STUDY AND ANALYSIS ON TOTAL ELECTRON CONTENT IN SEISMO-IONOSPHERIC COUPLING FOR EARTHQUAKE MONITORING IN THAILAND

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ABSTRACT

This research shows the study and analysis on the relationship between earthquake events and the Total Electron Content (TEC) of the ionosphere over Thailand during 2007-2020. The method for this research is to use the International GNSS Service (IGS) network and the International Reference Ionosphere (IRI) model for finding TEC in the ionosphere and analyze the correlation on earthquake events and ionosphere characteristics. The result is correlated between IGS TEC and earthquake events at 0.089, which shows the positive evidence of correlation on earthquake magnitudes and ionosphere. The relationship between IRI TEC and earthquake events correlates at 0.056, which shows the positive correlation between earthquake events and ionosphere. A significant correlation among IGS TEC, IRI TEC, and earthquake events obviously showed direct evidence of correlation coefficient on ionosphere disturbance and earthquake magnitudes at 5.0 and upward magnitudes. As the results, it guides to making the future work and the researchers will study the significance of the development of earthquake warning systems.

Keywords: Earthquake; TEC; IGS TEC; IRI TEC; Correlation

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I. INTRODUCTION

According to earthquakes, there are natural phenomena caused by vibrations or shaking of the earth's surface, occurring at any time without humans being able to tell us. Wherever any places in the world, earthquakes can probably occur, causing damage to their entire property and various buildings, including the loss of life. Earthquakes may be related to changes Total Electrons Content (TEC) in ionosphere. The researchers investigated that earthquakes effect on the ionosphere which TEC changes. The behaviour of ionosphere TEC anomalies before large earthquakes have emerged as promising parameters for earthquake precursor detection and suggest the existence of a correlation between ionosphere disturbances in TEC and earthquake occurrences (Sharma et al., 2021, pp. 1-7). TEC is an important parameter in ionosphere which directly affects the propagation of radio waves through the ionosphere.

TEC computation can be extracted from Global Navigation Satellite System (GNSS) receiver, International GNSS Service (IGS) and International Reference Ionosphere (IRI). There are many reports on the execution of different methods for the relationship and monitoring of the earthquake and ionospheric anomalies from ground and space measurements during seismic preparation period s before and after the main shock in a statistical (Shah & Jin, 2015, pp. 42-49; Shah et al., 2020, pp. 268-276). The researchers used the correlation for relationships between the earthquake events and the disturbance of ionosphere. For example, Afraimovich et al. (2004, pp. 339-354) studied the variations of the total electron content in the ionosphere from GPS data recorded during the Hector Mine earthquake of October 16th, 1999, California. Arikan et al. (2008, pp. 1-13) estimated the values of single station interfrequency receiver bias using GPS TEC. Cahyadi and Heki (2013, pp. 1777-1787) found the ionospheric disturbances of the 2007 Bengkulu and the 2005 Nias earthquakes, Sumatra, observed with a regional GPS network. Grawe and Makela (2015, pp. 472-483) investigated the ionospheric responses to the 2011 Tohoku, 2012 Haida Gwaii, and 2010 Chile tsunamis: Effects of tsunami orientation and observation geometry. Kakinami et al. (2021, pp. 1-12) studied the onset altitudes of co-seismic ionospheric disturbances determined by multiple distributions of GNSS TEC after the foreshock of the 2011 Tohoku earthquake on March 9th, 2011. Kenpankho et al. (2021, pp. 2152-2159) analyzed the real-time GPS receiver bias estimation. Kenpankho et al. (2013, pp. 1820-1826) compared the observed TEC values with IRI2007 TEC and IRI-2007 TEC with optional foF2 measurement predictions at an equatorial region, Chumphon, Thailand. In 2011, Kenpankho et al. (2011, pp. 365-370) made the comparison of GPS TEC measurements with IRI TEC prediction at the equatorial latitude station Chumphon, Thailand. Nishioka et al. (2021, pp. 1-12) analyzed the statistical analysis of TEC: long-term estimation of extreme TEC in Japan. The outcome of the statistical characteristics of seismo-ionospheric GPS TEC disturbances prior to global Mw was ≥ 5.0 earthquakes (1998–2014) (Shah & Jin, 2015, pp. 42-49). Ulukavaka and Inyurtb (2020, pp. 123-130) studied seismo-ionospheric precursors of strong sequential earthquakes in Nepal region. Moreover, Sharma et al. (2021, pp. 1-7) developed a monitoring system for ionospheric TEC variability before earthquakes.

According to study and investigation of the outcome of the statistical characteristics of seismo-ionospheric GPS TEC disturbances prior to global Mw was ≥ 5.0 earthquakes (1998–2014) (Shah & Jin, 2015, pp. 42-49), Ulukavaka and Inyurtb (2020, pp. 123-130) presented on seismo-ionospheric precursors of strong sequential earthquakes in Nepal region found that an acoustic gravity waves from earthquake significantly affected TEC values at magnitudes 2.0 to 2.5 less than pre-earthquake variations in the ionosphere. It has been observed that ionospheric anomalies might continue up to one month, 15 days prior to and following earthquakes. Pre-earthquake ionospheric TEC may plummet starting from five days till one day ago when earthquakes are at magnitudes equal to and higher than 6.0. Kenpankho et al. (2011, pp. 365-370) presented about comparison of GPS TEC measurements with IRI TEC prediction at the equatorial latitude station, Chumphon, Thailand, they found that the TEC derived from the IRI-2007 model agrees with the GPS TEC data mostly in the morning hours, but that it generally underestimates the GPS TEC. The maximum differences are about 15 TECU during the daytime and five TECU during the nighttime. The underestimation is more evident at daytime than at nighttime, and the development of a monitoring system for ionospheric TEC variability before the earthquakes (Sharma et al., 2021, pp. 1-7). The researchers applied and studied as the example research methodology to investigate the relationship between earthquake events and TEC of the ionosphere in Thailand during 2007-2020.

The research is aimed to study and analyze the relationship between earthquake events and the disturbance of ionosphere. This method focuses on the IGS TEC and IRI TEC and then finds the correlation between earthquake events and ionosphere. The researchers assumed that TEC results are to show a significant relationship with earthquake events, to guide the development of earthquake alarm, and to develop the telecommunication systems.

II. METHODOLOGY

A. Earthquake events data

For earthquake events, the earthquake data are received from Earthquake Observation Division, Thai Meteorological Department (TMD) site: https://earthquake.tmd.go.th/inside.html. The severity of an earthquake can be expressed in terms of both intensity and magnitude. The magnitude scale of earthquakes can be classified in Table 1.

Table 1: The magnitude scale of earthquakes.

Magnitudes	Interpretation
1.0-2.9	Hanging objects may swing.
3.0-3.9	The vibrations may be like a passing truck.
4.0-4.9	Windows may be broken, cause small or unstable objects to fall.
5.0-5.9	Furniture moves, chunks of plaster may fall from walls.
6.0-6.9	It damages to well-built structures, severely damages to poorly built ones.
7.0 or more	Building is displaced from foundations, things crack in the earth, and underground pipes broken.

In this research, according to the earthquake magnitude 1.0-2.0 as a rarely effective on TEC, researchers focused on the earthquake magnitude starting at 3.0 and above for comparing with TEC. We collected data on 472 earthquake events from 2007-2020 (Thai Meteorological Department [TMD], 2007, Online). There is classified by regions of Thailand as follows in Figure 1.

For investigating the relationship between earthquake events and TEC disturbance over Thailand during 2007-2020, researchers used the data from four regions of Thailand following as 1) Southern of Thailand and Andaman Sea; Phuket, Phangnga, Ranong, Suratthani, Chumphon, Trang, and Andaman sea; 2) Western of Thailand and Andaman sea; Kanchanaburi, Tak, and Andaman sea; 3) Northern of Thailand are Maehongson, Chiangmai, Lamphun, Chiangrai, Payou, Lampang, Phrae, Nan, and Uttaradit; and 4) Northeast of Thailand are Nakhon ratchasima, and Loei.

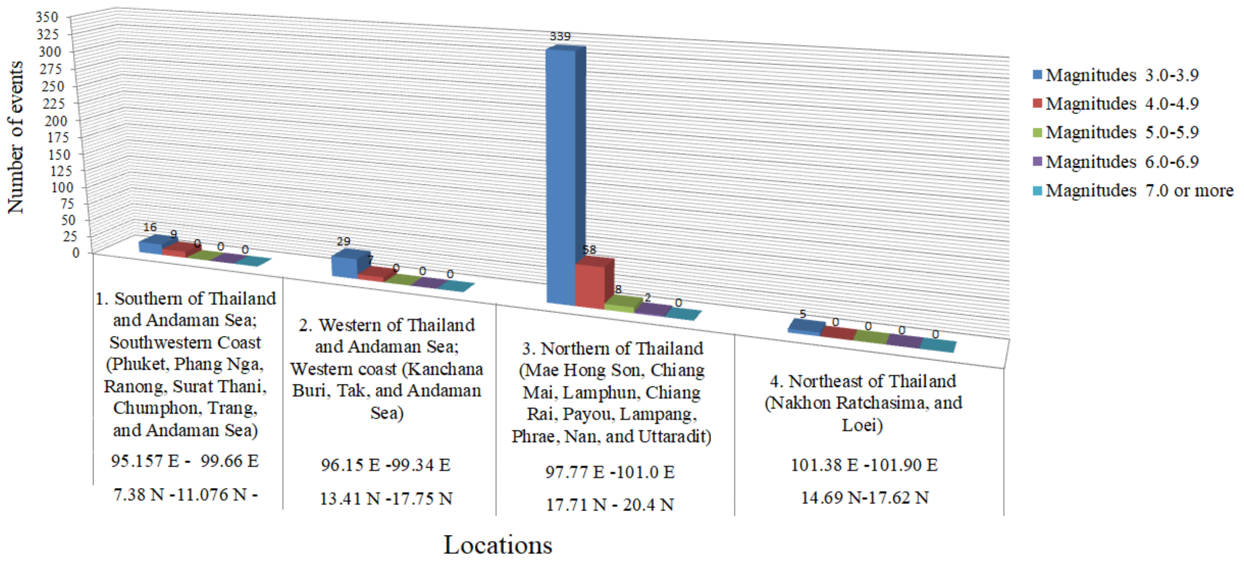

Figure 1: Earthquake events classified by magnitudes and regions of Thailand.

According to the information in Figure 1, the results of the earthquake events data in Thailand from 2007 to 2020 of 472 earthquake events of 3.00 Magnitudes upward as follows: 1) 389 earthquake events of magnitude 3.00 to 3.99, 2) 74 earthquake events of magnitude 4.00 to 4.99, 3) eight earthquake events of magnitude 5.00 to 5.99, 4) one earthquake event of magnitude 6.00 to 6.99, and 5) The event of magnitude 7.00 and upward does not exist.

B. Total Electron Content (TEC)

The TEC is the total electron content along a signal ray path between satellite and receiver which is assumed to include all the electrons in a column with a cross section of 1 m^2 and extending from receiver to satellite. TEC is measured in TECU with 1 TECU = 10^{16} el/m^2.

The Slant Total Electron Content (STEC) from a satellite to a receiver can be obtained from the differences among dual GNSS frequencies (f_1 and f_2), the pseudoranges (P_1 and P_2), and the difference between the carrier phases (L_1 and L_2) of the two methods as follows; (Blewitt, 1990, pp. 199-201; Ma & Maruyama, 2003, pp. 2084-2085).

$$TEC = \frac{2(f_1 f_2)^2}{k(f_1^2 - f_2^2)}(P_2 - P_1) \tag{1}$$

or

$$TEC = \frac{2(f_1 f_2)^2}{k(f_1^2 - f_2^2)}(L_1\lambda_1 - L_2\lambda_2) \tag{2}$$

In equations (1) and (2), f_1 is 1575.42 MHz, f_2 is 1227.60 MHz, P_1 and P_2 are the pseudoranges (P_1 measured on L_1, and P_2 measured on L_2), λ_1 and λ_2 are the wavelengths corresponding to f_1 and f_2 (λ_1 = 0.1904 m, λ_2 = 0.2444 m), L_1 is the phase of f_1 and L_2 is the phase of f_2, and k = 80.62 m^3/s^2.

Once STEC is known, we use STEC to find the Vertical Total Electron Content (VTEC). Where VTEC, in el/m^2, can be calculated and analyzed (Ma & Maruyama, 2003, pp. 2084-2085) as follows;

$$\mathrm{VTEC} = \mathrm{STEC} \times \cos\chi \tag{3}$$

where χ the zenith angle x is expressed as

$$\chi = \arcsin\left(\frac{R_E \cos\alpha}{R_E + h}\right) \tag{4}$$

where α is the elevation angle of the satellite, R_E is the mean radius of the Earth ≈ 6,378 km, and h is the height of the ionospheric layer, which is assumed to be 400 km (Ma & Maruyama, 2003, pp. 2084-2085).

C. IGS TEC data

The researchers used the TEC values from the IGS which are maintained and monitored by the International GNSS Service (IGS). The IGS relies on an international network of over 514 continuously operating dual frequency GNSS stations (International GNSS Service [IGS], 1998, Online). The IGS collects, archives, and distributes GNSS observation data sets. It provides the TEC map data available on the Internet, and these data can be accessed from the File Rapid and Final ionospheric TEC grid site: https://igs.org/, and then click link https://igs.org/products/#ionosphere. Ionospheric products are available through CDDIS website: https://cddis.nasa.gov/archive/gnss/products/ionex/YYYY/DDD/. Next, we searched TEC from IGS on selected seismic events of magnitude 3 and above according to earthquake events data from 2007 to 2020. The IGS information must be the same location, date, and times as the earthquake events were selected. We selected IGS station locations are available in Thailand and the closest distances to earthquake sources were Chiang Mai (18.761 N, 98.932 E), Chumphon (10.725 N, 99.374 E), and Chulalongkorn University (13.736 N, 100.534 E). We collected IGS TEC data five days before earthquake events and five days after earthquake events, there are 11 days in total. Finally, the IGS TEC values and the group magnitude scale of earthquakes data which classified by vibration near the epicenter were analyzed and displayed. The IGS TEC data collecting process is shown as a Figure 2.

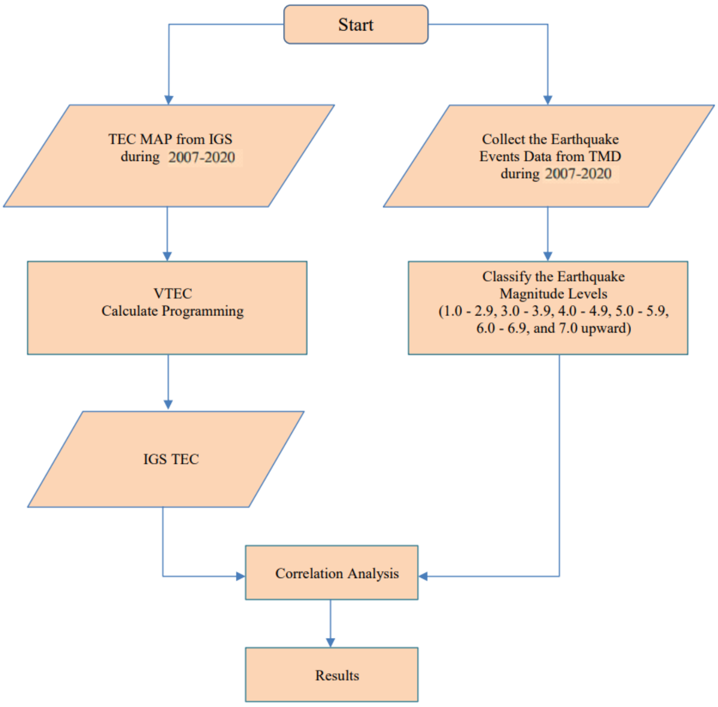

Figure 2: IGS TEC data collection and data analysis process.

The IGS station locations are available in Thailand is shown Figure 3.

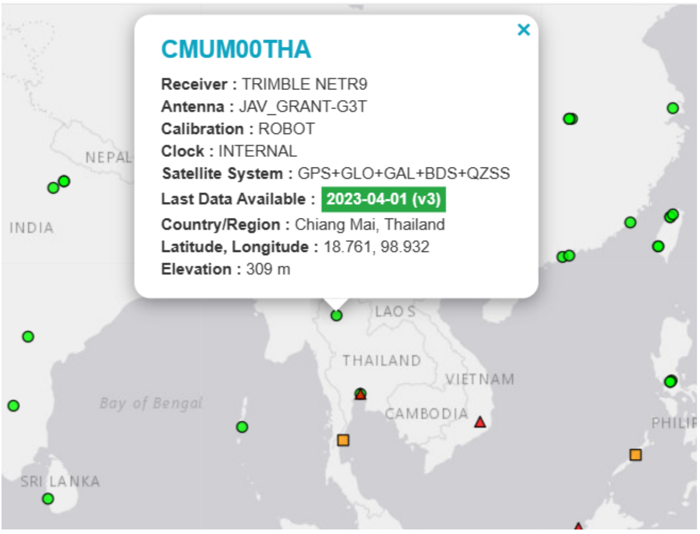

Figure 3: The locations of IGS station are available for Thailand.

D. IRI TEC data

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). The IRI TEC can be found from IRI model version 2016 site: ttps://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php. Several steadily improved editions of the model have been released. For given location, time, and date, IRI provides monthly averages of the electron density, electron temperature, ion temperature, and ion composition in the ionospheric altitude range. You can select desired output parameters of the model for example: independent variables (Year, Month, Day of month, Day of year, Hour of day, Height, etc.) and IRI model parameters (Electron density, Ratio of Ne and F2 peak density, TEC, Electron Temperature, Height of F2 peak, etc.).

For finding IRI TEC data, select the entered parameters as follows; date and time, coordinates (coordinates type, latitude, longitude, and height), profile type and range, optional input, and desired output parameters which can be selected as TEC output (National Aeronautics and Space Administration [NASA], 2022, Online). The IRI input parameters must be the same location, date, and times as the earthquake event were selected. We collected data five days before earthquake events and five days after earthquake events, there are 11 days in total. The procedure for calculating IRI TEC model is shown in Figure 4 and the process of data collection and analysis of IRI TEC as shown in Figure 5.

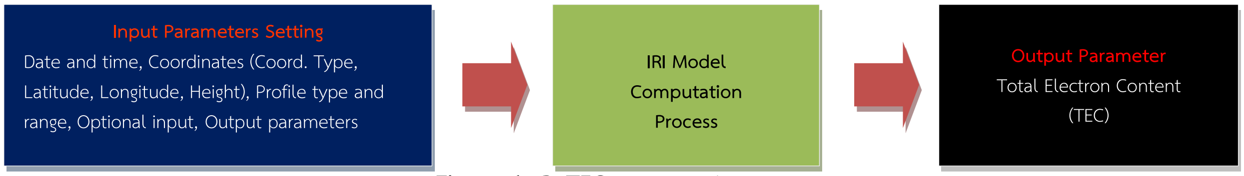

Figure 4: IRI TEC computation process.

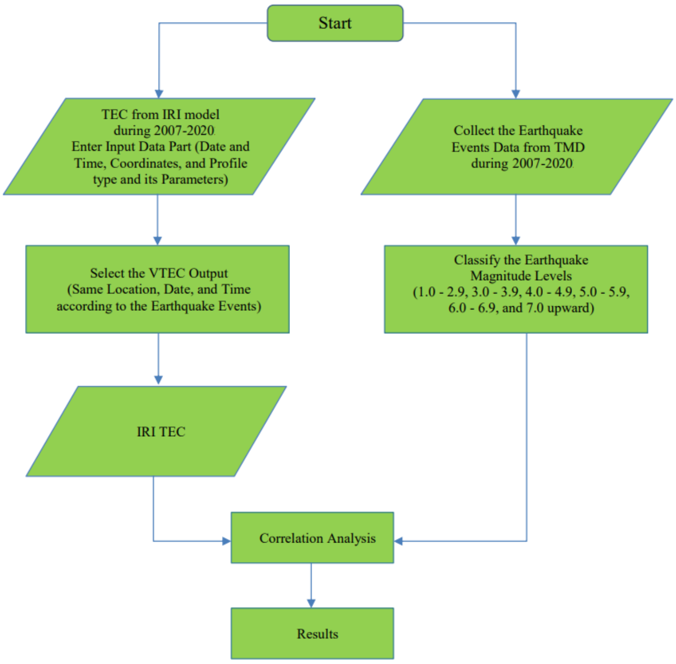

Figure 5: IRI TEC data collection and data analysis process.

E. Correlation coefficient

The correlation coefficient can be calculated (Mukaka, 2012, p. 69) following as

$$r = \frac{\sum_{i=1}^{n}(x_i - x)(y_i - y)}{\sqrt{\left[\sum_{i=1}^{n}(x_i - \bar{x})^2\right]\left[\sum_{i=1}^{n}(y_i - \bar{y})^2\right]}} \quad (5)$$

where, r is the correlation coefficient of the linear relationship between the variables x and y, x_i is the value of the magnitude of earthquake in a sample, $\bar{x}$ is the mean of the value of the magnitude of earthquake, y_i is the values of the TEC in a sample, and $\bar{y}$ is the mean of the values of the TEC.

The correlation coefficient meaning is as below;

the correlation coefficient value closes to -1 means having an inverse relationship,

the correlation coefficient value closes to +1 means having a direct relationship, and
the correlation coefficient value closes to 0 means no relationship.

This dataset is used to analyse the relationship between earthquake events and TEC changes in Thailand. For earthquake magnitudes of 5.0-5.9, 6.0-6.9, and 7.0 and above, as categorized previously, due to the limited occurrence of earthquakes, the researchers divided them into three groups for analysis. In this research, Earthquake magnitudes were divided into 3 groups: 3.0-3.9, 4.0-4.9, 5.0 and above. This allows us to compare daily TEC values from IGS TEC and IRI TEC.

III. RESULTS AND DISCUSSION

A. IGS TEC data results

The results show 472 earthquake events of magnitude at 3.0 and above compared with IGS TEC by data collecting from 2007-2020 as shown in Figure 6.

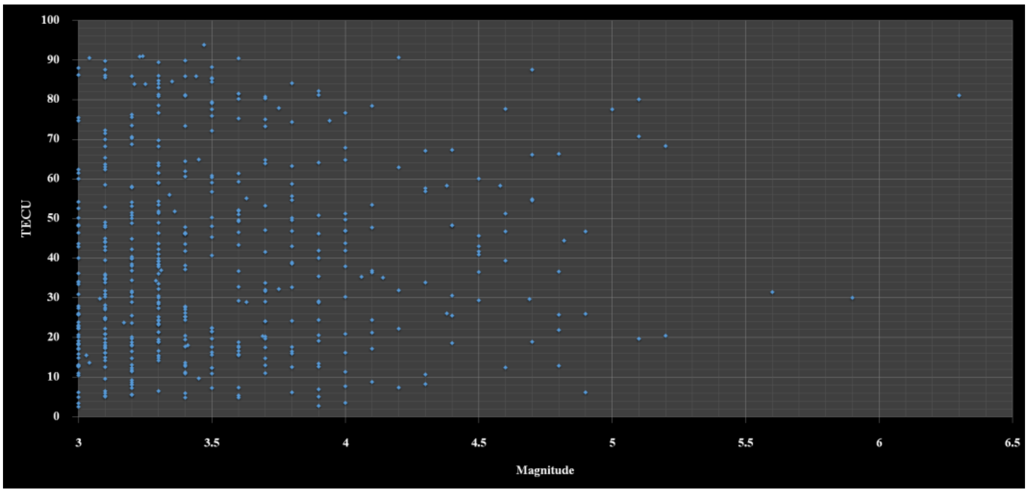

Figure 6: 472 earthquake events of magnitude at 3.0 and above compared with IGS TEC.

In Figure 6, this result can be implied that the magnitude above 4.1 gives the TEC value mostly above 10 TECU. The results show that the number of earthquake magnitude is high, the amount of TEC increases. At the results, there are the significant events that the earthquake is related to the disturbance of ionosphere.

B. IRI TEC data results

Moreover, the researchers investigated more on the comparison between the earthquake events and the disturbance of ionosphere by using the IRI TEC and earthquake events during 2007-2020 as shown in Figure 7.

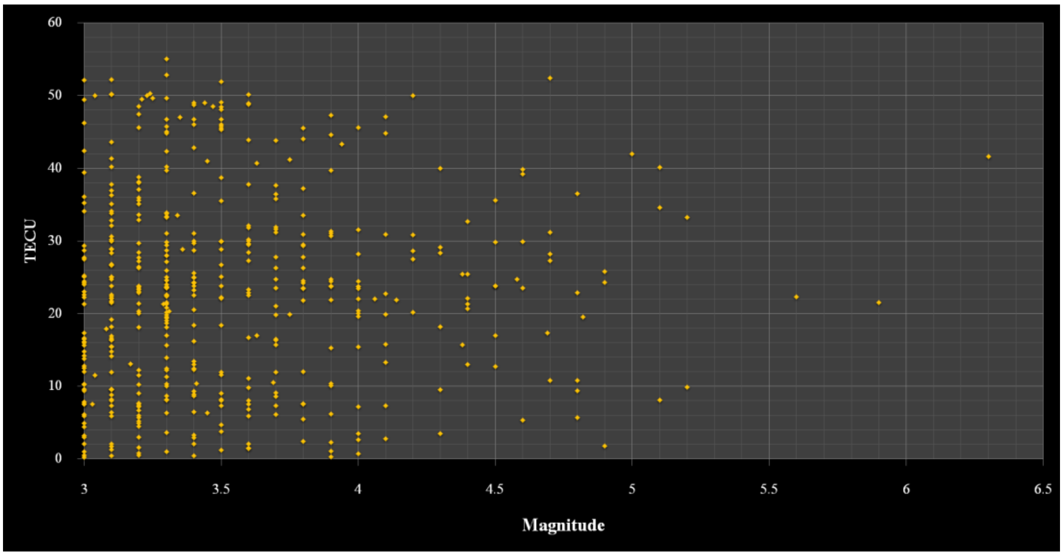

Figure 7: 472 earthquake events of magnitude at 3.0 and above comparing with IRI TEC.

In Figure 7, this result can be implied that the magnitude above 5.1 gives the TEC value mostly above 10 TECU. The results show that the number of earthquake magnitude is high, the amount of TEC increases. At the results, there are the significant events that the earthquake is related to the disturbance of ionosphere.

C. The relationship between earthquake events and the TEC of the ionosphere over Thailand during 2007-2020.

The results of the relationship between the earthquake events and the disturbance of ionosphere by using the IGS TEC, IRI TEC and 472 earthquake events during 2007-2020 as shown in Table 2.

Table 2: The relationship between the earthquake events and the IGS TEC and IRI TEC disturbance in ionosphere.

Correlation Coefficient / Magnitude of Earthquake	IGS TEC Earthquake Event Day	IRI TEC Earthquake Event Day
3.0 - 3.9	0.09170	0.03463
4.0 - 4.9	0.02426	0.00781
5.0 and upward	0.29561	0.27341
Correlation Coefficient in Total	**0.08926**	**0.05634**

Refer to Table 2, results of the relationship between the earthquake events and the TEC disturbance in ionosphere by using the IGS TEC, IRI TEC and 472 earthquake events during 2007-2020 as follows: 1) the correlation coefficient of earthquake events and ionosphere TEC anomalies using the IGS data is 0.089, 2) the correlation coefficient of earthquake events and ionosphere TEC anomalies using the IRI model is 0.056. For classification by the magnitude of the earthquake caused, there are correlation coefficients as follows: magnitude of 3.0-3.9 ($r_{IGS\ TEC}$ = 0.092, $r_{IRI\ TEC}$ = 0.092), magnitude of 4.0-4.9 ($r_{IGS\ TEC}$ = 0.024, $r_{IRI\ TEC}$ = 0.008), and magnitude of 5.0 and upward ($r_{IGS\ TEC}$ = 0.296, $r_{IRI\ TEC}$ = 0.273) respectively. The correlation coefficient curve is shown in Figure 8.

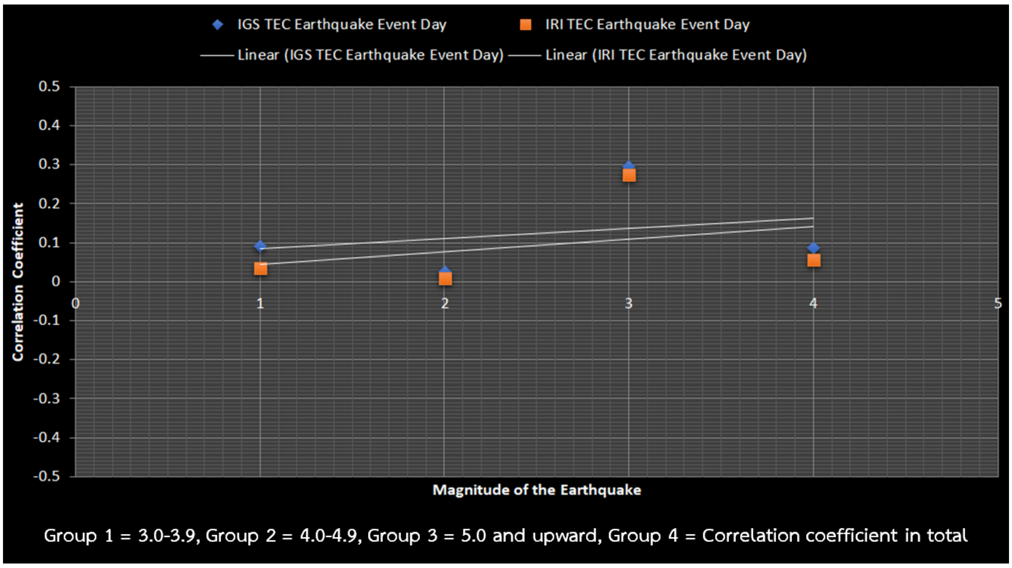

Figure 8: The correlation coefficient of the relationship between the earthquake events and the disturbance of ionosphere.

Figure 8 shows the evidence of correlation between earthquake events and the TEC values. The relationship among IGS TEC, IRI TEC, and earthquake events shows positive values as the direct evidence of correlation on earthquake magnitudes and ionosphere. The correlation values for 5.0 and upward magnitudes are 0.296 for IGS TEC and earthquake events and 0.273 for IRI TEC and earthquake events. The researchers found that the relationships among IGS TEC, IRI TEC, and earthquake events at 5.0 and upward magnitudes are significantly correlation values as direct relationship. According to the results of correlation at 5.0 and upward magnitudes, the TEC disturbances in ionosphere are significantly related to earthquake occurrence in Thailand.

According to the study and analysis on the TEC and earthquake events in Thailand, the researchers found that the seismo-ionosphere coupling occurs in the investigation during the years 2007-2020. This results evidence and support Ulukavaka and Inyurtb (2020, pp. 123-130) who studied the seismo-ionospheric precursors of strong sequential earthquakes in Nepal region. They found that the disturbance of ionosphere was likely related to the process of seismic connection with the ionosphere that occurred on April 25th, 2015. The significantly affected TEC values at magnitudes 2.0 to 2.5 less than pre-earthquake variations in the ionosphere. It has been observed that ionospheric anomalies might continue up to one month, 15 days prior to and following earthquakes. Pre-earthquake ionospheric TEC may plummet starting from five days till one day ago when earthquakes are at magnitudes equal to and higher than 6.0. The results were the ionospheric anomaly that occurs before an earthquake and ionosphere anomalies caused by aftershocks may be caused by large earthquakes. In addition, Shah and Jin (2015, pp. 42-49) investigated using the TEC of GPS global ionosphere maps (GIM). Statistical analysis of 10-day TEC data before global Mw ≥ 5.0 earthquakes shows significant enhancement 5 days before an earthquake of Mw ≥ 6.0 at a 95% confidence level. The finding of earthquakes with a focal depth of less than 60 km and Mw ≥ 6.0 is presumably the root of deviation in the ionospheric TEC because earthquake breeding zones have gigantic quantities of energy at shallower focal depths. Increased anomalous TEC is recorded in cumulative percentages beyond Mw = 5.5. Sharpness in cumulative percentages is evident in seismo-ionospheric disturbance prior to Mw ≥ 6.0 earthquakes. Seismo-ionospheric disturbances related to strike slip and thrust earthquakes are noticeable for magnitude

Mw 6.0-7.0 earthquakes. The relative values reveal high ratios (up to 2) and low ratios (up to - 0.5) within 5 days prior to global earthquakes for positive and negative anomalies. The anomalous patterns in TEC related to earthquakes are possibly due to the coupling of high amounts of energy from earthquake breeding zones of higher magnitude and shallower focal depth. Moreover, Sharma et al. (2021, pp. 1-7) developed a monitoring system for ionospheric TEC variability before the earthquakes which integrated TEC, geomagnetic storm, and solar flare data. They carried out a TEC anomaly study before earthquakes occurred. In the present study, an earthquake monitoring by using the observations of the ionosphere conditions before an earthquake may help in understanding earthquake precursors and space weather conditions.

IV. CONCLUSION

At the results and discussion, the relationships among IGS TEC, IRI TEC, and earthquake events at 5.0 and upward magnitudes are the significant events that the earthquake is related to the disturbance of ionosphere which shows the evidence of correlation on earthquake events and the TEC values monitoring in Thailand. The relationship among IGS TEC, IRI TEC, and earthquake events shows the direct evidence of correlation on earthquake magnitudes and ionosphere. The researchers found that TEC results are significant relationship with earthquake events at 5.0 and upward magnitudes which can be guided the development of earthquake alarm and developed the telecommunication systems as such Global Navigation Satellite Systems (GNSS).

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REFERENCES

Afraimovich, E. L., Astafieva, E. I., Gokhberg, M. B., Lapshin, V. M., Permyakova, V. E., Steblov, G. M., & Shalimov, S. L. (2004). Variations of the total electron content in the ionosphere from GPS data recorded during the Hector Mine earthquake of October 16, 1999, California. *Russian Journal of Earth Sciences*, *6*(5), 339-354.

Arikan, F., Nayir, H., Sezen, U., & Arikan, O. (2008). Estimation of single station interfrequency receiver bias using GPS-TEC. *Radio Science*, *43*(4), 1-13.

Blewitt, G. (1990). An automatic editing algorithm for GPS data. *Geophysical Research Letters*, *17*(3), 199-202.

Cahyadi, M. N., & Heki, K. (2013). Ionospheric disturbances of the 2007 Bengkulu and the 2005 Nias earthquakes, Sumatra, observed with a regional GPS network. *Journal of Geophysical Research: Space Physics*, *118*(4), 1777-1787.

Grawe, M. A., & Makela, J. J. (2015). The ionospheric responses to the 2011 Tohoku, 2012 Haida Gwaii, and 2010 Chile tsunamis: Effects of tsunami orientation and observation geometry. *Earth and Space Science*, *2*(11), 472-483.

International GNSS Service. (1998). *Ionospheric Products*. https://igs.org/products/#ionosphere

Kakinami, Y., Saito, H., Yamamoto, T., Chen, C.-H., Yamamoto, M.-Y., Nakajima, K., Liu, J.-Y., & Watanabe, S. (2021). Onset Altitudes of co-seismic ionospheric disturbances determined by multiple distributions of GNSS TEC after the foreshock of the 2011 Tohoku earthquake on March 9, 2011. *Earth and Space Science, 8*, 1-12.

Kenpankho, P., Chaichana, A., Trachu, K., Supnithi, P., & Hozumi, K. (2021). Real-time GPS receiver bias estimation. *Advances in Space Research*, *68*(5), 2152-2159.

Kenpankho, P., Supnithi, P., & Nagatsuma, T. (2013). Comparison of observed TEC values with IRI-2007 TEC and IRI-2007 TEC with optional *fo*F2 measurements predictions at an equatorial region, Chumphon, Thailand. *Advances in Space Research, 52*(10), 1820-1826.

Kenpankho, P., Watthanasangmechai, K., Supnithi, P., Tsugawa, T., & Maruyama, T. (2011). Comparison of GPS TEC measurements with IRI TEC prediction at the equatorial latitude station Chumphon, Thailand. *Earth Planets Space*, *63*(4), 365-370.

Ma, G., & Maruyama, T. (2003). Derivation of TEC and estimation of instrumental biases from GEONET in Japan. *Annales Geophysicae, 21*(10), 2083-2093.

Mukaka, M. M. (2012). A guide to appropriate use of correlation coefficient in medical research. *Malawi Medical Journal, 24*(3), 69-71.

National Aeronautics and Space Administration. (2022). *International Reference Ionosphere - IRI (2016) with IGRF-13 coefficients.* Community Coordinated Modeling Center (CCMC). https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php

Nishioka, M., Saito, S., Tao, C., Shiota, D., Tsugawa, T., & Ishii, M. (2021). Statistical analysis of ionospheric total electron content (TEC): long-term estimation of extreme TEC in Japan. *Earth, Planets and Space, 73*(1), 1-12.

Shah, M., & Jin, S. (2015). Statistical characteristics of seismo-ionospheric GPS TEC disturbances prior to global Mw ≥ 5.0 earthquakes (1998-2014). *Journal of Geodynamics, 92,* 42-49.

Shah, M., Ahmed, A., Ehsan, M., Khan, M., Tariq, M. A., Calabia, A., & Rahman, Z. U. (2020). Total electron content anomalies associated with earthquakes occurred during 1998-2019. *Acta Astronautica, 175*, 268-276.

Sharma, G., Soubam, M., Walia, D., Nishant, N., Sarma, K. K., & Raju, P. L. N. (2021). Development of a monitoring system for ionospheric TEC variability before the earthquakes. *Applied Computing and Geosciences*, *9*, 1-7.

Thai Meteorological Department. (2007). *Local earthquake.* https://earthquake.tmd.go.th/inside.html?pageNum_thaievent=0&totalRows_thaievent=10454

Ulukavaka, M., & Inyurtb, S. (2020). Seismo-ionospheric precursors of strong sequential earthquakes in Nepal region. *Acta Astronautica*, *166*, 123-130.