Effects of Equatorial Plasma Bubbles over Real-Time Kinematic Positioning in Low-Latitude Region

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Biography

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Abstract

Equatorial plasma bubbles (EPBs) refer to local ionospheric irregularity in low-latitude regions after sunset. They originate at the magnetic equator and then potentially spread to mid-latitude regions. As cm-level positioning techniques are increasingly important to various segments of society, the performance degradation of these systems due to EPB at low latitudes need to be investigated. In this work, we study the EPB effects on the performances of real-time kinematic (RTK) positioning at the short, medium, and long baselines at low-latitude stations in Thailand. We use the kinematic positioning mode provided by the free and open-source software (FOSS) package called RTKLIB and analyze the positioning errors. We observe the statistics of low-latitudes local ionospheric events such EPBs can affect the kinematic positioning and how much they can degrade the positioning accuracy at different seasons in 2022. It is found that the positioning errors are higher during the disturbance periods and more severe at the long baselines than the shorter ones, especially during the equinoctial periods.

1. INTRODUCTION

Global Navigation Satellite System (GNSS) is a satellite navigation system in which earth-orbiting GNSS satellites, ground control stations, and receivers are employed to determine the positions on earth (Parajuli, 2020). Many factors can affect the GNSS positioning accuracy such as satellite and receiver clock offsets, satellite and receiver biases, pseudorange errors, and delays in the ionosphere and troposphere (Saito et al., 2017). Among these errors, the propagation delay of GNSS signals due to the ionosphere is one of the most significant sources of ranging errors, but it can be corrected (Jacobsen & Dähnn, 2014). The ionospheric irregularities affect the HF radio propagation path calculation and degrade the positioning accuracy in GPS (Watthanasangmechai et al., 2012). The electron total content (TEC) in the ionosphere is one of the most important parameters that are typically analyzed; its variation is due to solar activity, seasons and time of day. Typically, TEC is higher during the daytime and lower during the nighttime.

But the disturbed ionospheric condition can also occur during the after-sunset and nighttime periods, especially in the equatorial region due to Equatorial Plasma Bubbles (EPB). The EPB can cause uneven variation of TEC and, as a result, the performances of the positioning system including kinematic positioning are degraded. Real-time kinematic (RTK) positioning offers centimeter-level positioning, which is widespread in today's technology (He et al., 2014). The RTK technology requires one more base stations to broadcast error correction to the rover stations (users). Rovers determine their positions using algorithms that incorporate ambiguity resolution and differential correction. The position accuracy achievable by the rover depends on, among other things, its distance from the base station called baseline (NovAtel Inc., 2015).

There are some previous studies about ionospheric effects on positioning performance. In (Jacobsen & Schäfer, 2012), the researchers noticed that the positioning errors increase exponentially with increasing ROTI and the standard deviation of errors increases from less than 10 cm to 3 m during the disturbed period since the RTK positioning system cannot provide the fixed solution. The global-scale study on the effects of ionospheric disturbances over Kinematic GPS positioning during the 2015 St. Patrick's Day geomagnetic storm events is also presented in (Yang et al., 2020). According to the observations, this storm severely increases the PPP positioning errors in high latitudes up to 10 m and moderately degrades the PPP performance in mid-latitude at 2 m. Another study on implication of ionospheric disturbances for precise GNSS positioning in Greenland during St. Patrick's Day storm is also presented in (Paziewski Jacek et al., 2022). The researcher observe a significant impact of ionospheric disturbances on the integer ambiguities resolution significantly degrading the accuracy of float RTK positioning as well as minor accuracy decrease in float solution during disturbed period. For single-frequency iono-free precise point positioning, ionospheric disturbance does not have impact on ambiguity resolution and accuracy. In (Bae & Kim, 2018), a performance analysis of Network-RTK technique for drone navigation considering ionospheric conditions in Korea is presented. The researcher performed the experiments during strong geomagnetic activities based on Kp-index and the RTK positioning performance can still provide sub-meter level. There is also another study on I95 ionospheric disturbance index for providing statistical information on expected residual ionospheric bias for helping RTK users on 7-year data (Wanninger, 2004).

However, global geomagnetic activities do not always cause the disturbances in local ionosphere and the phenomenon of the ionosphere is different in low latitudes due to the locally disturbed events caused by Equatorial Plasma Bubbles (EPBs) occurring after post-sunset, especially during the equinox. There are still less studies on effect of ionospheric disturbance over RTK at low-latitude region. Since Thailand is located on the magnetic equator, we can expect frequent and severe occurrences of EPB, especially during the solar maximum and ascending phase. So, in this work, we analyze the performance of kinematic positioning in the Bangkok area in 2022, the ascending phase of the solar cycle #25 in the short, medium, and long baseline. In addition, the relationship between positioning errors and ROTI is highlighted.

2. RELATED THEORIES

2.1. Ionospheric disturbances in low latitude region

Ionospheric disturbances are caused by global or local phenomena. The geomagnetic storm resulting from the solar flares affects the global ionosphere. It can be evaluated using a number of indices such as the Kp-Index and Disturbance Strom Time Index (Dst). The Kp-index is used to describe the disturbance of the Earth's magnetic field caused by the solar wind (Matzka et al., 2021). The index ranges from 0, for low activity, to 9, for high activity which may be caused by geomagnetic storms. However, global parameters do not always cause disturbances in the local ionosphere at low latitudes, equatorial plasma bubbles (EPB) is often referred to as ionospheric irregularities after sunset due to the Rayleigh-Taylor instability (Kelley, 1989). Since the electron density inside the EPB is very low, the ionospheric delay on nearby satellite-receiver paths may vary drastically depending on whether they travel through EPB or not.

One of the parameters to determine the local ionospheric disturbances is the Rate of TEC change Index (ROTI) (Pi et al., 1997). ROTI is the standard deviation of the Rate of TEC (ROT) during an interval of time, generally in 5-min time intervals. The ROTI index can be expressed as

$$ROTI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(ROT(i) - ROT)^2}\ , \qquad (1)$$

where *ROT* is the difference in Slant Total Electron Content (STEC) during a time interval which can be obtained from

$$ROT(i) = STEC(i+1) - STEC(i)\ , \tag{2}$$

where $STEC(i+1)$ and the $STEC(i)$ denotes STEC at epochs i and $(i+1)$.

2.2. Kinematic Positioning

Kinematic Positioning is a relative positioning method based on the code pseudorange and carrier phase measurements of the GNSS signal (Luo et al., 2016). Real-time kinematic positioning (RTK) is a type of relative positioning that can provide centimeter-level accuracy (Bisnath, 2020). In RTK, it includes two receivers: one is used as base station and the other is the rover station. Base station which already knows its precise location, so the location rover station can be computed with relative to base station measurement. The standard model of kinematic positioning is based on the double-differenced carrier phase and code data for each frequency (*RTKLIB Ver. 2.4.2 Manual*, 2019)

The double-difference measurement of code and carrier-phase including tropospheric and ionospheric delay can be expressed as

$$\emptyset_{rb,i}^{jk} = \rho_{rb}^{jk} - I_{rb,k}^{jk} + T_{rb}^{rk} + \lambda_i\left(B_{rb,i}^{j} - B_{rb,i}^{k}\right) + d\phi_{r,i}^{s} + \varepsilon_{\phi} \tag{4}$$

$$P_{rb}^{jk} = \rho_{rb}^{jk} - I_{rb,k}^{jk} + T_{rb}^{rk} + \varepsilon_{\phi} \tag{5}$$

Extended Kalman Filter is applied to obtain the solution by unknown state vector x for dual-frequency receiver as

$$x = (r_r^T, v_r^T, Z_r, G_{E,r}, Z_b, G_{E,b}, I^T, B_1^T, B_2^T)^T \tag{6}$$

where r is the rover's position, v is the receiver's velocity in ECEF (m/s), Z is the zenith total delay, G is the tropospheric delay gradient, I is the ionospheric delay and B is the carrier-phase bias.

The model is solved using a Kalman filter implementation, which produces a "float" solution, i.e., a solution for the position and ambiguities without integer constraints. These ambiguities are kept constant in time in the Kalman prediction step. The receiver position is not predicted but solved in "full kinematic" mode for every epoch. To handle the nonlinear model, the Kalman measurement update contains an iterative procedure. The fixed solution, based on integer ambiguities, is computed once sufficient epochs are accumulated. The fixed solution is only accepted if it passes the ratio test by LAMDBA method. In some cases, these ambiguities cannot be fixed resulting in float solution only.

To evaluate the positioning performance, horizontal positioning error (HPE) and vertical positioning error (VPE) a can be computed from the user position by RTK (latitude, longitude, height) in Geodetic coordinate, comparing to precise reference position of user (true position).

VPE can simply be computed from the difference of height between RTK position and true position.

$$VPE = height_{RTK\ Position} - height_{True\ Position} \tag{7}$$

HPE can be computed from the difference of latitude between RTK positioning $l$and True Position (ΔlatDifferene) and longitudinal difference between RTK positioning and true positioning (ΔlonDifferene) as followed.

$$a = sin^2\left(\frac{\Delta latDifference}{2}\right) + \cos(lat_{RTK})\cos(lat_{True})\,.\,sin^2\left(\frac{\Delta lonDifference}{2}\right) \tag{8}$$

$$c = a.atan2(\sqrt{a}, \sqrt{1-a}) \tag{9}$$

$$HPE = R.c \tag{10}$$

where R is the radius of earth (6371 km).

3. METHODOLOGY

In this study, we analyze the effects of ionospheric disturbances on the GPS kinematic positioning technique with different baseline lengths between the base and rover station near Suvarnabhumi Airport, Bangkok Thailand. Three station pairs are used to study the various baseline lengths of 4 km, 12 km, and 21 km respectively. RTKLIB is used to analyze the positioning errors of the rover station. The elevation angle mask of 15° ensures a sufficient number of visible satellites and avoids multi-path errors. At each baseline length, we analyze the positioning errors based on 1-second observation data of disturbed days determined by ROTI.

4. RESULTS AND DISCUSSIONS

We evaluate the RTK positioning performances at different baseline lengths. The computed positioning errors of 12 km baseline length in DOY 314, 2022 are shown in Figure 1 as well as the scatter plot between the standard deviation of positioning error and ROTI in Figure 2. On that day, the percentages of fixed and float solutions are 89.1 and 10.9 percent for the 4 km short baseline, 67.5 and 32.5 percent for the 12km medium baseline, and 45.3 and 54.7 percent for the 21km long baseline, respectively. We observed that the positioning errors significantly increase during the disturbed hours from cm-level to m-level accuracy. The boxplots of 95-percent positioning error by RTK during daytime (quiet period) and nighttime (disturbed period) are shown in Figure 3. We can see that the horizontal and vertical errors of all baseline lengths are 5 times higher during the disturbed period. Importantly; the errors increase to meter-level (around 4 meters) accuracy. The horizontal and vertical errors of all baseline lengths are high during the disturbed period; the errors are even higher at longer baseline lengths due to lower percentages of the fixed solutions. We can also see the rapid fluctuation in the available usable satellites during severe ionospheric disturbed condition.

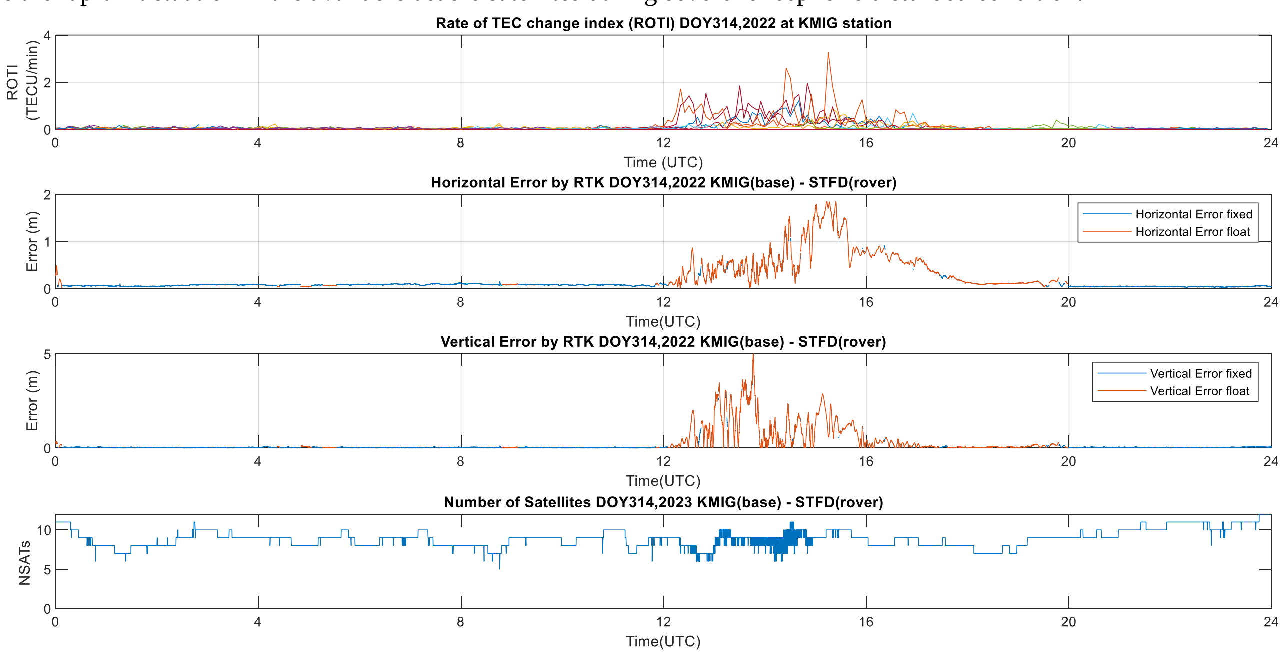

Figure 1. Positioning errors on DOY 314, 2022 at 12 km baseline length

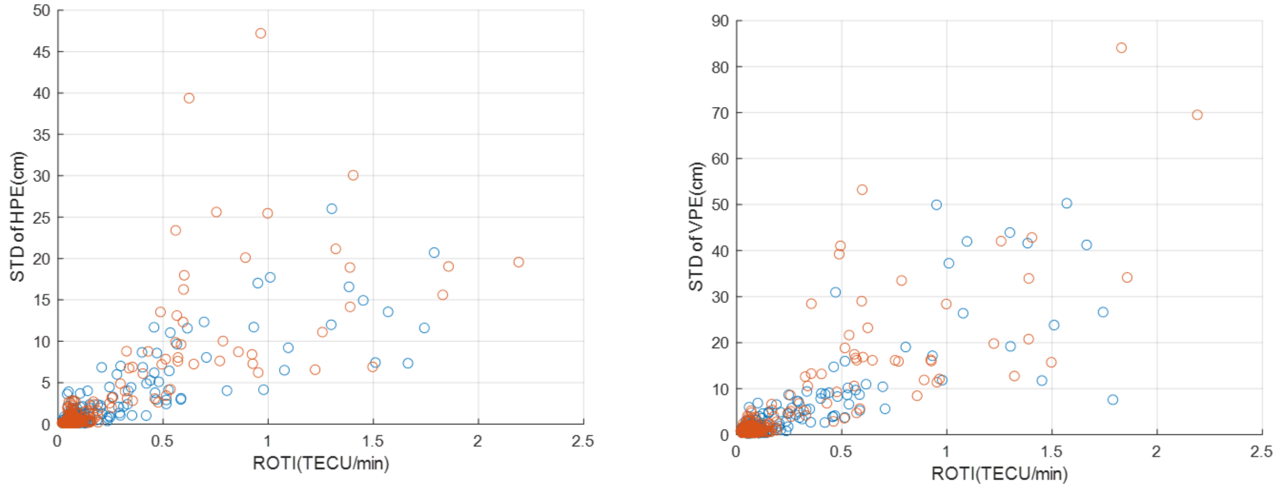

Figure 2. Positioning error by RTK with ROTI at 12km baseline length on DOY 296, 2022.

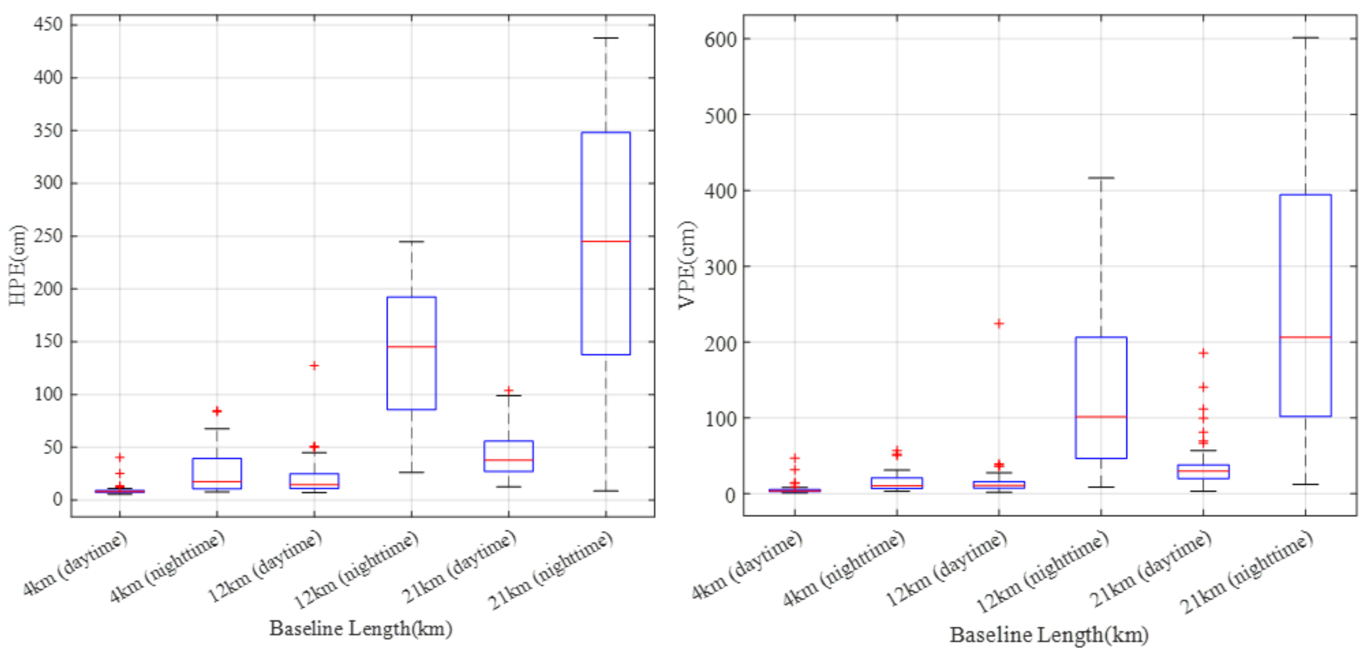

Figure 3. 95-percent Positioning errors by RTK at different baseline lengths in 2022.

The summary of overall nighttime positioning errors with Kp and ROTI index during the disturbed day of 2022 at baseline length of 12 km is shown in Figure 4. We notice that most of the high positioning errors occur at the equinox and high positioning errors are caused by local ionospheric events rather than global activities and the global geomagnetic activity (Kp) does not have much effect on local ionospheric conditions (ROTI) in Thailand region.

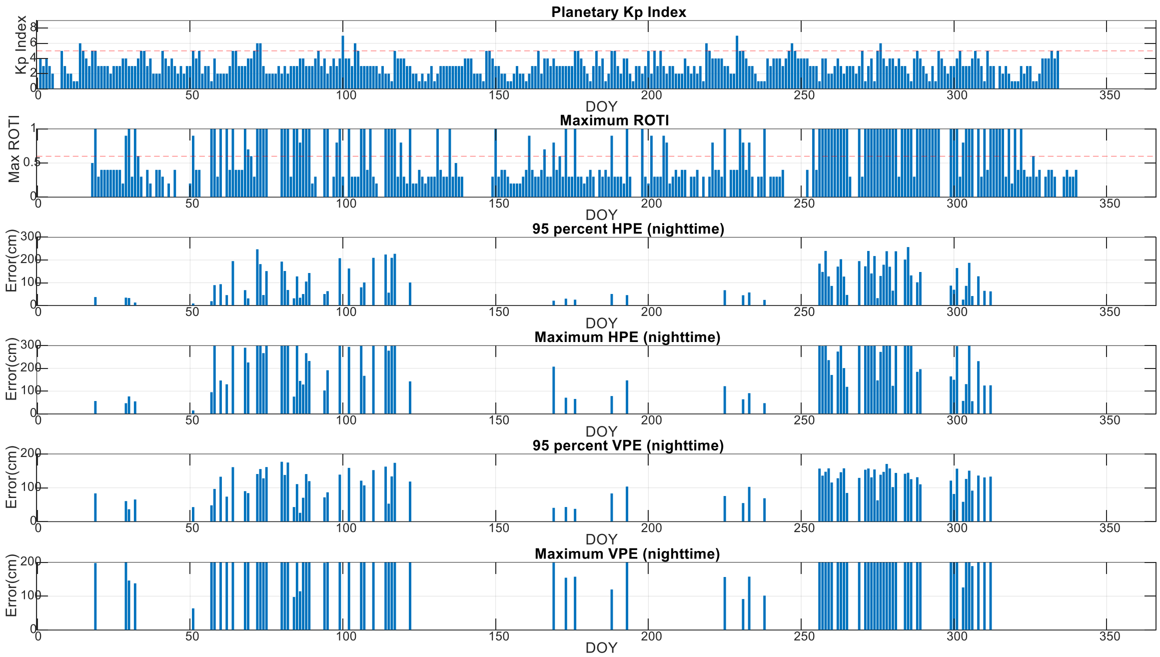

Figure 4. Summarized positioning errors of 2022 in 12km baseline length.

5. CONCLUSIONS

In this work, we analyze the RTK positioning performance at various baseline lengths in the low-latitude region. We observed that the positioning errors are high during the high ROTI conditions caused by ionospheric disturbed events and the errors are higher if the baseline lengths are longer significantly exceeding the cm-level accuracy. We can also conclude that severe degradation of RTK positioning performance can also be observed during the equinox caused by local ionospheric events such as EPBs in the low-latitude region. Since EPBs can significantly affect the RTK positioning performance in low-latitude regions, we need to improve the RTK accuracy during the ionospheric disturbed period in the future.

ACKNOWLEDGEMENT

We are thankful to the members of the Thai GNSS and Space Weather Information Data Center, Stamford International University and Aeronautical Radio of Thailand for providing GNSS Data, National Institute of Communication Technology (Japan) and Electronics Navigation Research Institute (Japan) providing the GNSS observation equipment. This work is supported by King Mongkut's Institute of Technology Research Fund (Grant no. KREF016422) and ASEAN IVO (http://www.nict.go.jp/en/asean_ivo/index.html) project, [GNSS and Ionospheric Data Products for Disaster Prevention and Aviation in Magnetic Low- Latitude Regions (Phase II)], was also involved in the production of the contents of this work and financially supported by NICT (http://www.nict.go.jp/en/index.html).

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