Spatial gradient of total electron content (TEC) between two nearby stations as indicator of occurrence of ionospheric irregularity

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Abstract. The relation between the occurrence of ionospheric irregularity and the spatial gradient of total electron content (TEC) during the post-sunset hours over the equatorial region is studied. Different instruments and techniques have been applied to study the behavior of these ionospheric irregularities. In this study, the Global Positioning System (GPS) based derived TEC was used to investigate the relation between the spatial gradient of TEC between two nearby located stations and the occurrence of ionospheric irregularity over the East Africa longitudinal sector. The gradient of TEC between the two stations (ASAB: 4.34° N, 114.39° E and DEBK: 3.71° N, 109.34° E, geomagnetic) located within the equatorial region of Africa were considered in this study during the year 2014. The rate of change of TEC based derived index ($ROTI$, $ROTI_{ave}$) is also used to observe the relation between the spatial gradient of TEC and the occurrence of ionospheric irregularities. The result obtained shows that most of the maximum enhancement/reduction in the spatial gradient of TEC observed in March and September equinoxes are more pronounced between 19:00 LT - 24:00 LT as the large-scale ionospheric irregularities do. Moreover, the observed spatial gradient of TEC shows two peaks (in March and September) and they exhibit equinoctial asymmetry where the March equinox is greater than September equinox. The maximum enhancement/reduction in the gradient of TEC and $ROTI_{ave}$ during the evening time period also show similar trends but after 1-2 hrs from the equatorial electric field (EEF).

The correlation between the spatial gradient of TEC and ROTI show a moderate correlation ($C = 0.58$ over ASAB, $C = 0.53$ over DEBK). In addition to latitudinal gradients, the spatial gradient of TEC has a significant contribution on the computation of TEC fluctuation. The spatial gradient of TEC between the two nearby located stations could be used as an indicator of the occurrence of ionospheric irregularities over both stations. The spatial gradient of electron density (TEC) near solar-terminator obtained from two nearby located Global Navigation Satellite System (GNSS) receivers may be used as an alternative method to estimate the strength of the zonal electric field.

Key words: Spatial gradient of TEC, $ROTI_{ave}$, ionospheric irregularities
1 Introduction

The ionosphere, which consists of free electrons and ions, frequently experiences irregular electron density. After sunset, the ionospheric plasma interchange instabilities present in the equatorial/low-latitude ionosphere generate large-scale depletions in the ambient electron density which leads to the formation of plasma density irregularities that affect radio communication and navigation system (Basu and Basu, 1981). The generation of the plasma irregularities can be related to the decrease in plasma production immediately after sunset and the fast recombination rate in the E-region ionosphere, which results in a steep gradient in electron density. The large enhancement of F region vertical plasma drift in the evening hours attests to the presence of enhanced eastward electric field is also another parameter which controls the generation of plasma density irregularities (Fejer, 1991; Fejer et al., 2008). This pre-reversal enhancement (PRE) in the vertical plasma drift moves the F region to higher altitudes (Abdu et al., 2009). When the altitude of F-region is high enough to overcome recombination effects, the Rayleigh-Taylor (R-T) instability mechanisms initiates growth in plasma fluctuations. The R-T instability considered primary responsible for the generation of ionospheric plasma density irregularities or plasma bubbles in equatorial and low-latitude region (Rao et al., 2006a; Fejer et al., 1999). Kelley (2009) reported that the existence of equatorial plasma bubbles (EPB) is attributed to the instability of the R-T plasma which is triggered by the intensification of the eastward equatorial electric field just before its reversal. The characteristics of ionospheric scintillation and ionospheric irregularities over the equatorial and low-latitude region in different longitudinal sectors during different solar and geomagnetic activities has been studied (e.g., Burke et al., 2004; Paznukhov et al., 2012; Oladipo and Schuler, 2013a; Seba and Tsegaye, 2015). From previous work, they have been studied by various instruments such as all-sky imager (Wiens et al., 2006), and very high-frequency radar observation (e.g., Otsuka et al., 2009; Ajith et al., 2016). Recently, GNSS signal analysis is an important tool to study the behavior of ionospheric irregularities (e.g., Pi et al., 1997; Nishioka et al., 2008; Watthanasangmechai et al., 2016; Magdaleno et al., 2017) because of its growing application in civilian and military applications.

The inhomogeneity of ionospheric electron distribution can cause sudden, rapid and irregular fluctuations of the amplitude and phase of the received signals, known as ionospheric scintillation (Wernik and Liu, 1974). As the GNSS signals pass through the ionosphere, the ionospheric irregularities also causes the delay of signals. The inhomogeneity of plasma in the ionosphere might be given as latitudinal (north-south) and longitudinal (east-west) (Jakowski et al., 2004). The spatial plasma density gradients can be represented by means of TEC changes per latitude or longitude (TECU/deg) or by their changes in distance (TECU/km). Radicella et al. (2004) and Nava et al. (2007) also presented the contribution of the horizontal gradients of vertical TEC to positioning error. The characteristics of horizontal ionospheric density gradients and their effects on trans-ionospheric radio wave propagation have been studied at different latitudes (Jakowski et al., 2005; Radicella et al., 2004). Rao et al. (2006a) estimated ionospheric spatial gradient from F-region peak electron density (NmF2) data using a chain of radio soundings. Based on the GNSS data acquired by dense distribution of receivers over Brazilian longitude sector, Cesaroni et al. (2015) highlights the relationship between intensity and variability of TEC gradients and the occurrence of ionospheric scintillation. Previous studies attempts to explain the relation between the latitudinal (N-S) gradient of TEC surrounding the anomaly region and ionospheric scintillation over different sectors (Rao et al., 2006b; Ray et al., 2006; Muella et al., 2008). Recently, Seba
et al. (2018) investigated the relation between equatorial ionization anomaly and night time equatorial spread F (ESF) over East Africa longitudinal sector using data from ground-based GPS stations and a horizontal meridional neutral wind model. However, very few studies have been done over equatorial/low-latitude region of Africa relating the latitudinal/longitudinal gradient of TEC/plasma density and the occurrence of ionospheric irregularities. To identify signals which severely suffer from ionospheric gradient, Ravi Chandra et al. (2009) and Rungraengwajiaka et al. (2015) used rate of change of TEC (ROT) and rate of change of TEC index (ROTI). From the definition, however, ROTI mixes both the spatial and temporal gradients of TEC variations. The longitudinal gradient of integrated Pederson conductivity in the E-region at sunset time play a fundamental role in the strengthening the PRE magnitude and affect the generation of ionospheric irregularities (Tsunoda, 1985). It is well known that PRE is a post-sunset phenomena which uplift the ionosphere and create a conducive condition for irregularity formation. This implies the magnitude of the zonal electric field is an important parameter for real-time prediction. It is also known that PRE is due to spatial gradient of electron density near solar-terminator. It is not easy to have the longitudinal gradient of electron density over Africa longitude sector as ionosondes are not available in nearby locations as well as study the correlation between the electron density gradient and occurrence of ionospheric irregularities. We know TEC is the integral of electron density, so a closely located GPS receivers would help us to estimate the strength of the zonal electric field and investigate the relation between the gradient of TEC and occurrence of irregularities. It is well known that ROTI is a proxy for occurrence of ionospheric irregularities and scintillations. In this study, the relationship between the spatial gradient of TEC and ROTI were established using ground GPS-TEC receiver from two nearby located stations to observe how gradient of TEC affect radio signals, hence give information that the horizontal electron density gradient as an important parameter to predict ionospheric scintillation. After establishing this relationship showing that both parameters give information about ionospheric irregularities, TEC gradient method may be an alternative as it is a simple computation of establishing the difference. From the study, the contribution of spatial gradient of TEC to ROTI computed from the two GPS-TEC receivers were presented. Moreover, the relation between the daytime eastward equatorial electric field derived from the equatorial electric field (EEF) model and the daytime equatorial electrojet obtained from ground based magnetometer measurements were also discussed. The study is the first of its kind in the African sector to present the relation between the spatial gradient of TEC and occurrence of ionospheric irregularities. This study insight about the possible relation between electric field and irregularities in the post-sunset period. The gradients of plasma density might be considered as an important parameter in the modeling of ionospheric irregularities and mitigating positioning errors on GNSS based application.

2 Data and analysis method

The GNSS data used for this study were obtained from University NAVSTAR Consortium (UNVCO) database (http://www.unavco.org/). We used the data from two receiver stations located in the East African region at Debark (Geog. Lat. 13° N, Geog. Long. 37.65° E, Geomag Lat. 4.13° N) and Asab (Geog. Lat. 13° N, Geog. Long. 42.65° E, Geomag. Lat. 4.85° N) for the period 2014. The receiver-independent exchange (RINEX) observation files obtained from the IGS website (http://igsocb.jpl.nasa.gov/) were processed by the GPS-TEC application software developed at Boston Collage by Gopi Seemala
(Seemala and Valladares, 2011; Ma and Maruyama, 2003). The TEC analysis software uses the phase and code values for both L1 and L2 GPS frequencies to eliminate the effect of clock errors and tropospheric water vapor to calculate relative values of slant TEC (Sardón and Zarraoa, 1997; Arikan et al., 2008). In order to avoid the multipath effects, different authors have used observation data above certain cutoff mask ranging from 15° to 35° (Chu et al., 2005; Mushini and Pokhotelov, 2011). In the current study, an elevation cutoff mask of 30° was used for all the VTEC computed. Mean vertical TEC (VTEC) values are obtained by averaging the VTEC over 30 min intervals for all satellites in view. Using the computed VTEC collected from the two receiver stations, the spatial gradient of TEC (difference of TEC between two stations per longitudinal separation) was computed for every time and then we analyzed the diurnal, monthly and seasonal variations of the spatial gradient of TEC. The spatial gradient of TEC between the two nearby stations located nearly along the same geographic latitude with longitudinal separation of about ∼5° or corresponding spatial separation of 535.7 km. Stations with the same latitude were selected to observe only the contribution of the longitudinal gradient to TEC to the probability of occurrence of ionospheric irregularities expressed by ROTI. The spatial gradient of TEC were computed using Eq. (1) (Ravi Chandra et al., 2009; Cesaroni et al., 2015).

\[
\text{Spatial gradient of TEC}(t) = \frac{VTEC_{asab}(t) - VTEC_{debb}(t)}{\Delta \text{lon}}
\]  

(1)

where \(\Delta \text{lon}\) represents the difference in the longitude between the two stations. In the analysis of spatial gradient of TEC between the two stations, we applied the absolute value of TEC gradient. Radicella et al. (2004) used the absolute value of gradient of TEC between two stations to explain the effect of horizontal gradient of plasma density to ionospheric delay.

The time variation of TEC also known as rate of change of TEC (ROT) and its derived indices are a good proxy for the phase fluctuation, which is a measure of large-scale ionospheric irregularities (Aarons et al., 1997) were used in this study. These kinds of indices can be used to characterize all the known features of equatorial spread F (ESF) (Mendillo et al., 2000). The rate of change of TEC (ROT) is given by

\[
\text{ROT} = \frac{TEC_i^k - TEC_i^{k-1}}{t_k - t_{k-1}}
\]

(2)

where \(i\) is the visible satellite and \(k\) is the time of epoch and ROT is in units of TECU/min. The ROTI is defined as the standard deviation of ROT over a 5-min period and mathematically given by Eq. (3) (Pi et al., 1997; Bhattacharyya et al., 2000; Nishioka et al., 2008). Usually, ROTI > 0.5 TECU/min indicates the presence of ionospheric irregularities at scale lengths of a few kilometers (Ma and Maruyama, 2006).

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

(3)

Oladipo and Schuler (2013b) employed the idea of Mendillo et al. (2000) to obtain a new index called \(\text{ROTI}_{ave}\) index given in Eq. (4). \(\text{ROTI}_{ave}\) index is the average of ROTI over 30 min interval for a satellite and then average over all satellites in
view. The index gives average level of irregularities over half an hour. Recently, \( ROTI_{ave} \) has been applied to demonstrate and explain the level of ionospheric irregularities over low-latitude/equatorial region of Africa (Oladipo et al., 2014; Bolaji et al., 2019; Dugassa et al., 2019). In this study, the rate TEC fluctuation index (ROTI) and \( (ROTI_{ave}) \) (Pi et al., 1997; Oladipo and Schuler, 2013b; Oladipo et al., 2014) were used to observe the occurrence of ionospheric irregularities.

\[
ROTI_{ave}(0.5hr) = \frac{1}{N} \sum_{n=1}^{N} \sum_{i=1}^{k} \frac{ROTI(n, 0.5hr, i)}{k}
\]

(4)

where \( n \) is the satellite number, \( 0.5hr \) is half an hour (0, 0.5, 1,..., 23.5, 24 UT), \( i \) is the 5 min section within half an hour \( (i = 1, 2, 3, 4, 5, 6) \), \( N \) is the number of satellites observed within half an hour and \( k \) is the number of \( ROTI \) values available within half an hour for a particular satellite. According to Oladipo and Schuler (2013b), the value of \( ROTI_{ave} < 0.4 \), \( 0.4 < ROTI_{ave} < 0.8 \) and \( ROTI_{ave} > 0.8 \), respectively represents the background fluctuation, existence of phase fluctuation, and severe phase fluctuation activities. These threshold values were used to observe the relation between the occurrence of ionospheric irregularities and the spatial gradient of TEC.

The magnetic data used in this study are obtained from International Real-Time Magnetic Observatory Network (INTERMAGNET) and Africa-Meridian B-field Education and Research (AMBER) installed in Addis Ababa and Adigrat, respectively. It provides one minute values of the northward (X), eastward (Y), vertical (Z) components of the Earth’s magnetic field, while horizontal component (H) is computed using Eq. (5).

\[
H = \sqrt{X^2 + Y^2}
\]

(5)

To avoid different offset values of different magnetometers, the nighttime baseline values in the H component (Eq. 6) are first obtained for each day and subtracted from the corresponding magnetometer data sets and obtain the hourly departure of H denoted \( \Delta H \) expressed by Eq. (7). The baseline value was defined as the average of the H component night time (23:00 - 02:00 LT) value of the Earth’s magnetic field.

\[
H_o = \frac{H_{23} + H_{24} + H_{01} + H_{02}}{4}
\]

(6)

where \( H_{23}, H_{24}, H_{01}, \) and \( H_{02} \) are respectively the hourly values of H at 23:00, 24:00, 01:00 and 02:00 in local time (LT).

\[
\Delta H(t) = H(t) - H_o
\]

(7)
where \( t \) is the time in hours ranging from 01:00 to 24:00 LT. The hourly departure \( \Delta H \) is then corrected for the non-cyclic variation (Eq. 8). This correction was proposed previously Rastogi et al. (2004) and defined non-cyclic variation as a phenomenon in which the value at 01:00 LT is different from that of local midnight (24:00 LT).

\[
\Delta c = \frac{\Delta H_{01} - \Delta H_{24}}{23}
\]  

The hourly departure of \( H (\Delta H) \) corrected for the non-cyclic variation corresponding to magnetometer data set gives the solar quiet variation (Sq) values as shown in Eq. (9):

\[
Sq(t) = \Delta H(t) + (t - 1) \times \Delta c
\]

where \( t = 1 \) to 1440. The equatorial electrojet current (EEJ) produces a strong enhancement in the H-component magnetic field measured by magnetometers located within \( \pm 5^\circ \) of the magnetic equator. Measurements of this magnetic field perturbation in equatorial magnetometers could provide a direct measure of the daytime equatorial electrojet (EEJ) and have strong relationships with dayside vertical velocity (\( E \times B \) drift) (Anderson et al., 2004, 2006; Yizengaw et al., 2012). The equatorial stations respond primarily to the EEJ and also to the ring current and the global quiet time Sq current system. However, ground magnetometers just outside the extent of the EEJ (\( \sim 6^\circ - 9^\circ \), off the dip equator) exhibit exact response to the ring and Sq currents, but near-zero response to the EEJ. To obtain the contribution of H-component field to the EEJ current (Eq. 10), we subtract the H-component value recorded at the off the equator (\( \sim 6^\circ - 9^\circ \) geomagnetic) magnetometer from the H-component value measured at the magnetic equator. The subtraction has been made to remove the contribution of the ring current and global Sq dynamo to the H-component. Table 1 gives the list of all the stations for which data has been used in this study.

\[
\Delta H = \Delta H_{AAE} - \Delta H_{ETHI}
\]

Table 1. Location information and the type of data used in this study.

<table>
<thead>
<tr>
<th>Name of stations</th>
<th>Code</th>
<th>Geo. lon</th>
<th>Geo. lat</th>
<th>Geom. lon</th>
<th>Geom. lat</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asab, Eritrea</td>
<td>ASAB</td>
<td>42.65° E</td>
<td>13° N</td>
<td>114.34° E</td>
<td>4.85° N</td>
<td>GPS-TEC</td>
</tr>
<tr>
<td>Debark, Ethiopia</td>
<td>DEBK</td>
<td>37.65° E</td>
<td>13° N</td>
<td>109.24° E</td>
<td>4.13° N</td>
<td>GPS-TEC</td>
</tr>
<tr>
<td>Addis Ababa, Ethiopia</td>
<td>AAE</td>
<td>38.77° E</td>
<td>9.04° N</td>
<td>110.47° E</td>
<td>0.18° N</td>
<td>Magnetometer</td>
</tr>
<tr>
<td>Adigrat, Ethiopia</td>
<td>ETHI</td>
<td>39.46° E</td>
<td>14.28° N</td>
<td>111.06° E</td>
<td>5.80° N</td>
<td>Magnetometer</td>
</tr>
</tbody>
</table>

The other data source used in this study is the Real-time model of the Ionospheric Electric Fields (http://geomag.org/models/PPEFM/RealtimeEF.html). The Prompt Penetration Electric Field Model (PPEFM) (Manoj and Maus, 2012) is a transfer
function model which models the daily variations coming from the solar wind, which are mapped in the interplanetary electric field (IEF) data. Eight years IEF data from the ACE satellite, radar data from JULIA, and magnetometer data from the CHAMP satellite were used to derive the transfer function. Using the real-time data from ACE satellite, the transfer function models the current variations in the equatorial ionospheric electric fields. The model takes time and location as input parameters and calculates the best estimates of the equatorial electric field. The model outputs provide the electric field generated as a result of the convective electric field, quiet time electric field, and both. In the present study, we have used only the background quiet-time electric field to observe the relation between the equatorial electric field (EEF) and the spatial gradient of TEC derived from the two nearby stations.

Recently, Nayak et al. (2017) used the real-time model of an electric field to observe the influence of prompt penetration electric field (PPEF) on the occurrence of ionospheric irregularities during 17 March 2015 geomagnetic storm over Indian and Taiwan longitudes. However, this model has not been applied yet to explain the electrodynamic phenomena over African low-latitude region. To use the model in this region, we should first present its relation with equatorial electrojet (EEJ), an indicator of the eastward electric field, during the daytime period over the equatorial region of Africa. To do this, ground-based magnetometer measurements one located at magnetic equator and another one at (∼ 6° − 9°) off-equator (Rastogi and Klobuchar, 1990; Anderson et al., 2002; Yizengaw et al., 2014) have been used. Over East Africa longitude, two magnetometer stations, one at Adigrat (ETHI, 14.3° N, 39.5° E, 6.0° N, geomagnetic) and the other at Addis Ababa (AAE, 9.0° N, 38.8° E, 0.2° N, geomagnetic) exists. ETHI and AAE stations belong to AMBER network (Yizengaw and Moldwin, 2009) and INTERMAGNET, respectively. The difference of the H component of the geomagnetic field of the two magnetometer stations, ∆H gives the equatorial electrojet (EEJ) current, which is a proxy to daytime electric field (Anderson et al., 2002; Yizengaw et al., 2014). The relation between the EEF obtained from the real-time electric field model and ∆H were determined. EEF derived from the real-time electric field were used in this study to explain its influence on nighttime enhancement/reduction of the spatial gradient of TEC and the occurrence of ionospheric irregularities. The temporal resolution of EEF and ∆H was 5min and 1 min, respectively. To make their resolution consistent, 5 min average of ∆H of each day were considered. In this study, ∆H derived from the horizontal (H) component of the geomagnetic field of the two stations during quiet days of the year 2012 were used. In this year, we have a large number of magnetometer measurements relative to other years. Monthly five quiet international days of the year 2012 (total of 38) obtained from (http://wdc.kugi.kyoto-u.ac.jp/qddays/index.html) were selected to show the correlation between ∆H and EEF. Since the equatorial electrojet is a day time phenomenon, only the daytime values of EEF and ∆H during (07:00 to 17:00 LT) were considered.

3 Results and Discussions

3.1 Relation between the day-time Equatorial Electrojet (EEJ) and Equatorial Electric Field Model (EEFM)

Figure 1a presents the diurnal variation of EEF and EEJ current signature of H-component of magnetic field on 26 March 2012 and Fig. 1b shows the correlation between the EEJ derived from ∆H and EEF obtained from equatorial electric field
model. The equatorial electric field is a key factor in determining the dynamics and structure of the low-latitude ionosphere (Fejer, 2011). For the first time it was detected by the Jicamarca (11.95° S, 76.87° W) incoherent scatter radar (ISR) and the Jicamarca Unattended Long-Term studies of the Ionosphere and Atmosphere (JULIA) system during the period from 1998 to 2008. However, there were no direct continuous electric field observations from ground-based and when available, mostly limited. Over the African region, there are no ground-based measurements of the zonal electric fields. Anderson et al. (2002) proposed $\Delta H$ deduced from ground-based magnetometers as a proxy of equatorial electrojet current. They reported that the vertical plasma drifts observed from Jicamarca ISR has a positive and linear relation with $\Delta H$ and henceforth the $\Delta H$ was widely taken as a substitution for the EEF. The relation between $\Delta H$ derived from H-component of magnetic field observations and EEF obtained from equatorial electric field model for each month five (5) international quiet days of the year 2012 during the daytime (07:00 - 17:00 LT) is shown in Fig. 1b. As illustrated in Fig. 1b, the daytime (07:00 - 17:00 LT) value of $\Delta H$ correlate positively and linearly with the quiet-time EEF with correlation coefficient of ($C = 0.60$). The magnitude and direction of the dayside vertical velocity ($E \times B$ drift) strongly correlates with $\Delta H$ (Anderson et al., 2004, 2006; Yizengaw et al., 2011). Studies show that the daytime electrodynamics play a decisive role in the initiation of post-sunset ESF (e.g., Mendillo et al., 2001; Valladares et al., 2001, 2004). The connection between the occurrence of ESF during the evening sector preceded by the rapid rise in F-layer and the strength of EEJ before sunset has been presented (Dabas et al., 2003; Burke et al., 2004; Kelley, 2009; Uemoto et al., 2010; Ram et al., 2007). Sreeja et al. (2009) reported observational evidence for the plausible linkage between the daytime EEJ related electric field variations with the postsunset F-region electrodynamics. Furthermore, Hajra et al. (2012) indicate that the afternoon/evening time variation of the eastward electric field as revealed through EEJ seems to play a dominant role in dictating post-sunset resurgence of EIA and consequent generation of spread-F irregularities. Even though $\Delta H$ and equatorial electric field derived model (EEF) do not correlate strongly enough over East Africa longitudinal sector, we might use the model derived equatorial electric field over equatorial/low-latitude region of Africa to explain some special features of ionospheric phenomena like plasma density irregularities and the enhancement/reduction of the spatial gradient of TEC between the two stations.

### 3.2 Relation between the equatorial electric field (EEF), the spatial gradient of TEC and occurrence of ionospheric irregularities

Figure 2a-l show the diurnal variation of the quiet-monthly mean of EEF (along $\sim 40^\circ$ E) and the quiet-monthly mean of the gradient of TEC in the year 2014. The red and blue curve indicate the EEF and the TEC gradient, respectively. The maximum enhancement/reduction in the gradient of TEC and the peak value in the EEF observed during the pre-midnight period was prevalent in the equinoctial months. After the post-sunset period, the maximum enhancement/reduction in the value of the gradient of TEC on solstice months was small compared to equinoctial months. The EEF start rising nearly after 16:00 LT and show enhancement in the evening local time ($\sim 18:00$ LT). Most of the maximum enhancement/reduction of the gradient of TEC was observed in the pre-midnight (19:00 - 24:00 LT) and postmidnight (24:00 - 06:00 LT) but after 1-2 hr of the post-sunset enhancement of the equatorial electric field. However, the spatial gradient of TEC observed during the daytime...
Figure 1. (a) Examples showing the diurnal variation of Equatorial Electric field Model (EEF) (Red panel) and ΔH (blue panel) during 26 March 2012 and (b) The correlation between the equatorial electrojet (EEJ) and quiet-time equatorial electric field model (EEF) during day-time (07:00-17:00 LT) period for quiet days of year 2012. The red line shows the linear fit of data points.

was relatively small compared to the evening time hours for most of the days. The maximum enhancement/reduction in the gradient of TEC observed in the evening period could be related to the pre-reversal enhancement in a zonal electric field.

Figures 3a - d indicate examples showing the diurnal variations of the spatial gradient of TEC and ROTI over ASAB and DEBK stations. The blue, black and the red curves, respectively, indicate the spatial gradient of TEC, and the phase fluctuation index (ROTI) over Asab and Debark. In the post-sunset hours, after 18:00 LT, the pattern of ROTI observed in both stations and the gradient of TEC show a similar trend. The enhancement in the gradient of TEC and the occurrence of irregularities in the post-sunset period could be explained by the presence of ionospheric electrodynamics. The post-sunset period electrodynamics is influenced by F-region dynamo which is governed by a longitudinal gradient of the electrical conductivity and thermospheric zonal wind (Crain et al., 1993). Anderson et al. (2004) showed that the scintillation activity is related to the maximum $E \times B$ drift velocity between 18:30 and 19:00 LT. Mendillo et al. (2001) have pointed out that the best available precursor for pre-midnight ESF is the EIA strength at sunset, which in turn influenced by the magnitude of PRE. Using differential TEC profiles, TEC (at 18:00 hr) - TEC (at 20:00 hr), Valladares et al. (2004) explained that the PRE of the vertical drift would reenergize the fountain effect.

It has been reported that the eastward component of electric field manifested by the vertical plasma drifts over equator and intensified around/shortly after sunset before reversing to westward is one of the most important parameters responsible
Figure 2. Comparison of Quiet-Monthly Mean of EEF derived from real-time electric field model at about (∼ 40° E) and spatial gradient of TEC between ASAB and DEBK in the year 2014.

... for driving many interesting ionospheric phenomena, like the Appleton density anomaly and the stability of the nighttime ionosphere (e.g., Horvath and Essex, 2003; Abadi et al., 2015). In the evening sectors, the vertical drift enhancement is of particular significance as it is the major drivers for the generation of ESF (Farley et al., 1970; Woodman, 1970; Basu et al., 1996; Fejer et al., 1999; Martinis et al., 2005). Tulasi Ram et al. (2006) reported that the rapid enhancement of post-sunset of the zonal electric field leads to a large vertical plasma drift ($E \times B$), thereby lifting the F-layer to higher altitudes resulting in a condition conducive for the generation of ESF. Vertical drifts are taken as the key parameters determining the dynamics of ionospheric F-region, and the occurrence of ESF. Ionospheric irregularities are mostly observed over equatorial/low-latitude region an hour or two hours after the PRE. Rastogi and Woodman (1978) showed ESF can appear at any time of the night other than the post-sunset period following the abnormal reversal of the vertical F-region drifts to an upward direction, with a delay of about 1-2 hr. From the figure, the post-sunset enhancement in the zonal electric field as shown in the equatorial electric field model has a profound effect on the enhancement of the spatial gradient of TEC during the post-sunset period. This might indicate that the spatial gradient of TEC as an indicator of the occurrence of ionospheric irregularities. Different researchers used the concept of ionosphere spatial gradient based on multi-GNSS observations within a small scale region to provide corrections and integrity information to the Ground-Based Augmentation System (GBAS) and they attribute the large
Figure 3. An example showing diurnal variation of the patterns of the spatial gradient of TEC and the ROTI over ASAB and DEBK stations on a) 30 March 2014, b) 10 April 2014, c) 20 September 2014 and b) 10 October 2014.

Figure 3. An example showing diurnal variation of the patterns of the spatial gradient of TEC and the ROTI over ASAB and DEBK stations on a) 30 March 2014, b) 10 April 2014, c) 20 September 2014 and b) 10 October 2014.

The patterns of the spatial gradient of TEC and ROTI during geomagnetic storm days were illustrated in Fig. 4a-d. These storm days are categorized as moderate magnetic storms (-100 nT ≤ Dst ≤ -50 nT) (Echer et al., 2013). When the presence of ionospheric irregularities are observed (ROTIave ≥ 0.4 TECU/min), the magnitude of spatial gradient of TEC in the post-sunset period is enhanced (during 13 September) and when the presence of ionospheric irregularities are suppressed (ROTIave ≤ 0.4 TECU/min), the magnitude of TEC gradient in the nighttime period is reduced (19 February and 27 August). During these seasons, however, the magnitude of TEC gradient shows enhancement in the daytime. Using phase fluctuation index (fp), Kassa and Damtie (2017) reported the inhibition effect of a storm of 19 September on the occurrence of ionospheric irregularities over Ethiopia.

Figures 5a and b show ionospheric irregularity occurrence using the phase fluctuation index (ROTIave) at ASAB and DEBK in the year 2014, respectively. The ROTIave values are indicated in the color scale. The occurrence of ionospheric irregularities at the two stations, as indicated by ROTIave value, is a post-sunset phenomenon. The implication of this is that the large-scale
Figure 4. An example showing diurnal variation of the patterns of the spatial gradient of TEC and the ROTI over ASAB and DEBK stations during geomagnetic storm days (a) 19 February 2014 (b) 12 April 2014 (c) 27 August 2014 and (d) 13 September 2014.

ionospheric irregularities, which are responsible for the scintillation of trans-ionospheric signals at GNSS frequencies, are more pronounced during post-sunset hours. The observed phase fluctuation shows monthly variations and there is also a seasonal trend in the occurrence of ionospheric irregularity (see., Fig. 7). Maximum irregularities are observed in March equinox months and minimum in June/July. During this period, the occurrence of phase fluctuation showing irregularities is observed mainly between 19:00 LT and 24:00 LT. As stated by Oladipo and Schuler (2013b), the value of $\text{ROTI}_{\text{ave}} \geq 0.4$ shows the presence of ionospheric irregularity.

Figure 5c shows the annual variation of the spatial gradient of TEC between DEBK and ASAB in the year 2014. In the computation of the spatial gradient of TEC (using Eq. 1), negative/positive values in the gradient of TEC were observed. The negative/positive values of TEC gradient depends on the value of TEC at the reference station and it denotes an increase/a decrease in the value of TEC gradient. The maximum enhancement and reduction in the value of the gradient of TEC were observed mostly during the post-sunset (18:00 - 24:00 LT) and postmidnight (24:00 - 06:00 LT) period. Equation (1) was applied to all days (364 days) of year 2014 in computing the spatial gradient of TEC. Out of the total observed daily maximum value of the gradient of TEC, about 194 days (in percent about 53 %) of them fall in this time period. There was also a case
where the maximum enhancements and reductions in the value of the gradient of TEC were observed in the early morning period.

*Figure 5.* Ionospheric irregularity occurrence at (a) Asab (ASAB), Eritrea (b) Debark (DEBK), Ethiopia. (c) spatial gradient of TEC between ASAB and DEBK, in year 2014. Daily maximum value of $ROT_{\text{ave}}$ (d) over ASAB, (e) over DEBK and (f) Daily maximum (blue) and minimum (red) values of spatial gradient of TEC, in year 2014. The $ROT_{\text{ave}}$ value in TECU/min is indicated in color code.

The maximum enhancement/reduction in the gradient of TEC observed during post-sunset and post-midnight period showing monthly and seasonal variations are the other features noticed from Figs. 5c and f. The maximum peak/reduced values of the spatial gradient of TEC observed in equinoctial months are greater than solstice months. Equinoctial asymmetry in the occurrence of TEC gradient was also noticed. TEC gradient in March equinox was greater than that in September equinox. The minimum values in the spatial gradient of TEC observed mostly during post-sunset and post-midnight periods show the same trend with that of the maximum enhancement in the gradient of TEC. They also show an equinoctial asymmetry, TEC gradient in March equinoxes were greater than the one obtained for September equinoxes.

Figures 5d and e present the daily maximum values of the phase fluctuation index ($ROT_{\text{ave}}$) over ASAB and DEBK stations, respectively and Fig. 5f shows the daily maximum and minimum value of the gradient of TEC in the year 2014. It is clearly observed from the figures that the enhancement in $ROT_{\text{ave}}$ and gradient of TEC shows monthly and seasonal...
variations, and also equinoctial asymmetry is observed. The daily maximum value of the spatial gradient of TEC between
the two stations shows similar trends with the daily maximum value of $ROTI_{ave}$ observed over ASAB and DEBK stations.
The trend they show has similarity with the time of occurrence of maximum enhancement, monthly and seasonal variations.
Moreover, the seasonal variation observed in both variables exhibits equinoctial asymmetry, where the March equinox was
greater than September equinoxes. The mechanism of generation of the enhancement in vertical drift just after sunset was
detailed by Farley et al. (2008). The magnitude of peak vertical drift is known to control the seasonal and day-to-day variations
in the occurrence of equatorial spread F (Manju et al., 2009; Tulasi Ram et al., 2006).

Figure 6 shows the relation between the spatial gradient of TEC and ROTI over ASAB and DEBK computed in the time
period of 19:00-24:00 LT for geomagnetic quiet days of the year 2014. For every quiet day of the year 2014, an average of
$\Delta TEC/\Delta lon$ and average of ROTI in the time period between 19:00 LT and 24:00 LT were computed. In this time period,
a peak value in TEC gradient about 2.5 TECU/deg and ROTI about 1 TECU/min were observed. In the computation of TEC
gradient, a positive and negative value in the TEC gradient were observed. The positive/negative in the TEC gradient means
a maximum enhancement/reduced in the plasma density relative to each other. To analyze the effect of the horizontal gradient
of TEC on navigation and communication during geomagnetic storms, Radicella et al. (2004) considered the absolute value
of TEC gradient. Here, we took the absolute value of the spatial gradient of TEC to describe the relationship between the
TEC gradient and ROTI. The correlation coefficient between $\Delta TEC/\Delta lon$ and ROTI is about 0.58 (in ASAB) and 0.53 (in
DEBK), respectively. It is well known that ROT is the combination of the spatial and temporal gradients. However, by giving
less attention to the spatial gradient effect, previous authors often use $\Delta TEC/\Delta t$ to explain the TEC fluctuation determination.
It is not only the temporal variation of TEC that contribute to the fluctuation in the phase and amplitude of the signals but also
the spatial gradient of TEC. The computed correlation coefficient between the TEC gradient and ROTI, here, gives an indication
of the contribution of the spatial gradient of TEC to ROTI (or ROT) usage. This can give the case where the spatial gradient of
TEC between two nearby located stations used as an indicator of occurrence of ionospheric irregularities. Cesaroni et al. (2015)
described the importance of the information provided by the TEC gradients variability and the role of the meridional TEC
grades in driving scintillation. By comparing the zonal and the meridional components of average and standard deviation of
$\Delta TEC$, Cesaroni et al. (2015) reported that the North-South (N-S) gradients of TEC are significantly larger than their East-
West (E-W) counterparts, regardless of the season. Saito and Yoshihara (2017) associated extreme ionospheric total electron
gradient with plasma bubbles for GNSS Ground-Based Augmentation System and they obtained a largest ionospheric gradient
of about 3.38 TECU/km.

Figure 7 presents the percentage occurrence of ionospheric irregularities over ASAB (blue) and DEBK (red) in the year
2014. The observation of this percentage occurrence is for all days of the year 2014 including both quiet and disturbed periods.
The percentage occurrence of irregularities was calculated by counting the number of days in a month with $ROTI_{ave} \geq 0.4$
TECU/min and dividing by the number of days in a month for which data are available, and multiplied by 100 % (Oladipo
et al., 2014). The two peaks of irregularity occurrence were observed around the middle of the equinoxes (i.e., in March and
September) at both stations. This could be related to the alignment of the magnetic field lines with a geographic meridian (Burke

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et al., 2004; Tsunoda, 2005, 2010). The seasonal variation of ionospheric irregularities exhibits an equinoctial asymmetry in its occurrence especially at the two peaks (i.e., in March and September), where March equinox is greater than that of September equinox. The maximum $\text{ROT}I_{\text{ave}}$ observed over this station in the year 2014 was about 1.8 TECU/min in March 2014. It is evident from the figure that the minimum level of $\text{ROT}I_{\text{ave}}$ was observed on December Solstice. Based on a few station observations, earlier studies indicated that equinoctial asymmetry in the occurrence of L-band scintillations may be attributed to differences in the meridional winds during two equinoxes (e.g., Nishioka et al., 2008; Maruyama et al., 2006; Otsuka et al., 2006). Nishioka et al. (2008) have shown the occurrence characteristics of plasma bubbles using GPS-TEC obtained all over the globe and found equinoctial asymmetry in the occurrence of plasma bubbles. They have suggested that equinoctial asymmetry could be due to the asymmetric distribution of integrated conductivities during these equinoctial periods. Using three ionosondes observations, Maruyama et al. (2006) reported that meridional wind is the key factor for the equinoctial asymmetry. Using multi-instrument observations, Sripathi et al. (2011) examined the equinoctial asymmetry in scintillation occurrence in the Indian sector and proposed the asymmetry in the electron density distribution and meridional winds as a possible causative mechanism. Manju et al. (2012) also reported equinoctial asymmetry in ESF occurrence and discussed the possible role of asymmetric meridional winds. Dasgupta et al. (1983) studied the equinoctial asymmetry in equatorial and low latitude F region ionization distribution and attributed it to neutral composition changes. Manju and Haridas (2015) observed a significant asymmetry in the threshold height between the vernal equinox and autumn equinox and underlines the distinct
differences in the role of neural dynamics in ESF triggering during the two equinoxes. The local time and seasonal trends of occurrence of ionospheric irregularities observed in this study are similar to those reported in the previous studies (Aarons, 1993; Basu et al., 1988; Olwendo et al., 2013; Amabayo et al., 2014; Seba and Tsegaye, 2015). Based on scintillation index ($S_4$) and GPS-TEC derived indices,Susnik and Forte (2011), Paznukhov et al. (2012), Oladipo and Schuler (2013b), Oladipo et al. (2014), Seba and Tsegaye (2015) and Mungufeni et al. (2016) reported the seasonal and equinoctial asymmetry in the occurrence of ionospheric irregularities over equatorial/low-latitude region of African.

![Percentage occurrence of ionospheric irregularities over Asab and Debark Year: 2014](image)

**Figure 7.** Percentage of occurrence of ionospheric irregularities over ASAB (red) and DEBK (blue) stations in the year 2014 based on $ROTI_{ave}$ index.

In terms of local time, monthly, and seasonal behavior the enhancement/reduction in the spatial gradient of TEC and occurrence of ionospheric irregularities show similar trends. And, it is evident from the above result that the spatial gradient of TEC between two nearby located stations where the two receivers lie nearly along the same latitudes could be used as an indicator of the occurrence of large-scale ionospheric irregularities. In the current study, the optimum distance between the two GNSS receivers and the threshold value of the gradient of TEC that could indicate the occurrence of ionospheric irregularities has not been considered. This will be done in our future work.

4 Conclusions

In this study, we present the possibility that the spatial gradient of TEC between two nearby located stations (ASAB and DEBK) over East Africa the longitudinal sector could be used as an indicator of the occurrence of large-scale ionospheric
irregularities. The following features were observed in the study. Most of the daily maximum enhancement and reduction of
the spatial gradient of TEC was observed in the pre-midnight and post-midnight period. In terms of seasons, months and local
times, the maximum enhancement/reduction in the spatial gradient of TEC and $ROTI_{ave}$ show similar trends. Both of them
show maximum enhancement/reduction during the months of March and September equinoxes. Equinoctial asymmetry both in
the spatial gradient and in the ROT was also observed, where March equinox was greater than September equinox. Peak values
in the spatial gradient of TEC and $ROTI_{ave}$ were observed about 1-2 hrs later from post-sunset enhancement of equatorial
electric field (EEF). The correlation coefficient between the magnitude of the spatial gradient of TEC and ROTI was about 0.58
(in ASAB station) and 0.53 (in DEBK station). Based on the above results, the spatial gradient of TEC between the two nearby
located stations lying along the same geographic and geomagnetic latitudes could be used as an indicator of the occurrence of
large-scale ionospheric irregularities. The spatial gradient of electron density (TEC) near solar-terminator obtained from two
nearby located GNSS receivers method may be an alternative method to estimate the strength of the zonal electric field. The
threshold value of the gradient of TEC and the minimum separation distance between stations were not presented in the current
study and this will be considered in the future investigation.

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Data availability

The data used in this study were obtained from ftp://cddis.gsfc.nasa.gov, http://geomag.org/models/PPEFM/RealtimeEF.html,

Competing interests

The authors declare that they have no conflict of interest.
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