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Original Research Article

Investigation of Tropospheric Radio Refractivity and other Relevant Parameters across Some Selected Locations in the Sahelian Region of Nigeria

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Abstract

The troposphere's internal processes are complex and exhibit nonlinear trends, which have a significant impact on the transmission and reception of high-quality signals worldwide. This study used measured monthly climatic data of temperature, relative humidity, and atmospheric pressure for Maiduguri and Sokoto from the National Aeronautic and Space Administration (NASA) over a forty-two-years period (1981 to 2022) to estimate the seasonal tropospheric radio refractivity and examine its variations with other meteorological parameters and refractive index. The refractivity gradiant, effective earth radius, and percentage contribution of the dry and wet term radio refractivity were also examined. According to the results, radio refractivity was found to be highest at the two locations during the rainy season and lowest during the dry season. In Maiduguri, during the rainy season and dry seasons are 361.4837 N-units in August, 272.4506 N-units in March while for Sokoto are 366.7093 N-units in August, 277.1162 N-units in February. For Maiduguri and Sokoto, the wet term (N_{wet}) contributes to the significant variation with 19.9753 % and 21.1831%, respectively, while the dry term (N_{dry}) contributes 80.0247 % and 78.8169 % to the total value of radio refractivity. The average refractivity gradients in the studied locations were found to be -42.3746 and -42.3928 N-units/km. Furthermore, it was discovered that Maiduguri and Sokoto had average effective earth radiuses (k-factors) of 1.3697 and 1.3698, respectively. These values implied super refraction propagation condition.

Keywords: Effective earth radius, meteorological parameters, radio refractivity, refractivity gradient, sahelian region.

1. INTRODUCTION

According to Adeyemi and Adebayo [1], the troposphere is the lowest layer of the earth's atmosphere, rising from sea level to an altitude of roughly 9 km at the poles and 17 km at the equator. The upper limit of the troposphere, above which the temperature rises little with height, is known as the tropopause. The variations in weather factors such as temperature, pressure, and relative humidity cause the tropospheric refraction at the lowest part of the earth [2]. Therefore, understanding refractivity is crucial to designing dependable and effective terrestrial and satellite radio communication systems. Similar to this, the troposphere's refractive index is a crucial factor to take into account when estimating the performance of terrestrial radio links. The air temperature, humidity, atmospheric pressure, and water vapour pressure all affect the atmosphere's radio refractive index. Radio waves can be refracted throughout their entire course, thus even slight changes to any one of these variables can have a big impact on how they propagate. The atmosphere's refractive index varies with space and time, leading to phenomena such as absorption, ducting, super-refraction, sub-refraction, and scattering. Temperature, pressure, and relative humidity measurements can be used to estimate the fluctuation of the refractive index and the specific attenuation of microwaves and radio waves in an indirect manner. Field strength in radio frequency telecommunications refers to the strength of the electromagnetic field received, which stimulates a receiving antenna and produces a voltage at a certain frequency to supply an input signal to a radio receiver [3].

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In projects involving terrestrial atmospheric electromagnetic propagation, such as point-to-point microwave communication, terrestrial radio and television broadcast, and mobile communication systems, radio refractivity—the bending of a radio signal as it propagates through media—is crucial [4]. According to Gao *et al*., [5], refraction and fading, range and elevation errors in radar acquisition, ducting and scintillation, and other phenomena in radio wave propagation are all caused by a medium's refractivity, which is measured by its index of refraction. In contemporary times, radio communications, encompassing mobile phone usage, digital broadcasting on land, and satellite signal propagation through the troposphere, greatly impact the behaviour of radio waves in the tropospheric layer of the Earth's atmosphere. Radio waves refract and acquire a refractive index as a result of propagating through the inhomogeneous troposphere [6, 7]. The characteristics of the atmosphere influence the propagation of all radio waves. Various components of the atmosphere have the ability to reflect, refractive, scatter, and absorb them [8].

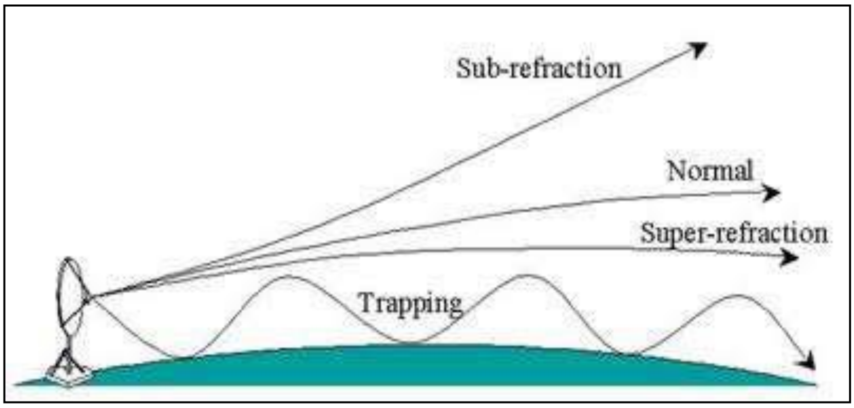

Figure 1: Refractive Conditions in the Atmosphere [9]

The modified refractivity (N units/km) of the atmosphere determines the refractive conditions of radio waves, which are shown in Figure 1 and can be categorised as sub-refractive, Normal (standard), super-refractive, or trapping. The ratio of a radio wave's velocity in a given medium to its velocity in free space is known as radio refractivity. Variations in the troposphere's air's radio refractive index govern the propagation of radio waves. In order to properly construct their communication station and create a suitable terrestrial radio link throughout a region, radio refractivity plays a role in defining the quality of UHF, VHF, and SHF signals [10].

This study is aimed at estimating the tropospheric radio refractivity for Maiduguri and Sokoto found in the Sahelian region of Nigeria. The variation of the location’s radio refractivity with climatic parameters and radio refractive index were investigated. The variation of dry and wet term radio refractivity along with their percentage contributions to the total radio refractivity were examined and finally the refractivity gradient and effective earth radius were estimated.

2. REVIEW OF THE RELATED LITERATURE

The comparative examination of tropospheric radio refractivity in Calabar, Nigeria, during the rainy season was evaluated by Iloke *et al*., [11]. Using data from the Nigeria Meteorological Agency (NIMET) for ten (10) years (2010 to 2019) during the rainy season, from March to October, they assessed the variations in radio refractivity in their study. They also computed the annual average of the refractivity using the given meteorological parameters. The analysis that was done typically reveals little fluctuations in refractivity during the time where the lowest value occurred in 2014 and the maximum value occurred during the wet season in 2016. With a coefficient of determination (R^2) value of 0.9902, the study demonstrated a linear relationship between water vapour pressure and refractivity. In contrast, the link between refractivity and temperature had a coefficient of determination (R^2) value of 0.8442. According to the study, it is reasonable to say that Calabar's weather conditions have been rather constant.

Tropospheric radio refractivity and other pertinent parameters are estimated and investigated over Accra, Ghana by Akpootu *et al*., [12]. The study's findings indicated that tropospheric radio refractivity is higher during the rainy season than it is during the dry season. The months of April and January had the highest and lowest monthly average values of tropospheric radio refractivity, with 384.356 and 371.6318 N-units, respectively, during the rainy and dry seasons. According to the annual values of tropospheric radio refractivity, the year 2016 had the highest value at 384.2550 N-units, while the year 2008 had the lowest value at 375.8681 N-units. The wet term radio refractivity accounts for the majority of fluctuation, with the monthly and yearly dry term contributions being 68.79% and 68.78%, respectively, to the total value of the radio refractivity. The average refractivity gradient and average effective earth radius (k-factor) measured for Accra for the study period were 1.39 and -44.1405 Nunit/km, respectively, indicating that super-refractive propagation predominates in the area.

Investigation of the Vertical Profile Radio Refractivity Gradient and Effective Earth Radius Factor (k-factor) in Transmission Link over Oyo, South Western Nigeria was the subject of a study done by Sheu *et al.*, [13]. The study's meteorological variables (wind speed, relative humidity, air temperature, and atmospheric pressure) were measured at the Emmanuel Alayande College of Education's School of Science in Oyo State, Nigeria. Their research was conducted utilising inexpensive, self-designed portable weather monitoring systems over the course of a year, from January to December 2020. The devices were installed on a 220 m Nigeria Television Authority (NTA) UHF channel 37 tower at Oke-Apitipiti in Oyo Town, Oyo State, with a height of 200 m from the ground. Utilising the computed mean data on a daily and monthly basis, the vertical surface radio refractivity and its gradient were examined. According to their data, January had the greatest value of -1.093E+26 N-units/km, while July had the lowest value of roughly -9.305E+19 N-units/km. Sub-refractive situations with variable degrees of propagation condition occurrence were confirmed over the months of January through July. Conversely, the majority of the study's super-refraction and ducting observations occurred from August to December.

A study on the refractive effect of k-factor on radio propagation over Lokoja, Nigeria, was conducted by Akinbolati *et al.*, [14]. They used ten years' worth of atmospheric data (from 2011 to 2020) on temperature, pressure, and humidity at both the surface (12 m) and 100 m above sea level (AGL) to conduct their study over the city of Lokoja, Nigeria. The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 provided the data. The yearly variation of the k-factor exhibits a similar pattern, with the lowest and highest values occurring in the dry and rainy seasons, respectively. Furthermore, with an overall mean value of 1.0003, the month of August had the highest mean value of 1.00042 and the month of January had the lowest value of 1.00040. This number was below the ITU-R suggested threshold of 1.33. For $k < 1.33$, the propagation effect is sub-refractive.

In the Guinea Savannah Region of Nigeria, Bello *et al.*, [15] studied the assessment of tropospheric radio refractivity and its variation with climatic variables. Using measured monthly climatic data of temperature, relative humidity, and atmospheric pressure for Makurdi and Ibadan over a 42-year period (1981 to 2022) from the National Aeronautic and Space Administration (NASA), their study estimated the seasonal tropospheric radio refractivity and examined its variations with other meteorological parameters and the refractive index. They looked at the proportion contributions of the dry and wet term radio refractivity, the refractivity gradient, and the effective earth radius. According to their findings, radio refractivity for the two locations was highest during the rainy season and lowest during the dry season. For Makurdi, during the rainy season, the maximum and minimum average values of radio refractivity were recorded as follows: 380.0641 N-units in May, 331.9776 N-units in January; and 379.9479 N-units in May, 352.2143 N-units in January for Ibadan. The wet term (N_{wet}) adds to the major variation with 29.1236 % and 30.5496 % for Makurdi and Ibadan, respectively, while the dry term (N_{dry}) contributes 70.8764 % and 69.4504 % to the total value of radio refractivity. Nonetheless, the average refractivity gradients in the studied locations were found to be -43.8583 and -43.1480 N-units/km. Furthermore, it was discovered that the average effective earth radius (k-factor) for Ibadan and Makurdi were 1.3790 and 1.3876, respectively. These values are consistent with the propagation conditions of super refraction.

Using meteorological data over Bauchi, Nigeria, Akpootu *et al.*, [16] conducted a study on analysis of tropospheric radio refractivity and other pertinent factors. In order to calculate the monthly tropospheric radio refractivity and its variation with other factors, the refractivity gradient, and the percentage contribution of the dry term (N_{dry}) and wet term (N_{wet}) radio refractivity, Bauchi relied on data from the National Aeronautics and Space Administration (NASA) archives. These data covered a 41-year period (1981–2021). Their findings demonstrated that August and February have the highest and lowest average values of radio refractivity, measuring 355.032 (N-units) and 273.255 (N-units), respectively, during the rainy and dry seasons. According to them, this suggests that radio refractivity was higher during the rainy season than within the dry season. The dry term accounts for 76.60 % of the total value, whereas the wet term adds to the notable variation in radio refractivity values. The average estimate of the refractivity gradient was determined to be – 40.854 N – units/km, confirming super-refraction propagation for Bauchi. This means that when the super-refraction criterion is met, electromagnetic waves are frequently bent downward towards the earth.

3. METHODOLOGY

3.1 Data Collection

The National Aeronautics and Space Administration (NASA) provided the measured monthly meteorological data of temperature, relative humidity, and atmospheric pressure for two (2) distinct locations in the Sahel Savannah climatic zone of Nigeria over a forty-two (42) year period (from 1981 to 2022). The state along with their respective latitude and longitude are given in Table 1.

Table 1: The latitude and longitude of the studied locations

Climatic Zone	Locations	Latitude	Longitude	State
Sahel Savannah	Maiduguri	11.85 °N	13.08°E	Borno
	Sokoto	13.02 °N	5.25°E	Sokoto

3.2. Estimation of Tropospheric Radio Refractivity

Three (3) variables affect the atmospheric refractive index (n): temperature, humidity (water vapour content), and atmospheric pressure. The refractive index (n) ranges from 1.000250 to 1.0004000, indicating that it is quite close to unity at or near the earth's surface and that variations in this value across time and space are negligible. The radio refractivity (N), which is connected to the refractive index (n) via the equation, is typically used to measure the refractive index (n) of air in order to make these values visible [3, 17, 18].

$$n = 1 + \frac{N}{10^6} \quad \ldots\ldots\ldots\ldots \; (1)$$

The unitless quantity known as radio refractivity (N) is represented in N-units. Therefore, it may be inferred from equation (1) that N usually falls between 250 and 400 N-units. The International Telecommunication Union (ITU) has recommended that the radio refractivity, N, be stated as follows in terms of measured meteorological parameters [18].

$$N = \frac{77.6}{T}\left(P + 4.810 \times 10^3 \frac{e}{T}\right) \quad \ldots\ldots\ldots \; (2)$$

Where the radio refractivity of the dry term is given by equation (3) according to ITU-R [18] through expansion of equation (2) [2, 19].

$$N_{dry} = 77.6\frac{P}{T} \quad \ldots\ldots\ldots\ldots \; (3)$$

And the radio refractivity of the wet term is given by equation (3) through expansion of equation (2) [2, 16, 18, 19].

$$N_{wet} = 3.73 \times 10^5 \frac{e}{T^2} \quad \ldots\ldots\ldots\ldots \; (4)$$

Where P is the atmospheric pressure (hPa), e is the water vapour pressure (hPa) and T is the temperature (K). The non-polar oxygen and nitrogen molecules are what cause the dry term. Since it is a function of pressure (P), it is correlated with air density. In the troposphere of the atmospheric layer, polar water contents dominate the wet term, which is related to vapour pressure.

According to ITU-R [20] and Freeman [3], equation (2) can be used to all radio frequencies; the inaccuracy is less than 0.5% for frequencies up to 100 GHz, and John [21] discovered that the average value of N = 315 was utilised at sea level.

The relationship between the water vapour pressure, e, and relative humidity have been provided by [22–26] as:

$$e = \frac{He_s}{100} \quad \ldots\ldots\ldots\ldots \; (5)$$

According to ITU-R [18], the saturation vapour pressure, e_s in (hPa) at temperature, *t* (°C) is given by

$$e_s = a\exp\left(\frac{bt}{t+c}\right) \quad \ldots\ldots\ldots\ldots \; (6)$$

The relative humidity (%) is represented by H. ITU-R [20] provided the values of the coefficients a, b, and c (water and ice). The water values used in this investigation are a = 6.1121, b = 17.502, and c = 240.97. They have an accuracy of ±0.20% and are valid between -20℃ and +50℃.

3.3. Estimation of Refractivity Gradient

In the troposphere, the radio refractivity, N, diminishes exponentially with height [20].

$$N = N_s\exp\left(\frac{-h}{H}\right) \quad \ldots\ldots\ldots\ldots \; (7)$$

Where H is the appropriate scale height and N is the refractivity at height h (km) above the level where the refractivity is N_s. It was recommended by ITU-R [20] that N_s and H be 315 km and 7.35 km, respectively, at average mid-latitude. Thus, N(h) as a function of height N is given by

$$N = 315\exp^{-0.136h} \quad \ldots\ldots\ldots\ldots \; (8)$$

Agunlejika and Raji [27] found that for seven (7) of the twelve (12) months of the year, the model with scale heights of 7.35 km and 7 km is advised for the global environment ITU-R [20] and the tropical environment John [21], respectively. These models produced notable precise results for the refractivity at the altitude of 50 m and 200 m. While 7.35 km scale height was found to perform better at 200 m, 7 km scale height tended to yield better results at 50 m altitude.

Equation (7) can be differentiated with respect to h to yield the refractivity gradient; as a result, the refractivity gradient is provided by Akpootu *et al.*, [17] as reported in Bello *et al.*, [28].

$$\frac{dN}{dh} = \frac{-N_s}{H}\exp\left(\frac{-h}{H}\right) \quad \ldots\ldots\ldots\ldots \; (9)$$

The refractivity gradient for a standard atmosphere is -39 N-units/km. John [21] states that the refractivity gradient's value in a standard environment is a good approximation for h values less than 1 km. Because John's [21] typical values for a standard atmosphere were used in this study, the refractivity of a standard atmosphere is $N_S = 312$ N-units.

According to Adediji and Ajewole [29], the vertical gradient of refractivity in the troposphere is a crucial element in determining path clearing and propagation effects like sub-refraction, super-refraction, or ducting.

(1) Sub-refraction occurs when $\frac{dN}{dh} > -40$

(2) Super-refraction occurs when $\frac{dN}{dh} < -40$

(3) Ducting occurs when $\frac{dN}{dh} < -157$

3.4. Estimation of Effective Earth Radius

Refractive conditions were classified as normal refraction or standard atmosphere, sub-refraction, super-refraction, and ducting, respectively, using the effective earth radius factor k. Accordingly, the equation [3, 30 – 33] is used to define k in terms of the refractivity gradient, dN / dh.

$$k = \left[1 + \frac{\left(\frac{dN}{dh}\right)}{157}\right]^{-1} \quad \text{……………………..…. (10)}$$

Near the earth's surface, $\frac{dN}{dh}$ is about -39 N-units/km which gives an effective earth radius factor, when $k = \frac{4}{3}$. This is known as standard atmosphere or normal refraction. Here, radio waves often leave the earth's surface in a straight line and flow unhindered into space. If $\frac{4}{3} > k > 0$. There is sub-refraction, which suggests that radio waves travel unusually far from the earth's surface.

When $\infty > k > \frac{4}{3}$ In this scenario, radio waves propagate abnormally near the earth's surface due to super-refraction, extending the radio horizon. Consequently, If $-\infty < k < 0$ waves exhibit ducting when their downward curvature exceeds the curvature of the earth.

4. RESULTS AND DISCUSSION

4.1. Variation of Radio Refractivity with Climatic Parameters and Radio Refractive Index for Maiduguri

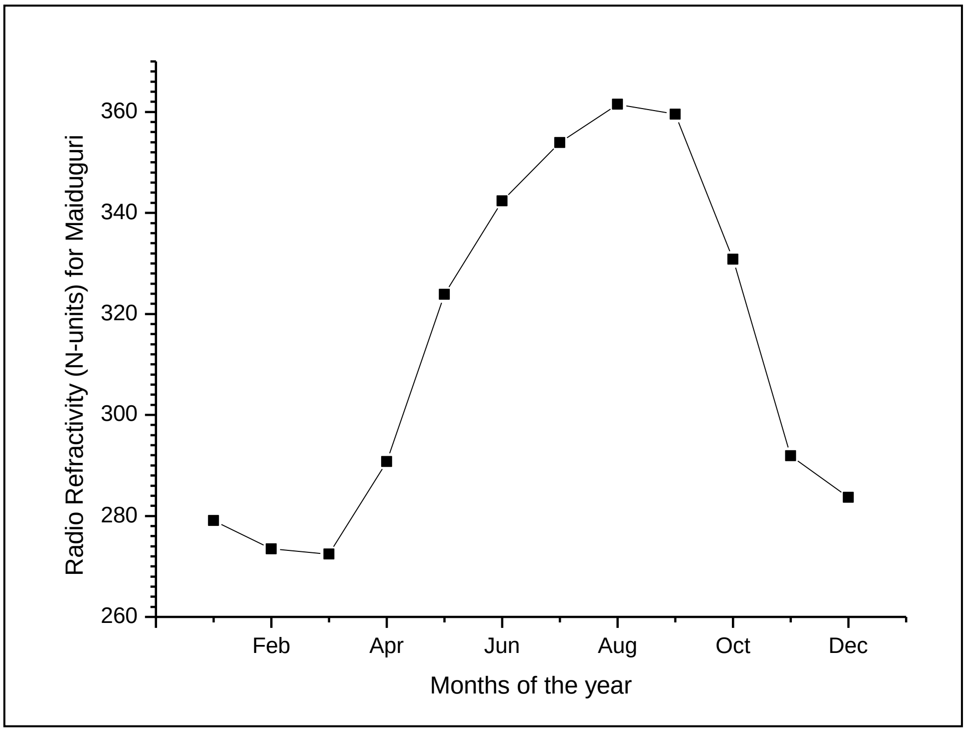

Figure 2: Seasonal Radio Refractivity Variation over Maiduguri

Figure 2 shows the seasonal variation in radio refractivity for Maiduguri over a 42-years period. Radio refractivity in Maiduguri, Borno State, Nigeria, varies with the month. It decreases gradually in January to a minimum of 272.4506 N-units in March, then abruptly in March to a peak of 361.4837 N-units in August. From August to September, it maintains an almost closed value, and in December, it drops to 283.6835 N-units. The figure did, however, clearly demonstrate that the radio refractivity value steadily decreases as the dry harmattan season begins in November and continues until March, when the minimum value is recorded. Radio refractivity observations for Maiduguri show a maximum average value of 361.4837 N-units in August, during the rainy season, and a lowest value of 272.4506 N-units in March, during the dry season. According to the results, refractivity was highest during the rainy season (average value: 337.5357 N-units) and lowest (average value: 280.1095 N-units) during the dry season. This observation is consistent with the research conducted by Akpootu and Iliyasu [33]; Emmanuel *et al*., [34].

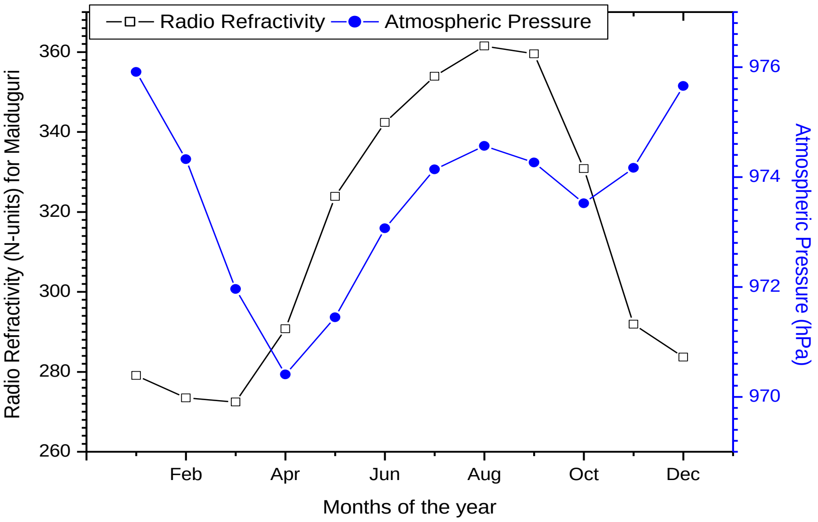

Figure 3: Seasonal Variation of Radio Refractivity with Atmospheric Pressure over Maiduguri

The seasonal variations in radio refractivity over Maiduguri during the study period are depicted in Figure 3. The atmospheric pressure decreases sharply from its maximum value of 975.9095 hPa in January to its lowest value of 970.4071 hPa in April. On the other hand, radio refractivity decreases gradually from January to its minimum value of 272.4506 N-units in March, then abruptly increases from March to reach its peak value of 361.4837 N-units in August, which maintains an almost closed value from August to September, and finally drops to 283.6835 N-units in December. The graph makes it evident that atmospheric pressure rises from April through August before abruptly dropping to October and then rising again until December, when it achieves a value of 975.6524 hPa. The figure shows that from January to March, when radio refractivity declines, atmospheric pressure likewise gradually drops from January to April. Additionally, it shows how radio refractivity drops from August to December. In a similar vein, atmospheric pressure drops in August, increases in October, and rises in December. Radio refractivity observations for Maiduguri show a maximum average value of 361.4837 N-units in August, during the rainy season, and a lowest value of 272.4506 N-units in March, during the dry season. Nonetheless, during the dry season, the maximum average atmospheric pressure value recorded is 975.9095 hPa in January, while during the rainy season, the lowest value is 970.4071 hPa in April. The findings showed that radio refractivity values were lowest during the dry season (average value of 280.1095) and highest during the rainy season (average value of 337.5357 N-units). The average atmospheric pressure during the dry season was 974.4019 hPa, the highest number recorded, while the average during the rainy season was 973.0571 hPa.

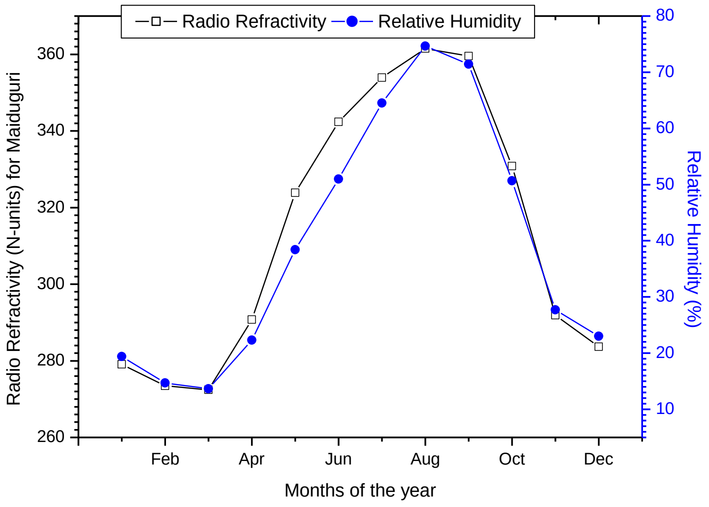

Figure 4: Seasonal Variation of Radio Refractivity with Relative Humidity over Maiduguri

Figure 4 shows the seasonal variation in Maiduguri's radio refractivity with relative humidity. The figure clearly demonstrated how the relative humidity and radio refractivity decreased from January to March, when they reached their lowest values of 13.6357 % and 272.4506 N-units, respectively. After reaching its highest value of 74.6650% in the month of August, the relative humidity then rises from its lowest point in March until December, when it falls sharply to a value of 23.1888 %. But starting in March, the radio refractivity likewise rises. It peaks in August at 361.4837 N-units, and then it nearly stays at that level through September before abruptly falling to 283.6835 N-units in December. According to the figure, radio refractivity appears to be directly correlated with relative humidity, as demonstrated by the way it varies with humidity in each month over the course of the study. Additionally, the figure demonstrated that the radio refractivity and relative humidity values steadily decreased until March, when the minimum values were recorded, since the dry harmattan season began in November. The study's findings showed that, as would be expected given that relative humidity is a measure of the amount of water in the atmosphere, it was highest during the rainy season (average value: 53.2934 %) and lowest during the dry season (average value: 19.6934 %) for the study area under consideration. Similarly, radio refractivity values, with average values of 337.5357 N-units and 280.1095 N-units, respectively, occurred during these seasons. It was noted that the radio refractivity's minimum average value during the rainy season, in August, is 361.4837 N-units, while during the dry season, in March, it is 272.4506 N-units. On the other hand, the highest relative humidity was recorded in August, the rainy season, with an average value of 74.6650 %, and the lowest relative humidity was recorded in March, the dry season, with an average value of 13.6357 %. According to the figure, radio refractivity and relative humidity reached their highest points in August during the rainy season and their lowest points in March during the dry season. This finding is consistent with research reported by Akpootu and Iliyasu [33]; Emmanuel *et al.*, [34].

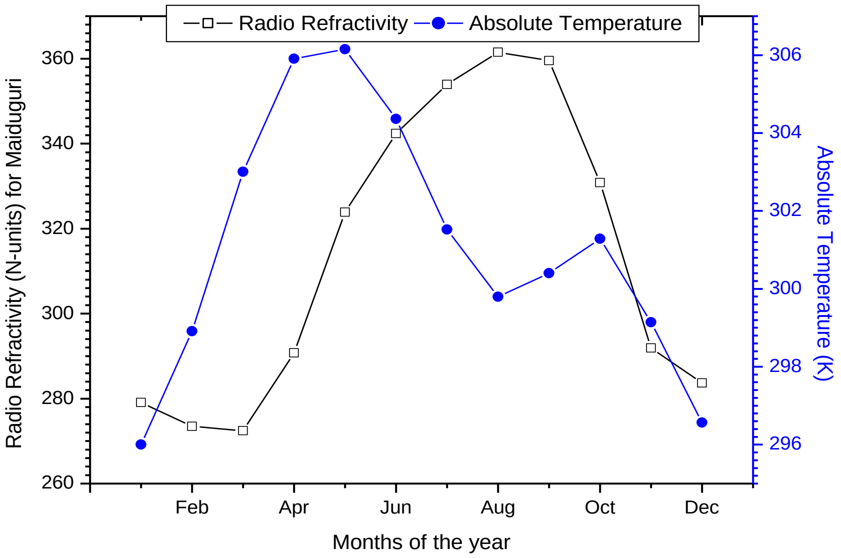

Figure 5: Seasonal Variation of Radio Refractivity with Absolute Temperature over Maiduguri

The seasonal differences in radio refractivity for Maiduguri are shown in Figure 5 together with the absolute temperature (Kelvin). The temperature rises sharply from its lowest point in January, 295.9990 K, to its highest point in May, 306.1536 K, and then abruptly drops to August. On the other hand, radio refractivity increases in March and reaches its maximum value of 361.4837 N-units in August. It then maintains this closed value from August to September before abruptly decreasing to 283.6835 N-units in December. The radio refractivity decreases gradually from January to its minimum value of 272.4506 N-units in March. In addition, the temperature rises in August, September, and October before progressively falling to 296.5695 K in December. The figure indicates that the radio refractivity values were recorded in the months of March and August, respectively, but the absolute temperature values were recorded in January and May, respectively. According to the findings, radio refractivity in Maiduguri was measured at a maximum average of 361.4837 N-units in August during the rainy season and at a low of 272.4506 N-units in March during the dry season. On the other hand, the highest recorded absolute temperature—306.1536 K—occurred in May during the rainy season, while the lowest recorded temperature—295.9990 K—occurred in January during the dry season. According to the study, the average value throughout the rainy and dry seasons was found to be 302.7759 K and 298.7256 K, respectively. Due to a high concentration of dust and aerosols suspended in the atmosphere, which tends to restrict the amount of solar radiation that reaches the region and the Sahelian region as a whole, low temperatures are seen during the dry season. These results are consistent with the research conducted by Akpootu and Iliyasu [35]; Akpootu *et al*., [36, 37].

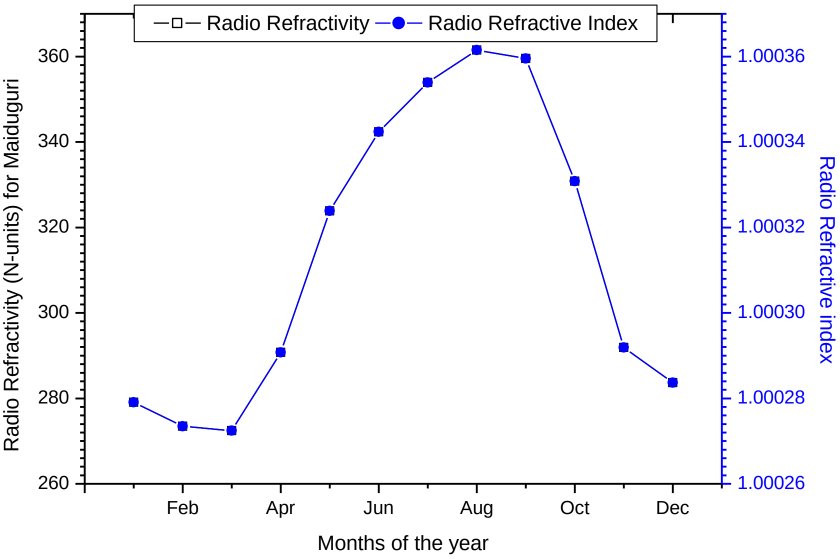

Figure 6: Seasonal Variation of Radio Refractivity with Radio Refractive Index over Maiduguri

The seasonal change of radio refractivity with radio refractive index for Maiduguri is shown in Figure 6. The outcome showed that there is a comparable pattern of fluctuation between the radio refractive index and radio refractivity values. The radio refractive index's maximum average value, recorded during the rainy season from July to September, was 1.0004. The lowest value, recorded during the dry season from January to March and November to December, was 1.0003, and during the rainy season, the same value was recorded in April, June, and October. Additionally, it was discovered that, during the rainy and dry seasons, respectively, the maximum and lowest average values of radio refractivity were 361.4837 N-units and 272.4506 N-units in the months of August and March. Nonetheless, the average value of the radio refractive index is the same in the rainy and dry seasons, at 1.003. Conversely, radio refractivity averages for the rainy and dry seasons are 337.5357 N-units and 280.1095 N-units, respectively.

4.1.2. Variation of Dry and Wet term Radio Refractivity for Maiduguri

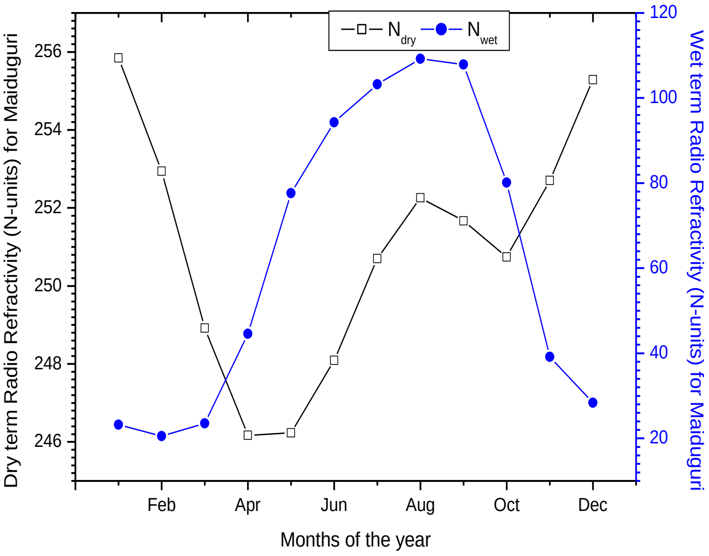

Figure 7: Seasonal Variation of Dry and Wet terms Radio Refractivity over Maiduguri

The seasonal change of wet term radio refractivity (N_{wet}) and dry term radio refractivity (N_{dry}) over Maiduguri is shown in Figure 7. The dry term radio refractivity (N_{dry}), as depicted in the figure, appears to decline gradually from its peak value of 255.8474 N-units in January to the minimum value of 246.1662 N-units in April. It then increases somewhat from April to May before increasing even more dramatically until August. In the dry period, radio refractivity also drops from August to October before rising rapidly to 255.2879 N-units in December. It is evident from the figure that the maximum values of 255.8474 N-units in January and 255.2979 N-units in December obtained for the dry term radio refractivity were observed during the dry season and the minimum values of 246.1662 N-units in April and 246.2305 N-units in May were found within the rainy season. The wet term radio refractivity slightly decreases from January to its minimum value of 20.5122 N-units in the month of February, and then also slightly increases from February to March, and finally suddenly increases and reaches its maximum value of 109.2258 N-units in August. The wet term radio refractivity decreases slightly from September to the month of December, and then increases from March to December. However, the rainy season was recorded for the wet term radio refractivity maximum value of 109.2258 N-units in August, whereas the dry season was observed for the minimum value of 20.5122 N-units in February. In addition, based on the study's results, it is clear that the dry term's radio refractivity contributes significantly to its overall value, while the wet term's radio refractivity, which exhibits a similar variation pattern, contributes primarily to its major variations.

4.1.3. Percentage Contribution of Dry and Wet term Radio Refractivity for Maiduguri

Table 1: Monthly Variation of the Percentage Contribution of N_{dry} and N_{wet} for Maiduguri

Month	N_{dry}-N_{wet}	$\%CN_{dry}$	$\%CN_{wet}$
Jan	232.6178	6.7985	0.6173
Feb	232.4311	6.7213	0.5451
Mar	225.3909	6.6144	0.6252
Apr	201.5751	6.5412	1.1849
May	168.6215	6.5429	2.0623
Jun	153.8282	6.5924	2.5048
Jul	147.4757	6.6618	2.7430
Aug	143.0320	6.7031	2.9024
Sep	143.8076	6.6875	2.8662
Oct	170.6357	6.6629	2.1286
Nov	213.5282	6.7150	1.0410
Dec	226.8924	6.7836	0.7545
Total		**80.0247**	**19.9753**

The percentage monthly variation contribution of the dry term and wet term radio refractivity to the overall radio refractivity is displayed in Table 1. Wet term radio refractivity has 19.9735%, while dry term radio refractivity has 80.0247 %, making up the majority of the overall radio refractivity for Maiduguri, Borno state, Nigeria, during the study period. Additionally, it was noted that the month of January had the highest monthly contribution of the dry term (6.7985%), while the month of April had the lowest (6.5412%). Similarly, for the wet term, the month of August has the highest monthly contribution (2.9024%), while the month of February has the lowest contribution (0.5451%).

4.1.4. Refractivity Gradient for Maiduguri

Equation (9) was used to estimate the refractivity gradient, and the result for Maiduguri was −42.3746 N-units/km. This suggests that the electromagnetic waves are bent downward towards the earth in the Maiduguri propagation, which is mostly super-refractive. The strength of the super-refractive state determines the level at which the bending happened. The wave path's curve gets closer to the earth's radius of curvature as the refractivity gradient continues to drop. When the bending of a radio wave's trajectory towards the ground is more than it would be in a typical positive refraction scenario, super refraction occurs.

4.1.5. Effective Earth Radius for Maiduguri

Equation (10) yielded the effective earth radius, or k - factor, of 1.3697. This suggests that super refractive propagation is predominant in Maiduguri. Meteorological factors such as temperature inversion, or a drop in the air's overall moisture content, can lead to a fall in the dielectric constant gradient with height and consequently, super refraction. When this occurs, the k-factor rises, thus flattening the corresponding curvature of the earth. Warm air passing over a cool body of water is a common scenario that might result in this type of irregular refraction. Water evaporation can raise the moisture content and lower the surface temperature, which can lead to a rise in temperature inversion. However, the aberrant bending of the microwave beam is not primarily caused by the temperature inversion. This effect is continuously increased approaching the surface due to the significant increase in the dielectric constant and water vapour content.

4.2.1. Variation of Radio Refractivity with Climatic Parameters and Radio Refractive Index for Sokoto

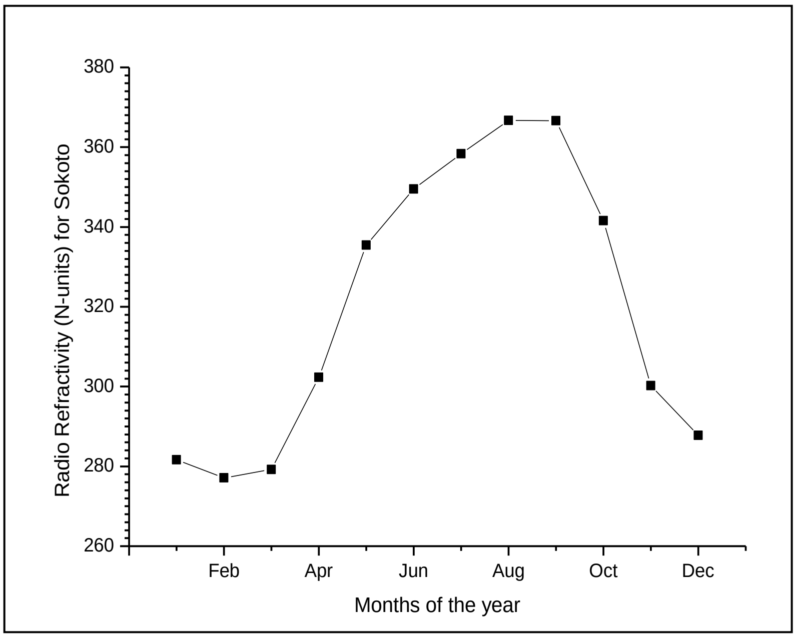

Figure 8: Seasonal Radio Refractivity Variation over Sokoto

Figure 8 displays the seasonal variation in radio refractivity for the study area and time period under examination. From January to February, the radio refractivity drops to its lowest value of 277.1162 N-units. From February to March, it increases slightly before continuing to rise gradually until it reaches the maximum value of 366.7093 N-units in August. From August to September, it stays relatively constant, but in December, it abruptly drops to 287.7585 N-units. The figure does, however, highlight how the radio refractivity value gradually decreases when the dry season arrives around November, reaching its lowest position in February. The findings indicated that radio refractivity averaged 345.8014 N-units during the rainy season, which was higher than that compared to 285.1835 N-units during the dry season. Additionally, the figure makes it evident that the lowest recorded value of radio refractivity for Sokoto was 277.1162 N-units in February during the dry season, and the highest recorded value was 366.7093 N-units in August during the rainy season. This observation aligns with the research conducted by Akpootu and Iliyasu [33]; Emmanuel *et al*., [34].

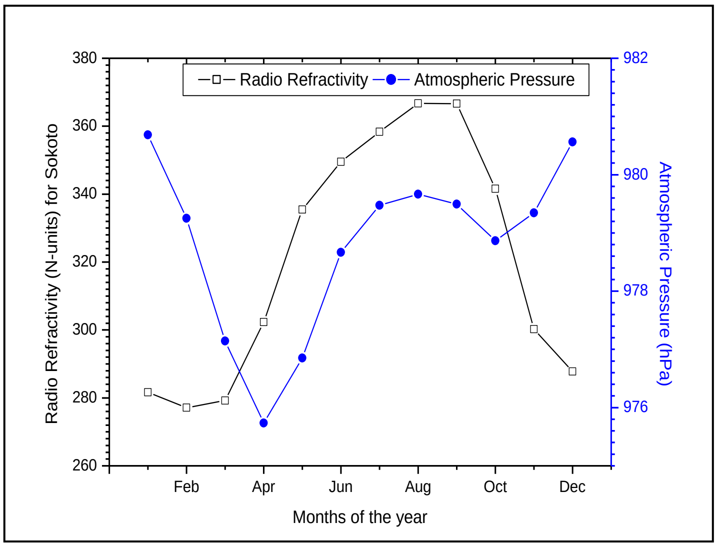

Figure 9: Seasonal Variation of Radio Refractivity with Atmospheric Pressure over Sokoto

Figure 9 shows the seasonal variation in radio refractivity with atmospheric pressure over Sokoto for the studied area and examined time period. From its highest point of 980.6857 hPa in January to its lowest point of 975.7333 hPa in April, the atmospheric pressure progressively drops. Additionally, radio refractivity decreases in January to a minimum of 277.1162 N-units in February, then increases slightly in February and March before gradually increasing again and reaching its peak value of 366.7093 N-units in August. It then maintains a nearly constant value in August through September before gradually declining to 287.7585 N-units in December. Nevertheless, atmospheric pressure rises more from April through August, then falls until October, when it rises once more until December, when it reaches 980.5643 hPa. The result clearly demonstrated that the radio refractivity value fell sharply and steadily until February, when the lowest value was recorded, as the dry harmattan season began in November. It also shows that the dry season's peak atmospheric pressure values, 980.6857 hPa and 980.5643 hPa, were recorded in January and December, respectively. In Sokoto, the maximum average value of radio refractivity observed during the rainy season is 366.7094 N-units in August, and the lowest value is 277.1162 N-units in February, which falls within the dry season. Similarly, the maximum average value of atmospheric pressure observed during the dry season is 980.6857 hPa in January, and the lowest value is 975.7333 hPa in April. The findings showed that radio refractivity has a low average value of 285.1835 N-units during the dry season and a high average of 345.8014 N-units during the rainy season. Furthermore the high value of atmospheric pressure were found during dry season with an average value of 979.3976 hPa and the low value within rainy season with an average value of 978.3932 hPa.

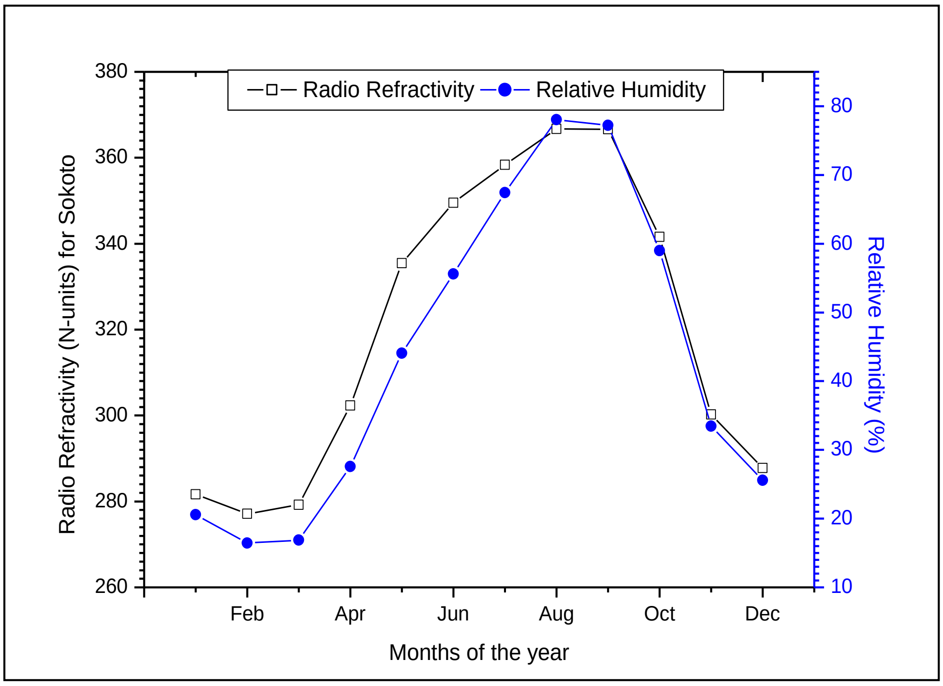

Figure 10: Seasonal Variation of Radio Refractivity with Relative Humidity over Sokoto

The seasonal change of radio refractivity over Sokoto with relative humidity is shown in Figure 10. Relative humidity and radio refractivity exhibit similar patterns of variation. The figure shows that radio refractivity decreases in January to its lowest value of 277.1162 N-units in February, then increases slightly in February and March before continuing to increase gradually until it reaches its peak value of 366.7093 N-units in August. It then maintains nearly constant values in August and September before abruptly declining to December. Comparably, relative humidity falls off gradually in January and reaches its lowest point of 16.4236 % in February. It then rises slightly in February and March before abruptly increasing again in April and reaching its highest point of 78.0521 % in August. It then maintains a closed value in August through September before abruptly falling to December. It also highlights the fact that, starting in November and continuing through February when the minimum values are recorded, there is a consistent decline in both radio refractivity and relative humidity readings as the dry harmattan season approaches. According to the results, radio refractivity values were recorded during the rainy and dry seasons, with an average of 345.8014 N-units and 285.1835 N-units, respectively. The value of relative humidity was high during the rainy season, with an average value of 58.4162 %, and low during the dry season, with an average value of 22.5725%. On the other hand, the radio refractivity maximum average value of 366.7093 N-units in August was found to be during the rainy season, while the lowest value of 277.1162 N-units in February was found to be during the dry season. With an average value of 78.0521% during the rainy season in August, the highest relative humidity was recorded, and with an average value of 16.4236% during the dry season in February, the lowest relative humidity was recorded. The figure makes it evident that relative humidity and radio refractivity have a direct relationship with one another, with the highest values occurring in the rainy season in August and the lowest values occurring in the dry season in February. This observation is consistent with the research that Akpootu and Iliyasu [33]; Emmanuel *et al*., [34] presented.

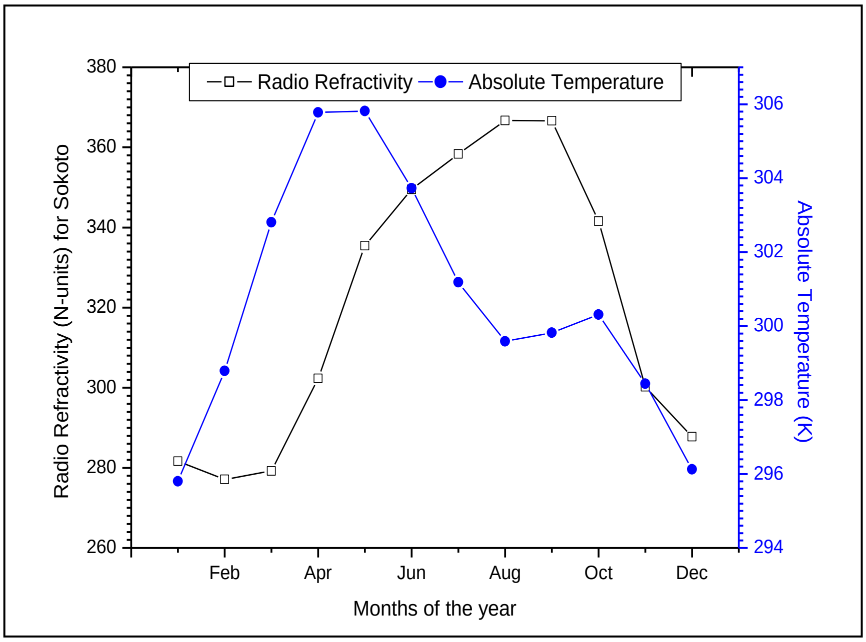

Figure 11: Seasonal Variation of Radio Refractivity with Absolute Temperature over Sokoto

Figure 11 shows the seasonal variation of radio refractivity over Sokoto with absolute temperature. From its lowest value of 295.8005 K in January to its highest value of 305.7774 K in April and nearly constant value till reaching its maximum value of 305.8148 K in May, the absolute temperature rises dramatically before abruptly falling to August. In addition, the absolute temperature rises from August through October before dropping precipitously to a low of 296.1248 K in December. In contrast, the radio refractivity falls from January to its lowest value of 277.1162 N-units in February, then rises slightly until it reaches its highest value of 366.7093 N-units in August. It then stays relatively constant from August through September before abruptly falling to 287.7585 N-units in December. The graphic illustrates that April and May saw the highest absolute temperature readings, while December and January saw the lowest values. However, February had the lowest radio refractivity value, while August and September had the highest values. Additionally, it shows that the radio refractivity and absolute temperature readings steadily decline when the dry season arrives by November, reaching their lowest points in February and January, respectively. The findings showed that radio refractivity has a low average value of 285.1835 N-units during the dry season and a high average of 345.8014 N-units during the rainy season. Additionally, the average absolute temperature was determined to be lowest during the dry season (298.3923 K) and to be highest during the rainy season (302.3188 K). The decrease in temperature values during the dry season is as a result of dust particles which tends to block the incoming solar radiation thereby reducing the temperature; this is in line with the study reported by Akpootu and Iliyasu [35]; Akpootu *et al*., [36, 37]. The graph makes it quite evident that the lowest recorded value of radio refractivity for Sokoto during the dry season is 277.1162 N-units in February, and the highest recorded value is 366.7093 N-units in August during the rainy season. However, during the rainy season in May, the highest average absolute temperature recorded for Sokoto was 305.8148 K, while during the dry season in January, the lowest number recorded was 295.8005 K.

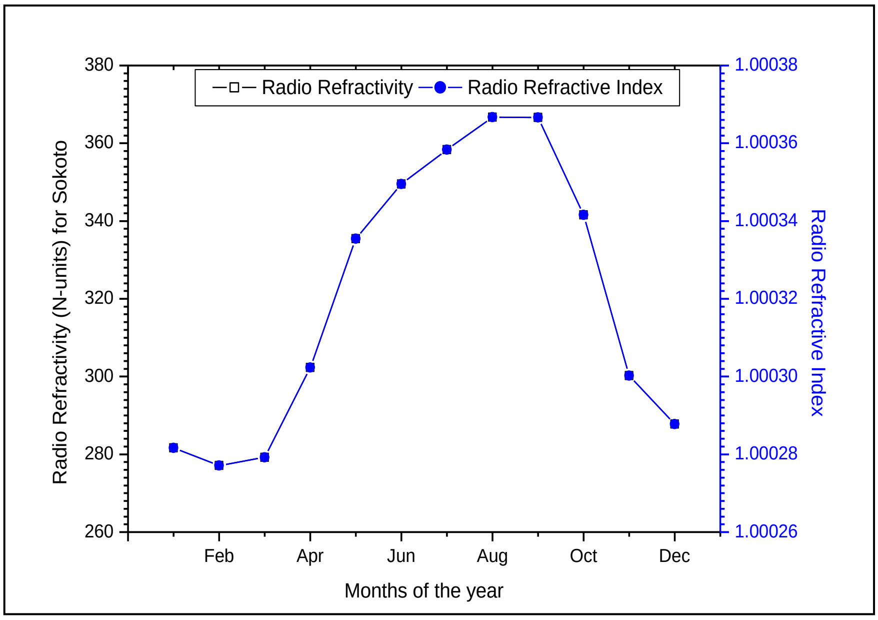

Figure 12: Seasonal Variation of Radio Refractivity with Radio Refractive Index over Sokoto

The seasonal change of radio refractivity with radio refractive index for Sokoto is shown in Figure 12. The outcome indicates that there is a comparable pattern of fluctuation between the radio refractive index and radio refractivity values. On the other hand, the lowest value of 1.0003 was found from January to June and October to December, where from January to March and November to December are within the dry season, and from April to June and October occurred in the rainy season. The highest average value of the radio refractive index, however, was observed during the months of July to September during the rainy season. Additionally, it was discovered that, during the rainy and dry seasons, respectively, the maximum and lowest average values of radio refractivity were 366.7093 N-units and 277.1162 N-units in the months of August and February. According to the figure, the average radio refractive index value during the rainy and dry seasons is roughly similar, at 1.0003. Conversely, the mean radio refractivity measured in the rainy season is 345.8015 N-units, but the dry season yields 285.1835 N-units.

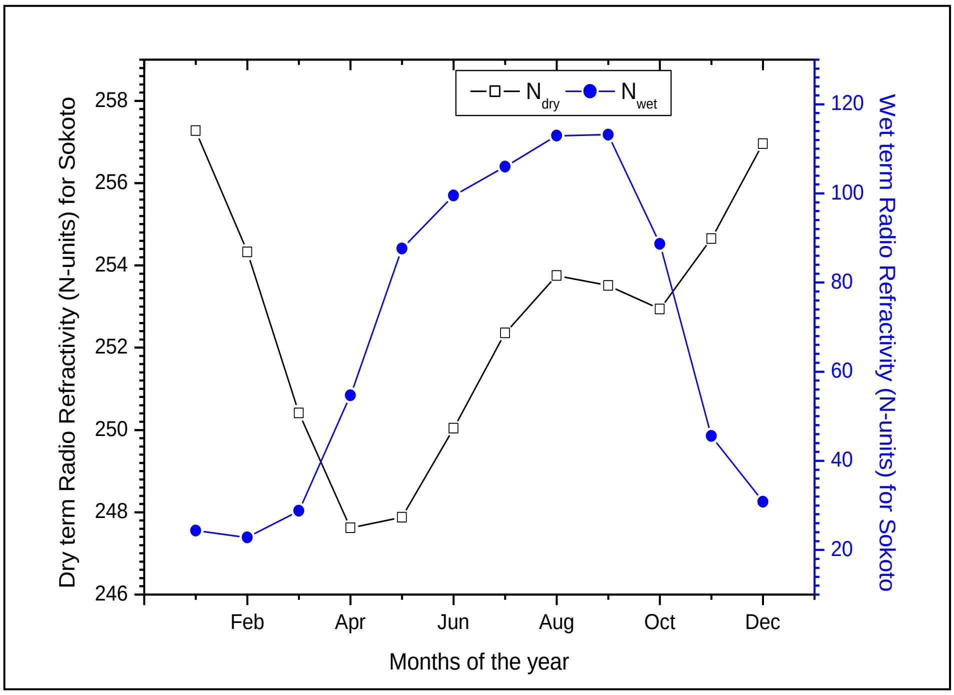

Figure 13: Seasonal Variation of Dry and Wet terms Radio Refractivity over Sokoto

The seasonal change of wet term radio refractivity (N_{wet}) and dry term radio refractivity (N_{dry}) is shown in Figure 13. The figure clearly illustrates how the dry term radio refractivity (N_{dry}) abruptly drops from its highest value of 257.2721 N-units in January to its lowest value of 247.6210 N-units in April. From April to May, it increases slightly before increasing progressively until August. In addition, the dry term radio refractivity decreases from August to October before rising significantly and reaching a new high of 256.9585 N-units in December. The wet term radio refractivity decreases slightly in January to reach its lowest value of 22.7881 N-units in February. It then increases slightly in February and March before gradually rising to a high value of 112.9558 N-units in August. From there, it slightly increases to reach its maximum value of 113.1339 N-units in September before beginning to decline to a new minimum value in December. The figure did, however, show that the dry term radio refractivity maximum value of 257.2721 N-units in January and 256.9585 N-units in December were acquired during the dry season, whereas the rainy season produced the lowest value of 247.6210 N-units in April. The rainy season had the wet term radio refractivity high values of 112.9558 N-units in August and 113.1339 N-units in September, while the dry season saw the lowest value of 22.7881 N-units in February. The outcome showed that while the wet term of radio refractivity contributes to the major variation of the radio refractivity because it follows the same pattern of variation as the radio refractivity, the dry term of radio refractivity is a big contributor to the total value of the refractivity.

4.2.3. Percentage Contribution of Dry and Wet Term Radio Refractivity for Sokoto

Table 2: Monthly Variation of the Percentage Contribution of N_{dry} and N_{wet} for Sokoto

Month	N_{dry}-N_{wet}	%CN_{dry}	%CN_{wet}
Jan	232.9121	6.6884	0.6333
Feb	231.5401	6.6119	0.5924
Mar	221.6121	6.5101	0.7487
Apr	192.9277	6.4375	1.4219
May	160.2895	6.4441	2.2770
Jun	150.5453	6.5005	2.5867
Jul	146.3785	6.5607	2.7552
Aug	140.7977	6.5969	2.9366
Sep	140.3788	6.5907	2.9412
Oct	164.2704	6.5757	2.3051
Nov	209.0908	6.6202	1.1843
Dec	226.1586	6.6803	0.8007
Total		**78.8169**	**21.1831**

Table 2 shows the monthly change in the percentage contribution to the overall radio refractivity for both the wet and dry terms. For Sokoto, Nigeria, it was found that during the examination period, the wet term radio refractivity had a value of 21.1831 %, while the dry term radio refractivity had a significant contribution of 78.8169 % to the total radio refractivity. The data indicated unequivocally that the dry term's monthly maximum contribution occurs in January (6.6884%) and the wet term's monthly minimum occurs in April (6.4375 %), while September (2.9412 %) and February (0.5924 %) represent the wet term's maximum and minimum monthly contributions, respectively.

4.2.4. Refractivity Gradient for Sokoto

Equation (9) was used to calculate the refractivity gradient, and the resulting value for Sokoto is -42.3928 N-units/km. This demonstrated that Sokoto's propagation is mostly super-refractive, meaning that electromagnetic waves are bent downward in the direction of the earth. The super-refractive condition's strength determines the level at which the bending happened. The earth's radius of curvature is getting closer to the wave path's curve as the refractivity gradient continues to drop. When the trajectory of a radio wave propagates towards the earth and bends more than it would in a typical positive refraction scenario, this phenomenon is known as super refraction.

4.2.5. Effective Earth Radius for Sokoto

Equation (10) was used to determine the effective earth radius, or k factor, of 1.3698. This suggests that the majority of the propagation in Sokoto is super refractive. Meteorological conditions that promote super refraction include temperature inversions, which occur when there is a rise in temperature with height, and decreases in the overall moisture content of the air. These variables can also reduce the dielectric constant gradient as height increases. The k-factor rises in this situation, thus flattening the corresponding earth's curvature. A common situation that could result in this type of anomalous refraction is the movement of warm air over a cool body of water. As a result of the water evaporating, the temperature near the surface drops and the moisture content rises, leading to a temperature inversion. However, the aberrant bending of the microwave beam is not primarily caused by the temperature inversion. This effect is continuously increased approaching the surface due to the significant increase in the dielectric constant and water vapour content.

Table 3: Comparison of Average values of Radio Refractivity for Maiduguri and Sokoto

Average Values	Maiduguri	Sokoto
Rainy	337.5357 N-units	345.8014 N-units
Dry	280.1095 N-units	285.1835 N-units
Maximum	361.4837 N-units	366.7093 N-units
Minimum	272.4506 N-units	277.1162 N-units

Table 3 compares the maximum and minimum values for Maiduguri and Sokoto, as well as the average radio refractivity values during the rainy and dry seasons. According to the results, Sokoto has greater average radio refractivity values during the rainy and dry seasons than Maiduguri. Similarly, Maiduguri's radio refractivity was lower than Sokoto's, with a minimum average value of 4.6656 N-units and a maximum average value of 5.2256 N-units.

Table 4: Comparison of Refractivity Gradient and k-factor for Maiduguri and Sokoto

Average Values	Maiduguri	Sokoto
Refractivity gradient	- 42.3746 N-units/km	- 42.3928 N-units/km
k-factor	1.36968	1.3698

Table 4 shows the refractivity gradient and k-factor comparison between Maiduguri and Sokoto. According to the computation, Sokoto has a greater k-factor than Maiduguri, although Maiduguri has a stronger refractivity gradient. Nonetheless, both locations show that super-refractive propagation is mostly found in Nigeria's Sahel savannah region.

Table 5: Comparison of Dry and Wet term Radio Refractivity for Maiduguri and Sokoto

Average Values	Maiduguri	Sokoto
Dry term	80.0247 %	78.8169 %
Wet term	19.9753 %	21.1831 %

Table 5 compares the radio refractivity of the dry and wet terms for Maiduguri and Sokoto. Sokoto's wet term radio refractivity is greater than Maiduguri's, whereas Maiduguri's dry term radio refractivity is greater with 1.2078%. From both sites, it is evident that the dry term primarily contributes to the total tropospheric radio refractivity, whereas the wet term adds to the radio refractivity variation pattern.

5. CONCLUSION

Using measured monthly meteorological parameters of temperature, relative humidity, and atmospheric pressure from the National Aeronautic and Space Administration (NASA), the tropospheric radio refractivity was estimated and investigated along with other relevant parameters for two locations in Nigeria's Sahel savannah climatic zone: Maiduguri (Latitude 11.85°N, Longitude 13.08°E) and Sokoto (Latitude 13.02°N, Longitude 5.25°E). Over a 42-years period (1981 to 2022), the locations' tropospheric radio refractivity was assessed using the recommended approach by the International Telecommunication Union (ITU). Radio refractivity was found to have the highest values in Maiduguri during the rainy season (337.5357 N-units and 345.8014 N-units on average) and the lowest values in Sokoto during the dry season (280.1095 N-units and 285.1835 N-units respectively). The highest and lowest average radio refractivity values for Maiduguri and Sokoto for the rainy and dry seasons, respectively, were 361.4837 N-units and 366.7093 N-units in August and 272.4506 N-units in March and 277.1162 N-units in February. It was found that throughout the course of the investigation, the dry term radio refractivity was a major contributor to the total radio refractivity with 80.0247% and 78.8169 %, while the wet term radio refractivity contributed to the major variations of the radio refractivity with 19.9753% and 21.1831% for Maiduguri and Sokoto, respectively. The average refractivity gradients in the studied locations were found to be -42.3746 and -42.3928 N-units/km. Furthermore, it was discovered that Maiduguri and Sokoto had average effective earth radiuses (k-factors) of 1.3697 and 1.3698, respectively. These values are consistent with the super refraction propagation circumstances found in Nigeria's Sahel savannah climatic zone. If appropriately used, the study's findings will be crucial for any research involving terrestrial atmospheric electromagnetic transmission, including mobile communication, terrestrial radio and television broadcasting, and point-to-point microwave communication.

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