

Research Paper

Statistical characterization of equatorial plasma bubbles over East Africa

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ARTICLE INFO

Keywords:

Equatorial plasma bubbles
Global navigation satellite systems
Ionospheric irregularities
Slant total electron content

ABSTRACT

Bubble-like structures that grow in the post-sunset F-region of the equatorial ionosphere have continued to raise concern and research interest among scientists. These structures, commonly referred to as Equatorial Plasma Bubbles (EPBs), have depleted electron densities surrounded by a denser plasma. When Trans-ionospheric radio signals interact with the EPBs, the signals get attenuated and scattered due to reflective, refractive and diffractive scattering effects of the EPBs on the signals. This compromises the quality, accuracy and reliability of information obtained from Global Navigation Satellite Systems (GNSS). In this study, we have used the Global Positioning System (GPS) slant Total Electron Content (sTEC) data to identify and characterize EPBs. This data was obtained from International GNSS Service (IGS) receivers located within the East African region identified by the geographic latitudes (-7 to $+7$)°N and geographic longitudes ($+29$ to $+41$)°E. Identification of the EPBs was based on the de-trended curve of the sTEC-time series while their characterization was based on the standard deviation of their depletion depths from their calculated mean depletion depth. On this basis, three categories of EPBs were obtained. Results obtained show that the occurrence of the different categories of EPBs have got a seasonal pattern.

1. Introduction

The post sunset ionospheric irregularities in the equatorial F region that evolve from the Raleigh Taylor Instability (RTI) have led to the generation of large scale plasma bubbles that extend poleward along magnetic flux tubes into the Appleton regions (Garcia et al., 2000a; Kelley, 1989). The generation of the plasma bubbles is more frequent in equatorial and low latitude regions than in mid-latitude and high-latitude regions (de Rezende et al., 2007; Amabayo et al., 2014; Mungufeni et al., 2015; Oladipo et al., 2017). Upon formation, the bubbles propagate eastwards at velocities ranging from 100 to 150 m s⁻¹ and can rise to high altitudes, above 1000 km (Wiens et al., 2006). Many researchers, e.g. de Rezende et al. (2007); Haase et al. (2010); Blanch et al. (2018), have referred to the plasma bubbles in the equatorial ionosphere as equatorial plasma bubbles (EPBs). The EPBs have been observed to have different shapes and sizes, and their lifespan ranges from a few minutes to several hours (Magdaleno et al., 2017).

The EPBs have raised scientific concern and research interest because of their negative consequences on communication and navigation

systems, such as the Global Navigation Satellite Systems (GNSS), that rely on trans-ionospheric radio signals. When a radio signal from a satellite traverses the ionosphere, it may be subject to ionospheric scintillation before reaching a ground based receiver as a consequence of the signal passing through ionospheric irregularities like EPBs (Olwendo et al., 2013; Wernik et al., 2004; Aarons et al., 1982). In the equatorial and low latitude regions, ionospheric irregularities mostly affect the amplitude and less frequently affect the phase of the radio signals (Pi et al., 2002; Amabayo et al., 2014). Severe amplitude scintillations can cause the received GPS signal intensity to drop below a receiver's lock threshold, forcing the receiver to reacquire the signal. Phase scintillations, on the other hand, may lead to cycle slips and loss of lock for receivers as they track the signal (Datta-Barua et al., 2003). Thus, EPBs can compromise the quality, accuracy and reliability of information being transmitted by radio signals (Paznukhov et al., 2012).

Different techniques have been used to study EPBs. These include the use of ground based instruments (like ionosodes, radar, airglow analyzers) and satellite equipment, including in-situ electron density measurements (Magdaleno et al., 2017). However, Aarons et al. (1996);

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Received 15 October 2019; Received in revised form 26 December 2019; Accepted 8 January 2020

Available online 4 February 2020

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Portillo et al. (2008) noted that the ground based instruments had many limitations. For instance, airglow detection is hampered by the presence of either clouds or moonlight, while a radar return indicates a highly localized detection of F-layer irregularities. In recent decades, identification and characterization of EPBs using GPS derived information has increasingly gained ground (Portillo et al., 2008). A network of GPS receivers can facilitate the simultaneous study of ionospheric irregularities over large regions by using the amplitude and phase fluctuations at L-band frequencies (Aarons et al., 1996; Portillo et al., 2008). These L-band radio frequencies are subject to a time delay which is proportional to the slant Total Electron Content (sTEC) along the radio signal path; sTEC being the total number of electrons integrated along a radio signal path from a GPS satellite to a ground-based GPS receiver (Seemala and Valladares, 2008; Norsuzila et al., 2010). Any variation in sTEC values has serious consequences on the propagation of the radio signals through the ionosphere, which can result in large errors in the estimated time and location derived from these signals (Maruyama et al., 2004). This has driven scientists to extensively study the variations in sTEC values. Fortunately, the increasing number of permanent GPS tracking receiver stations has provided large volumes of data suitable for continuous, near real-time or real-time monitoring of ionospheric irregularities.

The occurrence of EPBs has been observed to be simultaneous with L-band GPS scintillations (Wiens et al., 2006; Paznukhov et al., 2012; Jiao et al., 2014; Amabayo et al., 2014). Many of these studies have alluded to the fact that the depletion depth of EPBs plays a significant role in scintillation levels. The conventional indices, S_4 and σ_{ϕ} , have been used to characterize scintillation levels (Wiens et al., 2006; Jiao et al., 2014; Amabayo et al., 2014). These scintillation indices have been qualitatively linked to EPBs, but have never been quantitatively used to characterize EPBs due to the lack of a suitable index for the depth of depletion of EPBs. In this study, we have characterized EPBs based on the standard deviation of their depletion depths from a calculated mean depletion depth. Our method of characterization derives strength from the fact that the extent to which the EPBs scatter radio signals that traverse the ionosphere depends mostly on the depletion depths of the EPBs (Paznukhov et al., 2012; Jiao et al., 2014). The variation of the annual percentage occurrence of the observed EPBs with solar activity and the local strength of the Earth's magnetic field is also presented.

2. Data sources and processing

A permanent operation of a network of ground based GPS receivers can allow for continuous monitoring of the generation and evolution of EPBs on a large scale (Portillo et al., 2008). Consequently, in this study we used GPS data archived by selected IGS and UNAVCO receiver stations located within the East African region (geographic latitudes $(-7$ to $+7^\circ$ N and geographic longitudes $(+29$ to $+41^\circ$ E) to characterize the EPBs formed over the region. Although some of the receiver stations were installed in the region as early as 1995 e.g. MALI, others have been installed as recent as 2013. **However, many of these receiver stations did not have adequate data for research on seasonal and solar cycle variations of the frequency of occurrence of EPBs. The inadequacy of data was manifested by the numerous data gaps which probably were due to software and/or hardware breakdowns. Such receiver stations with limited data were not considered in this study.** Fig. 1 shows the distribution of the selected receiver stations used in this study.

The GPS Receiver INdependent EXchange (RINEX) files from the selected receiver stations were downloaded from Crustal Dynamics Data Information System (cddis) data centre via <ftp://cddis.gsfc.nasa.gov>, for the years 2008–2014. This study period was selected because it was on the ascending phase of solar cycle 24, one of the quietest/weakest solar cycles in centuries (<https://www.almanac.com/users/editors>). In addition to the period of study containing both the low (2008–2009) and high (2013–2014) solar activity periods for solar cycle 24, it presented a conducive ionospheric environment for

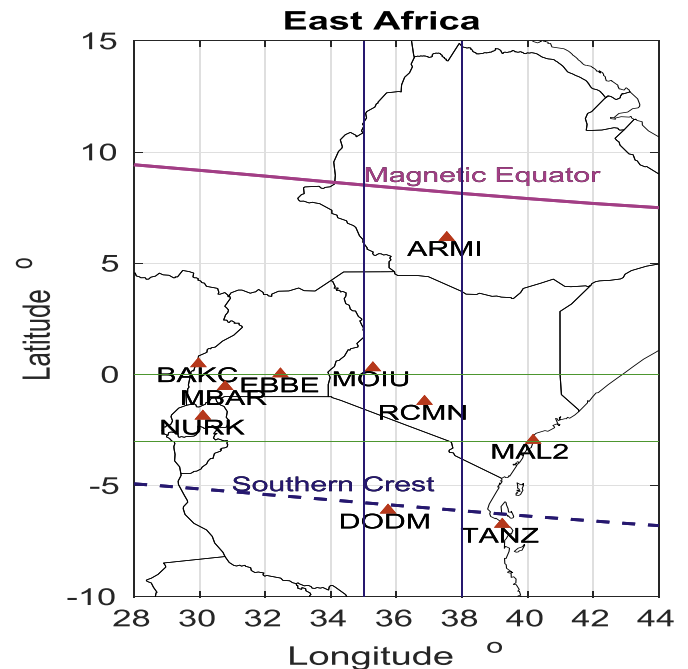


Fig. 1. Map of East Africa showing location of receiver stations used in the study.

analyzing the occurrence of EPBs with minimal ionospheric disturbances resulting from solar activities. The annual distribution of the data obtained from these selected receiver stations is shown in Table 1.

The RINEX data files were processed using GPS_TEC_v2.9.3 software (Seemala and Valladares, 2008) to extract the sTEC and vTEC (vertical TEC) values, the azimuth and the elevation angles of the satellites from the receiver station, and the ionospheric pierce point (IPP) latitudes and longitudes. To avoid multipath effects and some errors associated with tropospheric influences, only sTEC values along ray paths with elevation angles $\geq 30^\circ$ were considered. We calculated the Earth's magnetic field strengths at the locations of selected GPS receivers, which lay within a 3° latitude variance, using the International Geomagnetic Reference Field (IGRF) model obtainable at <http://geomag.colorado.edu/igrf-mag-elements-calculator>. The daily sunspot numbers (SSN) were downloaded from the National Centers for Environmental Information (NCEI) website via <https://www.ngdc.noaa.gov/stp/solar/ssnda.ta.html/>. For each of the years under consideration, the average annual SSN were calculated from the daily SSN.

We extensively explored the detrended curve technique of the sTEC-time series described fully by Portillo et al. (2008), to identify EPBs over the East African region. In their study, Portillo et al. (2008) had only considered one station, MAL2, in this region over a period of six months (January to June 2004). We have expanded the coverage to include ten receiver stations over a period of seven years, 2008 to 2014 (Refer to Table 1). This coverage would give a better description of the occurrence of EPBs over the East African region. Our choice of method was based on the fact that the detrended curve technique produced a replica of the original sTEC-time series without changing the relatively rapid variations in GPS sTEC observations. The key parameter in the detrended curve technique is to select a time window width, ww , for calculating the sTEC moving-average, sTEC-MAv, which best matched the original sTEC values as a function of time. The choice of the ww is done by trial and error method. It also requires setting parameters, ψ and ϕ for the minimum electron density depletion and the maximum electron density enhancements before and after the occurrence of a possible EPB, respectively. Both ψ and ϕ were set to remove outliers.

While employing the detrended curve technique of the sTEC-time

Table 1

GPS receiver stations used in the study (– indicates no available days with data).

Station Code	Geomagnetic	Geographic		Number of days per year with data						
	Lat (°N)	Lat (°N)	Lon (°E)	2008	2009	2010	2011	2012	2013	2014
ARMI	–3.08	6.06	37.56	331	93	247	364	366	365	365
MOJU	–9.42	0.29	35.29	40	288	314	351	363	281	348
MAL2	–12.18	–3.00	40.19	224	346	365	341	364	361	364
RCMN	–10.84	–1.22	36.89	–	27	313	331	165	293	174
NURK	–12.91	–1.94	30.09	–	–	98	284	192	364	363
TANZ	–16.91	–6.77	39.21	309	362	274	57	–	120	07
DODM	–16.10	–6.19	35.75	–	–	94	364	366	365	135
MBAR	–10.19	–0.60	30.74	210	365	179	158	184	340	364
EBBE	–10.40	0.04	32.44	215	338	192	365	366	177	–
BAKC	–10.63	0.35	29.89	189	334	352	216	–	–	–

series to identify EPBs, [Portillo et al. \(2008\)](#) explored ww values of 2700 s, 4140 s, 5460 s and 7260 s to obtain the sTEC-MAV which best matched the original sTEC-time series. They set the value of ψ to -5 TECu and ϕ to $+5$ TECu and found that ww value of 5460 s produced the best match between the sTEC-MAV and the original sTEC values as a function of time. [Portillo et al. \(2008\)](#) suggested that these parameters could be varied to obtain better results. In a similar study to identify EPBs, but using the Ionospheric Bubble Seeker (IBS) application, [Magdaleno et al. \(2012\)](#) used a ww value of 300 s and ψ value of -5 TECu without an upper bound for ϕ . Both studies were conducted over the low latitude regions of Africa and South America. In this study, we explored ww values of 300 s, 1200 s, 1800 s, 3000 s and 5460 s to compute sTEC-MAV that would best match the original sTEC-time series. In order to increase on the chances of observing EPBs, the value of ϕ was adjusted to $+8$ TECu instead of the $+5$ TECu suggested by the earlier studies. The value of $+8$ TECu was arrived at while having in mind that the magnitude of the recovery phase electron density enhancement for an instability should not exceed twice the set absolute value of ψ (-5 TECu) meant to identify electron density depletions synonymous with EPBs ([Portillo et al., 2008](#)). The depletion depth of an identified EPB was obtained using the expression

$$\text{Depletion depth} = \left(\frac{LMax + RMax}{2} - Min \right), \quad (1)$$

where LMax and RMax were the maximum electron density enhancements to the left and right of a depletion whose minimum electron density depletion value was Min.

If $t(RMax)$ and $t(LMax)$ represent the respective times when RMax and LMax occurred, then the apparent duration of the observed EPB was calculated using the expression

$$\text{Apparent duration} = t(RMax) - t(LMax). \quad (2)$$

Note that the apparent duration obtained in equation (2) did not reflect the lifespan of the EPB, but rather the time when the satellite signals traversed the EPB ([Portillo et al., 2008](#)).

[Table 1](#) showed that not all days of the selected study period had data available for analysis. For example, in 2008, stations RCMN and NURK did not have any single day with available data, while in 2011, station TANZ had only 57 days with data out of 365 days. Thus, for effective comparison of annual occurrence of EPBs, the number of EPBs observed on any given day across all available satellite links were analyzed. Similar to works done by [Jiao et al. \(2014\)](#), we assumed that EPBs were localized phenomena and therefore, chances of two or more simultaneous satellite signal passes through the same EPB were limited due to the spacing of the receivers and the configuration of the satellites. This allowed us to consider each EPB observed as a separate event thereby simplifying the statistical analysis. Hence, we counted the number of EPBs observed per day in all the selected receiver stations and then determined the annual modal frequency of EPB occurrence for each of the years being studied. The maximum annual modal frequency, f_{mo} , of

occurrence of EPBs was set as the expected daily observed number of EPBs across all stations, irrespective of the seasons. We then computed the expected annual number, N_{exp} , of occurrence of EPBs using the expression

$$N_{exp} = f_{mo} \times N_d, \quad (3)$$

where N_d is the number of days with data in a given year.

To normalize our observations, the number of EPBs observed, N_o , across all satellite links in a given year were counted and expressed as a percentage of the expected number of EPBs for that year. Thus the annual percentage occurrence of EPBs was computed from the expression

$$\text{Annual percentage occurrence of EPBs} = \left(\frac{N_o}{N_{exp}} \times 100 \right) \%. \quad (4)$$

3. Results and discussions

3.1. Identification of EPBs

The trial ww values of 300, 1200, 1800, 3000 and 5460 s were investigated with data obtained from all the selected receiver stations used in this study. In [Fig. 2](#), results obtained using ww values of 1800, 3000 and 5460 s with data obtained from receiver station DODM on 18/10/2010 from PRN 13 are presented.

From the left hand panels (a), (c) and (e) of [Fig. 2](#), it was evident that as the value of the ww was increased, the mismatch between the sTEC-MAV and the sTEC values became more pronounced. Infact, as the value of the ww tended to zero, a perfect match was obtained between the sTEC-MAV and the sTEC values. Hence, of the ww values investigated, ww value of 300 s produced the best match (Not shown in the figure). The sTEC-MAV values were subtracted from the sTEC values to generate the detrended curves of the sTEC-time series. The corresponding detrended curves for ww values of 1800, 3000 and 5460 s are shown in the right hand panels (b), (d) and (f) of [Fig. 2](#), respectively.

As the value of ww was reduced from 5460 s down to 300 s, results obtained showed that both the electron density depletion depth, ψ , and electron density enhancements, ϕ , in the recovery phases of the irregularities narrowed. This was evident in [Fig. 2](#), panels (b), (d) and (f) for results obtained with data from station DODM on 18/10/2010 from PRN 13. For ww values of 1800, 3000 and 5460 s, results from DODM showed that the corresponding values of ϕ were $+2.0$, $+4.5$ and $+8.1$ TECu, while the corresponding values of ψ were -6.8 , -10.5 and -14.0 TECu (Refer to [Fig. 2](#) panel (b), (d) and (f)). Both ww values 1800 and 3000 s satisfied the conditions set by threshold values of ϕ and ψ for occurrence of an EPB. While for ww value of 5460 s, the value of ϕ surpassed the set threshold value of $+8.0$ TECu, hence it did not qualify to be identified as an EPB. For ww values of 300 and 1200 s, the values of ψ were smaller than the set threshold value and could therefore not meet the conditions required for occurrence of EPBs. As a result, the irregularities obtained using ww values of 300 and 1200 s could not qualify to be considered as

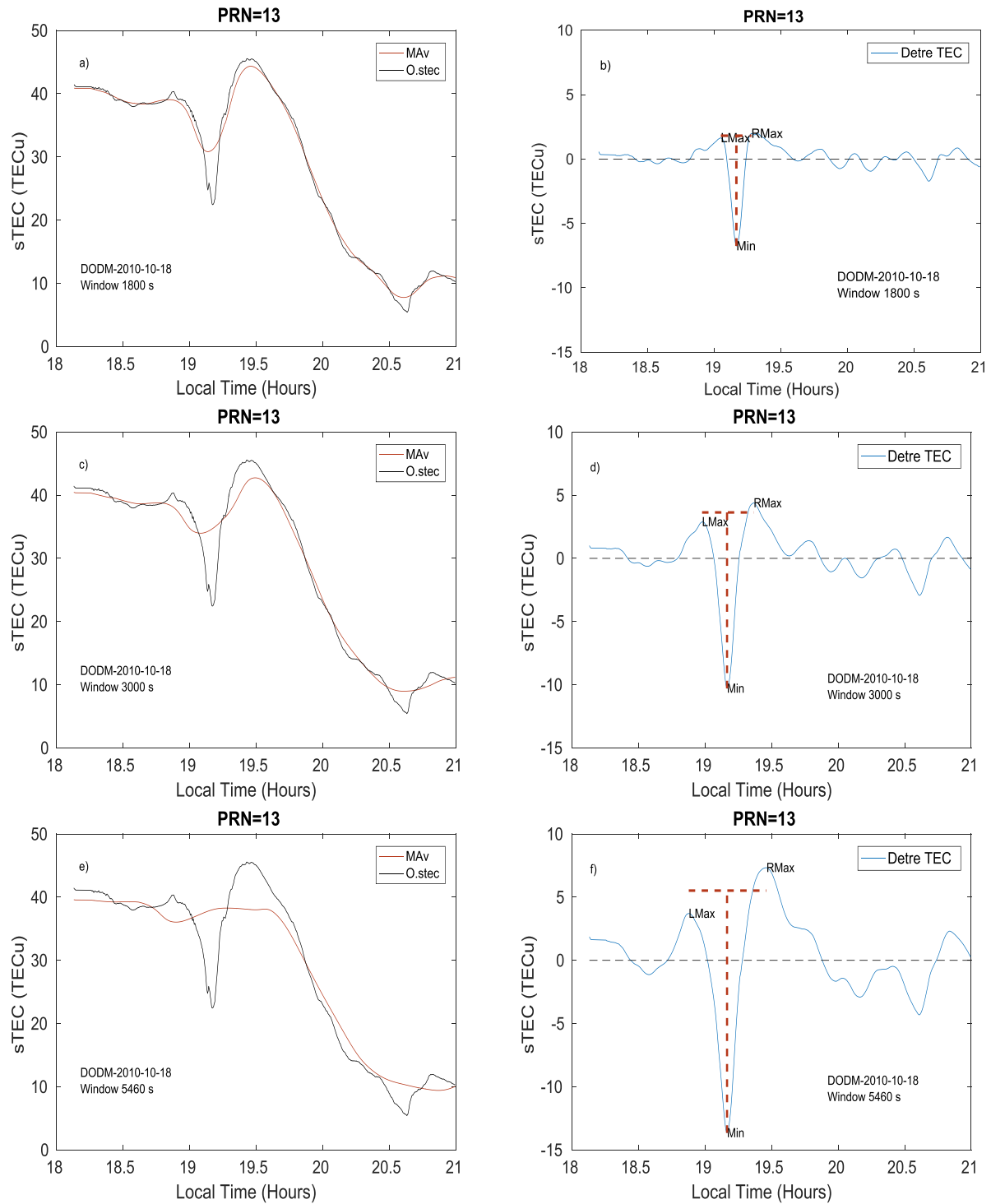


Fig. 2. Left panels: (a), (c) and (e) MAV and sTEC values plotted against local time for ww values of 1800, 3000 and 5460 s. Right panels: (b), (d) and (f) detrended curves of the sTEC-time series for ww values of 1800, 3000 and 5460 s.

EPBs. This explains why their figures were not presented. The same cross examination was conducted for all the other values of ww explored using data from all the selected receiver stations and similar results were obtained.

When ww value of 1800 s was applied to 2011 sTEC data obtained from station MAL2, 688 EPBs were observed compared to 419 for ww value of 1200 s and even fewer for ww value of 3000 s. The reduction in the number of observed EPBs as the value of ww was increased from 1800 s to 3000 s was attributed to the fact that increase in the value of

ww also increased the value of ϕ . Hence, many of the would be EPBs had ϕ values above the electron density enhancement threshold that we set for EPB occurrence. Similarly, reduction in the value of ww from 1800 s to 1200 s caused a reduction in the absolute value of ψ . Consequently, many probable EPBs were disqualified because the electron density depletions that resulted were less than the threshold value of ψ which we had set for the occurrence of EPBs. Since ww value of 1800 s produced a better match of the sTEC-MAV and sTEC values in addition to providing more chances for identifying EPBs, we chose ww value of 1800 s for use

in our study. The depletion depths and apparent duration of the identified EPBs, were indicated in Fig. 2, panels (b), (d) and (f), by the dotted vertical and horizontal red lines, respectively. Their values were calculated using equations (1) and (2).

Prior to and after the occurrence of an EPB, wave-like structures could be seen (Fig. 2 panels (b), (d) and (f)) in the detrended curve of the sTEC-time series whose crests and troughs did not satisfy the conditions set by the threshold values of ϕ and ψ , respectively. Such structures could not be classified as EPBs but they simply depicted other forms of irregularities in the ionosphere, like gravity waves. We also observed that a single satellite link could experience more than one EPBs in a given night, provided the conditions set for the threshold values of ϕ and ψ were met. This was evident in many of the selected stations, with an example shown in Fig. 3 (a) for PRN26 observed over receiver station MAL2 on 28/03/2011.

Makela et al. (2004) observed that low latitude ionospheric irregularities often manifest as depleted plasma regions that burst through the F-region into the peak region of the ionosphere. When radio signals traverse through these ionospheric irregularity regions, they may be subject to rapid measurable changes in their amplitude, phase and polarization, a phenomenon known as signal scintillation (Jakowski et al., 2005). Signal scintillation levels are commonly identified using the S_4 and σ_ϕ indices. In Fig. 3 (a), (b) and (c), we show how the identified EPBs over MAL2 on 28/03/2011 by PRN26 are associated with amplitude scintillation and phase scintillation, respectively. The amplitude and phase scintillations were analyzed using scintillation data obtained from the University of Nairobi SCINDA station UON on 28/03/2011 by the same PRN26. The results show a positive correlation between the occurrence of the observed EPBs, S_4 and σ_ϕ indices at about 20:00 and 23:00 h local time. Our assumption here is that the Ionospheric Pierce Points (IPP) of UON and MAL2 receivers were close enough for the ray paths from a given GPS satellite to the two receivers to traverse the same part of the ionosphere.

3.2. Variation of occurrence of EPBs with solar activity

The annual percentage occurrence of EPBs was calculated for all the stations under consideration using equation (4). In Fig. 4, we present the results obtained for the annual percentage occurrence of EPBs over a sparse scatter of selected receiver stations ARMI, MAL2, MBAR and DODM over the region of study. We also present the average annual SSN in the same figure for purposes of comparison. Fig. 4 shows that the average annual SSN in the years 2008 and 2009 were less than 80, indicating that these were low solar activity years. In the same period, the annual percentage occurrence of EPBs was observed to be minimal i.

e. less than 10%. The highest solar activity was registered in 2014 when the average annual occurrence of SSN was about 145. During the same year 2014, MBAR and MAL2 registered about 97% and 93% annual percentage occurrence of EPBs, respectively. DODM and ARMI also registered a peak occurrence of EPBs of about 59% and 15%, respectively. Generally, during low solar activity periods, the annual percentage occurrence of EPBs was proportionately low, as shown in Fig. 3. All stations analyzed showed higher annual percentage occurrence of EPBs during the high solar activity period (2012–2014) and low percentage occurrence of EPBs during the low solar activity years (2008–2009). This kind of correlation between annual percentage occurrence of EPBs and average Annual SSN confirmed what had earlier been noted among others by Huang et al. (2002); Lee et al. (2005); Manju et al. (2007). This positive correlation between the annual percentage occurrence of EPBs and average annual SSN could be explained by the fact that during high solar activity periods, there is an increase in the proportions of solar Extreme Ultraviolet (EUV) radiation. When directed towards the Earth, the solar EUV radiation penetrate into the Earth's upper atmosphere to cause ionization of neutral particles. This increases the E-field in the upper atmosphere, which in turn increases the vertical $\vec{E} \times \vec{B}$ upward force on plasma, forcing plasma to rise further. At sunset, the intensity of solar EUV radiation that penetrate into the Earth's atmosphere reduces greatly. This substantially reduces the rate of ionization in lower ionosphere and the ion-electron recombination process spontaneously takes over owing to the closeness of the ions and electrons. Thus, the ion density in the lower atmosphere drastically falls, creating a steep vertical plasma pressure gradient conducive for RT-instability which triggers the generation of EPBs. However during low solar activity periods, there is a reduction in the proportion of solar EUV radiation. This means that less ionization takes place during low solar activity periods and thus less upward plasma gradient is experienced during low solar activity periods. Consequently, the percentage occurrence of EPBs increases during high solar activity periods when the ionospheric irregularities are more pronounced. Dao et al. (2011); Huang et al. (2011); Yizengaw et al. (2013) noted that although EPBs were observed during both low and high solar activity periods, their occurrence rate was higher during high solar activity years.

3.3. Latitudinal and longitudinal variation of occurrence of EPBs

The region of study did not have GPS-receiver stations along the same longitude. We made the assumption that stations with longitudinal variation of about 3.0° could be considered close enough not to cause

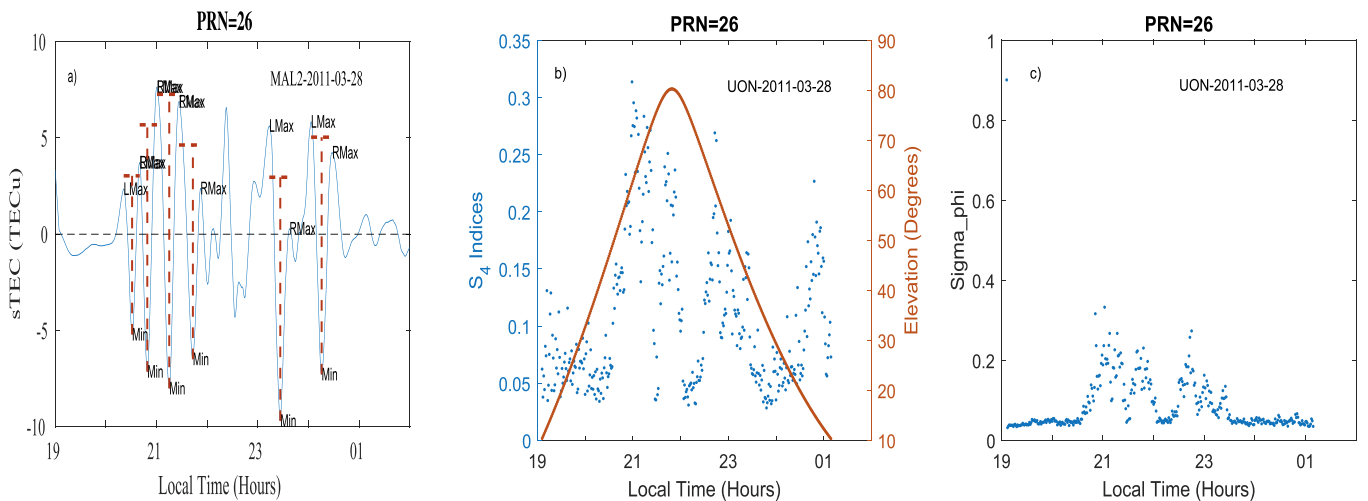


Fig. 3. (a) Observed EPBs (b) Amplitude scintillations (c) Phase scintillations.

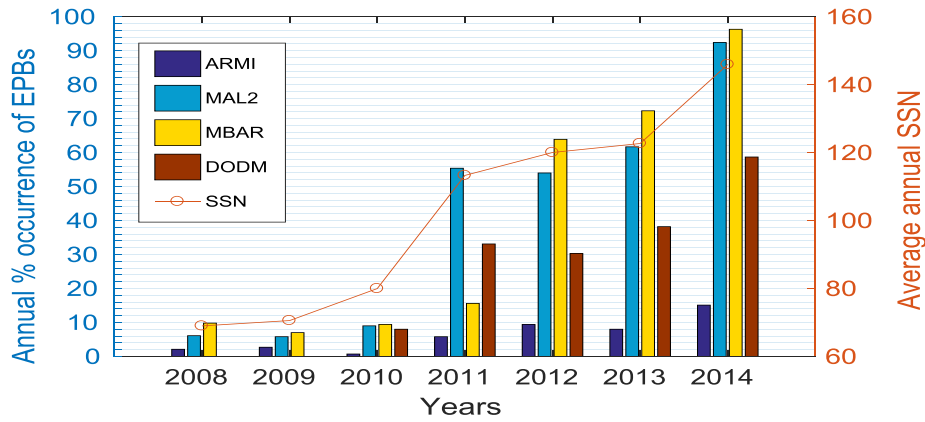


Fig. 4. Comparison of the annual % occurrence of EPBs from different locations and average annual SSN.

longitudinal variations. Therefore, we considered receiver station ARMI (6.06°N, 37.56°E), MOIU (0.29°N, 35.29°E), RCMN (−1.22°N, 36.89°E) and DODM (−6.19°N, 35.75°E) in our analysis of the latitudinal variation of occurrence of EPBs as shown in Fig. 5 (a). The alignment of these selected GPS receiver stations and their latitudinal variations can be visualized on the map of E. Africa shown in Fig. 1. The year 2008 was left out in the analysis because receiver stations DODM and RCMN did not have available data for that year. In 2009, no EPBs were detected over station RCMN due to insufficient data while station DODM had no data available for analysis. To analyse the longitudinal variation of the

occurrence of EPBs, we considered receiver stations MBAR (−0.60°N, 30.74°E) and MAL2 (−3.00°N, 40.19°E) which were separated by about 10° in longitude but had a latitudinal variation of 3° as can be seen in Fig. 1. The results obtained for the longitudinal variation of occurrence of EPBs is presented in Fig. 5 (b).

Receiver station ARMI is close to the magnetic equator, near the trough of the equatorial ionization anomaly (EIA) region, while receiver station DODM is furthest from the magnetic equator, in the region of the southern peak of the EIA (Refer to Fig. 1). Fig. 5 (a) shows that for the period 2009–2014, the annual percentage occurrence of EPBs was

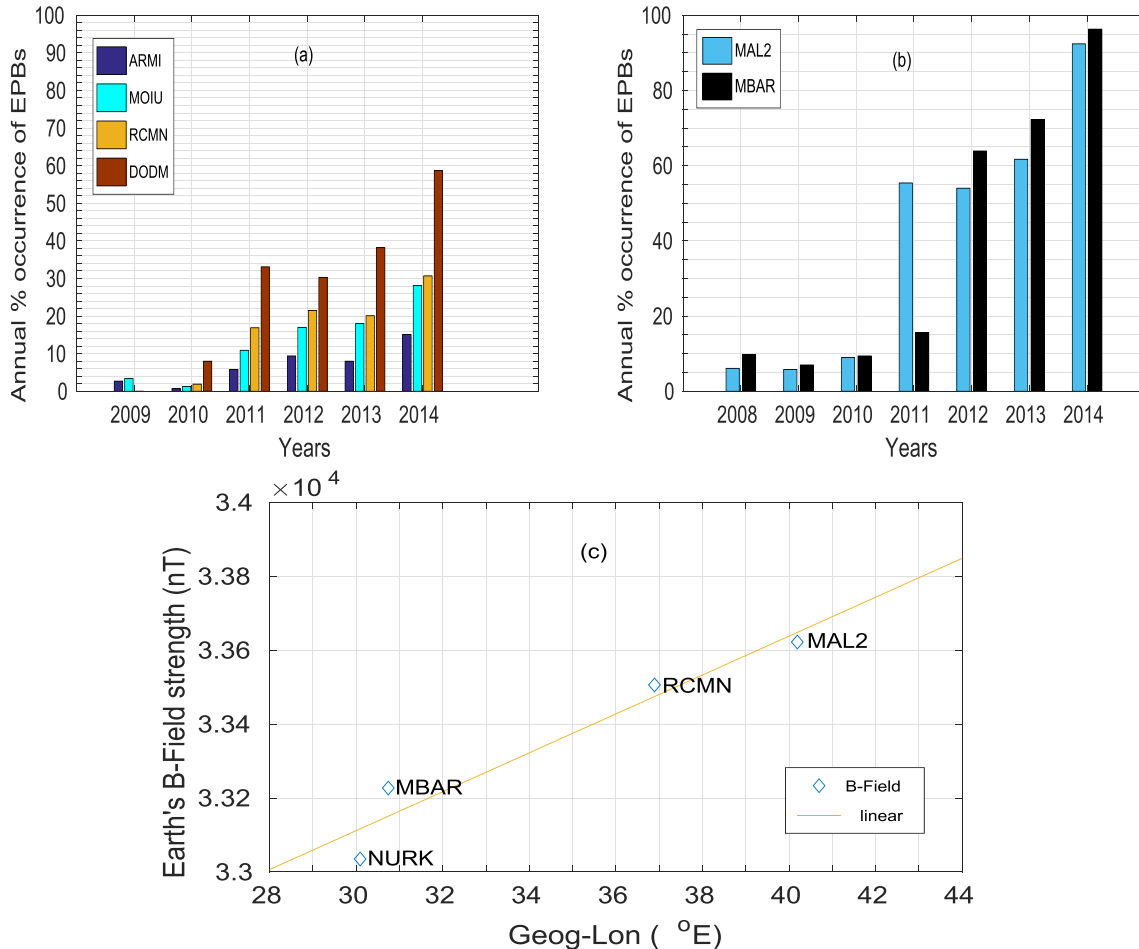


Fig. 5. (a) Latitudinal variation of annual % occurrence of EPBs (b) Longitudinal variation of annual % occurrence of EPBs (c) Variation of Earth's geomagnetic field strength with geographic longitude.

always lower for station ARMI compared to the other selected stations. As the distance from the magnetic equator increased, the annual percentage occurrence of EPBs also increased, with the peak observed at receiver station DODM. This trend was observed throughout the period of study. Stolle et al. (2008) noted that during daytime, the eastward electric field in the F region of the low latitude ionosphere was enhanced at dusk. This enlarged the equatorial fountain effect, causing the two peaks of the EIA to get stronger as the trough above the dip equator became weaker (Kelley, 1989; Fejer et al., 1999). The largest electron density appears on both sides of the magnetic equator at about $\pm 15^\circ$. The increased electric field in the peak of EIA region increases the upward thrust, $\vec{E} \times \vec{B}$, on plasma creating a conducive environment for RT instability, which leads to the increase in percentage occurrence of EPBs. This is in line with the deduction made earlier by Wan et al. (2018) when they noted that the largest occurrence rate for EPBs was at the peak of the EIA rather than at the magnetic equator.

According to the RT-plasma growth rate equation, the vertical component of plasma drift velocity is given by $\vec{V}_p = \frac{\vec{E} \times \vec{B}}{B^2}$, where $\vec{E}$ and $\vec{B}$ are the Earth's electric and magnetic field strengths, respectively. Evidently, $\vec{V}_p$ is higher when the value of the Earth's magnetic field strength is lower (Burke et al., 2004). Thus to analyse the longitudinal variation of the annual percentage occurrence of EPBs, we used the International Geomagnetic Reference Field (IGRF) model to compute the strength of the Earth's magnetic field over receiver stations NURK, MBAR, RCMN and MAL2. The results obtained are presented in Fig. 5(c) and they show that the Earth's magnetic field strength increases eastwards over the East African low latitude region. Consequently, the vertical component of plasma drift velocity increases Westwards in this region of study. Thus, the likelihood for the RT-mechanism to kick start are higher in the Western than in the Eastern regions of East Africa. This may account for the persistent greater annual percentage occurrence of EPBs observed over MBAR compared to MAL2 over the period of study as shown in Fig. 5 (b).

3.4. Seasonal distribution of occurrence of EPBs

Since the region of study lies in low latitudes of Eastern Africa, the seasons of the region were considered when analyzing the temporal distribution occurrence of the EPBs. These seasons include the December solstice (November to February), the vernal equinoxes (March and April), the June solstice (May to August) and the autumnal equinoxes (September and October). The years 2014 (high solar activity) and 2009 (low solar activity) were selected for this study. Receiver stations MBAR, MAL2, MOIU and DODM were considered for the high solar activity period since they had sufficient number of days with data. However,

receiver station DODM did not have data for the months of June to December. During the low solar activity period (2009), receiver stations MBAR, MOIU and DODM had very few observed EPBs which could not make any statistical sense. Hence they were left out in the analysis of low solar activity phenomena.

Fig. 6 (a) shows that during high solar activity, the occurrence of EPBs peaked in both the equinoxes and was minimal during the December and June solstices. The maximum number of EPBs were observed in March and September during the high solar activity year of 2014. By comparison, in 2014 the maximum number of EPBs observed from receiver stations MAL2, MBAR, MOIU and DODM in the month of March were 234, 218, 73 and 152 respectively. While in September, 208, 259 and 90 EPBs were observed from receiver stations MAL2, MBAR and MOIU respectively. The station DODM did not have data in the month of September 2014. In the low solar activity year 2009 (Refer to Fig. 6 (b)), the highest number of EPBs observed in station MAL2 was 19 in February followed by 14 in November. These figures show a considerable drop in the number of EPBs observed in low solar activity year compared to the number of EPBs observed during high solar activity period. Based on reasons advanced by Tsunoda (1985), the general trend seems to suggest that during high solar activity periods, there is increased occurrence of EPBs during equinoxes than during solstices. However, during low solar activity periods, more EPBs are formed during the December–January solstices compared to the other seasons. The high percentage of occurrence of EPBs during the equinoxes periods in high solar activity years could be explained by the fact that the solar terminator for the receiver stations was almost aligned to the geomagnetic flux tubes (Tsunoda, 1985). This occurred when the Solar zenith angle of the receiver stations was approximately equal to zero, a condition satisfied during equinoxes. In addition, during equinoxes, more ionization took place in the ionosphere as a result of the Sun being directly overhead. This increased the electric field in the ionosphere during the day time. After sunset, due to the Pre-Reversal Enhancement (PRE), the vertical upward thrust ($\vec{E} \times \vec{B}$) on plasma was greatly strengthened creating a conducive environment for RT-instability, which leads to the development of EPBs. This positive correlation between the strength of PRE and occurrence of EPBs had also been noted among others by Fejer et al. (1999).

3.5. Characterization of EPBs

The basis of our characterization was grounded in the fact that in the absence of electron density depletions, the ionosphere would be a homogeneous medium and thus satellite signals would not suffer the effects of ionospheric irregularities. According to Jiao et al. (2014); Wan et al. (2018), losses in GPS signal strengths shared more features with the amplitude (depletion depth) than with the rate of occurrence of

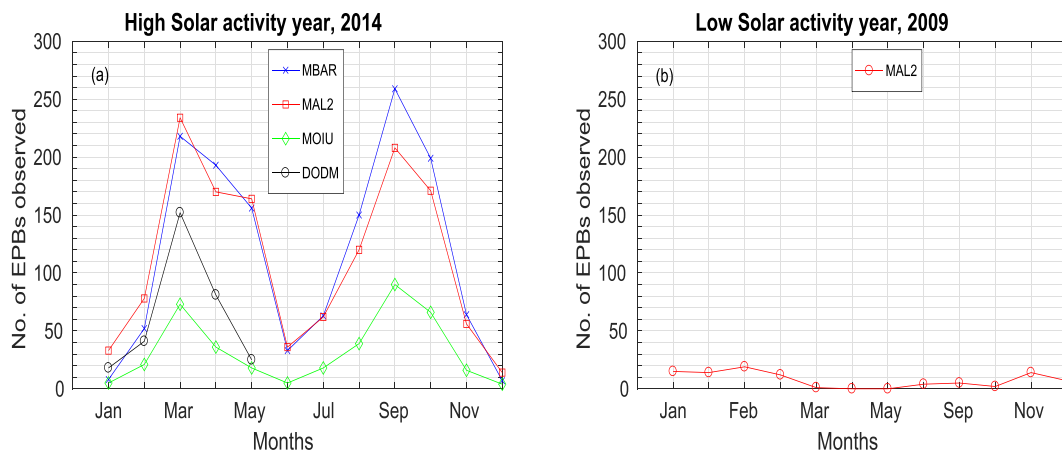


Fig. 6. Seasonal distribution of the number of EPBs observed per month.

electron density depletions. This was inferred to by Haase et al. (2010) when they detected an electron density depletion of about 7.10 TECu over Brazil to cause a scintillation S_4 index of about 0.10 while a depletion depth of about 12.0 TECu corresponded to an S_4 index of about 0.18. These results showed that the deeper the depletion depth of an EPB, the higher the resulting signal scintillation. In addition, Paz-nukhov et al. (2012) noted that EPBs with depletion depth of about 2 TECu do not produce any GPS signal scintillations.

We found that the apparent depletion depths of the identified EPBs in all the considered receiver stations varied between the set threshold, ψ , of 5.00 TECu and a maximum value of 30.00 TECu. These findings were consistent with what Blanch et al. (2018) noted when they observed EPBs with depletion depth of 47 TECu during high solar activity period and EPBs with depletion depths less than 20 TECu during low solar activity periods. We thus used this parameter (the apparent depletion depth) to characterize the EPBs. To achieve this characterization, we first computed the mean apparent depletion depth, $\bar{u}$, for all the EPBs observed during the study period and found that $\bar{u} = 9.79$ TECu. We then computed the standard deviation, σ , of the apparent depletion depths from $\bar{u}$. The calculated value of $\sigma = 2.04$ TECu. For purposes of this study, we categorized apparent depletion depth of EPBs $\leq 4\sigma$ as mild depletions. Those for which $4\sigma < \text{apparent depletion depth} \leq 6\sigma$ were considered to be moderate depletions while EPBs with apparent depletion depth $\geq 6\sigma$ were considered to have severe depletions. In Fig. 7, we present the different categories of apparent depletions of EPBs for the year 2012 for receiver stations ARMI, MOIU, NURK and RCMN. Fig. 7 also showed that the trend of occurrence of the different categories of EPBs had a seasonal pattern. All the categories peaked in equinoxes

months and were their occurrence was suppressed during the solstices. Based on this characterization, EPBs with moderate depletion depths have higher chances of occurrence over the East African region. The least prevalent are EPBs with severe depletion depths. This would therefore imply that GPS signals over the East African region often suffer moderate scintillations. However, this conclusion requires to be verified with more scintillation data collected over the region. Currently, the installation of SCINDA receivers over the region is limited.

Our interest was drawn to establish whether the different categories of EPBs formed over the East African region were time bound in their occurrence. Depending on their impacts on trans-ionospheric radio signals, the time of occurrence of the different categories of EPBs would provide vital information to GPS users on safety procedures when using GNSS applications. In Fig. 8, we present the time dependence of the occurrence of the different categories of EPBs using the year 2012 sTEC data, obtained from receiver stations ARMI, EBBE, DODM and MAL2. All the other stations in the study revealed similar patterns. These results showed that the occurrence of EPBs in the region of study was a post sunset phenomena irrespective of the category of its depletion depth. Formation of EPBs kicked off after 18:00 local time and peaked between 21:00 to 01:00 local time. Their occurrence was not evident after 03:00 local time. Many scholars, e.g. Fejer et al. (1999); Wan et al. (2018), have alluded to this fact. However, this study showed that there was no clear cut time boundary for the occurrence of each category of EPBs. All the categories occurred randomly between 18:00 to 03:00 local time.

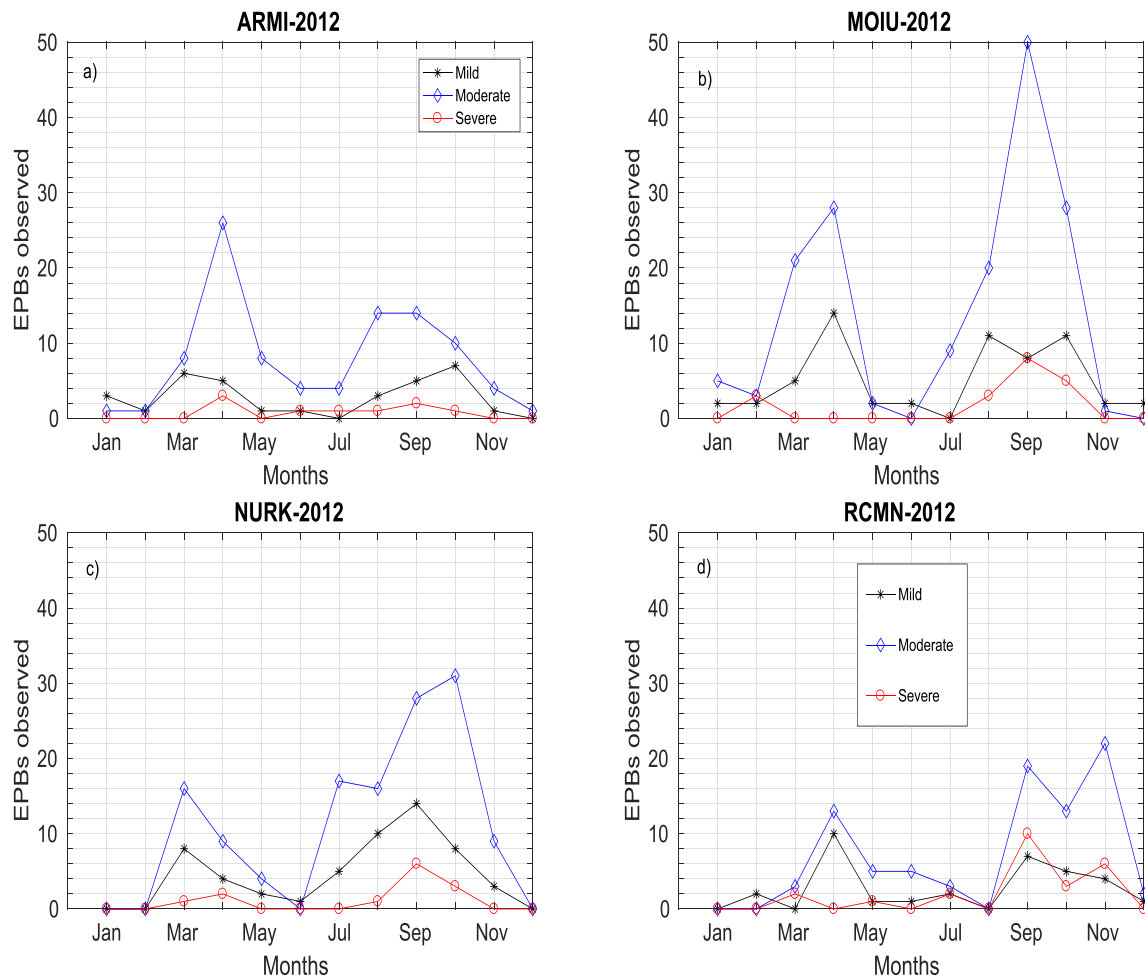


Fig. 7. Number of seasonal variation of the severity of EPBs observed in different receiver stations.

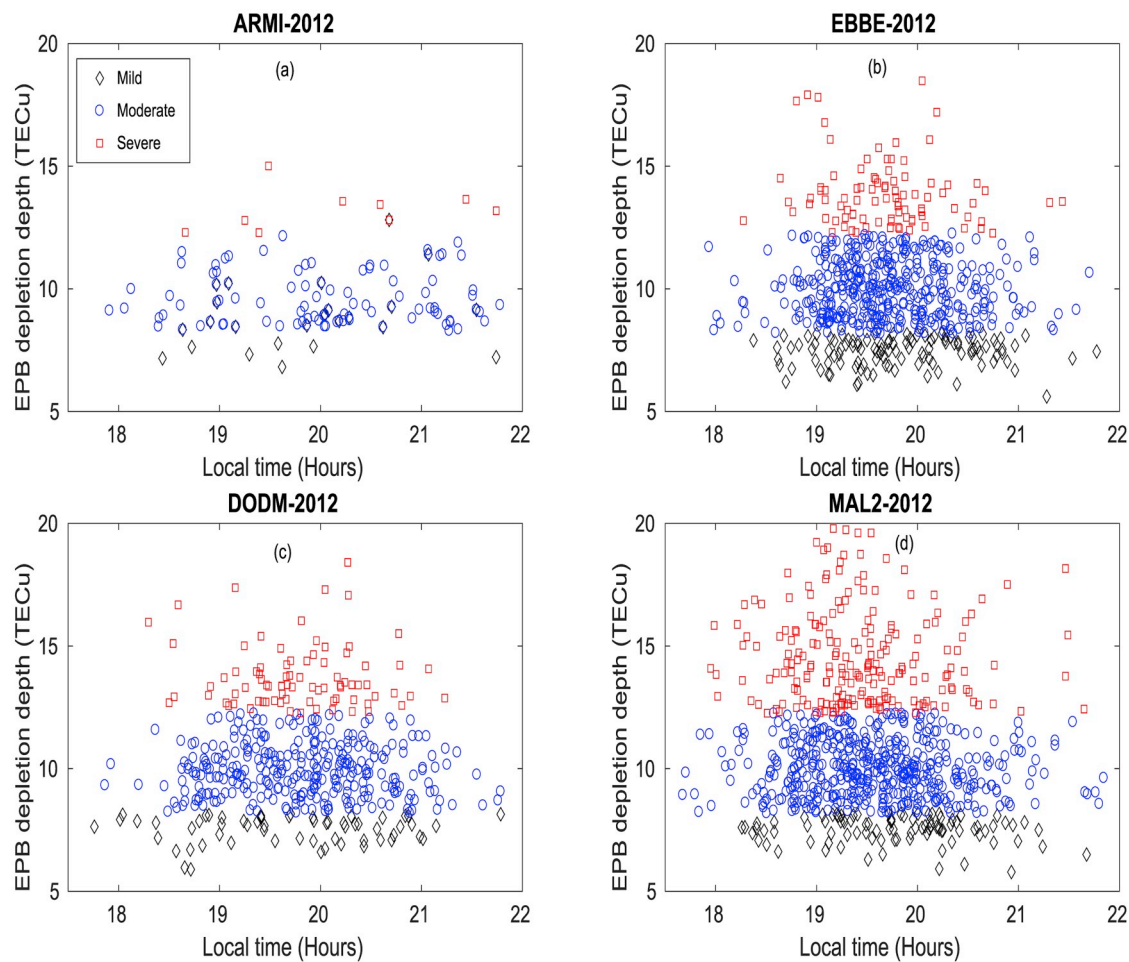


Fig. 8. Diurnal variation of occurrence of EPBs by their depletion depths.

4. Conclusion

In this study we used GPS sTEC data to identify and characterize EPBs observed over the low latitude region of East Africa bounded by geographic latitudes (-7 to $+7$)°N and geographic longitudes ($+29$ to $+41$)°E. Using the detrended curve technique; we were able to show that;

1. The occurrence of EPBs over the region very closely followed the trend of solar activity. The annual percentage occurrence of EPBs was high during high solar activity and low during low solar activity.
2. During high solar activity periods, the occurrence of EPBs was higher during equinoxes than during solstices. However, during low solar activity periods, the annual percentage occurrence of EPBs peaked in solstices. This suggests that the occurrence of EPBs is not predominantly dependant on seasons and solar activity.
3. EPBs could be characterized based on their depletion depths. However, there was need to carry out further investigations to establish the impacts of the different categories of EPBs on satellite radio communication signals.
4. The annual percentage occurrence of EPBs increased with distance from the magnetic equator into the EIA region.
5. The frequency of occurrence of EPBs was higher in the Western side of East African than in the Eastern side.

Acknowledgement

The authors acknowledge the financial support from International

Science Programme (ISP) of Uppsala University in Sweden towards this research. The administration and staff of the South African National Space Agency (SANSA) for the support in availing personnel, facilities and infrastructure during the course of the research. Special thanks to all the agencies from which data used in this study were obtained.

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