

Seasonal Analysis of Atmospheric Radio Wave Refractivity Over Gombe, Northeastern Nigeria

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Abstract: Atmospheric conditions play a critical role in radio wave propagation through mechanisms such as refraction, reflection, and scattering. This study examines the seasonal variability of atmospheric radio refractivity over Gombe, Northeastern Nigeria, using meteorological data obtained from the Nigerian Meteorological Agency (NiMET) for the period 2021–2022. Surface parameters, including temperature, atmospheric pressure, relative humidity, and water vapour pressure, were utilized to compute radio refractivity, refractivity gradient, and the effective Earth radius factor (k-factor). The results indicate a pronounced seasonal dependence of refractivity, with elevated values observed during the wet season due to increased atmospheric moisture content. The refractivity gradient reached minimum values of -49 N-units/km in 2021 and -47 N-units/km in 2022 during the rainy season, while maximum values of -37 N-units/km and -35 N-units/km were recorded for the respective years. The mean refractivity gradient for both years is lower than the standard atmospheric value of -40 N-units/km, suggesting enhanced refractive conditions. Furthermore, the mean k-factor values of 1.38 (2021) and 1.39 (2022) exceed the standard value of 1.33, indicating the dominance of super-refractive conditions over the study area. These atmospheric conditions imply increased downward bending of radio waves compared to the standard atmosphere, which may adversely impact radar performance and terrestrial microwave communication links. The findings provide valuable insights for the planning, design, and optimization of reliable radio communication systems in the region.

Keywords: Atmospheric Refractivity, Tropospheric Propagation, Seasonal Variation, Refractivity Gradient.

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I. INTRODUCTION

Radio wave propagation through the Earth's atmosphere is a complex physical process that is strongly influenced by spatial and temporal variations in atmospheric conditions. In an ideal free-space environment, electromagnetic waves propagate in straight lines at a constant velocity. However, within the atmosphere, variations in temperature, pressure, and moisture content alter the density and dielectric properties of air, causing radio waves to deviate from straight-line paths. These deviations manifest primarily as refraction, reflection, scattering, and attenuation, all of which can significantly affect the performance and reliability of radio communication systems (International Telecommunication Union, 2016; John T. Kraus, 1988; Leslie W. Barclay, 2003).

The lowest region of the atmosphere, known as the troposphere, plays a dominant role in terrestrial and Earth-space radio wave propagation. The troposphere extends from the Earth's surface to an altitude of about 10–18 km depending on latitude, and it is characterized by strong vertical gradients of temperature, pressure, and humidity (World Meteorological Organization, 2018; International Telecommunication Union, 2016). Korak (2003) stated that in the troposphere, the propagation of electromagnetic waves is mostly affected by the composition of the atmosphere. Atmospheric water molecules are polar, meaning they possess permanent dipole moments, whereas most other atmospheric gases are nonpolar but can acquire induced dipole moments in the presence of electromagnetic fields. Consequently, when electromagnetic radiation propagates through the atmosphere, these molecular interactions lead to variations in radio refractivity, contributing primarily to

polarization, reflection, and scattering of the incident radiation (Robert Hall, 1979; John T. Kraus, 1988). One of the most important parameters used to describe the influence of the atmosphere on radio wave propagation is atmospheric radio refractivity. Radio refractivity is a convenient scaled representation of the refractive index of air and depends primarily on atmospheric pressure, temperature, and water vapour pressure. Even though the refractive index of air differs from unity by only a small amount, this slight deviation is sufficient to cause appreciable bending of radio waves over long distances. Consequently, small changes in refractivity especially its vertical gradient can lead to significant propagation anomalies such as sub-refraction, super-refraction, and ducting.

In tropical regions, atmospheric refractivity exhibits strong temporal variability due to pronounced seasonal changes in meteorological conditions. Nigeria, located within the tropical belt, experiences two major seasons: the wet (rainy) season and the dry season. The wet season is associated with high humidity, increased cloud cover, and frequent rainfall, while the dry season is characterized by lower humidity, higher surface temperatures, and the influence of dry continental air masses. These seasonal differences lead to substantial variations in the moisture content and thermal structure of the troposphere, which in turn affect radio refractivity and its vertical distribution (International Telecommunication Union, 2016; Leslie W. Barclay, 2003).

Seasonal variability of radio refractivity has direct implications for the planning, design, and operation of radio communication systems. During periods of high refractivity, radio signals may experience enhanced bending, leading to extended coverage and, in some cases, interference beyond the intended service area. Conversely, low refractivity and weak refractivity gradients may result in reduced signal bending, shortened radio horizons, and possible coverage gaps. For radar systems, seasonal changes in refractivity can influence beam height estimation and target detection, while for terrestrial microwave links, they can affect path clearance and signal availability (John T. Kraus, 1988; Louis J. Ippolito, 2008).

Despite the practical importance of refractivity studies, accurate characterization of atmospheric refractivity remains challenging due to the dynamic nature of the lower atmosphere and limited availability of vertical meteorological data. In many developing regions, including Nigeria, routine radiosonde observations are sparse, and refractivity studies often rely on surface meteorological measurements obtained from weather stations. Nevertheless, surface-based refractivity analysis, when carried out systematically and over sufficient time periods, provides valuable insight into the prevailing propagation conditions of a given location (Bean and Dutton, 1966; World Meteorological Organization, 2018).

Several studies have investigated atmospheric radio refractivity across different regions of Nigeria. In 2019, an analysis of several Northern Nigerian stations was carried out

by Tanko et al., who found that radio refractivity exhibits notable seasonal variability, with higher values during the wet season (associated with high humidity and rainfall) and lower values during the dry season (characterized by reduced moisture). For example, among the stations studied (including Abuja, Lafia, Bauchi, Kaduna, Maiduguri, and Sokoto), the maximum refractivity reached about 385 N-units in August (wet season), while the minimum was about 282 N-units in March (dry season) (Tanko *et al.*, 2019).

Similarly, Akpootu and Iiyasu (2017) and Akpootu et al. (2024) have conducted several studies on tropospheric radio refractivity across different locations in Nigeria, showing consistent seasonal patterns and the strong influence of climatic variables on refractivity and its components.

In a recent study focusing on Bauchi in northeastern Nigeria, long-term monthly meteorological data (1981–2021) were used to compute surface radio refractivity using standard ITU-R formulations. The results revealed clear seasonal variation, with the highest average refractivity (≈ 355.03 N-units) occurring in August (wet season) and the lowest (≈ 273.26 N-units) in February (dry season). This confirms that radio refractivity is greater in the rainy season due to enhanced atmospheric moisture, in agreement with similar findings across Nigeria (International Telecommunication Union, 2016; Akpootu *et al.*, 2024). Also Agbo *et al.*, (2021) Study Daily and Seasonal Variations of Tropospheric Radio Refractivity at Akure in South- Western Nigeria using Campbell Scientific Automatic Weather Instrument and find out that the refractivity is higher during the rainy season than the dry season and carried out statistical regression analysis which show a strong positive correlation between refractivity and three meteorological parameters (relative humidity, temperature and pressure).

This study therefore aims to provide a detailed seasonal analysis of atmospheric radio wave refractivity over Gombe, Gombe State, Nigeria, using two years (2021–2022) of surface Meteorological data obtained from the Nigerian Meteorological Agency (NiMET). By estimating radio refractivity, refractivity gradient, and effective Earth radius factor.

II. THEORETICAL BACKGROUND OF THE STUDY

The troposphere is mainly described by three key atmospheric conditions: pressure, temperature, and relative humidity. Changes in these conditions affect the refractive index of air, which in turn influences how radio waves travel. When the refractive index varies significantly with height, it causes radio waves to bend, and this effect can be noticeable across all frequencies. Microwave signals, in particular, propagate through the troposphere, which is the lowest layer of the atmosphere and is not ionized. The refractive index of air is defined as (Otasun and Edekon, 2015).

$$n = \sqrt{\epsilon_r} = \frac{c}{v} \quad (1)$$

Where ϵ_r is the dielectric constant of the troposphere, c is the speed of light and v is the phase velocity of the wave in the medium.

However the refractive index of the troposphere is very important in predicting radio communication links which is mainly caused by the variation of Temperature (K), Pressure (mb), and Relative humidity in percentage (%). The radio refractivity N_s can be calculated using ITU-R (2016): as

$$N_s = N_{dry} + N_{wet}$$

Where N_s is the surface radio refractivity

The dry term of radio refractivity is given by:

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

The wet term of radio refractivity is given by:

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

Combining the above two equation:

$$N_s = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}$$

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \tag{2}$$

Where P is the atmospheric pressure, T is the absolute temperature in degree Kelvin and e is the partial pressure due to water vapor in millibar. The value of N varies with altitude since pressure, temperature and humidity normally decrease exponentially with height. Thus variation can be approximated using an exponential relationship.

The exponential refractivity model is expressed as:

$$N(h) = N_o e^{-\frac{h}{H}} \tag{3}$$

Where $N(h)$ radio refractivity at height (N -units), h height above earth surface, N_o Surface refractivity

(N -units), e is exponential constant and H is the refractivity scale height (km), in tropical region like.

Nigeria the scale height is usually around 7.35km

The water vapour pressure, e is given by:

$$e = \frac{RHe_s}{100} \tag{4}$$

Where RH is the relative humidity in percentage (%) and e_s is the saturated vapour Pressure.

The saturated vapour pressure e_s is given by:

$$e_s = 6.112e^{\left(\frac{17.502T}{T+240.97}\right)} \tag{5}$$

Where T is the value of temperature in degree Celcius ($^{\circ}C$)

The refractive index, n and refractivity, N are related by the equation given as (Otasou and Edekon,2015):

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

The refractivity gradient is thus defined as (Otasou and Edekon, 2015):

$$G = \frac{dN}{dh} \tag{7}$$

In a layered atmosphere for a ray at grazing angle, Snell;s law in spherical coordinates gives:

$$n(r)r \sin \theta = \text{const} \tan t \tag{8}$$

Where r is the distance from earth center, θ is the angle between the ray and vertical.

For near-horizontal ray $\theta=90^{\circ}$, so $\sin \theta=1$ and

$$n(r)r = \text{const} \tan t \tag{9}$$

Differentiating the above equation with respect to path length s .

$$\frac{d(nr)}{ds} = r \frac{dn}{ds} + n \frac{dr}{ds} = 0$$

For a near-horizontal ray $\frac{dr}{ds}$ is the change in height per unit path. The curvature $\kappa = \frac{1}{r_{ray}}$ is defined by

$$\frac{1}{r_{ray}} = -\frac{1}{n} \frac{dn}{dh} \tag{10}$$

The minus sign means if n decreases with height, ray curves downward.

For air $n=1.000315 \ll 1$ then $\frac{1}{r} = -\frac{dn}{dh}$, equation (6), becomes.

$$\frac{1}{r} = -10^{-6} \frac{dN}{dh}$$

Let us assume that the earth radius is modified. The effective earth radius is given by

$$R_e' = kR_e \tag{11}$$

R_e is the true earth radius = 6371km, k is the effective earth radius factor.

The effective Earth radius is defined so that a curved ray over the true Earth look like a straight ray over a sphere of radius R_e'

$$\frac{1}{kR_e} = \frac{1}{R_e} - \frac{1}{r} \quad \text{Which implies} \quad \frac{1}{k} = 1 + R_e 10^{-6} \frac{dN}{dh}$$

Therefore

$$k = \frac{1}{1 + 0.006371 \frac{dN}{dh}} \tag{12}$$

Table 1 Table of Radio Refractivity Propagation Condition

Refractivity Gradient (N-unit/km)	Propagation condition	k-factor
G > 39	Sub- refraction	k < 1.33
G = -39	Standard Atmosphere	k = 1.33
G < -39	Super refractivity	k > 1.33
Very negative	Ducting	k >>1.33

III. MATERIALS AND METHOD

➤ Materials

The data used were obtained from the Nigerian Meteorological Agency (NiMet) for the period of two years (2021 – 2022) for Gombe at an altitude of 523m above sea level. Data obtained were atmospheric parameters such as relative humidity, temperature, atmospheric pressure, recorded hourly which were averaged to monthly values, during synoptic hours in the meteorological enclosure with respect to each instrument and the time of measurement.

➤ Method

The surface refractivity calculated directly from the data obtained (temperature in kelvin, pressure in *hPa* and relative humidity) as input to equation (2), the radio wave refractivity at a height 1km, $N(h)$ was calculated using refractivity exponential equation (3). The refractive gradient, G was obtained using equation (7) and finally the effective earth factor which is sometimes called the earth k-factor was determined from the equation (12).

IV. RESULTS AND DISCUSSION

➤ Results

The results obtained was presented in tables and figures:

Table 2 Refractivity, Refractivity Gradient and k-Factor for the Year 2021

Months	Refractivity (N-UNITS)	Refractivity GRADIENT (G) (N-units/km)	Earth Radius FACTOR (k)
January	300	-38	1.32
February	288	-37	1.30
March	315	-40	1.34
April	328	-42	1.36
May	362	-46	1.41
June	367	-47	1.42
July	369	-47	1.43
August	372	-47	1.43
September	371	-47	1.43
October	383	-49	1.45
November	339	-43	1.38
December	292	-37	1.31
Mean		-43	1.38

Table 3 Refractivity Values for the Year 2022

Months	Refractivity (N-UNITS)	Refractivity GRADIENT (G)(N-unit/km)	Earth Radius FACTOR (K)
January	292	-37	1.33
February	279	-35	1.31
March	287	-36	1.32
April	348	-44	1.42
May	366	-47	1.46
June	368	-47	1.46
July	359	-46	1.44
August	369	-47	1.46
September	369	-47	1.46
October	310	-39	1.36
November	305	-39	1.35
December	288	-37	1.33
Mean		-42	1.39

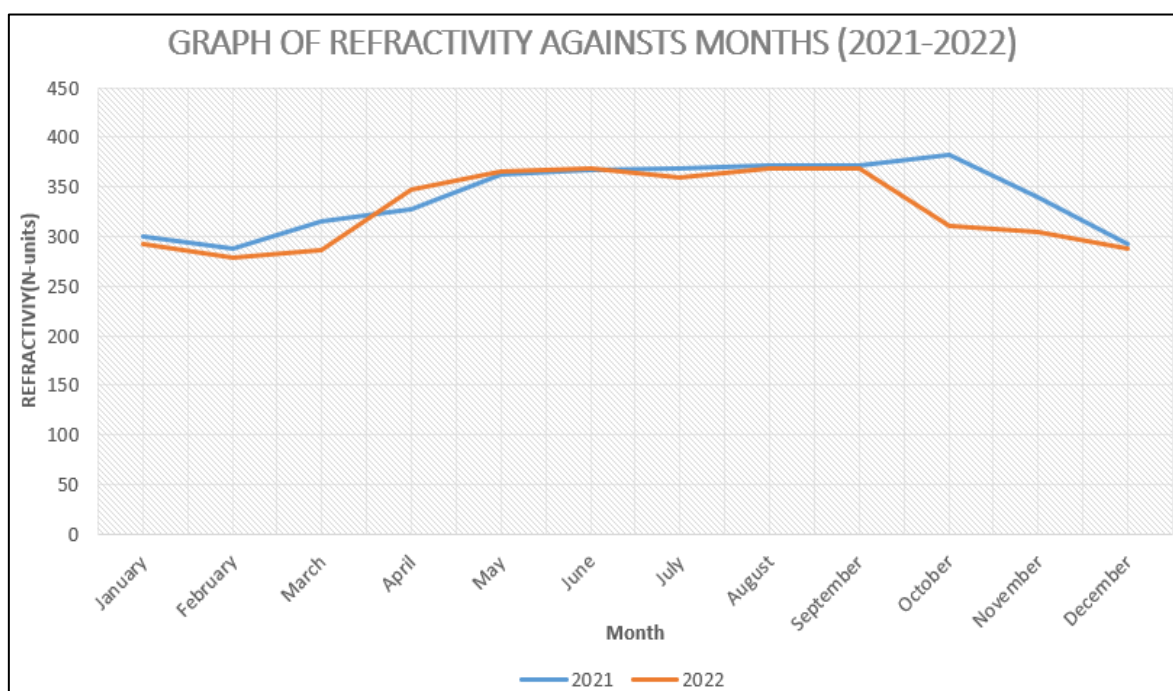


Fig 1 Graph of Refractivity Against Months for the Year 2021, 2022

➤ Discussion

Table 2 : Presents the monthly variation of surface radio refractivity (*N*), refractivity gradient (*G*), and effective Earth radius factor (*k*) for the year 2021.

A clear seasonal pattern is evident in the refractivity values. The lowest refractivity values occur during the dry season months, particularly February (288 N-units) and January (300 N-units). This reduction is primarily due to low atmospheric moisture content, as water vapour significantly contributes to the wet term of refractivity. During this period, the atmosphere is dominated by dry continental air masses, resulting in reduced dielectric polarization and hence lower refractivity.

As the year progresses into the wet season, refractivity increases steadily, reaching high values between May and October, with a peak of 383 N-units in October. This increase is attributed to high relative humidity and elevated water

vapour pressure associated with rainfall and cloud formation. The wet term of refractivity becomes dominant, leading to enhanced refractive index variations.

The refractivity gradient (*G*) ranges from -37 to -49 N-units/km, with a mean value of -43 N-units/km. Comparing these values with the standard atmospheric gradient (-39 N-units/km), it is observed that most months exhibit gradients more negative than the standard. This indicates the predominance of super-refractive conditions throughout much of the year, especially during the wet season months (June–October), where gradients reach as low as -47 to -49 N-units/km.

The effective Earth radius factor (*k*) varies between 1.30 and 1.45, with an average of 1.38. Since most *k*-values exceed the standard value of 1.33, this further confirms the dominance of super-refraction. The highest *k*-factor (1.45 in October) corresponds to the highest refractivity and strongest

negative gradient, showing a direct relationship between atmospheric moisture content and propagation conditions.

Overall, the results for 2021 indicate that radio wave propagation over Gombe is largely influenced by seasonal meteorological conditions, with enhanced signal bending and extended propagation ranges occurring during the rainy season.

Table 3: presents the corresponding results for the year 2022, allowing for comparison with the 2021 dataset.

The refractivity values follow a similar seasonal trend as observed in 2021. The lowest values occur during the dry season, with February recording the minimum value of 279 N-units, followed by January (292 N-units). These low values are consistent with reduced atmospheric humidity and confirm the strong dependence of refractivity on moisture content.

During the wet season, refractivity increases significantly, reaching peak values of about 369 N-units in August and September. Although slightly lower than the peak observed in 2021, the pattern remains consistent, indicating stable climatic control over refractivity behavior in the region.

The refractivity gradient ranges from -35 to -47 N-units/km, with a mean value of -42 N-units/km. In the early months of the year (January–March), the gradient is closer to the standard atmospheric value, suggesting near-normal or weak super-refraction conditions. However, from April onward, the gradient becomes more negative, indicating a transition into strong super-refractive conditions during the wet season.

The k -factor ranges from 1.31 to 1.46, with a mean of 1.39. As in 2021, most values exceed 1.33, confirming that super-refraction is the dominant propagation condition in 2022. The highest values of k (1.46) occur during peak rainy months (May–September), further emphasizing the role of atmospheric moisture in enhancing radio wave bending.

In summary, the 2022 results validate those of 2021, showing consistent seasonal variation and confirming that super-refractive conditions are prevalent in the study area.

Figure 1: illustrates the variation of refractivity with months for both 2021 and 2022, providing a visual representation of seasonal trends.

The graph shows a gradual increase in refractivity from January through the middle of the year, reaching a maximum during the wet season (around August–October), followed by a decline toward December. This pattern is consistent for both years, demonstrating strong seasonal reproducibility.

The close alignment of the two curves indicates that refractivity variation in Gombe is not random but is strongly controlled by predictable climatic cycles. Minor differences between the two years reflect natural variations in

meteorological parameters such as rainfall intensity and humidity levels.

The steep rise in refractivity during the onset of the rainy season (April–May) highlights the rapid increase in atmospheric moisture, while the gradual decline after the peak season reflects the transition back to dry conditions.

This graphical analysis reinforces the numerical results in Tables 2 and 3 and clearly demonstrates that atmospheric water vapour is the dominant factor influencing refractivity in the region.

V. CONCLUSION

The study has demonstrated that atmospheric radio refractivity over Gombe, Northeastern Nigeria, exhibits strong seasonal variability driven primarily by changes in atmospheric moisture content.

Refractivity values are significantly higher during the wet season due to increased relative humidity and water vapour pressure, while lower values are observed during the dry season as a result of reduced moisture content. This seasonal contrast clearly indicates that the wet component of refractivity plays a dominant role in tropical environments.

The refractivity gradient values obtained for both 2021 and 2022 are predominantly more negative than the standard atmospheric value of -39 N-units/km. This indicates that super-refractive conditions prevail over the study area for most of the year, particularly during the rainy season. The corresponding k -factor values, which are generally greater than 1.33, further confirm this observation.

The implication of these findings is that radio waves propagating through the troposphere over Gombe experience enhanced downward bending, leading to extended radio horizons and improved signal coverage during the wet season. However, this may also increase the likelihood of interference between communication systems operating on similar frequencies.

During the dry season, refractivity and its gradient approach standard atmospheric conditions, resulting in reduced bending of radio waves. This may lead to shorter communication ranges and potential signal degradation, especially for terrestrial microwave and radar systems.

The consistency observed between the 2021 and 2022 datasets suggests that the refractivity characteristics of the region are stable and largely governed by climatic patterns. This predictability is advantageous for the planning and design of communication systems, as seasonal effects can be anticipated and incorporated into system optimization.

In conclusion, the study provides valuable insight into the seasonal behavior of atmospheric refractivity and its impact on radio wave propagation in a tropical environment. The findings highlight the importance of incorporating local atmospheric conditions into the design, planning, and

operation of reliable radio communication systems. Future studies may extend this work by incorporating long-term datasets and vertical atmospheric profiles to further improve the accuracy of propagation models in the region.

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