Science World Journal Vol. 19(No 1) 2024
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

EXPLORING VERTICAL GRADIENTS OF RADIO REFRACTIVITY AND THEIR SIGNIFICANCE FOR RADIO WAVE PROPAGATION IN ABUJA, JOS AND MAKURDI OF NORTH-CENTRAL NIGERIA

*[1]Usman S.L., [2]Ikechiamaka F.N., [2]Akinbolati A., [1]Owolabi J.A., [1]Akusu C.O.

[1]Department of Physics, Nigerian Defence Academy, Kaduna, Nigeria
[2]Department of Physics, Federal University Dutsin-Ma, Nigeria

*Corresponding Author Email Address: usmansakinat885@gmail.com

ABSTRACT
Vertical radio refractivity gradients are essential for monitoring propagation conditions when designing and planning terrestrial radio links for communications in the lower atmosphere. Average data gathered from meteorological factors such as temperature, pressure, and relative humidity was used from 1980 to 2020 n this study. This study focuses on the vertical gradient of radio refractivity within the lower atmospheric layer, investigating its influence on factors like signal propagation, route clearance, and line-of-sight communication. The analysis encompasses three cities - Abuja, Makurdi, and Jos. In Figure 2 monthly average changes in the refractivity gradient are presented for Abuja. In addition, the seasonal radio refractivity gradient shows mean values of -110.000N/km for Abuja which shows that the refractivity condition is Super-Refraction, -77.553N/km for Jos which shows that the refractivity condition is Normal-Refraction and -97.209N/km for Makurdi which shows that the refractivity condition is Normal-Refraction respectively. Higher gradient values, G1, G2, and G3 were observed during the dry season (December-February) which could be attributed to dry air and steeper refractivity gradients. In contrast, lower gradient values were observed during the wet season (June-October) due to increased atmospheric moisture. Similarly, measured vertical radio refractivity gradient data, G1 N/km, G2 N/km, and G3 N/km for Jos displayed consistent fluctuations throughout the year. Similarly, measured vertical radio refractivity gradient data, G1 N/km, G2 N/km, and G3 N/km for Jos displayed consistent fluctuations throughout the year. Notably, wetter months exhibit higher refractivity gradient values, while drier months show lower values. G2 consistently records the highest gradient values, and despite varying magnitudes, the trends remain consistent. Finally, measured vertical radio refractivity gradient data, G1 N/km, G2 N/km, and G3 N/km for Makurdi indicate distinct fluctuations with the most negative values observed in November and December. The Dry Season witnesses relatively lower gradient values, while the Transition and Wet Seasons experience rising values, influenced by atmospheric shifts. The Higher negative values during the wet season suggest pronounced variations in the refractive index, affecting radio wave propagation. These findings emphasize the significance of refractivity gradient variations and their implications for radio wave behaviour particularly during different seasons.
Keynotes: Terrestrial radio links; meteorological variable; vertical radio refractivity gradient.

INTRODUCTION
Radio waves constitute a form of electromagnetic radiation found at the longer wavelength end of the electromagnetic spectrum. They encompass frequencies ranging from 3 kHz to as high as 300 GHz. These waves are utilized in various applications, including Frequency-modulated (FM) radio in the megahertz (MHz) range and Amplitude-modulated (AM) radio, commonly functioning within the kilohertz (kHz) range. The behavior of electromagnetic waves, especially within the troposphere, the lower atmospheric layer where meteorological phenomena occur, is substantially influenced by the atmospheric composition. The troposphere's dynamic nature, characterized by fluctuations in temperature, pressure, and relative humidity, plays a pivotal role in wave propagation. Variations in these factors lead to changes in the refractive index of air within this layer, which in turn affects the velocity of radio waves. Consequently, the non-uniformity of the atmosphere causes radio waves to experience curvatures during transmission, resulting in signal distortions and potential interference. A key determinant of radio wave behavior is the refractive index denoted by 'n,' a function of refractivity 'N.' This refractive index causes the bending of propagation paths, leading to disparate arrival times for identical signals traversing different routes. Such bending is responsible for the phenomenon of sub-refraction, super-refraction, and ducting in radio wave propagation. Central to atmospheric behaviour is the vertical gradient of refractivity, referred to as 'G.' Profiles of G values offer insights into propagation characteristics, aiding in the prediction of signal paths and aiding in the construction of communication stations for varying radio frequencies. A negative gradient causes signals to curve downward, while a positive gradient directs signals upwards and away from the line of sight. An accurate understanding of the vertical radio refractivity gradient, particularly when it relates to the atmosphere's radio refractivity, is crucial for radio engineers. This understanding facilitates precise forecasts of electromagnetic radio wave signals and informs the design of communication stations for different frequency ranges. Consequently, the utilization of meteorological data collected over the years specifically between 1980 and 2020, supports the examination of the vertical refractivity gradient within select states of North Central Nigeria. There are some related works. Oyedum and Gambo (1994) examined diurnal and seasonal variations of surface refractivity in Minna North Central, Nigeria. The study utilized four years of in-situ meteorological data from eight locations across Nigeria. It was observed that the diurnal refractivity variation was primarily influenced by the dry term in the rainy season and the wet term in the dry season. Results showed higher values during the wet season compared to the dry season. However, the study did not consider refractivity for high altitudes, which warrants further investigation. Gunashekar (2006) investigated the propagation of 2 GHz radio waves over sea paths in the English Channel. The

Science World Journal Vol. 19(No 1) 2024
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

study examined the relationship between specific over-sea propagation mechanisms (such as evaporation ducting and super-refraction) in the lower troposphere and signal strength distribution patterns, correlating them with meteorological parameters. Signal strength enhancements were observed during the late afternoon and evening periods in the spring and summer months. The study emphasized the importance of these findings for planning radio communication systems operating in marine and coastal regions on the UHF band. Olalekun et al., (2007) characterized secondary radio climatic variables for microwave and millimeter-wave link design in Nigeria. They analyzed secondary data obtained from five different regions in Nigeria over a five-year period (2009-2013). The study found that the k-factor values and geoclimatic factor (K) were higher the prescribed values of 1.33 by the ITU, suggesting that the results could serve as a valuable tool for microwave wireless link design in Nigeria. Adadiji and Adewole (2008) studied the vertical refractivity gradient in Akure, Nigeria, by measuring atmospheric variables using integrated sensor suits (ISS) at various heights above ground level. The measurements were made every 30 minutes using wireless weather stations positioned at different heights. The study showed that propagation conditions varied throughout the year, with sub-refraction prevalent between January and July, and super-refraction and ducting occurring mostly between August and December. Further research using long-term data and additional locations in the South Local Government Area of Ondo could provide more insights. Radio wave propagation is influenced by changes in the radio refractive index of air in the troposphere (Adediji and Ajewole, 2008). The changes can lead to the abrupt changes in propagation direction of a radio wave in the troposphere resulting in attenuation of signal. Based on this premise, studies on radio refractivity have become sacrosanct for radio engineers and scientists for the proper planning of radio links, power budget and coverage areas.

The Theory of Vertical Refractivity Gradient

The distinction between the speed of radio energy in a vacuum and its speed in a specific medium is referred to as the radio refractive index. This index, denoted as 'n,' decreases from 1.0003 at the near-Earth troposphere's surface to a value of unity (n = 1.0) at the uppermost layer of the atmosphere. Alternatively, the refractive index can be expressed more conveniently using the dimensionless parameter of refractivity, 'N.' This parameter quantifies the deviation of the refractive index from unity in terms of parts per million

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

Where N can be expressed in terms of wet term and dry term by

$$N = Ndry + Nwet = 77.6\frac{Pd}{T} + 72\frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} \text{ (N-units)} \tag{2}$$

The dry term of the radio refractivity, Ndry, is:

$$Ndry = 77.6\frac{Pd}{T} \tag{3}$$

Nwet term of the radio refractivity, Nwet, is:

$$Nwet = 72\frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2} \tag{4}$$

Where:
Pd is dry atmospheric pressure (hPa)
P is the total atmospheric pressure (hPa)
e is water vapour pressure(hPa)
And *T* is the absolute temperature (K).

And P= Pd+e (5)

Equation (2) may be used for radio frequencies up to 100 GHz. The error associated with the use of this expression is less than 0.5% (ITU-R, 2019).

The water vapor pressure *e* is usually calculated from the relative humidity, and saturated water vapor, using the expression: (ITU-R, 2019).

$$e = \frac{H.e_s}{100} \tag{6}$$

With:

$$e_s = EF.a.\exp\left[\frac{\left(b - \frac{t}{d}\right)t}{t + c}\right] \tag{7}$$

And:

$$EF = 1 + 10^{-4}\left[7.2 + P.\left(0.0320 + 5.9 \times 10^{-6} t^2\right)\right]$$

Where:

T is temperature $\left({}^oC\right)$
P is the total atmospheric pressure(hPa)
H is relative humidity (%),
es is saturation vapor pressure(hPa) at the temp t $\left({}^oC\right)$
a=6.1121
b=18.678
c=257.14
d=234.5

In general, variations in temperature (T), atmospheric pressure (P), and water vapour (e). The differentials of Eqn. 2 also revealed the relative relevance of these parameters (T, P, and e), particularly water vapour content: defined as the amount of variation from the

$$\partial N = 77.6\frac{\partial P}{T} - \left(77.6\frac{P}{T^2} + 7.46 \times 10^5 \frac{P}{T^3}\right)\partial T + 3.73 \times 10^5 \frac{\partial e}{T^2} (N - units) \tag{8}$$

For typical atmospheric conditions, pressure P= 1000hPa, relative humidity RH= 60%, temperature K= 290K and vapour pressure e= 13.7hPa. Eqn. 8 reduces to:

$$\partial N = 0.268\partial P - 1.132\partial T + 4.435\partial e \tag{9}$$

As can be seen from Eqn. 9, the contribution of e to the gradient of radio refractivity for a given change in radio refractivity is greater than that of T and P. This results mostly from the polarization of water vapour molecules upon interaction with the radio wave. Because of this action, the dielectric constant of water vapour rises, resulting in a proportionally bigger contribution to ∂N than to T and P. In a conventional atmosphere, P, T, and e likewise decrease with height, resulting in a gradient of N that is decreasing at a rate of 40 N/km.

The vertical radio refractivity gradient G (N-units/km) at the level is expressed as Adeyemi & Adedayo (2005).

$$G = \frac{dN}{dh} = -7.32 \exp(0.005577N) \text{ (N – units/ Km)} \quad (10)$$

Where 'N' represents the values of radio refractivity. When evaluating route clearance and propagation effects, the vertical refractivity gradient within the lowest atmospheric layer emerges as a pivotal factor. The gradient's values play a significant role in inducing propagation conditions such as sub-refraction, super-refraction and ducting (ITUR, 2019). Sub-refraction is marked by dN/dh > -40 N-units/km and a greater positive refractivity gradient 'G.' This configuration results in a diminished propagation range for radio wave signals as they move away from the Earth's surface and the line of sight. In extreme scenarios, radio transmissions might even be redirected into space. Conversely, under super-refractive conditions, dN/dh becomes less than -40 N-units/km, and 'G' assumes a more negative value. In this case, the radius of curvature for the radio wave path is smaller than the Earth's radius. Consequently, as rays ascend from the transmitting antenna, they undergo total internal reflection within the troposphere and return to Earth at a distance from the transmitter. This phenomenon extends the propagation distance. During ducting occurrences, radio waves exhibit a pronounced downward curvature exceeding that of the Earth. This corresponds to situations where (dN/dh -157 N-units/km). In scenarios exceeding the usual horizon, two phenomena arise: radio waves remain closely aligned with the Earth's surface, and the refractivity gradient must maintain a constant value over a height spanning several wavelengths. This arrangement facilitates the generation of exceptionally high signal intensities at extended ranges well beyond the line of sight through a process akin to waveguide propagation, known as ducting. As a result, signal strength could surpass its free space value (Okoro and Agbo 2012). In instances of uniform propagation circumstances occurring in a vacuum, where critical positive refraction is observed, radio wave signals will travel in straight paths.

METHODOLOGY

Source of Data

Monthly and yearly summaries of temperature, pressure, and humidity data for seven stations (Abuja, Makurdi and Jos) were sourced from the Nigerian Meteorological Agency (ECMRF-ERA5). The ECMRF-ERA5 maintains synoptic or observatory stations within the Federal Capital Territory, Abuja, which are recognized as Data Points by the International Meteorological Organization (WMO). These stations, namely Abuja, Jos (Plateau State), and Makurdi, serve as observatories or data collection sites for the North Central Region (Benue State). Notably, these weather stations are equipped with qualified meteorologists certified by the WMO. Within these observatories or data sites, a comprehensive suite of weather measurement instruments is available, encompassing rain gauges for precipitation measurement, thermometers for temperature assessment, barometers for air pressure evaluation, and hygrometers for relative humidity measurement. ECMRF-ERA5 collected data throughout the year at defined intervals, including half-hourly, hourly, and daily, on a national scale.

The data utilized for this study encompassed a 41-year duration, spanning from 1980 to 2020, and was sourced from the stations.

Figure 1: Map of Nigeria indicating the Study Area

RESULTS AND DISCUSSION

Analyzing the monthly mean variations in refractivity gradient (Ns, N100, and N250) changes across the cities of Makurdi, Abuja, and Jos from 1980 to 2020 resulted in the findings illustrated in Figures 2 to 5, respectively.

ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

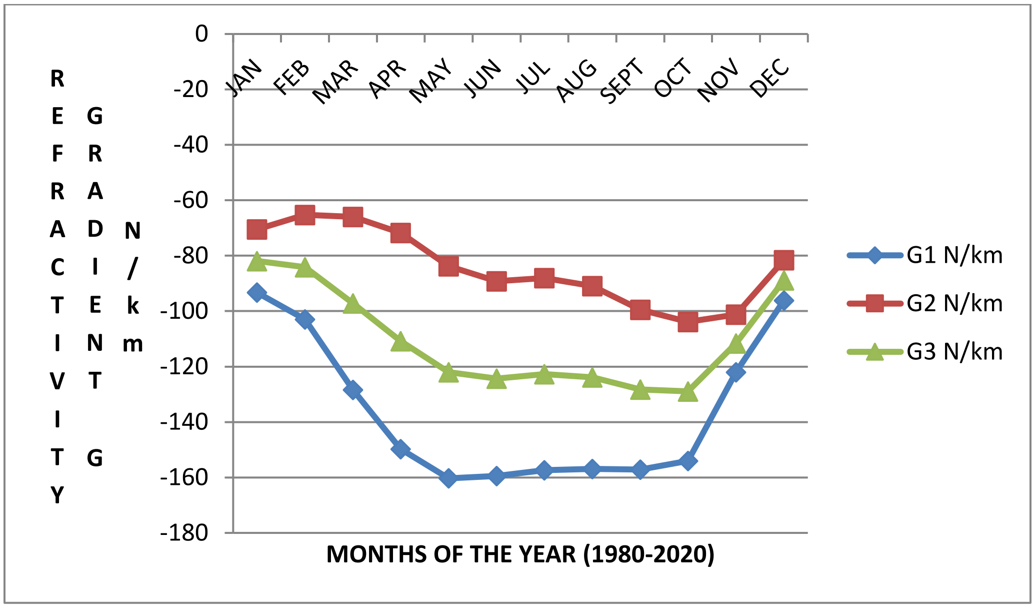

Figure 2: Yearly Vertical Radio Refractivity Gradient Monthly Average Variations across Abuja (1980-2020).

Figure 2 illustrates the monthly average changes in this gradient over Abuja from 1980 to 2020. The data is presented in three measurements: G1 N/km, G2 N/km, and G3 N/km, all exhibiting super refraction patterns throughout the year. These values display a distinct annual cycle, with certain months showing higher or lower values. During the Dry Season (December to February), G1, G2, and G3 experience relatively higher gradient values, such as -102.90N/km for G1 in February and -81.5681N/km for G2 in December. This could be attributed to the presence of drier air with lower moisture content, resulting in steeper refractivity gradients. In contrast, the Wet Season (June to October) sees lower gradient values, like -154.015N/km for G1, -88.0011N/km for G2, and -122.0370N/km for G3. This decrease could be linked to higher atmospheric moisture content leading to smoother refractivity gradients. Despite variations in magnitude, G1, G2, and G3 consistently follow similar trends over the years, suggesting persistent behaviour in the vertical radio refractivity gradient. The observed patterns align with the notion that drier air during the dry season and increased moisture during the wet season impact gradient values. Steeper gradients during the dry season can cause greater bending and scattering of radio waves as they traverse the atmosphere (Valina et al., 2011).

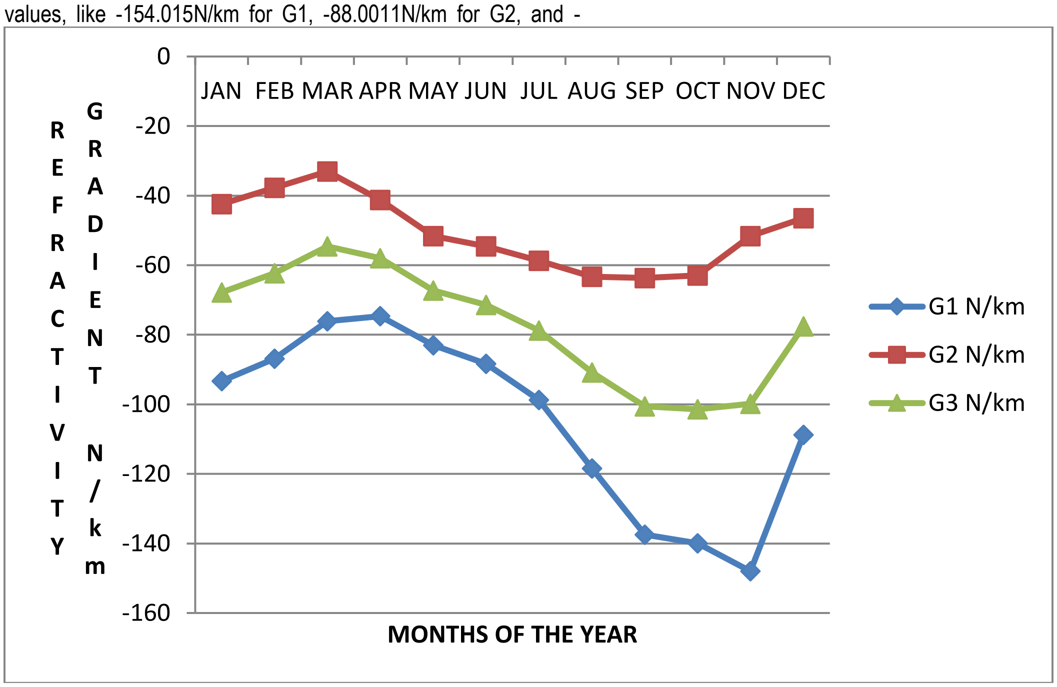

Figure 3: Monthly Average Variations of Vertical Radio Refractivity Gradient over Jos in the year (1980-2020).

Science World Journal Vol. 19(No 1) 2024
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

The vertical gradient of radio refractivity in the lowest atmospheric layer is a critical determinant of the effects on terrestrial line-of-sight links, encompassing ducting, surface reflection, and multipath interactions. This phenomenon is exemplified in Figure 3. The graph depicts the monthly average variations of vertical radio refractivity gradient (G) over Jos spanning from 1980 to 2020. The dataset includes three measurements: G1 N/km, G2 N/km, and G3 N/km. All three measurements exhibit consistent patterns of fluctuations throughout the year. Notably, there is a distinct peak in refractivity gradient values during wetter months, especially from June to September, while lower values are observed in drier months such as December and January. During the Wet Season (June to September), G1, G2, and G3 experience their highest values. This trend is likely influenced by increased atmospheric moisture content and higher temperatures, impacting the vertical gradient of refractivity.

In the Dry Season (December to February), refractivity gradient values are generally lower. This trend could be linked to drier air conditions and reduced temperature gradients within the atmosphere. Among the three measurements, G2 consistently records the highest gradient values, followed by G1 and G3. Despite varying magnitudes, the trends remain consistent across all three measurements, indicating a uniform vertical refractivity gradient behaviour. Elevated refractivity gradient values during the wet season can be attributed to heightened atmospheric moisture levels, which affect both the gradient itself and the propagation characteristics of radio waves. Conversely, lower refractivity gradient values during the dry season might be due to cooler and drier conditions, resulting in less pronounced variations in the refractive index with altitude. These fluctuations in refractivity gradient have a significant impact on the refraction and propagation of radio waves through the atmosphere. Higher refractivity gradients during wetter months could contribute to increased bending and scattering of radio waves, potentially influencing their paths and the quality of reception (Olalekan 2023).

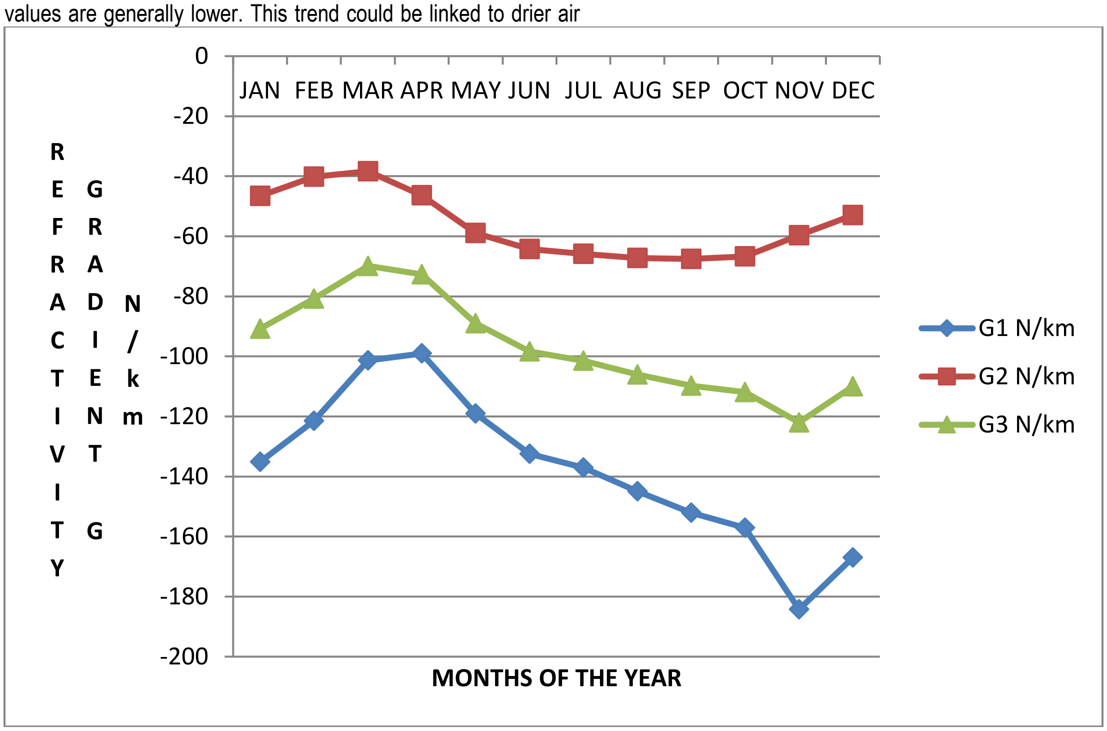

Figure. 4 shows annual average monthly variations in the vertical radio refractivity gradient above Makurdi (1980-2020).

The data provided presents a graph illustrating the monthly average variations in the vertical radio refractivity gradient over Makurdi from 1980 to 2020. The dataset encompasses three measurements: G1, G2, and G3, representing distinct vertical refractivity gradients at varying altitudes.

G1 values exhibit a distinct pattern of fluctuations across months, with the most negative values occurring in November and December, and the lowest values observed in March. This pattern indicates a relatively more negative refractivity gradient during the latter part of the year. G2 shows similar monthly fluctuations, with higher negative values in November and December, and the lowest values in March. This overall trend highlights intensified refractivity gradient changes in the second half of the year. G3 follows suit, with the highest negative values also found in November and December, and the lowest values in March. This reinforces the trend of heightened refractivity gradient towards the year's end.

Throughout the Dry Season (December to February), all three measurements (G1, G2, and G3) consistently exhibit relatively lower refractivity gradient values. This aligns with cooler and drier atmospheric conditions. During the Transition Season (March to May), refractivity gradient values start to rise, indicating the transition from the dry to the wet season.

The Wet Season (June to September) sees a continued increase in refractivity gradient values, potentially due to higher moisture levels and associated temperature changes during the rainy season. During the Late Wet Season to Early Dry Season (October to November), a significant peak in the refractivity gradient occurs as the wet season transitions back to the dry season.

All three measurements consistently follow similar patterns, indicating coherence in the behaviour of the refractivity gradient at different altitudes. November stands out with notably high negative values in G1, G2, and G3, suggesting specific atmospheric dynamics or weather patterns during that month. The observed variations in refractivity gradient values reflect changes in atmospheric conditions and how the refractive index changes with altitude. Higher negative values during the wet season imply that the vertical refractivity gradient becomes more pronounced during this period, likely due to increased moisture and temperature variations.

CONCLUSION

This research has provided valuable insights into the behaviour of vertical radio refractivity gradients in the lower atmospheric layer across different cities in Nigeria. The analysis focused on Abuja, Makurdi, and Jos, spanning the years 1980 to 2020. The consistent patterns observed in the monthly average refractivity gradient changes reflect the influence of seasonal variations and atmospheric conditions on radio wave propagation.

Overall, the research underscores the intricate relationship between atmospheric conditions and vertical refractivity gradients. This relationship has far-reaching implications for radio wave propagation and communication systems. The findings contribute to a deeper comprehension of how atmospheric factors influence radio signals behaviour and propagation paths, thus aiding in the optimization of communication networks and signal reliability under varying meteorological conditions.

REFERENCES

Abu-Almal A and Al-Ansai K (2010). Calculation of effective earth radius and point refractivity gradient in UAE. *International Journal of Antennas and Propagation*. Vol. Article ID 245070.

Adedeji A.T and Ajewole M.O (2008) vertical profile of radio refractivity gradient in Akure south-west Nigeria progress in Electromagnet Research C, vol.4,157-168.

Adediji A.T., and Ajewole M.O. (2008). Vertical profile of radio refractivity gradient in Akure south-west Nigeria. *Progress in Electromagnetics Research* C, Vol.4,157-168.

Adediji, A. T., and Ajewole, M. O. (2010). Microwave Anomalous Propagation (AP) Measurement over Akure South-Western Nigeria, *Journal of atmospheric and solar-Terrestrial physics*, vol.72, pp 550-555.

Adediji, A. T., Ajewole, M. O., and Falodun, S. E. (2011). Distribution of radio refractivity gradient and effective earth radius factor (k-factor) over Akure, South Western Nigeria*, Journal of atmospheric and solar-Terrestrial physics*, vol. 73, pp 2300-2304

Adediji, A. T., Mahamod, I., and Mandeep, J. S. (2013). Variation of radio field strength and radio horizon distance over three stations in Nigeria, *Journal of atmospheric and solar-Terrestrial physics,* vol. 109, pp 1-6

Adeyemi, B. and Adedayo, K. D. (2005). "Atmospheric radio refractivity and water vapour density Oshodi and Kano, Nigeria". Nigerian Journal of Pure and Applied Physics, Vol. 4, No.1, pp.11 – 12.

Akinbolati, A., and M. O. Ajewole (2020). Investigation of path loss and modeling for digital terrestrial television over Nigeria, *Elsevier Heliyon https:// dol.org/10.1016/j.heliyon. 2020,e04101.*

Akinbolati, A., Akinsanmi O., Ekundayo K. R. (2016) signal strength variation propagation profile UHF radio wave channel in Ondo State Nigeria. July 2016, *International journal of microwave and wireless technology* 6(4)

Ajayi, G.O (1989) 'Physics of the tropospheric radio propagation.' A proceeding of the ICTP College on Theoretical and experimental radio propagation Physics, Trieste, Italy, 6-24

Ajewole M O., Oyedum ., Adediji A T. (2013). Spatial variability of UHF/VHF electric field strength in Niger State Nigeria.

Bean B. R. and Dutton E. J. (1996). "Radio Meteorological" Us Department of Commerce National Bureau of Standard Monograph 92.

ITUR (2019). The radio refractivity index its formula and refractivity data recommendation ITU-R,453-456.

Okoro.O,N and Agbo G.A (2012) The Effect of variation of meteorological parameters on the Tropospheric Radio refractivity for Minna , Global journals Inc (USA)12(2),1,

Olalekan Lawrence Ojo (2023). Geo-spatial distribution of radio refractivity and the influence of fade depth on microwave propagation signals over Nigeria Vol. 18(3), pp. 72-83, DOI: 10.5897/IJPS2023.5036 Article Number: B13352271083 ISSN: 1992-1950

Valine, Tamosiunate Valina M., Tamosiunate S. and Zilinskas m., (2011). Variation of radio refractivity with height above ground electronics and electrical engineering, 5(111),23-26.