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INVESTIGATION OF TROPOSPHERIC RADIO REFRACTIVITY AND OTHER RELEVANT PARAMETERS USING METEOROLOGICAL VARIABLES OVER BAUCHI, NIGERIA

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ABSTRACT

The National Aeronautics and Space Administration (NASA) archives were used in this work to obtain the measured monthly average daily temperature, relative humidity, and atmospheric pressure over a 41-years period (1981–2021) for Bauchi (latitude $10.28°N$, longitude $9.81°E$) to calculate the monthly tropospheric radio refractivity. The site is located in Nigeria's midland climate zone. We also looked into the variation with other factors, the refractivity gradient, and the percentage contribution of the dry term (N_{dry}) and wet term (N_{wet}) radio refractivity. The results showed that during the rainy and dry seasons, respectively, the months of August and February had the highest and lowest average values of radio refractivity, measuring 355.032 (N-units) and 273.255 (N-units), respectively. This suggests that radio refractivity is higher during the rainy season than it is during the dry season. The wet term contributes to the significant fluctuation in radio refractivity values, while the dry term makes up 77.60 % of the total value. The average refractivity gradient estimate was found to be – 40.854 N – units/km suggesting super-refraction propagation for Bauchi indicating that electromagnetic waves are often bent downward towards the earth when the super refraction condition occurs.

Keywords: Bauchi, Meteorological parameters, Percentage contribution, Radio refractivity, Refractivity gradient

INTRODUCTION

A medium's refractivity, which is determined by its index of refraction, is a physical feature that affects radio wave propagation and is accountable for a number of occurrences (Jibrin *et al.*, 2021). Building a radio communication network requires careful consideration of the path taken by radio signals as they go from transmitter to reception (Akpootu and Rabiu, 2019). Numerous factors, including changes in climatic parameters like temperature, pressure, and humidity, have an impact on radio wave signal propagation in the troposphere (Okoro and Agbo 2012). A crucial component of this kind of radio propagation model is the troposphere's fluctuating radio refractivity (Okeke *et al.*, 2019). The Earth's and the atmosphere's properties have a significant impact on how radio waves propagate through the atmosphere (Tanko *et al.*, 2018). Along with changing with height, the atmosphere's refractivity will also have an impact on radio signals (Okoro and Agbo 2012). It is noted that radio refractivity varies both spatially and temporally (Tanko *et al.*, 2018).

The troposphere, or lowermost region of the atmosphere that is most directly relevant to human life, is caused by variations in weather-related variables such as temperature, pressure, and relative humidity (Akpootu and Iliyasu, 2017a). The troposphere, which tends to affect radio frequencies over 30 MHz, rises from the earth's surface to an altitude of roughly 10 km at the pole and 17 km at the equator (Hall, 1979). The frequency and power of the broadcast signals, as well as the condition of the troposphere where the signal will pass through, are the primary factors that determine how much the atmosphere affects radio transmissions (Kareem *et al.*, 2018). To evaluate the fluctuations in signal strength that happen at different locations of interest at different times of the year, a radio propagation model must be utilised. A crucial component of this kind of radio propagation model is the troposphere's fluctuating radio refractivity (Akpootu and Iliyasu, 2017a). Because tropospheric qualities in the troposphere cannot be altered due to the usual difficulties of radio wave transmission in this region, it is imperative that we have a sufficient grasp of how radio signals vary the tropospheric condition (Priscilla *et al.*, 2020). Several researchers have carried out studies in relation to investigating the radio refractivity in the troposphere and other pertinent characteristics for different locations around the globe. This include, Tanko *et al.* (2018); Akpootu *et al.* (2019a); Ojo *et al*. (2019), Priscilia *et al*. (2020); Akpootu *et al*. (2021a), Mmahi *et al*. (2022); Akpootu *et al*. (2024) to mention but a few.

Estimating tropospheric radio refractivity and its fluctuation with meteorological conditions for Bauchi is the focus of this work. Also, to investigate the variation of dry and wet term radio refractivity, investigate the variation of radio refractivity with radio refractive index, calculate the proportion contributions of the wet and dry terms to radio refractivity, as well as to calculate the location's refractivity gradient.

MATERIALS AND METHODS

Study Area

Bauchi, situated at latitude 10.28°N and longitude 9.81°E, with an elevation of 609.7 meters, it is situated in the Midland climatic zone of Nigeria (Akpootu *et al*., 2019b). The weather varies significantly throughout the year in a number of different ways. Lower measurements show a variance between 13.9°C (57°F) and 26°C (78.8°F), while higher temperatures vary from 29.6°C (85.3°F) to 39.2°C (102.6°F). Along with the drastic changes in temperature, there are also notable changes in humidity, which ranges from 19% to 78%. Monthly rainfall ranges from 0.0mm in December and January, to about 343mm in July (Odiana and Ibrahim, 2015). Another important aspect of Bauchi's climate, rainfall, fluctuates greatly year-round. In some months, the city receives almost no precipitation at all, but during the rainy season, it receives an abundance of precipitation—up to 169 mm (6.65 inches). In line with this, the number of days in a month that experience rain varies from 0 to 26.4, highlighting the difference between the rainy and dry seasons. The map of Nigeria showing the study location is shown in figure 1.

Figure 1: Map of Nigeria showing the study location

Data Collection and Analysis

The measured monthly meteorological parameters of atmospheric pressure, relative humidity and temperature spanning a period of forty-one (41) years (1981 to 2021) for Bauchi (latitude 10.28°N, longitude 9.81°E and altitude 609.7 m above sea level) were acquired through NASA at 2 m height. The study area is found in the midland climatic zone of Nigeria.

The atmospheric pressure, temperature, and humidity (water vapour content) all affect the refractive index (n) of the atmosphere. Refractive index (n) readings ranged from 1.000250 to 1.0004000, suggesting that there is very little change in this value over time and space and that it is very close to unity at or near the earth's surface. The refractive index (n) of air was determined using a number known as the radio refractivity (N), which is correlated with the refractive index (n), to make them more obvious (ITU-R, 2003; Freeman, 2007).

$$n = 1 + N \times 10^{-6} \quad (1)$$

N-units are used to express the dimensionless quantity known as radio refractivity (N). Consequently, it is simple to infer from equation (1) that N normally falls between 250 and 400 N-units. The International Telecommunication Union (ITU) has suggested that the radio refractivity (N) be stated as follows in terms of measured meteorological parameters (ITU-R, 2003).

$$N = \frac{77.6}{T}\left(P + 4810.0\frac{e}{T}\right) \quad (2)$$

where the dry term's radio refractivity is determined by

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

and the wet term's radio refractivity is determined by

$$N_{wet} = 3.730 \times 10^{5} e T^{-2} \quad (4)$$

where e is the water vapour pressure (hPa), T is the temperature (K), and P is the atmospheric pressure (hPa).

The non-polar nitrogen and oxygen molecules are the cause of the dry term. While the wet term is proportional to vapour pressure and dominated by polar water contents in the troposphere, it is related to air density since it is proportional to pressure (P).

ITU-R (2003) and Freeman (2007), mentioned that the equation as expressed in (2) can be utilised for all radio frequencies; for frequencies up to 100 GHz (Babin *et al.*, 1997). The average value of N≈315 was utilised at sea level, and the inaccuracy is less than 0.5% (ITU-R, 2003).

The formula indicates the link between the relative humidity and the water vapour pressure (e) (ITU-R, 2003; Akpootu *et al*., 2019c; Akpootu *et al*., 2021b,c; Iliyasu *et al*., 2023; Akpootu *et al*., 2023a).

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

The saturation vapour pressure, e_s according to ITU-R (2019) as reported by Akinbolati et al. (2024) is given by

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

In equation (5) and (6), the variables H, t, and e_s represent the relative humidity (%), temperature (°C), and saturation vapour pressure (hPa) at a given temperature (°C).

For this investigation, the values of the coefficients a, b, and c (water and ice) were taken from ITU-R (2003); for water, these values are a = 6.1121, b = 17.502, and c = 240.97, and they are valid with an accuracy of ±0.20% between -20℃ and +50 ℃. These values were also reported in the work of Akinbolati et al. (2024) as to be found in ITU-R (2019). In the troposphere, radio refractivity (N) likewise decreases exponentially with height (ITU-R, 2003).

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

where H is the appropriate scale height and N is the refractivity at the height h (km) above the level where the refractivity is Ns. According to ITU-R (2003), N_s and H are, on average, 315 km and 7.35 km at mid-latitude. Thus, the equation represents N as a function of height N (h);

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

However, according to Agunlejika and Raji (2010), they revealed that for seven (7) of the twelve (12) months of the year, the model produced reasonably accurate results for the refractivity at the altitude of 50 m and 200 m. The model used the scale height of 7.35 km and 7 km, as recommended for the global environment ITU-R (2003) and the tropical environment John (2005), respectively. While a 7.35 km scale height will perform better at 200 m, a 7 km scale height will get a better result at 50 m altitude.

After obtaining the refractivity gradient with respect to h by differentiating equation (7), we were able to derive the refractivity gradient as

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

The refractivity gradient for a standard atmosphere is -39 N-units/km. John (2005) states that the refractivity gradient's value in a standard environment is a good approximation for h values less than 1 km. The refractivity of a standard atmosphere was determined in this study using Ns = 312 N-Units, using the conventional values for a standard atmosphere.

According to Adediji and Ajewole (2008) criteria, the vertical gradient of refractivity in the troposphere is a crucial element in evaluating path clearing and propagation effects like sub-refraction, super-refraction, or ducting.

(i) Sub-refraction: $\frac{dN}{dh} > -40$

The radio waves in this instance (sub-refraction) migrate away from the earth's surface, resulting in a decrease in both the line-of-sight range and the propagation range. Refractivity, N, increases with height.

(ii) Super-refraction: $\frac{dN}{dh} < -40$

Electromagnetic waves are often bent downward towards the earth when the super refraction condition is present. The strength of the super-refractive state determines how much it bends. The rays leaving the transmitting aerial at relatively small angles of elevation will undergo total internal reflection in the troposphere and then return to the earth at a certain distance from the transmitter because the radius of curvature of the ray path is lower than the radius of the earth. The waves can skip a lot of distance when they reach the earth's surface and are reflected back from it, which causes multiple reflections to produce abnormally large ranges beyond the line of sight.

(iii) Ducting: $\frac{dN}{dh} < -157$

Throughout the ducting process, the waves bend downward with a curvature greater than that of the earth. When radio waves are angled downward, they may become trapped between an elevated duct and a troposphere border or layer, or between the troposphere and the surface of the land or ocean. In this wave guide-like propagation, very long ranges (far beyond line-of-sight) can provide very high signal strengths, and the signal intensity can exceed its free-space value.

RESULTS AND DISCUSSION

Radio Refractivity and its variation with other Meteorological Parameters for Bauchi

The seasonal change of Bauchi's radio refractivity is depicted in Figure 2. The radio refractivity in Bauchi decreased in January and reached its lowest value of 273.255 (N-units) in February. From February, it rose steadily until August, when it reached its peak of 355.032 (N-units), and then it progressively decreased to 285.415 (N-units) in December. During the rainy and dry seasons, respectively, the highest average value of radio refractivity recorded was 355.032 (N-units) in August and the lowest average value of 273.255 (N-units) in February. This observation is consistent with Tanko et al. (2019) investigation, which determined Bauchi's radio refractivity's greatest and minimum values to be 361.46 N units and 289.50 N units, respectively. The research period's rainfall patterns in Bauchi can be attributed to the pattern of fluctuation. The findings demonstrated that refractivity had low values during the dry season (average value of 283.657 N-units) and high values (average value of 343.155 N-units) during the rainy season. The high air humidity that causes high water vapour pressure to be detected in most parts of the nation is the cause of the high values seen during the rainy season, which runs from April to October.

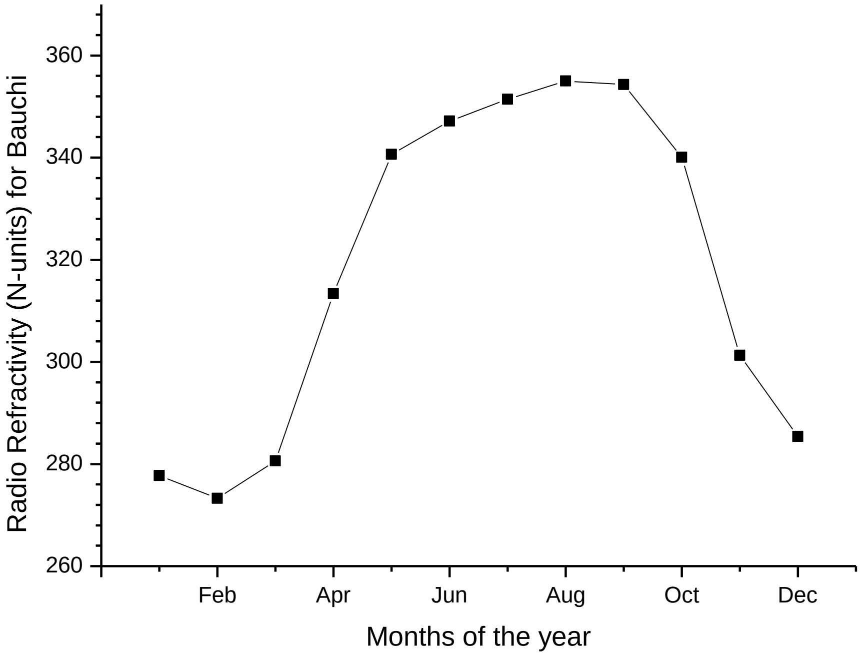

Figure 2: Monthly surface radio refractivity variation over Bauchi

The monthly change of radio refractivity with atmospheric pressure is depicted in Figure 3. From its highest point of 953.400 hPa in January to its lowest point of 949.522 hPa in April, the atmospheric pressure gradually drops. Radio refractivity was shown to rise from April to August in tandem with an increase in atmospheric pressure. Additionally, from August to December, the refractivity steadily falls as the air pressure gradually decreases from August to October then suddenly increases from October to December. Similar to how average values of refractivity are high during the rainy season (average value of 343.155 N-units) and low during the dry season (average value of 283.657 N-units), high values of atmospheric pressure were observed during the dry season (average value of 952.321 hPa) and low values during the rainy season (average value of 952.024 hPa). During the dry and rainy seasons in Bauchi, the maximum and minimum average values of atmospheric pressure were recorded as 953.400 hPa and 949.522 hPa, respectively. These observations occurred in the months of January and April.

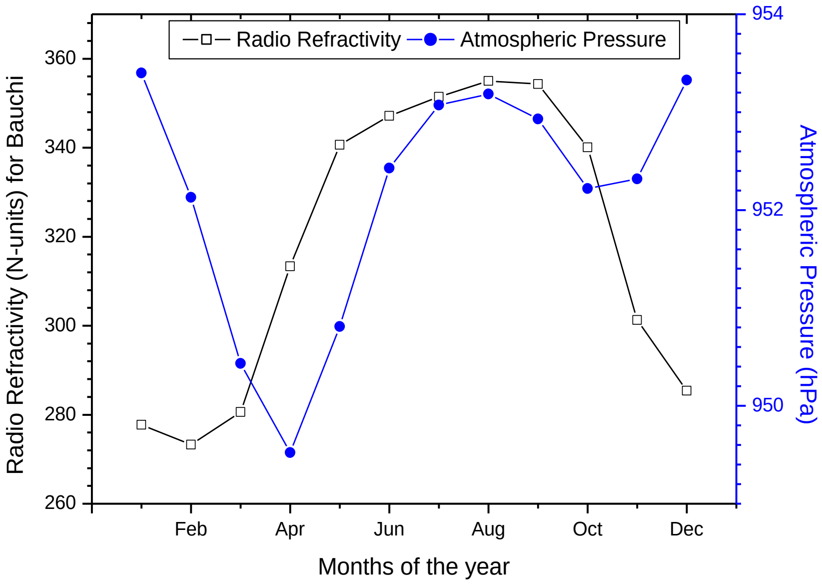

Figure 3: Monthly variation of surface radio refractivity with atmospheric pressure over Bauchi

The monthly change of radio refractivity for Bauchi with relative humidity is seen in Figure 4. The relative humidity and radio refractivity both experience significant drops in January and February, reaching their lowest values of 273.255 (N-units) and 18.853 %, respectively. From February, they steadily rise to their highest values of 81.927 % and 355.032 (N-units), respectively, in August and September, when they nearly stabilise. It was seen that both the radio refractivity and the relative humidity show a slight decline in February; additionally, it was noted that the relative humidity rises in tandem with the radio refractivity from February through August before falling in December. During the dry season, from January to February and October to December, there is a significant drop in both relative humidity and radio refractivity values. This could be because of high solar irradiance, which lowers the humid content of the atmosphere and, in turn, lowers radio refractivity. According to the study, the average value during the rainy and dry seasons was 66.764 % and 27.001 %, respectively. This indicates that the average value is higher during the rainy season and lower during the dry season. During the rainy and dry seasons, the highest and lowest recorded relative humidity readings were 81.927 % in August and 18.853 % in February, respectively. The outcome shown that relative humidity can provide insight into the tropospheric radio refractivity variation pattern in the atmosphere.

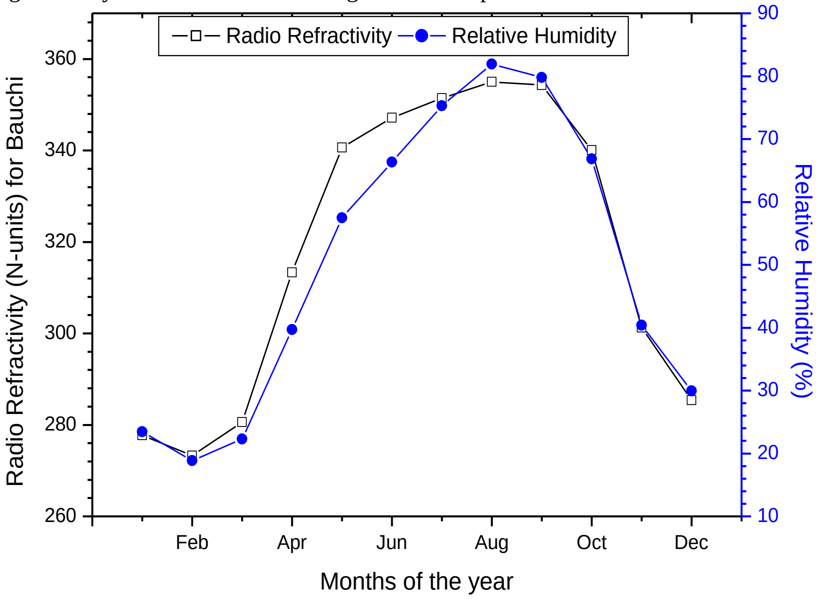

Figure 4: Monthly variation of surface radio refractivity with relative humidity over Bauchi

The monthly change of Bauchi's radio refractivity with temperature (in Kelvin) is seen in Figure 5. The temperature value rises from January through April, when it reaches its highest average value of 303.604 K. It then falls until August, then rises slightly in October and falls again in December. January to February exhibits a slight decrease in radio refractivity, which then rises from February to August before falling again in December. The radio refractivity showed an upward dip with a maximum peak, while the absolute temperature showed a downward dip. Radio refractivity evaluations decrease from August to December, but temperature values rise gradually from August to October and then fall in December. According to the study, the average temperature during the rainy and dry seasons is, respectively, 299.966 K and 297.843 K. The high temperature during the rainy season is caused by dust and aerosol particles suspended in the atmosphere, which lowers both the temperature and the amount of solar radiation reaching Earth. This finding is consistent with the research that Akpootu and Iliyasu (2017b); Akpootu *et al*. (2023b) presented. Due to the high moisture or humidity content in the atmosphere, radio refractivity values are noted to be high during the rainy season and low during the dry season, with 343.155 N-units and 283.657 (N-units), respectively. With an average temperature of 303.604 K for the rainy season, April had the highest temperature recorded, while January had the lowest temperature, with an average of 295.553 K.

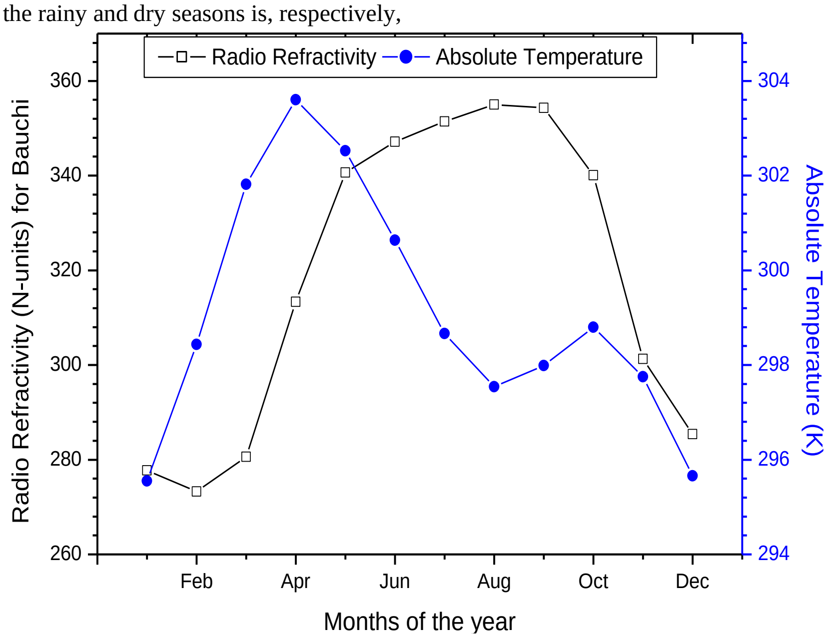

Figure 5: Monthly variation of surface radio refractivity with absolute temperature over Bauchi

Changes in Bauchi's Wet and Dry Term Radio Reactivity

The seasonal change of Bauchi's wet term (N_{wet}) and dry term (N_{dry}) radio refractivity is depicted in Figure 6. The outcome shown that the dry term of radio refractivity significantly adds to the radio refractivity's overall value for Bauchi. The dry term's pattern of variation is nearly identical to the atmospheric pressure pattern seen in figure 3, where the minimum and maximum values were recorded in the corresponding months of January and April. This pattern of variation demonstrates how the air density and atmospheric pressure are related to the radio refractivity's dry term. As a result, figure 2's wet term and radio refractivity show comparable fluctuations. The dry term and wet term have the highest average values in the months of January and August, at 250.323 (N-units) and 106.437 (N-units), respectively, while the lowest average values are found in the months of April and February, at 242.694 (N-units) and 25.679 (N-units), respectively. The findings of this investigation are consistent with those of Tanko et al. (2019), who discovered that the minimum values of dry term and wet term radio refractivity are 26.50 N-units and 256.23 N-units, respectively, and the maximum values are 264.66 N-units and 98.98 N-units. The outcome shows that while the dry term contributes mostly to the overall value of radio refractivity, the wet term of radio refractivity contributes to the major variation pattern of radio refractivity.

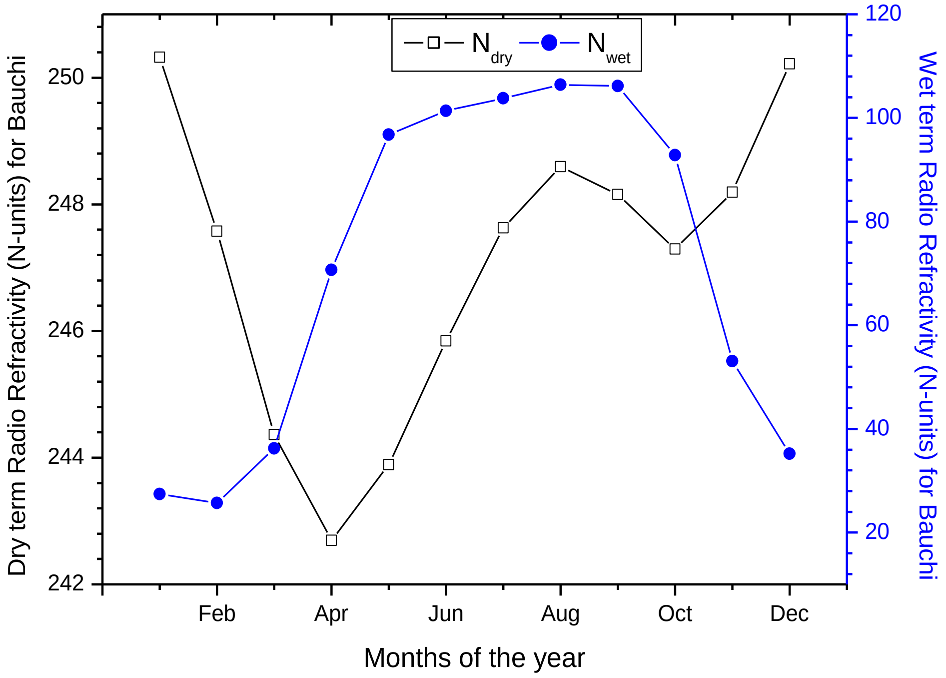

Figure 6: Monthly variation of dry and wet term surface radio refractivity for Bauchi

Changes in Radio Refractive Index and Radio Refractiviy for Bauchi

The seasonal change of Bauchi's radio refractivity with refractive index is shown in Figure 7. The results demonstrated seasonal change in the radio refractive index and values, with high values recorded during the wet season and low values during the dry season. The radio refractive index averages 1.000343 and 1.000283 during the rainy and dry seasons, respectively. In the rainy and dry seasons, the average radio refractivity values are 343.155 (N-units) and 283.657 (N-units), respectively. During the rainy and dry seasons, respectively, the maximum and minimum average values of radio refractivity were found to be 355.032 (N-units) and 273.255 (N-units) in the months of August and February. A similar variation pattern is shown in the illustration.

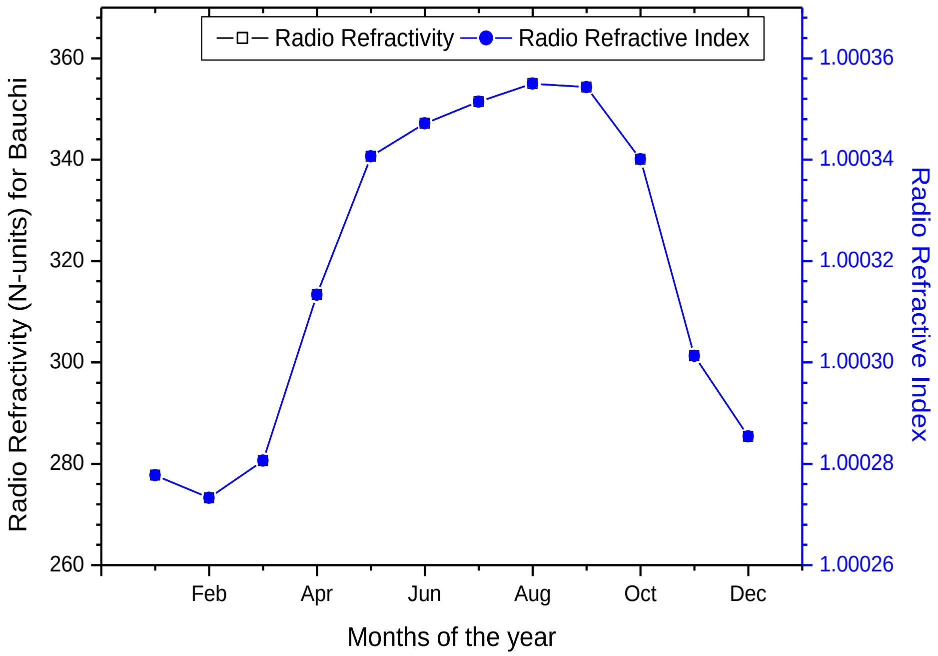

Figure 7: Monthly variation of surface radio refractivity with radio refractive index for Bauchi

Percentage Contribution of Dry term and Wet term Radio Refractivity for Bauchi

The percentage contribution of the dry term ($\%CN_{dry}$) and wet term radio refractivity ($\%CN_{wet}$) to the overall radio refractivity is displayed monthly variation in Table 1. It was found that, for Bauchi during the study period, the wet term radio refractivity had a contribution of 22.40 %, while the dry term radio refractivity contributed 76.60 % to the overall radio refractivity. Research also revealed that the dry term's maximum monthly contribution is 6.55 % in January and December, and the wet term's minimum is 6.35 % in April. Similarly, the wet term radio refractivity's maximum monthly contribution is 2.79 % in August, and the lowest is 0.67 % in February.

Table 1: Monthly variation of the percentage contribution of N_{dry} and N_{wet}

Month	N_{dry}-N_{wet}	$\%CN_{dry}$	$\%CN_{wet}$
Jan	222.92	6.55	0.72
Feb	221.90	6.48	0.67
Mar	208.12	6.40	0.95
Apr	172.04	6.35	1.85
May	147.10	6.38	2.53
Jun	144.50	6.43	2.65
Jul	143.85	6.48	2.72
Aug	142.16	6.51	2.79
Sep	141.98	6.50	2.78
Oct	154.49	6.47	2.43
Nov	195.11	6.50	1.39
Dec	215.02	6.55	0.92
Total		**77.60**	**22.40**

Refractivity Gradient for Bauchi

Equation (9) yielded a refractivity gradient of -40.854 N units/km for Bauchi. The results show that super-refractive electromagnetic wave propagation waves that are bent downward towards the Earth predominate in this area of Bauchi. The degree of bending depends on the strength of the super-refractive state. The wave paths curve will approach the radius of curvature of the earth as the refractivity gradient decreases.

CONCLUSION

This paper focuses on the challenge of determining tropospheric radio refractivity for Bauchi, a city in the midland climatic zone of Nigeria, under changing weather conditions. Using meteorological parameters such as atmospheric pressure, relative humidity, and temperature data from NASA, the International Telecommunication Union (ITU) recommended method was used to evaluate tropospheric radio refractivity for the locations over a 41-years period (1981 to 2021). The findings showed that during the rainy and dry seasons, average values of 343.155 (N-units) and 283.657 (N-units) were noted. This clearly demonstrates that radio refractivity is higher during the rainy season than it is during the dry season. In August and February, the highest and lowest recorded values of radio refractivity were found to be 355.032 (N-units) and 273.255 (N-units), respectively. The dry term (N_{dry}) makes up 77.60 % of the radio refractivity's overall value. This demonstrates that while the wet term (N_{wet}) contributes 22.40 % to the principal variation, the dry term radio refractivity contributes to the total value of radio refractivity. This study's average refractivity gradient was -40.854 N- units/km; the finding suggests that most propagation in Bauchi is super-refractive. The results of this study hold great significance for the optimal planning and construction of microwave communication lines and systems for Bauchi, located in the midland climate zone of Nigeria.

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