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ORIGINAL RESEARCH ARTICLE

Performance Analysis of Tropospheric Radio Refractivity along with Refractivity Gradient and Effective Earth Radius in the Coastal Zone of Nigeria

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ABSTRACT

Radio refractivity is the ratio of the velocity of radio waves in a specific medium to that in free space. Radio waves propagate according to variations in tropospheric radio refractive index. This study used the refractive index and other pertinent meteorological factors to calculate the radio refractivity of the seasonal troposphere and analyse its variability with monthly temperature, relative humidity, and atmospheric pressure measurements that were collected from the National Aeronautic and Space Administration (NASA) for Ogoja and Warri over a forty-two-year period (1981 to 2022). We looked at the proportion contributions of the dry and wet term radio refractivity, the refractivity gradient, and the effective earth radius. The outcome signified that in the two locations, radio refractivity values were lowest for the dry season and highest during the rainy season. For Ogoja and Warri, the highest and lowest average radio refractivity values recorded in the wet and dry seasons are, respectively, 382.9085 N-units in May, 346.4311 N-units in January, and 390.9042 N-units in April, 370.3009 N-units in January. For Ogoja and Warri, the wet term (N_{wet}) provides 31.5210 % and 30.1793%, respectively, to the primary variation in radio refractivity's overall value, whereas the dry term (N_{dry}) adds up to 69.8207 % and 68.4790 %. Mean refractivity gradients of -43.8326 and -44.5326 N-units/km were found in the subject areas under examination. Furthermore, it was discovered that the mean effective earth radius (k-factor) for Warri and Ogoja were 1.3959 and 1.3873, respectively. The values provided represent the propagation conditions of superrefraction.

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INTRODUCTION

From the standpoint of radio transmission, there are two primary layers of concentration: the troposphere and the lower atmosphere. It rises to a height of roughly 10 km and 17 km at the Earth's poles and at the equator, respectively, from the surface of the planet. It typically impacts radio frequencies higher than 30 MHz. Physical medium characteristic, as shown by its index of refraction, is known as tropospheric radio refractivity. According to Gao et al. (2008), it is in charge of a number of propagation radio wave phenomena. Subsequently, there is the ionosphere, an area spanning between 60 km and 700 km. It generates ions and free electrons that impact signals at specific radio frequencies, usually lower than 30 MHz.

Microwave frequency bands are used in mobile communication systems due to their wide bandwidth (Harada and Fujise, 2023). However, several atmospheric components can absorb, scatter, reflect, and refractively absorb electromagnetic wave (EMW) radiation in this range. The atmosphere itself has an impact on the propagation of electromagnetic waves (EMWs) across it (Johny *et al.*, 2009). The effects of the environment on communication systems can be broadly classified into three categories: scintillation, which is the distortion of the beam brought on by air turbulence on a tiny scale; refraction, which is the bending of the beam due to variations in atmospheric density along the beam path; and attenuation, which is the loss of radiation energy as a result of interaction between the radiation beam and components in the beam path by scattering or absorption (Adediji *et al.*, 2014).

Adediji and Ajewole (2008) state that variations in the troposphere's air's refractive index control radio wave propagation. Several factors affect how radio wave signals propagate in the troposphere, such as atmospheric pressure, temperature, and relative humidity. Accordingly,

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temperature, pressure, and relative humidity all affect how much refractivity varies in the troposphere (Saha *et al.*, 2005; Tomar, 2012). The primary determinant of radio wave behaviour is the troposphere radio refractive index. Because of this, tropospheric surface refractivity plays a crucial role in any electromagnetic radiation-based communication system (Ippolito, 1981). Tropospheric radio refractivity for diverse locales and climates has been extensively researched by numerous researchers, including Martin and Vaclav (2011), Ayantunji et al. (2011), Emmanuel et al. (2013), Adediji et al. (2017), Akpootu et al. (2019a), Akpootu et al. (2021a), Bello et al. (2024), and Akpootu et al. (2024a; b).

The direct measurement of radio refractivity is usually not feasible in field experiments. Hence, this present study employed the use of measured monthly meteorological data for relative humidity, temperature, and atmospheric pressure to estimate the tropospheric radio refractivity and investigate other relevant parameters across the coastal region of Nigeria.

The study focused on calculating the seasonal tropospheric radio refractivity over Ogoja and Warri in the coastal region of Nigeria and to explain it's fluctuation with climatic parameters and radio refractive index. Estimation of percentage contribution and seasonal variation in radio refractivity's dry and wet components, as well as refractivity gradient and effective earth radius for each location. The locations were chosen because, at the time of this study, no research has been carried out as investigated from the accessed works of literature.

METHODOLOGY

NASA provided the measured monthly meteorological data for relative humidity, temperature, and atmospheric pressure that were used in this investigation. The study areas that are being examined are Warri and Ogoja. Forty-two (42) years are the period of focus.

Three (3) variables affect the atmospheric refractive index (n): temperature, humidity (water vapour content), and atmospheric pressure (Akpootu *et al.*, 2024a). The tropospheric refractive index (n) ranges from 1.000250 to 1.0004000, demonstrating that it is at or near unity at the surface of the Earth and that variations in this value across time and space are negligible, as reported in Akpootu and Iliyasu (2017). The radio refractivity (N), which is connected to the refractive index (n) by equation (1), is commonly used to measure the refractive index (n) of air (Freeman, 2007; ITU-R 2019). This allows the values to be seen.

$$n = \frac{N}{10^6} + 1 \tag{1}$$

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. According to recommendations from the International Telecommunication Union (ITU), the radio refractivity (N), should be expressed incorporating meteorological factors that have been measured: ITU-R (2019).

$$N = \frac{77.60}{T}\left(P + 4810.0\,\frac{e}{T}\right) \tag{2}$$

The first term and second terms obtained through the expansion of equation (2) give the tropospheric radio refractivity of the dry term and wet terms, respectively, as seen in equations (3) and (4) (ITU-R, 2019; Akpootu and Rabiu, 2019; Akpootu *et al.*, 2024a).

$$N_{dry} = 77.60\,\frac{P}{T} \tag{3}$$

$$N_{wet} = 3.730 \times 10^5\,\frac{e}{T^2} \tag{4}$$

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

According to Freeman (2007), equation (2) can be utilized for all radio frequencies; the inaccuracy is less than 0.5% for frequencies up to 100 GHz, and John (2005) discovered that at sea level, the average value of N = 315 was used.

According to Akpootu et al. (2019b); Akpootu et al. (2021b,c); Iliyasu et al. (2023); Akpootu et al. (2023), Abdullahi et al. (2024a,b), as reported in ITU-R (2003); the connection between the water vapour pressure, e, and relative humidity H (%) is

$$e = \frac{He_s}{100} \tag{5}$$

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

where e_s is saturation vapour pressure in hPa, at a certain temperature (°C), t is the temperature (°C). ITU-R (2003) provided results of a, b, and c for water and ice. The water values used in this investigation are valid in temperatures between -20°C to +50°C. In the troposphere, N diminishes according to equation (7) (ITU-R, 2003).

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

The refractivity at height h (km) above the level where the refractivity is N_s is represented by N, and H is the appropriate scale height. ITU-R (2003) suggested that at average mid-latitude, N_s and H should be 315.0 km and 7.350 km, respectively. N(h) as a height function, where N is provided as

$$N = 315\exp^{-0.136h} \tag{8}$$

Agunlejika and Raji (2010) state that the tropical environment John (2005) and the global environment ITU-R (2003), respectively, are best served by the model with scale heights of 7.35 km and 7 km for seven (7) of the year's twelve (12) months. These models yielded very accurate findings for the refractivity at 200 and 50 metres above sea level. 7 km scale height tended to produce better results at 50 m altitude, whereas, at 200 m, 7.35 km scale height was determined to perform better. Equation (7) can be differentiated with respect to h to yield the refractivity gradient as provided by Akpootu et al. (2019a).

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

A conventional atmosphere has a refractivity gradient of -39 N-units/km. According to John (2005), for h values smaller than 1 km, the value of the refractivity gradient in a conventional environment is a good approximation. Since John's (2005) typical values for a regular atmosphere were used in this study, N_S=312 N-units represents the standard atmosphere refractivity.

According to Adediji and Ajewole (2008), Path-clearing and propagation effects like sub-refraction, super-refraction, or ducting are determined in large part by the troposphere's vertical refractivity gradient.

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

In sub-refraction, radio waves radiate forth from the surface of the Earth due to the rise in refractivity, or N, with height. As a result, the propagation range and line of sight are reduced.

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

When there is super refraction, the direction of the Earth's surface, electromagnetic waves are bent downward. At certain distances from the transmitter, rays that emerge at minuscule angles of elevation from the transmitting aerial will first experience total introspection within the troposphere. Once the waves are reflected off the surface of the Earth, they can skip quite far, creating irregular wide ranges that extend ahead of the line of sight owing to multiple wave reflections.

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

The conditions for ducting are contained in Bello et al. (2024).

Refractive conditions were classified as sub-refraction, super-refraction, ducting, and normal refraction or standard atmosphere, respectively. Accordingly, the equation by Hall (1989), Afullo et al. (1999), Freeman (2007), Maintham and Asrar (2003) were used to define the effective earth radius (k factor) in terms of the refractivity gradient, dN / dh.

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

The effective earth radius factor, which is roughly -39 N-units/km close to the Earth's surface, is given by dN/dh when k = 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. Sub-refraction indicates the unusual movement of radio waves. If 4/3 > k > 0. In this instance, super-refraction happens when ∞ > k > 4/3, causing radio waves to increase the radio horizon and propagate abnormally towards the surface of the Earth. As a result, ducting happens when - ∞ < k < 0 waves bend downward.

RESULTS AND DISCUSSION

The Variability of Radio Refractivity with Other Meteorological Parameters in Ogoja

For the length of time under consideration, Figure 1 describes the fluctuation (seasonal) of radio refractivity for Ogoja. At Ogoja, radio refractivity shows a steady rise from its lowest point in January (346.4311 N-units) to its highest point in May (382.9085 N-units). After that, it gradually decreases until August (376.9990 N-units), when it suddenly rises to 379.7975 N-units, dips in December after peaking in October. The maximum average radio refractivity value was 382.9085 N-units during the rainy months in May, with 346.4311 N-units being the lowest amount during the dry season in January. The outcomes demonstrated that radio refractivity had high values (379.7274 N-units) when it's rainy and low values (360.3558 N-units) when it's dry. The figure indicates a decrease in radio refractivity values in August, which may be related to the August break (Emmanuel *et al.*, 2013; Akpootu and Iliyasu, 2017), a brief spell of dry weather. Furthermore, it demonstrates that the dry harmattan season begins in November and ends in January. With the latter month recording the lowest value, the radio refractivity value decreases significantly and consistently. This variation is in line with that reported by Akpootu et al. (2019a).

Figure 2 portrays the variation of radio refractivity with atmospheric pressure over Ogoja during the period under investigation. Gradually, the atmospheric pressure dropped from January to its lowest value of 995.6643 hPa in March and slightly increased to April, which then sharply increased until it attained its peak value of 999.2690 hPa in July and reduced gradually to November, then increased to December. The radio refractivity shows a progressive increase from its lowest value of 346.4311 N-units in January to its maximum value of 382.9085 N-units in May. After that, the value steadily falls till it reaches 376.9990 N-units in August, then abruptly rises to 379.7975 N-units in October, and lastly falls to 352.6437 in December. According to the statistics, Ogoja experiences its highest atmospheric pressure during the August break. This observation is in line with research done on Osogbo by Akpootu et al. (2019a). For both radio refractivity and atmospheric pressure, a dip downward was also seen in addition to the maximum value with a dip upward.

Furthermore, it demonstrates that as the season of dry harmattan begins in December, atmospheric pressure increases and how the value of radio refractivity decreases abruptly and continuously up to January when the lowest amount was noted. In May, during the wet season, the peak recorded mean value of radio refractivity was

382.9085 N-units; in January, the lowest recorded value was 346.4311 N-units. Comparably, in July, during the wet season, the peak recorded mean value of air pressure was 999.2690 hPa, while in March, the lowest recorded value was 995.6643 hPa. The results indicate that radio refractivity has high values (379.7274 N-units) in the rainy season and low values (360.3558 N-units) throughout the dry season. Conversely, though, low values (996.5000 hPa on average) are seen during the dry seasons, and high values (997.9503 hPa on average) are reported in the rainy season. The implication is that low atmospheric pressure tends to increase the tropospheric radio refractivity values while high atmospheric pressure tends to decrease the tropospheric radio refractivity values.

In Figure 3, the seasonal variation of Ogoja's radio refractivity with relative humidity is shown. Radio refractivity increased and peaked in May at 382.9085 N-units before progressively falling to 376.9990 N-units in August, then it increased abruptly and reached a new peak in October at 379.7975 N-units before falling in December. In January, both relative humidity and radio refractivity had their lowest values at 67.4405% and 346.4311 N-units. The percentage of relative humidity rose gradually until September when it hit a record high of 90.6429 %. It started to decline after that and reached 72.3064 % in December. However, In August, radio refractivity and relative humidity both slightly decreased, and there was a more pronounced drop in radio refractivity; this result is consistent with the research reported by Emmanuel et al. (2013).

Additionally, the graph demonstrates how radio refractivity and relative humidity measurements fall off abruptly and consistently in December. High sun irradiation may be the cause of this, as it reduces atmospheric humidity. The greatest average relative humidity recorded throughout is 90.6429% in September, while the lowest is 67.4405 % in January. According to the results, the rainy season is associated with high relative humidity levels (89.0955%), whereas the dry season is associated with low relative humidity values (74.5604%). Similar to this, radio refractivity has low values in the dry season (average value: 360.3558 N-units) and high values (average value: 379.7274 N-units) in the rainy season.

A seasonal variation in tropospheric radio refractivity with absolute temperature for Ogoja is shown in Figure 4. The absolute temperature value rises from 297.2255 K in January to 299.7295 K in March, when it reaches its peak value. Subsequently, the value declines gradually until it reaches 297.4252 K in August. It then increases further in August to 298.3940 K in November before experiencing an abrupt dip to its lowest value of 297.2171 K in December. Commencing its lowest value of 346.4311 N-units, the radio refractivity also rises, reaching a peak value of 382.9085 N-units in May from January. Following that, it steadily decreases to 376.9990 N-units in August before sharply rising to reach 379.7975 N-units in October, and at last drop in December. It was noted that in August, there was a modest drop in both radio refractivity and absolute temperature. It also indicates that at the start of the dry harmattan season in November, the radio refractivity values and absolute temperature both show a steep and persistent decrease, which continue to fall until their minimum values are seen in December and January, respectively. The findings indicate that radio refractivity values are often low (358.3558 N-units) in the dry season and high (379.7274 N-units) during the rainy season. In a similar vein, the dry season records high absolute temperature values (298.2868 K on average), whereas the rainy season records low values (298.2317 K). Furthermore, it was noticed that the rainy and dry seasons corresponded to the maximum and least mean values of radio refractivity, which were 382.9085 N-units in May and 346.4311 N-units in January, respectively. Similarly, the figure shows that the dry season produced the highest and lowest absolute temperature readings, 299.7295 K in March and 297.2171 in December.

Figure 5 depicts the seasonal fluctuations in Ogoja's wet-term (N_{wet}) and dry-term (N_{dry}) radio refractivity. The dry-term radio refractivity decreases, going from January (260.2731 N-units) to 257.7776 N-units in March, which is its lowest value. It then slightly increases in April and rises sharply until it reaches July when it nearly stays constant until getting to its maximum point value of 260.6779 N-units in August. It decreases even further starting in August and continues until November, at which point it rapidly rises to 260.3103 N-units in December. From its lowest value of 86.1580 N-units in January, the wet-term radio refractivity gradually increases to a maximum value of 124.2437 N-units in May. After that, it decreases to August and continues to increase until it reaches 120.0497 N-units in October, before abruptly falling to a new minimum value of 92.3334 N-units in December. This observation is what Akpootu and Iliyasu (2017) looked into for Ikeja. The findings show that while the wet-term radio refractivity greatly contributes to its significant variance, the dry-term radio refractivity largely influences the overall value of radio refractivity.

Figure 6 illustrates the seasonal variation in radio refractivity with radio refractive index for Ogoja. The result shows that there are similarities between the radio refractive index and radio refractivity value patterns of variation. In January of the dry season, the radio refractivity value is 346.4311 N-units at the lowest, while in May of the wet season, it is 382.9085 N-units at the highest. This observation aligns with the investigation by Akpootu et al. (2021a) in Accra, Ghana. The results showed that radio refractivity had high values (379.7274 N-units) during the rainy season and low values (360.3558 N-units) during the dry season. Radio refractive index has an identical high and low average value of 1.0004 during the rainy and dry seasons.

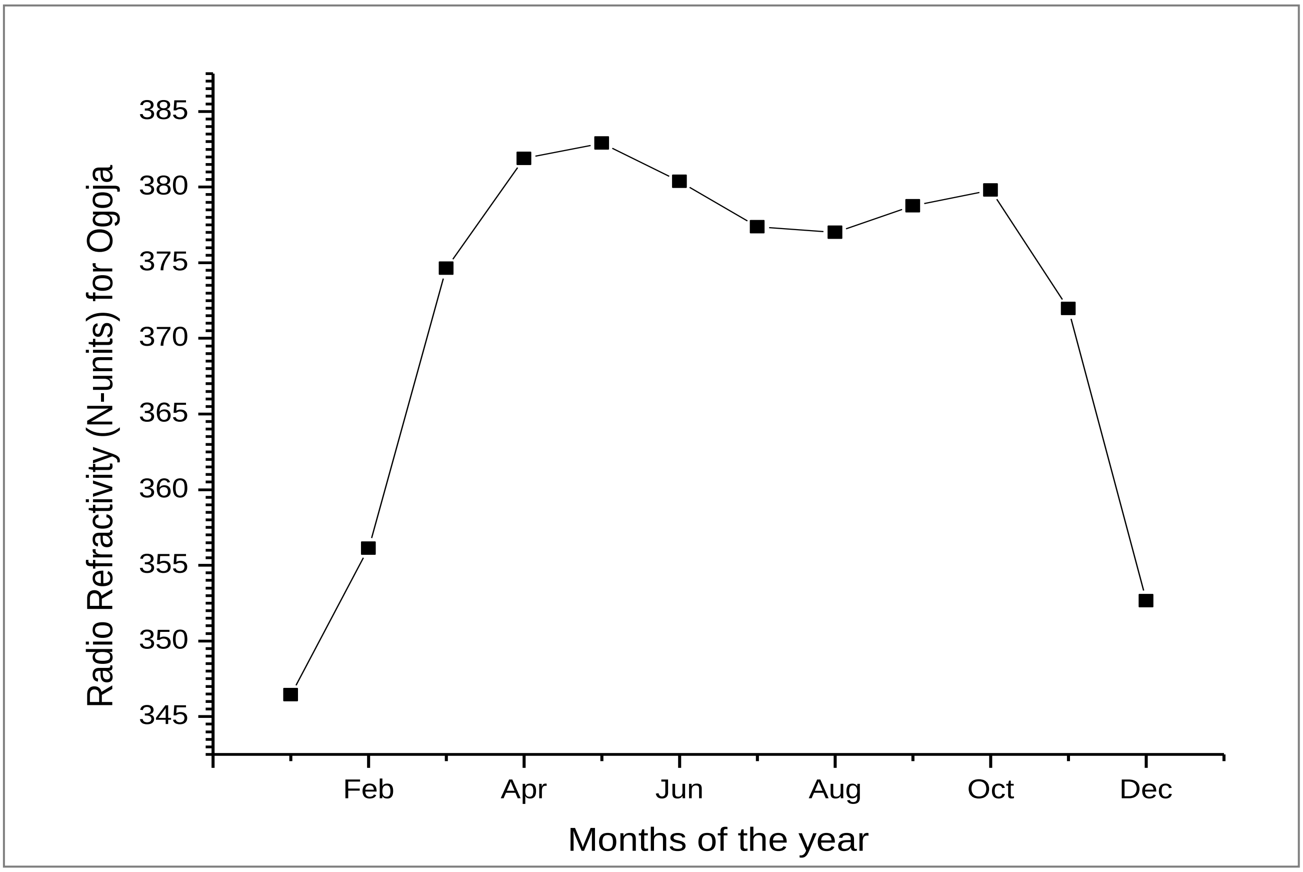

Figure 1: Seasonal radio refractivity variation for Ogoja

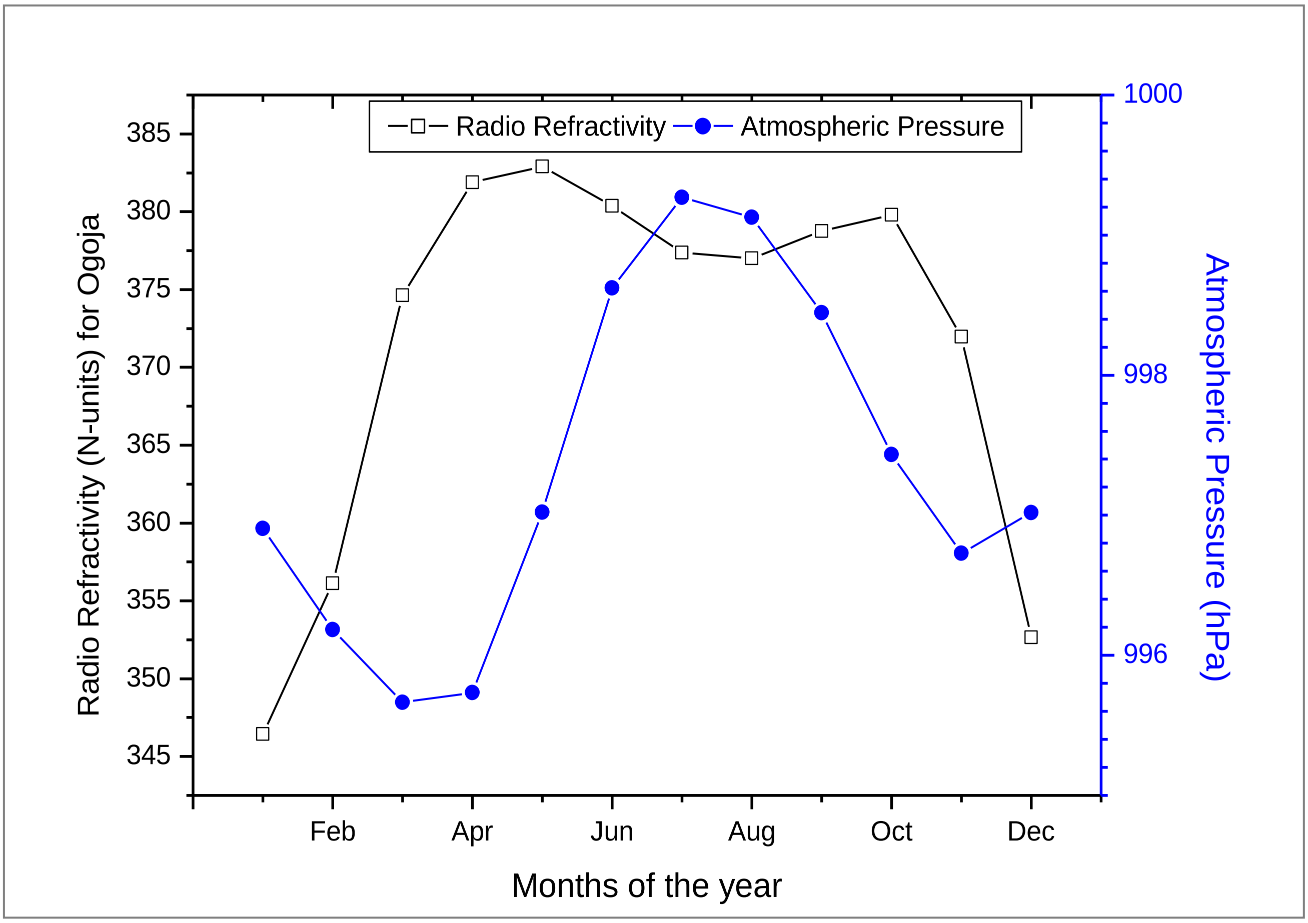

Figure 2: Seasonal variation of radio refractivity with atmospheric pressure for Ogoja

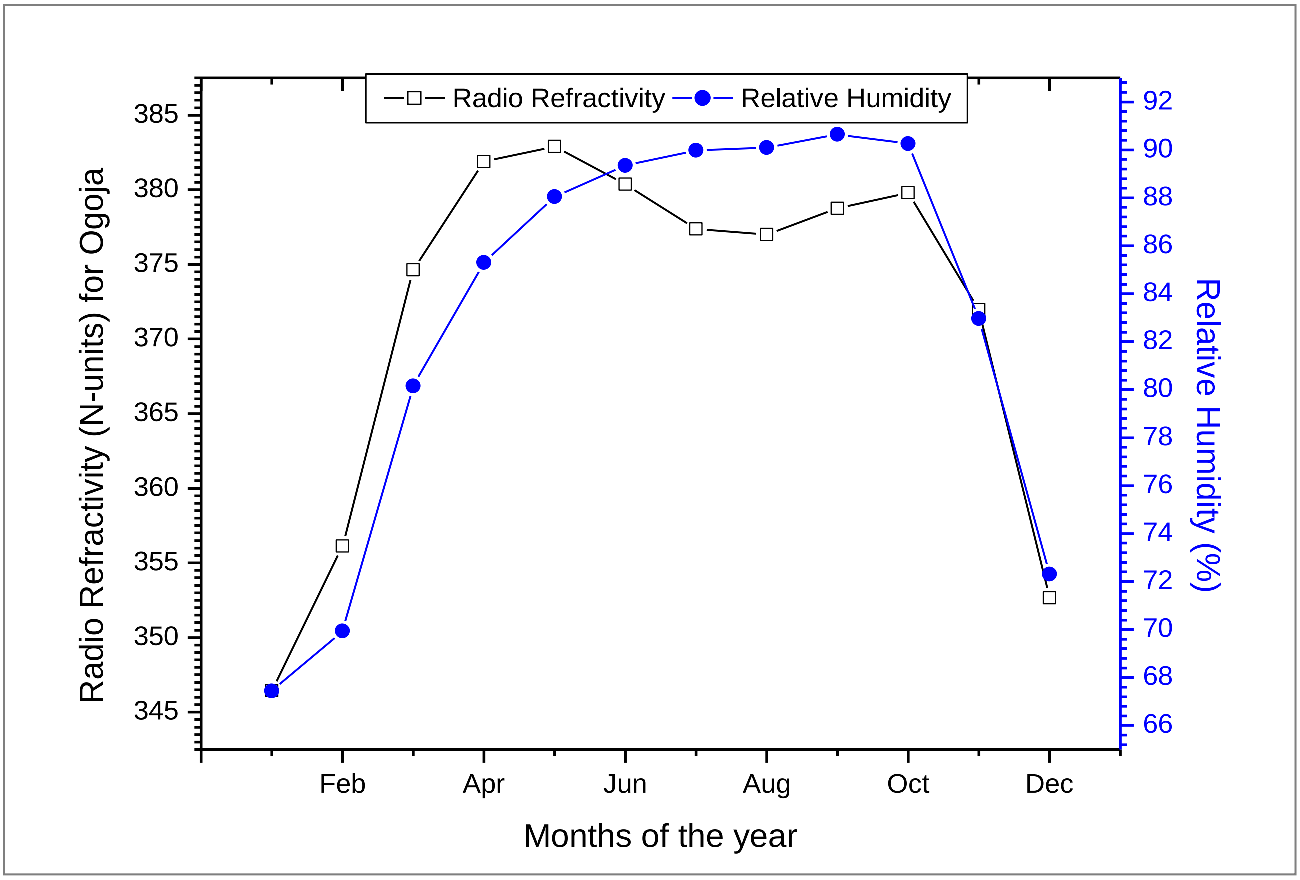

Figure 3: Seasonal variation of radio refractivity with relative humidity for Ogoja

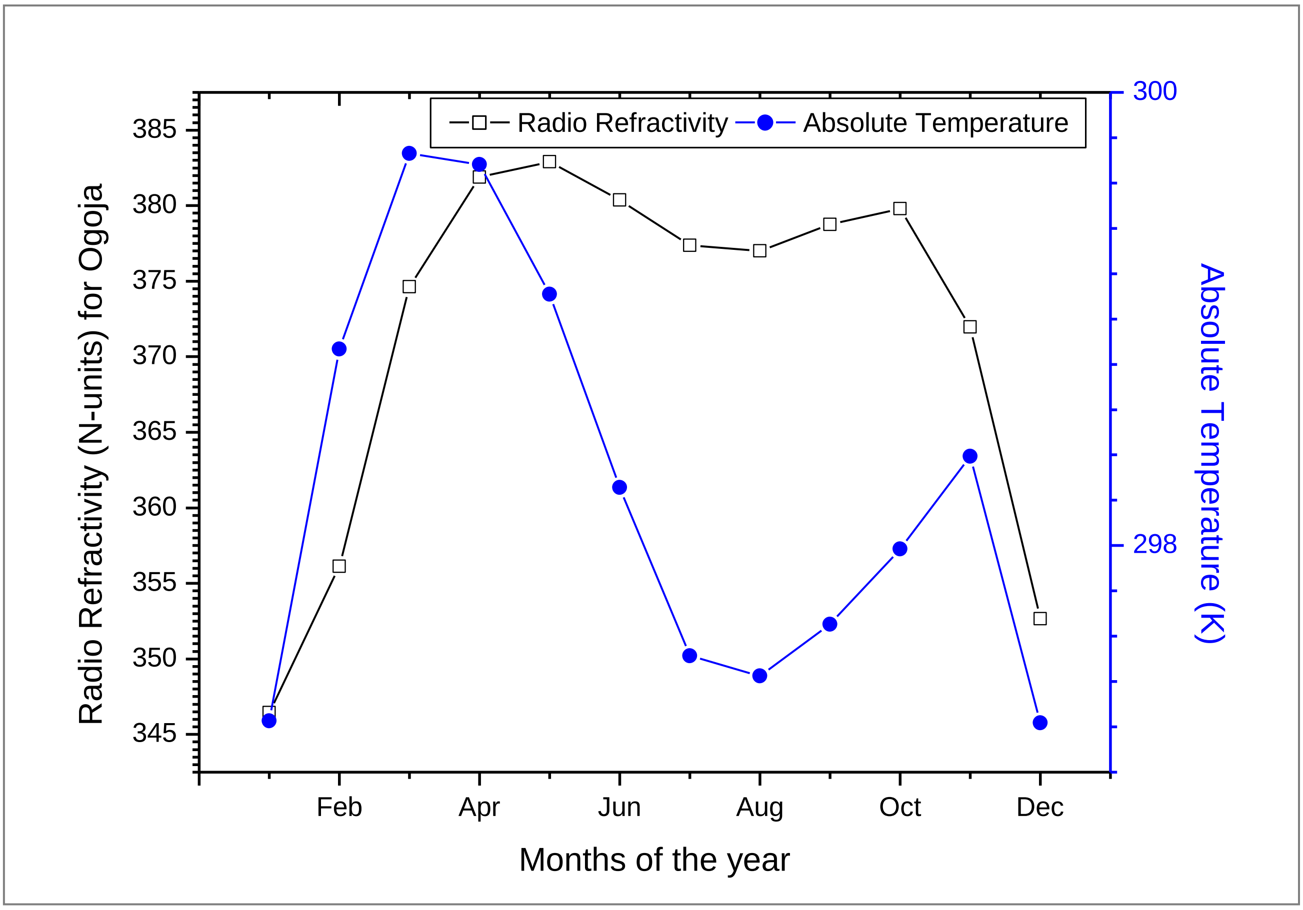

Figure 4: Seasonal variations in Ogoja's radio refractivity in relation to the absolute temperature

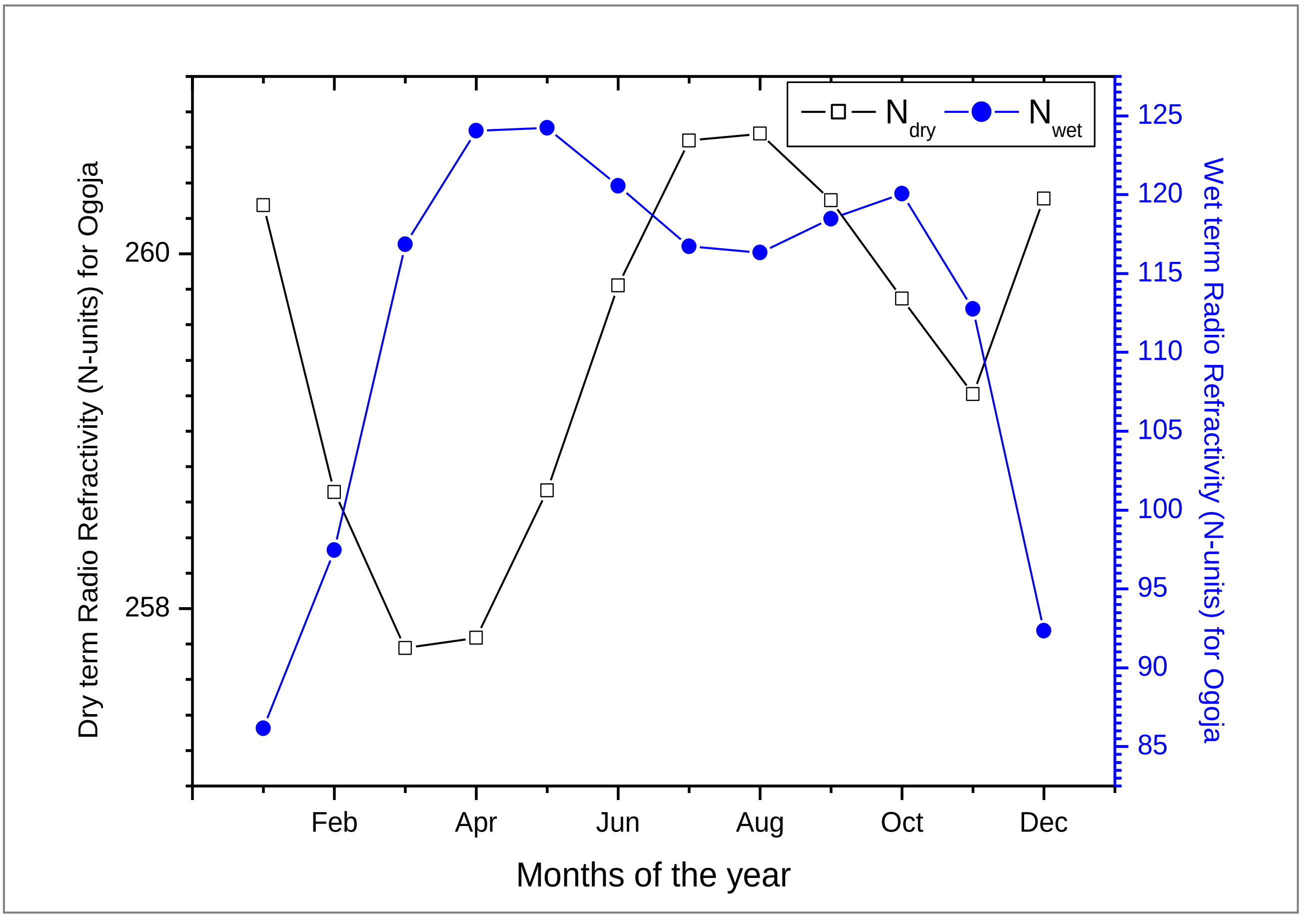

Figure 5: Seasonal variation of dry and wet terms radio refractivity for Ogoja

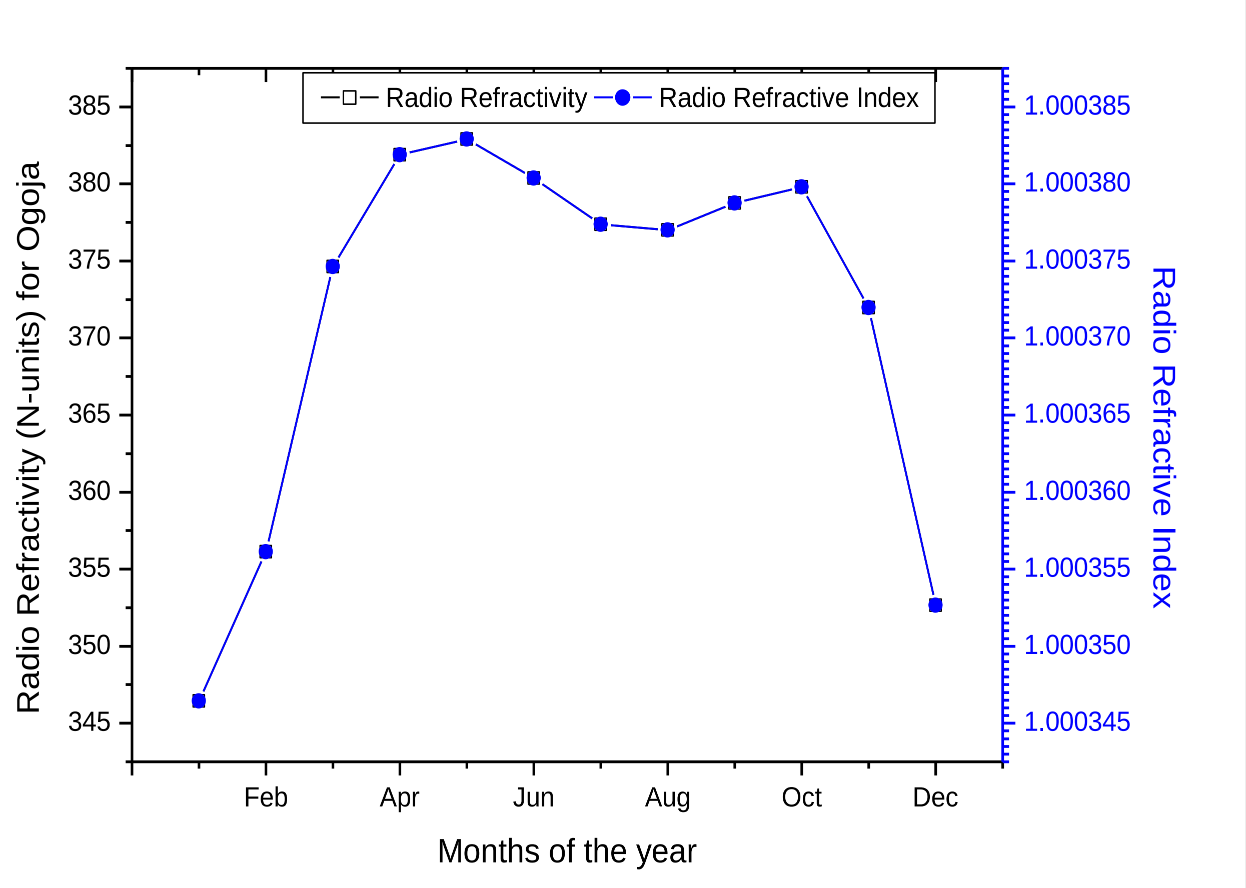

Figure 6: Seasonal variation of radio refractivity with radio refractive index for Ogoja

Refractivity Gradient for Ogoja

According to equation (9) for Ogoja, the refractivity gradient was -43.8326 N-units/km. The Earth is where the electromagnetic waves curled; this indicates that the majority of Ogoja propagation is super-refractive, indicating that in the direction of the Earth's surface, electromagnetic waves are bent downward.

Effective Earth Radius for Ogoja

Using equation (10), a k-factor of 1.3873 was obtained. This implies that the majority of Ogoja's propagation is super refractive. Meteorological conditions that promote superrefraction 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. 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 temperature inversion is not the primary cause of the anomaly the microwave beam is bent. The substantial rise in the dielectric constant close to the surface and the water vapour content cause this impact to steadily increase.

Percentage contribution Investigation

The wet and dry terms monthly percentage contribution is shown in Table 1. During the study period, it was found that for Ogoja, Cross River state, South-South Nigeria. A significant portion of the total radio refractivity came from the dry-term radio refractivity value, coming in at 69.8207%, while the wet-term radio refractivity accounted for 30.1793%. Moreover, in August, the maximum monthly dry term contributed 5.8450%, and its lowest contributor was 5.7799% in March. On the other hand, January had the lowest monthly contribution of 1.9318%, and May had the largest monthly contribution for the wet term (2.7858%). This implies that in May, the value of 2.7858% contributed to the total value of 30.1793% for the wet-term radio refractivity.

The Relationship between Radio Refractivity and Other Meteorological Parameters for Warri

Figure 7 shows how Warri's radio refractivity changed throughout the investigation. In Warri, Delta State, Nigeria, the tropospheric radio refractivity increased gradually from its lowest value in January of 370.3009 N-units to its highest value in April of 390.9042 N-units. It then maintained a nearly constant value until May, at which point it gradually decreased to 379.9820 N-units (August). From there, it grew suddenly until September, when it reached a new peak of 386.4949 N-units and then dropped to 374.4556 N-units in December. The radio refractivity value decreases significantly and consistently from November, when the dry harmattan season starts, until January when its lowest value was seen, as the figure shows. April records the highest average radio refractivity value for Warri during the wet season (390.9042 N-units), while January records the lowest value (370.3009 N-units). Both the rainy and dry seasons exhibit high levels of radio refractivity, as indicated by the average values of 385.7805 N-units and 379.7588 N-units, respectively. The graph unequivocally demonstrates that in August, the radio refractivity value decreased. During August break, a brief spell of dry weather in the area. This result is in line with studies by other researchers, including those investigated by Akpootu and Iliyasu (2017) and Akpootu et al. (2019a).

The seasonal relationship between atmospheric pressure and radio refractivity over Warri is seen in Figure 8. The atmosphere's pressure rises quickly and reaches its peak value of 1012.0476 hPa in July. It then begins to decline from July to November, which then abruptly increases to December. The atmospheric pressure declines from January to its lowest value of 1008.2048 hPa in March and then slightly increases in April. The radio refractivity steadily rises from its lowest point in January (370.3009 N-units) to its highest point in April (390.9042 N-units). It then maintains a nearly constant value in May before gradually decreasing to 379.9820 N-units (August), when it hits a new high of 386.4949 N-units in September, then decreases sharply until December. The figure demonstrated that as November marks the start of the dry season and atmospheric pressure rises until December, the value of radio refractivity decreases sharply and steadily until January when the lowest value was noted. Warri experienced the highest value of atmospheric pressure during the August break, according to observations made by Akpootu and Iliyasu (2017) and Akpootu et al. (2019a). In August, the radio refractivity also showed a downward dip, while the atmospheric pressure reached its highest value with an upward dip. During the rainy month in April, the maximum average value of radio refractivity was determined at 390.9042 N-units, while the lowest value was observed in January during the dry season at 370.3009 N-units. The rainy season's maximum average atmospheric pressure value was recorded in July at 1012.0476 hPa, while the dry season's lowest value was recorded in March. During the rainy season, high average atmospheric pressure levels (1010.6456 hPa) are observed, while low average values (1008.9929 hPa) are recorded during the dry season.

Throughout the investigation, Figure 9 displays the seasonal variations in relative humidity (RH) with radio refractivity over Warri. As the radio frequency becomes more intense and gets to its highest value of 390.9042 N-units in April and maintains almost a constant value to May, it falls steadily until August, when it hits 379.9820 N-units. Then, it spikes up again, getting to a peak of 386.4949 N-units in September, before dropping again until December. From January's lowest readings of 370.3009 N-units and 80.3233%, both parameters increased. The RH is progressively rising all year long, peaking in June at 91.1174% before declining in August. August through October when it reached its greatest value of 91.2705%, the relative humidity continued to rise. However, in December, it abruptly dropped. Relative humidity and radio refractivity do, however, slightly decrease in August. This result is in line with studies conducted by Emmanuel et al. (2013) and Akpootu and Iliyasu (2017). The figure illustrates the dramatic and continuous decrease in radio refractivity and relative humidity values in December, which may be caused by strong solar irradiation lowering atmospheric humidity levels. October records the highest mean relative humidity value (91.2705%), while January records the lowest (80.3233%), with the corresponding in both seasons. The highest average radio refractivity value noted during the rainy season in April was 390.9042 N-units, while the lowest recorded value during the dry season in January was 370.3009 N-units. The results show that in the rainy season, high relative humidity values—90.4941 % on average were recorded, whereas in the dry season, low values—84.1315 % on average—were reported. Additionally, radio refractivity shows high values (385.7805 N-units) on average during the wet season and low values (379.7588 N-units) on average throughout the dry season.

Figure 10 shows how the seasonal radio refractivity and Absolute temperature varied for Warri during the investigation period. The Absolute temperature increases from January, which attained its highest value of 299.8498 K in March, and decreases until it reaches its lowest value of 297.5019 K in August and further increases from August and gets to another maximum value of 298.9390 K in November then decreases to December. The radio refractivity showed progressive increases from its lowest value of 370.3009 N-units in January to its maximum value of 390.9042 N-units in April. It then maintained a nearly constant value through May and subsequently dropped off steadily until it reached 379.9820 N-units in August. Subsequently, it suddenly surged until it reached 386.4949 N-units, its greatest value again, in September. Finally, it started to drop in December. A similar observation was found in the study done by Akpootu and Iliyasu (2017) on Ikeja. August was shown to have a small drop in both parameters. It also shows that by November, when the dry season comes in. In December, both radio refractivity and absolute temperature show a discernible decline. Based on the data, the rainy season is when radio refractivity peaks (385.7805 N-units on average) and troughs (379.7588 N-units on average) during the dry season. An average value of 298.9430 K during the dry season and 298.3727 K during the rainy season was obtained, indicating that the absolute temperature is highest during the dry season. However, the absolute temperature reached its highest average value of 299.8498 K during March during the dry season and its lowest average value of 297.5019 K in the rainy season month of August. Conversely, the peak recorded average radio refractivity value of 390.9042 N-units (in April) and the least recorded value of 370.3009 N-units (in January), respectively, in the rainy and dry seasons.

Figure 11 shows the changes that occurred for the dry-term radio refractivity (N_{dry}) and wet-term radio refractivity (N_{wet}) over Warri during the investigation period. Dry-term radio refractivity increases to 263.9520 N-units, its greatest value, in August, then falls abruptly to November and then climbs once more to December. It lowers steadily from January to its lowest value of 260.9196 N-units in March, then rises again till it reaches its highest value in August. Its value ranged from 107.5557 N-units in January, the lowest, to 129.8244 N-units in April, the highest; the radio refractivity (wet term) rises substantially before progressively decreasing until August. The wet term continues to rise starting in August and reaches its peak value of 123.7778 N-units in October. It then stays rather stable until November, when it abruptly drops to a new low value of 111.9091 N-units in December. The radio refractivity (dry term) high value of 263.9520 N-units in August was correlated with the rainy season; also, the low value of 260.9196 N-units in March was associated with the dry season. The rainy season corresponds with the wet term radio refractivity's highest value of 129.8244 N-units in April, whereas that of the dry season corresponds with the minimum value of 107.5557 N-units for January and 111.9091 N-units in December. Given the pattern of fluctuation as atmospheric pressure, the results showed that while the dry-term radio refractivity makes up a sizable portion of the total value of the refractivity, the wet-term radio refractivity contributes significantly to its variation.

Figure 12 illustrates the seasonal variations of radio refractivity in relation to radio refractive index over Warri. The outcome demonstrates that the variation patterns for the two parameters are identical. On the other hand, the index of radio refractive shows a roughly constant value of 1.0004 from January to December, suggesting that about the same value occurred in both seasons. The greatest average radio refractivity value recorded throughout the rainy and dry seasons, respectively, was 390.9042 N-units in April, while the lowest value was 390.3009 N-units in January. The average readings of 379.7588 N-units in the dry season and 385.7805 N-units during the wet season show that high levels of radio refractivity are seen during each season, with the highest in the rainy season. The radio refractive index has an equal (approximately) high and low average value of 1.0004 during the rainy and dry seasons.

Refractivity Gradient for Warri

Equation (9), when applied to Warri, yields a refractivity gradient of -44.5326 N-units/km. This implies super-refractive propagation for Warri, indicating that in the direction of the Earth, the electromagnetic waves are bent downward. The strength of the super-refractive state dictates the degree of bending that occurs. In contrast to what would normally happen in a positive refraction scenario, where a radio wave bends closer to the Earth, this phenomenon is known as super refraction.

Effective Earth Radius for Warri

The effective earth radius (k factor), was found to be 1.3959 by using equation (10). This implies that Warri's propagation is mostly extremely refractive. Meteorological elements that cause a decline in the gradient of the dielectric constant with height and, as a result, superrefraction include temperature inversions and decreases in the total moisture content of the air. Cool water is being passed over by warm air frequently results in this kind of erratic refractive index. Temperature inversion may increase as a result of water evaporation, which can also enhance the amount of moisture and drop the temperature at the surface. Nevertheless, the temperature inversion is not the main reason for the aberrant microwave beam bending. The dielectric constant and content of water vapour both significantly increase as one approaches the surface, increasing this impact over time.

Table 1. Monthly fluctuation in N_{dry} and N_{wet} Percentage contributions to Ogoja

Month	Ndry-Nwet	%CNdry	%CNwet
Jan	174.1152	5.8359	1.9318
Feb	161.1953	5.7996	2.1853
Mar	140.9329	5.7799	2.6199
Apr	133.7918	5.7813	2.7814
May	134.4211	5.7998	2.7858
Jun	139.2620	5.8257	2.7032
Jul	143.9078	5.8441	2.6174
Aug	144.3568	5.8450	2.6082
Sep	141.8458	5.8365	2.6560
Oct	139.6981	5.8241	2.6918
Nov	146.4498	5.8120	2.5283
Dec	167.9768	5.8367	2.0703
Total		**69.8207**	**30.1793**

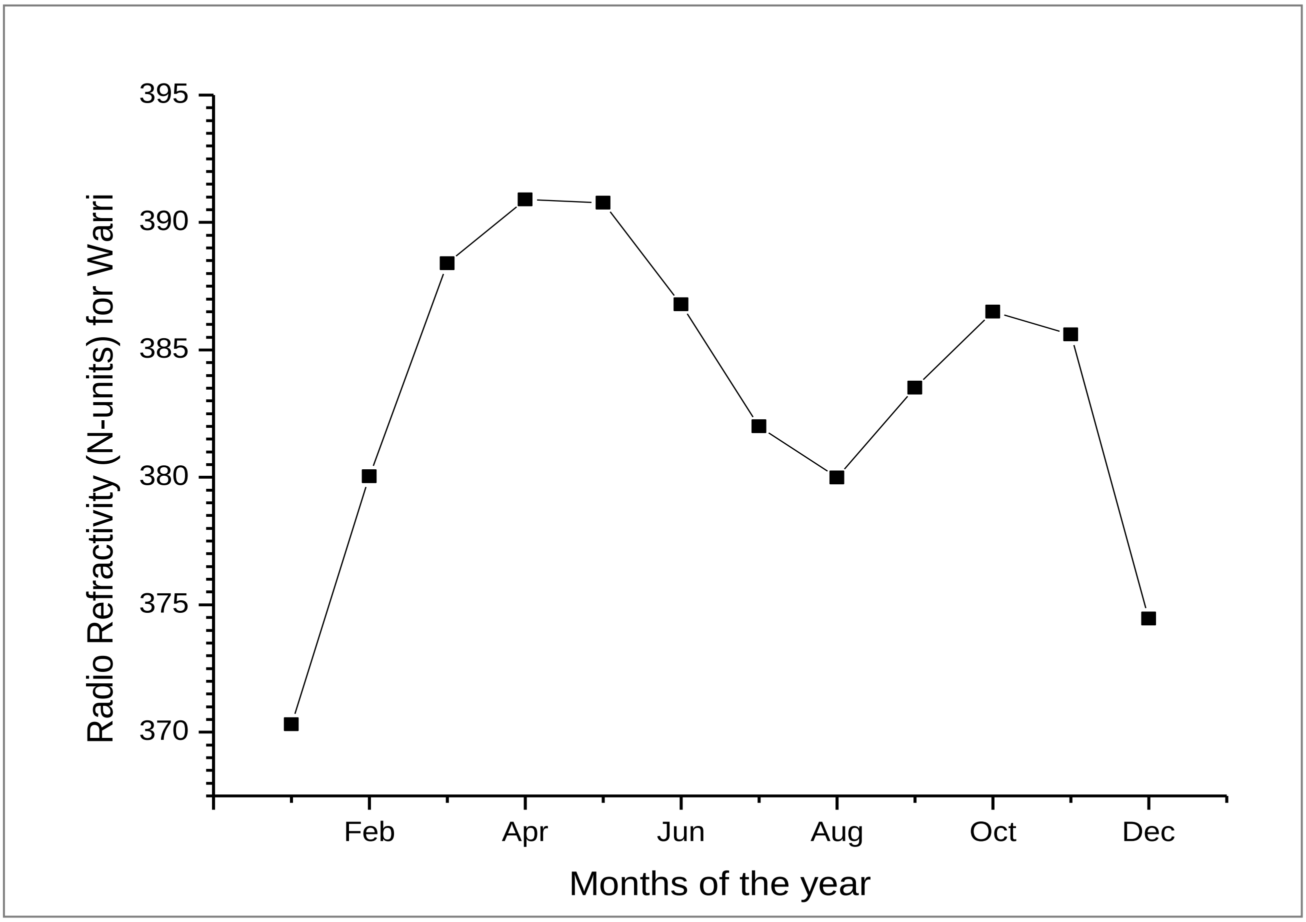

Figure 7. Variations in radio refractivity with the season over Warri

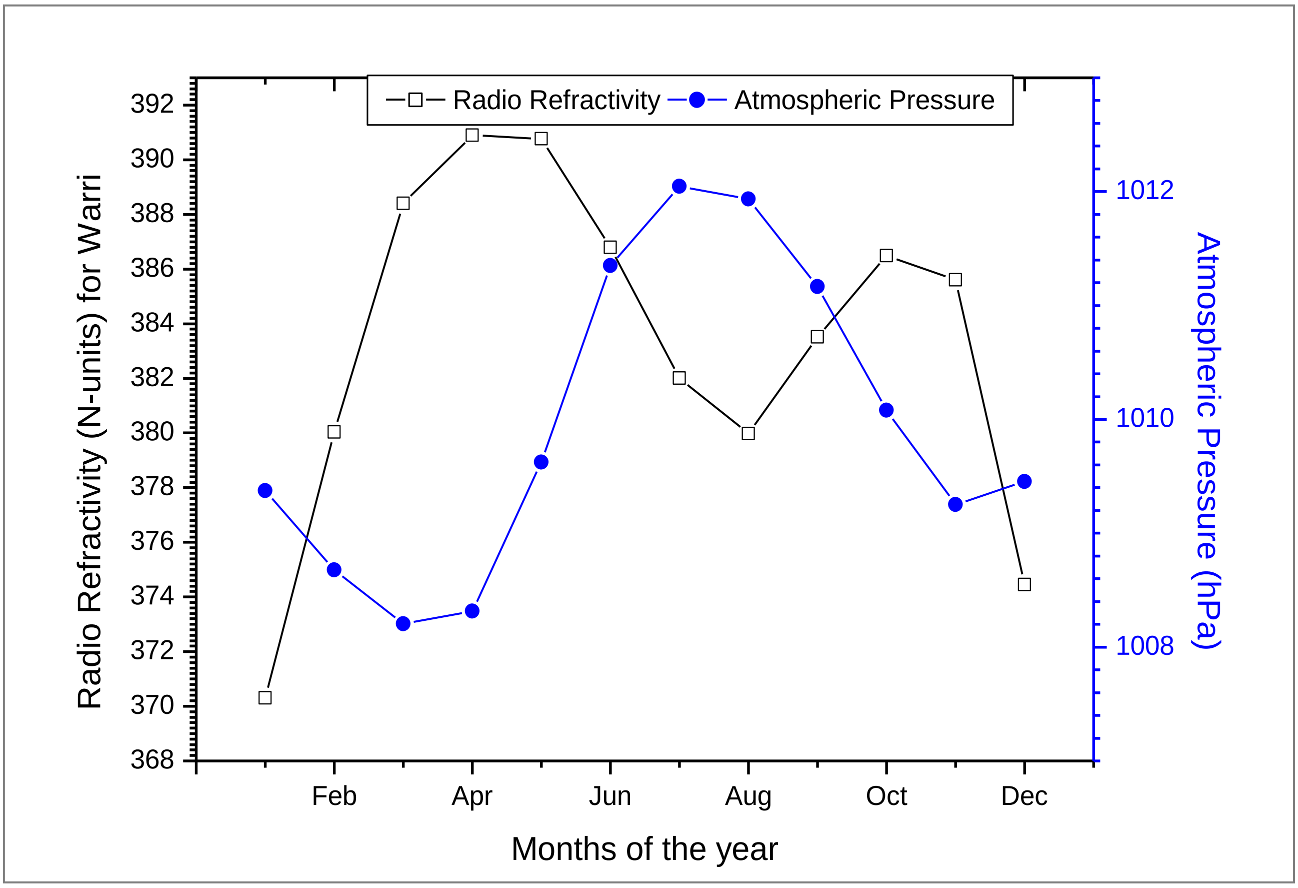

Figure 8. Seasonal differences between Warri's radio refractivity and atmospheric pressure

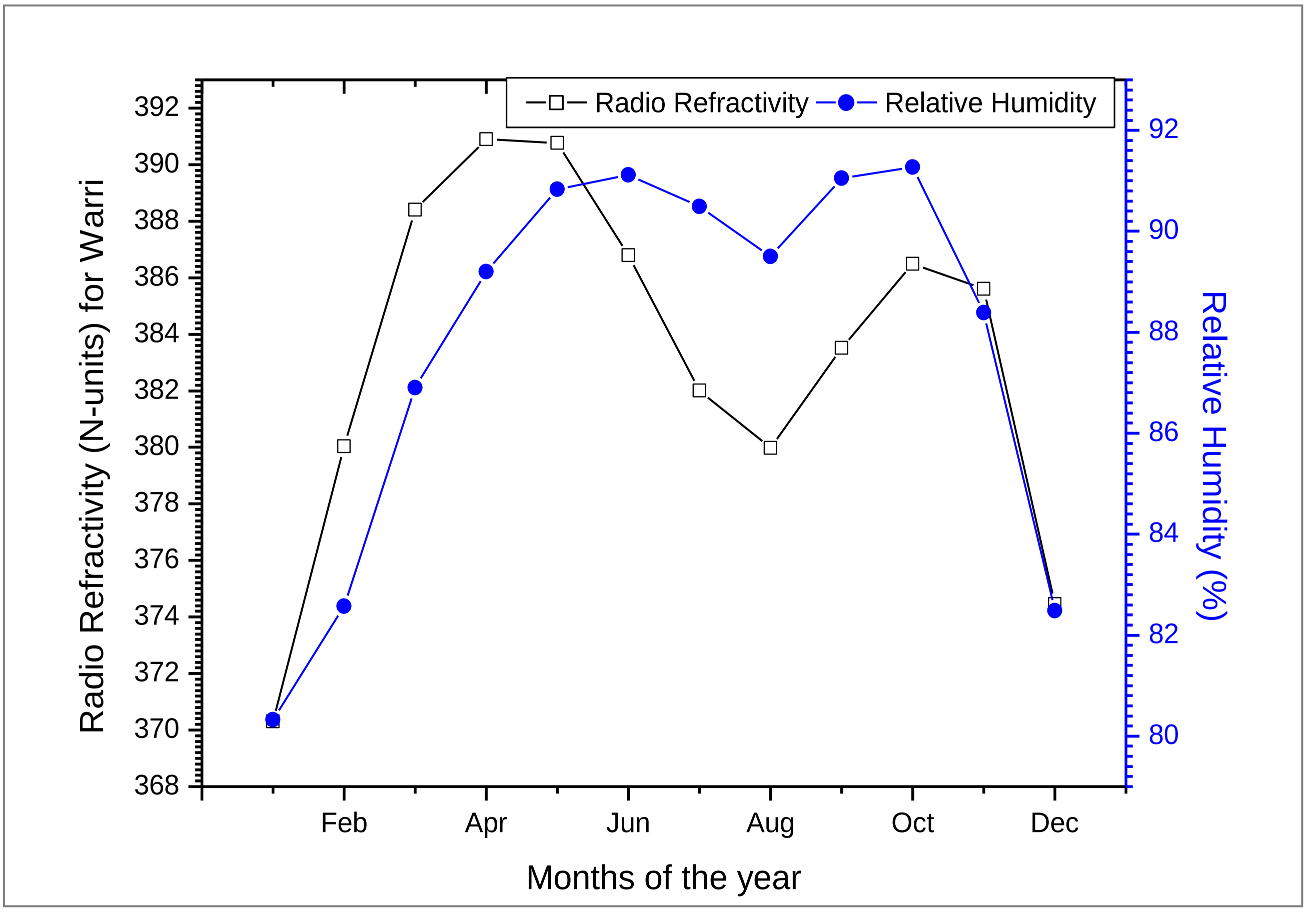

Figure 9. Seasonal differences in Warri's radio refractivity and relative humidity

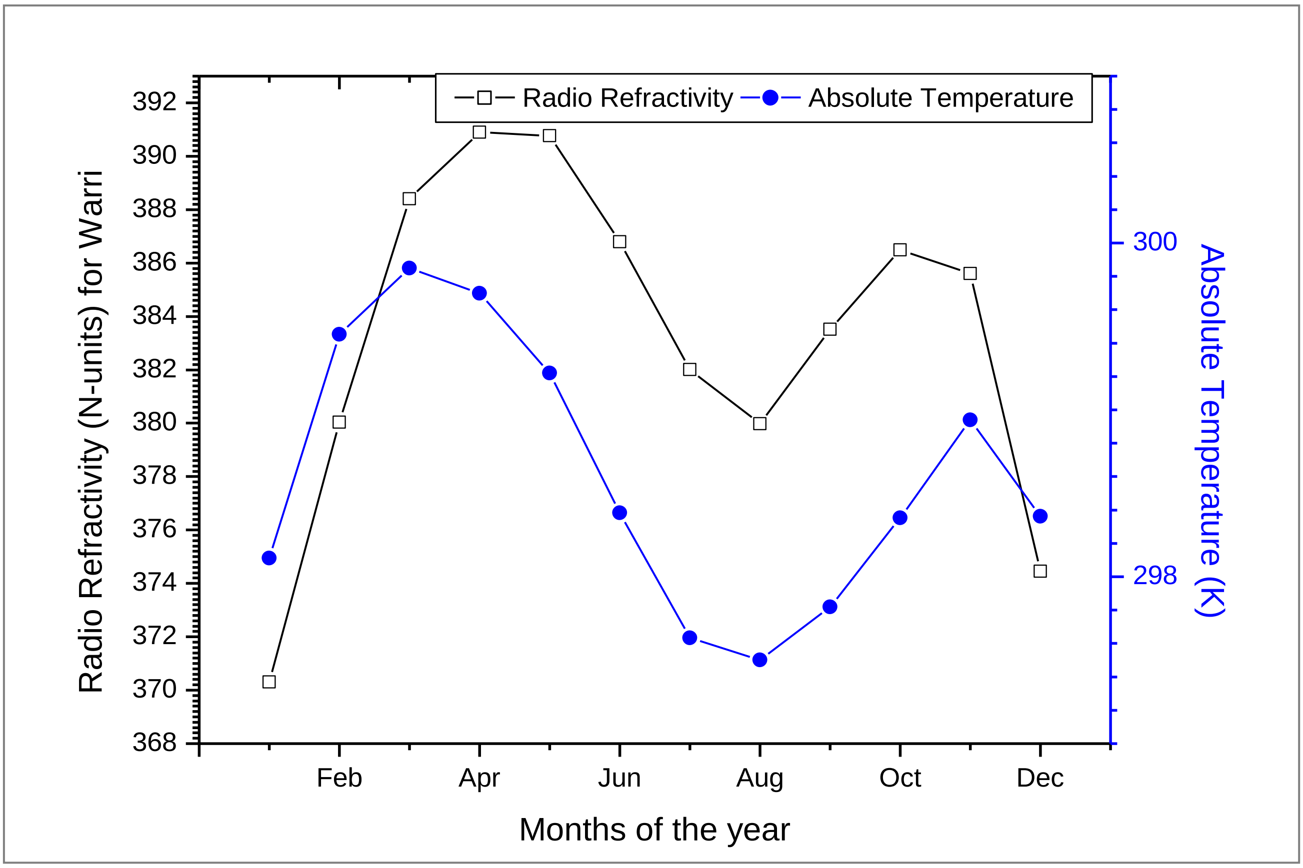

Figure 10. Seasonal changes in radio refractivity in relation to Warri's absolute temperature

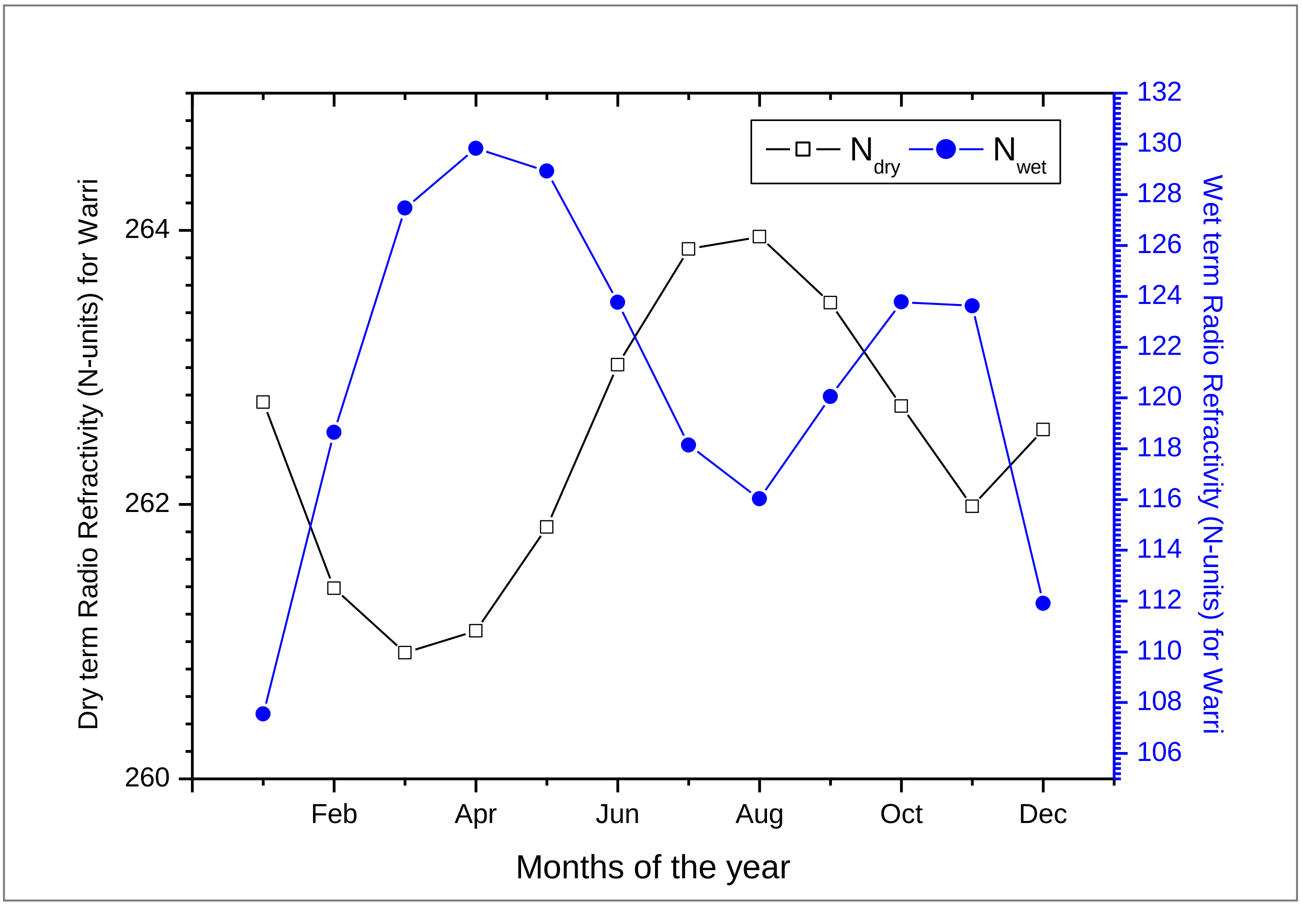

Figure 11. Seasonal differences in radio refractivity over Warri for dry and wet terms

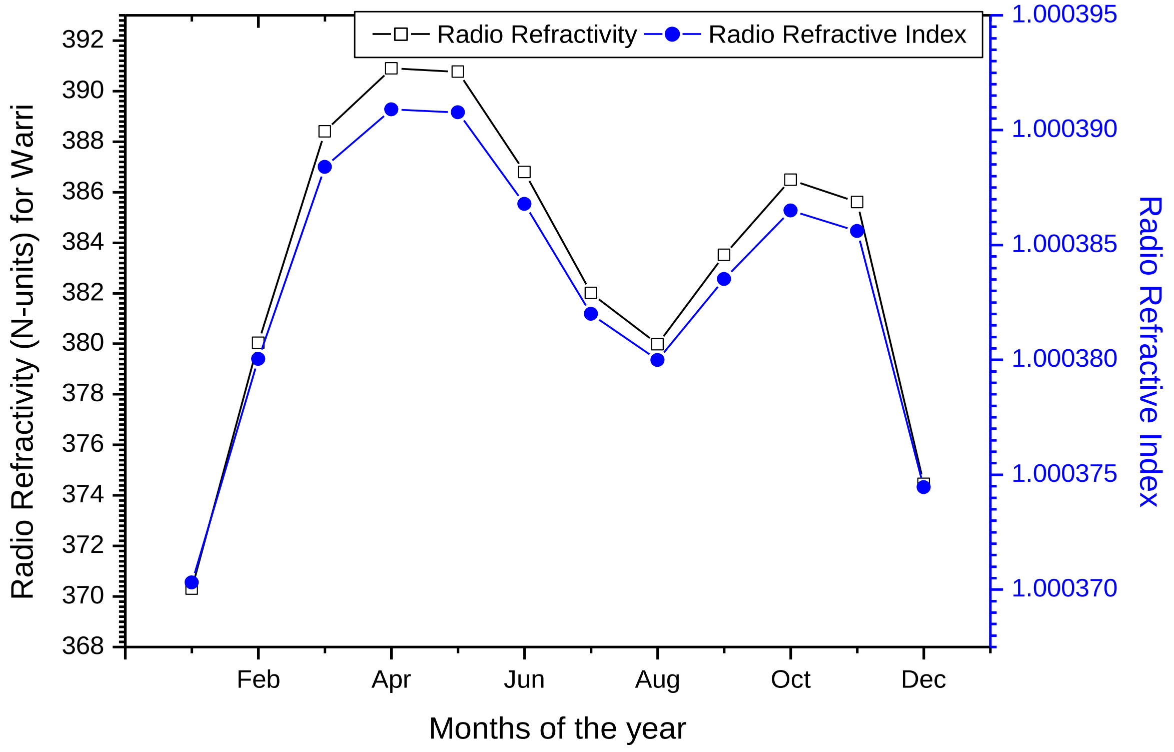

Figure 12. Seasonal differences in radio refractivity over Warri with radio refractive index

Percentage Contribution Analysis

The monthly change in percentage contribution to aggregate radio refractivity, in both the wet and dry terms, is displayed in Table 2. It was found that for the region under examination, the wet-term radio refractivity has a contribution of 31.5210 %. Conversely, 68.4790% of the total radio refractivity comes from the dry term. August and March had the percentage contributions of dry-term radio refractivity that are highest and lowest, 5.7390% and 5.6731%, respectively, while April and January had the maximum and lowest percentage contributions of wet-term radio refractivity, 2.8227 % and 2.3385%, respectively.

Table 2. Monthly fluctuation in N_{dry} and N_{wet} Percentage contributions to Warri

Month	N_{dry}-N_{wet}	%CN_{dry}	%CN_{wet}
Jan	155.1895	5.7128	2.3385
Feb	142.7453	5.6833	2.5796
Mar	133.4415	5.6731	2.7717
Apr	131.2555	5.6766	2.8227
May	132.9070	5.6930	2.8033
Jun	139.2513	5.7188	2.6911
Jul	145.7207	5.7371	2.5687
Aug	147.9219	5.7390	2.5228
Sep	143.4212	5.7285	2.6102
Oct	138.9393	5.7122	2.6913
Nov	138.3642	5.6963	2.6879
Dec	150.6374	5.7085	2.4332
Total		**68.4790**	**31.5210**

Table 3 compares the typical radio refractivity values throughout the wet and dry seasons, with Ogoja and Warri having the highest and lowest values. The results revealed that Warri's mean radio refractivity values are greater than Ogoja's during the rainy and dry seasons. Furthermore, Warri's radio refractivity averages are higher than Ogoja's, with differences of 7.9957 N-units and 23.8698 N-units for the maximum and minimum average values.

Table 3. Comparison of average values of radio refractivity for Ogoja and Warri

Season	Ogoja	Warri
	Av. Radio (N-Units)	**Refractivity**
Rainy	379.727	385.781
Dry	360.356	379.759
Maximum	382.909	390.904
Minimum	346.431	370.301

Table 4 compares the k-factor and refractivity gradient between Ogoja and Warri. According to the results, Warri has a greater k-factor than Ogoja, although Ogoja has a stronger refractivity gradient. However, these sites show that super-refractive propagation primarily occurs along the coastal zone of Nigeria.

Table 4. Comparison of Refractivity Gradient and k-factor for Ogoja and Warri

Average Values	Ogoja	Warri
Refractivity gradient	- 43.8326 N-units/km	- 44.5326 N-units/km
k-factor	1.3873	1.3959

Table 5 shows the contrast between the wet and dry terms radio refractivities for Ogoja and Warri. Ogoja's radio refractivity is greater than Warri's by 1.3417% in the dry term, and Warri's is higher than Ogoja's with an unchanged value in the wet term. As observed from both sites, the dry term mostly contributes to the total tropospheric radio refractivity, whereas the wet component adds to the pattern of radio refractivity change.

Table 5. Comparison of Dry-term and Wet-term Radio Refractivity for Ogoja and Warri

Average Values	Ogoja	Warri
Dry-term	69.8207 %	68.4790 %
Wet-term	30.1793 %	31.5210 %

CONCLUSION

An estimate of tropospheric radio refractivity was made and examined in this study along with other relevant parameters at two locations in the coastal climatic zone of Nigeria: Ogoja and Warri. The findings showed that for Ogoja and Warri, respectively, radio refractivity peaked during the rainy season (379.7274 N-units and 385.7805 N-units on average) and decreased during the dry season (360.3558 N-units and 379.7588 N-units on average). The highest and lowest average radio refractivity measured for Ogoja and Warri all through the rainy and dry seasons, respectively, were 382.9085 N-units in May and 390.9042 N-units in April, along with 346.4311 N-units and 370.3009 N-units in January. It was discovered during the investigation that the dry-term radio refractivity was a significant contributor to the overall radio refractivity with 69.8207% and 68.4790%, while the wet-term radio refractivity contributed to the major differences with 30.1793% and 31.5210% for Ogoja and Warri, respectively. The average refractivity gradients in the study areas under inquiry were found to be -43.8326 and -44.5326 N-units/km. Furthermore, it was discovered that Ogojo and Warri had average effective earth radiuses (k-factors) of 1.3873 and 1.3959, respectively. These values implied that super refraction propagation condition is found in Nigeria's coastal climatic zone. Further studies can be investigated across other climatic zones alongside the field strength variability and radio horizon distances.

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