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Evaluation of the Vertical Profile of Radio Refractivity and its Gradients in a Tropical Atmosphere

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Abstract

This paper evaluates radio refractivity and its gradients over Abuja, the Federal Capital Territory of Nigeria, using five years' upper air meteorological data obtained from the Nigerian Meteorological Agency (NiMet). From the results obtained, radio refractivity was observed to decrease with increasing altitude. Also, higher refractivity values were observed in wet season, while lower values were recorded in dry season. An average refractivity value of 326 N-Units was obtained at 1 km altitude, while average refractivity gradient values of -34 N-Units/km and -40 N-Units/km were recorded for the dry and wet season months respectively. A total average value of -38 N-Units/km for refractivity gradient was obtained for the five-year study period, thus making the atmospheric condition over Abuja to be sub-refractive. The effective earth radius factor (k-factor) computed for the location was also observed to be higher in the wet season months than the dry season months. An average k-factor value of 1.32 was obtained for the study period.

1. Introduction

The ratio of a radio wave's velocity in free space to its velocity in a certain medium is known as radio refractivity. Changes in the radio refractive index of the air in the troposphere control the propagation of radio waves. The troposphere is the lowest layer of the atmosphere, stretching from the surface of the earth to an altitude of about 10 km at the earth's poles and 17 km at the equator. It is the layer of the atmosphere that is most intimately tied to human life. The path of the propagating radio waves is curved when the troposphere's radio refractive index changes significantly [1, 2]. Due to variations in some key atmospheric weather variables like atmospheric temperature, pressure, and relative humidity in the troposphere, the various elements that make up the atmosphere have a significant impact on how electromagnetic waves propagate in the troposphere. The refractive index of air in the troposphere also varies depending on changes in certain atmospheric meteorological variables [3-5]. Studies on the transmission of electromagnetic waves have been done, and the findings indicate that air refraction has an impact on the transmission of electromagnetic waves [6]. The inhomogeneous spatial distribution of the air's refractive index results in undesirable outcomes including multipath fading, interference and attenuation of radio signals. Radio communication, aeronautics, environmental monitoring, disaster prediction, navigation, and radar systems are all hindered by these impacts [7]. This abnormal radio wave propagation results in intense consequences like the full breakdown of communication between the transmitters and receivers or even the missing of intended targets by radars [8]. In order to prevent issues from arising owing to anomalous radio wave propagation and unexpected path loss that impacts the operation of these systems, radio refractivity variation studies are important in telecommunication network, navigation and surveillance systems. For the appropriate design of a communication system and the planning of a good terrestrial radio link throughout a region, radio refractivity plays a key role in defining the quality of UHF, VHF, and SHF signals [9]. Radio engineers frequently need surface and elevated refractivity data to precisely predict electromagnetic wave transmissions and characterise radio channels. In this paper, the vertical profile of radio refractivity and refractivity gradients is evaluated in Abuja, the Federal Capital Territory of Nigeria, a tropical country. Similar studies have been carried out in other locations in Nigeria [10-17] but there is need for continuous data update in the light of climate change.

2. Methodology

The five years (2014-2018) daily radiosonde data of temperature, pressure and relative humidity at altitudes of 700 m - 16 km was obtained from the Nigerian Meteorological Agency (NiMet), Abuja, Nigeria. The daily measured upper atmospheric data of temperature, pressure, relative humidity with heights were averaged to get the monthly mean data and the monthly values were also averaged to get the yearly values. These were analysed to evaluate the saturated vapour pressure (es), water vapour pressure (e), radio refractive index (N), refractive index gradients (G) and effective earth radius factor (k-factor). The vapour pressure (e) is estimated from [1]:

$$e = \frac{H\, e_s}{100} \tag{1}$$

where H is the relative humidity and es is the saturated vapour pressure.
es is also estimated from [1]:

$$e_s = 6.11exp\left[(19.7t)/(t+273)\right] \tag{2}$$

t is the temperature in °C.
The radio refractivity (N) is estimated from [18]:

$$N = \frac{77.6}{T}\left(P + 4810e_T\right) = N_{dry} + N_{wet} \tag{3}$$

where Ndry and Nwet represent the dry and wet components of refractivity and are given as:

$$N_{dry} = 77.6\frac{P}{T} \tag{4}$$

where b is the slope and a is the intercept.

$$N_{wet} = 3.73 \times 10^5 \frac{e}{T^2} \tag{5}$$

T is the absolute temperature (K) and P is the atmospheric pressure (hpa).
The radio refractivity gradient is estimated from [18]:

$$G = \frac{N_1 - N_2}{h1_1 - h_2} \tag{6}$$

where G is the radio refractivity gradient, while N1 and N2 are the radio refractivity values at heights h1 and h2 respectively.
The effective earth radius factor (k-factor) is estimated from [18]:

$$k \approx \left[1 + \frac{\left(\frac{dN}{dh}\right)}{157}\right]^{-1} \tag{7}$$

where k is the effective earth radius factor and dN/dh is the change in radio refractivity with height (the radio refractivity gradient).

For k = 4/3 (or dN/dh = -40 N/km): Normal Refraction (8)

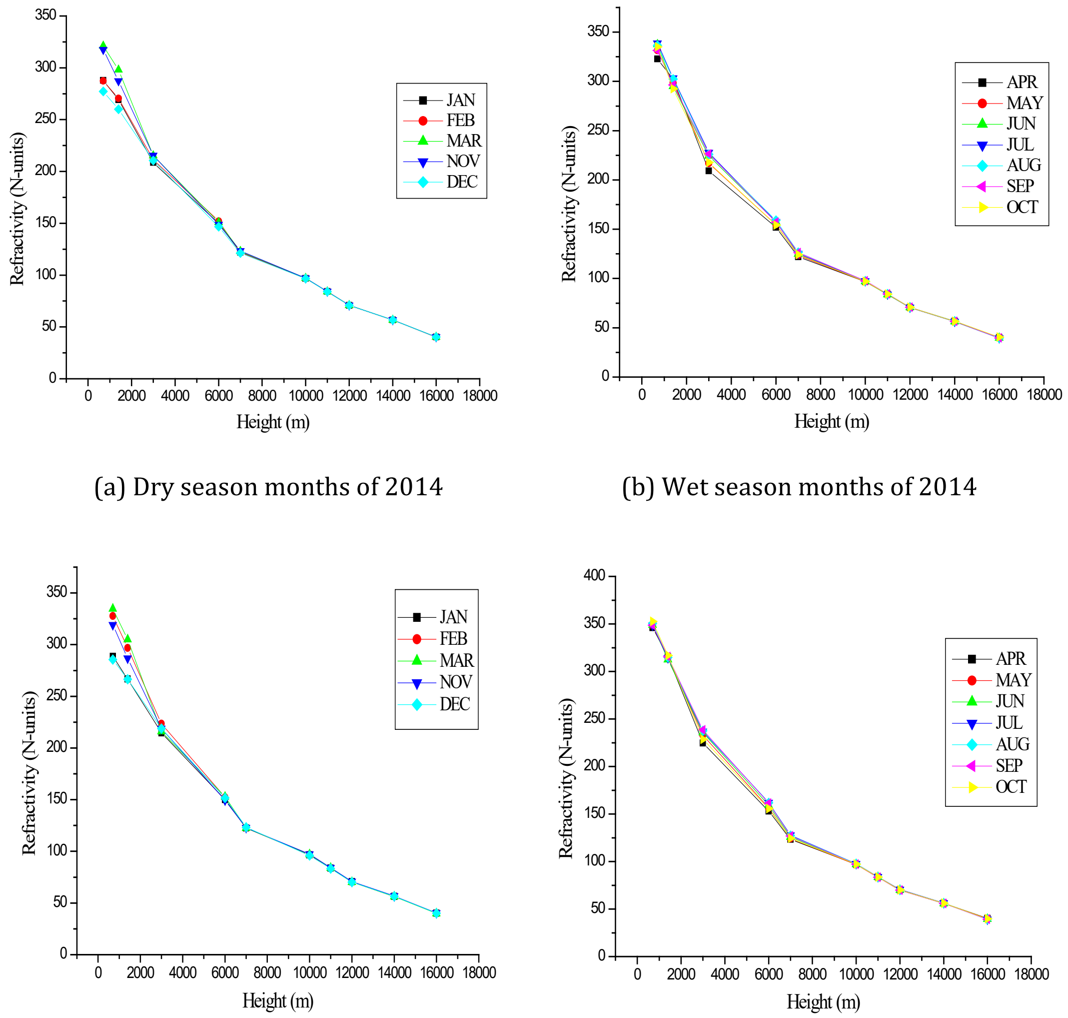
$$4/3 > k > 0 \text{ (or } dN/dh > -40 \text{ N/km): Sub-refraction} \quad (9)$$

$$\infty > k > 4/3 \text{ (or } -157 \text{ N/km} < dN/dh < -40 \text{ N/km): Super-refraction} \quad (10)$$

3. Results and Discussion

3.1 Variation of Refractivity with Altitude

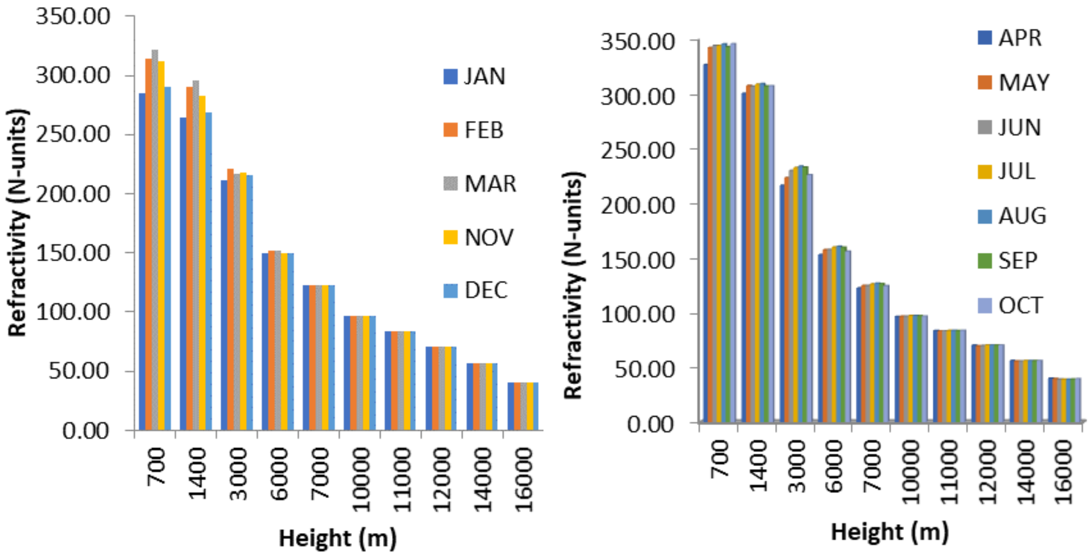
Fig.1 (a-d) depicts the dry and wet seasonal variation of radio refractivity with altitude for the first year (2014) and the last year (2018), while Fig.2 (a-b) shows the cumulative average dry and wet seasonal variation of refractivity from 2014 - 2018.



(a) Dry season months of 2014 (b) Wet season months of 2014

(c) Dry season months of 2018 (d) Wet season months of 2018

Fig. 1 *Mean radio refractivity-altitude profile*



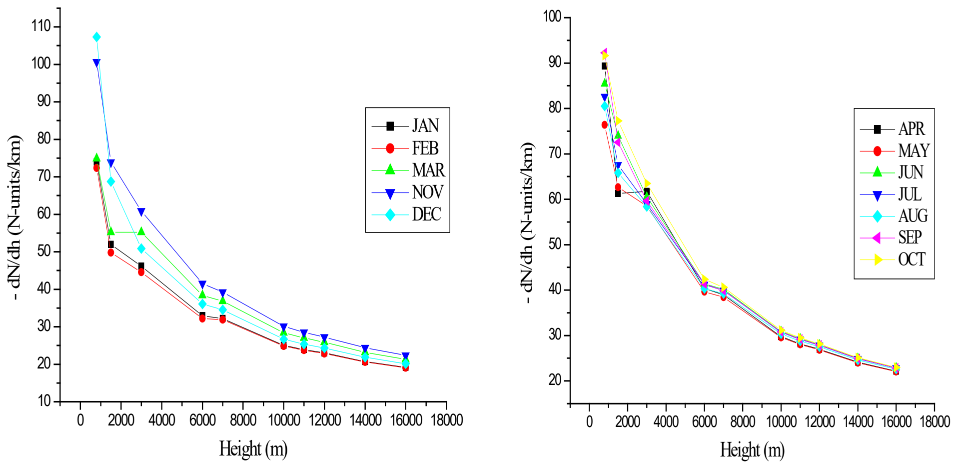
(a) Dry season months of 2014-2018 (b) Wet season months of 2014-2018

Fig. 2 *Average radio refractivity-altitude profile from 2014-2018*

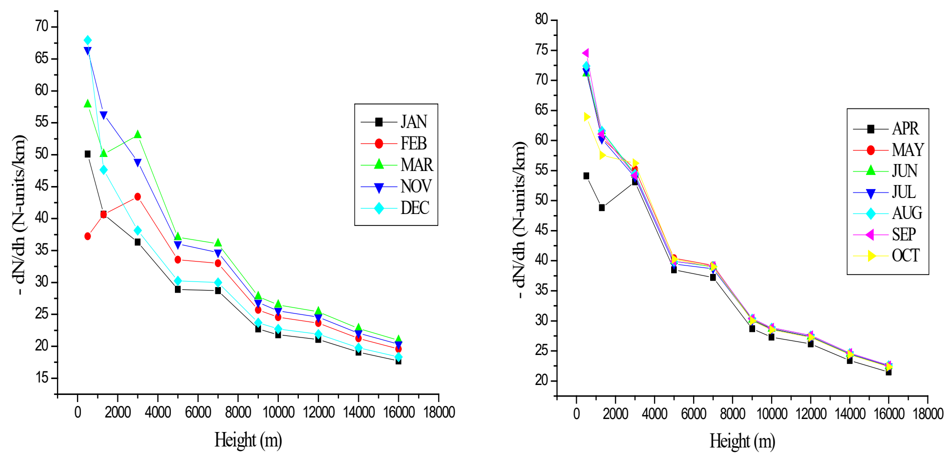
It is observed from Fig. 1 and 2 that refractivity values over Abuja show trends of gradual decrease with increasing altitude. For year 2014, the computed refractivity values decrease from 318.73 N-Units to 40.01 N-Units as the height increases. The same trend is observed for 2018 as refractivity values decrease from 333.24 N-Units to 39.82 N-Units. The average computed refractivity values for the five years' period (2014-2018) as shown in Fig. 2 ranged from 326.21 N-Units to 39.86 N-Units from the lowest to the highest altitude. This is because the three components of refractivity, that is, temperature, pressure and relative humidity decrease with increasing altitude. Also, it is because most weather activities are found close to the earth`s surface and this makes refractivity values to be higher at lower altitude than at higher altitude. These effects are observed in both seasons (dry and wet). It can also be observed from the figures that refractivity values are lower in the dry season months (November – March) than the wet season months (April – October). This is a consequence of less moisture contents in the atmosphere during the dry season period, which also results from the influx of large quantity of dry dust-laden north easterly wind in the region. The high values of refractivity recorded during the wet season months are due to the influence of large quantity of moisture-laden tropical maritime air or south westerly wind resulting from the continuous migration of the Inter-tropical discontinuity (ITD) with the sun. This is in agreement with the works of [19-23]. Also, in 2014, the highest refractivity value of 338.69 N-Units at approximately 1 km altitude was observed in July, while the lowest value of 277.30 N-Units at the same altitude was computed in December. For 2018, the highest refractivity value at approximately 1 km altitude was computed as 352.50 N-Units, while the lowest value was 285.60 N-Units, recorded at the same altitude. At same 1 km altitude, the average values of refractivity from 2014 - 2018 show an increase from April to October for the wet months in the range 326.50 N-Units to 345.60 N-Units. For the dry season months, the values are seen to increase in the range of 285.30 N-Units to 322.10 N-Units. At close to 2 km altitude, the average refractivity values from 2014 - 2018 in the wet months also showed a similar increase from April - October in the range 300.40 N-Units to 309.30 N-Units, while the dry month's values ranged from 264.60 N-Units to 295.60 N-Units. Therefore, it is generally observed that average refractivity values for the five-year study period ranged from the lowest value of 285.30 N-Units in January to the highest value of 345.60 N-Units in October.

3.2 Variation of Refractivity Gradient

Fig. 3 (a-d) shows refractivity gradient-altitude profile for the dry and wet season months of 2014 and 2018, while Fig. 4 (a-b) shows the average refractivity gradient-altitude values for 2014-2018.

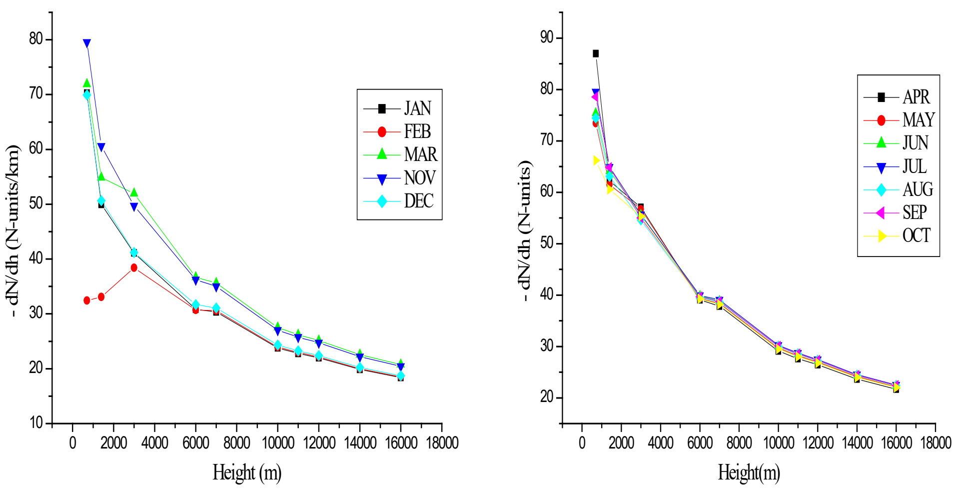


(a) Dry season months of 2014 (b) Wet season months of 2014



(c) Dry season months of 2018 (d) Wet season months of 2018

Fig. 3 *Mean refractivity gradient-altitude profile*



(a) Dry season months (b) Wet season months

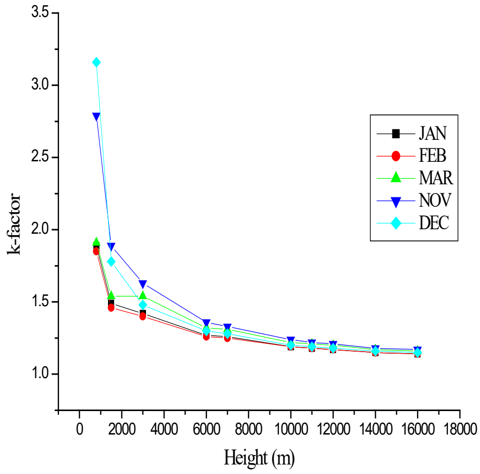
Fig. 4 *Average refractivity gradient-altitude profile for 2014-2018*

The refractivity gradient values in Fig. 3 and 4 are observed to increase with altitude. For year 2014, the values for the dry months ranged from -72.33 N-Units/km in February to -107.31 N-Units/km in December at approximately 1 km altitude, while the values for the wet season months at the same altitude ranged from -76.39 N-Units/km in May to -92.25 N-Units/km in September. For year 2018, the refractivity gradient values for the dry season months at approximately 1 km altitude ranged from -37.22 N-Units/km in February to -67.96 N-Units/km in December, while in the wet season months, the values ranged from -54.12 N-Units/km in April to -74.54 N-Units/km in September.

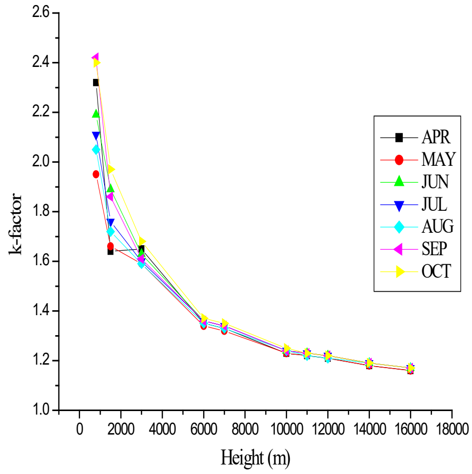
The average refractivity gradient for the five-year study period (2014-2018) at approximately 1 km and 2 km altitudes were computed as -71.55 N-Units/km and -57.33 N-Units/km respectively. It is generally observed from the result that refractivity gradient values are slightly higher in the dry months than the wet months. The highest value of -18.39 N-Units/km was observed in January at an altitude of 16 km. This month is a typical dry month that is accompanied by extreme harmattan with very cold nights and mornings and hot daytime. The lowest value of -79.55 N-Units/km was observed in July at approximately 1 km. This month is a typical wet month. Average refractivity gradient values of -33.81 N-Units/km and -40.47 N-Units were recorded for the dry and wet seasons respectively. A total average refractivity gradient value of -38 N-Units/km was computed for the period of study. This average value places the propagation of radio waves over the study area as sub-refractive.

3.3 Variation of Effective Earth Radius Factor (K-Factor)

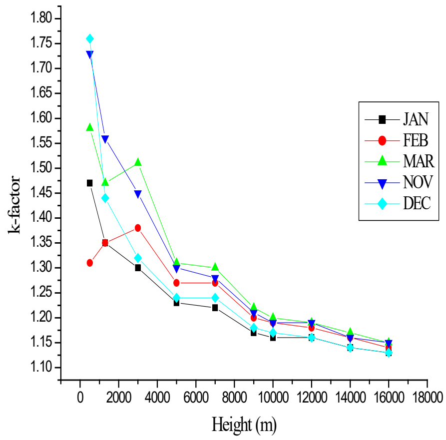
Fig. 5 (a-d) shows the variation of effective earth radius factor (k-factor) for dry and wet seasons of 2014 and 2018 at different altitudes, while Fig. 6 (a-b) shows the five (5) years (2014-2018) average variation of k-factor for both seasons.



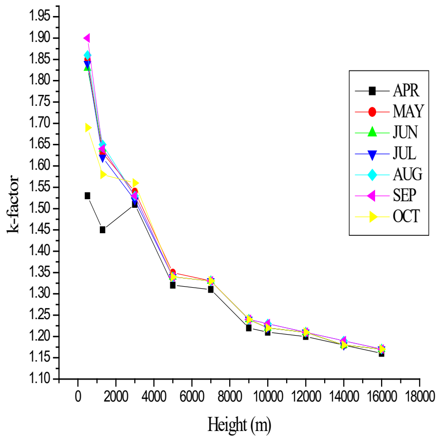
(a) Dry season months of 2014



(b) wet season months of 2014

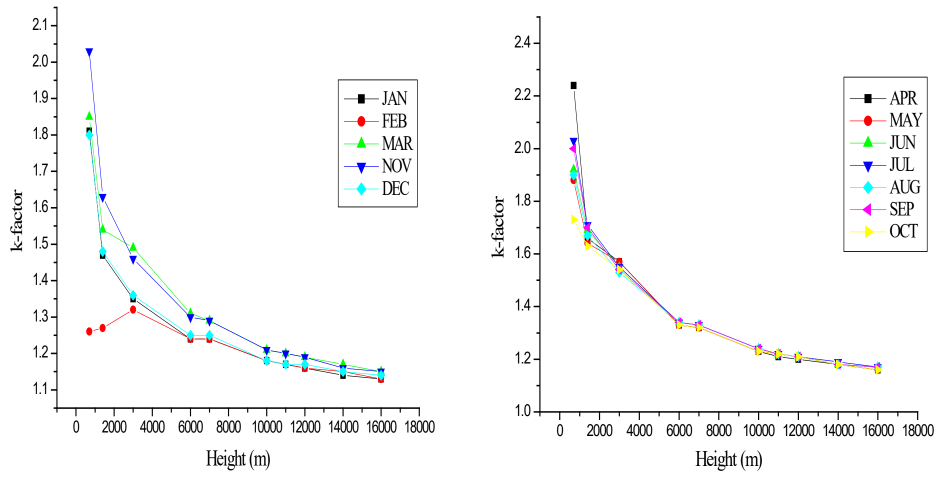


(c) Dry season months of 2018



(d) Wet season months of 2018

Fig. 5 *Mean k-factor for 2014 and 2018*



(a) Dry season months of 2014-2018 (b) Wet season months of 2014-2018

Fig. 6 *Average k-factor for 2014-2018*

From Fig. 5 and 6, the k-factor values are observed to decrease with increasing altitude, and slightly higher in the wet months than the dry months. For 2014, the k-factor values in the dry months at a height of approximately 1 km varied from 1.85 in February to 3.16 in December, while the wet month's values varied from 1.95 in May to 2.40 in October. For 2018, the computed k-factor values in the dry months ranged from 1.31 in February to 1.76 in December, while the wet month's values ranged from 1.53 in April to 1.90 in September. The total average values of k-factor deduced for the five-year study period (2014-2018) in the dry season months ranged from 1.13 in January at 16 km to the highest value of 2.03 in November at 1 km. For the wet season months, the values varied from 1.16 in April, May and October at 16 km to the highest value of 2.24 in same April but at a height of 1 km. A total average value of 1.32 was computed for both dry and wet seasons for the five-year study period thereby affirming the sub-refractive condition of the atmosphere over Abuja.

4. Conclusion

The computed radio refractivity values over Abuja showed that refractivity decreases with increasing altitude and values for the wet season months were higher than values for the dry season months. At an altitude of 1 km in the wet season months, refractivity values ranged from 326.50 N-Units to 345.60 N-Units, while the dry season values ranged from 285.30 N-Units to 322.10 N-Units. Also, average radio refractivity gradient and k-factor values of -38 N-Units/km and 1.32 respectively were computed for the five-year study period. These values show that the atmospheric condition over Abuja is sub-refractive. The results obtained are useful and required for the design and planning of terrestrial radio systems over Abuja and other regions with similar climate conditions especially in North Central Nigeria.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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