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Long-Term Characterization of Vertical Radio Refractivity Gradients and Tropospheric Propagation Conditions over North-Central Nigeria Using ERA5 Reanalysis Data

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Abstract

This study presents a comprehensive long-term evaluation of vertical radio refractivity and refractivity gradients over selected locations in North-Central Nigeria. Forty-one years (1980–2020) of meteorological data obtained from the ERA5 reanalysis dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF) were analyzed. Air temperature, atmospheric pressure, and relative humidity at heights of 12 m, 100 m, and 250 m above ground level (AGL) were used to compute radio refractivity using ITU-R formulations. Vertical refractivity gradients were subsequently derived and interpreted within established propagation regime classifications. Results reveal a consistent decrease in refractivity with increasing altitude across all locations. Wet-season refractivity values exceed dry-season values due to enhanced moisture contribution to the wet refractivity component. Mean vertical refractivity gradients were −125.65 N/km in Minna, −87.36 N/km in Lokoja, and −77.54 N/km in Jos. These values exceed the standard atmospheric gradient (≈−39 N/km) in magnitude, indicating persistent super-refraction conditions, particularly in lowland and humid environments. The findings demonstrate that regional topography and atmospheric moisture distribution significantly influence radio wave bending characteristics. Incorporating location-specific vertical refractivity gradients into terrestrial propagation models is essential for improving reliability and interference prediction in subtropical continental climates.

Keywords: Radio refractivity; vertical refractivity gradient; super-refraction; atmospheric propagation; ERA5; Nigeria.

I. INTRODUCTION

Radio wave propagation in the troposphere is strongly influenced by atmospheric refractivity, which varies with temperature, pressure, and water-vapour content. These variations alter the refractive index of air and consequently affect the bending, attenuation, and coverage characteristics of radio waves [1]. Because atmospheric refractivity changes with altitude, radio waves do not propagate along straight-line paths but undergo curvature determined by the vertical refractivity gradient.

The vertical refractivity gradient is a critical parameter in determining propagation regimes, including sub-refraction, standard refraction, super-refraction, and ducting. Under standard atmospheric conditions, refractivity decreases gradually with height, producing slight downward bending of radio waves. When the gradient becomes more negative than the standard value (approximately −39 N/km), enhanced downward bending occurs, leading to super-refraction and potentially ducting under sufficiently strong conditions [1], [2].

Previous investigations in Nigeria have largely focused on surface refractivity behavior. Reference [3] examined seasonal variations of surface refractivity in Minna and reported higher wet-season values attributed to moisture enhancement, while [4] demonstrated the dominant role of humidity in diurnal and seasonal refractivity variability across Nigerian cities. Although these studies provide insight into near-surface conditions, they do not fully characterize vertical refractivity structure.

An analysis on the vertical refractivity gradients over Akure was also conducted, with significant seasonal dependence of propagation regimes reported in [2]. Reference [5] further demonstrated the influence of meteorological parameter variations on tropospheric refractivity in Minna and Jos. Beyond Nigeria, [6] showed that strong refractivity gradients can significantly enhance signal strength along sea paths at microwave frequencies, emphasizing the importance of refractivity structure in anomalous propagation phenomena, while [7] highlighted the practical importance of radio climatic variables for microwave and millimetre-wave link design in Nigeria.

Despite these contributions, long-term altitude-dependent refractivity studies remain limited for North-Central Nigeria. This study therefore evaluates vertical radio refractivity at 12 m, 100 m, and 250 m above ground level using the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis version 5 (ERA5) data from 1980–2020 and characterizes corresponding propagation regimes through computed refractivity gradients.

II. RADIO REFRACTIVITY THEORY

A. *Atmospheric Refractivity Formulation*

Radio refractivity N is related to the refractive index n by (1).

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

Radio refractivity in the troposphere is expressed as the sum of dry and wet components [1]:

$$N = N_d + N_w \quad (2)$$

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

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

Where P is the atmospheric pressure (hPa), T is the temperature (K), and e is the water-vapour pressure (hPa). Water-vapour pressure is determined from relative humidity:

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

$$e_s = 6.112 \exp\left(\frac{17.67(T-273.15)}{T-29.65}\right) \quad (6)$$

The wet component dominates seasonal refractivity variability in tropical regions [3], [4].

B. *Vertical Refractivity Gradient*

The vertical refractivity gradient is defined as

$$G = \frac{dN}{dh} \quad (7)$$

For discrete height levels:

$$G = \frac{N_2 - N_1}{h_2 - h_1} \quad (8)$$

Where height $h$is expressed in kilometres, yielding gradient units of N/km [2].

Standard atmospheric conditions correspond to approximately −39 N/km, with more negative gradients indicate super-refraction, while weakly negative or positive gradients indicate sub-refraction [1], [5]. A summary of Refractive Propagation conditions is presented in Table I, while the refractive ray-path behavior under these regimes is illustrated in Fig. 1.

Table I. Summary of Refractive Propagation conditions based on vertical refractivity gradient $\left({dN}/{dh}\right)$ [8], [9], [10].

Refractive Condition	Gradients [N/Km]
Sub-refraction	${dN}/{dh} > -39$
Normal Refraction	${dN}/{dh} \approx -39$
Super-refraction	$-157 < {dN}/{dh} < -39$
Trapping or Ducting	${dN}/{dh} \leq 157$

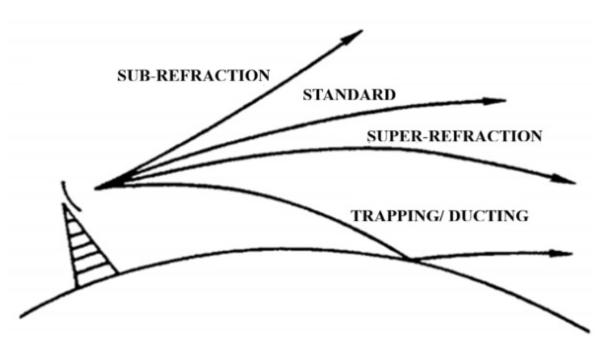

Fig. 1. Refractive conditions [11].

III. Materials and Methods

A. Materials

1) Study Area

The study was conducted over selected locations in North-Central Nigeria, a region characterized by pronounced seasonal variability and diverse topographical features. The locations considered are Jos (Plateau State), Minna (Niger State), and Lokoja (Kogi State), which were selected to represent contrasting climatic and elevation conditions within the region. Jos (Latitude 9°53′ N, Longitude 8°51′ E) is situated on the Jos Plateau and is characterized by relatively high elevation and cooler climatic conditions. Minna (Latitude 9°37′ N, Longitude 6°30′ E) lies within the inland lowland zone and experiences typical tropical continental conditions, while Lokoja (Latitude 7°47′ N, Longitude 6°45′ E) is located near the confluence of the Niger and Benue Rivers and is influenced by warmer and more humid atmospheric conditions [12]. These geographical differences significantly affect local meteorological parameters and, consequently, radio refractivity behaviour [5], [4].

The selection of these locations enables a comparative assessment of how altitude, regional climate, and proximity to major water bodies influence the vertical structure of radio refractivity and propagation conditions. The geographical distribution of the study area locations is shown in Fig. 2.

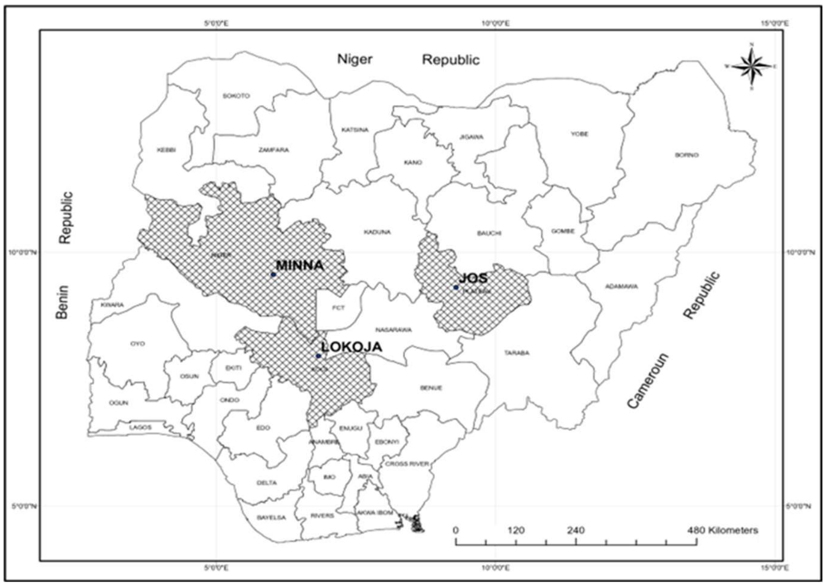

Fig. 2. Map of the study area showing Jos, Minna and Lokoja [12].

2) Data

Meteorological data were obtained from the ECMWF Reanalysis version 5 (ERA5) dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), for Jos, Minna, and Lokoja over 1980–2020 at 12 m, 100 m, and 250 m above ground level (AGL).

B. Methods

1) Refractivity and Gradient Computation

Radio refractivity at each height level was computed using (1) – (6). Temperature was converted to Kelvin, pressure expressed in hPa, and relative humidity retained in percent. Vertical refractivity gradients were calculated using (8) with heights expressed in kilometres. Yearly means and seasonal averages (wet and dry seasons) were derived. Gradient values were classified according to standard propagation thresholds [1].

2) Statistical Analysis

Trend and correlation analyses were performed to examine long-term variability. Regression models were used to evaluate relationships between refractivity and rainfall. The coefficient of determination (R^2) was employed to assess model fit.

IV. Results and Discussion

A. Vertical Distribution of Radio Refractivity

The yearly mean radio refractivity values computed at 12 m, 100 m, and 250 m above ground level (AGL) reveal consistent altitude-dependent and seasonal variability across Jos, Minna, and Lokoja.

1) Refractivity at 12 m AGL

Fig. 3 shows strong seasonal modulation of refractivity at 12 m AGL for all locations. The observed ranges over the 41-year period are:

(a) Minna: 329.98–387.40 N-units
(b) Lokoja: 330.20–377.59 N-units
(c) Jos: 289.84–374.01 N-units

The maximum refractivity in Minna (387.40 N-units) exceeds its minimum value (329.98 N-units) by 57.42 N-units, corresponding to a seasonal variation of about

17.4% relative to the minimum value. Lokoja exhibits a similar variation of about 14.3%, while Jos shows a larger relative variation of about 29.1%, primarily due to its lower dry-season baseline.

Jos generally records lower refractivity values than Minna and Lokoja. This is expected because Jos is at higher elevation, leading to lower atmospheric pressure and therefore a reduced dry term N_d in (3). Reduced moisture content at altitude also suppresses the wet term N_w in (4).

Wet-season refractivity peaks correspond to periods of increased humidity, confirming that moisture-driven variability dominates refractivity behavior in the region, consistent with established Nigerian refractivity studies [3], [4], [5].

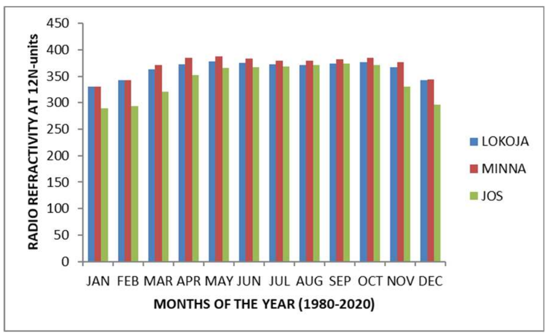

Fig. 3. Yearly variations of radio refractivity over study locations 12 m AGL (1980-2020).

2) Refractivity at 100 m AGL

Fig. 4 indicates that refractivity at 100 m AGL remains seasonally modulated but decreases relative to 12 m across all locations. This reduction reflects the expected decline of atmospheric density and moisture content with altitude in the lower troposphere.

Across the study period, the average reduction between 12 m and 100 m is typically on the order of 8–15 N-units depending on location and season, confirming the monotonic vertical decay of refractivity.

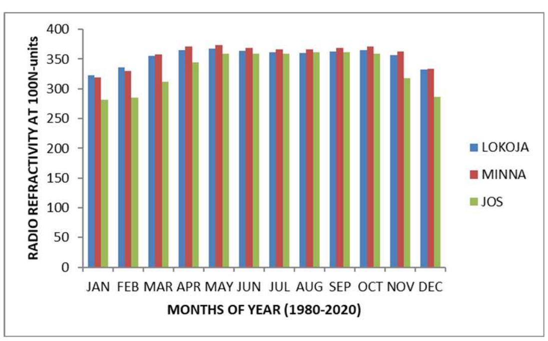

Fig. 4. Yearly variations of radio refractivity over study locations 100 m AGL (1980-2020).

3) Refractivity at 250 m AGL

Fig. 5 shows further reduction in refractivity at 250 m AGL. Maximum and minimum values at this level are approximately:

(a) Minna: 306.24–357.25 N-units
(b) Lokoja: 315.41–356.82 N-units
(c) Jos: 275.26–352.36 N-units

The vertical decrease from 12 m to 250 m is approximately:

(a) Minna: ~30–40 N-units
(b) Lokoja: ~25–35 N-units
(c) Jos: ~30–60 N-units

The comparatively larger range in Jos is consistent with elevation-driven stratification effects and reduced pressure baseline.

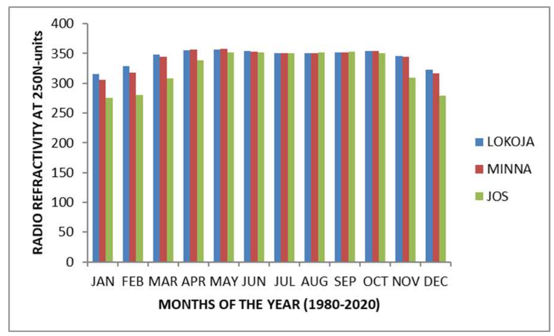

Fig. 5. Yearly variations of radio refractivity over study locations 250 m AGL (1980-2020).

B. *Vertical Refractivity Gradient Characteristics*

Fig. 6 presents the yearly mean vertical refractivity gradients computed using (8). The long-term mean gradient values are:

(a) Minna: −125.65 N/km
(b) Lokoja: −87.36 N/km
(c) Jos: −77.54 N/km

For comparison, the standard atmospheric gradient is approximately −39 N/km. Thus:

(a) Minna's gradient is about 3.22 times more negative than standard,
(b) Lokoja's gradient is about 2.24 times more negative,
(c) Jos's gradient is about 1.99 times more negative.

These magnitudes indicate persistent super-refraction (see Table II), implying stronger downward bending of radio waves than under standard atmospheric assumptions. The theoretical ray-path implications of these refractive regimes are consistent with the geometries illustrated in Fig. 2 (refractive propagation conditions).

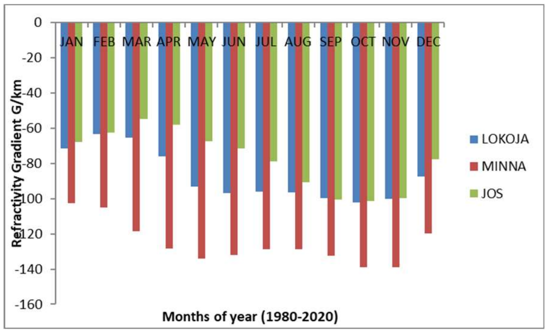

Fig. 6. Yearly variations of refractivity gradient over study locations (1980-2020).

Table II. Long-term mean vertical gradients

Location	Gradient (N/km)	Regime
Minna	−125.65	Super
Lokoja	−87.36	Super
Jos	−77.54	Super

C. *Seasonal Propagation Regime Classification*

The gradients in Fig. 6 are consistently more negative than the standard value (≈ −39 N/km), indicating that super-refraction is the prevailing regime over the three locations. Table III summarizes the seasonal ranges of refractivity at 12 m, 100 m and 250 m AGL and highlights two robust features: (a) refractivity is systematically higher in the wet season at all heights due to increased water-vapour contribution to the wet term, and (b) refractivity decreases monotonically with height in both seasons, consistent with decreasing moisture and air density in the lowest troposphere. The more negative gradients observed during wet-season months imply stronger downward ray bending, extended radio horizons and a higher likelihood of long-range interference during the rainy period.

Table III, Seasonal mean radio refractivity (n-units) at different heights.

Location	Season	12 m AGL (N-units)	100 m AGL (N-units)	250 m AGL (N-units)
Lokoja	Dry	325–340	315–330	300–315
Lokoja	Wet	360–378	345–365	330–350
Minna	Dry	330–345	320–335	305–320
Minna	Wet	365–387	350–370	335–357
Jos	Dry	285–305	275–295	260–280
Jos	Wet	340–374	325–350	310–352

D. *Rainfall Variability and Moisture-Driven Refractivity Behavior*

Fig. 7 shows that peak rainfall typically occurs between May and September across the locations, aligning with periods of increased refractivity magnitude. Although rainfall does not explicitly enter (2) – (6), it is a strong proxy for atmospheric moisture content and therefore correlates with increases in humidity and water-vapour pressure e, which drive the wet refractivity component.

This alignment supports the conclusion that moisture variability is the primary physical driver of seasonal refractivity enhancement in the study region.

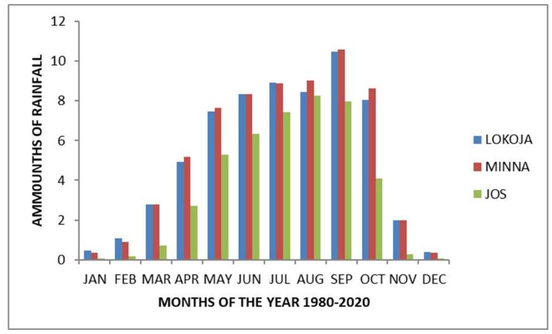

Fig. 7. Yearly mean rainfall variability over Jos, Minna, and Lokoja (1980–2020).

E. *Implications for Terrestrial Communication Systems*

The persistent super-refractive gradients observed across the study locations imply that terrestrial propagation conditions frequently exceed standard atmospheric assumptions used in conventional radio planning. Practical implications include:

(a) Extended radio horizon and enhanced received signal strength at longer ranges;
(b) Increased probability of inter-service interference, especially during wet-season months;
(c) Seasonal variability in microwave link reliability due to refractivity-driven bending effects;
(d) A strong requirement for location-specific gradient incorporation in terrestrial propagation models and network design.

Minna exhibits the strongest gradients and is therefore most prone to enhanced propagation and potential anomalous effects, followed by Lokoja. Jos shows comparatively moderated behavior due to elevation-related reductions in pressure and moisture.

V. Conclusion

Using ERA5 reanalysis data (1980–2020), this study quantified altitude-dependent radio refractivity at 12 m, 100 m and 250 m AGL and derived vertical refractivity gradients over Jos, Minna and Lokoja in North-Central Nigeria. Refractivity decreases with height in all cases, while wet-season values exceed dry-season values due to enhanced moisture contribution. The long-term mean gradients (Minna: −125.65 N/km; Lokoja: −87.36 N/km; Jos: −77.54 N/km) are substantially more negative than the standard atmospheric gradient ($\approx -39\ N/km$), confirming persistent super-refraction—strongest in the lowland/humid sites. These conditions imply enhanced downward ray bending, extended propagation ranges and increased seasonal interference risk, underscoring the need to incorporate location-specific vertical gradients in terrestrial link planning and propagation modelling for the region.

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