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Ionospheric Minimum Frequency Variability over Ilorin

[*1]Bello, S.A., [2]Adeniyi, J.O., [3]Oladipo, M.O, [4]Shehu J.S., [1]Sharafa, S.B., [5]Kazeem, A.K., [6]Akinyemi,G. A., [1]Yusuf, K.A.

[1]Department of Physics, Faculty of Physical Sciences, University of Ilorin, Kwara State
[2]Department of Physical Sciences, Landmark University, Omu-Aran, Kwara State
[3]Department of Physics with Electronics, Koladaisi University, Ibadan
[4]Department of Physics, Bayero University Kano
[5]Department of Physics, Edo State University Iyamho, Edo State.
[6]Department of Physical Sciences, Redeemer's University, P.M.B. 320, Ede, Osun State, Nigeria
Corresponding Author:
[1]Department of Physics, Faculty of Physical Sciences, University of Ilorin, Kwara State
Email: bello.sa@unilorin.edu.ng; Phone number: +2348035118210

Abstract

Using ground-based Digisonde records from the University of Ilorin Ionospheric Observatory (8.5° N, 4.5° E) over the year 2010, this study examined the equatorial ionospheric minimum frequency (f_{min}) over Ilorin, Nigeria. We looked at both seasonal and diurnal changes in f_{min}. From a pre-dawn minimum to an afternoon maximum, the diurnal pattern shows a consistent increase, which is followed by a fall after sunset. Seasonal findings reveal significant daytime variability between 1200 and 1400 UT (LT = UT + 1 h), with the highest noon peak observed during the equinoxes and the lowest during the solstices. Midday peak values ranged between 2.05 and 2.7 MHz across the months studied. The increased electron density in the ionospheric D-layer is responsible for these observed peaks.

Keywords: Ionosphere, ionospheric minimum frequency, f_{min}, absorption, D-region.

1. Introduction

The ionosphere, which stretches from about 60 km to the point where it mixes with interplanetary plasma, is the area of the upper atmosphere where significant ionization takes place. It is essential to radio communication, because the refractive index of the ionospheric plasma, the signal frequency, and the electron oscillation frequency all affect wave behaviour. High-frequency (HF) radio waves travel through the ionosphere by reflection, which usually takes place in the E and F-regions; however, attenuation, which mostly takes place in the D-region, is the main cause of their energy loss [1]. This attenuation results from electron and ion motion, damping, and collisions with neutral particles [2]. The ionospheric structure is influenced by various factors across global and mesoscale domains [3], with variability broadly attributed to solar ionizing flux, meteorological processes, and solar wind conditions.

Understanding the frequencies supported by the ionosphere across different times, seasons, and solar activity levels is essential for predicting optimum signal reception. A key parameter in this regard is the ionospheric minimum frequency (f_{min}), which represents the practical lower limit below which communication cannot be maintained between two stations. In addition to studying phenomena like Polar Cap Absorption (PCA) and Sudden Ionospheric Disturbances (SID), f_{min} is used to differentiate between times of high and low solar activity [4]. According to comparative research conducted close to the magnetic dip equator [5-6] f_{min} shows seasonal, diurnal, and longitudinal fluctuations, with significant differences between the South American and African sectors. Research using the IRI-2012 model has demonstrated a significant linear correlation between D-region electron density and f_{min} [7], demonstrating its value for tracking non-deviative propagating high-frequency radio absorption in the ionosphere. Ionization in the D-region is primarily driven by cosmic rays, solar hydrogen Lyman-α emissions, solar flares, and ultraviolet radiation [1], [6], [8]. Consequently, f_{min} variability indicates changes in D-region electron density and ionospheric absorption rates. There are three traditional methods (A1, A2, and A3) for measuring HF signal absorption, involving the transmission of radio waves and measuring attenuation at the receiving end [9]. In addition to these, sweep-frequency techniques, which are recorded as ionograms by ionosondes, provide valuable data.

Much of the attenuation of HF signals is caused by non-deviative absorption in the D-region, which is proportional to electron density and a function of the collision frequency between electrons and neutral particles [10]. Therefore, variations in f_{min} recorded on an ionogram serve as an indicator of absorption [6] and can be used to determine the index of ionospheric absorption [4]. While the theoretical concepts of D-region absorption are well-documented, characterizing its regional morphology remains a challenge. This paper presents the diurnal and seasonal variations of f_{min} over Ilorin to further characterize its behaviour within the West African sector.

2. Material and Method

The DPS-4 Digisonde in Ilorin, Nigeria (8.5° N, 4.5° E) provided the f_{min} data used in this investigation. Although the Digisonde records measurements every 15 minutes, this study utilized hourly resolution data to examine broader diurnal and seasonal trends. These values were extracted from the ionogram records as illustrated in Figure 1, which displays a sample auto-scaled ionogram from the Ilorin Digital Portable Sounder (DPS) featuring the E, F1, and F2 layers.

The investigation utilizes records from March to November 2010. This timeframe encompasses the terminal operational phase of the Digisonde, during which data quality was verified and accessible before subsequent equipment failure. To ensure the reliability of the analysis, the raw hourly data underwent a systematic cleaning process where outliers and artifacts resulting from the equipment's final operational instability were removed.

Following data validation, the analytical methodology focused on diurnal and seasonal averaging. To delineate clear daily trends, hourly measurements were averaged for each month to minimize transient noise while preserving the underlying physical behaviour of the ionosphere. For seasonal characterization, the data were partitioned into four distinct groups: the March equinox (March and April), the June solstice (May, June, and July), the September equinox (August, September, and October), and the December solstice (November). Finally, a comparative analysis was performed by plotting these monthly-averaged values against local time, allowing for a robust examination of diurnal variations and seasonal shifts in the targeted ionospheric parameters.

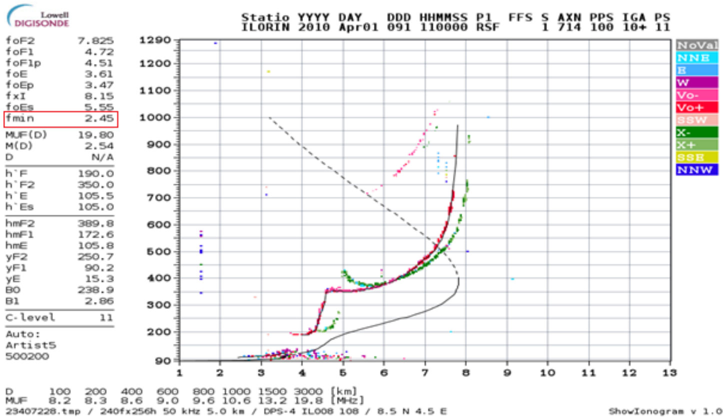

Figure1: Sample of an auto-scaled ionogram obtained from the digisonde sounder (DPS-4) installed at the Ilorin station (8.5° N, 4.5° E)

To analyze the diurnal behaviour of the ionosphere while minimizing the influence of day-to-day variability or transient geophysical disturbances, the monthly median of the $f_{\min}$ parameter was calculated for each hour. The monthly median, denoted as $M_{f_{\min}}$, is defined as the central value of the distribution of hourly observations for a given month. For a specific hour h, the median value is calculated from the set of daily observations $x_{h,1}, x_{h,2}, \ldots, x_{h,n}$ as:

$$M_{f_{\min}}(h) = \text{median}\{x_{h,1}, x_{h,2}, \ldots, x_{h,n}\}$$

where n represents the total number of days in the month with valid $f_{\min}$ measurements. Using the median instead of the mean ensures that the resulting diurnal plots, presented in Figure 2, are robust against outliers or brief periods of equipment instability during the terminal operational phase of the Digisonde.

3. Results and Discussion

The diurnal plots of the monthly median values of f_{min} for the months of March through November 2010 are shown in Figure 2. The monthly median of f_{min} is denoted as M_{fmin}. Before declining after dusk, f_{min} often increases progressively from a predawn low to a midday high. The pre-dawn minimum is typically recorded at 0600 UT (0700 LT), whereas the afternoon peak typically happens between 1200 and 1400 UT. Interestingly, secondary nighttime peaks appear between 2100 and 2300 UT. These nighttime f_{min} values typically range from 1.95 to 2.5 MHz, with the exception of April, which exhibits peaks as high as 2.7 MHz. Generally, the midday peak values for the study period range between 2.05 and 2.7 MHz.

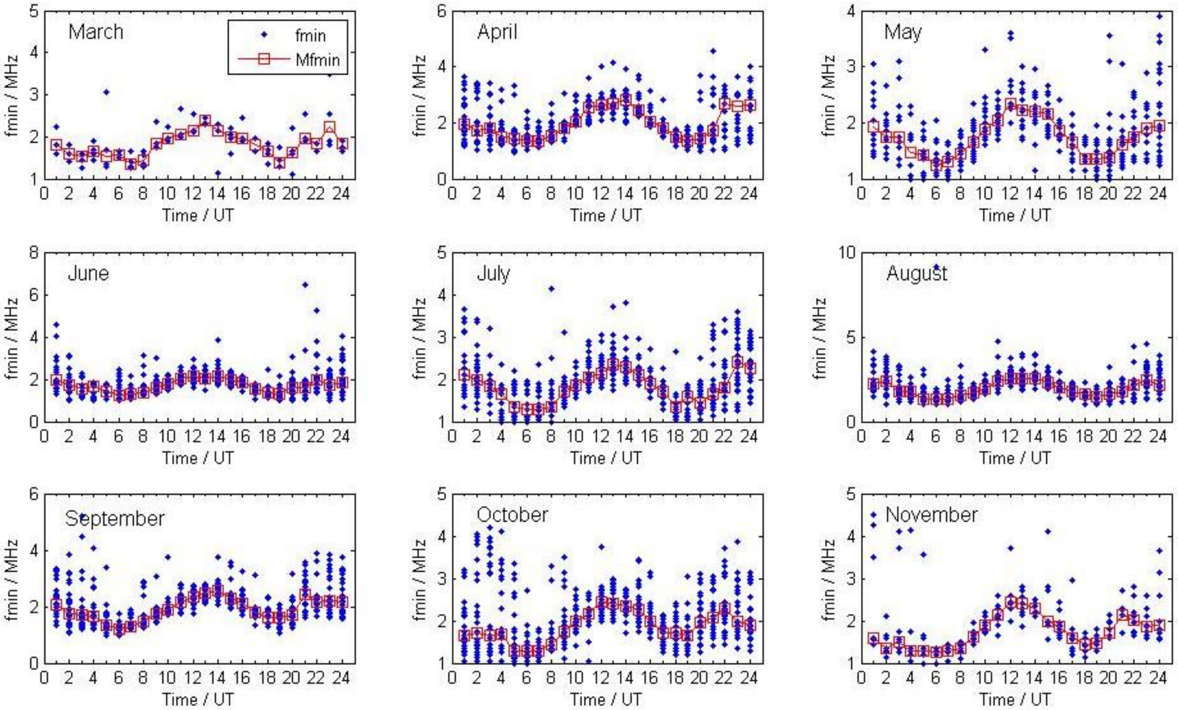

Figure 2: Diurnal variation of f_{min}over the Ilorin station from March to November 2010. The scatter plot displays hourly data points (blue), while the solid line represents the monthly median values, M_{fmin} (red).

The diurnal seasonal fluctuation of f_{min} for 2010 is shown in Figure 3a. March equinox, June solstice, September equinox, and December solstice are the categories into which the data are divided. Figure 3b illustrates these individual seasonal averages, while the right panel compares the combined equinoctial (E-season) and solstice (S-season) behaviour. The E-season comprises March, April, August, September, and October, while the S-season includes May, June, July, and November.

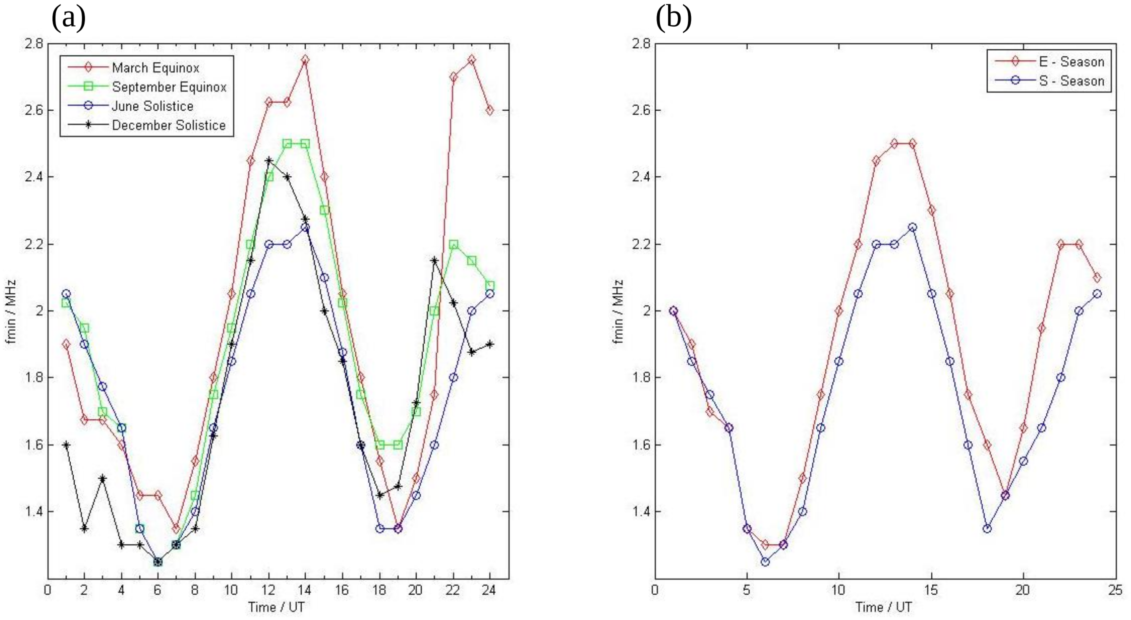

Figure 3: Seasonal variation of the ionospheric minimum frequency (f_{min}) obtained from the Digisonde. (a) Seasonal variation in f_{min} during the March equinox, September equinox, June solstice, and December solstice. (b)The comparative behaviour between the equinox season (E-season) and the solstice season (S-season).

Observations from Figure 3 indicate significant seasonal changes during the daytime (0700 to 1900 UT). The March equinox records the highest f_{min} value of ~2.75 MHz, while the June solstice records the lowest peak of roughly 2.28 MHz. Nighttime values generally range from 1.9 to 2.2 MHz, with a morning minimum between 0100 and 0700 UT of 1.6 to 2.05 MHz. Both E- and S-seasons exhibit pre-sunrise peaks at approximately 2.00 MHz. Notably, maximum f_{min} values are consistently recorded during the E-season, whereas the lowest values are found in the S-season.

The observed diurnal increase in f_{min} from pre-sunrise is driven by enhanced photoionization. Values peak between 1200 and 1400 UT and then start to decline right after sunset. The equilibrium between solar-driven generation and chemical recombination processes mostly determines the ionospheric electron concentration. Since solar ionizing radiation forms the ionospheric layers, solar activity, the principal cause of ionospheric variability, continues to have direct control over them.

The diurnal trend of f_{min} reflects the strong influence of solar radiation on ionospheric ionization. The ionosphere is divided into D, E, F1, and F2 layers during the day. The E and F layers are where HF signals are mostly reflected, while the D-region is where non-deviative absorption causes a large amount of energy loss. As a result, higher electron concentration in the D-region is responsible for the midday f_{min} peaks. The removal of the D and E layers is responsible for the decrease in f_{min} during the night, demonstrating that f_{min} is a good indicator of D-region electron density.

Our findings are consistent with the regional morphology reported by [7] at the Jicamarca (12° S, 76.87° W) station, particularly regarding ionospheric behaviour near the magnetic dip equator. The seasonal variability, characterized by equinoctial maxima and solstice minima, aligns with the trends established for the West African sector. Furthermore, the observation that f_{min} effectively functions as a proxy for D-region electron density, confirms the utility of these Digisonde measurements for monitoring non-deviative absorption in this region. While our absolute peak values show minor local variations compared to the results of [7], the overall seasonal trend and the timing of the midday maximum remain in agreement, reinforcing the validity of these initial observations for the Ilorin station.

4. Conclusion

The diurnal and seasonal fluctuations of the ionospheric minimum frequency (f_{min}) above the Ilorin station were examined in this study. Our results indicate that f_{min} exhibits a distinct diurnal pattern, characterized by a steady increase to a midday maximum of approximately 2.70 MHz, followed by a decline after sunset. Seasonally, f_{min} demonstrates significant variability, with the equinoctial periods recording higher noontime peaks compared to the solstice periods.

These findings confirm that f_{min} is primarily governed by photoionization processes driven by solar radiation. The increased electron density of the ionospheric D-layer, which can cause the attenuation of HF radio signals, is responsible for the observed midday peaks during the day. Since this region serves as the main medium for the absorption of low radio frequencies, the lower values reported at night lend credence to the idea that the D-layer varnishes after sunset. Additionally, we identified secondary nighttime peaks occurring between 2100 and 2300 UT, suggesting a more complex nocturnal ionospheric structure.

Ultimately, this study confirms that f_{min} serves as a reliable proxy for monitoring D-region electron density. The results provide an important new insight into how solar seasonality and photoionization impact f_{min} variability in the equatorial ionosphere. Further coordinated ground-based and *in-situ* observations are recommended to fully characterize the processes responsible for the observed D-region dynamics.

Acknowledgment

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