Investigation of the latitudinal occurrence rate of ionospheric plasma bubble in case of strong and weak pre–reversal enhancement in Southeast Asia

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Abstract. We used ionosonde and GPS receivers during March–April in 2004–2005 and 2011–2015 to investigate the latitudinal variation of equatorial plasma bubble (EPB) occurrence rate in cases of strong and weak pre-reversal enhancement (PRE). The ionosonde at Chumphon in Thailand was used to estimate the PRE strength. Ten GPS receivers in Southeast Asia, ranging from magnetic latitude (ML) of 4.4°S to 21.6°S, were used to investigate the latitudinal variation of EPB occurrence rate. In the case of strong PRE, the EPB occurrence rates decrease from 38.9% to 34.9% at ML of 4.4°S–7.2°S. Continuously, the occurrence rate increases and reaches the peak (44%) at ML of 9.3°S; afterward, the occurrence rate rapidly decreases and reaches below 5% at ML of 21.6°S. In the case of weak PRE, the occurrence rate decreases from 21.8% at ML of 4.4°S, seems constant (15.3%–16%) at ML of 8.2°S–12.1°S, and reaches less than 5% at ML of 16.1°S. Generally, the EPB occurrence rate and its latitudinal extension in case of strong PRE are higher than that in case of weak PRE. Interestingly, we found that the latitudinal occurrence rate peak of the EPB in case of strong is farther than that in case of weak PRE.

1. Introduction

The equatorial plasma bubble (EPB) refers to the depletion of plasma densities in the night time equatorial and low-latitude F-layer of the ionosphere. The EPB is generated by Rayleigh–Taylor instability (RTI) mechanism. One of the critical factors for the growth rate of RTI in the plasma bubble generation is the enhancement of the eastward electric field in the evening sector, known as the pre-reversal enhancement (PRE) [1,2,3,4]. Equation 1 shows the growth rate of RTI in the plasma bubble generation.

\[ \gamma = \left( \frac{g}{v_{in}} + \frac{E_0}{B} \right) \frac{1}{n_0} \frac{\partial n_0}{\partial z} \]  (1)

where \( \gamma \) is the growth rate of the instability, \( E_0 \) is the eastward electric field, \( g \) is gravitational acceleration, \( v_{in} \) is ion-neutral collision frequency, \( n_0 \) is plasma density, \( B \) is the magnetic field,
and \( \partial n_0 / \partial z \) is the altitudinal gradient density of the plasma. In Equation (1), \( E_0 \) represents the PRE. From equation (1), we can see that the growth rate of RTI will be tremendous if the PRE is large and small if the PRE is small. The PRE creates the vertical drift \( E \times B \) lifting the ionospheric F-layer to the high altitude where the factor of \( g / v_{in} \) becomes large, and thus the plasma bubble can be generated. The magnitude of PRE depends on various factors such as geomagnetic activity, solar cycle, season, and longitude [5].

The latitudinal variation of the EPB occurrence rate had been studied using different instruments such as ionosonde, GPS receiver, and in-situ measurement by satellite [6,7,8,9,10]. The study [6] utilized ionosondes and GPS receivers to investigate the effect of PRE on the latitudinal extension of the plasma bubble in Southeast Asia and disclosed that the magnitude of PRE has a good correlation with the latitudinal extension of the plasma bubble. By using the GPS receiver, the study [7] observed the latitudinal variation of the plasma bubble based on the height on the dip equator (HODE) parameter. The study [7] found that the EPB occurrence rates are almost constant below 600 km of HODE and smaller above 600 km of HODE. The study [8] studied the latitudinal variation of bubble occurrence using the Atmosphere Explorer E (AE-E) satellite. The study [8] discovered that the EPB occurrence rate is limited to about 20° on either side of the dip equator. Moreover, the study [9], using the Communication/Navigati...
Figure 1. Geographic locations of ionosonde (marked by the red circle) and GPS receivers (marked by red and black stars) that used in this study. GPS receivers characterized by red and black stars belong to Sumatran GPS Array (SuGAr) and International GNSS Service (IGS), respectively. The blue circle is the field of view at an altitude of 350 km for each GPS receiver with an elevation angle higher than 40°. The black line is the magnetic equator.

Table 1. GPS receivers used in this study

| Stations name | Stations code | Network | Geographic latitude Long (°) | Latitude Lat (°) | Magnetic latitude Lat (°S) |
|---------------|---------------|---------|-------------------------------|-----------------|--------------------------|
| Ujung Muloh   | UMLH          | SuGAr   | 95.3 E                        | 5.0 N           | 4.4                      |
| Pulau Balai   | PBLI          | SuGAr   | 97.4 E                        | 2.3 N           | 7.2                      |
| Pulau Sekuai  | PSKI          | SuGAr   | 103.3 E                       | 1.1 S           | 8.2                      |
| Air Bangis    | ABGS          | SuGAr   | 99.3 E                        | 0.2 N           | 9.3                      |
| Muko-muko     | MKMK          | SuGAr   | 101.0 E                       | 2.5 S           | 11.9                     |
| Lunang        | LNNG          | SuGAr   | 101.1 E                       | 2.4 S           | 12.1                     |
| Manna         | MNNNA         | SuGAr   | 102.8 E                       | 4.4 S           | 14.0                     |
| Bakosurtanal  | BAKO          | IGS     | 106.8 E                       | 6.4 S           | 16.4                     |
| Christmas Island | XMIS   | IGS     | 105.6 E                       | 10.4 S          | 20.0                     |
| Coco Island   | COCO          | IGS     | 98.8 E                        | 12.7 S          | 21.6                     |
Figure 2. Enhancement of the virtual height of the F layer or $h'F$ after sunset due to PRE obtained from Chumphon ionosonde for whole data set (equinox months of 2004–2005 and 2011–2015).

Figure 1 describes the geographic latitude and longitude of the ionosonde and GPS receivers used in this study. Details of ten GPS receivers are described in table 1. The ionosonde used in this study belongs to the Southeast Asia Low-Latitude Ionospheric (SEALION) network [12]. The ten GPS receivers span from magnetic latitudes (ML) of $\sim$4.4°S to $\sim$21.6°S. Seven of those marked by red stars in figure 1 belong to International GNNS Service (IGS), and the three others marked by black stars belong to Sumatran GPS Array (SuGAr).

In this study, the virtual height of the ionosphere F-layer ($h'F$) measured by the ionosonde, is used to assess the strength of PRE. We compute the time derivative of the virtual height ($dh'F/dt$) to get the upward movement velocity of the ionosphere F-layer due to the PRE.

Figure 2 describes the variations of the virtual height of the ionospheric F-layer ($h'F$). It shows $h'F$ at 3 MHz from 18:00–20:00 local time (LT) for the whole data set during March and April of 2004–2005 and 2011–2015. We scaled the $h'F$ manually from the ionogram of ionosonde. The figure shows that the $h'F$ starts increasing at around 18:00 LT. During the time interval of 18:30–19:00 LT, the $h'F$ values continuously enhance. At 19:00–20:00 LT, the $h'F$ values tend to be constant, and even some of them decrease. Furthermore, we consider that the PRE causes the $h'F$ increase at 18:30–19:00 LT. Therefore, we used the time derivative of $h'F$ in the interval of 18:30–19:00 LT as a proxy for PRE strength.

As mentioned before, we analyzed data obtained from GPS receivers to estimate the latitudinal variation of the EPB occurrence rate. The GPS receiver records files containing the pseudo-range and carrier-phase observables in RINEX format. Total electron content (TEC) is estimated from the geometry free combination of carrier-phase and pseudo-range. This TEC includes biases. Therefore, the TEC must be calibrated to eliminate the biases [13,14]. We used software developed by Gopi Seemala to process the RINEX file and to estimate the calibrated TEC. We used the calibrated TEC provided by the GOPI software to calculate the rate of the TEC change index (ROTI). In particular, we used the vertical TEC (VTEC) derived from the GOPI software for our ROTI calculation. Details for TEC calculation from the GOPI software can be found through this link http://seemala.blogspot.com.

We detect the EPB occurrence using the ROTI. ROTI is a proxy for the detection of phase
fluctuations induced by the presence of EPB. ROTI is defined as the standard deviation of the rate of TEC (ROT) for each five minutes interval, as proposed by a study [15]. Equations 2 and 3 show ROT and ROTI values are defined respectively.

\[ \text{ROT} = \frac{\Delta \text{TEC}}{\Delta t} \]  

\[ \text{ROTI} = \sqrt{\langle \text{ROT}^2 \rangle - \langle \text{ROT} \rangle^2} \]  

Where \( \Delta \text{TEC} \) is differential VTEC at interval time \( \Delta t \), whereas, \( \Delta t \) is the sampling rate in VTEC measurement. TEC is calculated in the TEC unit (TECu), while ROT and ROTI are calculated in TECu/min (1 TECu = 10^{16} \text{electrons/m}^2).

ROT has the same sampling rate as TEC, i.e., 30-seconds. The VTEC with an elevation angle higher than 40° is used in computing ROT. This elevation cut-off set aims to exclude the biases by the multipath effect. Following Equation (3), we consider for ROTI calculation in a 5-minute window. Since the ROT is computed at 30-s cadence and the ROTI is computed in a 5-minutes window, we can investigate the irregularities embedded in the EPB at scale of 3–30 km, assuming that the velocity of the ionospheric pierce point (IPP) of the GPS ray path in order of 100 m/s [16,17].

We defined the occurrence of EPB at a particular receiver when ROTI value is higher than 0.2 TECu/min, and below this value, it is set as the EPB does not occur. As examinations in our data, ROTI values below 0.2 TECu/min are considered because of non-ionospheric effects, such as multipath effects. Therefore, we set the ROTI higher than 0.2 TECu/min alongside the elevation angle of more than 40° to eliminate significantly non-ionospheric effects. Thus, the ROTI threshold can detect the ionospheric irregularities with amplitude higher than 0.2 TECu/min.

The examples of how we identify the occurrence and non-occurrence of EPB are shown in figures 3a and 3b, respectively. Figures 3a and 3b describe the ROTI values obtained from the BAKO GPS receiver on 22 and 23 March 2004. ROTI values for 25 GPS satellites are plotted in blue dots. It is seen from figure 3a that there is no EPB occurrence on 22 April 2004, represented by the ROTI values almost constant below 0.2 TECu/min (red dashed line) from 19:00 to 24:00 LT. In contrast, figure 3b shows an example of our method in observing the plasma bubble occurrence. We can see that before 20:30 LT, the ROTI values are constant, and during 20:30–22:30 LT, the ROTI values become more extensive than the threshold and tend to be lower than the threshold at the time interval of 23:00–24:00 LT. In figure 3b, we considered the occurrence of EPB on the night of 23 March 2004 represented by the ROTI values higher than 0.2 TECu/min at 20:30–22:30 LT.

**Figure 3.** ROTI measured at BAKO GPS receiver on 22 (a) and 23 (b) March 2004. The red dashed line is the threshold to define the occurrence and non-occurrence of EPB. ROTI with a value higher than the threshold is associated with the presence of the EPB.
3. Results
In this study, the ROTI occurrence rate in each station describes the latitudinal variation of the EPB occurrence rate. The ROTI occurrence rate in each station is obtained by measuring the ratio between the number of ROTI with the value higher than 0.2 TECu/min and the number of ROTI in observation from 19:00 to 24:00 LT. In our study, we also classify the latitudinal occurrence rate of ROTI enhancement associated with the EPB in each station in two cases that is, strong and weak PRE cases. The PRE threshold for the ionospheric irregularities, such as plasma bubble generation, had been discussed in some of the previous studies [5,9,18]. The study [18] found that the EPB reaching the top side of the ionosphere can be generated when vertical drift velocities of PRE exceeding 30 m/s. Based on the study [18], the definitions for strong and weak PRE cases in our study are described as follows. For the case of strong PRE, we collect the ROTI data from GPS receivers on the nights when the PRE is equal to or higher than 30 m/s based on the ionosonde observation. On the other hand, in the case of weak PRE, the ROTI data from GPS receivers are collected on the nights when the PRE values are less than 30 m/s.

The examples of how we obtained the ROTI occurrence rate in each station in the cases of strong and weak PREs are described in figures 4a and 4b, respectively. Figures 4a and 4b represent all ROTI values that we collected from BAKO station on the nights with strong and weak PRE values, respectively, and they are aimed to illustrate how we compute the ROTI occurrence rate in BAKO station in the cases of strong and weak PREs. In the case of weak PRE (figure 4a), we calculate the occurrence rate of ROTI with the ratio between the number of blue dots with the ROTI value higher than 0.2 TECu/min (red dashed line) and the number of all blue dots collected from 19:00 to 24:00 LT. Therefore, we obtained the occurrence rate of 19.3% for the case of strong PRE for BAKO station. Using the same way, we achieved the occurrence rate of 2.5% for the case of weak PRE for BAKO station (figure 4b). After we compute the ROTI occurrence rate in each station, it is plotted as a function of magnetic latitude based on the PRE values to illustrate the latitudinal variation of the EPB occurrence rate, as shown in figure 5.

Figure 5 shows the latitudinal variation of EPB occurrence rate in cases of strong and weak PREs in each station used in this study. It is described by the ROTI occurrence rate, which is plotted as a function of magnetic latitude. Blue and black curves represent the ROTI occurrence rate in each station for the cases of strong and weak PREs, respectively. Names of stations are pointed out on the top side of figure 5.

In the case of strong PRE, the ROTI occurrence rates decrease from 38.9% to 34.9% at magnetic latitudes (ML) of ~4.4°S until ~7.2°S, afterward the occurrence rates increase and reach the peak (44%) at ML of ~9.3°S. Furthermore, the occurrence rate rapidly decreases and reaches less than 5% at ML of ~21.6°S. On the other hand, in case of weak PRE, the occurrence rate decreases from 21.8% at ML of ~4.4°S and shows a plateau (15.3% to 16%) at ML of ~8.2°S to ~12.1°S and reaches less than 5% at ML of ~16.1°S.

Based on figure 5, we found that the EPB occurrence rates in the case of strong and weak PREs are different. In general, the EPB occurrence rate in case of strong PRE is higher than the EPB occurrence rate in case of weak PRE. Interestingly, we also found that the latitudinal extension of the EPB occurrence rate in the case of strong PRE is farther than that in the case of weak PRE. If we see the occurrence higher than 2% in figure 5, it pointed out that in case of strong PRE, the occurrence rate of ROTI enhancement associated with EPB occurrence reaches ML of ~21.6°S (2.3%) meanwhile, in case of weak PRE the EPB occurrence rate only reaches ML of ~16.1°S (2.5%). Another finding is the peak of ROTI enhancement occurrence rates in cases of strong and weak PRE are different. The peak of the ROTI occurrence rate in case of strong PRE is 44% at ML of ~9.3°S, whereas the peak of the ROTI occurrence rate in case of weak PRE is 21.8% at ML of ~4.4°S. The last finding is that the EPB occurrence rates tend to be constant from ML of ~8.2°S to ~12.1°S in case of weak PRE. It is shown by the black curve in figure 5 that the ROTI occurrence rate seems flat at these latitudes afterward decreases and becomes zero at ML of ~21.6°.
Figure 4. ROTI values in case of weak PRE (a) and in case of strong PRE (b) that are used to compute ROTI occurrence rate at BAKO stations. The red dashed line is the threshold to define the occurrence and non-occurrence of EPB. ROTI with a value higher than the threshold is associated with the presence of the EPB.

Figure 5. ROTI occurrence rate as a function of magnetic latitude (ML) based on PRE values: strong PRE and weak PRE.
4. Discussion

Based on figure 5, we summarize the findings in this study in four parts, which are described as follows. First, we found that generally, the EPB occurrence in the case of strong PRE is higher than the EPB occurrence rate in the case of weak PRE. Second, the latitudinal extension of EPB occurrence rate in case of strong PRE is farther than that in case of weak PRE. Third, the peak of the EPB occurrence rate in cases of strong and weak PREs occurs at different latitudes. The peak of EPB occurrence rate in case of weak PRE occurs at ML of ~9.3°S, while the peak occurrence rate in case of weak PRE occurs at ML of ~4.4°S. The last is, we also found that the latitudinal occurrence of EPB is constant from ML of ~8.2°S to ~12.1°S in case of weak PRE.

As mentioned before, the EPB occurrence rate in case of strong PRE is higher than the weak PRE. This finding indicates that the magnitude of PRE controls the EPB occurrence. Based on the RTI mechanism (equation (1)), the growth rate of RTI increases as increasing the electric currents driven by the eastward electric field (PRE). So, it makes sense if the strong PRE raises the high EPB occurrence rate. The study [9] found that the EPB probability is small when the PRE is zero and becomes 80% when the PRE is higher than 40 m/s. On the other hand, the study [10] found that in equinoctial months, the EPB occurrence increase with increasing the vertical drift velocity (PRE). In the study [10], for the pacific region when the PRE is higher than 20 m/s, the EPB occurrence is higher than 10%. In our study, we revealed that the EPB occurrence is 21.8% when the PRE is weak (PRE less than 30 m/s), and the EPB occurrence reaches 44% when the PRE is strong (PRE equal to or higher than 30 m/s). This finding points out that the EPB occurrence in our study both in cases of strong and weak PRE is higher than in the study [10]. The reason is the study [10] analyzed the EPB occurrence at the top side of the ionosphere using the in-situ satellite while in our study, we used ionosonde and GPS receiver to interpret the EPB occurrence from the bottom side of the ionosphere. Hence, it is our discussion about why we detected the EPB occurrence rate higher than that in the study [10].

Next, we found that the latitudinal of EPB occurrence rate extends farther when the PRE values are strong compared to when the PRE values are weak. It is pointed by figure 5 that the EPB occurrence reaches the ML of ~21.6°S for the case of strong PRE, while for the case of weak PRE, the EPB occurrence rate reaches ML of ~16.1°S. We suggest that besides controlling the EPB occurrence rate, the PRE also plays a vital role in the latitudinal occurrence rate of EPB. Again, from Equation (1), stronger PRE results in the higher growth rate of RTI in the plasma bubble generation. Stronger PRE could help plasma bubble evolution growing to higher altitudes and latitudes. Therefore, the latitudinal extension of the EPB occurrence depends on the magnitude of PRE. The study [6] found that the EPB reaches the ML of 10°–20° when the maximum upward \( E \times B \) drift associated with the PRE ranges from 10 to 70 m/s, and this finding also implies that the magnitude of PRE has a good correlation with the latitudinal extension of EPB. As improvements for the study [6], we could distinguish that the EPB reaches ML of ~16.1°S in case of weak PRE (below 30 m/s), and the EPB reaches ML ~21.6°S in case of strong PRE (≥ 30 m/s).

Another finding in this study is, the peak of EPB occurrence rate in cases of strong and weak PREs occurs in different latitudes. In the case of strong PRE, the peak of EPB occurrence rate is 44% and lies at ML of ~9.3°S, while in case of weak PRE, the peak of EPB occurrence rate is 21.8% and lies at ML of ~4.4°S. The strength of PRE is the critical factor causing this difference. Since the ROTI represents a measure of TEC fluctuation, higher ROTI values mean a larger amplitude of TEC fluctuations and then the presence of ionospheric irregularities of given scales. It is well-known that the amplitude of ionospheric irregularities (plasma density fluctuation) is effectively enhanced by higher background plasma density [19]. Higher background ionospheric plasma density in the low latitude region is at the Equatorial Ionospheric Anomaly (EIA). Therefore, the higher amplitude of ROTI associated with the EPB occurrence could occur at the peak of EIA in the low latitude region. Furthermore, stronger PRE happened in the evening sector in the equatorial region can push the location of EIA up to farther latitudes. Consequently, the latitudinal peak of the EPB occurrence rate deduced from GPS ROTI measurement is farther following the site of the EIA.
Furthermore, our finding on the difference between the latitudinal peak of EPB occurrence rate in the case of strong and weak PREs is different from the result in the study [7]. The study [7] reported that the EPB occurrence rate is almost constant below 600 km of HODE and become smaller above 600 km of HODE. Therefore, this finding is a new contribution to the study of the latitudinal occurrence rate of EPB deduced from GPS ROTI measurement. As we discussed before, the latitudinal occurrence rate of EPB observed by GPS ROTI is also affected by the location of EIA, and the magnitude of PRE controls the latitude of EIA. Surely, to see the effect of EIA on the latitudinal occurrence of EPB, further study should have a latitudinal network of GPS receiver to measure latitudinal background density.

The last finding is that in case of weak PRE, the EPB occurrence rates are constant at ML from \(-8.2^\circ S\) to \(-12.1^\circ S\). As explained before, the EPB occurrence is affected by plasma background density. Furthermore, we speculated that the plasma background density is constant at a range of ML from \(-8.2^\circ S\) to \(-12.1^\circ S\). Hence, the occurrence rate of EPB deduced from ROTI measurement also will be constant at these latitudes. However, further investigation is needed to get more explanation of why the occurrence rate of EPB is constant at these latitudes.

5. Conclusion
We investigated the latitudinal variation of EPB occurrence rate using ionosonde at Chumphon in Thailand and GPS receivers around Southeast Asia. We employed the data from those instruments during equinox (March–April) in 2004–2005 and 2011–2015. Our findings can be summarized as follow. In the case of strong PRE, the ROTI occurrence rates decrease from 38.9% to 34.9% at ML of \(-4.4^\circ S\) until \(-7.2^\circ S\), afterward the occurrence rates increase and reach the peak (44%) at ML of \(-9.3^\circ S\). Furthermore, the occurrence rate rapidly decreases and reaches less than 5% at ML of \(-21.6^\circ S\). On the other hand, the occurrence rate directly decreases from 21.8% at ML of \(-4.4^\circ S\) to the value of less than 5% at \(-16.1^\circ S\) in case of weak PRE. Based on the findings above, we disclosed statistically that the EPB occurrence rate in case of strong PRE is generally higher (44%) than that in the case of weak PRE (21.8%). We also disclosed that the latitudinal extension of EPB occurrence rate in case of strong PRE is farther than that in case of weak PRE. The EPB reaches ML of \(-21.6^\circ S\) in case of strong PRE, while in case of weak PRE, the EPB reaches ML of \(-16.1^\circ S\). Moreover, we found that the peak of the EPB occurrence rate in cases of strong and weak PRE occurred at different latitudes. The peak of the EPB occurred at ML of \(-9.3^\circ S\), whereas in the case of weak PRE, the peak of the EPB occurrence rate occurs at ML of \(-16.1^\circ S\). We also found that in case of weak PRE the EPB occurrence rate is 21.8% at ML of \(-4.4^\circ S\), the occurrence rate tends to be constant (15.3% to 16%) at ML from 8.2°S to \(-12.1^\circ S\), and the occurrence rate reaches less than 5% at ML of \(-16.1^\circ S\).

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