

Assessment of Tropospheric Radio Refractivity and Its Variation with Climatic Variables Over Zaria, Nigeria

*¹Akpootu, D. O., ¹Aminu, Z., ²Nouhou, I., ³Yusuf, A., ⁴Idris, M.,
⁵Aliyu, M. A., ⁶Salifu, S. I., ¹Kola, T. A and ¹Agidi, O. E.

¹Department of Physics,
Usmanu Danfodiyo University,
Sokoto,
Nigeria

²Département de Physique, Faculté des Sciences et Techniques (FST),
Université Dan Dicko Dankoulodo,
Maradi
République du Niger

³Department of Science Education,
Ibrahim Badamasi Babangida University,
Lapai,
Nigeria

⁴Department of Physics,
Bayero University Kano,
Nigeria

⁵Sokoto Energy Research Centre (SERC),
Usmanu Danfodiyo University,
Sokoto State,
Nigeria

⁶Department of Physics,
Kogi State College of Education Technical,
Kabba,
Nigeria

Email: davidson.odafe@udusok.edu.ng; profdon03@yahoo.com

Abstract

To achieve optimal performances, radio link/system planning and design must take radio refractivity estimation very seriously. This study utilizes measured average daily temperature, relative humidity, and atmospheric pressure for forty-one-year period (1981–2021) obtained from the National Aeronautics and Space Administration (NASA) archives for Zaria (latitude 11.10° N, longitude 7.68° E) strategically located in Nigeria's midland climate zone to calculate the monthly tropospheric radio refractivity and look into how it varies with other meteorological factors and radio refractive index. The percentage of the contribution of dry term (N_{dry}) and wet term (N_{wet}) to radio refractivity and refractivity gradient were investigated. The findings indicated that radio refractivity was higher during the rainy season (August) and lower during the dry season (February), with a maximum mean value

*Author for Correspondence

of 350.8733 N-units and a minimum mean value of 284.1975 N-units, respectively, found in those months. The wet term contributes to the significant fluctuation of the radio refractivity, whereas the dry term makes up 76.03% of the total value. The gradient of mean refractivity estimated for Zaria was found to be -43.8709 N – units/km indicating super-refraction propagation condition.

Keywords: Dry term, radio refractivity, wet term, refractivity gradient, Zaria

INTRODUCTION

The troposphere is the part of the atmosphere most directly associated with human life. It is the lowest layer of the earth's atmosphere and region of all weathers on earth (Akpootu and Iliyasu, 2017a). The troposphere extends from the earth's surface to altitude of about 10 km at the earth's pole and 17 km at the equator and tends to affect radio frequencies above 30 MHz (Hall, 1979). At the lower part of the earth called the troposphere, the tropospheric refraction is due to the fluctuations of weather parameters like temperature, pressure and relative humidity (Akpootu and Iliyasu, 2017a). One of the main ways to transmit and receive information is through radio transmission. These signals typically lose some energy when they move from one place to another for a variety of reasons. Since radio signals are propagated by carrier waves travelling through the earth's atmosphere it becomes imperative to understand the wave's mechanism of propagation through different environments and their conditions (Iloke *et al.*, 2020).

Because the troposphere's refractive index is so close to unity, variations in this value affect radio wave propagation. The range of the radio waves is estimated by the height dependence of the refractivity. Therefore, the refractivity of the atmosphere will not only affect the curvature of the ray path but will also provide some insight into the fading of radio waves through the troposphere (Adediji and Ajewole, 2008). The characteristics of the atmosphere influence the propagation of all radio waves. They can be reflected, refracted, scattered and absorbed by different atmospheric constituents (Safdar *et al.*, 2012). Refraction of radio waves can be categorized as either sub-refractive, standard, super-refractive or trapping, depending on the vertical gradient of the modified refractivity (N units Km^{-1}) of the atmosphere (Kulesa *et al.*, 2016). Emmanuel *et al.* (2017) and Falodun and Okeke (2012) also reported the occurrence of abnormal propagation such as super refractive, sub refractive and ducting across Nigeria. The accurate knowledge of radio refractive index of the lower atmosphere is important in the planning and designing of terrestrial radio links for communication networks, radar and propagation applications (Caglar *et al.*, 2006; Naveem *et al.*, 2011).

Several studies on tropospheric radio refractivity have been carried out across the globe. Okeke *et al.* (2019) carried out a study on the radio refractivity over Awka, South Eastern Nigeria. The result of their findings showed that the radio refractivity during the wet season is greater than those obtained during the dry season; the refractivity gradient shows that the frequency of the propagation conditions varies. They discovered also that the sub-refraction condition which is common from January to May and August to December while super-refraction was noticed predominantly between June and July respectively. Akpootu *et al.* (2019) developed empirical models for estimating tropospheric radio refractivity in Osogbo, Nigeria. In another study, Akpootu *et al.* (2021a) estimated and investigate the variability of tropospheric radio refractivity and radio field strength over Accra Ghana, the result of their study revealed that tropospheric radio refractivity is higher during the rainy season than in the dry season in the months of April and January with 384.356 N-units and 371.6318 N-units respectively. During the study period, Accra's average refractivity gradient and average

effective earth radius (k-factor) were estimated to be -44.1405 N-units/km and 1.39, respectively suggesting super-refractive propagation.

This study was carried out to (i) calculate the variation of tropospheric radio refractivity in relation to meteorological parameters for Zaria (ii) investigate the variation of dry and wet term radio refractivity (iii) investigate the changes in radio refractivity with radio refractive index (iv) calculate the percentages that dry and wet term radio refractivity contribute and (v) estimate the refractivity gradient.

METHODOLOGY

The temperature, relative humidity, and atmospheric pressure measurements made each month covering a period of forty-one (41) years (from 1981 to 2021) that was used for this present study was acquired from the National Aeronautics and Space Administration (NASA). The study is focused on Zaria, Kaduna State (latitude 11.10° N, longitude 7.68° E) found in the midland region of Nigeria.

Three (3) variables affect the atmosphere's refractive index (n): temperature, humidity (water vapour content), and atmospheric pressure. The refractive index (n) ranged from 1.000250 to 1.0004000, suggesting that it is extremely close to unity at or near the earth's surface and that there is very little fluctuation in this value over time and space. To make them more noticeable, the refractive index (n) of air was measured by a quantity called the radio refractivity (N) which is related to the refractive index (n) (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. In terms of measured meteorological parameters, the International Telecommunication Union (ITU) has recommended the radio refractivity (N) to be expressed as; (ITU-R, 2003).

$$N = \frac{77.6}{T} \left(P + 4810 \frac{e}{T} \right) = N_{dry} + N_{wet} \quad (2)$$

where the radio refractivity of the dry term is given by

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

and the radio refractivity of the wet term is

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

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

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 used for all radio frequencies; for frequencies up to 100 GHz (Babin *et al.*, 1997). The error is less than 0.5% and at sea level, the average value of $N \approx 315$ was used (ITU-R, 2003).

The relationship between the water vapour pressure (e) and relative humidity is given by the expression (ITU-R, 2003; Akpootu *et al.*, 2019a; Akpootu *et al.*, 2021b,c; Iliyasu *et al.*, 2023; Akpootu *et al.*, 2023).

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

where

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

The saturation vapour pressure (hPa) at temperature t ($^{\circ}\text{C}$) is represented by the symbol e_s in equations (5) and (6), where H is the relative humidity (%) and t is the temperature in Celsius. The values of the coefficients a , b and c (water and ice) was presented in (ITU-R, 2003) for this study, that for water was adopted and given by $a = 6.1121$, $b = 17.502$ and $c = 240.97$ and are valid between -20° to $+50^{\circ}$ with an accuracy of $\pm 0.20\%$. The radio refractivity (N) also decrease exponentially in the troposphere with height (ITU-R, 2003).

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

where H is the applicable scale height and N is the refractivity at the height h (km) above the level where the refractivity is N_s . ITU-R (2003) proposes that at mean mid-latitude; N_s and H are 315 km and 7.35 km respectively. Hence, N as a function of height $N(h)$ is expressed by the equation;

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

However, according to the work of carried out by Agunlejika and Raji (2010), they revealed that the model using the scale height of 7.35 km and 7 km as recommended for global environment ITU-R (2003) and tropical environment John (2005) respectively gave reasonably accurate results for the refractivity at the altitude of 50 m and 200 m for seven (7) out of the twelve (12) months of the year. 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.

The refractivity gradient was computed by taken the derivative of equation (7) with respect to the height, h .

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

The refractivity gradient for a standard atmosphere is -39 N-units/km. According to John (2005) when $h < 1\text{km}$, refractivity gradient is well approximated by its value in a standard atmosphere. In this study, the typical values for a standard atmosphere were used and the refractivity of a standard atmosphere was obtained as $N_s = 312$ N-Units

The vertical gradient of refractivity in the troposphere is an important parameter in estimating path clearance and propagation effects such as sub-refraction, super-refraction or ducting according to Adediji and Ajewole (2008) criteria

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

Refractivity, N , increases with height and in this case (sub-refraction), the radio waves move away from the earth surface and the line-of-sight range and the range of propagation decrease consequently.

(2) 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 successive reflections to produce unnaturally enormous ranges beyond the line of sight.

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

The waves bend downward throughout the ducting process with a curvature larger than the earth's. When radio energy is bent downward, it can get caught between an elevated duct and a boundary or layer in the troposphere, or between the troposphere and the earth's or sea's surface. Very high signal strengths can be obtained at very long ranges (far beyond line-of-sight) and the signal intensity may exceed its free-space value in this wave guide-like propagation.

RESULTS AND DISCUSSION

The Variation of Radio Refractivity with Other Meteorological Parameters for Zaria

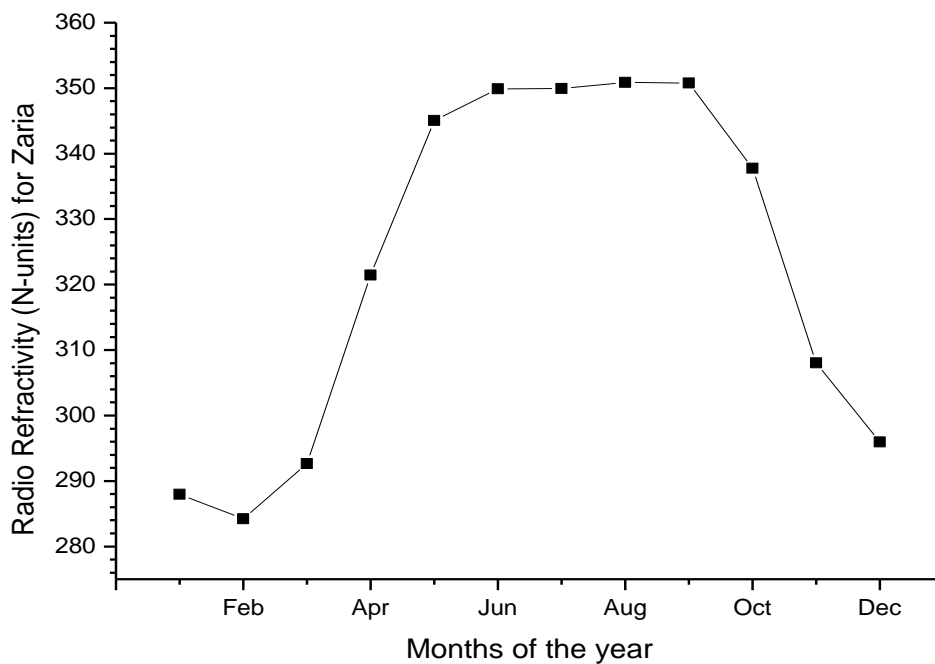


Figure 1. Monthly mean radio refractivity variation over Zaria

The seasonal change of radio refractivity for Zaria is seen in Figure 1 during the period of forty-one (41) years. The figure showed a slight decrease from January to February, when it reached its lowest value of 284.1975 N-units and continuously increases in March and reaches its highest point in August at 350.8733 N units which suddenly decreases gradually to 295.9633 N – units in December. During the rainy and dry seasons, respectively, the highest average value of radio refractivity recorded was 350.8733 N-units in August and the lowest value of 284.1975 N-units in February. The high values of radio refractivity and its variation is in agreement with the result reported by Tanko *et al.* (2019) where they obtained the maximum and minimum values of radio refractivity for Kaduna to be 367.41 N – units and 289.96 N – units during the rainy and dry season. The pattern of fluctuation can be linked to Zaria's rainfall patterns over the study period. The findings demonstrated that refractivity had low values during the dry season (average value of 293.7686 N-units) and high values (average value of 343.6764 N-units) during the rainy season. The high air humidity (approximately 86%) that results in the high water vapour pressure that is seen in most parts of the nation during the rainy season (April to October) is the cause of the high values. Low water vapour pressure and high temperatures during the dry season (November to March) may be the cause of the observed low radio refractivity values.

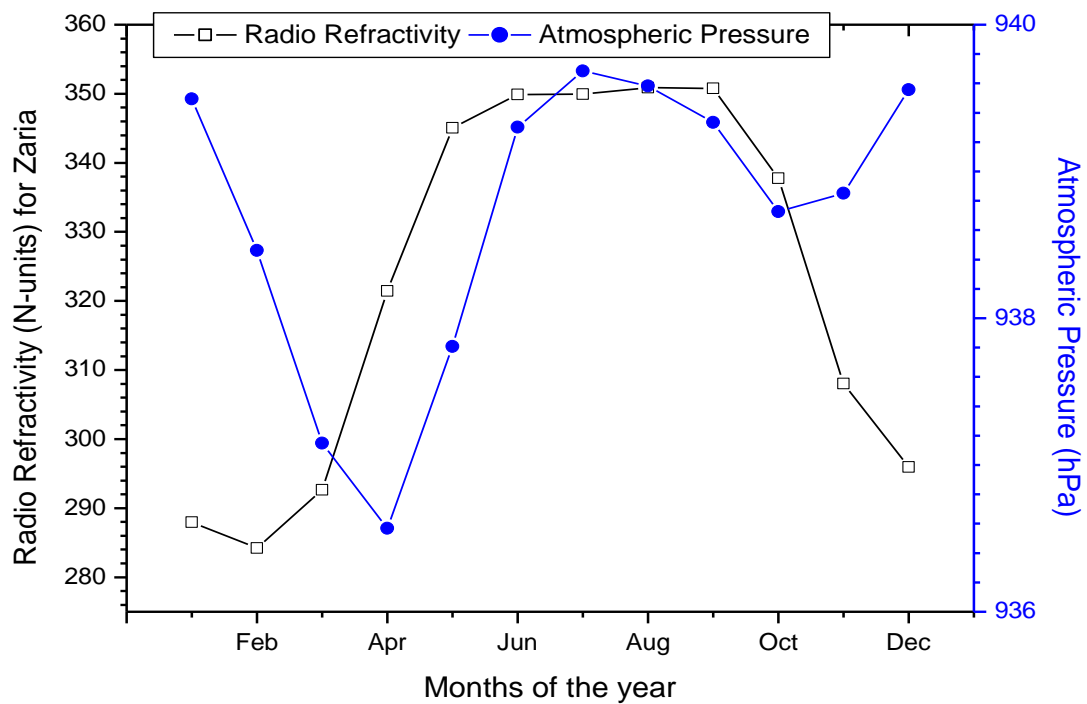


Figure 2. Monthly mean variation of radio refractivity with atmospheric pressure over Zaria

The monthly change of radio refractivity with atmospheric pressure is seen in Figure 2. The atmospheric pressure gradually drops from January to April, when it achieves its lowest value of 936.5683 hPa. Then, in July, it abruptly rises with a significant increase in values, reaching its highest value of 939.6854 hPa. Refractive index was found to rise from March to August in tandem with an increase in atmospheric pressure from May to July. It was found that the refractivity increases gradually from July to August and drops to December while the atmospheric pressure drops from July to October and rises from November to December. The average atmospheric pressure during the rainy season was 938.7153 hPa, while the average refractivity during the dry season was 938.7024 hPa. Similarly, the average refractivity values during the rainy and dry seasons were 343.6764 N-units and 293.7686 N-units, respectively. It is important to note that these terms do not vary exactly in the same months. Taking into account their values during the rainy and dry seasons reveals that the dry term of radio refractivity is related to air density because it is proportional to atmospheric pressure. The highest recorded average radio refractivity value for Zaria is 939.6854 hPa in July, while the lowest recorded value is 936.5683 hPa in April.

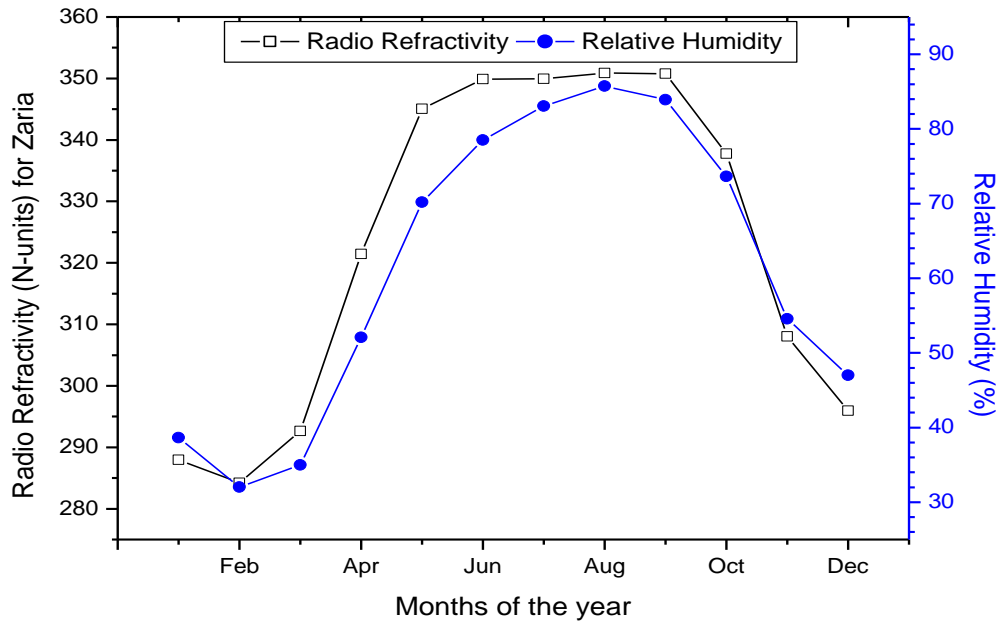


Figure 3. Monthly variation of radio refractivity with relative humidity over Zaria

The monthly change of relative humidity and radio refractivity is displayed in Figure 3. The radio refractivity and relative humidity decreases from January to their minimum values in February with 284.1975 N - units and 32.0271% respectively, and increases simultaneously from February to their maximum values of 350.8733 N - units and 85.7534% respectively in August and drops down to December. The radio refractivity and relative humidity were found to show a slight decrease in February; on the other hand, a slight decrease in radio refractivity was noted from June to August. Relative humidity was shown to rise with radio refractivity from February to August and then decrease until December. The values of radio refractivity and relative humidity fell sharply in February. This could be because of high solar irradiation throughout the month, which decreased the amount of humidity in the atmosphere and consequently decreased radio refractivity. The average value during the rainy and dry seasons, according to the study, was 75.3095% and 41.4435%, respectively. This indicates that the rainy season has higher values and the dry season has lower values. In August, during the wet season, the maximum relative humidity value recorded was 85.7534%, while in February, during the dry season, the lowest value recorded was 32.0271%. This study's findings demonstrated that radio refractivity is reflected in relative humidity.

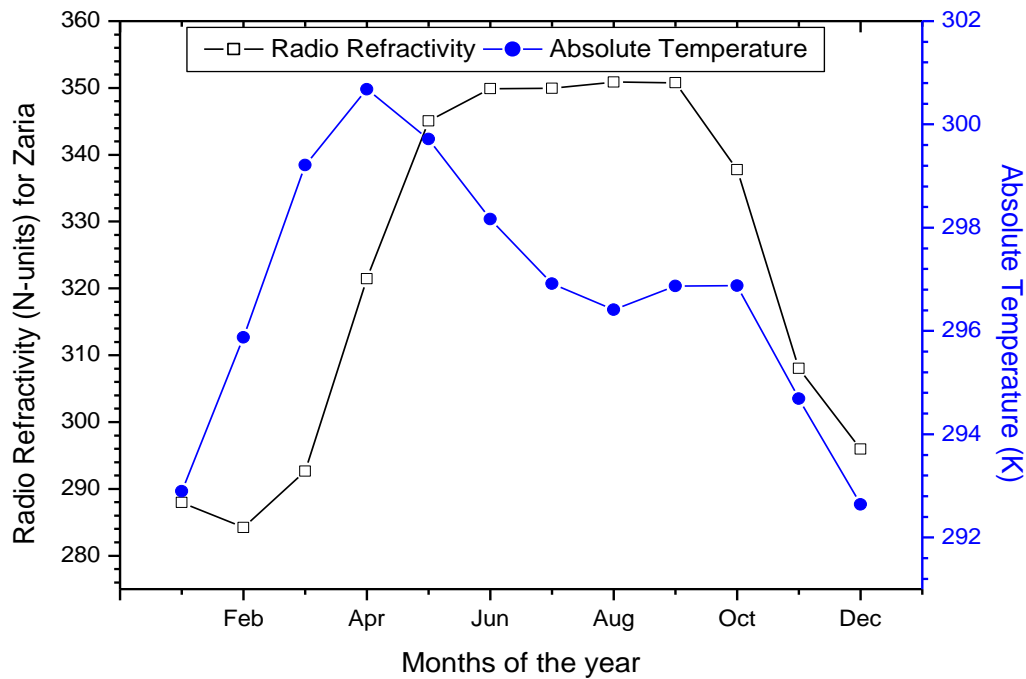


Figure 4. Monthly fluctuation of radio refractivity with absolute temperature over Zaria

The monthly change of radio refractivity for Zaria with temperature (in Kelvin) is displayed in Figure 4. The radio refractivity increases from February to the month of August, when it reaches its maximum of 350.8733 N units. The temperature decreases from August to the month of October, when it suddenly increases, and then drops to its lowest value of 292.6385 K in December. The temperature increases from January to the month of April, when it reaches its maximum average value of 300.6766 K, while the values of radio refractivity decrease gradually to December. While the radio refractivity evaluations show a slight downward dip in February, rising to reach its peak value in August, and a drop in December, the temperature values show practically a straight-line pattern that rises from January to April and from October to December. In August, there was a maximum peak with an upward dip in the radio refractivity and a downward dip in the temperature. The average temperature during the rainy and dry seasons was 297.9479 K and 295.0626 K, respectively. The high temperatures during the rainy season are caused by dust and aerosol particles suspended in the atmosphere, which lowers the temperature and the amount of solar radiation that reaches Earth. This observation is in line with the study reported by Akpootu and Iliyasu (2017b). The radio refractivity has values of 343.6764 N-units during the wet season and 293.7686 N-units during the dry season, respectively. The month of April has the highest average temperature of 300.6766 K, while the month of December has the lowest average temperature of 292.6385 K.

Variation of Dry term and Wet term Radio Refractivity for Zaria

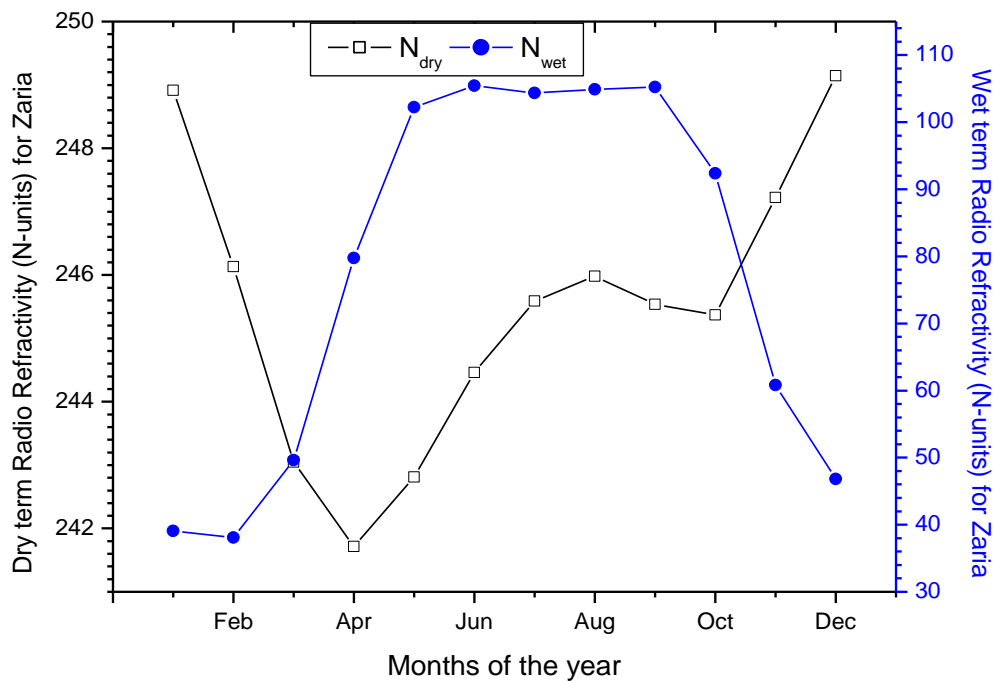


Figure 5. Monthly variation of dry and wet term radio refractivity for Zaria

The variation of wet term radio refractivity (N_{wet}) and dry term radio refractivity (N_{dry}) is displayed in Figure 5. Taking into account the findings of our investigation. It is evident that a significant portion of Zaria's total radio refractivity value comes from the dry term of radio refractivity. The dry term's pattern of change is nearly identical to that of atmospheric pressure, suggesting that the dry term of radio refractivity is correlated with air density and proportional to atmospheric pressure. On the other hand, Figure 1's wet term and radio refractivity show comparable fluctuation. The months of December and June have the highest average values of dry term and wet term radio refractivity, at 249.1454 N-units and 105.4269 N-units, respectively, while the months of April and February have the lowest average values, at 241.7139 N-units and 38.0661 N-units, respectively. The result in this study is in line with the work reported by Tanko *et al.* (2019) where they found the maximum average values of dry term and wet term radio refractivity to be 265.78 N - units and 102.91 N - units while the minimum average values are 259.07 N - units and 24.18 N - units respectively. The result revealed that while the dry term of radio refractivity has a significant role in the overall value, the wet term primarily influences the variance of the radio refractivity.

Variation of Radio Refractivity with Radio Refractive Index for Zaria

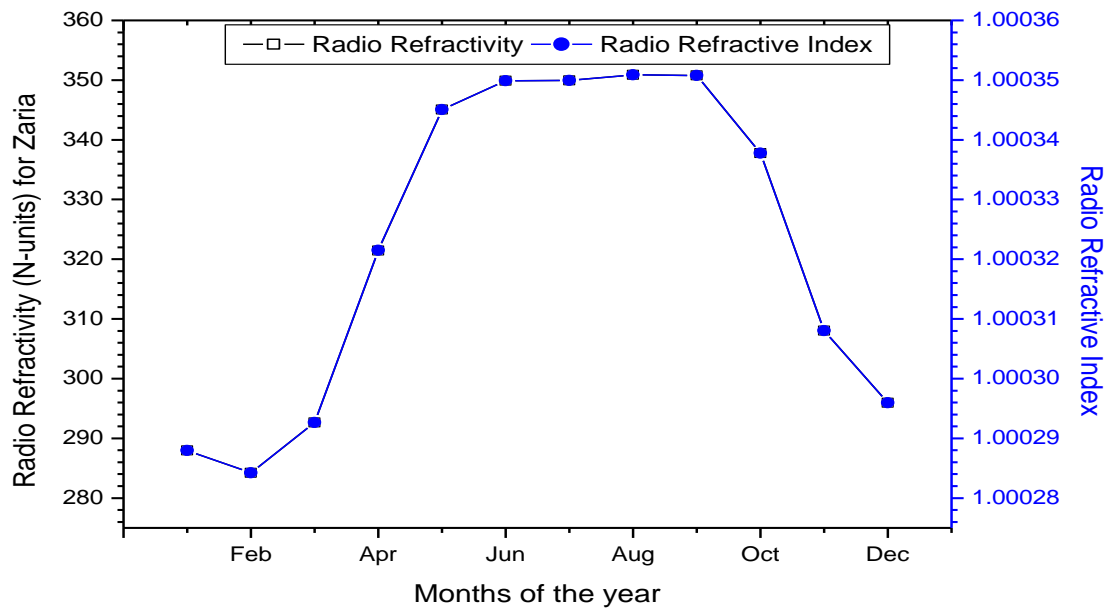


Figure 6. Monthly variation of radio refractivity with refractive index for Zaria

The seasonal change of Zaria's radio refractivity with refractive index is depicted in Figure 6. It was found that there was seasonal change in the radio refractive index and, by extension, the radio refractivity values, with high values during the rainy season and low values during the dry one. Radio refractive index averages are 1.000343 during the wet season and 1.000294 during the dry season. Radio refractivity averages 343.6764 N-units during the wet season and 293.7686 N-units during the dry season. Radio refractive index and radio refractivity were obtained at their highest points during the wet season in August (1.000351 and 350.8733 N-units, respectively), and at their lowest values in February (1.000284 and 284.1975 N-units, respectively) during the dry season.

Percentage contributions of Dry term and Wet term Radio Refractivity for Zaria

Table 1. Variations in the % contributed per month of N_{dry} and N_{wet}

Month	$N_{dry}-N_{wet}$	%CN _{dry}	%CN _{wet}
Jan	209.86	6.42	1.01
Feb	208.07	6.35	0.98
Mar	193.42	6.27	1.28
Apr	161.96	6.24	2.06
May	140.57	6.27	2.64
Jun	139.03	6.31	2.72
Jul	141.22	6.34	2.69
Aug	141.09	6.35	2.71
Sep	140.31	6.34	2.72
Oct	153.00	6.33	2.38
Nov	186.40	6.38	1.57
Dec	202.33	6.43	1.21
Total		76.03	23.97

The percentage contribution of the dry term and wet term radio refractivity to the overall radio refractivity is displayed monthly variation in Table 1. For Zaria, Kaduna state, which is located in Nigeria's midland climatic zone, it was found that the dry term radio refractivity contributed significantly to the total radio refractivity throughout the study period, accounting for 76.03%, while the wet term radio refractivity contributed just 23.97%. Additionally, it was noted that the dry term's maximum monthly contribution occurs in December (6.43%), with the lowest contribution occurring in April (6.24%). Similarly, the wet term's maximum monthly contribution occurs in June and September (2.72%), with the lowest contribution occurring in February (0.98%).

Refractivity Gradient for Zaria

By applying the expression in equation (9) to Zaria, the refractivity gradient was found to be -43.8708 N - units/km. The outcome suggests that most of the propagation in this area of Zaria is super-refractive, meaning that electromagnetic waves are bent downward towards Earth. The strength of the super-refractive condition determines the degree of bending. The wave path's curve will get closer to the Earth's radius of curvature as the refractivity gradient decreases. When a radio wave's trajectory bends farther towards the ground than it would in the case of typical positive refraction, this is known as super-refraction. The refractivity gradient obtained in this study is in line with the result found by Akpootu and Iliyasu (2017a); Akpootu *et al.* (2019b) where they obtained super-refractive of -44.32 N - units/km for Ikeja, Nigeria and -42.69 N - units/km for Osogbo, Nigeria.

CONCLUSION

Using meteorological parameters of atmospheric pressure, relative humidity, and temperature data from NASA, the International Telecommunication Union (ITU) recommended method was used to assess tropospheric radio refractivity for Zaria over a 41-year period (1981 to 2021). The findings showed that radio refractivity in Zaria is higher during the rainy season than it is during the dry season, with average values of 343.6764 N-units and 293.7686 N-units found during the rainy and dry seasons, respectively. During the rainy and dry seasons, respectively, the maximum and lowest values of radio refractivity were determined to be 350.8733 N-units and 284.1975 N-units in the months of August and February. The wet term (N_{wet}) contributes 23.97% to the overall value of radio refractivity, whereas the dry term (N_{dry}) contributes 76.03%. This suggests that the wet term (N_{wet}) contributes to the significant variation and the dry term (N_{dry}) to the total value of radio refractivity. The average refractivity gradient of -43.8709 N - units/km was obtained for this study area indicating that Zaria is mostly super-refractive propagation. The study's findings are very important for the best planning and construction of microwave communication lines and systems in the research area and other areas with comparable climate data.

ACKNOWLEDGEMENTS

The National Aeronautics and Space Administration (NASA) management and employees are appreciated by the authors for providing online access to all of the data utilised in this work.

REFERENCES

- Adediji, A. T and Ajewole, M. O (2008). Vertical Profile of Radio Refractivity Gradient in Akure South-west Nigeria. *Progress in Electromagnetic Research*, C. 4: 157-168. DOI: 10.2528/PIERC08082104
- Agunlejika, O and Raji, T. I (2010). Validation of ITU-R Model for Atmospheric Refractivity Profile in a Tropical Region. *International Journal of Engineering and Applied sciences (IJEAS)*. 2 (4): 72-82
- Akpootu, D. O and Iliyasu, M. I (2017a). Estimation of Tropospheric Radio Refractivity and its Variation with Meteorological Parameters over Ikeja, Nigeria. *Journal of Geography, environment and Earth science International*. 10 (1): 1-12. DOI: 10.9734/JGEESI/2017/32534
- Akpootu, D. O and Iliyasu, M. I (2017b). Estimation of the Monthly Albedo of the Earth's Atmosphere over Sokoto, Nigeria. *Archives of Current Research International*., 7(3): 1 – 10. DOI: 10.9734/ACRI/2017/33196
- Akpootu, D. O and Rabi, A. M (2019). Empirical Models for Estimating Tropospheric Radio Refractivity over Osogbo, Nigeria. *The Open Atmospheric Science Journal*. 13: 43-55. DOI: 10.2174/1874282301913010043
- Akpootu, D. O., Abubakar, M. B., Nouhou, I., Idris, M., Iliyasu, M. I., Ohaji, D. E., Fagbemi, S. A and Aina, A. O (2021b). Estimation of Terrestrial Solar Radiation and its Variation with other Meteorological Parameters over Lokoja, Nigeria. *International Journal of Current Science Research and Review*., 4(8): 966-973. DOI: 10.47191/ijcsrr/V4-i8-13
- Akpootu, D. O., Iliyasu, M. I., Nouhou, I., Abubakar, M. B., Ohaji, D. E., Aina, A. O., Haliru, A. S and Sani, M. Y (2021c). Estimation and Investigation of Geopotential and Scale heights over Iseyin, Nigeria. *International Journal of Current Science Research and Review*., 4(9), 1070-1078. DOI: 10.47191/ijcsrr/V4-i9-01
- Akpootu, D. O., Momoh M., Abdullahi Z., Umar M. (2023). Estimation of Surface Water Vapour Density and its Variation with other Meteorological Parameters over Akure, Nigeria. *Saudi Journal of Engineering and Technology*., 8(8): 189-199. DOI: 10.36348/sjet.2023.v08i08.001
- Akpootu, D. O., Mustapha, W., Rabi, A. M., Iliyasu, M. I., Abubakar., Yusuf, S. O and Salifu, S. I (2019a). Estimation of Surface Water Vapour Density and Its Variation with Other Meteorological Parameters Over Owerri, South Eastern, Nigeria. *Hydrology*., Vol. 7, No 3, 46 – 55. Doi: 10.11648/j.hyd.20190703.12.
- Akpootu, D. O., Said, R. S., Mustapha, W., Arewa, S. P., Sulu, H. T., Iliyasu, M. I and Salifu, S. I (2019b). Performance Analysis of Tropospheric Radio Refractivity on Radio Field Strength and Radio Horizon Distance and its Variation with Meteorological Parameters over Osogbo, Nigeria. *International Journal of Advances in Scientific Research and Engineering (IJASRE)*., 5(10): 81 – 97. DOI: 10.31695/IJASRE.2019.33545
- Akpootu, D.O., Idris, M., Nouhou, I., Iliyasu, M.I., Aina, A.O., Abdulsalami, M.J., Ohaji, D.E and Abubakar, M.B (2021a). Estimation and Investigation of the Variability of Tropospheric Radio Refractivity and Radio Field Strength over Accra, Ghana. *HSAO Journal of Atmospheric & Earth Science*. 5 (1): 1-9. DOI: 10.24966/AES-8780/100026
- Babin, S. M., Young, G. S and Carton, J. A (1997). A New Model of the Oceanic Evaporation Duct. *Journal of Applied Meteorology*. 36, 193-204
- Caglar, Y., Peter, G and William, S.H (2006). Estimation of Radio Refractivity from Radar Clutter using Bayesian Monte Carlo Analysis. *IEEE Transactions on Antennas and Propagation*. 54 (5): 1318-1327
- Emmanuel, I., Babatunde, A and Ogolo, E (2017). Characteristics of Anomalous Refractive Condition in Nigeria. *Journal of Atmospheric and Solar Terrestrial Physics*. 164
- Falodun, S.E, and Okeke, P.N (2012). Radio Wave Propagation Measurement in Nigeria (Preliminary Report). *Journal of Theoretical and Apply Climatology*. Volume 113. 127-135

- Freeman, R. L (2007). Radio system design for telecommunications (3rd edition). New York: Wiley-Inter science
- Hall, M.P.M (1979). Effects of the Troposphere on Radio Communication. Institute of Electrical Engineers
- Iliyasu, M. I., Akpootu, D. O., Momoh, M., Abdullahi, Z., Yusuf, A., Muhammad, N., Sidi, S. A., Aruna, S., Umar, M and Sani, M. Y (2023). Estimation and Correlation of Surface Water Vapour Density in Benin, Nigeria. *Asian Journal of Research and Reviews in Physics.*, 7(4), 43-56. DOI: 10.9734/AJR2P/2023/v7i4148
- Iloke, J.I., Kamgba, F.A and Akonjom, N.A (2020). Comparative Analysis of Tropospheric Radio Refractivity during Rainy Season in Calabar, Nigeria. *International Journal for Research in Applied science and Engineering Technology (IJRASET)*. 8 (1): 45-98
- International telecommunication Union recommendation, ITU-R (2003). The radio Refractive Index: its Formula and Refractivity data.453-459
- John, S. S (2005). Introduction to RF Propagation. John Willey and sons, Inc. Hoboken, New Jersey
- Kulesa, A.S., Barrios, A., Claverie, J., Garrett, S., Haack, T., Hacker, J.M., Hansen, H.J., Horga, K., Hurtaud, Y., Lemon, C., Marshall, R., McGregor, J., McMillan, M., Periard, C., Pourret, V., Price, J., Rogers, L.T., Short, C., Veasey, M and Wiss, V.R (2016). The Tropical Air-Sea Propagation Study (TAPS). *Bulletin of the American Meteorological Society*. 98 (3): 517-537 DOI: <https://doi.org/10.1175/BAMS-D-14-00284.1>
- Naveem, K.C., Trivedi, D.K and Roopam, G (2010). The Impact of K-factor on Wireless Link in Indian Semi Desert Terrain. *International Journal of Advanced Networking and Applications*. 02 (4): 776-779.
- Okeke, N.B., Isaac-Onerime, O.S., Okoye, O.V and Nuhu, A.T (2019). Study of the Radio Refractivity over Awka, South Eastern Nigeria using Meteorological Parameters on the Troposphere during Dry and Wet Seasons. *International Organization of Scientific Research (IOSR) Journal of Applied Physics (IOSR-JAP)*., 11 (2): 62-67. DOI:10.9790/4861-1102016267
- Safdar, A., Shazad, A.M., Khurram, S.A., Shahid, A.K and Rana, L.A (2012). Statistical Estimation of Tropospheric Radio Refractivity Derived from 10 years Meteorological Data. *Journal of Atmospheric and Solar-Terrestrial Physics*. 77 Pp 96-103 <https://doi.org/10.1016/j.jastp.2011.12.001>
- Tanko, M.M., Sarki, M.U and Bilya, M.A (2019). Seasonal Variation of Radio Refractivity of Some Selected Stations in Northern Nigeria. *Current Journal of Applied Science and Technology*. 32 (1): 1-12 DOI:10.9734/CJAST/2019/45326