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Study on the occurrence characteristics of VHF and L-band ionospheric scintillations over East Africa

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A study of the occurrence of ionospheric scintillations at the VHF and L-band frequencies was carried out at two stations in East Africa, viz. University of Nairobi (Geog 1.3°S, 36.8°E; dip -22.9°) and Makerere University (Geog 0.3°N, 32.5°E; dip. -20.6°) during 2011 and 2012, respectively. Observations were made for the nighttime period (1800 to 0600 hrs LT). It was found that pre-sunset scintillations were more frequent from January to March, and after the March equinox, the onset times quickly shifted to pre-midnight and lasted up to pre-dawn hours. Pre-midnight and post-midnight scintillations have been associated with range-type spread-F and frequency-type spread-F, respectively; while pre-sunset scintillations have been linked to the E-region irregularities. The co-existence of both the VHF and L-band frequency scintillations was also observed, but the small scale irregularities responsible for the L-band scintillations could not exist beyond local midnight. Of particular interest to note were the VHF scintillation signatures at the onset, which were highly structured in short duration patches, but having longer duration with reduction in intensity as time progressed.

Keywords: VHF scintillation, L-band scintillation; Ionospheric scintillation, Solar activity

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1 Introduction

Society now has become more and more dependent on space-based technology and this has led to increased research in the origin and development of ionospheric scintillations[1-5]. When radio waves from global navigation satellite systems (GNSS) or from geostationary satellites pass through ionospheric irregularities of electron density, they develop random phase and amplitude fluctuations before they reach ground stations. These trans-ionospheric radio waves interfere constructively and destructively as they pass through the electron density irregularities, resulting in the receiver, on the ground, experiencing temporal phase and amplitude variations known as scintillations[6-8]. Scintillations are defined as the random fluctuations in amplitude and phase of radio signals traversing a region of turbulence in the ionosphere. They are produced when a radio signal travelling through a turbulent medium, undergoes scattering due to changes in the refractive index. For weak scintillation, maximum contribution to the amplitude fluctuation comes from irregularities having scale sizes of the first Fresnel zone[9]. For GPS L-band scintillations, this scale works out to be about 400 m; while for VHF frequencies (250 MHz), the irregularity size is about 1 km[10]. Satellite communication links in the very high frequency/ultrahigh frequency (VHF/UHF) range can suffer severe scintillation effects in amplitude and phase due to the presence of irregularities in electron density in the F-region of the ionosphere[2]. The occurrence of these irregularities have been reported to reduce with decreasing solar activity as a result of the decreased height of the F-region leading to a decrease in the percent occurrence of scintillations[9].

Scintillation measurements have been used as a tool to detect the presence of irregularities of electron density in the ionosphere. This knowledge helps researchers determine the spatial and temporal distribution of these irregularities. It also helps them to understand the physical processes that lead to the formation of ionospheric irregularities. Analysis of multi-station scintillation measurements has been used in the determination of the morphology of irregularities and has contributed greatly to the design specifications of the communication systems[10-13]. Along with the scintillations at VHF, there are invariably scintillations at GPS frequencies, where severe amplitude scintillations at the L1 frequencies in post-sunset hours are also recorded[2,14,15]. It has also been reported in the literature that in the generation phase, both the kilometer and meter scale equatorial irregularities during post sunset hours co-exist[16]. However, in the post-midnight period, occurrence probability of amplitude scintillations at VHF frequencies is reduced, while the small-scale irregularities that are responsible for scintillations at L1 frequency are found to be almost absent[9,16]. Other researchers[12,14] have observed that when the scintillation index, S_4, attains large values, some receivers are badly affected by loss-of-lock, which may last for some time (a few minutes to one hour), with equipment malfunction and this hampers TEC observations. The loss-of-lock condition of the receiver may lead to severe disturbance on the navigation and communication link, which is considered quite serious in many critical applications.

VHF amplitude scintillations have been recorded both during daytime[17] and nighttime[18,19]. The daytime scintillations are linked to E-region irregularities and are correlated with the growth of the E_s layer critical frequency, f_oE_s. Patel *et al.*[17] observed quasi-periodic scintillations during daytime and attributed them to the periodic variations of the gravity waves which, it is assumed, are the governing process in generating irregularities. The nighttime scintillations, which have been attributed to spread-F, have been observed at both post-sunset and pre-midnight in small patches with durations of less than 30 minutes[2,16]. Irregularities in the nighttime equatorial ionosphere have been studied for several decades using different ionospheric scintillation observations[2,9,10,15,16,20]. The post-sunset scintillations near the anomaly crest are mainly produced by equatorial electron density irregularities[2,15]. At the magnetic equator around sunset, the F-layer may rapidly rise and develop a steep bottom-side density gradient due to the combined effects of recombination of the F1 and E-layers and an actual increase in the vertical plasma drift ($E \times B$) due to pre-reversal enhancement (PRE) of an eastward electric field, making the background conditions suitable for the plasma instabilities to occur, eventually resulting in the generation of a wide spectrum of irregularities often spanning several orders of magnitude. These nighttime irregularities of the equatorial ionosphere are called equatorial spread-F (ESF) irregularities and their occurrence is found to vary with season, latitude, longitude, solar, and magnetic activity. Of the wide spectrum of irregularities, the intermediate scale length (from 100 m to a few km) irregularities cause scintillation on VHF, UHF, and L-band signals. The primary process is believed to be the Rayleigh-Taylor (R-T) instability on the bottom side of the post-sunset equatorial F-region, which may cause a plasma depleted region referred to as the equatorial plasma bubble (EPB) to rise to the topside and develop smaller scale structures[9].

The average plasma density within the ‘bubble’ is reduced by 1-4 orders of magnitude relative to the background ionosphere[11,20]. Once generated, the bubbles move upwards and sometimes attain altitudes greater than 1000 km above the magnetic equator. These irregularities are highly field aligned and therefore, when they reach higher altitudes, the latitudinal extent may reach the Equatorial Ionization Anomaly (EIA) region, eventually producing strong irregularities across the spectrum of intermediate scale sizes because of the background electron density being relatively higher as compared to that over the dip equator[9]. Hence, scintillations observed on UHF/VHF signals transmitted from a geostationary satellite recorded at the equator and the EIA region have been extensively used to monitor relative strengths of intermediate scale length irregularities at equator and crest region[21].

Several researchers have shown that VHF/UHF scintillations occur during equinoctial months[7,21-23]. Somayajulu *et al.*[22] have shown that the latitudinal extent of post-sunset VHF scintillations producing irregularities that were observed during the equinoctial months of high sunspot years were controlled by the generation and growth of F-region irregularities over the magnetic equator; and Valladares[23] also showed that UHF scintillations occurred preferentially during equinoctial months. Vyas & Dayanandan[18] reported that the percentage occurrences of VHF scintillations showed a good correspondence with the monthly mean PRE of the $E\times B$ vertical drift velocities at the equator and both parameters showed a clear seasonal behaviour with equinoctial maxima followed by winter and a summer minima during both high and low sunspot activity years. It was also observed that the PRE in the $E\times B$ drift over the equator was the most crucial parameter that controlled the development of irregularities causing intense VHF scintillations. Further, during the high sunspot activity year 2001, these conditions were more sharply defined in the equinoctial months than in winter and summer months. Most of these studies have revealed that the nature of the scintillations was quite patchy over the anomaly crest, while more or less continuous over the magnetic equator. Generally, it was observed that the number of scintillation patches decrease as the duration of the patch increases.

In equatorial Africa, there have been a number of studies, on seasonal and solar activity dependence of ionospheric scintillations, carried out mainly at the L-band frequencies using GPS receivers[1,2,14,24,25]. They have all observed highest scintillation occurrences during equinoctial months and minimum occurrence during solstice months in conformity with the earlier results from Indian[8,9,12,17] and American[5,7,10,11,13] sectors. It is well established that the occurrence of ESF and the associated irregularities show distinct dependence on longitude, latitude, season and solar activity. The extent of ionospheric variability as revealed through studies of scintillations at different frequencies (VHF and L-band) together with diurnal TEC variations may reveal important ionospheric characteristics over the East African region and this has been the motivation for the present study. The present paper presents a study of the occurrence of ionospheric scintillations at the VHF and L-band frequencies produced by irregularities with kilometer and meter scale sizes, respectively. Data were obtained from GPS SCINDA receivers and VHF-spaced receivers stationed at the University of Nairobi (Geog 1.3°S, 36.8°E; dip -22.9°) and Makerere University (Geog 0.3°N, 32.5°E; dip -20.6°) during 2011 and 2012, respectively.

2 Data acquisition

The high data-rate NovAtel GSV400B GPS receivers used in this research are part of the network of GPS receivers in equatorial Africa which have been deployed by Boston College and the Air Force Research Laboratory (AFRL)[2]. Along with the GPS receivers, data from the VHF spaced receivers at the two stations, whose antennae are placed about 80-100 m apart in the magnetic EïW direction have also been used. The two stations are located about 500 km apart, with University of Nairobi (UoN) (Geog 1.3°S, 36.8°E; dip -22.9 °) and Makerere University (Mak) (Geog 0.3°N, 32.5°E; dip -20.6°). The GPS satellites transmit radio signals at two frequencies namely L1 (1575.42 MHz) and L2 (1227.60 MHz). Due to the dispersive nature of the ionosphere, these two radio signals propagate at different velocities[26] and this information is used in retrieving the total electron content. Ionospheric scintillations at the L-band frequency were monitored by computing the S4 index, which is the statistical measure of the intensity of the amplitude scintillation of the L1 GPS signals. Measurement of 250 MHz scintillations was carried out using the VHF spaced antennae.

As the radio signals travel through a turbulent medium to the receiver on the ground, the irregularities in the medium produce amplitude and phase scintillations that are recorded by the receiver. The amplitude fluctuations of the recorded signal are statistically characterized by the scintillation index, S4, defined as the ratio of the standard deviation of signal intensity and the averaged signal intensity, and is given by:

$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}$$

where, I, is the signal intensity. Scintillation data collected from the GPS and VHF receivers were separately computed by the respective systems at 60 s intervals. The VHF spaced receiver scintillations were analyzed together with the GPS L-band scintillations at the two stations in East Africa during the same periods so as to characterize the irregularities in this region.

3 Results and Discussion

The VHF amplitude scintillations at both stations were recorded simultaneously with the L-band scintillations. Some days in the selected period of study had no data due to power failure or due to non-functioning of the equipment. At the UoN station, all months of 2011 were considered and at the Mak station, data were available only from July to December 2012 with October having data for all the days. The intensity of scintillations was given by the scintillation index, S4, which is defined as the normalized standard deviation of the signal. In general, the number of scintillation occurrences during daytime was much less than those during nighttime at the VHF frequency and hardly any scintillation have been observed during daytime in the L-band frequency range. In this paper, discussions are based on observations made for the nighttime period starting from 1800 to 0600 hrs LT, which is equivalent to 1500 to 0300 hrs UT in the considered sector. It is important to note that for consistency only the occasions, when the scintillation index has been S4 Ó0.2, are considered.

3.1 Initiation time and duration of scintillations

Analysis of onset times of VHF scintillation was carried out on the data obtained from the UoN station for all the months of 2011. VHF scintillations were found to occur mainly during post-sunset as well as post-midnight hours. However, in the months of

January and up to early March 2011, the UoN station observed scintillations during pre-sunset hours also. The different onset times of the VHF scintillations at this station during 2011 are shown in Fig. 1. For comparison, the onset times for the L-band scintillations during the same period were investigated and are shown in Fig. 2. It was observed that these exhibited much lower S4 indices than those at VHF frequencies and were found to occur mostly from post-sunset to pre-midnight local time. Figure 1 shows that pre-sunset scintillations were more frequent from January to March and these extended to post-sunset, but quickly died off towards local midnight. After the equinox (21st March), the scintillation onset times suddenly shifted to pre-midnight for most occurrences and lasted up to pre-dawn hours. The September equinox, on the other hand, recorded delayed onset times starting after sunset but ending before midnight with very few occurrences extending to post-midnight and very mild ones to pre-dawn. The June solstice (May, June and July) exhibited very few serious scintillations, which were concentrated around midnight. In August, scintillations were more intense and started a little earlier than the previous months. Unfortunately, there was no data available for some days in August till early September. During the December solstice (November and December), VHF scintillations were observed mainly from just after sunset to pre-midnight, with much lower S4 indices than in the previous months.

Similar ionospheric research has been carried out by a number of researchers in the equatorial regions of the Indian[8,9,15,17] and the American[7,16] sectors. Sripathi *et al.*[9] reported equinoctial asymmetry in the occurrence of scintillations, similar to those observed in the present research. In their case, however, there was no noticeable time difference in the onset time

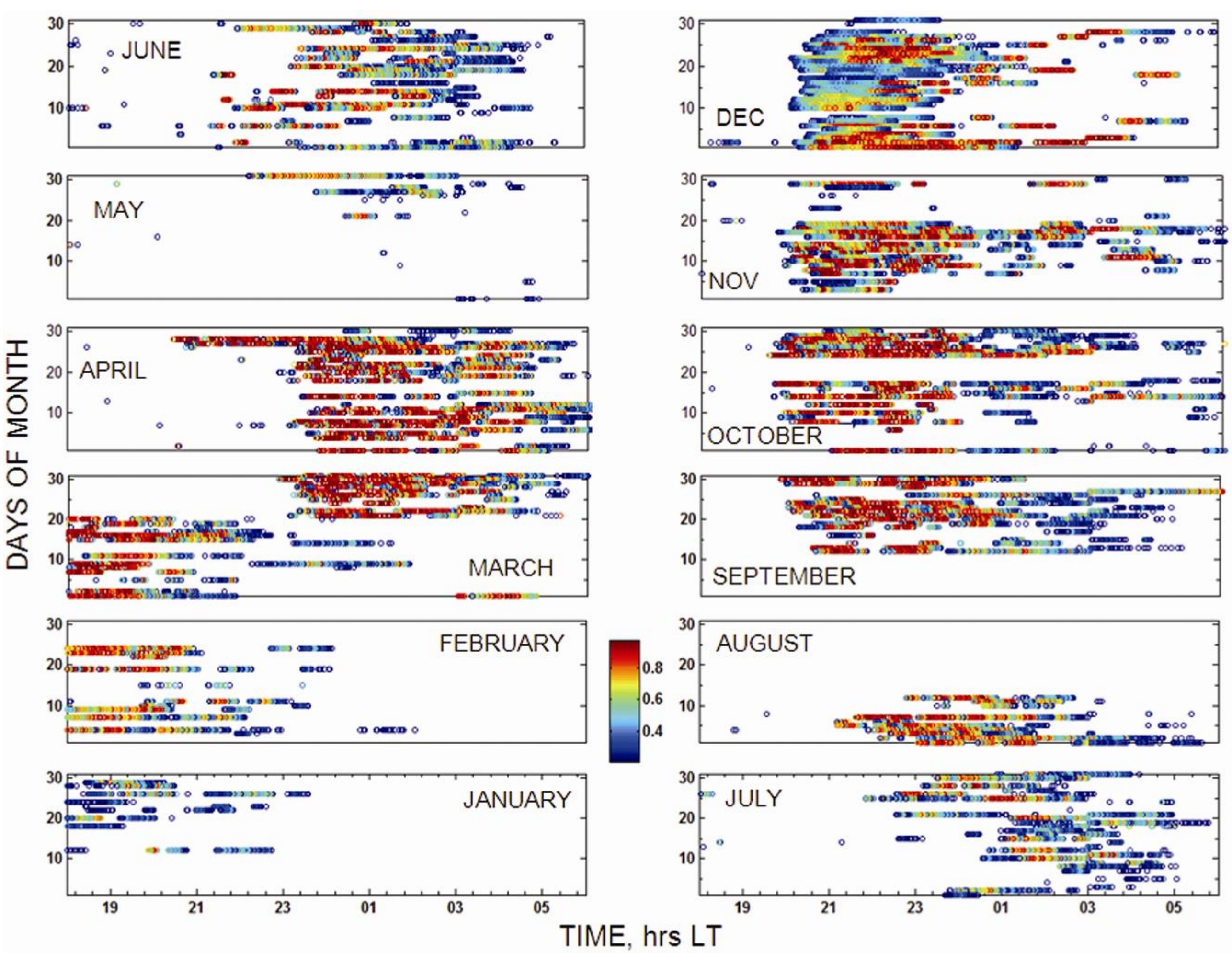

Fig. 1ð VHF scintillations during 2011 at UoN from 1800 to 0600 hrs LT

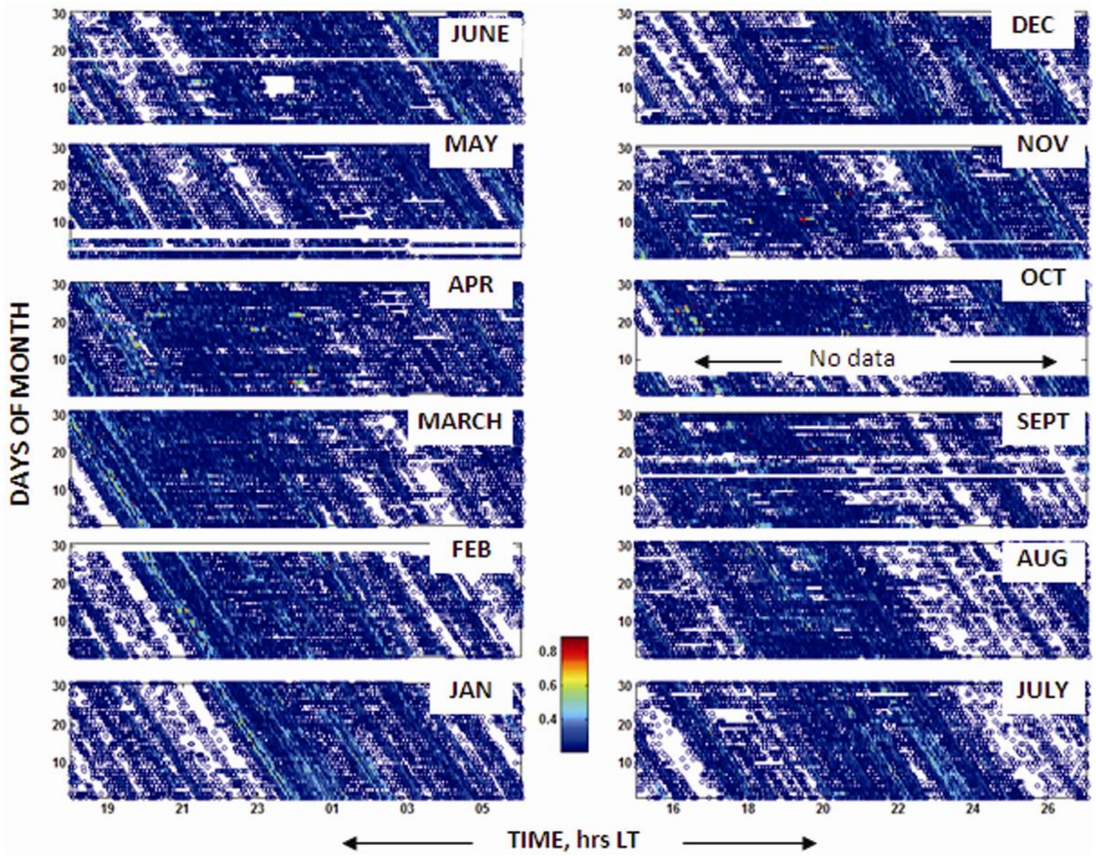

Fig. 2ó L-band scintillations during 2011 at UoN from 1800 to 0600 hrs LT

of scintillations between the vernal and autumnal equinoxes. The equinoctial asymmetry has been attributed to more enhancements in the background electron density during the vernal equinox than that of the autumnal one.

In the present study, correspondence of VHF and L-band scintillations are reported. Figure 3 shows VHF and L-band scintillations on 25 October 2011 at UoN and on 24 September 2012 at Mak. The GPS satellites used to monitor L-band scintillations were identified as PRN 19 on 25 October 2011 and as PRN 3 on 24 September 2012, whose tracks were in the meridional direction. For example, GPS satellite tracks for the four satellites that exhibited scintillations between 2100 hrs LT and local midnight (1800 ï 2100 hrs UT) on 25 October 2011 are shown in Fig. 4. The tracks for the different GPS satellites are marked by their corresponding PRN numbers, with the arrows denoting the direction of each satellite. It is observed that the ionospheric pierce point (IPP) for satellites PRN 1, PRN 11 and PRN 19 passed from north-west (NW) to south-west (SW), while PRN 7 passed from SW to NW. This confirms the meridional direction of PRN 19 during the observations. Figure 3 shows that on these days, just like other days under this study, the post-sunset scintillations are shown to extend to well past midnight into the early hours of the morning at VHF frequencies; whereas at the L-band frequencies, scintillations have a much smaller duration of occurrence with a lower S4 index. On each day, the onset times for the VHF and L-band scintillations is approximately the same, with those at the L-band frequency dying off before midnight. This shows the co-existence of both the kilometer and the meter scale-size irregularities at the initiation of scintillations, but as time progresses, the small scale irregularities responsible for the L-band scintillations cease to exist beyond local midnight. Scintillations at the VHF frequencies were seen to be more intense before midnight than after midnight. Rama Rao *et al.*[12] and Prasad *et al.*[6] made similar observations in the equatorial region of the Indian sector and associated the intense pre-midnight scintillations with fast fading rates of scintillations, which were much higher at the VHF than at the L-band frequencies.

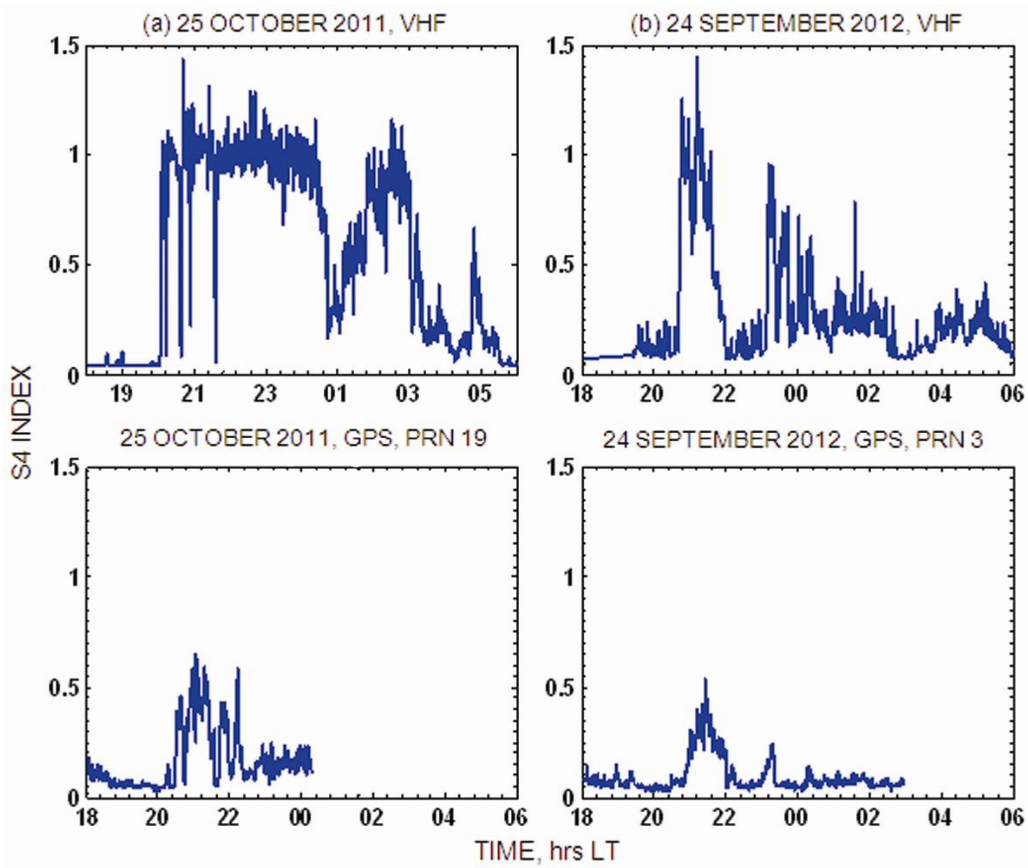

Fig. 3ð VHF (upper) and L-band (lower) scintillations on: (a) 25 October 2011 over UoN and; (b) 24 September 2012 over Mak

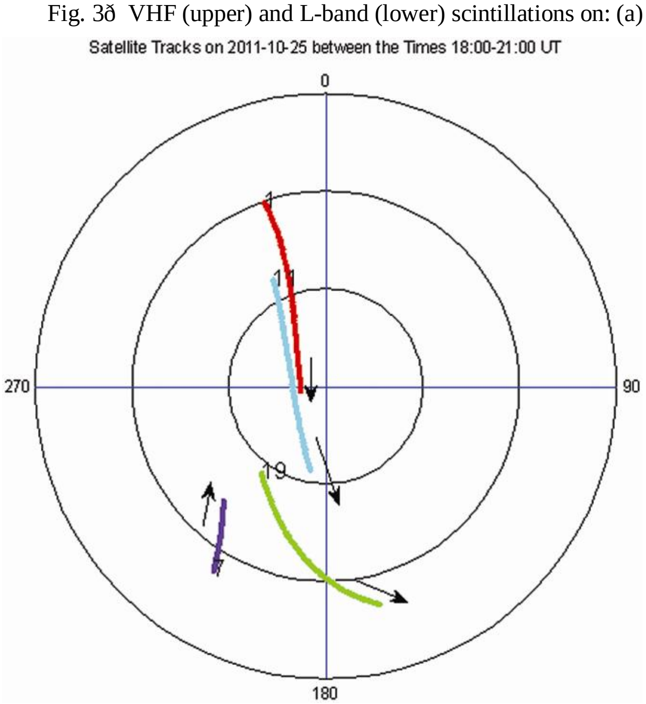

Fig. 4ð GPS satellite tracks on 25 October 2011 between 1800 and 2100 hrs UT [the numbers represent the respective PRNs and the arrows beside each curve denote the satellite direction]

In general, nighttime scintillations are primarily due to the presence of plasma density irregularities (plasma-depleted bubbles) within the F-region. These bubbles are lifted to the topside of the ionosphere through the R-T instability mechanisms leading to small-scale irregularities (~100 ï 500 m) that are responsible for producing strong scintillations at the L-band frequencies. The co-existence of these small size irregularities with kilometre-size irregularities causes intense scintillations at the VHF frequencies[6]. Aarons *et al.*[27] reported that high solar flux conditions result in greater electron density in the F-region leading to enhanced scintillation activity even at L-band frequencies. Pre-midnight scintillations have been associated with range type spread-F, while post-midnight scintillations have been associated with frequency type spread-F[17]. Scintillations that occur before sunset have been linked to the E-region irregularities[20]. It was observed that some VHF scintillations, which get initiated before sunset can last up to midnight; while those starting during post-sunset hours can extend up to dawn, as shown in Fig. 5. Figure 5(a) shows an example of VHF

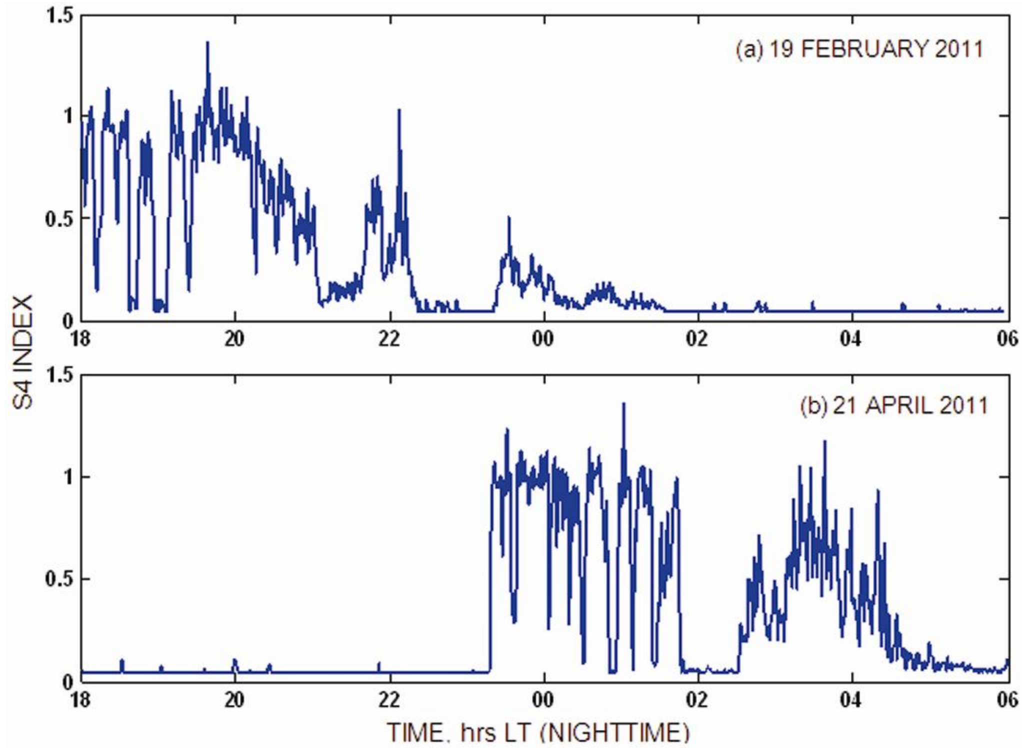

Fig. 5ó VHF scintillation onset times on: (a) 19 February 2011 (upper panel); and (b) 21 April 2011(lower panel) as observed at UoN

scintillations on 19 February 2011, where the onset time of intense scintillations was during pre-sunset hours and this lasted up to post-sunset, with small patches extending up to midnight (2100 hrs UT). Figure 5(b) shows intense irregularity structures that were initiated during post sunset hours (on 21 April 2011) and persisted through midnight up to the early morning hours. The figures show that during onset times, the VHF amplitude pattern is structured in shorter duration patches, but as the scintillations extend into the night, the signature becomes more rugged, with longer duration and reducing in intensity until it dies off. The intense scintillations during pre- and post-sunset have been associated with range type spread-F and can also be exhibited as depletions in the total electron content, suggesting that they are of the plasma bubble-induced type, while those after midnight are associated with frequency type spread-F, shown on ionograms[12]. In their research, Vyasi & Dayanandan[18] reported that the scintillation durations before and after midnight were seasonally dependent.

3.2 Percentage occurrence at the VHF and L-band frequencies

Generally, at the VHF frequency, much higher amplitude scintillations were depicted than at the L-band frequency. Figure 6 shows the percentage occurrence of the strength of VHF and L-band scintillations during 2011 as observed at the UoN station. Equinoctial months of March-April (vernal) and September-October (autumnal) revealed higher occurrences of larger S4 index than the other months. This is more pronounced in the VHF scintillations [Fig. 6(b)], where the S4 index reached as high as >0.8 on a significant number of days. At the L-band frequency [Fig. 6(a)], overall the strength of scintillation had been weaker and the S4 index had not crossed 0.2-0.3 more frequently and it touched 0.6 very rarely. Other equatorial regions from the Indian and American sectors have also reported similar seasonal dependence of the VHF and L-band scintillations. For example, in India[17], scintillations are favoured during the equinoctial months (March, April, Sep, Oct), followed by winter months (Jan, Feb, Nov, Dec) and then summer (May-Aug). This has been attributed to the seasonal and solar activity dependence of maximum electron density of the F-region and the associated equatorial electro-dynamical processes that would set the stage for the plasma instability to operate.

3.3 Effects of solar cycle trend

To compare scintillation occurrence during 2011 and 2012 of the ascending phase of the solar cycle, the month of October was chosen for comparison

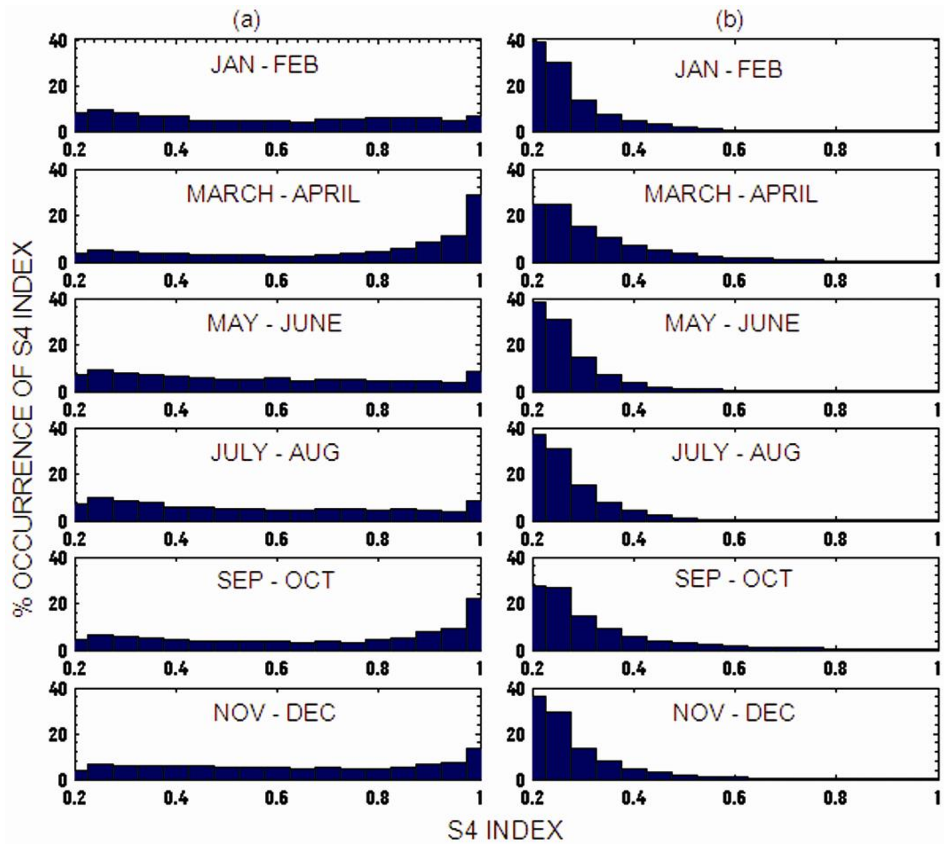

Fig. 6ð Percentage occurrence of the: (a) VHF; and (b) L-band scintillations at the UoN station during 2011 [vertical axis depicts % occurrence of the S4 index and horizontal axis gives the S4 index]

since it had data for all the days in both 2011 (at UoN) and 2012 (at Mak). In an earlier study[28], scintillations at these stations were compared and despite the (small) latitudinal difference, there were no noticeable differences in the scintillation occurrence. Hence, in this study it is assumed that the data at both these stations can be used to see the solar cycle dependence in the occurrence of scintillations. Figure 7 shows the comparison of scintillations during the two years and it can be seen that the occurrence of intense scintillations was more during 2011 than 2012. At the VHF frequency, it is observed that the percentage occurrence for scintillations with S4 Ó0.8 was more in 2011 than in 2012. The same can be observed at the L-band frequencies. One would have expected scintillations with higher S4 index in 2012, since both years are in the ascending phase of solar cycle 24. However, according to the solar data obtained from the NOAA (National Oceanic and Atmospheric Administration) Space Weather Prediction Centre (SWPC), the Sun was more active during October 2011 than in 2012. Figure 8 shows the variation of the radio flux 10.7 cm, and the sunspot numbers during 2011 and 2012 and it can be seen that October 2011 was a month of high solar activity. The increase of scintillations due to solar activity may be due to the variations in the background electron density within the ionosphere.

In addition, the month of October 2011 experienced severe geomagnetic storms and this could have contributed to the observed high scintillation values. Storms are generally associated with strong corona mass ejections (CME) events, which may lead to the inhibition or the generation of ionospheric scintillations. In their findings, Prasad *et al.*[6] reported that the geomagnetic activity inhibited the occurrence of scintillations, while Shang *et al.*[29] observed both the inhibition and generation of scintillations during geomagnetic storms. In both cases, an increase in the height of the F-layer base was observed. It was concluded that even if an increase in the height of the F-layer base was expected to result in scintillations, there might be other processes that inhibit the occurrence of irregularities and scintillations. In an earlier report[28] over the East African region, however, it was observed that the geomagnetic storm in

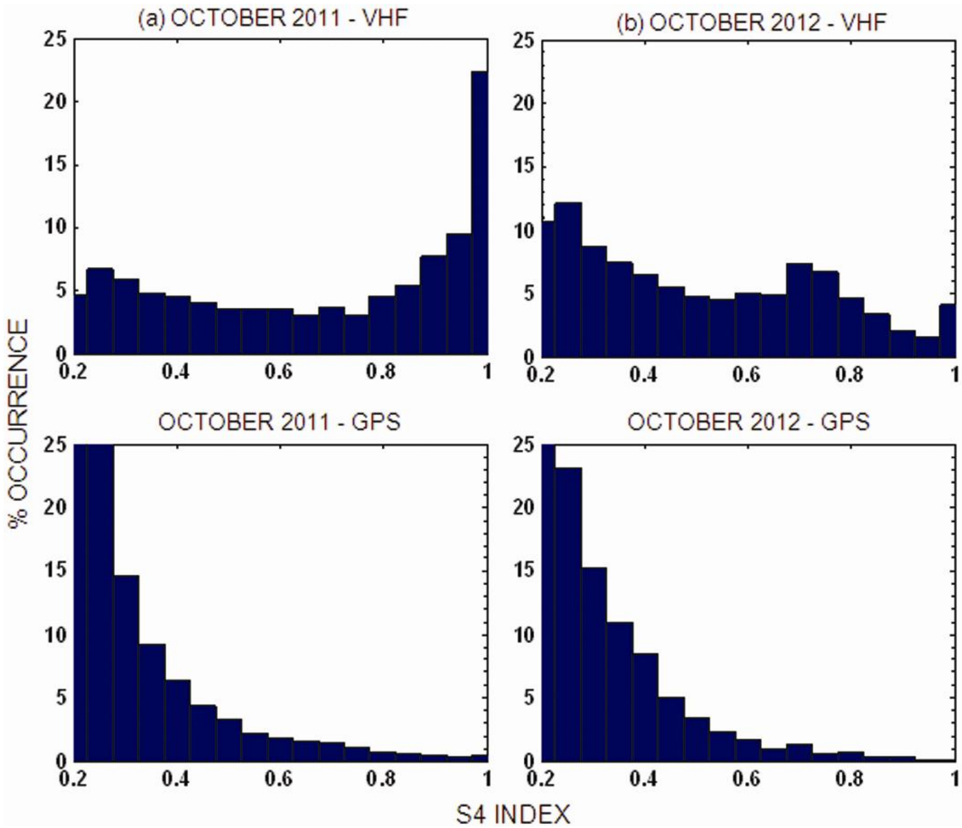

Fig. 7ð Comparison of VHF (upper panels) and L-band (lower panels) scintillations during: (a) October 2011; and (b) October 2012 [vertical axis depicts % occurrence of the S4 index and horizontal axis gives the S4 index]

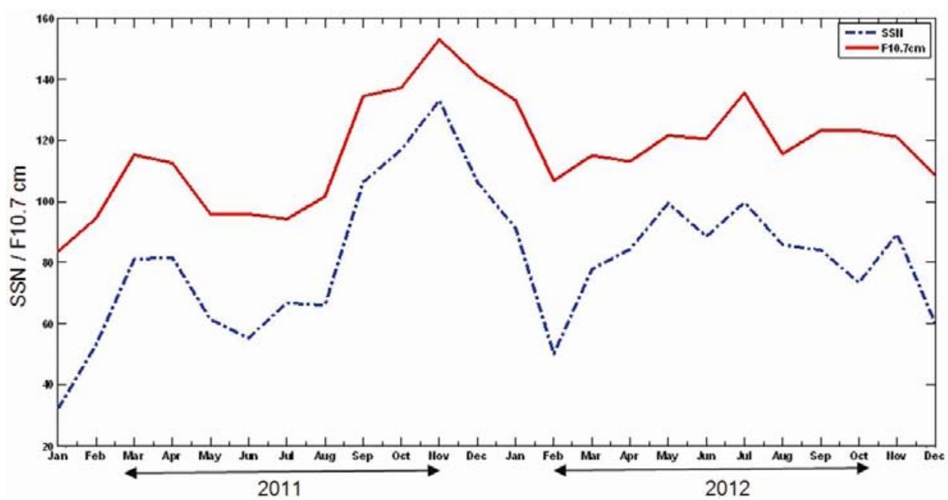

Fig. 8ð Solar indices for 2011 and 2012: Radio flux F10.7 cm (solid line); and sunspot number (SSN) (dashed line)

October 2011 induced significant fluctuations in the total electron content that were characterized by a high rise in the S4 index.

4 Conclusions

Measurements of nighttime (1800-0600 hrs LT) VHF and L-band scintillations have been carried out from two stations in East Africa. Different onset times of the scintillations at both frequency ranges were observed throughout the period of observation, but more pronounced was the equinoctial asymmetry in the occurrence of scintillations at the VHF frequencies, where the September equinox recorded delayed onset times compared to the March equinox.

On particular days, onset times for the VHF and L-band scintillations were observed to be approximately the same, indicating the co-existence of both the kilometer and the meter scale-sizes irregularities at the initiation of scintillations. The VHF scintillations were seen to last throughout the night on some days, while there were hardly any L-band scintillations observed after midnight. Generally, nighttime scintillations are primarily due to the presence of plasma density irregularities within the F-region. Pre-midnight and post-midnight scintillations have been associated with range-type spread-F and frequency-type spread-F, respectively, while scintillations that occur before sunset have been linked to the E-region irregularities. Of particular interest to note was the VHF scintillation signature at the onset, which was highly structured in short duration patches, but having longer duration with reduction in intensity as time progressed.

The percentage occurrence of scintillations at both frequency ranges exhibited a seasonal dependence, with equinoctial months exhibiting higher S4 index occurrence than other months. Effects of the solar cycle trend on the scintillations was investigated based on data for October of 2011 and 2012, which revealed that more intense scintillations were exhibited in 2011 than in 2012 at both frequencies. This was attributed to the higher solar activity and to the intense geomagnetic storms that occurred during October 2011.

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