derivatives become

$$\frac{\partial f(x_i, y_i, z_i)}{\partial x_i} = -\frac{x^k - x_i}{\rho_i^k},\ \frac{\partial f(x_i, y_i, z_i)}{\partial y_i} = -\frac{y^k - y_i}{\rho_i^k},\ \frac{\partial f(x_i, y_i, z_i)}{\partial z_i} = -\frac{z^k - z_i}{\rho_i^k}. \tag{5}$$

From Eq. (2), the linearized pseudorange equation become

$$P^k = \rho_i^k - \frac{x^k - x_i}{\rho_i^k}\Delta x_i - \frac{y^k - y_i}{\rho_i^k}\Delta y_i - \frac{z^k - z_i}{\rho_i^k}\Delta z_i + c(dt_i - dT^k) + I^k + T^k + S^k + \varepsilon^k. \tag{6}$$

Let

$$l^k = P^k - \rho_i^k + c\left(dT^k\right) - I^k - T^k - S^k \tag{7}$$

and

$$a_{x_i}^k = -\frac{x^k - x_i}{\rho_i^k}, a_{y_i}^k = -\frac{y^k - y_i}{\rho_i^k}, a_{z_i}^k = -\frac{z^k - z_i}{\rho_i^k} \tag{8}$$

When Eq. (7) was rearranged, and the ε^k term was ignored, we obtain

$$l^k = a_{x_i}^k \Delta x_i + a_{y_i}^k \Delta y_i + a_{z_i}^k \Delta z_i + c\left(dt_i\right). \quad (9)$$

In the matrix form, Eq. (9) can be written as

$$\begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ \vdots \\ l^k \end{bmatrix} = \begin{bmatrix} a_{x_i}^1 & a_{y_i}^1 & a_{z_i}^1 & c \\ a_{x_i}^2 & a_{y_i}^2 & a_{z_i}^2 & c \\ a_{x_i}^3 & a_{y_i}^3 & a_{z_i}^3 & c \\ \vdots & \vdots & \vdots & \vdots \\ a_{x_i}^k & a_{y_i}^k & a_{z_i}^k & c \end{bmatrix} \begin{bmatrix} \Delta x_i \\ \Delta y_i \\ \Delta z_i \\ dt_i \end{bmatrix} \quad (10)$$

or

$$\mathbf{L}=\mathbf{AX} \quad (11)$$

Where **L** is a vector of *k* observations (must have at least 4 elements),**A** is a matrix of linear function (design matrix) with *k*×4 dimensions and **X** is the vector of the unknowns. Using the least square method, we obtain

$$\mathbf{X} = (\mathbf{A}^{\mathrm{T}}\mathbf{A})^{-1}\,\mathbf{A}^{\mathrm{T}}\mathbf{L}. \quad (12)$$

Once Δx_i, Δy_i, Δz_i are found, the estimated receiver position are obtained from Eq. (3).

2.3 Klobuchar model

The Klobuchar model is used to compensate for the ionosphere delay. This simple model is based on an empirical approach. The GPS satellites broadcast the coefficients of the Klobuchar model for estimating ionospheric delay with single frequency users. In this work, we calculate the ionospheric delay by using the Klobuchar model following thesteps in [15]. The vertical ionospheric time delay (I_{L1}) is given by

$$I_{L1} = \begin{cases} \left[5\cdot 10^{-9} + A_I \cdot \left(1 - \frac{X_I^2}{2} + \frac{X_I^4}{24}\right) \right] & ;\left|X_I\right| \le 1.57 \\ 5\cdot 10^{-9} & ;\left|X_I\right| > 1.57 \end{cases} \quad (13)$$

where$A_I$is the amplitude of ionospheric delay, X_I is the phase of the ionospheric delay. Therefore, the ionospheric range delay ($I_{Klobuchar}^k$) can be expressed as

$$I_{Klobuchar}^k = I_{L1} \times c \quad (14)$$

where*c* is velocity of light.

2.4 IGS TEC data

The IGS TEC data is collected and distributed by the International GNSS Service (IGS) and it is used to generatevertical TEC map in the IONEXformat. We can calculate the ionosphere delay (I) from TEC data as follows:

$$I = \frac{40.3}{f^2}\text{TEC} \tag{15}$$

The GPS signal delay from ionosphere depends on TEC and GPS frequency. For example of L1 frequency, the ionosphere delay with 1 TECU (1 TECU = 10^{16} electrons/m^2) is about 16 centimeters. The IGS data can be downloaded from the FTP site: ftp://cddis.gsfc. nasa.gov/pub/gps/products/ionex/.

3. Results and Discussion

The raw data are collected from the GPS station at King Mongkut's Institute of Technology Ladkrabang or KMITL (Bangkok: 13.7278ºN, 100.7726ºE) and 2 stations from Department of Public Work and Town and Country Planning at CHMA (Chiang Mai: 18.8368ºN, 98.9705ºE), SRTN (SuratThani: 9.1322ºN, 99.3314ºE) in Thailand.We convert the raw data tothe RINEX (Receiver Independent Exchange Format)which includethe observation data, navigation data and Klobuchar coefficients. For this work, we select the data obtained in March equinox, June solstice, September equinox and December solstice, 2014 with the elevation mask of 5 degrees.

In Figure 1, we show the monthly median of ionospheric delay obtained from the Klobuchar model with L1 frequency and the IGS TEC at 3 stations.The horizontal axis represents the universal time (UT), and to convert to the local time, we need to add 7 hours to the UT. In addition, in terms of the seasonal variation, the delay, which is proportional to the total electron content (TEC) is higher during the equinox season than the winter/summer season due to the higher solar strengths. The satellite delay is generally at higher during daytime than nighttime due to higher ionization levels resulting from the sun energy. The ionospheric delay from the Klobuchar model generally underestimates the IGS TEC, butit overestimates the IGS TEC in the early morning.At CHMN station, the maximum ionospheric delay difference is6.255 meters in March equinox during daytime. The ionospheric delays from IGS TEC are about 2.793 to 17.780 meters in equinox and they are about 1.494 to 12.616 meters in solstice. At KMITL station, the maximum ionospheric delay difference is5.889 meters in March equinox during nighttime. The ionospheric delays from IGS TEC areapprox. 2.046to 16.781 meters in equinox and they areapprox1.624 to 12.746 meters in solstice. At SRTN station, the maximum ionospheric delay difference is5.158 meters in March equinox during nighttime. The ionospheric delays from IGS TEC areapprox 2.907 to 14.029 meters in equinox and they areapprox.1.267 to 9.840 meters in solstice. For seasonal variation, the ionospheric delay in equinox is more than solstice. The ionospheric delays from IGS TEC are close to those from the Klobuchar model at the STRN stationin solstice.

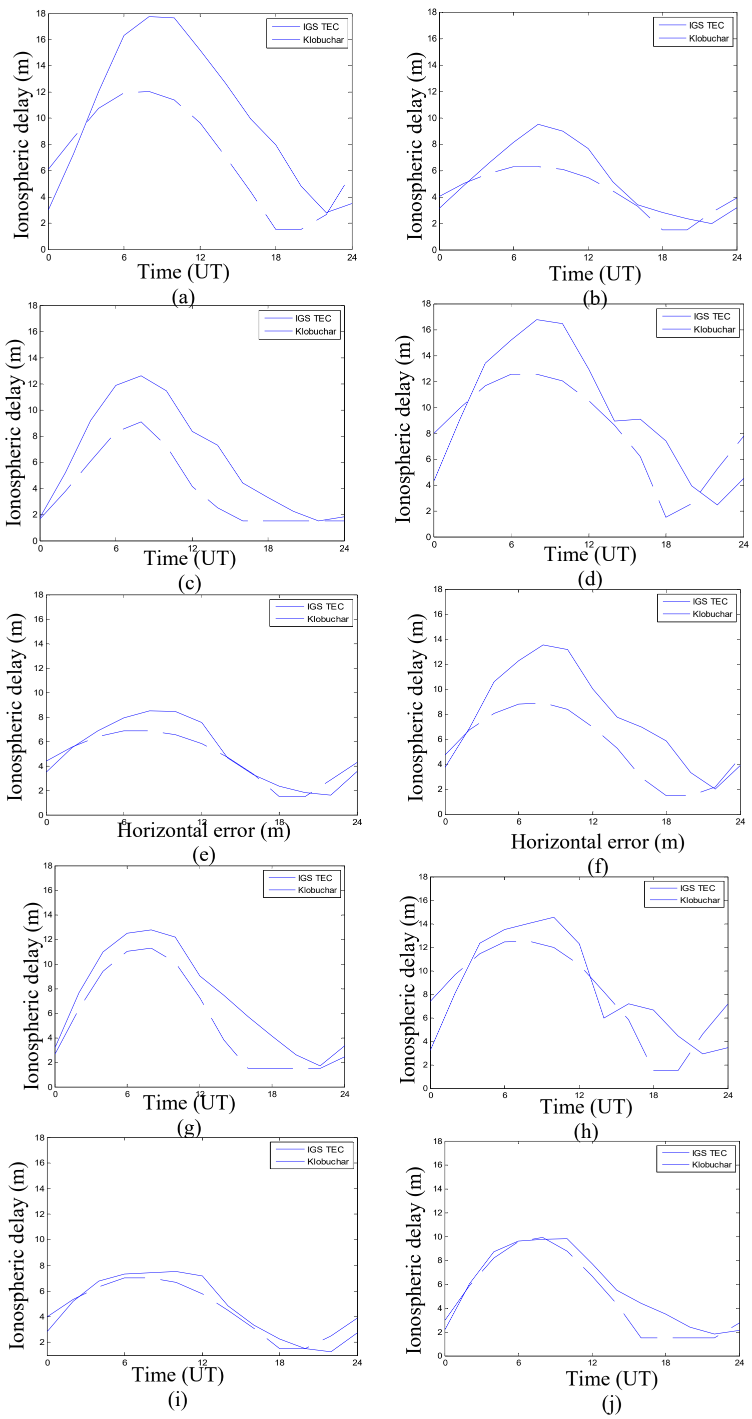
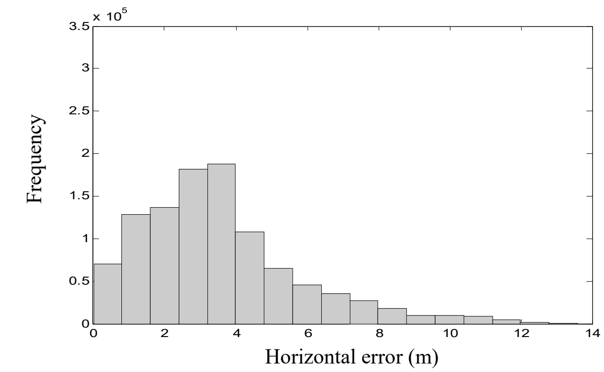
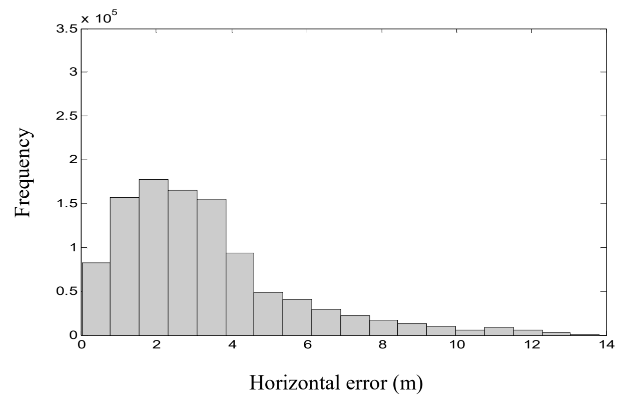


Figure 1. Comparison of monthly median ionospheric delay at 3 stations in March, June, September and December 2014.(a)CHMA, March equinox, (b) CHMA, June solstice, (c) CHMA, December solstice, (d) KMITL, March equinox, (e) KMITL, June solstice, (f) KMITL, September equinox, (g) KMITL, December solstice, (h) SRTN, March equinox, (i) SRTN, June solstice and (j) STRN, December solstice.

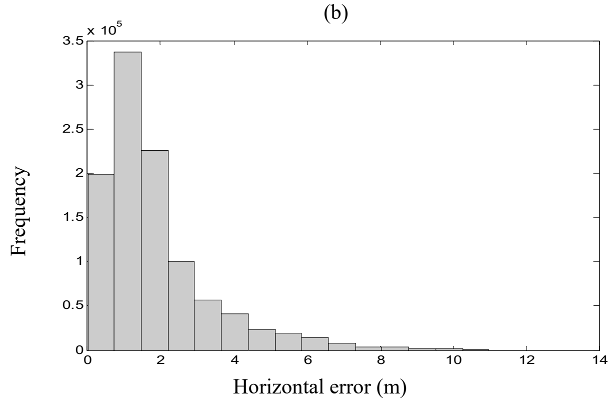
The GPS receiver positions of 3 stations are estimated by the least square method. We show the horizontal error histograms at KMITL station in March equinox, 2014 with and without ionospheric delay compensations from the Klobuchar model and IGS TEC data as shown in Figure 2. The results show the frequency of horizontal errors for the case without ionospheric delay compensation, with Klobuchar and IGS TEC compensation are about 3.0, 2.0 and 1.0 meters respectively.



(a)



(b)



(c)

Figure 2. The horizontal error histogram at KMITL station in March equinox, 2014. (a) without ionospheric delay compensation, (b) with Klobuchar compensation and (c) with IGS TEC compensation.

Therefore, the IGS TEC compensation gives better improvement in the positioning accuracy than the uncompensated case and the compensation with the Klobuchar model. Then, we compute the statistics of the horizontal errors at 3 stationsat various seasons and show the standard deviation (STD) of the horizontal error and the 95% error in Table 1. The 95% error is defined as the amount of horizontal error at the 95% of total samples points counting from the leftmost error of the histogram. Thestandard deviation (STD) in solstice is lower than that in equinox at each station. At CHMN station, the lowest STD is 0.737 meter with the IGS TEC compensation in June solsticeand the highest STD is 2.642 meters with the Klobuchar compensation in March equinox. At KMITL station, the lowest STD is 0.602 meter with the IGS TEC compensation in June solstice and the highest STD is 2.316 meters with the Klobuchar compensation in March equinox. At SRTN station, the lowest STD is 0.547 meter with the IGS TEC compensation in June solstice and the highest STD is 1.208 meters with the Klobuchar compensation in March equinox.

Table 1. Statistical Horizontal Errors at 3 stations

		Statistical Horizontal Errors							
Station	Ionospheric delay	March		June		September		December	
		STD (m)	95% error (m)	STD (m)	95% error (m)	STD (m)	95% error (m)	STD (m)	95% error (m)
CHMA	Without Iono. compensation	2.639	8.277	0.947	3.475	no data	no data	1.823	6.030
	With Klobuchar compensation	2.642	7.992	0.951	3.409	no data	no data	1.608	5.385
	With IGS TEC compensation	1.578	4.951	0.737	2.575	no data	no data	1.197	3.947
KMITL	Without Iono. compensation	2.230	7.667	0.936	3.396	1.748	5.861	1.727	5.721
	With Klobuchar compensation	2.316	7.409	0.874	3.100	1.822	5.599	1.690	5.229
	With IGS TEC compensation	1.503	4.423	0.602	2.172	1.595	4.685	1.156	3.528
SRTN	Without Iono. compensation	1.271	4.571	0.725	2.742	no data	no data	0.881	3.226
	With Klobuchar compensation	1.208	4.293	0.735	2.753	no data	no data	0.859	3.063
	With IGS TEC compensation	1.166	3.523	0.547	1.960	no data	no data	0.617	2.291

The 95% horizontal error in solstice is also lower than the 95% horizontal error in equinox. At CHMN station, the lowest 95% error is 2.575 meter with the IGS TEC compensation in June solstice and the highest 95% error is 7.992 meter with the Klobuchar compensation in March equinox. At KMITL station, the lowest 95% error is 2.172 meter with IGS TEC compensation in June solstice and the highest 95% is 7.409 meter with Klobuchar compensation in March equinox. At SRTN station, the lowest 95% error is 1.960 meter with IGS TEC compensation in June solstice and the highest 95% error is 4.293 meter with Klobuchar compensation in March equinox. Furthermore, the STD and 95% error decrease where station is lower latitude for all seasons.

When compared with Klobuchar and IGS TEC compensation, the 95% error with IGS TEC compensation is lower than 95% error with Klobuchar compensation at all stations. The maximum percentage reduction of 95% error is 10.697% in December at CHMN stationfor the case with Klobuchar compensation. The maximum percentage reduction of 95% erroris42.311% in March equinox at KMITL stations for the case with IGS TEC compensation.

4. Conclusions

In this work, we analyze the ionospheric delay by using the Klobuchar model and the IGS TEC at CHMN, KMITL and SRTN stations in2014. According to the results, the ionospheric delay from the Klobuchar model generally underestimates the IGS TEC.The maximum difference is about6.255 meters at CHMN stationin equinox and it is similar at SRTN station in solstice. The ionospheric delay varies in seasonal and the delay in equinox is higher than solstice.The positioning accuracy using the ionospheric delay based on the IGS TEC is better than the Klobuchar model. The maximum percentage reduction of 95% error with the IGS TEC compensation is 42.311% at KMITL station while the corresponding maximum percentage reduction of 95% error with the Klobuchar compensation is 10.697%at CHMN station.For seasonal variation, the STD and 95% error in solstice is lower than equinox.The STD and 95% error at the low-latitude station is lower than the high-latitude station for all seasons in Thailand.

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