

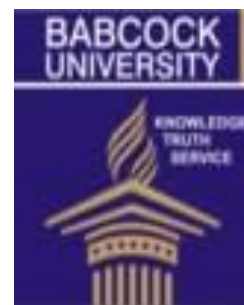


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Ionospheric N_mF2 Morphology and $F2$ -Region Height of Electron Density Response over Ilorin during low solar activity

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Abstract

The $F2$ region peak electron density (N_mF2) morphology and the height of electron density (h_mF2) response was investigated over Ilorin (lat. 8.31°N , long. 4.34°E , dip lat. 2.95°), a station along the equatorial anomaly trough, during Low Solar Activity (LSA). Diurnally, N_mF2 and h_mF2 are visibly more prominent during the daytime than the nighttime, having two characteristic peaks: pre-noon and post-noon peaks, except in h_mF2 that has post-sunset peak during the nighttime. The N_mF2 pre-noon peak with a magnitude range: $(7.3\text{--}8.6) \times 10^{11} \text{ m}^{-3}$ is observed around 0800–0900 LT, while h_mF2 of magnitude range: (316–353) km is observed around 1000 LT. The N_mF2 post-noon peak magnitude range: $(6.7\text{--}11.7) \times 10^{11} \text{ m}^{-3}$ is observed around 1500 and 1800 LT, while h_mF2 post-sunset peak magnitude range: (310–392) km is observed around 1800 and 1900 LT during the entire season. In general, the pre-noon peak magnitude is less compared to the post-noon/post-sunset peak magnitude for all seasons. Seasonally, the N_mF2 highest magnitudes were reached during the post-noon in the equinoctial months. The h_mF2 highest magnitudes during post-sunset peak were observed in solstices, and also, annually, the post-noon/post-sunset peak is higher than the pre-noon peak for all the seasons. The rapid electron drift in h_mF2 away from the equator is responsible for the sharp drop in N_mF2 after sunset in all seasons. Seasonal peaks in general are suspected to be controlled by the enhanced $\mathbf{E} \times \mathbf{B}$ drifts and the atmospheric wind.

Keywords: N_mF2 ; h_mF2 ; Pre-noon peak; Post-noon peak; Post-sunset peak; Equator anomaly; Low Solar Activity

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 refractivity and minimal radio wave attenuation. However, variations in the ionospheric peak electron density (N_mF2), and hence, the response of the height of electron density (h_mF2) provide clues as to what is happening within the $F2$ region as a whole.

Observations show that the ionospheric N_mF2 and h_mF2 increase after sunrise, with increases occurring more frequently at low latitudes (Gordienko *et al.*, 2005). The maximum is attained in the early afternoon and plummets from just after sunset. The N_mF2 and h_mF2 are usually highest near the equator.

The equatorial anomaly, characterized as the occurrence of a trough in the ionization density at the equator and crests at about 17° in magnetic latitude in each hemisphere, has been described as arising from the electrodynamics at the equator (Babatunde *et al*, 2017). 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). 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 $E \times B$ drift moves the ionization vertically upwards during the day and downwards at night. This upward motion of ionization during the day is referred to as the equatorial fountain (Babatunde *et al*, 2017), 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 N_mF2 spread pattern and the response of h_mF2 characteristics, several works have been carried out. Jayachandran, *et al.* (1995), Oladipo *et al.* (2008), Atac *et al.* (2009) and Adebesein (2013 a and b) investigated the representation of ionospheric behavioural patterns as they relate to the short time variability of the ionospheric electron content and peak electron density, variability of N_mF2 , and $F2$ layer characteristics in h_mF2 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 characteristics of the ionospheric N_mF2 and h_mF2 profiles during various seasons, day, time, solar events, and latitude. Alagbe (2012) and Ouattara (2013) reported the variation of these ionospheric parameters 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 characterized by a dominant afternoon peak

and 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 utilized to establish an empirical local ionospheric forecasting model to predict f_oF2 in Lanzhou (Chen *et al.* 2010). Similarly, Olga Maltseva (2021) utilized 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, dip lat. 2.95°) were used to estimate the N_mF2 . The present work investigates the diurnal, seasonal and annual variation of the F2 region of N_mF2 morphology and h_mF2 response over the single equatorial station of Ilorin (latitude 8.31°N, longitude 4.34°E, dip lat. 2.95°) in the North Central zone of Nigeria, during low solar activity period. 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.

1. Data and Method

2. The data used consists of ionospheric F2 region parameters like the critical frequency (f_oF2), peak

electron density (N_mF2) and the height of peak electron density (h_mF2). For ionospheric F2 region critical frequencies (f_oF2) and the heights of peak electron density (h_mF2), the hourly values for a 10-day quiet period were taken over Ilorin (latitude 8.31 N, longitude 4.34 E, dip lat. 2.95°), an ionospheric station in the North central zone of Nigerian in West Africa. The study is for the year 2010, a period of low solar activity (LSA). The datasets for f_oF2 and h_mF2 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.

3. The digisonde sounds at interval of 15 minutes; this time is too small to reveal the changes we want to study. An hourly interval resolution data of F2 region parameters for f_oF2 and h_mF2 was therefore used for the study which reveals noticeable changes in F2 region.

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

$$5. N_mF2 = 1.24 \times 10^{10} \cdot (f_oF2)^2$$

(1)

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

7. For the seasonal pattern, the hourly mean values of N_mF2 and h_mF2 of the representative months were used. The representative months are April, July, October and November which stand for the seasons of Spring, Summer, Autumn and Winter respectively. 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 averaging, we made use of the mean monthly values across each hour.

Results and Discussions

3.1 Variation Patterns of Peak electron density (N_mF2)

Figure 1 highlights the average seasonal variation of the peak electron density (N_mF2) over Ilorin during low solar activity. 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 $(7.3–8.6) \times 10^{11} m^{-3}$ for all seasons. The least pre-noon peak of electron density concentration was observed in Summer (magnitude: $7.3 \times 10^{11} m^{-3}$), followed by the Winter (magnitude: $7.5 \times 10^{11} m^{-3}$), then the Autumn (magnitude: $8.4 \times 10^{11} m^{-3}$), and the greatest pre-noon peak of electron density concentration was in Spring (magnitude: $8.6 \times 10^{11} m^{-3}$) around the same local time during this period of solar activity. Thereafter, there is a general daytime reduction in electron density, creating a trough 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 $(6.1–7.5) \times 10^{11} m^{-3}$ for the entire season. Around noon time, the N_mF2 of F2 region ionosphere attained a production enhancement by solar radiation and stable dynamically with recombination losses. It is noticed that N_mF2 increases after sunrise which is more prominent at lower latitude according to Fejer (1997). Maximum is attained early in the afternoon and a rapid decrease occurred 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 $11.7 \times 10^{11} /m^3$ around 1800 LT and lowest in the solstices months especially in Summer with a magnitude of $6.7 \times 10^{11} /m^3$ around 1800 LT. The results above are in total agreement with the results obtained for Ouagadougou ($12.4^\circ N$, $1.5^\circ E$; dip 5.9°) by Radicella and Adeniyi (1999), Oladipo et al. (2009) and Sawadogo, et al. (2019) during a low solar activity period. Both the observed pre-noon and afternoon N_mF2 peaks in the F2-region variation, are due to variations of vertical $E \times B$ plasma drifts (Fejer et al. 1999; Adebesein et al. 2013a).

At nighttime (1800–0500 LT), a general sharp drop in N_mF2 is noticeable immediately after sunset. This sharp drop was observed around 1800 LT. This decay is continuous during all seasons till around 0500 LT, at which time a pre-sunrise minimum occurs. For this nighttime event, the electron density is lowest in Summer (magnitude: $1.4 \times 10^{11} /m^3$) and highest during Spring (magnitude: $7.2 \times 10^{11} /m^3$).

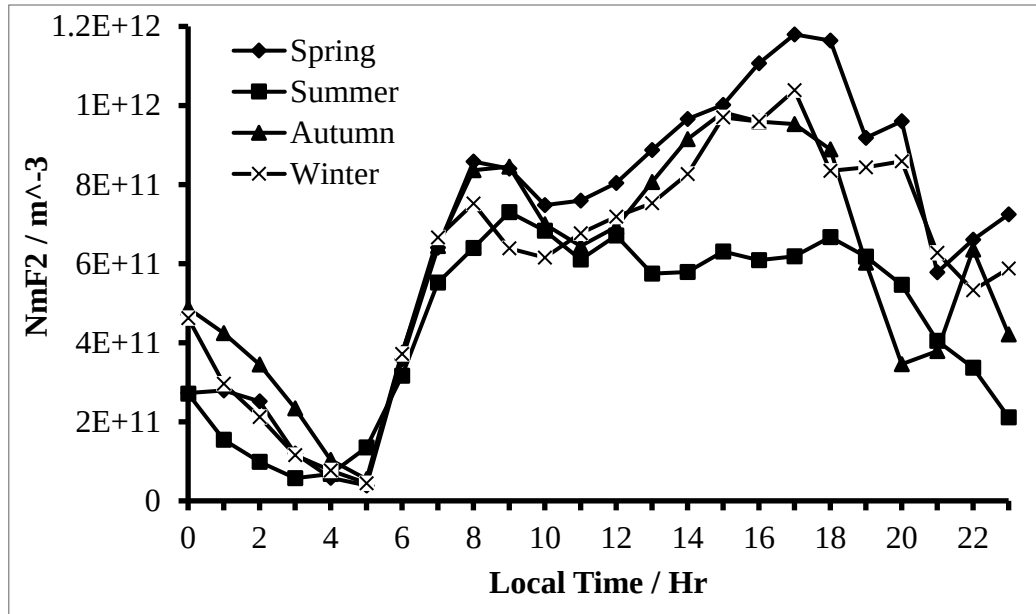


Figure 1: Average Hourly Diurnal Peak Electron Density (N_mF2) over Ilorin for Solar Minima period

Observations are further interpreted on an annual basis. Figure 2 depicts hourly average annual variation plot of peak electron density (N_mF2) during low solar activity. For this LSA period, the post-noon peak of an average magnitude $9.5 \times 10^{11} / \text{m}^3$ around the local time of 1700, which is greater than the pre-noon peak with an average magnitude of $7.7 \times 10^{11} / \text{m}^3$ around 0800 LT of N_mF2 annual variation was clearly observed in figure 4 for the entire season.

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

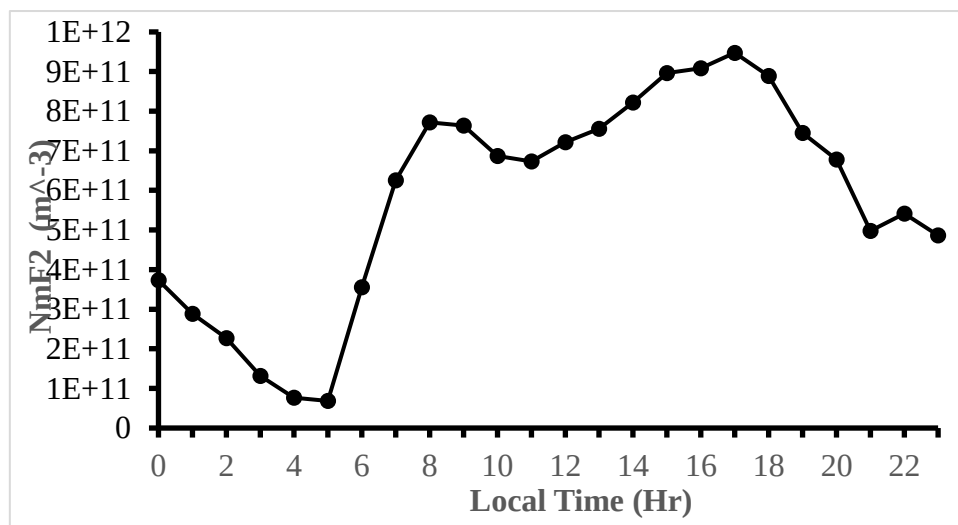


Figure 2: Annual Pattern of Peak Electron Density (N_mF2) for all seasons over Ilorin

3.2 Seasonal h_mF2 Observations

3.2 Seasonal h_mF2 Observations

Depicted in Figure 3 is the corresponding average seasonal height of the $F2$ peak electron density shown in Figure 1. The h_mF2 observations for all the seasons indicate a sharp and gradual rise within the sunrise period of 0600–1000 LT. During the daytime, there is a pre-noon peak around 1000 LT with a magnitude range of (316–353) km for all seasons. The least h_mF2 pre-noon peak was observed in Summer (magnitude: 316 km) and the highest h_mF2 pre-noon peak of h_mF2 was in Spring (magnitude: 353 km) around the same local time during this period of solar activity. It is believed that the stronger vertical $E \times B$ drift in equinoctial season moves the plasma to a higher altitude where the recombination loss becomes much weaker; the plasma in higher altitudes therefore has a longer lifetime, and then yields a higher magnitude in Spring, which is in consonance with Chen *et al.* (2008). Thereafter, a much wider variation scope between the period 1100 and 1600 LT is observed and the h_mF2 magnitude is between (310–367) km within this period for all seasons. A sharp rise was witnessed between 1600–1900 LT at all season to reach a h_mF2 second peak (post-sunset peak) except during June solstice. During nighttime period, a post-sunset peak of h_mF2 was recorded between 1800 and 1900 LT for the entire season. However, the highest h_mF2 magnitude was recorded in Winter (392 km) around 1800 LT and the least h_mF2

magnitude was observed in Summer (310 km) around 1900 LT. According to Adebesein *et al.* 2013a, the positive correlation between h_mF2 and the F region vertical drift found during the nighttime between 1800 and 2100 LT could be helpful in representing the post-sunset peak of h_mF2 around 1800 and 1900 LT here. Immediately after this time, a sharp drop was observed in the seasonal pattern up till 0500 LT with a magnitude range of 245–320 km. The differences between the pre-noon peaks and the post-sunset peaks magnitudes are not much pronounced except during the Winter.

It has also become necessary to show the average height profile for the entire 24-hour plot of h_mF2 here. The average h_mF2 revealed that our result is in agreement with general theory that above 300 km, the apparent vertical velocity is about the same as the vertical $E \times B$ plasma drift (Bittencourt and Abdu, 1981). Hence, our result corroborates the fact that during daytime, the h_mF2 shows rapid increase in height. Our result therefore suggests that between 0900 and 2100 LT, the general theory that vertical drifts obtained by digisonde measurements only match the $E \times B$ drift if the F region is higher than 300 km is reliable, but does not hold for the nighttime (2200–0600 LT) and early morning (0600–0900) periods in the present study during low solar activity. In essence, the 300 km condition does not sufficiently hold for the representation of vertical plasma drift at nighttime during low solar activity.

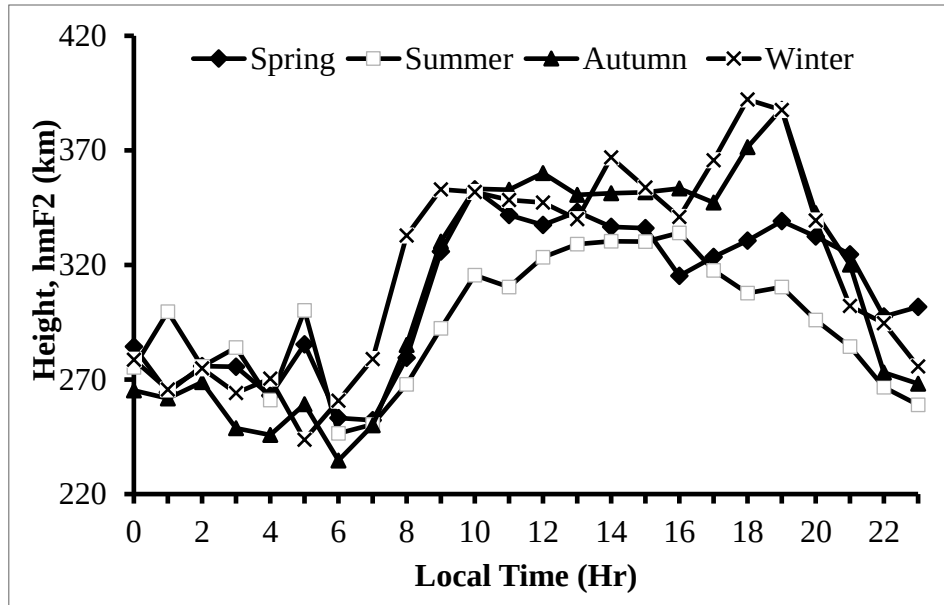


Figure 3: Average Seasonal Height of the $F2$ Peak Electron Density during Low Solar Activity

Highlighted in Figure 4 is the average hourly annual height of the $F2$ peak electron density shown similar to Figure 3. The post-sunset peak of an average magnitude 356 km around 1900 LT, which is greater than the pre-noon peak with an average magnitude of 343 km around 1000 LT was observed in Figure 4 for the h_mF2 annual variation for this LSA period during the entire season.

Annually, the variation of the daytime broader variation in h_mF2 that creates a trough between

the local time of 1500 and 1700 LT is higher than the variation of h_mF2 nighttime continuous sharp drop around 1900 LT after sunset until a pre-sunrise minimum time around 0600 LT was observed for all seasons. The continuous decay in N_mF2 also shows concurrent rise in h_mF2 magnitudes due to vertical $E \times B$ drift during post-sunset period resulting from the electrons moving rapidly away from the equator at a region of low recombination loss rate.

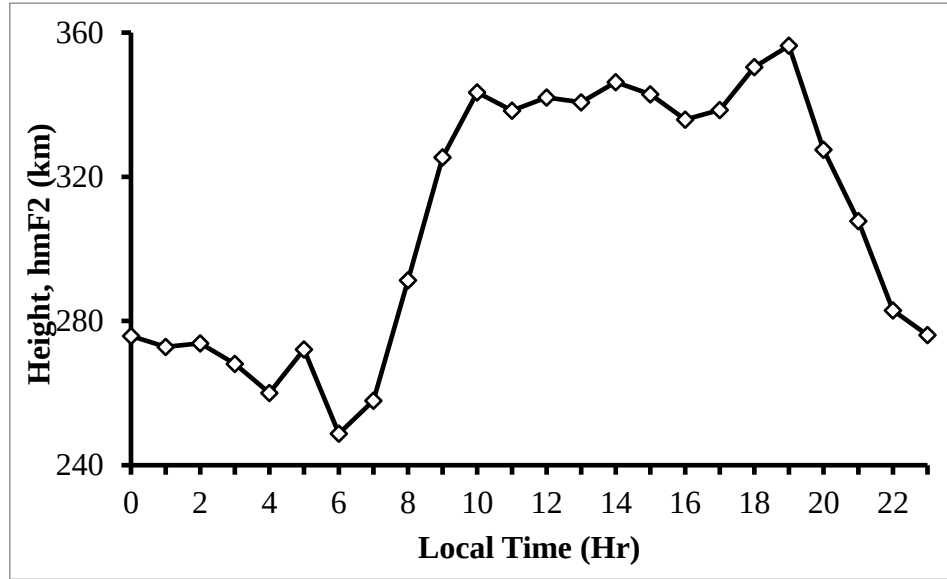


Figure 4: Average Hourly Annual Height of the F2 Peak Electron Density for Solar Minima

8. Summary and Conclusion

The results of this paper are summarised as follows:

- The diurnal observation revealed that N_mF2 is more pronounced during the daytime with a mean magnitude: $(7.3\text{--}7.5) \times 10^{11} \text{ m}^{-3}$ than the nighttime mean magnitude: $(1.4\text{--}7.2) \times 10^{11} \text{ m}^{-3}$ 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 superimposition of Spread-F on the background electron density.
- The least magnitudes of N_mF2 variation were attained during the pre-noon peak between 0800 LT and 0900 LT with a magnitude range of $(7.3\text{--}8.6) \times 10^{11} \text{ m}^{-3}$. For this pre-noon peak,

the average highest magnitude was observed in equinoctial months. The post-noon peak average magnitudes observed between 1500 and 1800 LT range between $(6.7\text{--}11.7) \times 10^{11} \text{ m}^{-3}$ for all seasons. In all the seasons, the pre-noon peak is less than the post-sunset peak. Annually, the average pre-noon peak of $7.7 \times 10^{11} \text{ m}^{-3}$ magnitude was observed around 0800 LT while the post-noon peak was $9.5 \times 10^{11} \text{ m}^{-3}$ around 1700 LT during the entire season for the LSA period.

- A h_mF2 pre-noon peak with a magnitude range of (316–353) km around 1000 LT during the daytime while during the nighttime, a post-sunset peak of h_mF2 with a magnitude range of (310–392) km between 1800 and 1900 LT were observed for all seasons during this period of LSA. The differences between the pre-noon peaks and the post-sunset peaks

magnitudes are not much pronounced except during the Winter.

- During nighttime, an observed enhancement in h_mF2 directly after sunset (Fig. 3) is a pointer to the fact that ions are moved to a state of lower recombination coefficient and hence electron density should be sustained for an elongated period. However, this was not so, as a decrease in electron density was evident from our plot (Figure. 1). This is because the influx of a post-sunset peak in upward plasma drift is indicative of sudden faster electron depletion from the equatorial ionosphere.
- Seasonal peaks in N_mF2 as well as in h_mF2 are suspected to be controlled by the enhanced $E \times B$ drifts and atmospheric wind. This agrees with the result of some previous works.

Acknowledgements

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