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TOTAL ELECTRON CONTENT DERIVED FROM GLOBAL POSITIONING SYSTEM DURING SOLAR MAXIMUM OF 2012-2013 OVER THE EASTERN PART OF THE AFRICAN SECTOR

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ABSTRACT

This work presents results of diurnal, seasonal and latitudinal variations of vertical Total Electron Content (TECv) derived from GPS receivers at four locations, [Dodoma (6.19^{o}S, 35.75^{o}E), Mzuzu (11.43^{o}S, 34.01^{o}E), Zomba (15.38^{o}S, 35.33^{o}E) and Tete (16.15^{o}S, 33.58^{o}E)] during the solar maximum period of 2012 – 2013. The receivers are located directly below the EIA and at approximately the same longitude, ~ (33 – 3 ^{o}E) within the eastern part of the African sector. Diurnal and latitudinal variations of TECv are presented for an average of the five (5) quietest days of each of the four seasons: March equinox, June solstice, September equinox and December solstice; for the seasonal variations all months in a year were considered. Results showed that TECv is characterized by consistent minimum diurnal variations during presunrise hours, rises steeply during the sunrise period to the maximum peak during the daytime, followed by a decrease to a minimum during nighttime. The values of TECv from all stations used and for both years (2012 and 2013) showed semiannual variations. Our study also showed that, the day maximum value of the TECv decreased significantly with the increase in latitude.

Keywords: Global Positioning System, Total Electron Content.

INTRODUCTION

Scientific studies aimed at developing a better understanding of the physical and chemical processes taking place in the ionosphere and plasmasphere have been undertaken using a wide range of tools, including the Global Positioning System (GPS). The primary functions of the GPS have been to provide users with navigation, positioning and time information on a global scale (Norsuzila et al. 2010). However, in the recent past it has become popular for providing information about the total electron content (TEC) within the ionosphere (Liu et al. 2013).

Derivation of TEC from GPS is based on the fact that, ionospheric refraction introduces time delays on the GPS signals on their path from the GPS satellite, at a height of about 20,000 km, to a receiver on the ground (Chauhan et al. 2011, Oron et al. 2013). Variations in TEC cause fluctuations in the amplitude and phase of the GPS signals as they transit the ionosphere. The amount of the time delay produced by the ionosphere is directly proportional to the TEC along the path from a satellite to a tracking receiver (Zewdie 2012).

The variations at low and equatorial latitudes are high since the size and variability of the free electron density is usually the largest in these regions. Several studies have been conducted on TEC variability at equatorial and low latitudes regions (example: Bagiya et al. 2009, Norsuzila et al. 2010, Chauhan et al. 2011, Oron et al. 2013).

Oron et al. (2013) studied the Ionospheric TEC variations during the ascending solar activity phase at an equatorial station, Kampala (0.3^{o}N, 32.6^{o}E) in geographic coordinates, in Uganda. They observed that, equinoctial months showed higher TEC values than solstice months. They also observed that, the diurnal pattern of TEC exhibits a steady increase from about sunrise to an afternoon maximum and then falls to attain a minimum just before sunrise. Similar pattern was observed at other equatorial stations by Bagiya et al. (2009) at Rajkot (22.3^{o}N, 70.8^{o}E), India, Leong et al. (2011) using GPS data from MyRTKnet in Malaysia which covers approximately the area from 0°N to 7.5°N and from 95°E to 120°E and Bolaji et al. (2012) at Ilorin (8.47°N, 4.68°E), Nigeria using GPS receiver for the year 2009. Leong et al. (2011) observed a gradual increase in TEC with decreasing latitude. Warnant et al. (2000) investigated the variation of the TEC with solar activity at three stations in Belgium, Dentergem (50.95^{o}N, 3.4^{o}E), Brussels (50.85^{o}N, 4.33^{o}E) and Waremme (50.68^{o}N, 5.25^{o}E) and reported higher values of TEC with increasing solar activity. Perevalova et al. (2010) in their study of diurnal TEC behavior using Global Ionospheric Maps (GIMs) observed the solar activity sensitivity of TEC to be stronger in the daytime than at night and more evident at lower latitudes.

There has not been much investigation of the day-to-day variations in TEC over the eastern part of the African sector. Few studies done over this region have been mainly focused in the northern part of the region which lies along the equatorial region. Examples include: Oron et al. (2013) at an equatorial station, Kampala (0.3^{o}N, 32.6^{o}E) in geographic coordinates, located in Uganda and Olwendo et al. (2012) over the Kenyan region ((Malindi: 2.9^{o}S, 40.1^{o}E) and (Nairobi: 1.2oS, 36.8oE)) during a very low solar activity phase. The region within 12^{o}S to 27^{o}S geomagnetic coordinates (~ 6^{o}S to 17^{o}S geographic coordinates) has not been studied due to lack of data in these areas. However, a number of GPS receivers have been installed at various locations over this region since 2010.

In this paper the results of the diurnal, seasonal and latitudinal variations of TEC derived from GPS receivers at four locations across the eastern part of the African sector during solar maximum 2012 – 2013 are presented.

MATERIALS AND METHODS

This study has been carried out by analyzing the ionospheric TEC derived from the Africa array and IGS network of ground based dual-frequency GPS receivers located directly below the Equatorial Ionization Anomaly (EIA) and at approximately the same longitude, ~ (33 – 35) ^{o}E within the eastern part of the African sector. Stations used were Dodoma (6.19^{o}S, 35.75^{o}E), Mzuzu (11.43^{o}S, 34.01^{o}E), Zomba (15.38^{o}S, 35.33^{o}E) and Tete (16.15^{o}S, 33.58^{o}E), all in geographic coordinates. Figure 1 presents the map view of the locations of these stations in the region, and Table 1 shows both geographic and geomagnetic coordinates of the stations used. The GPS data from these stations were accessed from the UNAVCO website (http://www.unavco.org/).

The slant TEC (TECs) is obtained using equation (1).

$$TECs = \frac{1}{40.3}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)(P_1 - P_2) \qquad (1)$$

where P_1 and P_2 are pseudoranges observable on L1 and L2 signals, f_1 and f_2 are the corresponding high and low GPS frequency respectively.

Since the electron content is measured from different satellites with differing elevation angles, the TECs are converted into corresponding vertical TEC (TECv) by assuming the ionosphere to be compacted into a thin shell at a height h, where in this study h is 400 km. In order to obtain TECv from the TECs which is measured at the time interval of 30 s, a mapping function M(e) (equation 2) is used, which takes the curvature of the Earth into account as given by Klobuchar (1986) as follows: .

$$M(e) = \left[1 - \left(\frac{\cos(e)}{1 + h/R_E}\right)^2\right]^{-\frac{1}{2}} \qquad (2)$$

Here *e* is an elevation angle of a satellite and R_E is the Earth's mean radius.
Thus,

$$TECv = M(e) \times TECs - (b_s + b_r + b_{rx}) \qquad (3)$$

where b_S is satellite bias, b_r is a receiver bias and b_{rx} is a receiver interchannel bias.

To calculate TECv, the GPS-TEC processing software developed at the Institute for Scientific Research, Boston College, U.S.A. by Gopi K Seemala (http://seemala.blogspot.com) was used. This software reads raw data, processes cycle slips in phase data, reads satellite biases from International GNSS Service (IGS) code file (if not available, it calculates them), calculates receiver bias, and calculates the interchannel biases for different satellites in the receiver.

To ensure the obtained data have no unwanted errors which might result from the effect of multipath, a minimum elevation angle of 30° was used. In order to get a single curve for a day from many values of TECv which are obtained at a time from different satellites, an average of all TECv was done

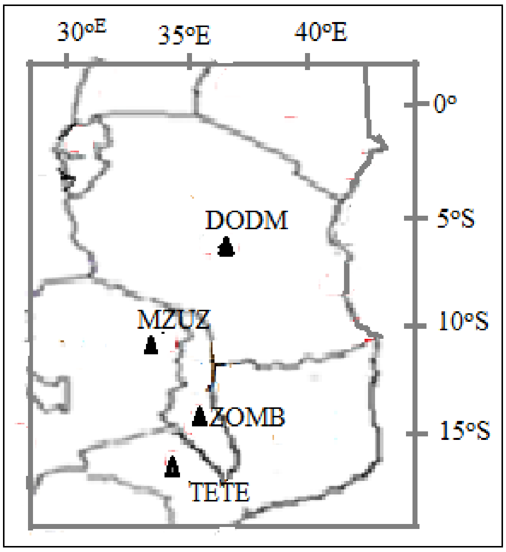

Figure 1: A map of Eastern Africa region showing the locations of GPS receivers used in this study

We studied the diurnal and latitudinal variations of TECv by taking the average of the five (5) international geomagnetic quiet days of each of the four seasons in a year: March equinox, June solstice, September equinox and December solstice, derived from all the visible satellites from the four stations located directly below the EIA within the eastern part of the African sector. On the other hand, the seasonal variations of TECv were obtained by taking the average of the five (5) quietest days of each month for all months in the two years used in this study. The international geomagnetic quiet days are accessible at the World Data Center for Geomagnetism, Kyoto website (http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/qddays-cgi).

Table 1: Geographic and geomagnetic coordinates of the stations used in this study

Station	Geographic Coordinates		Geomagnetic Coordinates	
Code	Latitudes	Longitudes	Latitudes	Longitudes
DODM	6.19°S	35.75°E	16.10°S	107.22°E
MZUZ	11.43°S	34.01°E	21.88°S	104.92°E
ZOMB	15.38°S	35.33°E	26.07°S	105.58°E
TETE	16.15°S	33.58°E	26.94°S	103.66°E

RESULTS AND DISCUSSIONS

The results presented here are from the analysis of TECv values measured by GPS receivers from four stations, Dodoma, Mzuzu, Zomba and Tete. The TECv obtained from these stations were examined for diurnal, seasonal and latitudinal variations. It was found that characteristics of TECv depend primarily on the time of the day, season of the year and on the position of the station with respect to the magnetic (geographic) equator.

Diurnal Variations of TECv

The diurnal variations of TECv for equinoxes and solstices months for all selected stations are shown in Figures 2 - 5. It can be observed from these Figures that TECv was characterized by consistent minimum diurnal variation during the night, rises steeply during the sunrise period at approximately 04:00 UT (07:00 LT) to the maximum peak during the daytime, between 12:00 and 14:00 UT, followed by a decrease to a minimum during nighttime. The observed trend of the daytime TECv variation in this region is complicated due to the transition dynamics between the low and the mid-latitudes regions. Also the post noon maxima vary differently from one season to another. In addition to that, in this region, the duration of the day maximum was observed to increase with increasing latitude.

Figure 2 shows the variations of TECv at Dodoma for (a) 2012 and (b) 2013; for this station the results showed complex and irregular variations of TECv especially during afternoon hours, and the pattern varied from day to day. The complexity and irregularity were more evident during equinox months than during solstice months. This could be due to the combined effect of various physical mechanisms and dynamics in this region (Liu et al. 2013) because the Dodoma station (geog. lat. 6.19°S and magn. lat. 16.10°S) lies in the region which at certain times falls in low latitude region when EIA expands, and at other times not, depending on solar activity condition.

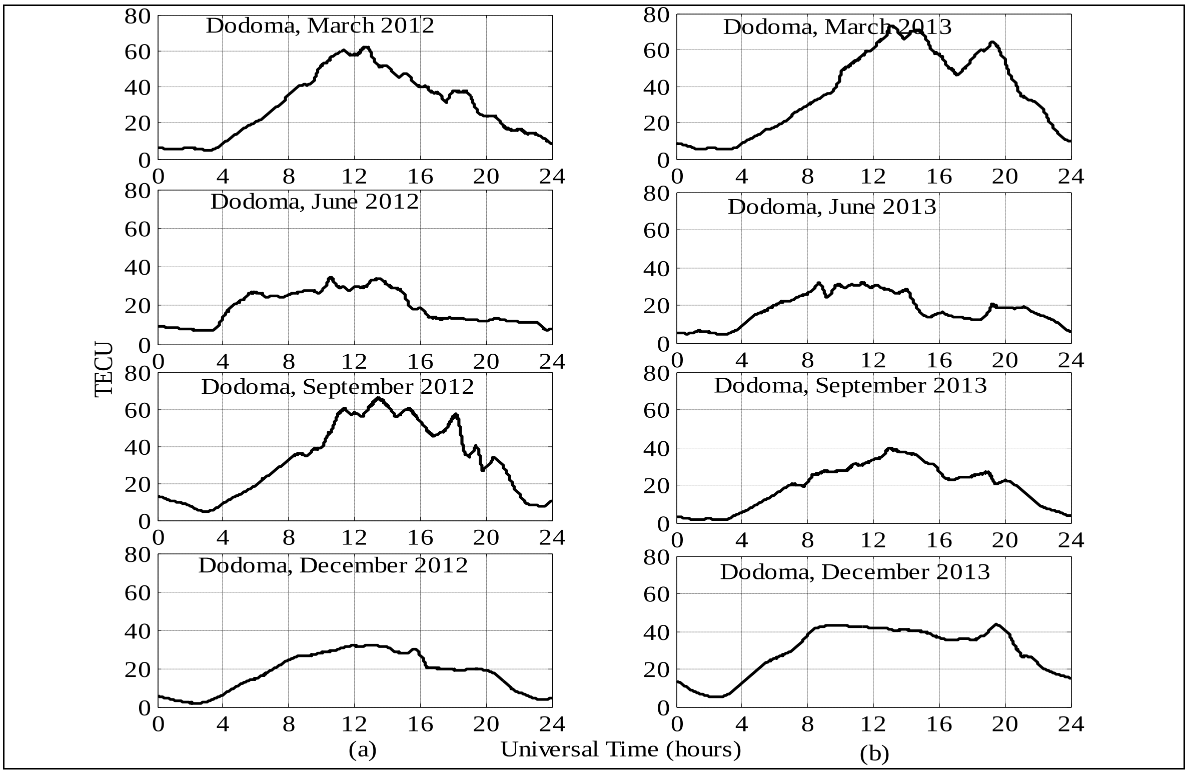

Figure 2: Diurnal variations of TECv for typical quiet days for equinoxes and solstices months at Dodoma for (a) 2012 (left panel) (b) 2013 (right panel).

The results of diurnal variations of TECv from Mzuzu are presented in figure 3. There were no data for September equinox and December solstice at this station for the year 2013.From the results, TECv variations during March equinox for both years and during September equinox for 2012, showed pre-reversal enhancement, although the times of occurrence differ between these two distinctly equinoxes. The results also showed that, the daytime maximum peak during June solstice for both years was broad but low as compared to other periods. The daytime maximum peak here was observed to start at around 6:00 UT and ended at around 14:00 UT. Further, during December solstice of 2012, the daytime maximum peak was noted to occur a bit late compared to other seasons, i.e. at around 15:00 UT. From the Figure, it is also seen that, from around 2:00 UT to 3:00 UT of December 2012, TECv variations showed enhancement but this was likely caused by data irregularities during that time.

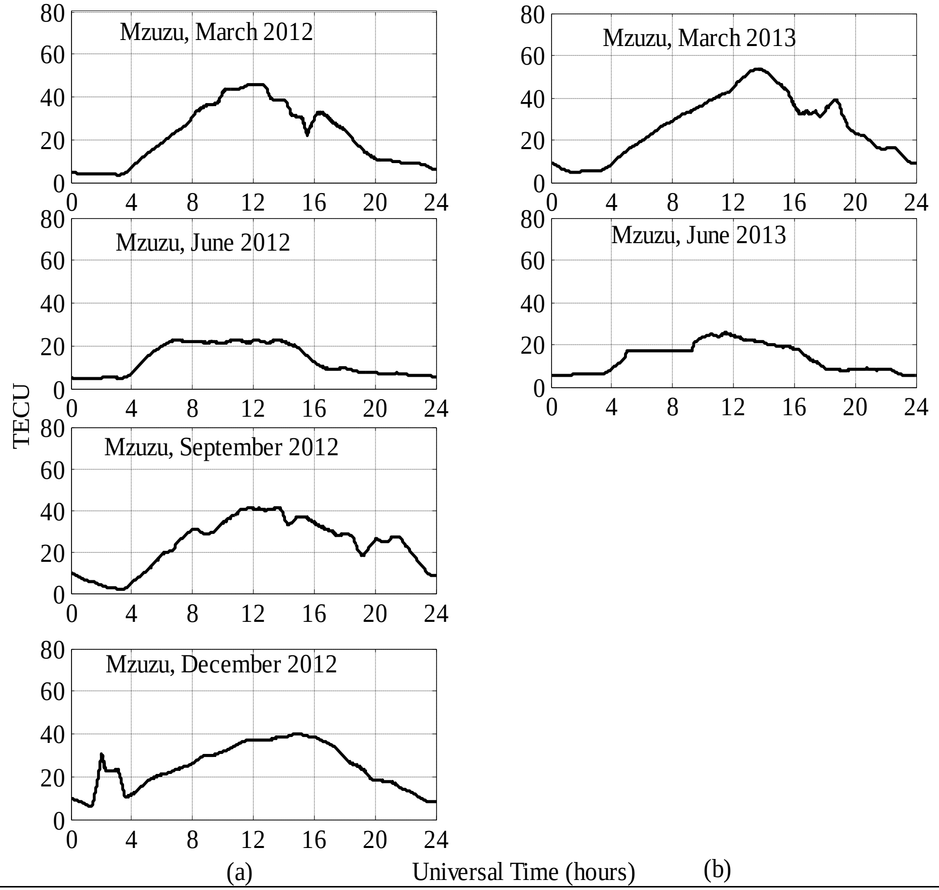

Figure 3: Diurnal variations of TECv for typical quiet days for equinoxes and solstices months at Mzuzu for (a) 2012 (left panel) (b) 2013 (right panel).

Figure 4 presents the variations of TECv at Zomba for (a) 2012 and (b) 2013. Unlike the behaviour of TECv of attaining the maximum peak between 12:00 UT and 14:00 UT, here the daytime maximum peak is broad during June solstice for both years and during December for 2013. This broad maximum peak was observed to start even before 8:00 UT and goes up to around 14:00 UT. On the other hand, during December solstice, the maximum peak goes up to 17:00 UT for 2012, and up to 20:00 UT for 2013.

Figure 5 presents the results for variations of TECv at Tete during (a) 2012 and (b) 2013. As for Zomba station, it is clearly observed that, the daytime maximum peak is broad during June solstice for both years and during December for 2013. The broad daytime maximum variation of TECv begins as early as around 8:00 UT and extends widely to around 15:00 UT. During December solstice of 2013, the daytime maximum extends to around 20:00 UT. For equinoxes, the day maximum peak occurred between 12:00 UT and 14:00 UT and was higher than those for solstices.

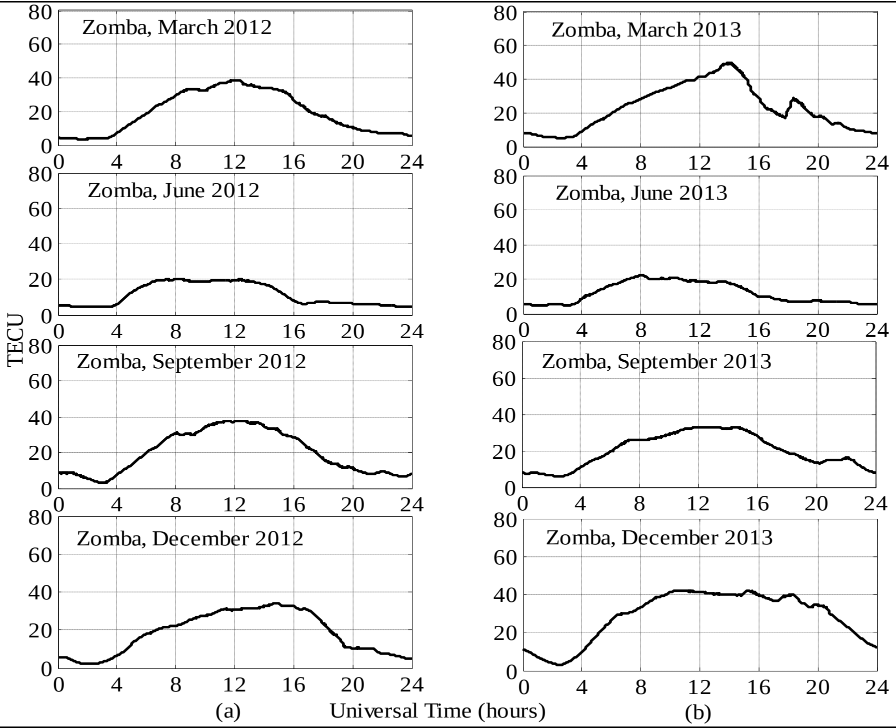

Figure 4: Diurnal variations of TECv for typical quiet days for equinoxes and solstices months at Zomba for (a) 2012 (left panel) (b) 2013 (right panel)

The diurnal variation in TECv is caused by the daily rotation of the Earth about its own axis following the apparent movement of the Sun. However, the net diurnal change in the quiet day low latitude ionosphere mostly depend on the photo-ionization production and recombination losses associated with the local solar radiation and the field-aligned diffusion of the transported electrons from the equator (Panda et al. 2015). As the sun rises, the ionization increases and results into more concentration of electron near the F2 peak at the ionosphere. This process influences an increase of TECv where it attains maximum value at the local noon time (Adebiyi et al. 2014, Chakraborty et al. 2014).

In addition, during the day, as the radiation from the sun increases, the temperature of the ionosphere also increases which then cause the loss rate of ions to increase until when it overcomes the production rate, then gradually TECv starts to decrease. Furthermore, following a dying down of solar EUV production after the sunset, the small amount of TEC values which are observed during the night hours are influenced by the downward **E** × **B** drift velocity, which makes the ionosphere to be lowered to altitudes where the chemical losses are larger (Bolaji et al. 2012, Oron et al. 2013). These TECv chemical losses are further built up continuously up to the midnight until presunrise hours. The study by Purohit et al. (2011) reveals that, the variation of TECv shows much dependence on solar radiation flux than on any other parameter. Chauhan et al. (2011) and Oron et al. (2013) attributed the night time decrease in TECv to the size of the magnetic flux tubes. These tubes are so small such that the electron content in them subsides so rapidly after sunset due to the low temperatures in the thermosphere in the night leading to low TEC values. After the sunrise, the magnetic field tubes are again filled resulting in the rapid increase in ionization.

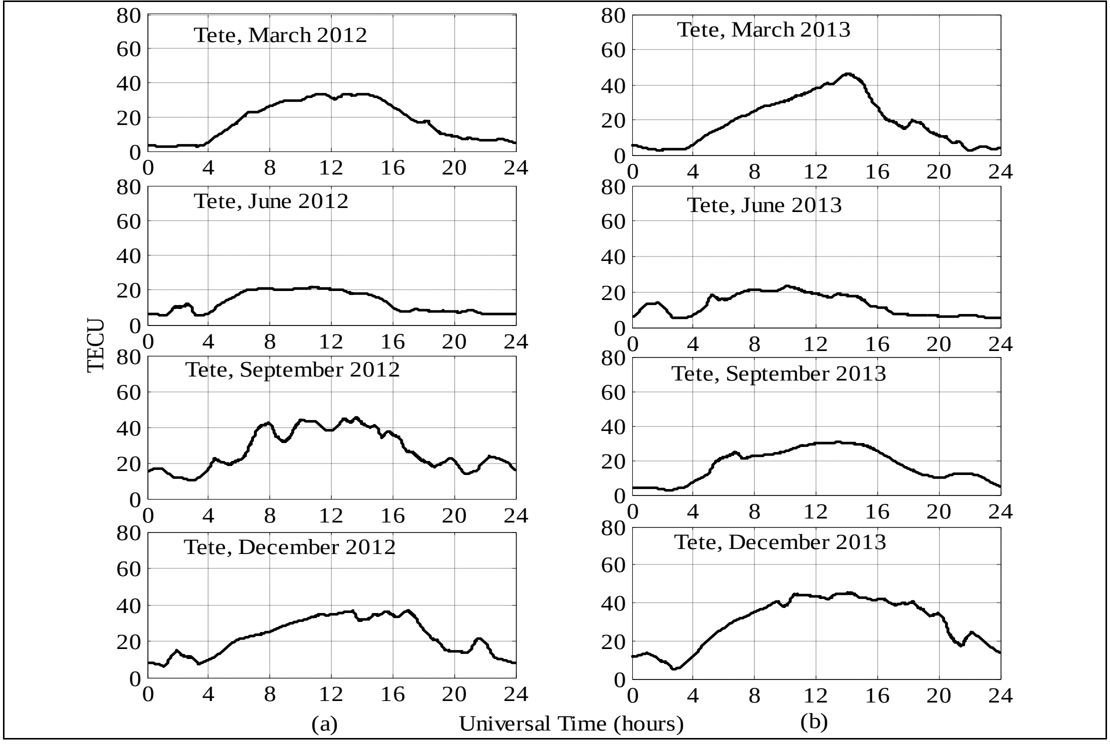

Figure 5: Diurnal variations of TECv for typical quiet days for equinoxes and solstices months at Tete for (a) 2012 (left panel) (b) 2013 (right panel).

On the other hand, the post-sunset enhancement in TECv is caused by the fountain effect pattern of plasma motion that occurs in the equatorial regions flowing along the earth's magnetic field lines of force. Furthermore, the zonal and meridional components of the prevailing neutral winds contribute in occurrence of this phenomenon as reported by Horvath and Essex (2000) and Shim (2009). Also, many investigations reveal that the equatorial electric field has an influence in the variations of the equatorial and low latitude F2 layer ionosphere under both geomagnetically quiet and active conditions (Huba et al. 2005, Maruyama et al. 2007, Liu et al. 2008).

Seasonal Variations of TECv

The seasonal variations of TECv are presented in Figures 6. From the figure it is clearly observed that the seasonal variations of the TECv are modulated by the levels of solar activity. The observation from the figure shows that, the maximum values of TECv occurred between 9:00 UT and 14:00 UT, and the minimum values occurred during night time hours, i.e. from 19:00 UT through 5:00 UT.

The highest values of TECv were observed to occur during September, October and November, and January, February and

March, whereas the minimum values occurred during June and July. For the year 2012, the highest values of TECv of about 65 – 70 TECU were observed during October at Dodoma, whereas at Mzuzu it was observed during October and November. For 2013, the highest values of TECv of the same amount, about 65 – 70 TECU, were observed to occur during March and October at Dodoma.

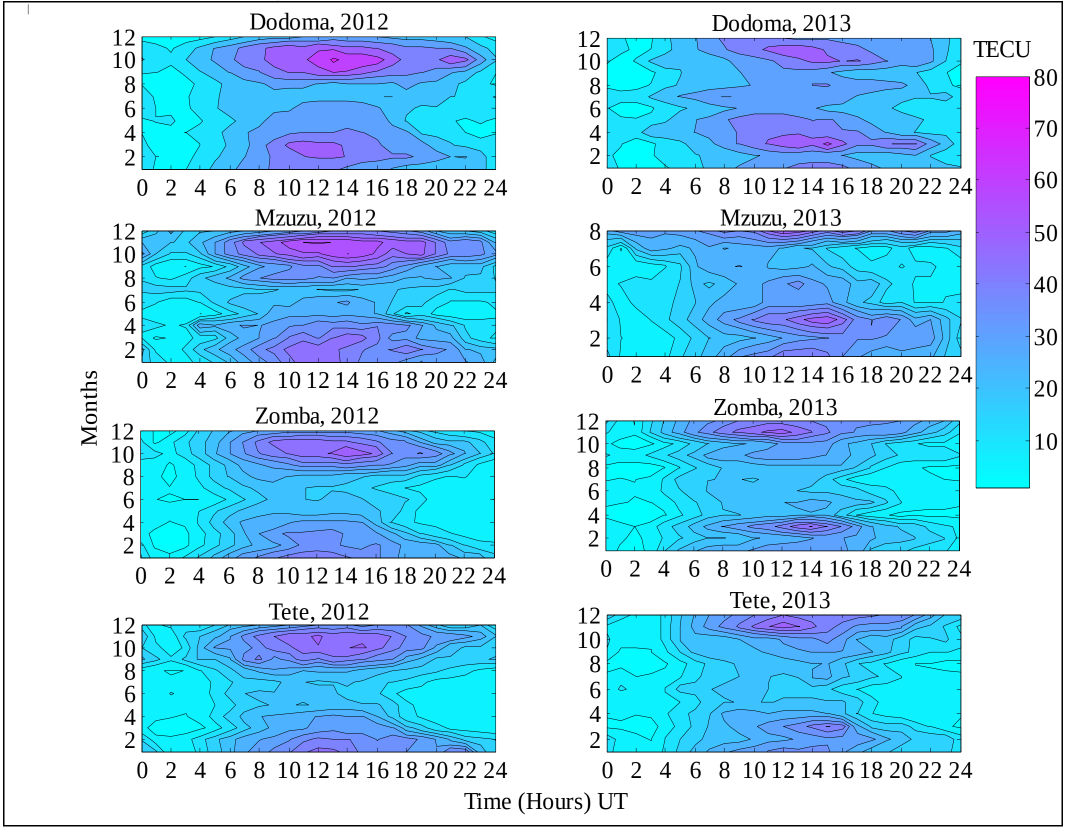

Figure 6: Seasonal variations of GPS derived TECv over the eastern African region for the year 2012 (left panel) and 2013 (right panel).

On the other hand, December solstice showed higher values of TECv than June solstice. This is influenced by the fact that, the stations used are located in the southern hemisphere where solar radiations are higher during December solstice than June solstice, and this is contributed by the fact that, sub-solar point is in the southern hemisphere where GPS stations are located (Purohit et al. 2011). Another explanation for this characteristics of TECv was given by Akala et al. (2013) which suggested that the southern hemisphere during the December solstice might have received more energy than the northern hemisphere because the offset between the geographic and magnetic poles is larger in the southern hemisphere.

The values of TECv from all stations used and at both years (2012 and 2013) showed semiannual variations. The two peaks exhibited were observed to occur during March and October/November for each year. Several authors have suggested different mechanisms for the occurrence of semiannual variations of TEC in the ionosphere. Bergeot et al. (2013) suggested that the variation of [O/N_2] contributes as a controlling factor for the semiannual variation of TECv at middle and low latitudes. This effect is due to electron density variation which is owing to the changes of the temperature, composition or both (Nagar et al. 2015). Seaton (1956) first proposed that increasing the N_2 concentration leads to a decrease in the number of electrons, while decreasing the N_2 concentration leads to enhanced electron densities. Hence, the decrease in O/N_2 ratio will result in higher electron density and therefore highest values of TEC during equinoctial months (Rama Rao 2006, Bagiya et al. 2009). Scherliess and Fejer (1999) proposed that semiannual variation is due to larger daytime **E × B** drift velocities in the equinoctial months (February, March, April, August, September, and October) and winter months (November, December, and January) than in the summer months (May, June, and July). Millward et al. (1996) explained the ionospheric semiannual variations based on the variations in the solar EUV input due to the global thermospheric circulation. Bailey et al. (2000) attributed semiannual variation by the variation of the noon solar zenith angle which is an essential factor for the production of ionization. In addition, semiannual variation is due to the fact that, in the low and middle latitude region, the ionospheric plasma density is primarily influenced by the solar zenith angle, where the effect of neutral composition during equinox is exceeded by the effect of solar zenith angle and causes the greater plasma density during equinox than during solstices (Zhao et al. 2008).

Latitudinal variations of TECv

The results of latitudinal dependence of TECv variation are presented in Figure 7. General observations from the figure show that, the day maximum values of the TECv decreased significantly with the increase in latitudes southwards, especially during March equinoxes and June solstices for both years.

The values of TECv between 10:00 UT to 17:00 UT were observed to differ from one season to another, taking the values between 30 TECU and 55 TECU as observed in Figure 7. During night time hours, the values of TECv were almost the same in all seasons. However, higher values of TECv, of about 40 TECU to 55 TECU were observed at the midday during September equinox and December solstice at all stations. This result agrees with the study by Rama Rao et al. (2006) from the Indian network of GPS receivers, and also a study by Leong et al. (2011) at Malaysia from 2003 - 2009. This is because the solar radiation becomes more oblique to the atmosphere with the increase in latitude in either hemisphere, thus, the intensity of radiation and production of free electrons decrease with increasing latitude. This scenario influences the gradual increase of TECv towards the anomaly crest regions, and the decrease further from the anomaly crest until it attains lower value at mid-latitude regions (Panda et al. 2015).

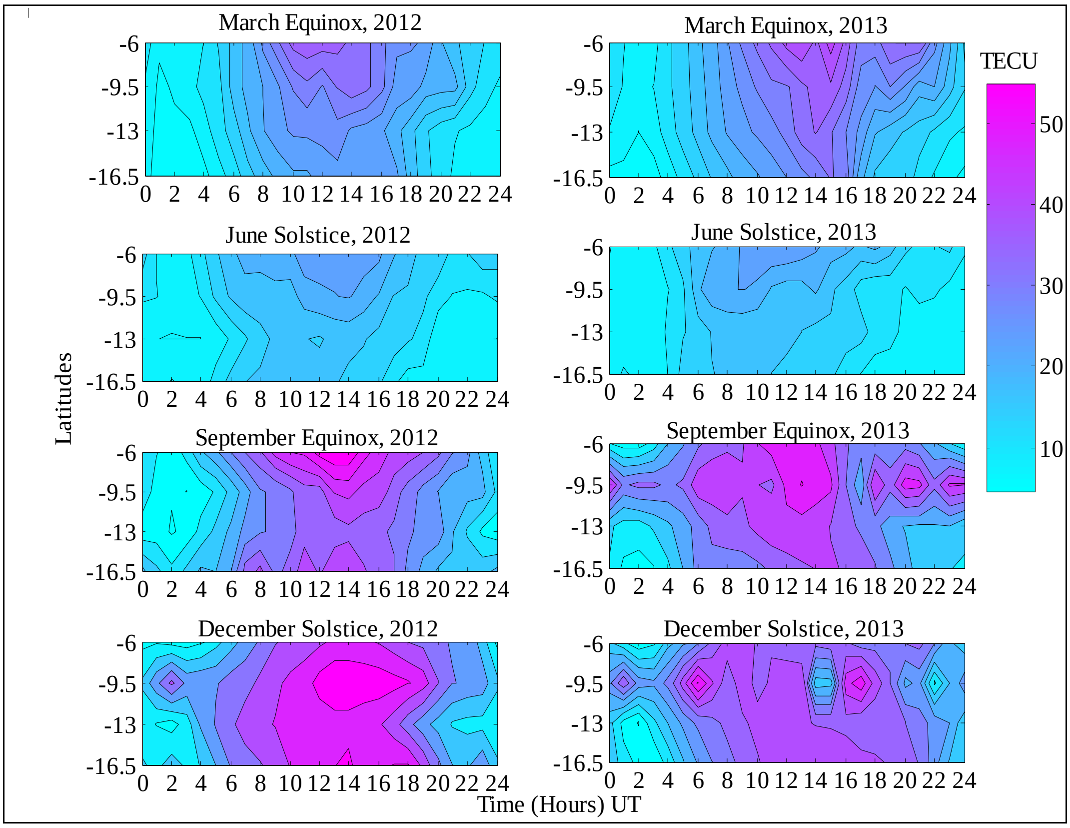

Figure 7: Latitudinal variations of TECv over the eastern Africa region for the year 2012 (left panel) and 2013 (right panel) (all latitudes in ^{o}).

CONCLUSIONS

This study has been carried out by analyzing the ionospheric TEC derived from the Africa array and IGS network of ground based dual-frequency GPS receivers within the eastern part of the African sector from four Stations namely, Dodoma (6.19^{o}S, 35.75^{o}E), Mzuzu (11.43^{o}S, 34.01^{o}E), Zomba (15.38^{o}S, 35.33^{o}E) and Tete (16.15^{o}S, 33.58^{o}E). From the results presented, TECv is characterized by consistent minimum diurnal variation during the night, rises steeply during the sunrise period at approximately 04:00 UT (07:00 LT) to the maximum peak during the daytime, between 12:00 and 14:00 UT, followed by a decrease to a minimum during nighttime again. It was also noted that, TECv variations at Dodoma showed complex and irregular variations especially during afternoon hours and varied from day to day without remarkable pattern. These complex variations are more evident during equinox months than during solstice months. The daytime maximum peak observed at Mzuzu, Zomba and Tete was broad but low as compared to other periods especially during June solstice.

From seasonal observations, the highest values of TECv were observed to occur during September, October and November, and January, February and March, whereas the minimum values occurred during June and July. Also the values of TECv from all stations used and at both years showed semiannual variations.

The latitudinal variations of TECv showed that, the day maximum value was decreasing with the increase of latitudes. During night time hours, the values of TECv were almost the same in all seasons and at all latitudes.

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