An Investigation of Equatorial Ionospheric Irregularities under Solar Maximum in the 24th Solar Cycle in Middle and East Africa Using GPS

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Abstract— Ionospheric irregularities exert scintillations on electromagnetic waves when the waves pass through them. So they are interesting for satellite signal propagation in the ionosphere at the magnetic equator and low latitudes. The global navigation satellite system (GNSS) observations recorded at ground-based tracking sites have been a convenient database for investigating ionospheric irregularities. The irregularities over Africa during solar maximum years of 2013–2014 in the 24th solar cycle were investigated in this study by employing the Global Positioning System (GPS), which is a GNSS system. Six African GPS tracking sites of the International GNSS Service (IGS) network were adopted. First three sites were located at low latitudes close to the geomagnetic equator, in Middle and East Africa (from the Atlantic coast to the Indian coast). The other three were located at middle latitudes and at about the same longitudes as the aforementioned low-latitude sites. Equatorial irregularities were characterized by hourly GPS phase-fluctuation index. This index categorized irregularities into three levels: they are background, moderate, and strong irregularities. The important climatological results have been obtained as followings. First: The equinoctial irregularity occurrence rates over the three low-latitude sites decreased slowly from Middle to East Africa (94%, 89%, 83% and 87%, 73%, 64% for moderate and strong irregularities, respectively). Likewise, the June solstitial rates were also decreased similarly (90%, 88%, 74% and 67%, 58%, 37%). However, the December solstitial rates decreased faster (55%, 24%, 28% and 26%, 10%, 7%). Thus, the equinoctial and June solstitial occurrence rates were also high in East Africa (83% and 64%; 74% and 37%), while the December solstitial one was low (only 28% and 7%). Second: Although moderate and strong irregularities occurred very frequently over the low latitude sites (e.g., 94% and 87%), they over the three middle latitude sites all were nearly at the background level (i.e., nearly 0% and 0%). This indicates the irregularities did indeed come from the equator. Third: Although the equinoctial irregularities were dominant, the June solstitial irregularities also occurred frequently and their occurrence rates were comparable to the equinoctial ones, especially in Middle Africa. As for the December solstitial irregularities, they were obviously of minor importance when compared to both the equinoctial and June solstitial ones. The prominent June solstitial rates in Middle Africa may be due to the northward shifted geomagnetic equator (located in the northern hemisphere) and small declination angles.

1. INTRODUCTION

Ionospheric irregularities can exert amplitude and phase scintillations on electromagnetic waves if the waves traverse them [1]. This effect may cause severe signal fading and loss of lock at a receiver. Therefore, ionospheric irregularities are interesting for satellite radio signal propagation.

Ionospheric irregularities usually occur in the F region of the ionosphere, and can be observed by high frequency (HF) radio sounding as spread F, which is a spread of HF echo trace on the ionogram [2]. In addition, the irregularities can also be observed by global navigation satellite systems (GNSS), such as the Global Positioning System (GPS), and the observation result is consistent with that of spread-F echoes [3]. Furthermore, some strong irregularities can reach the top of the ionosphere and can be observed in situ by satellite [4].

Owing to lack of appropriate observation data over the low-latitude Africa, the climatology study of African equatorial irregularities is few. There was a study used slant total electron contents to study equatorial bubbles during the first 6 month of 2004 (a solar minimum year) and showed that the bubbles tends to occur during spring equinox and has obviously less occurrence in East Africa [5]. Nowadays, the GPS geodetic database has become more completed than before. This offers a good opportunity to study the climatology of equatorial irregularities over Africa, especially during solar maximum period. The purpose of this paper is to investigate equatorial irregularities under solar maximum in the 24th solar cycle in Middle and East Africa Using GPS.

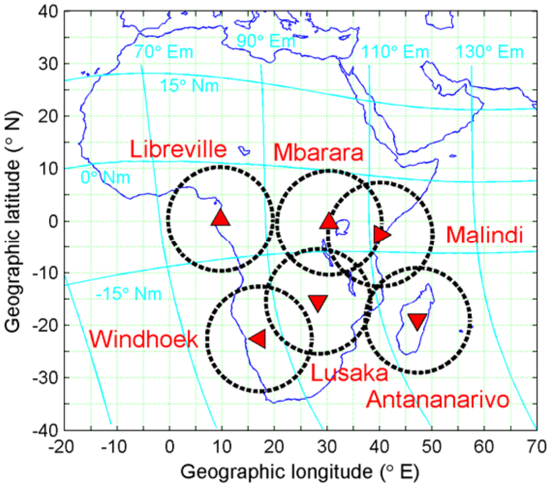

Figure 1: Locations and view fields of GPS tracking sites in Middle and East Africa.

2. DATABASE AND METHOD

The just past 2013–2014 are high solar activity years in the 24th solar cycle, with moderate smoothed yearly sun spot number of 64.9 and 78.9, respectively (both > 50). Six GPS tracking sites of the International GNSS Service (IGS, http://www.igs.org) were found in the middle-east African sector. Their marker names were NKLG, MBAR, MAL2, WIND, ZAMB, and ABPO, which are located in Libreville (Gabon), Mbarara (Uganda), Malindi (Kenya), Windhoek (Namibia), Lusaka (Zambia), and Antananarivo (Madagascar), respectively. For the sake of readability, these sites are represented by the city names at which they are located. The locations of the sites and the fields of view at the height of 400 km with 15° elevation angle over the sites are shown in Figure 1 as triangle symbols and dash circles, respectively. Libreville, Windhoek, Mbarara and Lusaka are in Middle Africa; likewise, Malindi and Antananarivo are in East Africa. The background smooth cyan lines in Figure 1 are auxiliary geomagnetic grid lines, which are in corrected geomagnetic latitude (°Nm) and longitude (°Em). Libreville, Mbarara, and Malindi are at low geomagnetic latitudes (within ±15° Nm) close to the geomagnetic equator (0° Nm); likewise, Windhoek, Lusaka, and Antananarivo are at middle latitudes (outside ±15° Nm). The relations between local time (LT) and universal time (UT) are as the following: for Libreville and Windhoek: LT = UT + 1; for Mbarara and Lusaka: LT = UT + 2; for Malindi and Antananarivo: LT = UT + 3.

The nocturnal ionospheric irregularities are detected using hourly GPS phase-fluctuation index during 1800-0600 LT at each site. GPS phase fluctuations, which were practically high-pass filtered time variation of total electron contents with cutoff period of 25 minutes, were used as an indicator to detect ionospheric irregularities [6]. For quantitatively characterizing GPS phase fluctuations, the hourly phase-fluctuation index F_p is defined as the average of all the quarterly index f_p of satellites available to a site in an hour multiplied by 1000, and the index f_p is the median value of absolute phase fluctuations of a satellite in a 15-minute interval [7,8]. The magnitude of F_p indicates the strength of existing irregularities: $F_p \leq 50$ represents the GPS phase fluctuations come from background noise of irregularities; $F_p > 200$ means the GPS signal is severe influenced by strong irregularities; $50 < F_p \leq 200$ stands for the existence of moderate irregularities.

3. RESULTS AND DISCUSSION

Figure 2 demonstrates an example of comparison for ionospheric irregularity strengths between low and middle latitudes on 2 March 2014. Over Mbarara (low latitudes), irregularities occurred during 17-24 UT (19-02 LT) and caused severe disturbances for vertical total electron contents and phase fluctuations. The hourly index $F_p > 200$ indicated that there occurred strong irregularities during 17-23 UT. However, there were only moderate irregularities ($F_p > 50$) over Lusaka (middle latitudes) during 19-22 UT. The irregularities over Lusaka is considerable weaker than that over Mbarara. Besides, the irregularities over Mbarara occurred earlier than those over Lusaka. Therefore, it seemed that the irregularities were generated at the geomagnetic equator or at low latitudes and then expanded to middle latitudes (i.e., they were equatorial irregularities).

Figure 3 depicts the monthly occurrence rates of nocturnal ionospheric irregularities over Libre-

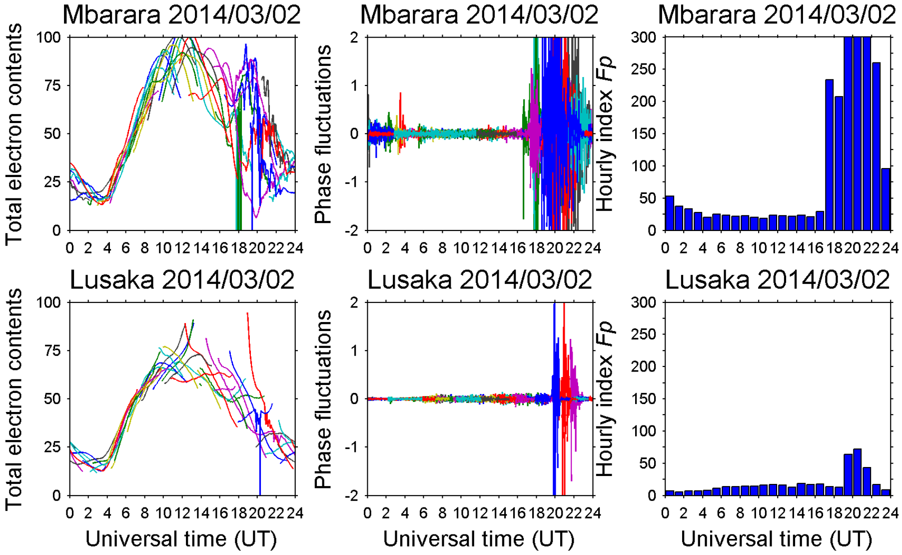

Figure 2: Examples of GPS derived total electron contents, phase fluctuations, and hourly phase fluctuation index F_p over Mbarara and Lusaka for comparison.

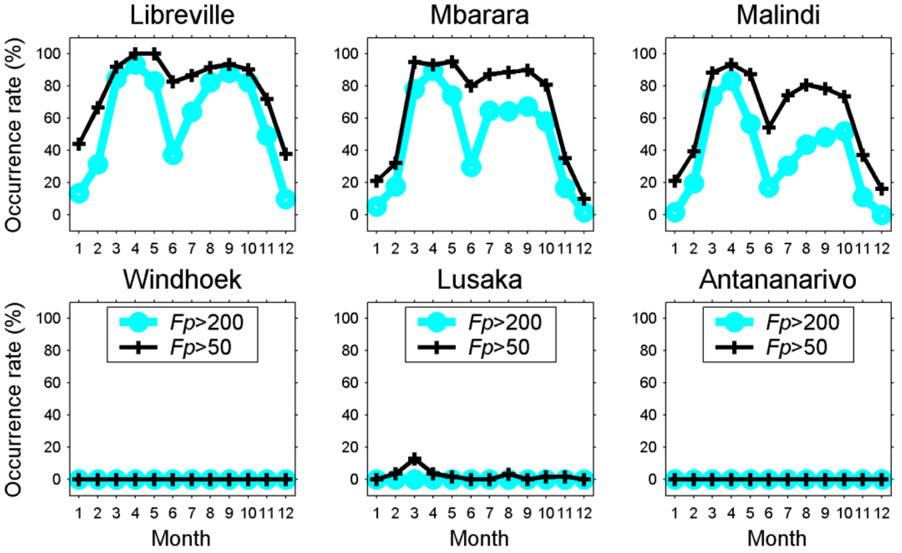

Figure 3: Monthly occurrence rates of nocturnal ionospheric irregularities.

ville, Mbarara, Malindi, Windhoek, Lusaka, and Antananarivo. First, the monthly occurrence rates at middle latitudes (Windhoek, Lusaka, and Antananarivo) were low (nearly 0%) and obviously smaller than those at low latitudes (Libreville, Mbarara and Malindi). This confirms the aforementioned assumption that the irregularities origined at the geomagnetic equator or low latitudes rather than at middle latitudes. By the way, the equatorial irregularities have a narrow latitudinal extent, but are extended in longitude. Second, the patterns of monthly occurrence rate at low latitudes are similar each other, despite that the rates seemed slightly decreasing from west (the Atlantic coast) to east (the Indian coast).

Figure 4 shows the seasonal occurrence rates of nocturnal ionospheric irregularities, which is another aspect of Figure 3. The equinoctial irregularity occurrence rates over the three low-latitude sites decreased slowly from Middle to East Africa (94%, 89%, 83% and 87%, 73%, 64% for moderate and strong irregularities, respectively). Likewise, the June solstitial rates also decreased similarly (90%, 88%, 74% and 67%, 58%, 37%). However, the December solstitial rates decreased faster (55%, 24%, 28% and 26%, 10%, 7%). Thus, the equinoctial and June solstitial occurrence rates were also high in East Africa (83% and 64%; 74% and 37%), while the December solstitial one

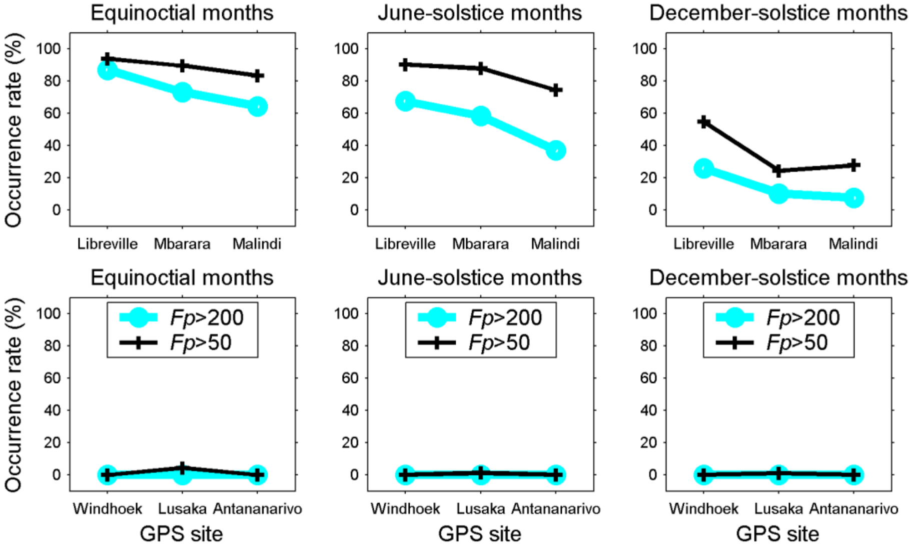

Figure 4: Seasonal occurrence rates of nocturnal ionospheric irregularities.

was low (only 28% and 7%). Although the equinoctial irregularities were dominant, the June solstitial irregularities also occurred frequently and the occurrence rates were comparable to those of equinoctial ones. The June solstitial irregularity occurrence rates have a peak in Middle Africa which nearly catches up with the equinoctial occurrence rate. As for the December solstitial irregularities, they were obviously of minor importance when compared to both the equinoctial and June solstitial ones.

In general, the seasonal climatology of low-latitude ionospheric irregularities can be adequately explained by the alignment of the solar terminator and local geomagnetic meridian [9, 10]. For Middle and East Africa, although the declination angles (the angle between the geomagnetic and geographic meridians) are small (compared to those over the Atlantic Ocean as shown in Figure 1), it still can be expected that the best alignment of the solar terminator and local geomagnetic meridian occurs in December-solstice months. So the December-solstice occurrence rate should be larger than the June-solstice one. However, this expectation doesn't meet the result. Another mechanism proposed by [11] can perhaps be considered here: The magnitude of the $E \times B$ upward drift velocity of pre-reversal enhancement (PRE) at the magnetic equator plays a dominant role on the variability of F region irregularities. Additionally, the late reversal time of the PRE velocity at the magnetic equator would also help the generation of F region irregularities in the equatorial ionosphere. The latest and the earliest reversal times occur in the magnetic equator's local summer and winter, respectively. In Africa, because the magnetic equator is located in the northern hemisphere (as shown in Figure 1), so the June-solstice occurrence rate is larger than the December-solstice one.

Equatorial ionospheric irregularities are plasma bubbles, which often occur in the F region of the ionosphere after sunset near the geomagnetic equator. The irregularities are originally formed on the bottom side of the F region by linear Rayleigh-Taylor instability and then rise and may up to the top of the ionosphere by nonlinear Rayleigh-Taylor instability [12]. They also elongate along geomagnetic fields off the equator to low and even middle latitudes. High equinoctial irregularity occurrence rate is due to large $E \times B$ upward drift in equinoctial months. Both the northward shifted geomagnetic equator (located in the northern hemisphere) and small declination angles in low latitudes may make irregularities occur frequently in June-solstice months but seldom in December-solstice months.

4. CONCLUSIONS

This study has investigated the nocturnal ionospheric irregularities in Middle and East Africa during solar maximum period using the GPS. The aforementioned results and discussion can lead to the following conclusions. (1) The low latitude irregularities come from the geomagnetic equator. (2) The low latitude irregularities often develop in equinoctial and June-solstice months but less develop in December-solstice months. (3) The June solstitial irregularity occurrence rates have a crest in Middle Africa which nearly catches up with the equinoctial occurrence rate. (4) The solstitial irregularity occurrences may be due to the northward shifted geomagnetic equator and small declination angles in low latitudes.

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