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Characteristics of ionospheric minimum frequency obtained by DPS-4 digisonde and comparison with IRI-D-region electron density over Jicamarca station

Bello*, S. A., Lawal, T. O., Orosun, M. M., Ige, S. O., Adebanjo, G.D. and Yusuf, K.A.

Department of Physics, Faculty of Physical Sciences, University of Ilorin, Ilorin, Nigeria.

Abstract

The ionospheric minimum frequency (fmin) is one of the parameters measured by an ionosonde representing the least frequency for which a high frequency (HF) radio signal reflected and received by the ionosphere. Using the digisonde measurement at the Jicamarca station (12º S, 76.87 º W), a statistical study of the temporal variation of fmin was studied. The result also demonstrated the relationship existing between fmin and the electron density of the D-region (NmD) obtained from the IRI-2012 model prediction. We observed generally that the magnitude of fmin is lower during the night time and higher during the daytime. The monthly noontime averages of fmin are highest in February with value reaching 5.23 MHz while outside this period, fmin is within the range of ~1.80 (at night time) to 2.60 MHz (maximum in the morning). This indicates the possibility of radio absorption below the fmin value. We observed a similar trend between the values of fmin and NmD. Both parameters exhibit midday peak and maxima in the southern summer season. The correlation coefficient (r) of 5.4 was obtained between fmin and NmD when the measured frequency is ≥ 3.00 MHz. Considering D-region as an absorbing layer, the correlation tends to indicate a possible significant relationship between fmin and NmD. This infers the usefulness fmin as a proxy parameter for studying radio absorption in the ionosphere.

Keyword: ionospheric minimum frequency; high frequency; radio wave absorption; digisonde; IRI-2012

1. Introduction

The ionosphere is an important region in the upper atmosphere responsible for the propagation of HF signals. In recent times, there have been a good number of studies on the variability of the ionosphere (e.g. Simmons *et al.*, 2016) with most emphasis on the ionospheric F-layer (Bhagavathiammal *et al.*, 2016;Venkatesh *et al.*, 2016), total electron content (Adebiyi *et al.*, 2014; Zhu *et al.*, 2016) and equatorial electrojet (Yamazaki and Maute, 2016). However, the discussion on the communication aspect of the propagating HF signal, which is the utmost reason for the development of the ionospheric model, is considerably receiving little attention (Friedrich and Torkar, 2001). The propagated HF signal loss in the ionosphere mainly in the D-region is yet to be fully understood owing to the few available literatures on the study of radio absorption in the D-region.

*Corresponding Author: Bello, S. A.
Email:bioyesaeed@gmail.com

Although, the theoretical concept surrounding D-region radio absorption is well reported over the years, however, the technics in making measurements to observe the morphology of the electron density of the D-region has being a challenge for researchers. For example, there are divided opinions on the dependence of electron density of the D-region on solar activity level (Danilov, 1998).

The propagated HF signal loss in the ionosphere is mainly caused by the non-deviative absorption in the D-region. The non-deviative absorption is relative to the electron concentration in the D-region and collisional frequency. The common techniques used in measuring non-deviative absorption are the A1, A2 and A3 methods. The A1 techniques involve the measurement of the received amplitude of echoes from the ionosphere at a fixed frequency (see Piggot *et al*., 1957 for details description of the method). The A2 method is commonly referred to as riometer (relative ionospheric opacity meter) and measures the intensity of the randomly fluctuating wideband noise from galactic radio sources impinging on the Earths from the deep space (Stauning, 1996). The A3 method works by recording the output of a continuous radio transmitter in oblique incidence (e.g., Chukwuma, 2000). The backdrop of the A1-A3 techniques is the use of a fixed frequency for measurements. An alternative to this measurement technique is the use of fmin method, which uses sweeps of frequency from 3-30 MHz in probing the ionosphere. The ionosphere can be probed using in-situ and ground-based measurement. An example of the in-situ measurement of the ionosphere involves the use of rocket (Siskind *et al*., 2018) and satellite (Cooper *et al*., 2019; Na, 2019; Wang, 2016).

The ionosonde being one of the oldest ground-based methods of observing the ionosphere continue to be relevant in taken accurate measurements of the rate of change of ionospheric vertical electron density profiles over different locations (Reinisch *et al*., 2004). The measured fmin from an ionosonde extracted from an ionogram serve as a rough estimate of the non-deviative absorption. The non-deviative absorption exists when the refractive index, μ is approximately unity but where the product of electron concentration (N) and collision frequency (ν) is large (Davies, 1990). The fmin has been used to study solar activity events e.g. in studying the effect of the solar eclipse on the ionization in the ionosphere (Chandra, *et al*., 2007), the effect of solar flare on radio wave absorption in the ionosphere (Sharma *et al*., 2010). Bello *et al*. (2017a) reported the variability of the fmin at two equatorial stations Ilorin and Jicamarca. Therein, they have established the minimum/threshold frequency for different seasons at Ilorin to be in the range of 2.30 to 2.70 MHz while that of Jicamarca station is between 2.30 to 2.90 MHz. They obtained a different pattern in the variability of the fmin in both stations. This present study, however, characterizes the temporal variation of fmin over Jicamarca station and makes a comparison with the electron concentration of the D-region (NmD) obtained from the International Reference Ionosphere model (IRI) model.

2. Materials and Methods

Data used in this present study are obtained from the digital ionosonde of the type DPS4-digisonde sounder installed at Jicamarca (12°S, 76.68°E) station in the Southern American sector. The hourly five geomagnetic quiet days values of ionospheric fmin data are analysed for each month in the year 2010. The geomagnetic quietest days are set of days with no geomagnetic disturbances, Ap index less than 24 and Kp index less than 3. The record of the international quietest days can be obtained from the World Data Center (WDC) website at http://wdc.kugi.kyoto-u.ac.jp/qddays/. The year 2010 follows the extreme (deep) solar minimum period of the years 2008/2009. The year 2010 is a low solar activity period with solar index F10.7 of 80 sfu (27-day average). Figure 1 gives the monthly averages of F10.7 during 2010 collected from https://omniweb.gsfc.nasa.gov/form/dx1.html. The hourly variation of fmin and F10.7 values for the entire period of study are given in Figure 2.

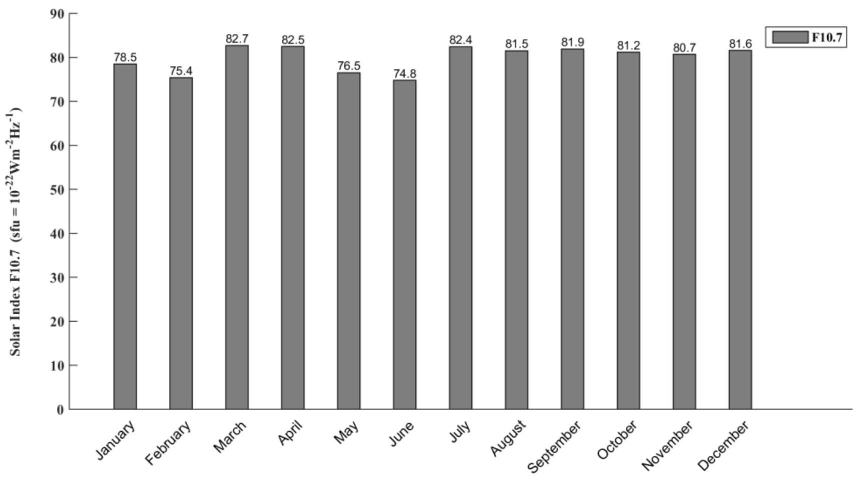

Figure 1: Monthly averages of the solar index during the year 2010

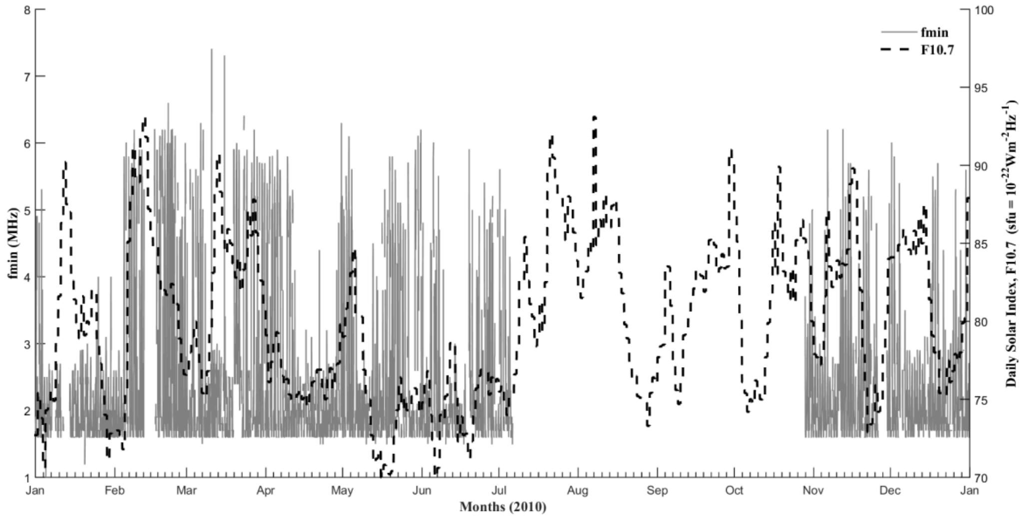

Figure 2: Hourly values of fmin and F10.7 during the year 2010.

The measured values of fmin are retrieved from the Global Ionospheric Radio Observatory (GIRO), where the distribution and location of the digisonde network can be found at http://giro.uml.edu/. Detailed information on GIRO operations of the DPS-4 type digisonde is in the works of Reinisch *et al*. (2005, 2004). In addition, the scaled ionogram data set is from http://giro.uml.edu/didbase/scaled.php.

We selected fmin parameter from a well-scaled ionogram with a confidence score of 70% upward (see Bello *et al*. 2017a, 2017b). An ionogram record is presented in the form of a graphical plot of the ionospheric measured parameters as shown in figure 3. The value of fmin from the ionogram is indicated in the red box. We have used all the selected five quietest days for the year 2010 except for the month of July, August to October. Data for these months were unavailable largely due to technical fault from the measuring digisonde.

The ionospheric D-region electron density (Ne) was obtained from the latest version of the IRI-2012 model. The D-region electron density (Ne) is denoted in the IRI parameters has a density of D peak (NmD), m^{-3} and can be estimated by inputting the year, local time (hour), geographical (or geomagnetic) coordinate (longitude and latitude) in the IRI model interactive web version in the line https://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html.

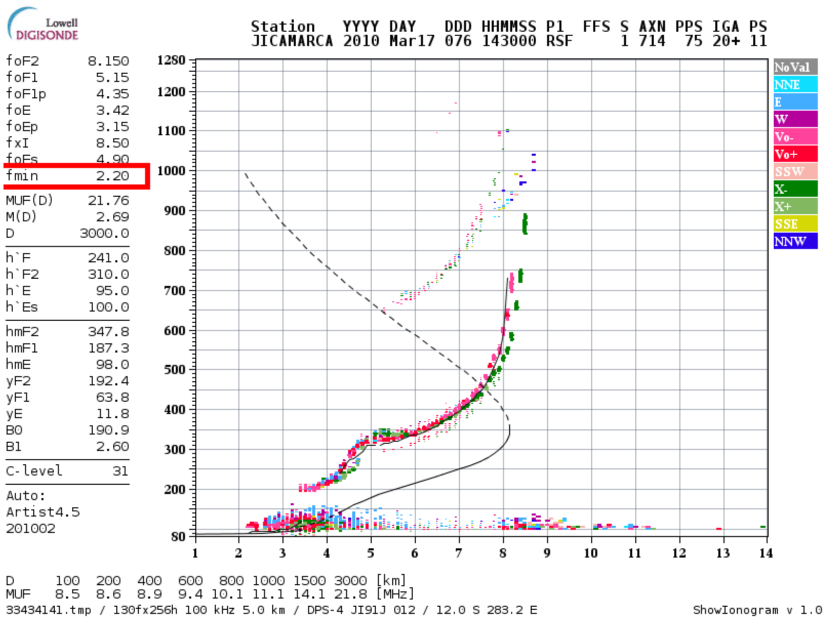

Figure 3: A sample record of an ionogram obtained from digisonde installed at Jicamarca station.

3. Result and Discussion

3.1 Characteristics of the ionospheric fmin parameter

The diurnal monthly averages of the observed fmin over Jicamarca station for the year 2010 is given in figure 4. The figure gives the scatter plot of the hourly values of the five quietest days in the months of January to June and November to December. The monthly values of the fmin are represented by the grey circle and their monthly averages (Mfmin) are the black line with the error bar. The error bar is the calculated standard deviation of the hourly fmin data. It can be observed that the measured fmin exhibit diurnal and seasonal variation having maximum values during the daytime and lowest value at night time. Observe that fmin value during the night time (2000 LT) to the morning time (0000- 0700 LT) before sunrise is lowest with values in the frequency ranges of ~1.82 to 2.00 MHz. This ranges of frequencies serve as the typical baseline level/threshold frequency for the region under study.

The breakdown of the fmin values during the different periods of the months summarized in table 1, shows that fmin begin to rise from morning (0700-0900 LT) towards the midday to reach a maximum value at 1200 LT. Afterwards, the values of fmin reduce to baseline level during night time. The values of fmin also show significant seasonal changes. For instance, the highest midday values of fmin occur during March equinox (February, March, and April) and lowest in the southern summer/December solstice (November, December, and January).

However, the midday value of fmin during the southern winter/June solstice (May, June, and July) is moderate and higher than December solstice. It is important to raise caution when using the midday value of fmin as an equivalent frequency that must be attained to avoid radio absorption. A typical day with an enhanced fmin could be as a result of the contributing effect of a solar flare to the ambient ionospheric stratified layers (e.g. Sharma *et al*., 2010).

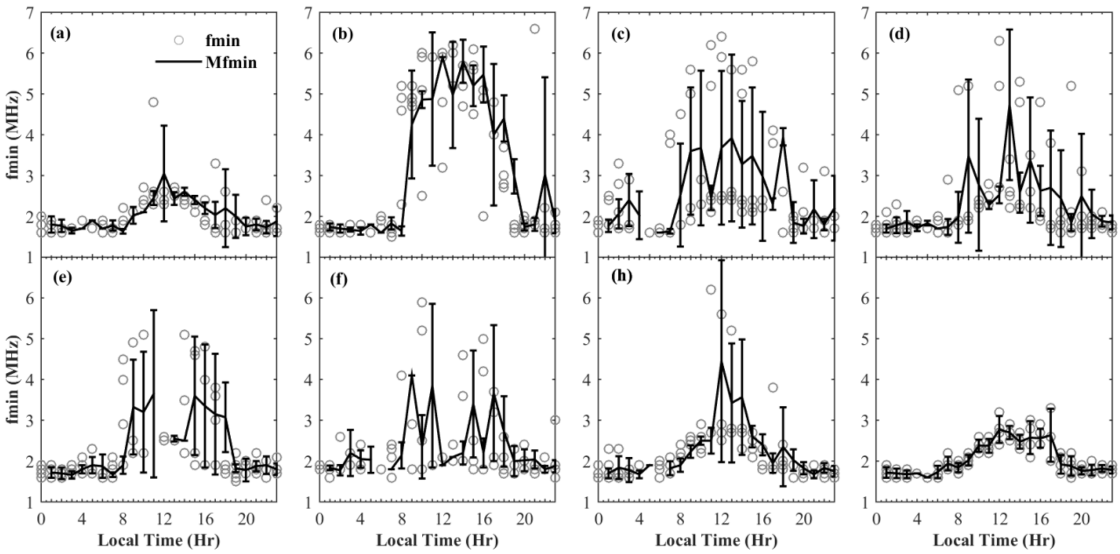

Figure 4: The diurnal monthly averages of measured fmin at Jicamarca station for the year 2010. The months are: (a) January (b) February (c) March (d) April (e) May (f) June (g) November and (h) December

From the analysis of the result, the use of the average values of fmin grouped between 0000-0900 LT (morning), 1000-16000 LT (afternoon) and 17000-2300 LT (night time) gives a clearer representation of fmin values as supposed to using the absolute midday value at a specific local time. This is because fmin values are used to give a rough estimate of the least possible HF frequency that can be propagated in the ionosphere. As a consequence, the radio frequency below this range is susceptible to radio absorption. Hence, the values in Table 1 gives the various fmin values measured at Jicamarca station during the year 2010. Bello *et al*. (2017a) have reported the observed seasonal variation in the magnitude of fmin.

The observed difference in the midday peak of fmin during equinoctial and December solstice can be attributed to the electron concentration at the ionospheric D-region. The explanation for the build-up of ionization of the ionosphere during the daytime that resulted in an increase in the magnitude of fmin at local noontime is due to the increase in the photoionization processes. Most of the ions/electrons concentration is mainly controlled by the dominant role of the production process (due to solar radiation) and chemical recombination (Adebiyi *et al*., 2014). During this period, all of the ionospheric layers are formed by the solar ionizing radiation, under the direct control of solar activity which is primarily responsible for the variation of the ionosphere (Hao and Zhang, 2012). Consequently, HF signals are reflected in the F-layer with possible energy losses of the propagating signal in the E and D-region (Zeng *et al*., 1997; Nishino *et al*., 1998).

Table 1: Monthly average value of ionospheric fmin (MHz) measured at Jicamarca station during the year 2010

Period	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0000 – 0900 LT	1.84	2.34	2.60	2.03	2.04	2.16	–	–	–	–	1.86	1.87
1000 – 1600 LT	2.60	5.23	3.49	2.96	3.16	3.30	–	–	–	–	2.85	2.59
1700 – 2300 LT	1.88	2.29	2.11	2.03	2.00	2.11	–	–	–	–	1.88	1.81

The diurnal trend of fmin reveals the effect of solar radiation as a strong influence on the amount of ionization of the ionosphere. At night, the electron density of ionospheric D-region diminishes as the process of photoionization process ceased. As a result, the values of fmin during the night are observed to be lower than daytime values. This suggests that fmin could be a good indicator and a proxy parameter for the absorption of radio signal propagating in the ionosphere.

3.2 Assessment of fmin and D-region Ne

The temporal variation of fmin and the electron density of D-region (NmD) obtained from the IRI-2012 model are given in figure 5. It is important to state that the IRI adopted the FIRI model developed by Friedrich and Torkar (2001). The model was based on a compilation of reliable rocket data. Herein, a brief description of the measurement of the NmD in the IRI-model is given. The model is typically based on the Faraday rotation experiment. This method allows for an in situ measurement of the absolute electron density of the D-region using propagating HF radio signal that is transmitted from the ground to a flying rocket payload. The variations of the received signal are due to the total electron content between the ground transmitter and the receiver on board the rocket payload. The electron content of the D-region is then obtained by differentiating with respect to altitude. A comprehensive description of this method is in the work of Friedrich and Torkar (2001).

Figure 5(a) shows the contour plot of fmin value measured at Jicamarca station. The days with no data is indicated with the empty white space. It can be observed that the magnitude of fmin is generally small during the night time and morning period. Note that the values of fmin are generally ≤ 2.00 MHz. Similar features seen in the contour plot of figure 5(b) shows that the values of the ionospheric electron density of D-region (NmD) is small and ~ 4 x 10^8 m^{-3} for a period in the morning and at night time. During the daytime, the value of fmin reaches a maximum between 0900-1500 LT. The increase in the value of fmin has been attributed to the amount of electron concentration in the D-region during the daytime. From figure 5b where the magnitude of NmD is at the maximum with a corresponding increase in fmin values is almost about the same time.

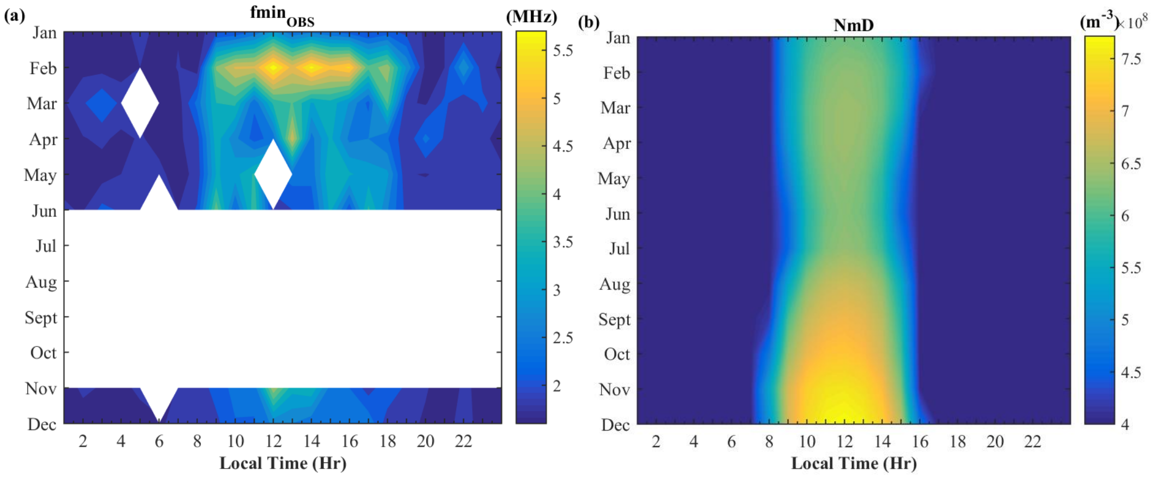

Figure 5: The contour plot of (a) measured fmin and (b) NmD obtained from IRI-2012 model

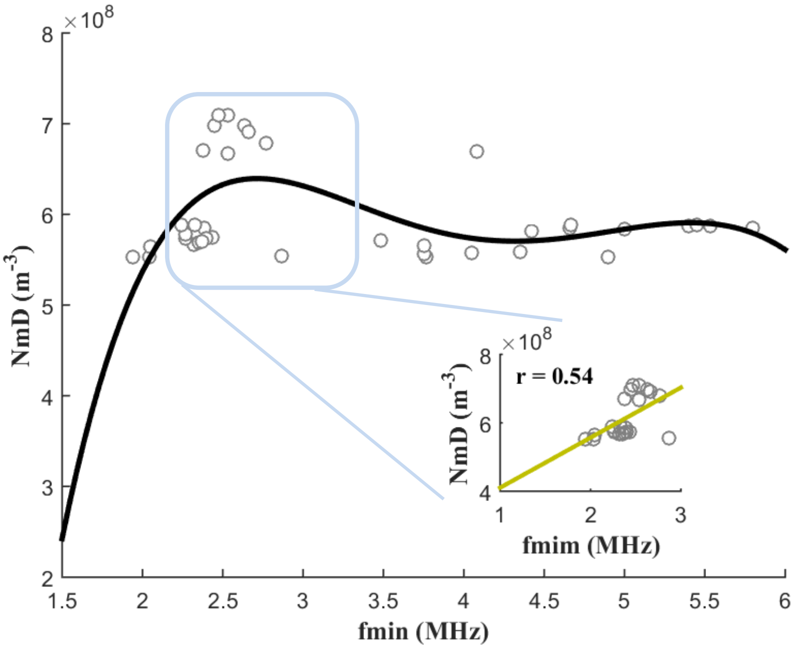

Figure 6: The magnitude NmD as a function of ionospheric fmin. The inserted plot shows the value of fmin not greater than 3 MHz and the correlation coefficient is 0.54

In terms of seasonal variation, fmin is highest in the month of February while NmD is highest between October-December. In general, both fmin and NmD increase in magnitude during December solstices (southern-summer). Despite the identified data gap (see figure 5), the result presented in this current study is consistent with the earlier works of Thomas (1962), Kotadia and Gupta (1976) and Sato (1981) which they found the midday value of fmin to be maximum in summer. Thomas (1962) and Sato (1981) compared fmin with absorption index (L) and reported the occurrence of fmin winter anomaly which coincides with high radio absorption during the winter season.

Figure 6 shows the scatter plot of NmD and fmin during the daytime. The average values of NmD and fmin for each month were calculated for the periods centred on 1200 LT. The daytime averages values of NmD and fmin are the calculated averages over a period of 5 h (1000 –1400 LT). From figure 6, the black curve indicates the polynomial fit of order 5. We can observe that the relationship between NmD and fmin is linear when fmin is in the range of frequency between $1.94 \leq \text{fmin} \leq 3$ MHz as indicated in the inserted plot. The correlation coefficient ($r = 0.54$) is significant. However, beyond this frequency, the linearity deteriorates and the polynomial behaviour takes over. The linearity of fmin with NmD confirms the general opinion that fmin could be used as a proxy parameter of HF radio wave absorption in the ionosphere.

4. Conclusion

The study examined the temporal variation of ionospheric fmin over Jicamarca station in the Southern-American region for geomagnetic quiet days in the year 2010. The relationship between the noontime fmin and NmD obtained from the IRI-2012 model was studied. The study obtained the following results:

1. Both fmin and NmD are found to be higher during the daytime than night time. Apart from that, their magnitudes show maxima during southern summer.
2. The relationships between the two parameters are found to be linear when fmin data is not greater than 3 MHz. At this frequency range, the correlation between fmin and the electron density of ionospheric D-region is significant while outside this range is nonlinear.

3. In the region under study, the obtained threshold frequency in the range of $1.94 \leq$ fmin ≤ 3 MHz during geomagnetic quiet condition serves as a baseline for the absorption of HF signal at the lower portion of the ionosphere.

The findings of this current study underscore the importance of fmin to the study of ionospheric physics and related space weather events such as polar cap absorption (PAC), sudden ionospheric disturbance (SID) and solar flare effect on ionospheric morphology.

Acknowledgement

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