Morphology of Ionospheric f_oF2 And N_mF2 over Ilorin during Low Solar Epochs

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Abstract

The F2 region critical frequency (f_oF2) and peak electron density (N_mF2) morphology was investigated over Ilorin (latitude 8.31°N, longitude 4.34°E) during a Low Solar Epochs (LSE), a station along the equator anomaly trough. Diurnally, f_oF2 and N_mF2 are visibly more prominent during the day than at night with two characteristic peaks: pre-noon and post-noon peaks. The f_oF2 and N_mF2 pre-noon peak magnitude range: (7.7–8.3 MHz) and (7.3–8.6) × 10^{11} /m^{-3} respectively is less compared to the f_oF2 and N_mF2 post-noon peak magnitude range: (7.3–9.7 MHz) and (6.7–11.7) × 10^{11} /m^{-3} respectively. Seasonally, the highest values were attained during the post-noon peak in the equinoctial months compared to the solstices months, and also, annually, the post-noon peak is higher than the pre-noon peak. The rapid electron drift away from the equator is responsible for the sharp drop in f_oF2 and N_mF2 after sunset in all seasons. Seasonal peaks in f_oF2 and N_mF2 are suspected to be controlled by the enhanced E × B drifts and the onset and turn-off of solar ionization, which is consistent with some earlier results obtained at some stations in the African region during low solar epoch periods.

Keywords: *f_oF2; N_mF2; Pre-noon Peak; Post-noon Peak; Equator anomaly; Low Solar Epochs*

1. Introduction

The F2 region is the most important region in the ionosphere and it is used for long range radio frequency communications due to its thickness and minimal radio probe attenuation. However, variations in the critical frequency (f_oF2) provide clues as to what is happening within the F2 region as a whole.

Observations show that f_oF2 increases after sunrise, with increases occurring more frequently at low latitudes. The maximum is attained in the early afternoon and plummets just after sunset. f_oF2 is usually highest near the equator. The variation of f_oF2 along the afternoon fixed-hour line depending on the station's solar cycle epochs and seasonal effect is known as the equatorial anomaly.

The equatorial anomaly, on the other hand, characterised as the occurrence of a trough in the ionization concentration at the equator and a crest at about 17° in magnetic latitude in each hemisphere, has been well described as arising from the electrodynamics at the equator. Tidal oscillations in the lower ionosphere move plasma across the magnetic field lines, which are horizontal at the magnetic equator.

The resulting E-region dynamo sets up an intense current sheet referred to as the equatorial electrojet (Anderson *et al.*, 2002; Babatunde *et al*, 2017). Though, these dynamo electric fields are transmitted along the dipole magnetic field lines to F region altitudes, where the uplift of ionization takes place. The zonal current flows eastward during the day and westward at night. Since an electric field is established perpendicular to the magnetic field, an E × B drift moves the ionization vertically upward during the day and downward at night. This upward motion of ionization during the day is referred to as the equatorial fountain, since ionization rises above the magnetic equator until pressure forces become appreciable, that it slows down and, under the force of gravity, moves along the field lines and is deposited at higher tropical latitudes.

For a better understanding of the f_oF2 spread, several works have been carried out. Lastovcka, *et al.* (2008), Oladipo *et al.* (2008), Atac *et al.* (2009) and Adebesin (2012) investigated the representation of ionospheric variability of f_oF2 at different seasons, times of day, solar cycles, and latitudes.

To better grasp, the behaviour of the F2 region ionosphere, Ouattara and Zerbo (2011); Bilitza *et al.* (2014); Tariku (2015); Sawadogo *et al.* (2019); and Diabaté, *et al.* (2019) have highlighted the variability of its critical frequency f_oF2 profiles during various seasons, days, times, solar events, and latitudes. Clette *et. al*. (2014) and Ouattara (2013) reported the variation of this ionospheric parameter through in situ measurements in equatorial regions of Africa and classified the diurnal profile of f_oF2 as Plateau profile, a dome profile, an inverse profile characterised by a dominant afternoon a peak and a noon profile due to the presence of a trough around noon and a double peak (morning and afternoon peaks). Bai *et al.* (2020) combined the entropy weight method to develop the f_oF2 prediction model and provided reliable long-term predictions. A support vector machine model was utilised to establish an empirical local ionospheric forecasting model to predict f_oF2 in Lanzhou, Chen *et al.* (2010). Similarly, Olga Maltseva (2021) utilised the total electron content (TEC) to estimate f_oF2 and demonstrated the results for three stations in the southern hemisphere.

In the current study, f_oF2 data from Ilorin (latitude 8.31°N, longitude 4.34°E) were used. The present work investigates the diurnal, seasonal and annual f_oF2 morphology over the single equatorial station of Ilorin (latitude 8.31°N, longitude 4.34°E) in the North Central of Nigeria during low solar epochs as well as the variation of the F2 region peak electron density (N_mF2). Some earlier works (e.g., Radicella and Adeniyi 1999; Anderson *et al.* 2006; Oladipo *et al.* 2009) adopted the idea of using representative months for each of the seasons and their results are reasonable and well documented.

2. Data and Method

The data used consists of ionospheric F2 region parameters like the critical frequency (f_oF2), and peak electron density (N_mF2). For ionospheric F2 region critical frequencies (f_oF2), the hourly values were taken over Ilorin (latitude 8.31 N, longitude 4.34 E), an ionospheric station in the North central part of Nigeria in West Africa. The study is for the year 2010, a period of low solar epochs. The datasets for f_oF2 were obtained from the Digital Ionogram DataBase (DIDBase), and the ionograms were manually edited with the SAO Explorer software package. The occurrence probability is the number of F2 region events in a certain hour divided by the number of observed ionograms in this hour for a month.

The digisonde sounds every 15 minutes: this time is too short to reveal the changes we want to study. An hourly interval resolution data of F2 region parameters was therefore used for the study, which revealed noticeable changes in F2 region.

The N_mF2 values were derived from the f_oF2 data using the relation in equation (1):

$$N_mF2 = 1.24 \times 10^{10} \cdot (f_oF2)^2 \quad (1)$$

where N_mF2 is given in m^{-3} and f_oF2 in MHz.

For the seasonal pattern of the f_oF2 morphology, data for the months of April, July, October, and November respectively represents the seasons of Spring, Summer, Autumn and Winter. Each set of data covers the entire 24 hours of the day for each of the four representative months of the year 2010. For the annual variation, we used of the mean monthly values across each hour.

3. Results and Discussions

3.1 Ionospheric f_oF2 Observations

Figure 1 represents the average seasonal variation of the critical frequency (f_oF2) over Ilorin during the low solar epoch (LSE) year of 2010. In general, f_oF2 increases from sunrise around 0500 LT and reaches its first peak (pre-noon peak) before 1200 LT around 0800–0900 LT for all seasons. The least f_oF2 first peak magnitude (7.7 MHz) was observed in the Summer season while the greatest peak magnitude (8.3 MHz) was observed in the Spring around the same local time during this period of solar epochs. Thereafter, there is a general daytime reduction in f_oF2, reaching a minimum between 1000 and 1200 LT for the entire season. The highest reduction was yet again in Spring (magnitude: 7.7 MHz around 1000 LT), while the least was in Summer (magnitude: 7.0 MHz around 1100 LT), followed by the Winter (magnitude: 7.1 MHz around 1000 LT), and then the Autumn (magnitude: 7.2 MHz around 1100 LT) during the low solar epochs. Around local noon, the F2 region ionosphere had reached a dynamic stability with respect to losses by recombination, and production by solar radiation according to Fejer (1997). Observations have shown that f_oF2 increases after sunrise; the increase being more prominent at lower latitudes. Maximum is reached in the early afternoon and there is a rapid decrease shortly after sunset. A second peak (the post-noon peak) was between 1500 and 1800 LT for all seasons. During the solar epochs, the magnitude of the post-noon peak was least in the Summer (7.3 MHz) season, and the highest magnitude peak was observed again in the Spring (9.7 MHz) around the same local time during this period of solar epochs. The two f_oF2 peaks observed, according to Chou and Lee (2008); Adebesin *et al.* (2013b), are ascribed to abrupt electron density gradients triggered by the onset and turn-off of solar ionization, as well as the superimposition of spread-F on the background electron density.

Concerning the night-time variation of f_oF2 (1800–0500 LT), a general sharp drop is noticeable immediately after sunset for the entire season. This sharp drop started around 1800 LT. This decay is continuous during all seasons until around 0500 LT, at which time a pre-sunrise minimum occurs. For this night-time event, the critical frequency is lowest in Summer (magnitude: 2.5 MHz) and highest in Spring (magnitude: 7.6 MHz). Both the observed pre-noon and afternoon f_oF2 peaks in the F2-region variation, is due to variations of vertical E × B plasma drifts (e.g., Fejer *et al.* 1995; Adebesin *et al.* 2013a).

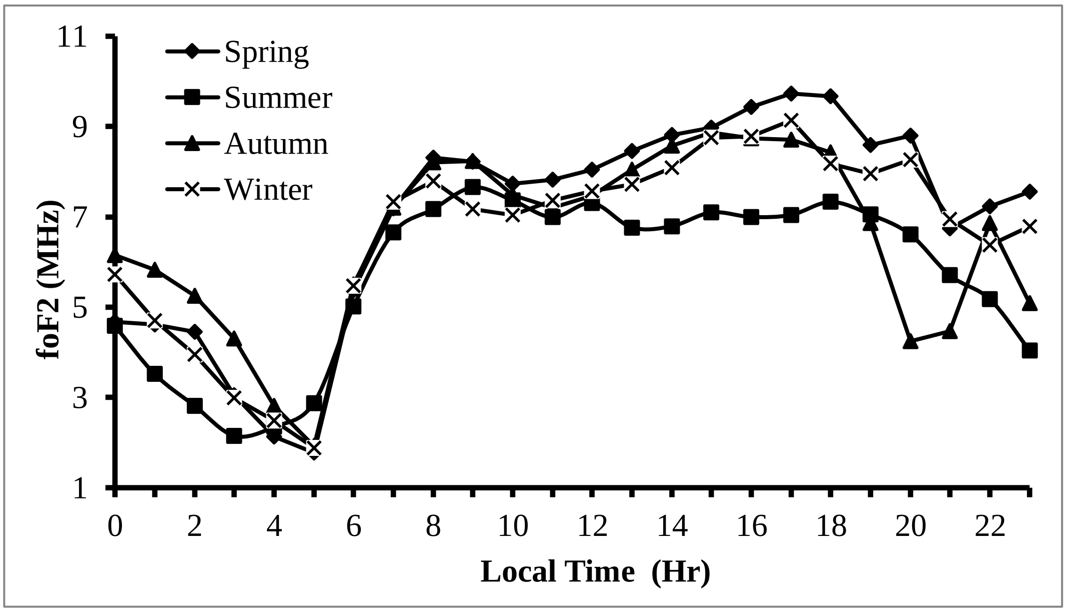

Figure 1: Diurnal variation of f_oF2 for all seasons over Ilorin during periods of Low Solar Epoch.

The hourly annual plot of f_oF2 variation against local time (LT) is represented in figure 2. The plot revealed that, during the LSE period, an annual average magnitude of 7.9 MHz around 0800 LT for the pre-noon peak, which is a bit lesser than its post-noon peak value of 8.7 MHz around 1700 LT as clearly observed was recorded for the entire season. There is an average annual daytime reduction in f_oF2, reaching a minimum between 1000 and 1100 LT before the noon time of 1200 LT for all seasons. Annually, the nighttime variation decays sharply downward during the entire season until f_oF2 increases from sunrise around 0500 LT. This observation is in total agreement with the results obtained for Ouagadougou (12.4◦N, 1.5◦E; dip 5.9◦) by Adeniyi *et al.* (2007) and Alagbe (2012) during a low solar epochs period.

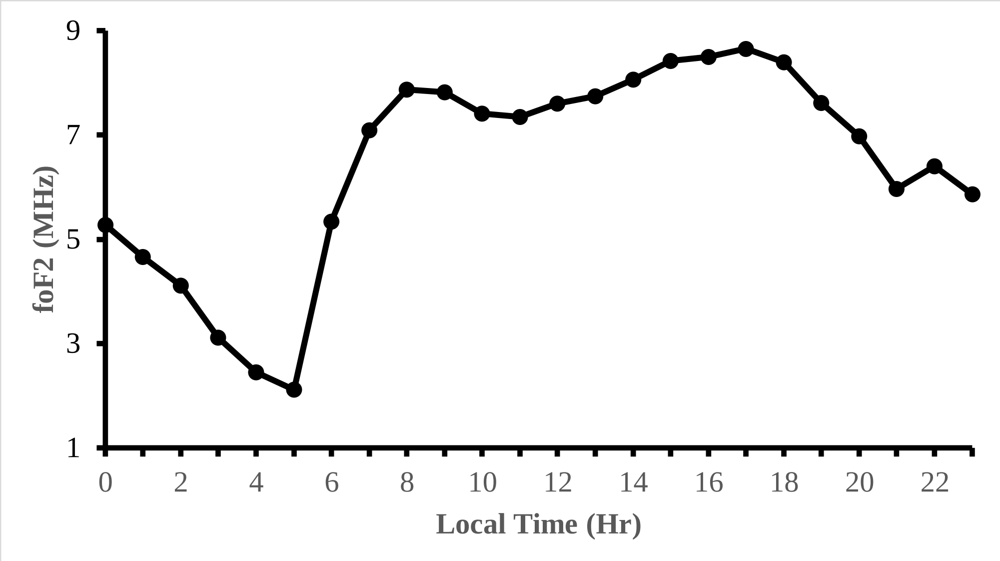

Figure 2: Annual variation of f_oF2 for all seasons during the Low Solar Epoch period.

3.2 Variation Pattern of Peak electron density (N_mF2)

Figure 3 highlights the average seasonal variation of the peak electron density (N_mF2) over Ilorin during low solar epochs. N_mF2 increases from sunrise around 0500 LT and reaches a pre-noon peak before 1200 LT around 0800–0900 LT with a magnitude range of (7.3–8.6) × 10^{11} m^{-3} for all seasons. The least pre-noon peak of electron density concentration was observed in Summer (magnitude: 7.3 × 10^{11} m^{-3}), followed by Winter (magnitude: 7.5 × 10^{11} m^{-3}), then Autumn (magnitude: 8.4 × 10^{11} m^{-3}), and the greatest pre-noon peak of electron density concentration was in Spring (magnitude: 8.6 × 10^{11} m^{-3}) around the same local time during this period of solar epochs. Thereafter, there is a general daytime reduction in electron density, creating a hollow and reaching a minimum between 1000 LT and 1100 LT before local noon of 1200 LT. The least reduction was experienced in Summer, while it is highest in Spring with a magnitude range of (6.1–7.5) × 10^{11} m^{-3} for the entire season.. Around noon, the N_mF2 of the F2 region ionosphere have shown to attained a production enhancement by solar radiation and be stable dynamically with recombination losses. This agrees with Fejer 1997, that N_mF2 increases after sunrise which is more prominent at lower latitudes. Maximum is attained early in the afternoon and a rapid decrease occurs shortly after sunset. A post-noon peak was recorded between

1500 and 1800 LT for the entire season. This condition of the appearance of peak electron density yet again is highest during the equinoctial months, especially in Spring, with a magnitude of 11.7 × 10^{11} /m^3 around 1800 LT and lowest in the solstices months, especially in Summer, with a magnitude of 6.7 × 10^{11} /m^3 around 1800 LT. The above corollary is in total agreement with the results obtained for Ouagadougou (12.4°N, 1.5°E; dip 5.9°) by Radicella and Adeniyi (1999), Oladipo *et al.* (2009) and Sawadogo, *et al.* (2019) during a low solar epochs period. At nighttime (1800–0500 LT), a general sharp drop in N_mF2 is distinct immediately after sunset. This sharp drop was observed around 1800 LT. This decay is continuous during all seasons until around 0500 LT, at which time a pre-sunrise minimum occurs. For this nighttime event, the electron density is lowest in Summer (magnitude: 1.4 × 10^{11} /m^3) and highest in Spring (magnitude: 7.2 × 10^{11} /m^3).

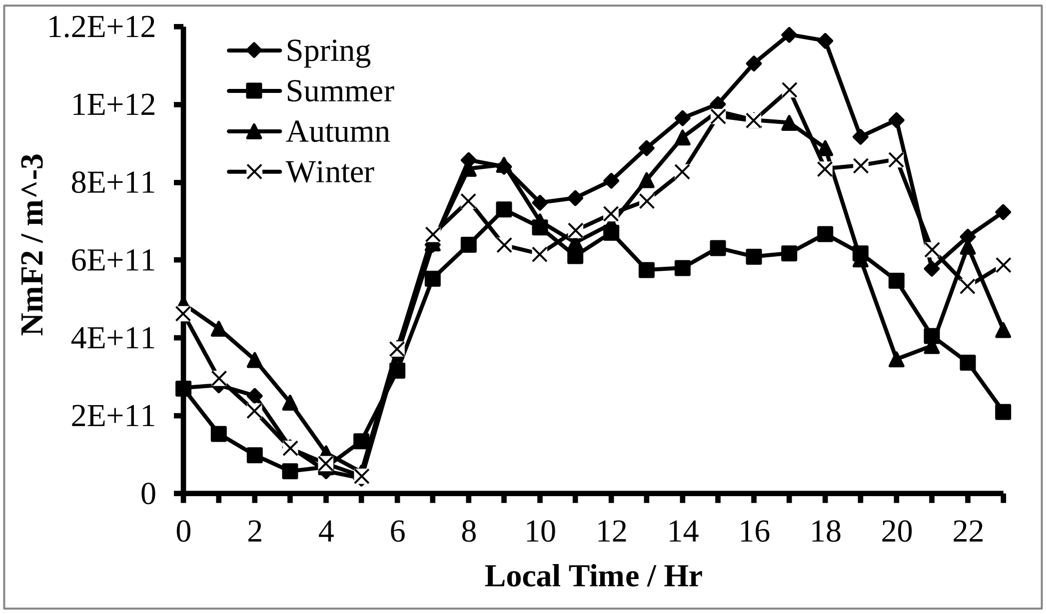

Figure 3: Average Hourly Diurnal Peak Electron Density (N_mF2) over Ilorin for the Solar Minima Period.

Observations are further interpreted on an annual basis in Figure 4, which depicts an hourly average annual variation plot of peak electron density (N_mF2) during low solar epochs for the entire season. For this LSE period condition, the post-noon peak of an average magnitude of 9.5 × 10^{11} /m^3 around the local time of 1700, which is greater than the pre-noon peak with an average magnitude of 7.7 × 10^{11} /m^3 around 0800 LT of N_mF2 annual variation was clearly observed in figure 4 for all seasons.

Annually, the variation of the day-time reduction in N_mF2 that creates a trough around 1100 LT is higher than the variation of the N_mF2 night-time continuous sharp drop around 1800 LT after sunset until a pre-sunrise minimum time of around 0500 LT was observed during all seasons.

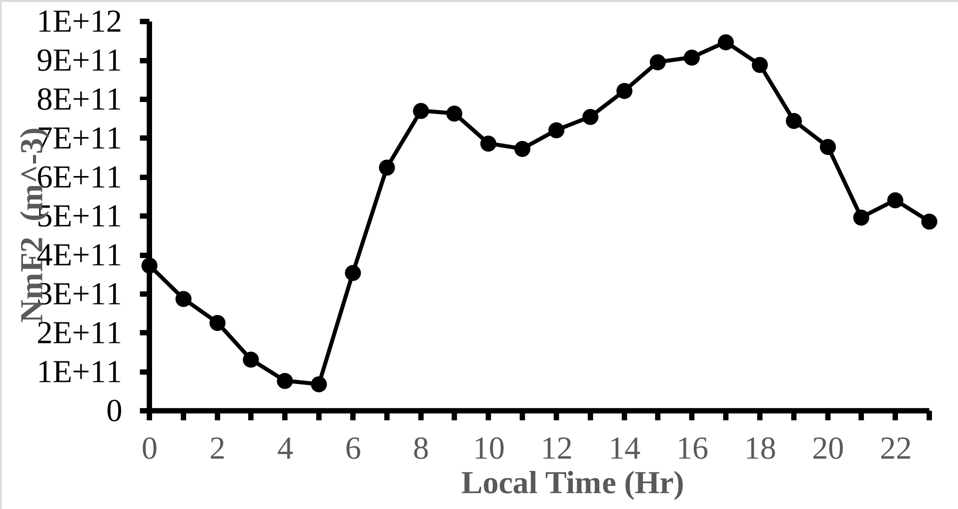

Figure 4: Annual variation of Peak Electron Density (N_mF2) for all seasons over Ilorin

4. Summary and Conclusion

In this study of ionospheric data from Ilorin, a station located along the equatorial ionization anomaly (EIA). The results of this paper were summarily presented as follows:

- The diurnal observation revealed that f_oF2 and N_mF2 are both more pronounced during the nighttime (2.5–7.6 MHz) and (1.4–7.2) × 10^{11} m^{-3} than the daytime (7.0–7.7 MHz) and (7.3–7.5) × 10^{11} m^{-3} respectively for the entire season having two characteristic peaks: pre-noon and post-noon peaks. The two characteristic peaks were ascribed to abrupt electron density gradients triggered by the onset and turn-off of solar ionization and the superimposition of spread-F on the background electron density. It can therefore be concluded that the ionospheric parameters: f_oF2 and N_mF2 post-noon peaks magnitudes are by a factor of 1.2 greater than the pre-noon peaks for all seasons during this LSE period.

- The lowest magnitudes of f_oF2 variation were attained during the pre-noon peak between 0800 LT and 0900 LT with a magnitude range of (7.7–8.3 MHz). For this pre-noon peak, the highest was observed in spring (8.3 MHz), followed by the autumn season (8.2 MHz), then winter (7.8 MHz) and the least in summer (7.7 MHz). The post-noon peak was observed between 1500 and 1800 LT for all seasons. In all the seasons, the pre-noon peak is lower than the post-sunset peak. Annually, the average pre-noon peak of 7.9 MHz magnitude was observed around 0800 LT while the post-noon peak was 8.7 MHz around 1700 LT for the LSE period.

- The nighttime downward N_mF2 variation coincides with the enhanced f_oF2 variation. The sudden faster electron drift away from the equator is responsible for the sharp drop in f_oF2 and N_mF2 immediately after sunset in all the seasons.

- Seasonal peaks in f_oF2 as well as in N_mF2 are suspected to be controlled by the enhanced E × B drifts and atmospheric wind which agrees with the results of some previous works.

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