

Spatiotemporal Dynamics of Near-Surface Micro-Scale Refractivity Gradient: Implications for Terrestrial Wireless Communications

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Abstract

This study investigates the spatiotemporal dynamics of near-surface micro-scale radio refractivity and its implications for terrestrial wireless communications across Nigeria, with particular interest in the near-surface atmosphere where modern street-level communication infrastructure increasingly operates. Using spatially continuous MERRA-2 data at 2 and 10 m altitudes, near-surface refractivity and the micro-scale refractivity gradient were estimated and spatially represented through ordinary kriging to map contours across Nigeria. The results reveal a pronounced geographical structure in near-surface refractivity, increasing from the relatively dry northern interior toward the more humid southern and coastal regions, with values of approximately 310–320 N-units in parts of the north and up to about 390 N-units in the south at both altitudes. The estimated micro-scale refractivity gradient is predominantly negative and becomes progressively stronger toward central and southern Nigeria, with the most pronounced values reported around the southeastern and coastal environments. These show that the near-surface atmosphere is not spatially uniform and that relatively small vertical changes within the lowest few meters produce substantially different propagation conditions. These variations are particularly important for microwave links and other terrestrial systems operating close to the ground, because strong refractivity gradients promote atmospheric trapping, with consequences including extended radio range, unexpected distant-signal reception, co-channel interference, multipath propagation, fading, unstable links and radar anomalies. Overall, the study provides a useful spatially explicit foundation for incorporating micro-scale atmospheric variability into wireless network planning, path-clearance assessment, interference management and the development of more resilient terrestrial communication infrastructure in Nigeria.

Keywords: near-surface refractivity, micro-scale refractivity gradient, localized wireless propagation impairments, terrestrial wireless communications, chaotic micro-environment

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1. Introduction

The Earth atmosphere is a dynamic, invisible medium through which our entire terrestrial wireless infrastructure depends. When a radio wave is transmitted from a cell tower or a microwave dish, it traverses a fluid ocean of gases whose density, temperature, and moisture content are in a state of constant flux. This continuous shifting alters the speed of the electromagnetic wave, causing it to bend or refract as it propagates through the troposphere (International Telecommunication Union [ITU-R], 2019). The magnitude of this bending is governed by the radio refractive index, a parameter that quantifies how sharply a wave will curve relative to the Earth's surface. The atmospheric conditions shift from hour to hour and season to season making the trajectory of a transmitted signal to highly vary. The atmosphere an active participant, rather than a passive background, in the transmission of information (Amajama et al., 2025; Alimgeer et al., 2018).

For telecommunications engineers, this atmospheric variability presents a formidable challenge that directly impacts network reliability and performance. Modern terrestrial systems, particularly, the dense 5G networks and point-to-point microwave links, rely on precise line-of-sight alignment and predictable path clearance. When the atmosphere behaves normally, radio waves curve gently downward, extending the horizon slightly beyond the geometric line of sight. However, when localized weather phenomena create steep gradients in temperature or humidity, the radio wave can bend unpredictably, leading to severe propagation impairments. A wave might bend upward, creating unexpected shadow zones and dropped connections, or it might bend so sharply downward that it becomes trapped near the ground, traveling vast distances to interfere with distant receivers operating on the same frequency (Babayo et al., 2026; Durodola et al., 2025). As the demand for higher frequencies and tighter network geometries grows, understanding and predicting these atmospheric interactions is fundamental to designing resilient, interference-free wireless communication systems that withstand the erratic nature of the air.

Radio refractivity is a fundamental meteorological and radiophysical parameter that quantifies how the speed of electromagnetic waves changes as they propagate through the Earth's atmosphere. Determined primarily by three atmospheric variables: temperature, pressure, and water vapor pressure. The atmosphere is a stratified envelope in which refractivity varies significantly from one altitude to another. Atmospheric pressure and water vapor pressure decrease exponentially with height, causing refractivity to decline as altitude increases through the troposphere. However, this decrease is rarely linear, as temperature inversions and humidity gradients, create complex vertical profiles. The vertical gradient of refractivity is the critical factor that determines the curvature of a radio wave's path relative to the Earth's surface. Depending on the rate of change of refractivity with altitude, the atmosphere can be classified into normal, sub-refractive and super-refractive, each of which forces radio waves to bend in distinct ways, thereby profoundly altering their propagation paths (Ojo & Adenodi, 2019; Adeola et al., 2026). Understanding these vertical variations is vital, as the trajectory of a signal emitted from a broadcast tower or a satellite ground station can be drastically altered within just a few hundred meters of altitude.

The explosive expansion of modern telecommunications has fundamentally reshaped where radio waves actually travel, shifting the focus of network design from the sky to the street. Unlike traditional macro-cell towers that sit tens or hundreds of meters above the ground, contemporary urban infrastructure relies heavily on 5G small cells, Internet of Things (IoT) sensor networks, and short point-to-point millimeter-wave links deployed right at street level. Consequently, the vital wireless is within the first 10 meters of the Earth's surface. This architectural shift means that the performance of our most data-intensive technologies is governed by the hyper-local physics of the atmospheric boundary layer (Adenodi, 2026). When a 5G signal travels between a streetlight-mounted transmitter and a receiver just a few meters away, it passes through a chaotic micro-environment heavily influenced by urban heat islands, surface roughness, and direct evaporation from the soil, making the lowermost layer of the atmosphere the critical battleground for maintaining signal integrity (Ogunjo et al., 2013; Bichi et al., 2026).

It is within this narrow, ground-hugging zone that micro-scale refractivity gradients diverge drastically from the smoother, more predictable profiles of the upper atmosphere. In the free troposphere, temperature and moisture change gradually over kilometers, resulting in relatively stable vertical refractivity gradients. However, in the atmospheric surface layer, the Earth's surface acts as a direct, immediate source and sink for both heat and water vapor. Intense solar heating during the day creates steep temperature profiles, while evaporation traps immense amounts of moisture near the ground, only for these conditions to reverse rapidly during nocturnal cooling (Adenodi, 2026). These meteorological parameters fluctuate violently across a tiny spatial gap, such as between 2 and 10 meters, making the vertical refractivity gradient yields extreme values that trigger localized surface ducting or severe sub-refraction. These sharp micro-scale discontinuities are entirely missed by traditional upper-air assessments, leaving a dangerous blind spot in the planning of street-level wireless infrastructure.

Sub-refraction occurs when the refractivity gradient decreases more rapidly with height than in a standard atmosphere. The radio wave is bent upward, away from the Earth's surface, rather than following the natural curvature of the planet. For wireless communications, this has the immediate implication of reducing the radio horizon, effectively shrinking the coverage area of a transmitter. It can lead to severe signal fading and the creation of shadow zones where receivers that would normally have line-of-sight connectivity suddenly lose the signal entirely. This is particularly problematic for ultra-high frequency (UHF) and microwave links, which rely on precise line-of-sight alignment, as the unexpected loss of signal causes dropped calls, intermittent data flows, and a degradation of network reliability (Ekah et al., 2022). Conversely, super-refraction represents the second major effect, happening when the refractivity gradient decreases less rapidly with altitude than the standard rate. The radio waves are bent downward toward the Earth's surface more sharply than normal. It extends the radio horizon beyond the geometric line of sight, causes the signals to overshoot their intended target cells and interfere with distant receivers operating on the same frequency. In densely packed communication networks, such as modern cellular configurations, super-refraction can disrupt frequency reuse plans, leading to cross-talk, reduced signal-to-noise ratios, and an overall degradation in the quality of service experienced by users (Sa'adu et al., 2020).

The most disruptive effect is trapping commonly referred to as atmospheric ducting. This extreme form of super-refraction occurs when a sharp, steep decrease in humidity or a strong temperature inversion creates a layer of the atmosphere where the refractivity gradient becomes so negative that radio waves are completely trapped and forced to propagate within this layer. When radio signals enter this duct, it can travel over hundreds of kilometers beyond its intended coverage area with very little attenuation. For wireless communications, ducting severely causes distant signals to inexplicably appear in local receivers, leading to tremendous interference, crossed

signals, and the total disruption of communication links. Receivers located just outside the duct may experience a total loss of signal because the energy has been siphoned away by the trapping layer (Babayo et al., 2026).

Another effect is signal fading and scintillation, driven by the turbulent micro-fluctuations of refractivity within the atmosphere. As a radio wave passes through this turbulent medium, different parts of the wavefront encounter varying refractive conditions, causing the signal's phase and amplitude to fluctuate rapidly over time. For wireless communications, this multipath fading and scintillation can cause rapid drops in signal strength that outpace the ability of standard error-correction protocols to compensate. This results in high bit-error rates, reduced data throughput, and the need to implement costly adaptive equalization and power control mechanisms to maintain stable links (Durodola et al., 2025; Lami et al., 2026).

Given the profound implications of these atmospheric effects on the reliability and quality of wireless networks, there is an urgent need to thoroughly evaluate the spatiotemporal dynamics of radio refractivity below the 10m altitude in Nigeria. Historically, researchers have approached atmospheric refractivity at the macro-scale levels creating a significant void in the current literature regarding micro-scale refractivity variability spatially and vertically at street levels. To bridge this critical knowledge gap, this study aims to comprehensively assess the spatiotemporal dynamics of the micro-scale radio refractivity gradient within the atmospheric surface layer. By using spatially continuous meteorological data at 2 and 10 m above ground level, seek to quantify and map the vertical refractivity gradient and its corresponding effective Earth radius factor k-factor across the study area. It will also endeavors to classify the occurrence of distinct propagation regimes, namely sub-refraction, super-refraction, and surface trapping, capturing the sharp, localized atmospheric discontinuities that traditional single-height assessments overlook. This work provides a robust, data-driven foundation for optimizing terrestrial link path clearance, mitigating co-channel interference, and enhancing the overall reliability of next-generation wireless communication infrastructure.

2. Methodology

2.1 Study Area and Data Source

The geographic focus of this study is Nigeria, serving as a natural laboratory for investigating micro-scale atmospheric dynamics due to its highly diverse topography and distinct climatic zones. It is located in the tropical region of West Africa between latitudes 4°N and 14°N, Nigeria spans approximately 923,768 square kilometers, featuring a dramatic north-south gradient in both geography and weather (Adenodi, 2026). The southern coastal region, bordered by the Gulf of Guinea, is characterized by a tropical monsoon climate with persistently high humidity and heavy rainfall. Moving inland, the terrain transitions through the dense rainforests of the south, into the vast savanna grasslands of the central middle belt, and finally rises to the montane plateaus before descending into the semi-arid, Sahel-influenced landscapes of the far north. This pronounced environmental contrast means the country experiences extreme seasonal shifts, driven by the northward and southward migration of the intertropical discontinuity. These shifts bring moist, maritime air from the Atlantic Ocean during the wet season and dry, dust-laden Harmattan winds from the Sahara Desert during the dry season. Such intense spatial and temporal variations in moisture and temperature make Nigeria uniquely suited for mapping the effect of micro-scale refractivity gradients on wireless communications form and migrate across different geographic boundaries (Amajama et al., 2025; Adenodi et al., 2016).

The meteorological data driving this analysis were acquired from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), at two distinct near-surface altitudes, 2 and 10 m above ground level.

2.2 Refractivity, Micro-Scale Refractivity Gradient and Effective Earth Radius Factor Estimation

Translating raw meteorological data into actionable radio propagation metrics at the two critical near-surface altitudes of 2 and 10 m requires the standard model recommended by the International Telecommunication Union (ITU-R, 2019), which defines N as a function of total atmospheric pressure P , absolute temperature T , and water vapor pressure e using the formula:

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

With the individual refractivity values at the lower and upper bounds of the surface layer established, the next critical step is to determine how sharply these conditions change over this vertical distance, a metric known as the micro-scale refractivity gradient. This dictates whether a terrestrial radio wave will follow the Earth's curvature, bend upward into the sky, or become trapped near the ground. This gradient, denoted as (Ojo &

Adenodi, 2018; 2019):

$$\frac{dN}{dh} = \frac{N_{2m} - N_{8m}}{0.01 - 0.002}$$

This denominator is exceptionally small, making the gradient extremely sensitive and the micro-scale gradient powerful, isolating the intense, hyper-local thermodynamic shifts of the atmospheric boundary layer to dictate the real-world performance of street-level 5G and IoT networks (Adeola et al., 2026). Translating this atmospheric bending into a practical engineering metric, the estimation of the Effective Earth Radius Factor, commonly known as the k-factor is required. This is derived directly from the near-surface refractivity gradient using the formula (Ojo & Adenodi, 2019; Babayo et al., 2026):

$$k = \frac{157}{157 + (dN/dh)}$$

Ordinary kriging interpolation technique was utilized to contour the near-surface refractivity at both heights and the micro-scale refractivity gradient. The contours were overlaid on the administrative map of Nigeria.

3. Results and Discussion

The results are presented below in subsections.

The contour map in Figure 1 shows a clear north–south gradient in near-surface refractivity at 2 m above ground, with refractivity generally increasing from the dry northern to the more humid southern region. The lowest values of 310–320 N-units occur in the far north. This is around parts of Borno, Yobe and the northern-eastern corridor, while approximately 315–320 occur across areas of Sokoto, Katsina, Zamfara, Kano and Jigawa. Moving southward, the near-surface refractivity progressively rises through roughly 325–340 N-units across Bauchi, Gombe, Kaduna, Kebbi and Niger states, indicating a gradual increase in the refractive properties of the near-surface atmosphere. This north–south pattern is physically meaningful because the northern environment is generally warmer and drier, with less atmospheric moisture, whereas the southern region is increasingly influenced by moist air from the Gulf of Guinea.

Across the central belt, the ear-surface refractivity becomes noticeably higher with values of about 345–365 N-units. Around Abuja and neighboring parts of Niger, Nasarawa and Kogi, values are approximately 345–355 N-units, while areas farther south, including Kwara, Ekiti, Osun and Ondo, reach roughly 355–380 N-units. In the eastern and southeastern interior, the values also increase substantially: Plateau is around 350–355, Taraba is approximately 355–365, and Benue is close to 370 N-units. The east–west pattern is therefore less uniform than the north–south trend. In general, near-surface refractivity increases toward the west and south, particularly across southwestern Nigeria, while the southeastern and northeastern sectors show localized variations. The contours around the southwest are particularly striking, with values rising through 365, 370, 375, 380 and 385 N-units toward the coastal zone.

The maximum near-surface refractivity on the map is approximately 390 N-units, concentrated in the far southwestern/coastal area around Lagos and its immediate surroundings, with the 385–390 N-unit contours extending through parts of Ogun, Ondo and the coastal southwest. Very high values, approaching 390 N-units, are also visible toward the Niger Delta and coastal southeastern region, including parts of Rivers, Bayelsa, Akwa Ibom and Cross River. The overall dynamics is a strong transition from minimum values of about 310 N-units in the far north/northeast to maximum values near 390 N-units in the humid southern and coastal belt: a difference of roughly 80 N-units. The map portrays the atmosphere becoming progressively more refractive southward.

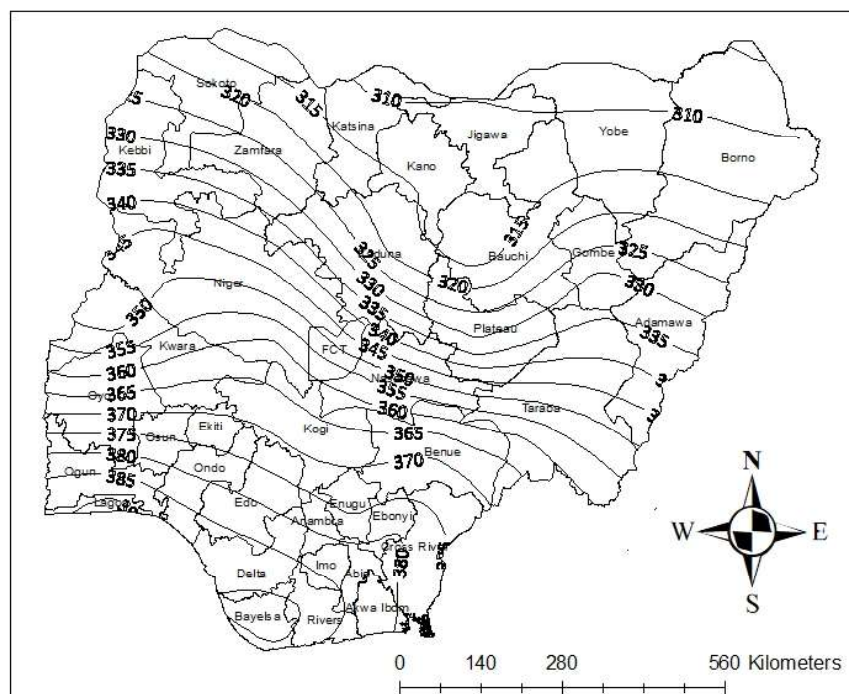


Figure 1: Spatiotemporal Dynamics of Refractivity at 2m

Figure 2 presents the dynamics of near-surface refractivity at 10 m above ground, revealing a pronounced spatial gradient across Nigeria, with refractivity generally increasing from the northern interior toward the south. The lowest values are concentrated in the northern and northeastern parts of the country, where the contours range from approximately 310 to 330 N-units. A value of about 310 N-units occurs around Katsina and the adjoining northern-central area, while Sokoto is crossed by a contour of about 315 N-units. Values increase through approximately 320–325 N-units across parts of Zamfara, Kebbi and Jigawa, while portions of Kano, Kaduna, Yobe and Borno generally lie within the lower-to-middle range of roughly 315–330 N-units. Thus, moving from the dry northern environment toward the central belt, the near-surface refractivity progressively increase, reflecting a transition toward an atmosphere with greater moisture and hence greater refractivity.

The increase becomes much more evident across central Nigeria, where near-surface refractivity generally rise through 330, 335, 340, 345 and 350 N-units. Around Niger, Kaduna and the Abuja, refractivity is approximately 330–345 N-units, while Nasarawa, Plateau and parts of Taraba are associated with values around 345–355 N-units. In Benue, the contours reach approximately 350–360 N-units, indicating a substantial increase compared with the northern states. There is also an appreciable west–east variation, although the dominant pattern remains north–south. In the western part of the country, the contours rise particularly strongly through Kwara, Osun, Ekiti, Ondo and Ogun, reaching about 350–380 N-units. In the eastern interior, values around 320–340 N-units occur across portions of Gombe and Adamawa, increasing to roughly 330–350 N-units toward Taraba and the southeastern states. This shows the western and southern parts generally experience higher near-surface refractivity than the northeastern interior but the increase is not uniform.

The highest near-surface refractivity of about 385–390 N-units occur in the southernmost and coastal portions of Nigeria, with the maximum appearing around the coastal southwestern area and extending toward the coastal southeastern sector. The southwest shows a particularly clear sequence from about 350 N-units in Kwara through 360–370 N-units in Osun and Ekiti, 375–380 N-units in Ondo and Ogun, and approximately 385–390 N-units around Lagos. Very high near-surface refractivity is also evident around parts of Cross River, Akwa Ibom and the coastal Niger Delta. Consequently, the map depicts a north-to-south increase from a minimum of about 310 N-units to a maximum of about 390 N-units, representing an overall difference of roughly 80 N-units.

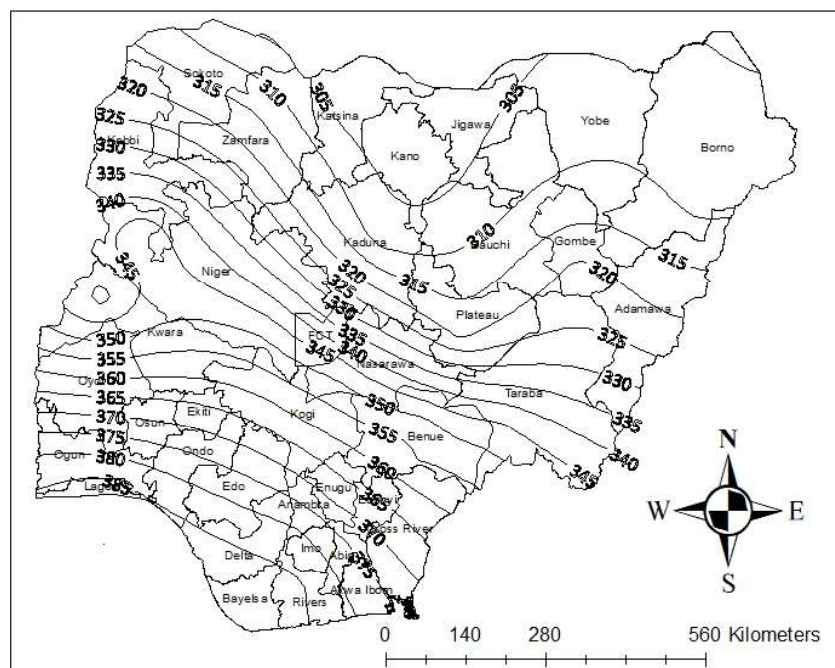


Figure 2: Spatiotemporal Dynamics of Refractivity at 8m

3.2 Micro-Scale Refractivity Gradient

Figure 3 presents a predominantly negative micro-scale refractivity gradient between 2 and 10 m altitudes across Nigeria, with values ranging approximately from -200 to about $-2,000$ N-units/m. The broadest and most systematic feature is the strong spatial variation from north to south. In the northern part of the country, the gradient is relatively weak, with values around -200 to -800 N-units/m. Borno contains contours near -200 , -400 , -600 and -800 N-units/m, while Yobe extends through approximately -400 to -800 N-units/m. Farther west, Sokoto, Zamfara and Kebbi show values generally between about -400 and -800 N-units/m, while Katsina and Kano are associated with contours around -800 to $-1,200$ N-units/m. Moving southward into the central belt, the magnitude increases considerably: Kaduna and Bauchi contain values around $-1,200$ to $-1,400$ N-units/m, whereas parts of Plateau, Nasarawa and Adamawa approach $-1,400$ to $-1,600$ N-units/m. This progression indicates that the difference in refractivity between the altitudes becomes increasingly pronounced toward the central and southern parts of the country.

The west-east variation is also substantial, although it is more spatially complex than the north-south pattern. In the western and southwestern regions, contours generally become more negative toward the south, with approximately -800 N-units/m around Kwara, -900 to $-1,000$ N-units/m across parts of Oyo and Osun, and about $-1,000$ to $-1,200$ N-units/m around Ekiti, Kogi and the Abuja/Nasarawa transition. The central contours around Kogi and Nasarawa are particularly tightly packed, suggesting a relatively rapid change in the micro-scale refractivity gradient over a short horizontal distance. In the eastern half, values become progressively more negative from Gombe and Adamawa (about $-1,200$ to $-1,600$ N-units/m) toward Taraba, Benue and Cross River. A notable closed contour occurs over Benue, indicating a localized area of comparatively distinct gradient values rather than a simple uniform southward progression. The map suggests that the micro-scale refractivity gradient strengthens from the relatively dry northern interior toward the wetter southern belt, while local departures from this trend occur around the central highlands and southeastern region.

The most negative micro-scale refractivity gradients are concentrated in the southeastern and coastal part of Nigeria, where the contours become very closely spaced and appear to reach approximately $-1,800$ to $-2,000$ N-units/m around Cross River and the adjoining southeastern states, with similarly strong values extending through Ebonyi, Enugu, Imo, Abia and Akwa Ibom. The southwestern coastal area around Lagos also shows a relatively strong gradient, reaching roughly $-1,400$ to $-1,500$ N-units/m, but it does not extreme values indicated farther southeast. Conversely, the least negative gradient is about -200 N-units/m, located in the far northeastern sector, particularly around northern Borno and adjoining Yobe, with similarly weak gradients extending toward parts of

the northwest. Thus, the overall dynamic is a transition from weakly negative gradients in the north (around -200 to -800 N-units/m) to strongly negative gradients in the central and southern regions (roughly $-1,200$ to $-2,000$ N-units/m.). The increasingly negative gradient toward the humid south indicates that refractivity changes more sharply with height between the altitudes, with the strongest vertical variation concentrated around the coastal atmospheric environment. Given these ranges of micro-scale refractive gradients, the near-surface refractivity is ducting, causing extended radio range, co-channel interference, unstable wireless communications, radar anomalies, multipath propagation and signal fading.

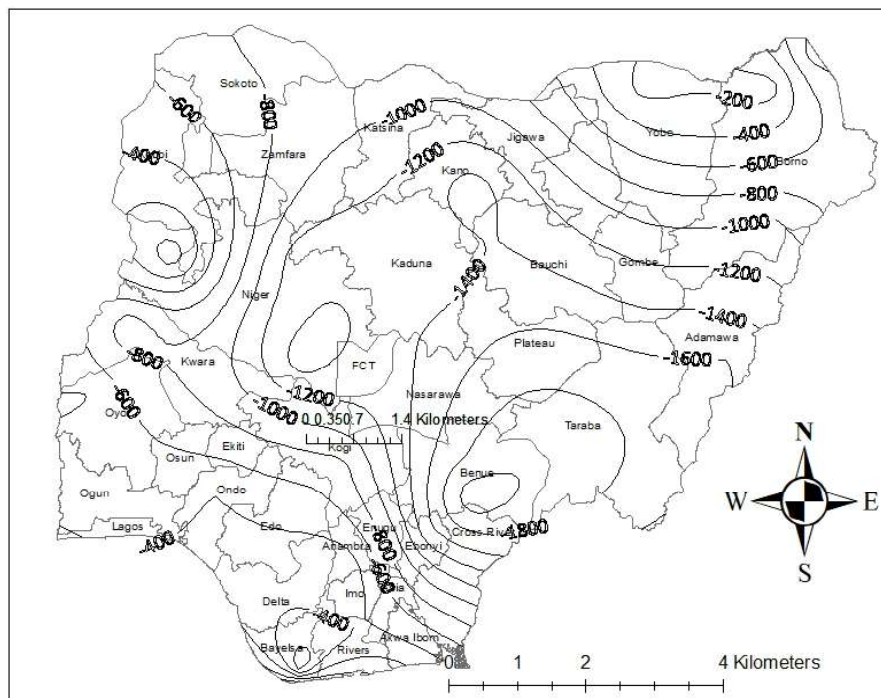


Figure 3: Spatiotemporal Dynamics of Micro-Scale Gradient

4. Conclusion and Recommendation

The study demonstrates that near-surface atmospheric refractivity over Nigeria is highly variable both geographically and vertically within the lowest few meters of the atmosphere, making the micro-scale atmospheric environment an important consideration in terrestrial wireless communication planning. The comparison of the 2 and 10 m refractivity fields shows a broadly consistent north–south increase, from approximately 310 N-units in the northern interior to about 390 N-units in the southern and coastal regions, while the predominantly negative 2–10 m refractivity gradient indicates that refractivity generally decreases with increasing height over the investigated surface layer. The strongest reported gradients occur in the southeastern and coastal parts of the country, whereas the weakest occur in the northern interior, demonstrating that the magnitude of near-surface vertical variability is itself geographically dependent. From a communications perspective, these patterns are important because strong vertical refractivity variations modify radio-wave curvature and promote anomalous propagation, thereby altering coverage and link availability, creating interference conditions, multipath and signal instability. It is therefore recommended that micro-scale refractivity information be incorporated into terrestrial wireless networks and microwave links design and optimization, rather than relying on conventional single-height or upper-atmospheric refractivity assessments. This study provides a strong basis for moving from a generalized atmospheric representation toward a more realistic micro-scale, location-aware approach to reliable wireless communication planning in Nigeria.

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