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Long-Term Assessment of Secondary Radioclimatic Parameters in a Coastal Tropical Environment: Evidence of Persistent Super-Refraction and Elevated k-Factor for Terrestrial Wireless Link Design in Toru-Orua, Nigeria.

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Abstract

The secondary radioclimatic parameters play a crucial role in the performance, reliability and design of the terrestrial wireless communication system especially in the humid tropical regions where atmospheric components have great effects on radiowave propagation. This research studies the temporal variation of radioclimatic variables at Toru-Orua, a coastal community in the Niger-Delta area of Nigeria, using eleven years (2015-2025) of hourly ERA5 reanalysis data. The derivation of surface radio refractivity, vertical refractivity gradient, effective earth radius factor, and geoclimatic factor was done using the ITU procedure. The findings indicate that surface refractivity varies significantly on a diurnal and seasonal basis and is mainly caused by thermodynamics in the boundary-layers, availability of moisture, rainfall variability. Vertical refractivity gradient is predominantly negative which implies that the dominance of super-refraction and intermittent ducting, especially at night time, early morning hours and at the beginning of the wet season. The derived actual Earth radius factor is always larger than the standard ITU value of 4/3 with an average annual value of 1.67, indicating that the assumed standard atmospheric refraction is inappropriate for link design in Toru-Orua. The computed geoclimatic factor exhibits weak seasonal variability between 5.8E-05 and 6.5E-05 with an annual mean of 6.18E-05, consistent with values reported for other southern Nigerian coastal locations. In general, the results highlight the increased vulnerability of terrestrial radio links in Toru-Orua to anomalous propagation and increased fade margin requirements, emphasizing the need for site-specific radioclimatic characterization in network planning and optimization across coastal tropical environments.

Keywords: Radioclimatic Parameters; Refractivity Gradient; Effective Earth Radius Factor; Geoclimatic Factor; Terrestrial Wireless Radio Link; Toru-Orua

1. Introduction

The propagation path followed by a radiowave within the troposphere is basically controlled by the refractive properties of the atmosphere, which is a function of the combined effects of air temperature, pressure, and water vapour content. The spatio-temporal change in these meteorological parameters alters the refractive index of the air, thus affecting the radio signal bending, multi-path fading, and interference of terrestrial communication paths (*ITU-R, 2023*). Subsequently, precise characterisation of the atmospheric refractivity conditions is required in the effective design and performance assessment of terrestrial microwave, Radar, VHF, and UHF wireless systems. Although the attenuation caused by rainfall is well-known as one of the greatest threats to radiowaves, particularly in the tropical region, it is not the sole factor in atmospheric disturbance of radiowave propagation (*Chakravarty & Maitra 2010; Mandeep & Hassan 2015; Al-Samman et al., 2020; Sodunke et al., 2025; Lawal et al., 2025*). Radio refractivity, vertical refractivity gradient, effective Earth radius factor, and geoclimatic factor (k-factor) are also secondary radioclimatic parameters that are equally important in determining radio path geometry, radio horizon distance, diffraction loss, and occurrence of anomalous propagation phenomena (*ITU-R, 2019*). These parameters have a direct impact on the link availability, the fade margin and the efficiency of frequency reuse, especially the line-of-sight terrestrial system. In humid tropical and coastal environments such as Toru-Orua, where strong moisture gradients and temperature inversions occur frequently, application of inaccurate secondary radioclimatic parameters in link budget design can lead to poor coverage prediction and increased susceptibility to interference (*Emmanuel et al, 2013*).

Niger-Delta region Nigeria is characterised by complicated atmospheric behaviour which is caused by the constant presence of high humidity, closeness to the Atlantic Ocean, good river networks and intense seasonal variability. These conditions could enhance low refractivity gradients and consequently multiple instances of super-refraction and ducting that can substantially distort predicted signal paths (*Salonen & Uppala, 1991; Eduediuyai et al., 2019; Alappattu et al., 2022*). Nonetheless, there is limited long-term site-specific researches on statistical estimation of radioclimatic parameters in many parts of the Niger-Delta. The objectives of the present study are: (i) to derive surface and near-surface radio refractivity at 1km altitude; (ii) to compute vertical refractivity gradients and statistically categorize them according to standard propagation refraction conditions; (iii) to determine the effective earth radius factor, geoclimatic factor and to study their seasonal variation and implications on terrestrial links in Toru-orua. This study is intended to provide a long-term climatological evaluation of these factors, which will be used to offer sound radioclimatic contributions to the design of terrestrial radio systems and help enhance the plan of wireless communication in Toru-Orua and its environments.

1.1 Climatology and Significance of Research Location

Toru-Orua is a neighborhood of Sagbama Local Government in Bayelsa State, which lies in the heart of the Niger-Delta region of southern Nigeria. It is the host community to the University of Africa, Toru-Orua, a state-government owned tertiary institution established in 2016. The region is located in the lowlands of the coastal plain that is characterized by flat to slightly wavy terrain with an elevation of about 13 m above mean sea level, latitude of 5.10^{o} N and longitude of 6.00^{o} E (*Wombu & Ekemub, 2025*). The proximity of this geographical location to the Atlantic Ocean and the presence of river networks and mangroves, exerts a strong influence on local atmospheric structure and moisture distribution. Climatically, Toru-Orua experiences a humid tropical monsoon climate marked by persistently high relative humidity, elevated surface temperatures, and pronounced seasonal variability driven by the West African monsoon circulation. The wet season usually reigns between April and October with an average annual rainfall of 2,700 mm and prevalence of damp south-westerly air masses. The dry season is comparably a brief season that prevails between November and March and it is influenced by drier continental airflow. These features favour large vertical gradients of temperature and water vapour in the lower troposphere, which have been reported to have significant impact on radio refractivity and its distribution vertically (*Emmanuel et al, 2013; ITU-R, 2023*).

Toru-Orua is especially vulnerable to anomalous propagation effects such as super-refraction and ducting due to the combination of high humidity, high frequency stratification of the atmosphere, and closeness to the coastal and riverine areas. The community is becoming an increasingly strategic location of interest due to the escalating demand in high-capacity terrestrial wireless infrastructure, such as microwave backhaul connections, fixed broadband access, and VHF/UHF radio and television services to support academic, residential and commercial operations. To the best of our knowledge, assessment of prevailing secondary radioclimatic factors has not been previously reported for this location. Consequently, it is crucial to conduct a comprehensive radioclimatic characterisation of Toru-Orua that would support reliable terrestrial radio-link design, interference mitigation, and network optimization in the Niger-Delta environment. Hence, the uniqueness of the research involves the first long-term ERA5-based assessment and quantification of radioclimatic parameters in Toru-Orua.

2. Materials and Methods

2.1 Source of Data and Instrumentation

The atmospheric data used in this research is the hourly ERA5 reanalysis data, downloaded from the database of Copernicus Climate Change Service (C3S), produced by the European Centre for Medium-Range Weather Forecasts (*C3S, 2023*). ERA5 offers a globally coherent representation of the atmospheric state through the assimilation of satellite, radiosonde and surface observations in a numerical weather prediction system, which is more accurate and more temporally continuous than traditional in-situ measurements (*Hersbach et al., 2020*). It has been shown to be suitable for radioclimatic analysis in many areas especially where ground-based atmospheric observatory stations are sparse (*Li et al., 2022*). Hourly ERA5 data provided on a spatial resolution of $0.25^{o} \times 0.25^{o}$, covering an eleven-year period (2015–2025) were extracted over the study location. The extracted meteorological parameters are air temperature T, dewpoint temperature T_d, and geopotential heights H that are necessary to calculate secondary radioclimatic propagation parameters based on the ITU-R recommendations (*ITU-R, 2023*). The data was retrieved at ground surface and pressure level of 1000 hPa and 975 hPa, allowing evaluation of near ground-level refractivity gradients applicable to radio propagation for intra- terrestrial links.

The hourly data were concatenated and aggregated into monthly, seasonal and annual statistical data to enable resourceful assessment of secondary radioclimatic parameters.

2.2 Determination of Secondary Radioclimatic Factors

The secondary radioclimatic parameters computed and analyzed in this study are radio refractivity, vertical radio refractivity gradient, effective earth radius factor, and geoclimatic factor. The computation procedure follows strictly the formulations and recommendations of the International Telecommunication Union (ITU), ensuring direct applicability of the results to terrestrial radio system design. Surface refractivity N_s, was computed using equation (1) (*ITU-R, 2023*).

$$N = N_d + N_w = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (1)$$

where N_d and N_w are the respective dry and wet terms of radio refractivities in N-*unit*. P is the ground surface atmospheric pressure in hectopascal (hPa), T is the ground surface absolute air temperature in Kelvin (K) retrieved from ERA5, and e is the ground surface water-vapor pressure in hectopascal (hPa). When dewpoint temperature data is available, the water-vapor pressure can be determined more accurately using equation (2).

$$e = 6.1121 \exp \left[\frac{17.62\, T_d}{T_d + 240.12}\right] \quad (2)$$

where T_d is the dewpoint temperature in °C. The wet term N_w often contributes 30–50% of total refractivity, particularly in humid coastal regions like the study location, meaning ignoring dew-point temperature would severely underestimate refractivity gradients and the occurrence of super-refraction and ducting. Refractivity N_{1km} at 1km altitude was estimated by interpolating N_{1km} between the ground surface, 1000 hPa, and 975 hPa levels using the exponential refractivity model in equation (3) (ITU-R, 2023).

$$N(h) = N_s \exp(-\beta h) \quad (3)$$

where $N(h)$ is the refractivity at altitude $h = 1km$, N_s is the surface refractivity, β is the refractivity decay constant obtained from refractivities N_a and N_b at two known pressure levels 1000 hPa, and 975 hPa respectively.

$$\beta = \frac{1}{h_b - h_a} \ln\left(\frac{N_a}{N_b}\right) \quad (4)$$

Seasonal and diurnal variability of these refractivities were subsequently analysed. Equation (5) was applied to calculate the vertical refractivity gradient $\frac{dN}{dh}$ at the first kilometer in the troposphere (*ITU-R, 2019*)

$$\frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} \quad (5)$$

where $N_1$and N_2 are the refractivities at the ground surface h_1 (≈ 0) and at height h_2. The computed hourly refractivites were aggregated into daily and monthly values, then categorized statistically into sub-refraction, standard refraction, super-refraction, and ducting regimes based on ITU-R threshold values stated in equations (6)-(9). (*ITU-R, 2019*). A non-standard atmospheric refraction is the one in which the refractivity gradient is less than or greater than -40 Nkm^{-1} as illustrated in equations (6)-(9).

Sub-refraction if $\frac{dN}{dh} > -40\ N\ km^{-1}$ (6)

Standard refraction if $\frac{dN}{dh} = -40\ N\ km^{-1}$ (7)

Super-refraction if $-157 < \frac{dN}{dh} < -40\ N\ km^{-1}$ (8)

Ducting (trapping) if $\frac{dN}{dh} < -157\ N\ km^{-1}$ (9)

The effective Earth radius factor, k, was derived from the refractivity gradient using equation (10).

$$k = \left(1 + \frac{\left(\frac{dN}{dh}\right) R_e}{10^6}\right)^{-1} \quad (10)$$

where R_e is the true Earth radius. The recommended global geodetic constant of 6,371 km was applied as the true Earth radius in this study (ITU-R P.530-17, 2019). Lastly, the geoclimatic factor K was derived from refractivity gradient using equation (11).

$$K = 10^{-4.6 - 0.0027\left(\frac{dN}{dh}\right)} \quad (11)$$

Statistical analysis of the monthly and seasonal variability and their implications on terrestrial link were subsequently assessed. Computation of the radioclimatic parameters was executed using version 3.13.9 of the Python programming language.

3. Results and Discussion

3.1. Temporal Variability of Surface Radio Refractivity

Surface refractivity plays a vital role in the curvature of radio path within the first kilometer of the troposphere. Its temporal variation, which is a function of ground surface temperature, air pressure, and water vapour pressure, determines the bending of radio signals with respect to the earth's curvature in the troposphere; hence, it is important to understand its diurnal variation. Figure 1 shows a clear diurnal cycle in surface radio refractivity over Toru-Orua.

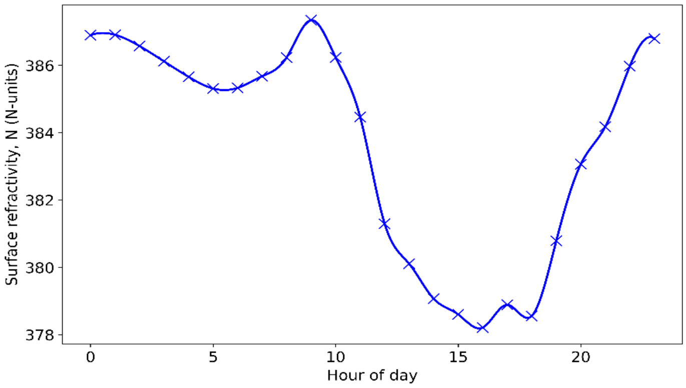

Figure 1: Diurnal variation of surface radio refractivity over Toru-Orua

Higher refractivity values are observed during the late night and early morning hours, corresponding to nocturnal cooling and moisture accumulation within the surface boundary layer. The magnitude of surface radio refractivity decreases gradually from peak value of 387 N-units at 9:00 hours to a minimum of 379 N-units around 16:00 hours. This is attributed to the gradual heating of the earth surface by solar radiation and enhanced turbulent mixing. Refractivity begins to rise again during the evening as the sun sets around 18:00 hours and the ground surface cools, enabling moisture accumulation which returns refractivity to 385 N-units at 00:00 hours of the next day, and the daily cycle continues. The depression observed at about 6:00 and the spike recorded at about 17:00 could be attributed to the chaotic complex dynamics of the atmosphere caused by temperature inversion, updraft, buoyancy quasi-equilibrium, turbulence etc (*McIntyre, 2002; Raymond et al., 2015*). This pronounced diurnal behaviour highlights the strong influence of boundary-layer processes on surface refractivity in the humid Niger-Delta environment and underscores the importance of accounting for time-dependent atmospheric variability in terrestrial radio-link design.

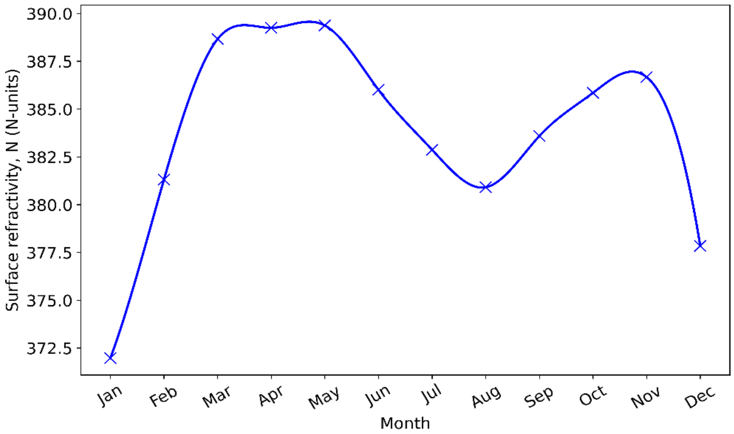

Figure 2: Monthly variation of surface radio refractivity over Toru-Orua

The seasonal variation of surface refractivity over Toru-orua was studied with the aid of monthly plot shown in Figure 2. A critical observation of the monthly trend and precipitation pattern in the Niger-Delta region reveals the strong influence of atmospheric moisture on refractivity. The monthly rainfall pattern in the Niger Delta region, exhibits double maxima with peaks occurring mostly around June and October, and a dry spell in July-August (*Orji et al., 2022; Chinago et. al., 2020*). The monthly mean of surface refractivity attains a lowest value of 371 N-units in January which coincides with the peak of the dry season when continental hot air masses dominate and reduce near-surface moisture content. A rapid increase is observed from about 381 N-units in February to a maximum of 389 N-units in May. This period corresponds to the onset and intensification of the West African monsoon, which introduces moist maritime air and significantly enhances the wet component of refractivity. Peak values occur between April and May, consistent with the establishment of persistent high humidity conditions at the beginning of the rainy season associated with the coastal regions of Nigeria (*Oyewole, 2014; Mekala, 2023*). Refractivity decreases from about 386 N-units in June to 381 N-units in August. The August low value may be attributed to the famous August-break, a short period between late July and early August during which rainfall ceases (*Adedeji et al., 2018; Lawal et al., 2020*). Although, recent studies have reported gradual disappearance of August-break in some areas in the Niger Delta, reduction in the amount rainfall during this period remains a primary factor responsible for low refractivity (*Chineke et al., 2010; Oga & Oga, 2023*). A secondary increase is observed from about 384 N-units in September to a second peak of 387 N-units in November, associated with gradual resumption of rainfall and moisture accumulation near the ground surface. The sharp decline in December marks the on-set of dry-season usually accompanied by dust-laden harmattan. This seasonal behaviour is in consonant with earlier studies on surface refractivity in areas of the Niger-Delta and southern Nigeria, which report strong wet-season enhancement and dry-season suppression of surface refractivity due to moisture variability and boundary-layer dynamics.

3.2. Temporal Variation of Refractivity Gradient and Anomalous Propagation

The diurnal variation of the vertical refractivity gradient at 1 km altitude over Toru-Orua, presented in Figure 3 depicts the influence of surface refractivity discussed previously. The gradient is predominantly negative throughout the period which indicates continuous non-standard propagation conditions in the lower troposphere. The mean hourly values fall below -147.5 N-unit/km during the early hours (00:00-9:00), indicating extreme super-refraction and tendency of ducting occurrence for some days.

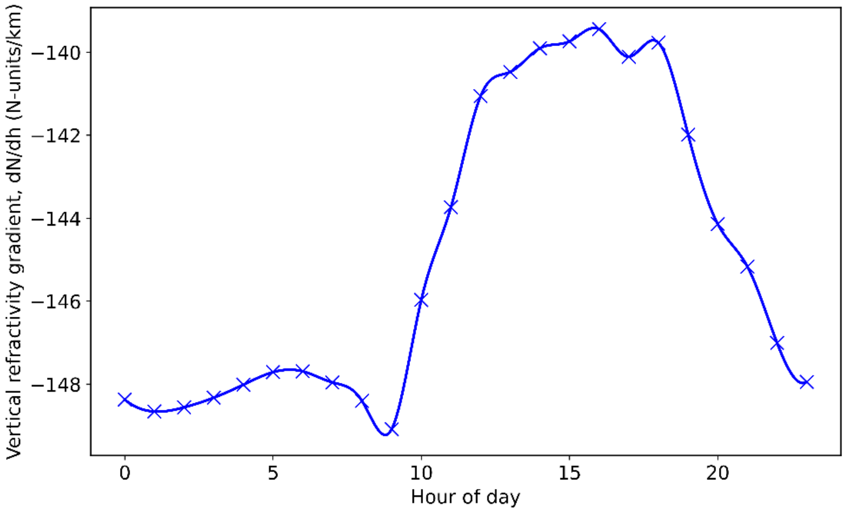

Figure 3: Diurnal variation of vertical refractivity gradient over Toru-Orua

This implies that the bending or curvature of radiowaves exceeds what is expected in a standard atmospheric refraction. This behaviour is occasioned by enhanced surface cooling, nocturnal stability, and moisture accumulation. As the sun rises around 9:00, the gradient increases gradually from about -149.4 N-unit/km to a maximum of -140.8 N-unit/km at 15:30 due to intense solar radiation and turbulent mixing within the convective boundary layer. The gradual reduction in solar radiation resulted to a fall in the gradient to about -147.8 N-units/km in the last hour of the day and maintain slightly-varying values within this neighbourhood until the next solar radiation. Similar pattern of the diurnal cycle but variant magnitudes has been reported over the coastal and humid regions of southern Nigeria (*Ajayi & Barbaliscia, 1990; Tyabo et al., 2018; Falodun et al., 2019*). The persistence high negative gradients observed in Figure 3 suggests that super-refraction and ducting anomalous propagation dominate over the study location, especially during the late and early hours. This day-night cycle has significant consequences on the reliability of terrestrial microwave links, successful estimation of the Earth-radius factor, geoclimatic factor and risk of interference in Niger-Delta environment.

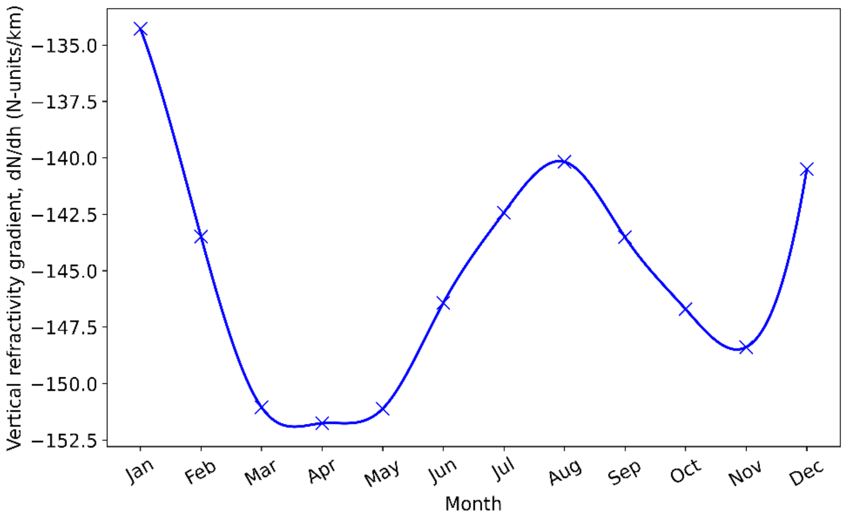

Figure 4: Seasonal variation of vertical refractivity gradient over Toru-Orua

The average monthly variation of refractivity gradient shown in Figure 4 revalidates the persistence occurrence of abnormal refraction throughout the year. Comparison of Figure 2 and Figure 4 shows that surface refractivity has a perfect inverse relationship with the refractivity gradient, indicating that surface temperature, pressure and humidity are the major determinants of the propagation condition in the lower troposphere. The double dips occurring in March-May and October-November corresponds to the surface refractivity double peaks shown in figure 2 when rainfall and humidity reach their peaks. The extremely low value of about -152 N-units/km observed between March and April implies occasional occurrence of ducting during this period while super-refraction dominates in the rest of year. In ducting conditions, radio signals can become trapped between a layer in the lower atmosphere and the surface, resulting to skip zones and beyond the horizon transmission (*Saha, 2008; Sabiru et al., 2024*). Under this condition, propagated radio signal usually travel beyond intended range and cause signal interference. This implies that propagated radio signals, particularly in radars and point-to-point antenna systems may not hit their intended targets due to multiple ground reflections suffered by the radiowaves. It is necessary to fine tune radio configuration to match the derived site-specific radioclimatic parameters during this period to achieve optimum system performance. The upward trend observed from about -135 N-unit/km in November to a maximum of 148 N-units in January is attributed to nocturnal stability, reduced convective mixing, and moisture trapping near the surface enhance refractive stratification. Generally, the seasonal cycle highlights how regional climate plays a strong role in creating refractivity gradients and demonstrates that abnormal propagation conditions are persistent throughout the season but more intense during dry season in the study location.

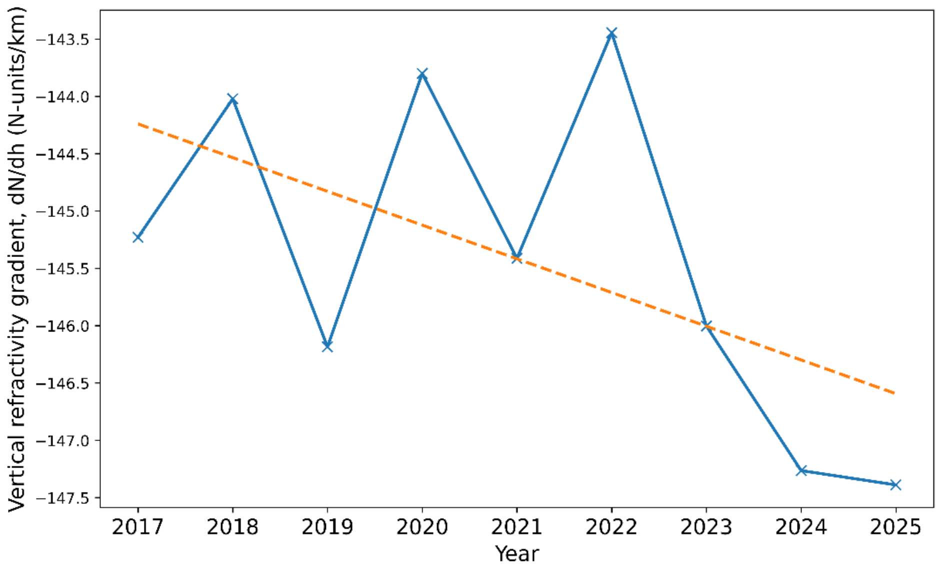

Figure 5: Inter-annual trend of vertical refractivity gradient over Toru-Orua

The annual trend of refractivity gradient over Toru-Orua was investigated during the study period. Figure 5 reveals notable inter-annual variability with a weak long-term downward trend. The steep decline in the value of refractivity gradients over recent years suggest enhanced refractive stratification in the lower troposphere, which may be linked to inter-annual moisture variability, changing boundary-layer dynamics, recent global climate shift and cumulative wet season effects.

3.3 Estimation of Effective Earth Radius Factor

The effective earth radius factor (k-factor) is one of the vital secondary radioclimatic parameters required in the link budget design of terrestrial radio links. Its spatio-temporal variation warrants continuous monitoring and assessment for an efficient wireless communication system. The average monthly k-factor was computed for the study period and presented in table 1.

Table 1: Estimated Effective Earth Radius Factor and Geoclimatic Factor

Month	k-factor	k-factor Std Dev ($\times 10^{-5}$)	Geoclimatic Factor ($\times 10^{-5}$)	Geoclimatic Factor Std Dev ($\times 10^{-7}$)
January	1.40	4.39	5.8	89.6
February	1.54	1.57	6.1	70.6
March	1.99	2.33	6.4	74.9
April	2.10	1.99	6.5	10.5
May	2.00	2.47	6.4	11.3
June	1.64	5.41	6.2	11.4
July	1.52	7.75	6.1	25.1
August	1.45	6.65	6.0	30.7
September	1.54	8.13	6.1	15.9
October	1.65	7.05	6.3	46.6
November	1.74	6.59	6.3	55.9
December	1.48	7.68	6.0	82.6

The k-factor values show clear seasonal variability throughout the year. The monthly values range from approximately 1.40 – 2.1, indicating persistent deviation from the standard atmospheric conditions (k = 1.33). The results align with the refractivity gradients, which revealed the persistent occurrence of non-standard refractions. Peak k-factors occur during the early wet-season months (March–May) coincide with strongly negative refractivity gradients, intense rainfall, high humidity and enhanced moisture stratification associated with the onset of the West African monsoon. These conditions favour super-refraction, leading to extended radio horizons and increased interference risk on terrestrial microwave links (Sirkova, 2019). It should be noted that occasional ducting may arise during this period due to extremely low negative gradients. Minimum k-factor of 1.47 observed in August correspond to the famous August-break as discussed previously. The increment observed from 1.54 in September to a maximum of 1.74 in November signifies the resumption of rainfall accompanied by high humidity and enhanced moisture content. Lower values were also noticed in dry-season months, particularly in December and January, reflecting enhanced vertical mixing and reduced refractive curvature. *However, the extremely low values of the monthly mean standard deviations presented in table 1 indicates that* k-factor exhibits negligible variability, indicating stable refractive conditions. The persistence high value of k-factor (>1.33) further confirm that standard refraction is rarely representative of propagation conditions in the Niger-Delta environment. The k-factor results corroborate the dominance of super-refraction and likely occurrence of ducting identified in Section 4.2 and provide a stable, literature-consistent framework for interpreting effective Earth curvature under near-ducting conditions. The average annual mean for the study period is 1.67 with a standard deviation of *3.8E-05*. This implies that the ITU recommended standard refraction of 1.33 is not a proper representative of prevailing propagation condition in Toru-Orua. The computed annual mean for the study location aligns with the reported average annual mean of 1.39, 1.40, 1.47, 1.60 and 1.63 for Ogoja, Warri, Auchi, Lagos, and Calabar respectively (Ukhurebor & Odesanya, 2019; Lawal & Ayodeji; 2017, Ezenugu et al., 2017; Bello et al., 2024). The corresponding percentage differences relative to the present study are 16.8%, 16.2%, 12.0%, 4.2%, and 2.4%, respectively, with closer agreement observed for coastal locations such as Lagos and Calabar.

3.4 Determination of Geoclimatic Factor and Its Implication for Terrestrial Links

It is important to estimate the correct value of the geoclimatic factor in order to cater for the adequate fade margin necessary for a reliable radio link performance (*Adediji et al., 2025*). The percentage of time during which a fade depth exceeds a threshold value is usually estimated from the seasonal variation of geoclimatic factor which is of great importance for localized multipath fading prediction. The computed geoclimatic factors for the study location are presented Table 1. The average monthly geoclimatic factor vary between 5.8E-05 and 6.5E-05 throughout the year with an annual mean and standard deviation of 6.18E-05 and 2.2E-06 respectively. This weak month-to-month spread reflects that 1-km gradients smooth near-surface variability; The highest monthly magnitudes observed between March and May coincide with the maximum and minimum values of k-factor and refractivity gradient respectively. These values serve as strong indicators of higher rain-attenuation risk and greater fade-margin requirements. Similarly, high fade margin must be budgeted and provided in October and November when geoclimatic factor rise to 6.4E-05 since ITU guidance links larger geoclimatic indices and stronger gradients to increased outage probabilities and recommended higher design fade margins for terrestrial links. The monthly standard deviation analysis further reveals that geoclimatic factor exhibits moderate seasonal variability with peaks in the dry season months. The magnitudes and seasonality of the secondary radioclimatic factors broadly agree with published coastal studies, implying noticeable seasonal variability and similar double peaks. Specifically, the obtained mean annual geoclimatic factor aligned closely with the 6.39E-05, 2.39E-05, 4.46E-05, and 6.54E-05 reported in literature for Yenagoa, Port Harcourt, Lagos and Calabar respectively (*Lawal & Omotoso, 2023; Oluwafemi & Olla, 2021; Etokebe et. al., 2016*)

4. Conclusions

This research paper has provided a long-term evaluation of radioclimatic parameters necessary for the design of terrestrial wireless links over Toru-Orua and its surroundings in the Niger-Delta region of Nigeria, using eleven years of high-resolution ERA5 reanalysis data. The findings indicate a strong diurnal, seasonal and inter-annual fluctuation in surface refractivity which is predominantly controlled by the boundary-layer processes, moisture availability and precipitation. Vertical refractivity gradients were observed to be predominantly negative, supporting the supremacy of super-refraction and sporadic ducting. Consequently, the practical Earth radius factor was always higher than the standard value of 4/3, with an average annual value of approximately 1.67, showing that standard atmospheric assumptions are insufficient in this coastal habitat to allow reliable radio communication links. The monthly geoclimatic factor at 1 km altitude showed a weak seasonal variation with the mean phase of about 6.18E-05. The implications of these findings are higher risks of attenuation, anomalous propagation, extended radio horizons, and higher levels of interference, hence the derived site-specific radioclimatic parameters are recommended for terrestrial link budget to achieve higher fade margins and optimum link performance. A limitation of this study is the reliance on reanalysis data rather than in-situ measurements. Future work should incorporate ground-based observations and higher temporal resolution datasets.

5. Patents

Author Contributions: *Conceptualization, Y.B.L.; Methodology, Y.B.L. and M.A.S; Software, Y.B.L..; Validation, M.A.S.; Formal Analysis, Y.B.L. and M.A.S; Investigation, Y.B.L. and M.A.S; Resources, Y.B.L.; Data Curation, M.A.S.; Writing—Original Draft, Y.B.L. and M.A.S.; Writing—Review & Editing, Y.B.L. and M.A.S.; Visualization, Y.B.L. and M.A.S.; Supervision, Y.B.L. and M.A.S.; Project Administration, Y.B.L. and M.A.S; Funding Acquisition, Y.B.L. and M.A.S*

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