The Ionospheric Total Electron Content Behavior at Equatorial and Polar Stations

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***Abstract*—The characteristic of ionosphere behavior is of spatial and temporal variations. The ionosphere behavior was determined by identifying the total electron content (TEC) variation. The investigation on TEC variation had been made over an equatorial station, Libreville (NKLG) station (0.4162° N, 9.4673° E), and a polar station, Ny-Alesund (NYA1) station (78.9235° N, 11.9099° E) in year 2009 and 2013, each representing different level of solar activity. The hourly averaged vertical TEC (VTEC) is used to observe the TEC variation under diurnal, seasonal, and geomagnetic storm variations. The diurnal TEC variations in March and September 2009 experienced a double TEC peak structure. The TEC variation over the NKLG station in the low and high solar activity depicted the same observation where the TEC variation began to rise until it reached its maximum TEC peak around noon to the late evening, and it falls after the sunset hours until it reached its minimum TEC at pre-dawn hours. The diurnal TEC variations for all months at the NYA1 station showed rapid fluctuations of TEC by the presence of more peaks of TEC. The seasonal TEC variations showed its highest TEC peak in spring and lowest TEC peak in summer at NKLG station during both 2009 and 2013. The great fluctuations of TEC obviously observed during the winter and spring. The maximum seasonal TEC peak at NYA1 station mainly occurred around the late evening hours to the extent of pre-dawn hours. The moderate geomagnetic storm on 22 July 2009 caused an increment of TEC at both stations during the storm time meanwhile the moderate geomagnetic storm on 6 July 2013 caused a decrement of TEC at both stations during the storm time.**

***Index Terms*—Equator; Polar; TEC;**

I. INTRODUCTION

The ionosphere is a region composed of free electrons and positive ions of the atmosphere. The existence of charged particles in the ionosphere itself brings a great influence on the electrical properties within the region thus makes a possibility for communicating over far distances. The ionosphere situated approximately between 50 and 350 km above the Earth’s surface which allows the reflection of the signal to occur. The possibility to communicate over far distances is by multiple hops between the ionosphere and the Earth’s surface. The ionosphere consists of distinct electron density regions which are D, E, F1, and F2 region. D region is situated between 60-90 km, E region is situated between 100-125 km, F1 region is situated around 150-300 km and the F2 region is situated around 350 km. These regions are variable. The D and F1 regions disappear at night and the E region becomes much weaker. Meanwhile, the F2 region tends to remain although at reduced ionization intensity (Zolesi and Cander, 2014).

The radio-wave signals propagation through ionosphere is affected by varying conditions such as reflection, refraction, diffraction, absorption, polarization, and scattering. The phase advance and Doppler shift of a carrier, group time delay of modulation, Faraday rotation of polarization and wedge refraction of the wave direction are dependent on the line integral of the electron density along the ray path through the ionosphere, called as total electron content (TEC) with the unit of 1 TEC unit = 10^{16} electrons/m^2 (TECU). Therefore, total electron content holds an important parameter for the accuracy of radio communication links system by adequate correction representing a limiting error for the accuracy (Sezen et al., 2013). The total electron content measurement is obtained by the following equation:

$$TEC = (STEC)\cos\left[\arcsin\left(\frac{R_E\cos\alpha}{R_E+h}\right)\right] \quad (1)$$

where: STEC = Slant total electron content
R_E = Earth’s radius (6378.137 km)
α = Elevation angle
h = Maximum height of electron density

The characteristic of the spatial and temporal structure of the ionosphere enables the investigation of ionospheric effects on the radio-wave propagation to be made. However, the spatial and temporal TEC is highly varied and influenced by various factors such as geographical location (latitude and longitude), solar activity level, time, seasons, and also geomagnetic activity (Habarulema et al., 2010), (Li et al., 2010). The TEC variation shows prominent changes in geographical location particularly at low latitude (<30°) and high latitude (>60°) because of geographical latitudes. The low latitude is situated near the geomagnetic equator where surrounded by the high current of the electromagnetic field. The high latitude is situated above 60° and particularly the polar region is above 78° in which located near to the polar dipoles and auroral zones.

The TEC variation at low latitude primarily around the equator region is strongly affected by an electromagnetic field that runs horizontally over the magnetic equator. This leads to the massive expansion electrical conductivity over the equator. The E region would experience the ‘electrojet’ current and the F region is subject to electrodynamic lifting called a ‘fountain effect’. These apparent phenomena could disrupt the ionosphere (Olwendo et al., 2012), (Acharya et al., 2010). The TEC variation at high latitude is more complex primarily due to the geomagnetic field runs vertically to connect the outer magnetosphere to the high latitudes. The high latitude is greatly influenced by the outer magnetosphere and the solar wind other than the very high energy emitted from Sun radiation (Shi et al., 2013).

Large diurnal changes occur, particularly in the lower ionosphere. The maximum electron density is around 300 km and it decays steadily at higher altitudes [1]. At night, the F1 region disappears and the E region tends to fall in peak electron density. The electron density in the D region usually cannot be observed as the electron density is extremely low. The peak electron density of F2 region is higher in daytime than at night. It reaches its maximum around noon and tends to fall to its minimum around the midnight. However, at high latitudes, the electron density is majorly depending upon the season, particularly during the long period of sunlight or darkness. The TEC variability observed highest is in equinoxes, followed by summer and the lowest in winter. For the nighttime, the TEC variability is also shown highest in equinoxes [2].

During geomagnetic quiet days, the daily TEC variation show marked day-to-day variations under diurnal, seasonal, and solar intensity factor. However, during geomagnetic disturbance days, additional currents circulate in the ionosphere. The additional currents are strong in high latitudes and are stronger over the night than over the day. The currents are associated with the interaction of solar wind with the magnetosphere. The trapped charged particles spiral around the magnetic equator and formed a ‘ring current’ [3]. These charged particles around the equator influence the electrons in the ionosphere. The magnetic storm disturbance is represented by three phases which are the initial phase, the main phase, and the recovery phase. The degree of geomagnetic disturbance is indicated by some indices, for example, the D_{ST} indices, and the A_E indices [4], [5]. For NKLG station, D_{ST} Index is an indicator that gives the best measure of the geomagnetic storm intensity particularly around the equator and low latitude region. Meanwhile, for NYA1 station, A_E Index was an added indicator to determine geomagnetic storm intensity and its effect on TEC variation, particularly at the high latitude station.

II. DATA AND METHODOLOGY

GPS has been widely used in navigation and communication systems including in TEC monitoring. The International GNSS Service (IGS) has become one of the important sources of real-time TEC observations. The data used for this research were obtained from the IGS, particularly from two receiver stations, namely Libreville, Gabon (0.4162° N, 9.4673° E) and Ny-Alesund, Norway (78.9235° N, 11.9099° E). The timezone used is the universal time (UT) zone, which for the equatorial-latitude station, Libreville station, LT is 1 h ahead of UT. For the polar-latitude station, Ny-Alesund station, LT is 1 h ahead of UT during winter and 2 h ahead of UT during summer.

Required ionospheric data is in the format of RINEX files, IONEX files, and ephemeris files. RINEX files are obtained from Crustal Dynamics Data Information System (CDDIS) server, IONEX files are obtained from Center for Orbit Determination in Europe (CODE) server, and ephemeris files are obtained from IGS data and products server. The D_{ST} and A_E Index data were obtained from the Data Analysis Center for Geomagnetism and Space Magnetism, Kyoto University (http://wdc.kugi.kyoto-u.ac.jp/index.html). The data covered a low solar activity (2009) and a high solar activity (2013).

III. RESULTS AND DISCUSSION

A. Diurnal TEC Variations

The hourly averaged TEC value is used to determine the diurnal TEC variations. The diurnal TEC variations in March, June, September, and December at the respective station during 2009 and 2013 are shown in Figure 1 and Figure 2 below. The diurnal TEC variations in March at the NKLG and NYA1 station exhibited distinctive variation pattern. The diurnal TEC peak at the NKLG station showed the double TEC peak during March and September in 2009, which is similar to the observation found by [6]. [6] claimed that two TEC peaks were found around the March-April at the Brazilian equatorial and low latitude region. The maximum diurnal peak in March 2009 showed its highest TEC of 35 TECU at late evening at 1500 UT. The maximum diurnal peak in September 2009 showed its highest TEC of 29 TECU at 1200 UT. [7] mentioned that TEC over the equatorial zone has a slightly irregular distribution, as such a remarkable double TEC peak-structure in the equatorial area. Besides, [8] also found that there are two TEC peaks at the equinoxes for the low latitude area. The maximum diurnal peak in March and September 2013 was 87 TECU at 1300 UT, and 73 TECU at 1500 UT, respectively.

However, the diurnal TEC variations in June and December 2009 showed its highest TEC value with only one maximum diurnal TEC peak at 1300 UT, respectively. The maximum diurnal TEC peak in June and December were 23 TECU and 33 TECU, respectively. A similar observation was found in the diurnal TEC variations in June and December 2013 where its maximum diurnal TEC peak found at 1400 UT with 79 TECU and 81 TECU, respectively. The TEC variations over the NKLG station in the low and high solar activity depicted the same observation where the TEC variations began to rise until it reached its maximum TEC peak around noon to the late evening, and it falls after the sunset hours until it reached its minimum TEC at pre-dawn hours. It explains the ionospheric TEC behavior at the equatorial region, and it is in agreement to [9], [10], and [11]. Besides, the diurnal TEC variations in 2009 and 2013 also experienced the annual anomaly where the TEC value in December was higher than in June.

The diurnal TEC variations in March, June, September, and December at NYA1 station exhibited more than two peaks of TEC, approximately four peaks of TEC during both years. The TEC variations at NYA1 station was relatively high in temporal and spatial distribution mainly because of the direct solar wind interaction between the magnetopause and ionosphere at the high latitudes. These rapid fluctuations of TEC at NYA1 station indicated the characteristic feature of the polar ionosphere. This is in accordance with the variability of solar radiation and solar zenith angle at high latitude regions. This observation result is in agreement to [12] and [13].

The TEC values observed in March, June, September, and December 2009 varied between 3-9 TECU, 12-15 TECU, 27-41 TECU, and 27-38 TECU, respectively. Meanwhile, the TEC values observed in March, June, September, and December 2013 varied between 35-50 TECU, 37-54 TECU, 34-51 TECU, and 30-47 TECU, respectively. The TEC values observed were higher in September and December 2009 during the polar night. It explains the solar zenith angle plays an important role in higher TEC value around September to December 2009 at the

NYA1 station, and it is in agreement to [14]. Besides, the NYA1 station is located around the auroral oval, thus the rapid fluctuations of TEC observed for all the months during both years might be caused by the influence of the energy particle precipitation within the auroral oval.

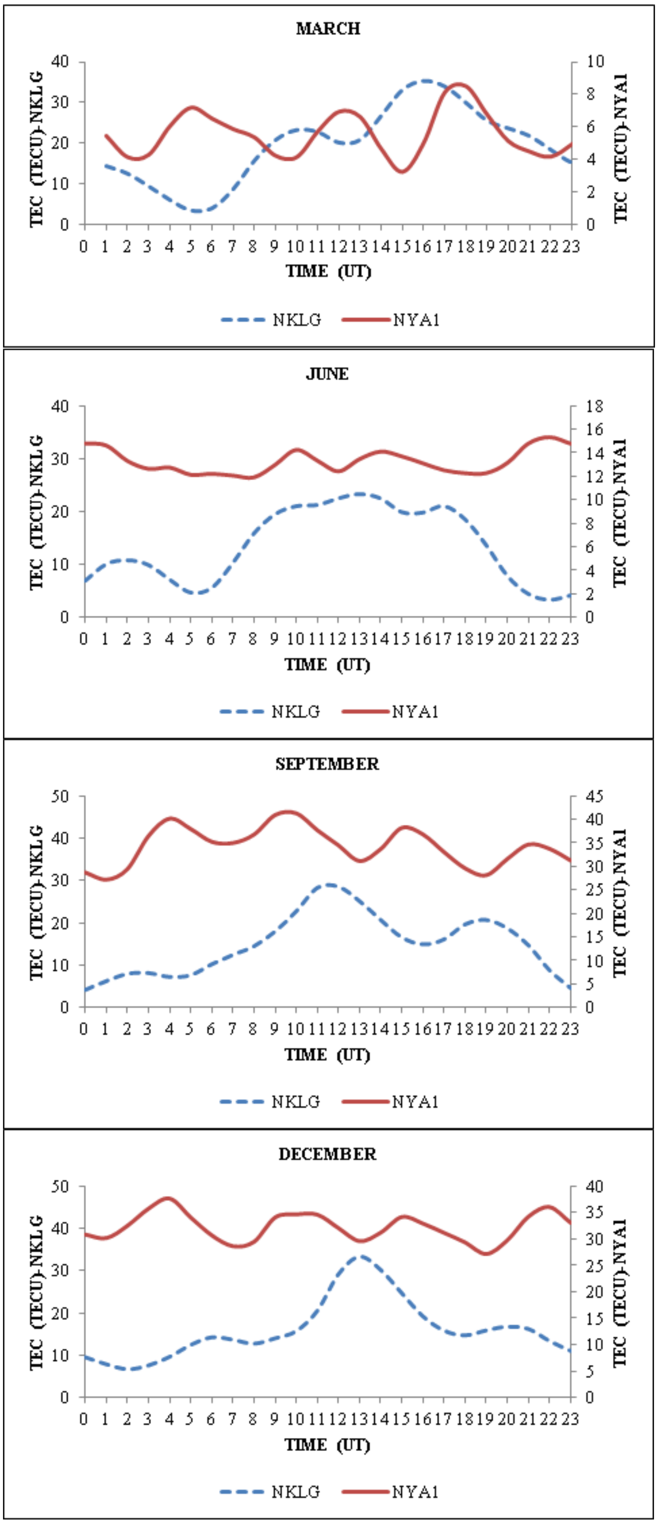


Figure 1: The diurnal TEC variations in 2009. The dotted and solid lines representing NKLG and NYA1 station, respectively.

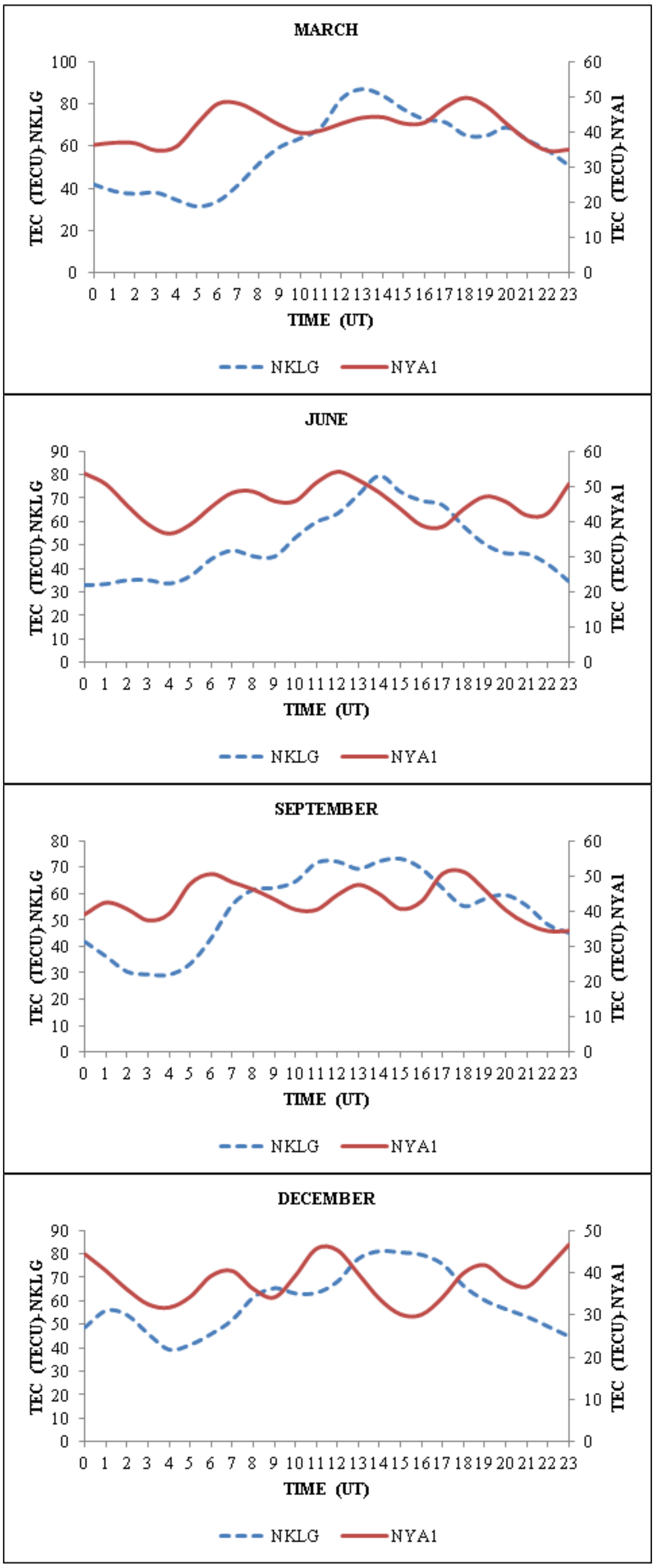


Figure 2: The diurnal TEC variations in 2013. The dotted and solid lines representing NKLG and NYA1 station, respectively.

B. Seasonal TEC Variations

Based on Figure 3 and 4, the seasonal TEC variations showed its highest TEC peak in spring and lowest TEC peak in summer at NKLG station during both 2009 and 2013. The TEC peak in spring 2009 and 2013 were 28 TECU at 1500 UT, and 80 TECU at 1300 UT, respectively, meanwhile the TEC peak in summer 2009 and 2013 were 23 TECU, and 75 TECU, respectively, both at 1400 UT. The TEC peak in spring was higher in 2013 than in 2009 because of the solar activity level, thus, more ionization produced in high solar activity year.

However, the seasonal TEC variations at the NYA1 station for both years showed an indefinite TEC variation pattern. It is because of the great factor of solar zenith angle at the high latitude regions. The great fluctuations of TEC are obviously observed during the winter and spring. The maximum seasonal TEC peak at NYA1 station mainly occurred around the late evening hours to the extent of pre-dawn hours. It is opposite to the TEC behavior at the NKLG station where the maximum seasonal TEC peak mainly occurred around the noon. The seasonal TEC at noon at the NYA1 station for both years were the minimum seasonal TEC. The seasonal TEC variations in 2009 at the NYA1 station ranged 8-36 TECU meanwhile in 2013 ranged 42-49 TECU. It shows the TEC value falls within a higher range in 2013 than in 2009 due to the higher solar activity level.

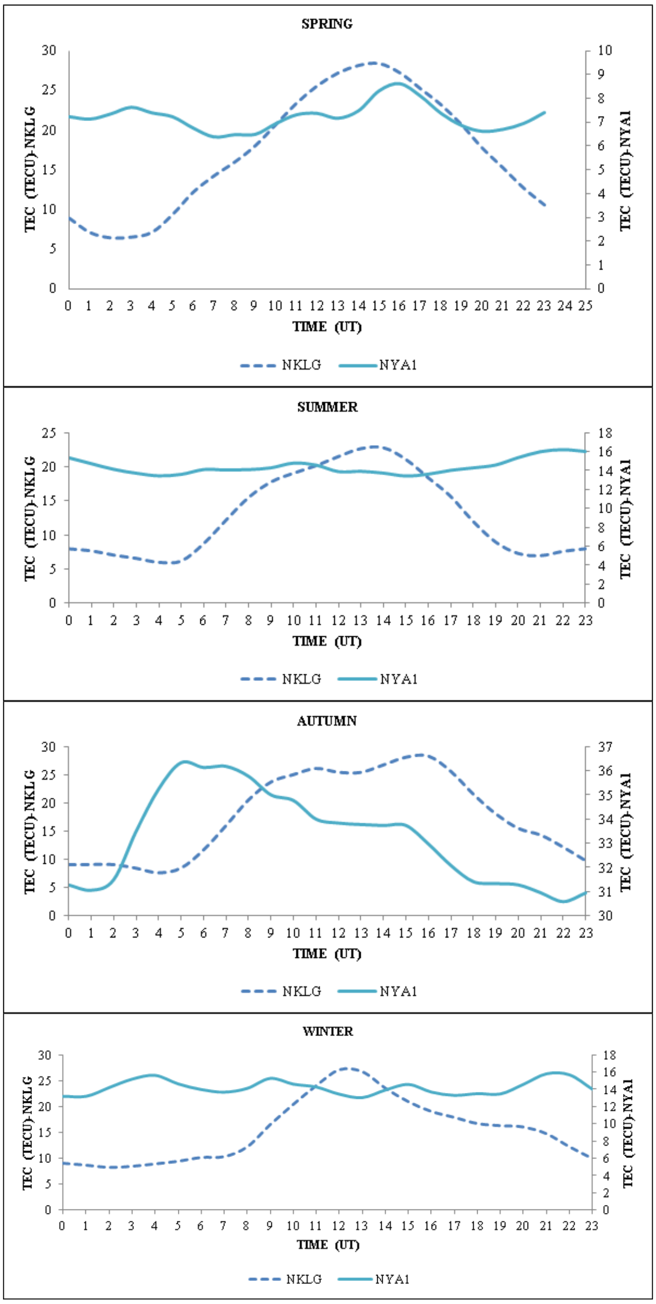


Figure 3: The seasonal TEC variations in 2009. The dotted and solid lines representing NKLG and NYA1 station, respectively.

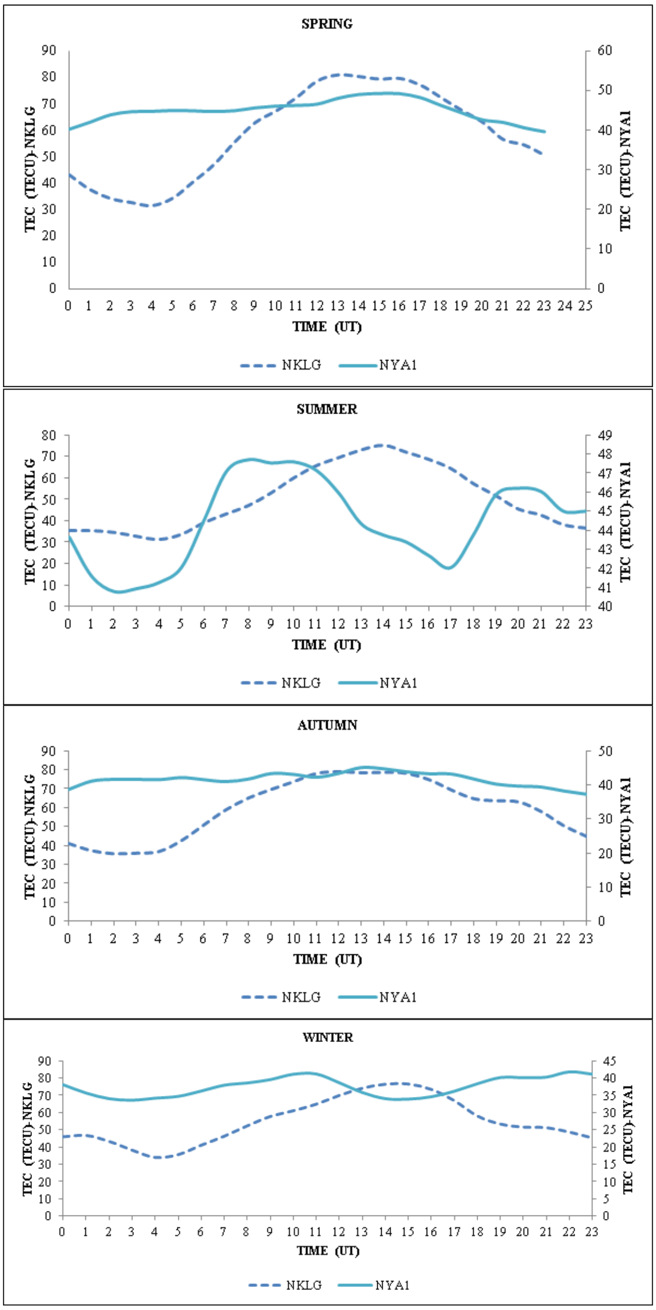


Figure 4: The seasonal TEC variations in 2013. The dotted and solid lines representing NKLG and NYA1 station, respectively.

C. Geomagnetic Storm TEC Variations

Based on Figure 5 and 6, a moderate geomagnetic storm on 22 July 2009 at NKLG station was investigated to determine the TEC variation under disturbed ionosphere. A sudden decrease in D_{ST} value was recorded at storm sudden commencement (SSC) to a minimum value of -83 nT at 0600 UT on 22 July. SSC was observed at 2100 UT on the day before. For the A_E Index, it reached 1400 nT. Based on Figure 7, for the NKLG station, the storm occurred at 0600 UT and the TEC value observed during the time was increased by 3 TECU from 11 TECU to 14 TECU. The percentage increase of TEC was 34%. It is in agreement to [15] where the authors found positive storm indicated that the TEC value increased during storm period. It is also mentioned that the storm on 22 July 2009 may be due to recurring fast solar wind stream. The authors suggested that the positive storm at NKLG station might be due to prompt penetration electric field (PPE) of reverse polarity. It means that the downward direction of E x

B drift velocity due to westward electric field creates the inverse fountain effect thus transporting the plasma back towards the equator. For the NYA1 station, the storm occurred at 0600 UT and the TEC value observed during the time was increased by 1 TECU from 14 TECU to 15 TECU. The percentage increase of TEC was 11%. A correlation analysis done by [16] showed almost no correlation between TEC and geomagnetic activity at the high latitude in low solar activity level. This is opposed to the study done by [17] where the authors observed where there were strong TEC fluctuations during geomagnetic storms found at the high latitude, particularly above the 55°N latitude in low solar activity level.

Based on Figure 8 and 9, a moderate geomagnetic storm on 6 July 2013 at NKLG station was investigated to determine the TEC variation under disturbed ionosphere. The D_{ST} value showed a sudden decrease at SSC to a minimum value of -79 nT at 1800 UT on 6 July. SSC was observed at 2200 UT on the day before. For the A_E Index, it reached more than 2000 nT. Based on Figure 10, for the NKLG station, the storm occurred at 1800 UT and the TEC value observed during the time was decreased by 1 TECU from 50 TECU to 49 TECU. The percentage decrease of TEC was 2%. According to [18], the negative storms are due to composition (O/N_2 density ratio) changes. The authors also found the negative storms occurred at equatorial latitude regions in the American sector. For the NYA1 station, the storm occurred at 1800 UT and the TEC value observed during the time was decreased by 2 TECU from 48 TECU to 46 TECU. The percentage decrease of TEC was 4%.

According to [19], the positive and negative storm effects have occurred during the storm periods and did not follow a definite pattern.

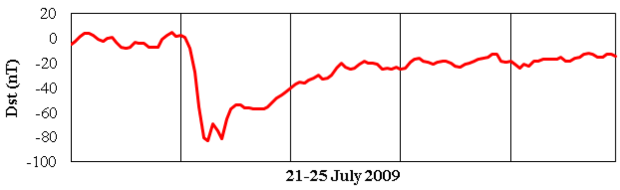


Figure 5: The D_{ST} Index on storm period 2009

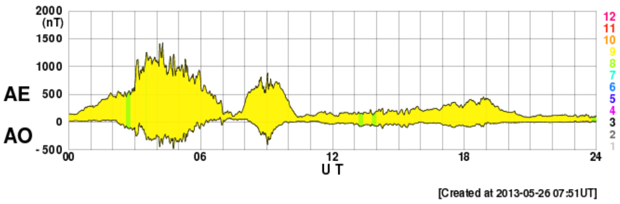
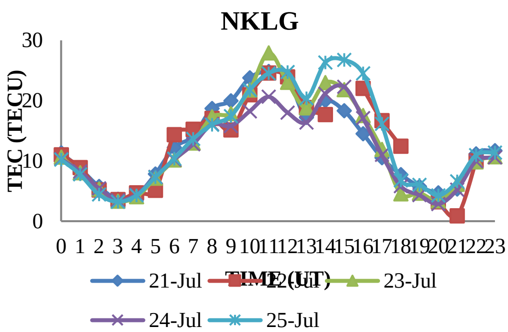
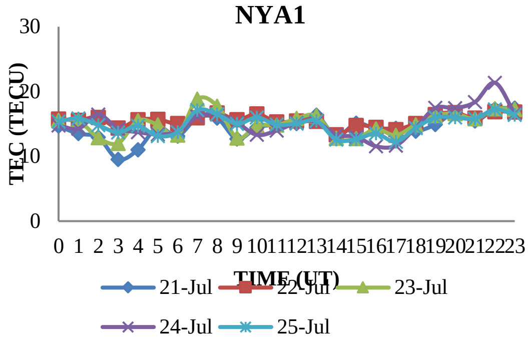


Figure 6: The A_E Index on storm period 2009



(a)



(b)

Figure 7: The storm TEC variations on 21-25 July 2009.

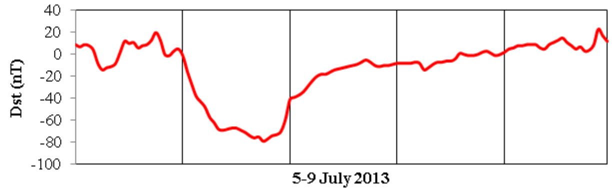


Figure 8: The D_{ST} Index on storm period 2013.

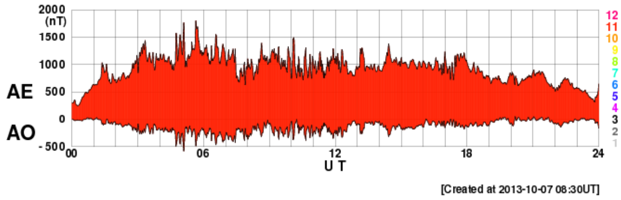
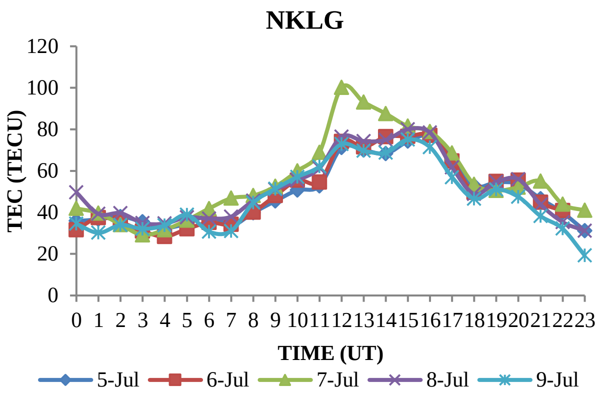
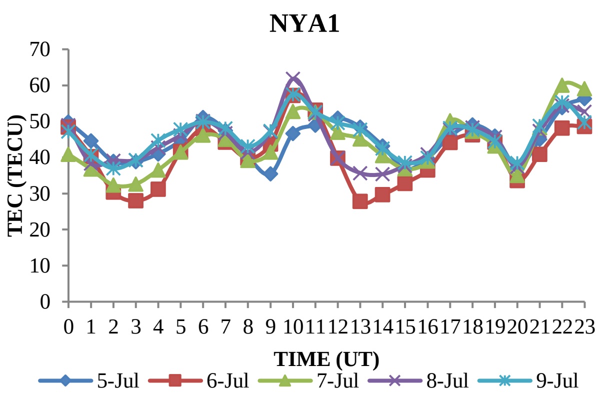


Figure 9: The A_E Index on storm period 2013.



(a)



(b)

Figure 10: The storm TEC variations on 5-9 July 2013.

IV. Conclusion

The diurnal TEC variations in March and September 2009 experienced a double TEC peak structure. The TEC variation over the NKLG station in the low and high solar activity depicted the same observation where the TEC variation began to rise until it reached its maximum TEC peak around noon to the late evening, and it falls after the sunset hours until it reached its minimum TEC at pre-dawn hours. It explains the ionospheric TEC behavior at the equatorial region. The diurnal TEC variations for all months at the NYA1 station showed rapid fluctuations of TEC by the presence of more peaks of TEC. These rapid fluctuations of TEC at NYA1 station indicated the characteristic of the polar ionosphere. This is in accordance with the variability of solar radiation and solar zenith angle at high latitude regions. The seasonal TEC variations showed its highest TEC peak in spring and lowest TEC peak in summer at NKLG station during both 2009 and 2013. The great fluctuations of TEC are obviously observed during the winter and spring. The maximum seasonal TEC peak at NYA1 station mainly occurred around the late evening hours to the extent of pre-dawn hours. The moderate geomagnetic storm on 22 July 2009 caused an increment of TEC at both stations during the storm time meanwhile the moderate geomagnetic storm on 6 July 2013 caused a decrement of TEC at both stations during the storm time. The positive and negative storm effects have occurred during the storm periods and did not follow a definite pattern.

Throughout the investigation on TEC variation at these different latitudes, it will bring beneficial practical applications towards the country. Researchers can use the obtained findings as guidelines to support other findings that run similar investigation by different locations. They can also imply these findings into prognosis databases.

The knowledge of the space weather phenomenon is definitely valuable for further usage by operators, scientists and engineers, for example, warning, mitigating and/or predicting the effect of the space weather conditions. The findings of this work may be used by the government officials as well as constituents from the electric power, telecommunications and emergency management sectors so that they became increasingly aware of the risks posed by space weather. It will be improving the nation's readiness for severe space weather.

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