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Evaluation of daily tropospheric radio refractivity, refractivity gradient and geoclimatic factor over Otukpo, Benue State, Nigeria

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Abstract

Radio refractivity is a key parameter for reliable terrestrial microwave-link design because the tropospheric propagation of radio waves is strongly affected by atmospheric refractive properties. Daily meteorological data spanning 23 years (2000–2022) were analysed to characterise surface radio refractivity (N_s), estimate refractivity at 100 m altitude (N_{100}), determine the radio refractivity gradient (RRG), and compute the geoclimatic factor (K-factor) over Otukpo, Benue State, Nigeria (7.22°N, 8.15°E; 91 m altitude). Surface refractivity was calculated using the International Telecommunication Union–Radiocommunication Sector (ITU-R) P.453-14 three-term equation with temperature, relative humidity, and surface pressure data from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) reanalysis database. N_{100} was estimated with the ITU-R exponential refractivity profile, and the RRG and K-factor were computed using ITU-R P.530-18. Seasonal and interannual variability were assessed from monthly and annual averages. The grand mean surface refractivity was 374.21 N-units, about 61 N-units higher than the height-adjusted ITU-R reference value ($\approx$ 313 N-units). Refractivity showed a distinct bimodal seasonal pattern, with the highest value in May (384.32 N-units) and the lowest value in January (350.44 N-units) during the Harmattan season. The mean RRG and mean K-factor were estimated as −50.57 N-units km^{-1} and 1.4757, respectively, corresponding to an effective Earth radius of about 9,402 km. These values were derived from observed surface refractivity climatology using the ITU-R model and are not direct measurements of vertical atmospheric structure. The results show that refractivity over Otukpo is generally higher than standard ITU-R conditions, indicating that locally derived propagation parameters are more representative for terrestrial microwave-link planning. These estimates should be confirmed in future studies using upper-air or high-resolution atmospheric profile data.

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1. Introduction

The propagation of radio waves in the troposphere is fundamentally governed by the refractive properties of the troposphere, the lowest and most meteorologically active layer of the Earth's atmosphere. In this region, variations in atmospheric parameters,

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especially temperature, atmospheric pressure, and water vapour content, directly affect the refractive index of air. These variations are generally expressed in terms of radio refractivity (N), a dimensionless quantity that describes the degree to which electromagnetic waves bend or refract during propagation [1]. The refractivity gradient, the change in refractivity with height, is also important because it determines the prevailing propagation conditions, including refraction and ducting. Depending on the climatic environment, these conditions can improve or degrade radio-signal performance.

Accurate characterisation of refractivity and its vertical gradient is essential in communication engineering for the design and optimisation of terrestrial and satellite radio links. Knowledge of local atmospheric refractive behaviour affects critical parameters such as link budget, line-of-sight distance, field-strength prediction, and fading margins. The geoclimatic factor (K-factor), which is related to the effective Earth radius under atmospheric refraction, is also important in radio-link design and antenna-height calculations [2]. These parameters vary by geographical location and are strongly regulated by climate patterns, altitude, and seasonal cycles. Therefore, long-term, site-specific investigations are needed to develop realistic radio-propagation models, especially under complex and highly variable atmospheric conditions.

The climatic environment of Nigeria, especially in tropical areas such as Otukpo, Benue State, has considerable seasonal and interannual variability because of the influence of tropical continental and tropical maritime air masses. Otukpo has distinct wet and dry seasons, with marked differences in temperature, humidity, and atmospheric stability, all of which influence radio refractivity and its gradient [3]. Refractivity values tend to rise during the wet season because of high humidity, whereas the dry season provides conditions conducive to stronger vertical gradients and anomalous propagation events. These atmospheric characteristics make the region relevant for radio-propagation studies, especially given the increasing demand for telecommunications and related infrastructure.

Although global communication networks, internet services, microwave links, and transmission systems are increasingly used in Otukpo and its environs, empirical studies of long-term atmospheric refractivity behaviour remain limited. Most previous studies on refractivity in Nigeria have focused on coastal or large urban areas, while inland tropical areas such as Otukpo have received less attention [4]. In addition, few studies have analysed long-term or decadal refractivity variations or assessed the surface and 100 m altitude simultaneously. Knowledge of refractivity behaviour at these altitudes is important because many communication antennas and transmitter installations operate within this height range, and their performance is sensitive to atmospheric variations within the boundary layer [5].

This study addresses this research gap by estimating and characterising temporal variations of daily tropospheric radio refractivity, refractivity gradient, and the geoclimatic factor at 100 m altitude from 2000 to 2022. The work analyses more than two decades of atmospheric data to identify long-term patterns, seasonal behaviour, and the magnitude of atmospheric effects on radio-wave propagation in the region. Comparisons of refractivity characteristics at the surface and at 100 m also provide insight into the vertical structure of the lower atmosphere and the propagation environment experienced by communication systems. The findings are expected to support radio-communication planning, prediction of propagation impairments, improvement of signal reliability, and development of more accurate propagation models for the climatic conditions of Otukpo.

1.1. Radio refractive index and refractivity

The refractive index (n) is a dimensionless parameter that measures the degree to which electromagnetic waves are slowed and bent by the atmosphere. For radio frequencies, the refractive index is expressed as Ref. [1]:

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

In this study, N_s represents surface refractivity, while N_{100} represents refractivity at 100 m. The surface radio refractivity is given by

$$N_s = 77.6\frac{P_d}{T} + 72\frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2}, \tag{2}$$

where the dry term of radio refractivity, N_{dry}, is

$$N_{\text{dry}} = 77.6\frac{P_d}{T}, \tag{3}$$

and the wet term of radio refractivity, N_{wet}, is

$$N_{\text{wet}} = 72\frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2}. \tag{4}$$

Thus, the total surface radio refractivity is expressed as

$$N_s = N_{\text{dry}} + N_{\text{wet}}. \tag{5}$$

Here, P is the total atmospheric pressure (hPa), T is the absolute temperature (K), and e is the water-vapour pressure (hPa). The water-vapour pressure is

$$e = \frac{\text{RH} \times e_s}{100}, \tag{6}$$

where RH is relative humidity (%) and e_s is the saturation vapour pressure (hPa), obtained from

$$e_s = 6.1121 \exp\left(\frac{17.502\theta}{\theta + 240.97}\right), \tag{7}$$

where θ is the temperature in °C. The dry atmospheric pressure P_d (hPa) is obtained from

$$P_d = P - e. \tag{8}$$

Equations (1), (2), (3), (4), (5), (6), (7), and (8) define the refractivity quantities and show that both the dry component, which is determined by air pressure and temperature, and the wet component, which is determined by humidity, contribute to refractivity.

1.2. Radio refractivity gradient

The radio refractivity at height h above the Earth's surface is given by

$$N(h) = N_s \exp\left(-\frac{h}{H}\right), \tag{9}$$

where $N(h)$ is the refractivity at height h, N_s is the surface refractivity, and H is the scale height; $H = 7.35$ km [1]. The refractivity gradient ($\mathrm{d}N/\mathrm{d}h$) is the rate of change of refractivity with height. The refractivity gradient at 100 m was determined from the variation of refractivity between the surface and 100 m height using the relationship reported by Ref. [6]:

$$\frac{\mathrm{d}N}{\mathrm{d}h} = \frac{N_{100} - N_s}{h_{100} - h_s}. \tag{10}$$

Together with equation (9), the 100 m gradient in equation (10) was used for the near-surface layer. The refractivity gradient for heights greater than 100 m was represented by the general expression

$$RRG(h) = \frac{dN(h)}{dh} = N_{100} \exp\left[-\frac{(h - 100)}{H}\right]. \tag{11}$$

Equation (11) gives the general two-level gradient form. At altitudes near the Earth's surface (0–500 m), this gradient is critical for determining the bending of radio waves. The standard atmospheric refractivity gradient is approximately −40 N-units km^{-1}. When the gradient becomes more negative than −100 N-units km^{-1}, super-refraction or ducting can occur, causing waves to be trapped within a tropospheric layer and to propagate beyond the horizon [7]. Conversely, when the gradient is greater than −40 N-units km^{-1}, sub-refraction occurs, leading to weaker bending and reduced coverage.

According to Ref. [1], gradients in the lowest 100 m of the atmosphere are important because they control the probability of signal reflection, fading channels, and tropospheric ducting. Therefore, studying refractivity gradients at 100 m altitude over Otukpo is important for assessing communication-system reliability.

1.3. Geoclimatic factor and effective Earth radius

The geoclimatic factor (K-factor), as introduced in International Telecommunication Union–Radiocommunication Sector (ITU-R) recommendations, provides a location-specific quantification relevant to multipath-fading probability, which is particularly important in tropical climates such as Otukpo. The K-factor expresses how the Earth's curvature appears to change because of atmospheric refraction and is used in radio propagation to determine how radio waves bend in the troposphere. The mathematical expression for the K-factor at height h is given by [8]:

$$K(h) = \frac{1}{1 + \frac{\mathrm{RRG}(h)}{157}}. \tag{12}$$

The K-factor is also referred to as the effective Earth radius factor and is used to classify radio refractivity into normal or standard refraction, sub-refraction, super-refraction, and ducting. In terms of the Earth-radius factor, standard refractivity occurs at $K = 1.33$; sub-refraction, or bending of radio waves away from the Earth's surface, occurs at $1.33 < K < \infty$; super-refraction, or bending of radio waves toward the Earth, occurs at $0 < K < 1.33$; and ducting occurs at $-\infty < K < 0$.

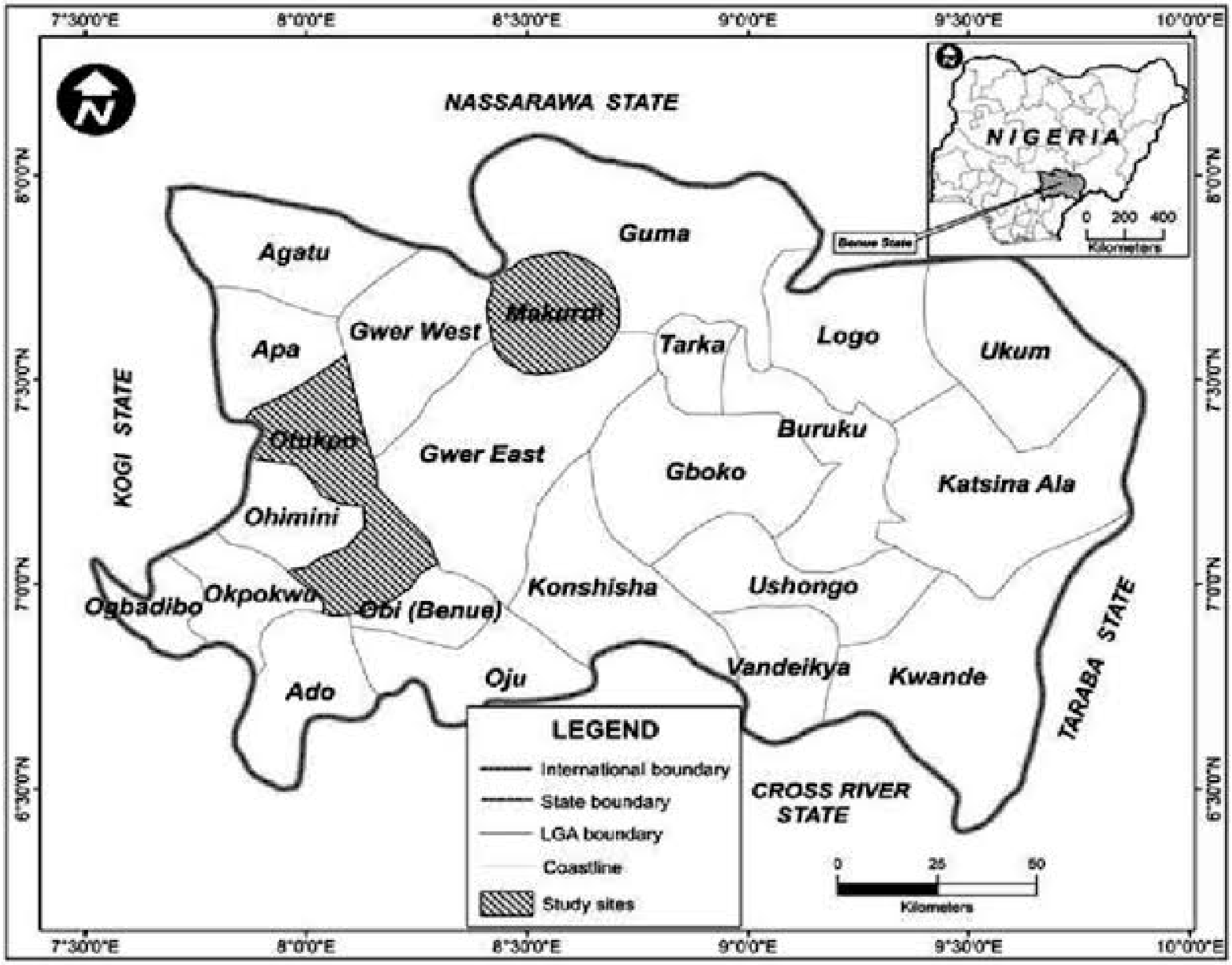

Figure 1: Map of Benue State showing the study area, Otukpo.

2. Materials and methods

2.1. Study area

Otukpo town is the administrative headquarters of Otukpo Local Government Area and is one of the most important urban centres in southern Benue State, Nigeria. Geographically, it lies at approximately latitude 7.22°N and longitude 8.15°E, at an altitude of 91 m above mean sea level, within the Benue Valley in Nigeria's North-Central geopolitical zone. The town has an estimated population of more than 100,000 and is home to the Idoma people as the predominant ethnic group, alongside other groups including the Igede, Tiv, Hausa, Igbo, and Yoruba [9]. Climatically, Otukpo lies within the Guinea Savannah zone, a tropical wet-and-dry climate. It has two distinct seasons: a wet season (April–October), characterised by heavy rainfall, elevated relative humidity, and active convective activity driven by the northward advance of the Inter-Tropical Convergence Zone (ITCZ); and a dry season (November–March), characterised by high daytime temperatures, low relative humidity, and dry, dusty north-easterly Harmattan winds from the Sahara Desert. Average annual rainfall is approximately 1300 mm, with daily temperature ranging from 20 °C to 37 °C Refs. [3, 10]. These climatic variations strongly influence tropospheric refractivity and radio-wave propagation across the region. The study area is shown in Figure 1.

The town is situated along a major terrestrial microwave-communication corridor serving the North-Central, South-East, and South-South geopolitical zones of Nigeria. Despite the growing telecommunication infrastructure in and around Otukpo, no previous long-term empirical investigation of tropospheric radio refractivity, refractivity gradient, and geoclimatic factor has been reported for this location. Because Otukpo is in the Guinea Savannah climatic zone, with well-defined seasonal variations in atmospheric moisture, it is scientifically and practically important for radio-propagation studies. The tropospheric radio refractivity, refractivity gradient, and K-factor were computed using equations (2), (9), and (10). Time-series plots of these parameters were then produced to show their temporal variation from 2000 to 2022.

2.2. Source of data

The data used in this research were obtained from the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), reanalysis dataset of the National Aeronautics and Space Administration (NASA), accessed through the NASA Prediction of Worldwide Energy Resources (POWER) web portal [11]. The dataset was downloaded through the NASA POWER data access portal and covers the period 1 January 2000 to 31 December 2022, yielding a total of 8,401 daily records. It contains daily surface meteorological parameters for Otukpo, including temperature (°C), relative humidity (%), and atmospheric pressure (hPa).

The meteorological data obtained from MERRA-2/NASA POWER were used because of their high temporal resolution, global spatial coverage, continuous gap-free record, and established reliability for atmospheric propagation studies in tropical Africa Refs. [12, 13]. The dataset has also been widely validated and adopted in previous Nigerian refractivity investigations Refs. [14**?** , 15].

2.3. Computation of surface radio refractivity

The methodological framework adopted in this study included the computation of surface refractivity and refractivity at 100 m altitude, derivation of the tropospheric radio refractivity gradient at 100 m altitude, derivation of the K-factor at 100 m altitude, and statistical analysis of their temporal variations over Otukpo for 2000–2022. Surface radio refractivity (N_s) was formulated from the daily meteorological parameters obtained from the NASA POWER (MERRA-2) dataset using the ITU-R method via equations (2) and (6)–(8). The computation was implemented in a Microsoft Excel spreadsheet. Each of the 8,401 daily records was sequentially processed through equations (13), (14), (15), (16), and (17) as follows.

First, the average daily temperature in degrees Celsius, T^c, was transformed to absolute temperature in Kelvin, T, using

$$T(\mathrm{K}) = T^c + 273.15. \tag{13}$$

Second, the saturated water-vapour pressure (e_s) in hPa was estimated from the daily temperature using the August–Roche–Magnus approximation:

$$e_s = 6.1121 \exp\left(\frac{17.502\theta}{\theta + 240.97}\right), \tag{14}$$

where θ is the temperature in °C. Third, the actual water-vapour pressure (e) in hPa was computed from relative humidity and saturated vapour pressure using

$$e = \frac{\mathrm{RH} \times e_s}{100}. \tag{15}$$

Fourth, the partial pressure of dry air (P^d) in hPa was derived from total atmospheric pressure and water-vapour pressure using

$$P^d = P - e. \tag{16}$$

Finally, surface radio refractivity was computed with the ITU-R three-term formula:

$$N_s = 77.6\frac{P_d}{T} + 72\frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2}. \tag{17}$$

The first term on the right-hand side of equation (17) is the dry component (N_{dry}) of surface refractivity, while the combined second and third terms constitute the wet component (N_{wet}), the dominant source of temporal variability under tropical humid conditions Refs. [16, 17].

2.4. Tropospheric radio refractivity calculation at 100 m altitude

The variation of tropospheric radio refractivity with height was analysed using the ITU-R exponential profile in equation (9), with the scale height H set to 7.35 km [1]. The refractivity at a height of 100 m ($h = 0.1$ km) is

$$N(h) = N_s \times \exp\left(-\frac{h}{H}\right). \tag{18}$$

Substituting $h = 0.1$ km and $H = 7.35$ km gives

$$N_{100} = N_s \times \exp\left(-\frac{0.1}{7.35}\right) \approx 0.9865 \times N_s. \tag{19}$$

Equations (18) and (19) define the 100 m refractivity calculation. Here, N_{100} is the refractivity at 100 m altitude and N_s is the surface refractivity. The exponential factor $\exp(-0.1/7.35) \approx 0.9865$ is a constant derived from the ITU-R standard scale height of 7.35 km, which represents the internationally recommended e-folding height for the near-surface refractivity profile. This computation was also implemented in Microsoft Excel, producing a daily time series of N_{100} for 2000–2022.

2.5. Computation of tropospheric radio refractivity gradient at 100 m altitude

The refractivity gradient, the rate of change of refractivity with altitude, was calculated using refractivity values at the surface and at 100 m altitude according to

$$\frac{\mathrm{d}N}{\mathrm{d}h} = \frac{N_{100} - N_s}{h_{100} - h_s}. \tag{20}$$

In equation (20), N_{100} is the 100 m altitude refractivity, N_s is the surface refractivity, h_{100} is the 100 m height (0.1 km), and h_s is the surface height (0 km). Substituting the values of h_{100} and h_s gives the RRG at 100 m in equation (21):

$$\mathrm{RRG} = \frac{N_{100} - N_s}{0.1} \quad [\text{N-units km}^{-1}]. \tag{21}$$

Because N_{100} is always less than N_s in a normally refracting atmosphere, the RRG is negative under normal propagation conditions. The derived daily RRG values were analysed to examine temporal and seasonal variations in atmospheric radio-propagation conditions over Otukpo. The ITU-R standard atmosphere refractivity gradient is about −40 N-units km^{-1}.

2.6. Computation of geoclimatic factor at 100 m altitude

The K-factor at 100 m altitude was calculated from the standard expression in equation (12). The K-factor represents the apparent curvature of the Earth's surface caused by atmospheric refraction and is important in the design and planning of terrestrial microwave communication links. According to Ref. [18], it is defined as

$$K(h) = \frac{1}{1 + \frac{\mathrm{RRG}(h)}{157}}. \tag{22}$$

Here, RRG(h) is the radio refractivity gradient (N-units km^{-1}) at altitude h. For the ITU-R standard atmosphere with RRG = −40 N-units km^{-1}, equation (22) yields

$$K = \frac{1}{1 + (-40/157)} = \frac{1}{0.7452} \approx 1.333 = \frac{4}{3}. \tag{23}$$

Equations (22) and (23) give the local and standard K-factor calculations, respectively. The value 4/3 is the well-known effective Earth radius approximation used in standard microwave-path design. If $K > 4/3$, the condition is super-refractive and increases the effective Earth radius and radio horizon; if $K < 4/3$, the condition is sub-refractive and decreases the effective Earth radius and radio horizon. Microsoft Excel was used to compute the K-factor, and the daily values were analysed together with the RRG to examine the dominant radio-propagation regime over Otukpo.

2.7. Data and graphical analysis

Detailed statistical and graphical analyses were carried out on the computed daily time series of surface refractivity (N_s), refractivity at 100 m (N_{100}), RRG, and K-factor. The data were divided into wet season (April–October) and dry season (November–March) to evaluate the effect of seasonal climatic changes on the refractivity parameters. Statistical tools, including arithmetic mean, standard deviation, and range, were used to evaluate temporal variability and trends across the 23-year study period. Monthly climatological means for each parameter were computed by averaging all daily values within a given calendar month across 2000–2022. This produced a 12-point seasonal climatological cycle for each parameter and captured the bimodal wet-season pattern and Harmattan dry-season trough characteristic of the Guinea Savannah climate of Otukpo. Annual means were computed by averaging all daily values within each calendar year, producing 23 annual mean values per parameter for interannual trend analysis.

Pearson product-moment correlation analysis was applied to quantify the linear relationships between daily surface refractivity (N_s) and each of the three input meteorological variables—relative humidity, atmospheric temperature, and surface pressure—across all 8,395 daily paired observations. The Pearson correlation coefficient r is

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \times \sum(y_i - \bar{y})^2}}. \tag{24}$$

Equation (24) defines the Pearson coefficient, where x_i and y_i are paired daily values of the two variables, and $\bar{x}$ and $\bar{y}$ are their respective grand means. Statistical significance of each correlation was assessed using a two-tailed t-test. The coefficient of determination (r^2) was also computed to quantify the fraction of total variance in N_s that is linearly attributable to each meteorological predictor.

Daily and seasonal variations of refractivity and its gradient were graphically represented using time-series plots and bar charts produced in Microsoft Excel for visualisation and presentation. These analyses facilitated the identification of seasonal and interannual variations in tropospheric radio refractivity, refractivity gradient, and K-factor over Otukpo for 2000–2022 and enabled comparison of the computed parameters with ITU-R standard values and with results reported in the literature for other Nigerian and West African stations.

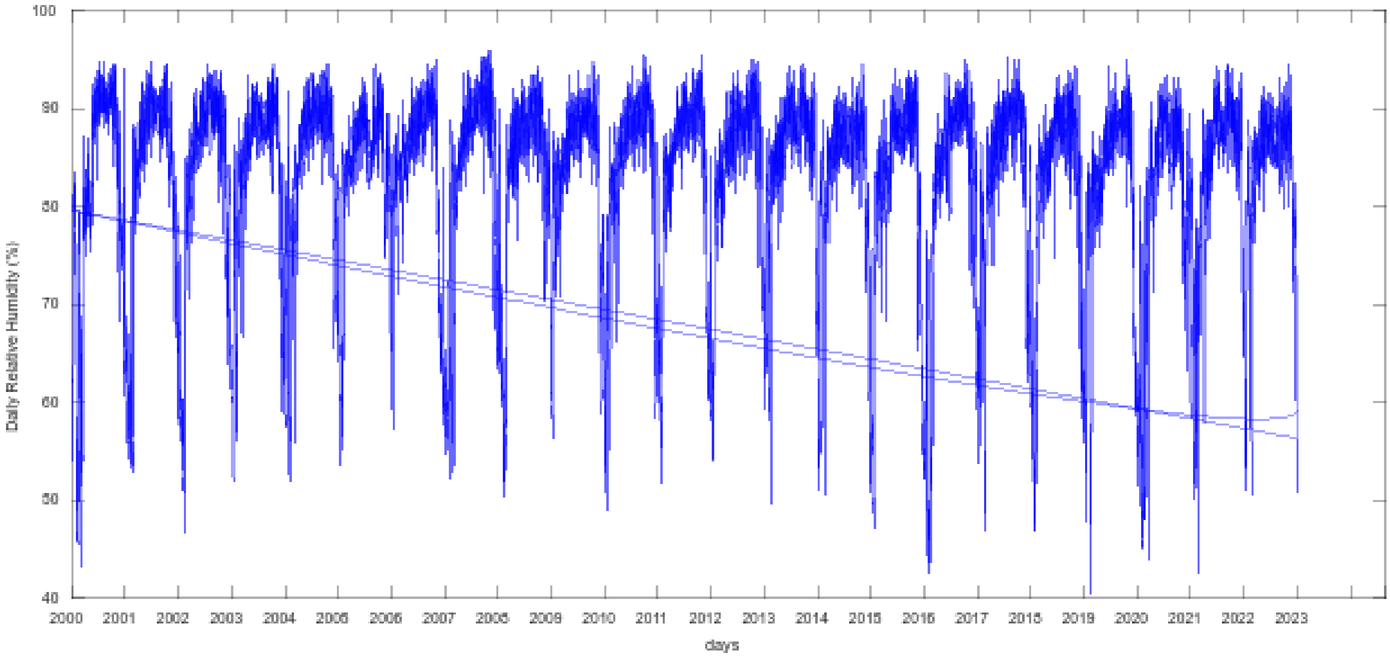

Figure 2: Time series of daily relative humidity (%) for Otukpo, Nigeria, 2000–2022.

3. Results and discussion

3.1. Time series of secondary meteorological data

3.1.1. Relative humidity

The time series of daily relative humidity for Otukpo from 2000 to 2022 is presented in Figure 2. Throughout the 23-year record, relative humidity exhibited a pronounced and persistent seasonal oscillation associated with the dominant control of the West African Monsoon system on atmospheric moisture in the Guinea Savannah climate zone. Relative humidity rose above 80% during the wet seasons (April–October), driven by the northward penetration of moisture-laden southwesterly winds associated with the ITCZ. Values fell below 40% during the Harmattan dry season (November–February), when dry, dusty northeasterly airflow from the Sahara Desert suppressed moisture advection from the Atlantic. January consistently recorded the lowest daily humidity values in each year, marking the peak of Harmattan influence, while peak values were most frequently attained in August at the height of the monsoon. The wide seasonal amplitude of relative humidity, approximately 40 percentage points between seasonal extremes, establishes it as the most dynamically variable of the three meteorological inputs and, as shown in the correlation analysis, the primary driver of surface radio refractivity variability at the station.

3.1.2. Atmospheric temperature

Figure 3 displays the time series of daily atmospheric temperature for Otukpo over the study period. Temperature had a relatively small seasonal range compared with relative humidity, a feature typical of tropical continental stations at this latitude. Values fluctuated daily but were generally of the order of 20 °C to 37 °C over the record period. The highest temperatures were consistently observed in the late dry season and early wet season (March–April), when intense pre-monsoon solar radiation heats the land surface before evaporative cooling begins with the rains. A secondary warm episode typically appears in October–November as the retreating ITCZ leaves behind drier, cloudless conditions. The coolest temperatures were recorded in December–January under the influence of Harmattan air masses and reduced solar insolation around the winter solstice. A subtle long-term warming tendency is discernible in the interannual envelope of the time series, consistent with projected regional warming for sub-Saharan West Africa. From a propagation standpoint, temperature modulates refractivity both directly through the dry term of the ITU-R formula and indirectly by controlling saturated vapour pressure and, for a given relative humidity, actual atmospheric water-vapour content.

3.1.3. Surface atmospheric pressure

The time series of daily surface atmospheric pressure at Otukpo for 2000–2022 is shown in Figure 4. Surface pressure values were stable throughout the record, oscillating within a narrow band of approximately 1,002–1,006 hPa. This stability is consistent with the tropical location of the station, where large synoptic-scale pressure systems are absent. A faint seasonal modulation is nevertheless apparent, with marginally elevated pressures during the dry season, when the Saharan anticyclone extends southward, and slightly reduced pressures during the monsoon season, associated with the thermal low of the ITCZ. This cycle has an amplitude of less

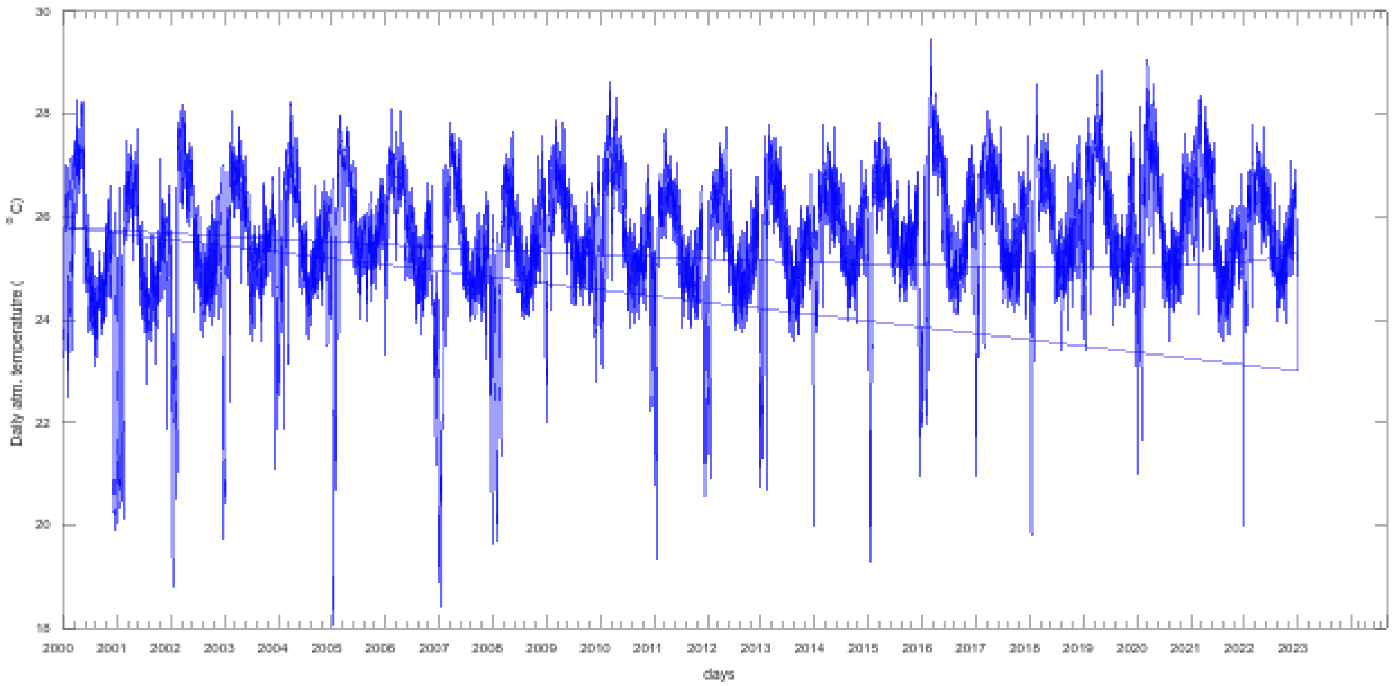

Figure 3: Time series of daily atmospheric temperature (°C) for Otukpo, Nigeria, 2000–2022.

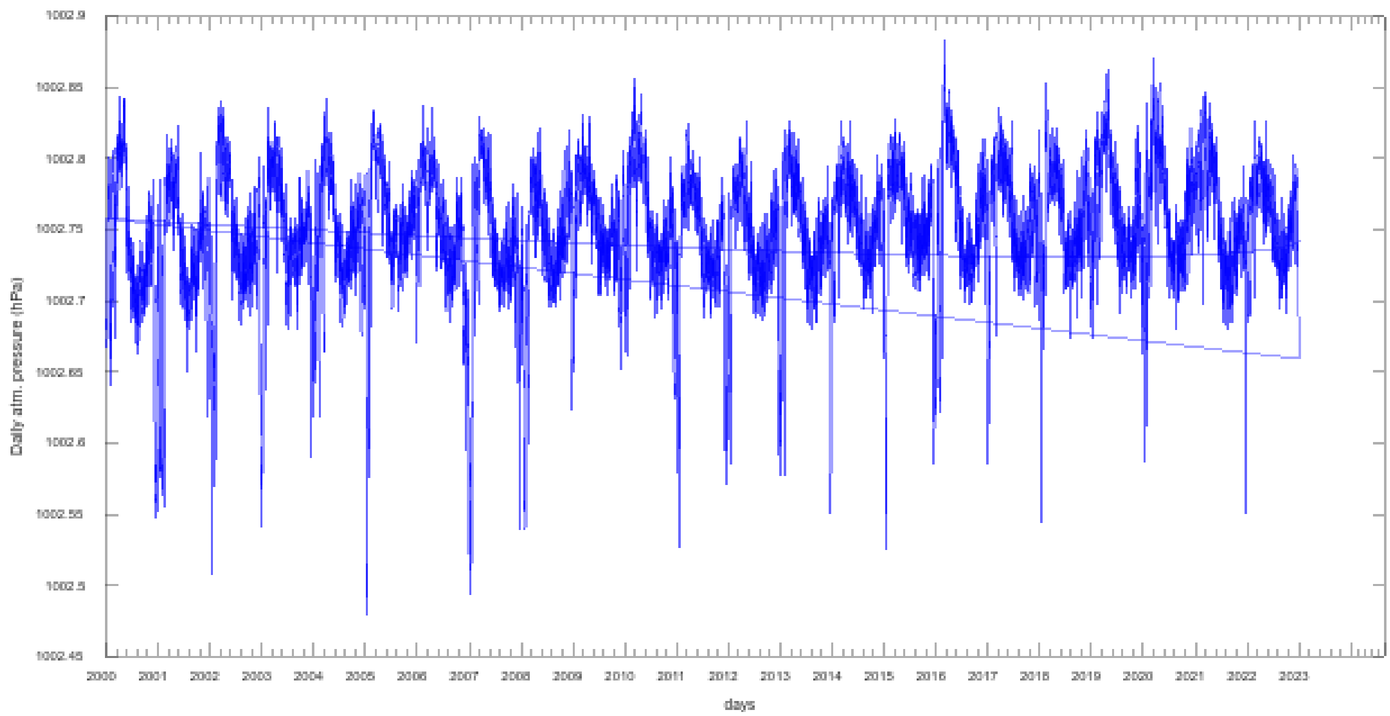

Figure 4: Time series of daily surface pressure (hPa) for Otukpo, Nigeria, 2000–2022.

than 5 hPa, much smaller than the seasonal variation in relative humidity. Thus, surface pressure is the least important parameter for seasonal variations in total refractivity, even though it accounts for about 60–70% of the magnitude of surface refractivity at any time through the dry term in the formula. The high refractivity values, together with consistently high pressure at this near-sea-level inland station (91 m), further strengthen the high refractivity generated by the tropical moisture regime.

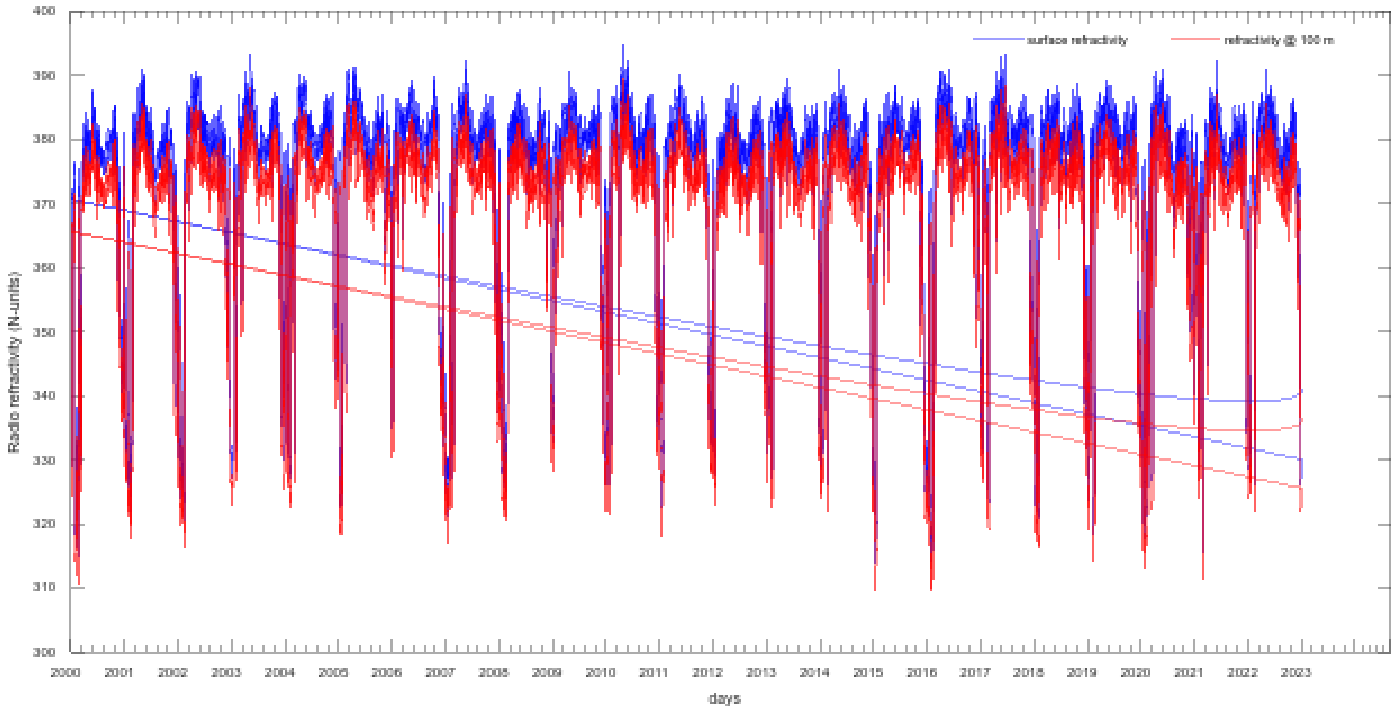

Figure 5: Time series of computed surface refractivity and refractivity at 100 m for Otukpo, Nigeria, 2000–2022.

3.2. *Surface refractivity and refractivity at 100 m height*

Figure 5 shows the time series of computed surface radio refractivity and refractivity at 100 m height for Otukpo from 2000 to 2022. The two quantities were calculated from daily meteorological data using the standard ITU-R three-component formula. The dry term was based on surface pressure and temperature, and the wet term was based on actual vapour pressure derived from temperature and relative humidity. The seasonal character of the refractivity time series is similar to that of relative humidity, further indicating that atmospheric moisture is the major factor influencing the refractive state of the lower troposphere.

The minimum N_s was 313.65 N-units and the maximum was 394.84 N-units, with an overall grand mean of 374.21 N-units and a standard deviation of 15.43 N-units across the entire record. This grand mean is much greater than the ITU-R sea-level standard refractivity of 315 N-units [18]. Even after reducing the station altitude of 91 m using an ITU-R exponential height profile to an adjusted reference value of about 313 N-units, the mean value for Otukpo remains approximately 61 N-units higher. This difference is almost entirely due to the high water-vapour content typical of the tropical Guinea Savannah climate of Benue State. Refractivity at 100 m (N_{100}) follows the seasonal trend of surface N_s throughout the time series but is systematically lower at each time step, consistent with the exponential decrease of radio refractivity with height. The mean value of N_{100} for the study period was 369.15 N-units, slightly below the surface mean. This near-surface offset is directly proportional to the vertical refractivity gradient.

3.3. *Radio refractivity gradient*

The RRG at 100 m estimated from the Otukpo data for 2000–2022 is shown in Figure 6. The RRG measures the rate of change in refractivity from the surface to 100 m height in N-units km^{-1} and defines the refractive category of the atmosphere: standard refraction (RRG = -40 N-units km^{-1}), super-refraction, and ducting Refs. [16, 18]. The computed RRG values for all dates at Otukpo were negative throughout the study period, indicating that the troposphere was normally to super-refracting on all dates. The overall grand mean RRG was -50.57 N-units km^{-1}, and daily values ranged between -42.39 and -53.36 N-units km^{-1}. The mean RRG is more negative than the ITU-R standard of -40 N-units km^{-1} but remains far above the ducting threshold of about -157 N-units km^{-1}. This indicates a regime of moderately enhanced refraction, typical of humid tropical continental stations, as reported for Akure and other parts of Nigeria Refs. [17, 19, 20]. Seasonal variations in the RRG are closely linked to the monsoon moisture cycle: values are generally less negative in December–January during the dry season and more negative in April–June during the first wet season.

3.4. *Geoclimatic factor*

The time series of the estimated K-factor at Otukpo from 2000 to 2022 is shown in Figure 7. The K-factor is directly related to the RRG and is the effective Earth radius factor for microwave path-profile analysis. The standard atmosphere used by the ITU

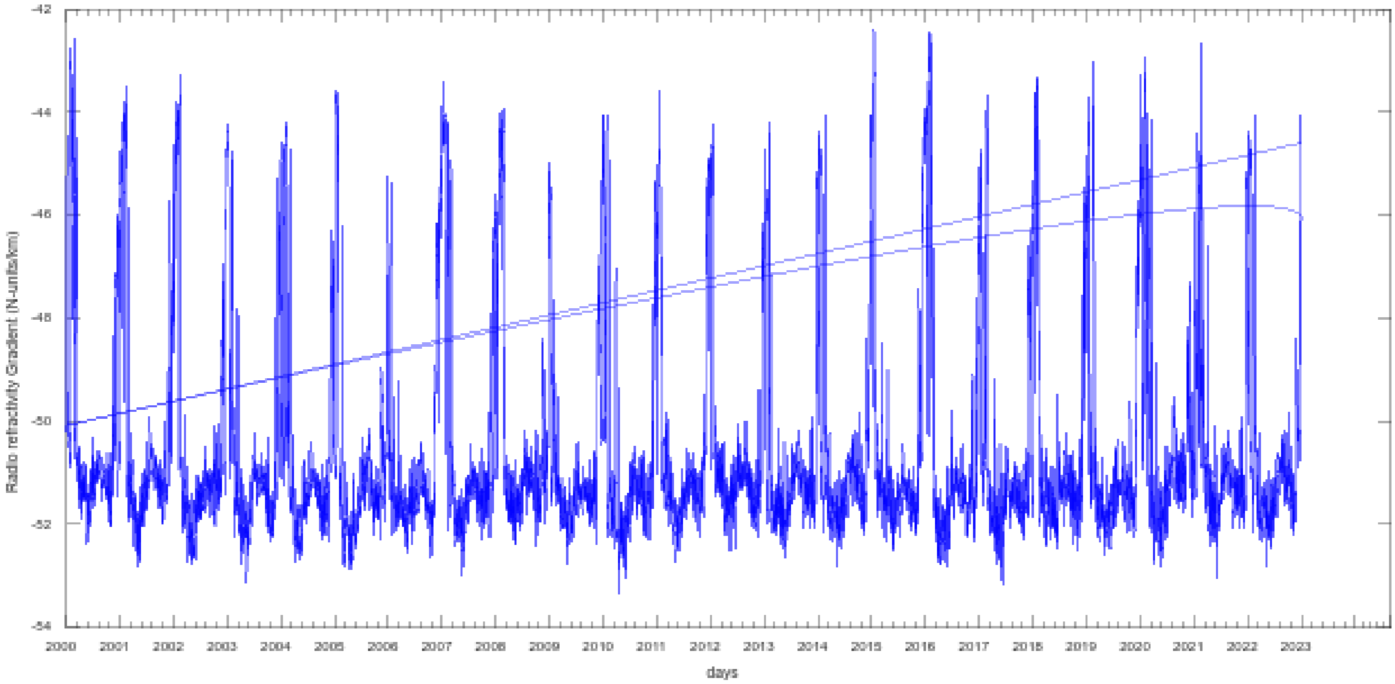

Figure 6: Time series of the estimated radio refractivity gradient at 100 m for Otukpo, Nigeria, 2000–2022.

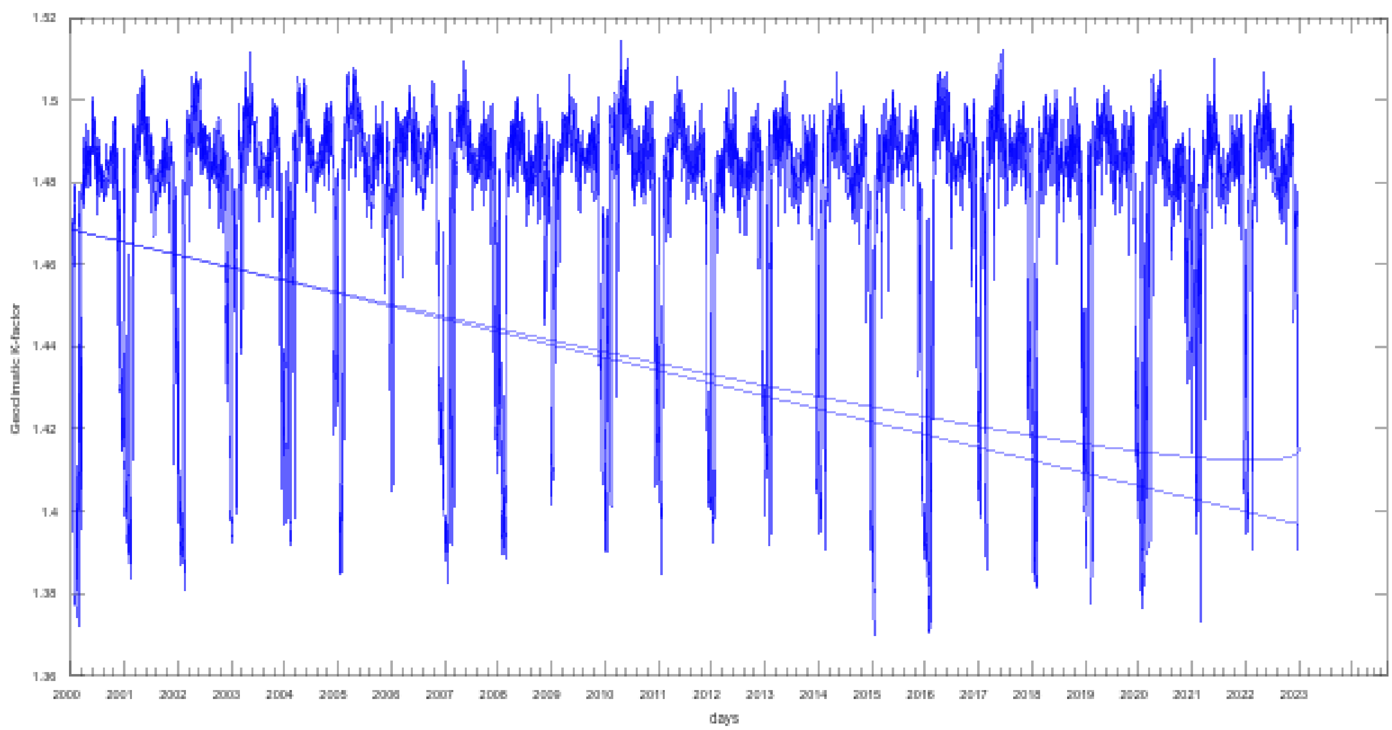

Figure 7: Time series of the estimated geoclimatic factor at 100 m for Otukpo, Nigeria, 2000–2022.

has $K = 4/3 \approx 1.333$; higher values indicate super-standard conditions with a longer radio horizon, while lower values indicate sub-refractive conditions with a shorter radio horizon [21].

The K-factor at Otukpo was consistently higher than the standard value of 4/3 during the 23-year time series. The daily grand mean was 1.4757, with values ranging from 1.3698 to 1.5148. This result implies that engineers or planners who assume the standard $K = 4/3$ value in designing microwave paths in the Otukpo area may underestimate radio-ray path curvature and introduce predictable

Table 1: Monthly climatological mean values of N_s, N_{100}, RRG, and K-factor for Otukpo (2000–2022).

Month	N_s (N-units)	N_{100} (N-units)	RRG (N-units km^{-1})	K-factor
January	350.44	345.70	-47.356	1.43290
February	363.56	358.64	-49.128	1.45641
March	379.07	373.95	-51.226	1.48449
April	383.64	378.46	-51.843	1.49304
May	384.32	379.13	-51.935	1.49434
June	381.54	376.38	-51.558	1.48900
July	378.73	373.61	-51.179	1.48365
August	377.95	372.85	-51.074	1.48218
September	379.98	374.84	-51.348	1.48602
October	381.11	375.96	-51.500	1.48818
November	375.15	370.08	-50.695	1.47710
December	354.71	349.92	-47.934	1.44011

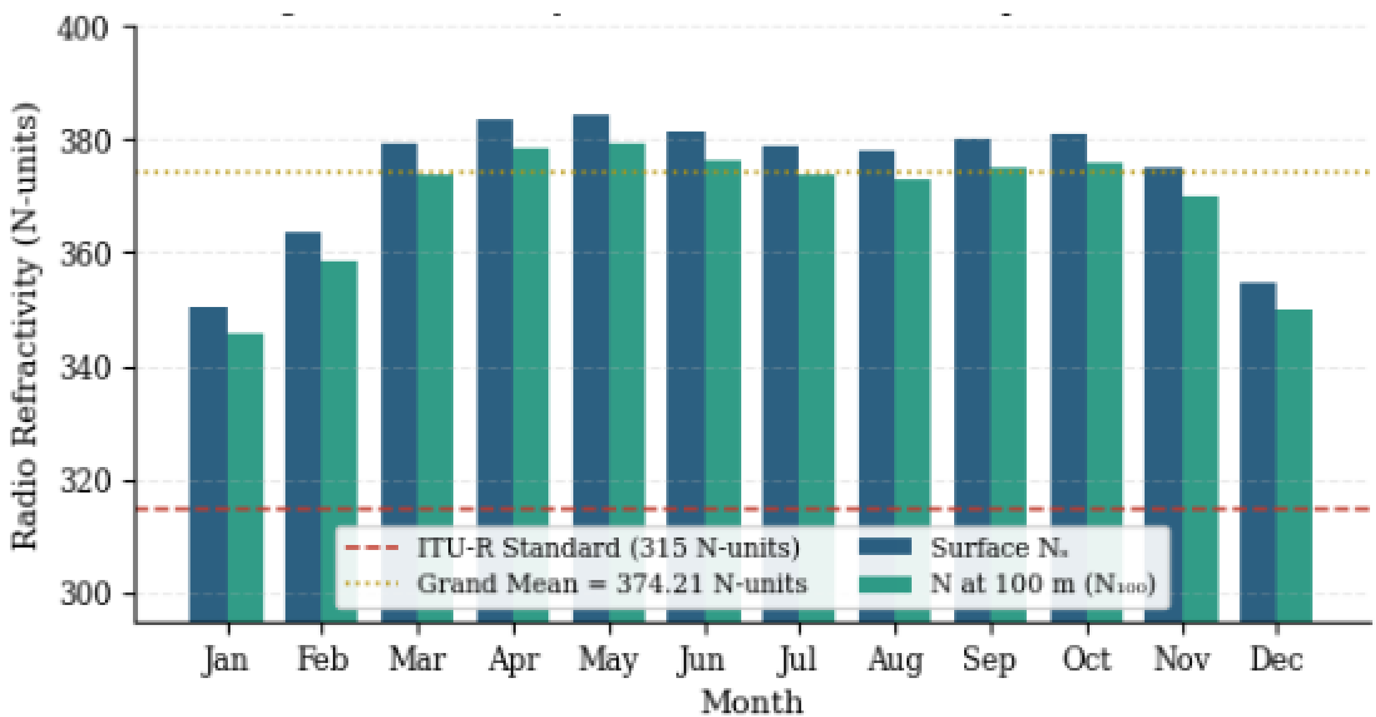

Figure 8: Monthly climatological mean N_s and N_{100} for Otukpo (2000–2022).

error into path-clearance calculations. Locally derived K values are therefore recommended.

3.5. Seasonal variation of propagation parameters over Otukpo

Monthly climatological means were determined by averaging all daily values within each calendar month across the 23-year study period (2000–2022). The resulting 12-point seasonal cycles are presented in Table 1 and Figures 8–10.

Figure 8 and Table 1 show that surface N_s follows a well-defined bimodal seasonal cycle characteristic of the Guinea Savannah climate. The annual minimum of N_s = 350.44 N-units occurs in January during the peak Harmattan season, when atmospheric moisture is lowest. A rapid increase begins in February–March as the ITCZ migrates northward and moisture-laden monsoon winds advance. The first seasonal peak is reached in May (N_s = 384.32 N-units), representing the height of the first wet season. A modest plateau and slight dip occur in July–August, corresponding to the climatological August break, a well-documented mid-season pause in rainfall characteristic of the Guinea Savannah zone [10]. The second wet season (September–October) sustains elevated refractivity close to the May peak before a rapid decline through November and December as the Harmattan re-establishes. The seasonal amplitude of surface N_s (May maximum minus January minimum) is 33.88 N-units, confirming that the propagation

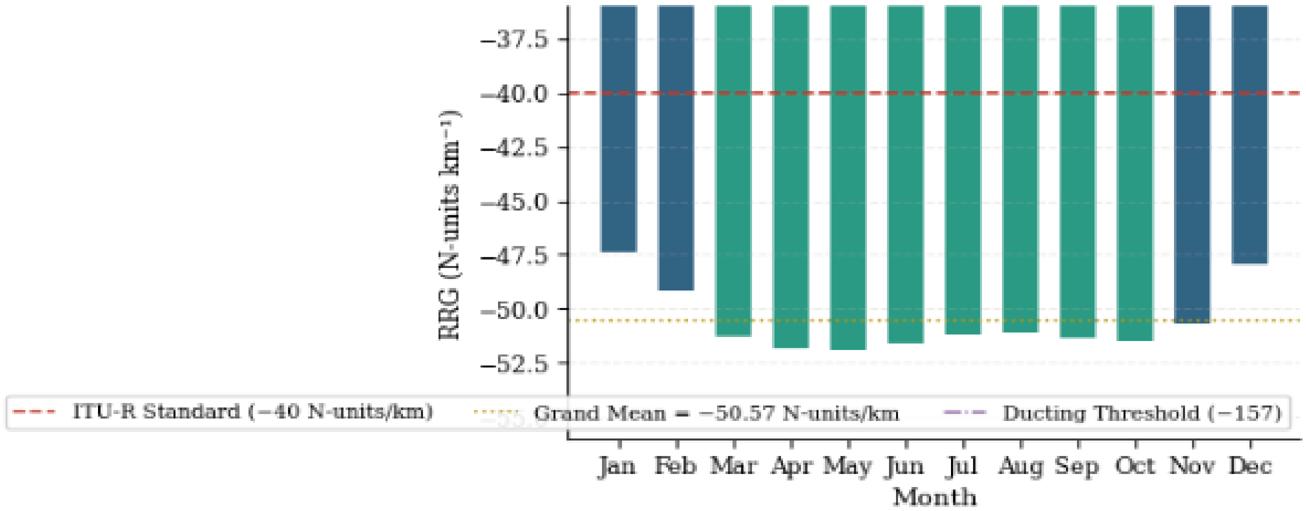

Figure 9: Monthly climatological mean RRG at 100 m for Otukpo (2000–2022).

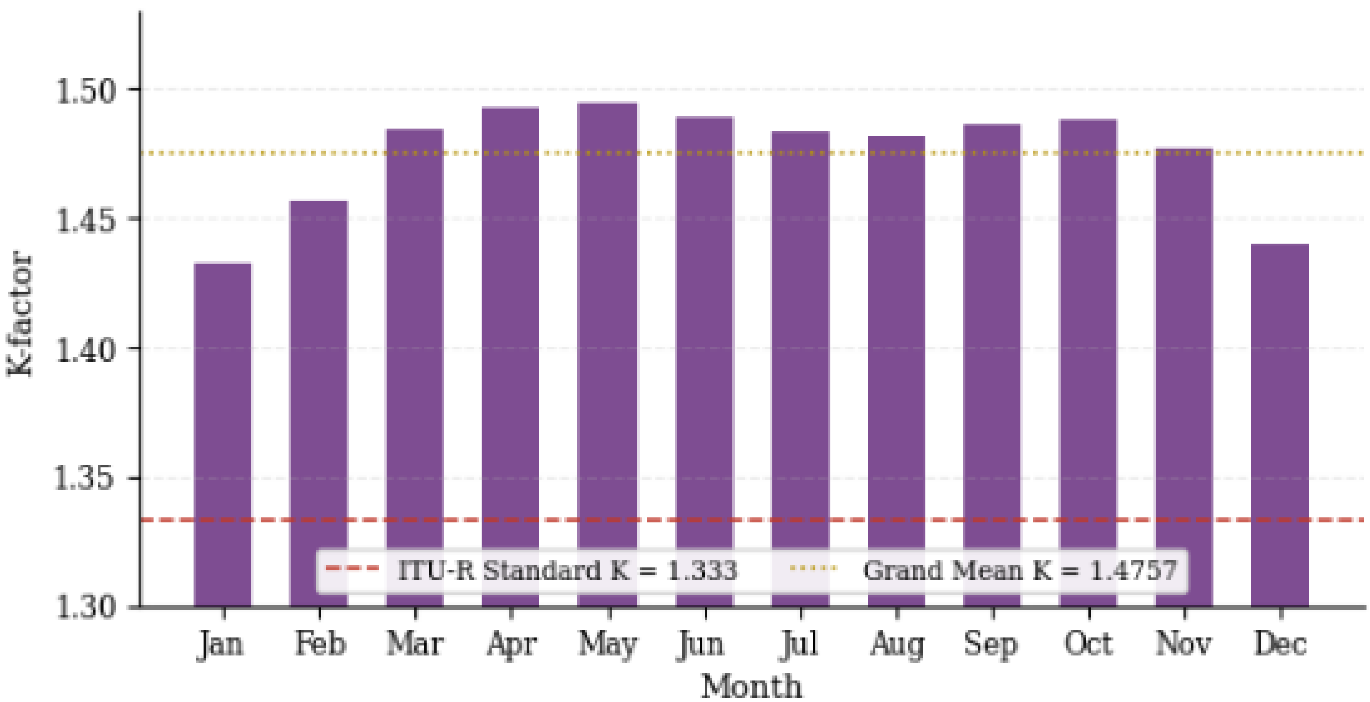

Figure 10: Monthly climatological mean K-factor at 100 m for Otukpo (2000–2022).

environment at Otukpo varies substantially between the wet and dry seasons. Similar bimodal seasonal cycles have been reported at other Guinea Savannah Nigerian stations, including Makurdi [3], the broader Guinea Savannah region [15], and Akure [22].

The seasonal variation of RRG shown in Figure 9 and Table 1 closely follows that of N_s. The RRG is most negative in May (−51.935 N-units km^{-1}) at the first wet-season peak and least negative in January (−47.356 N-units km^{-1}) during the Harmattan. All 12 monthly mean RRG values are more negative than the ITU-R standard gradient of −40 N-units km^{-1}, confirming persistent super-standard refraction at Otukpo in every month of the year. The seasonal range of monthly mean RRG is approximately 4.58 N-units km^{-1}. This persistent super-standard refraction throughout all seasons increases the likelihood of multipath fading, extended interference paths, and anomalous signal enhancement on terrestrial links year-round. Engineers designing high-availability (> 99.99%) microwave links in the Benue Valley should account for this elevated fading risk in all seasons Refs. [6, 23].

Figure 10 and Table 1 present the seasonal cycle of the K-factor. K peaks at 1.49434 in May and reaches its annual minimum of 1.43290 in January. In every month of the year, the average K value is higher than the ITU-R standard value of 1.333. During the dry

Table 2: Annual mean values of N_s, RRG, and K-factor for Otukpo (2000–2022).

Year	N_s (N-units)	RRG (N-units km^{-1})	K-factor
2000	369.84	-49.978	1.46764
2001	371.35	-50.181	1.47049
2002	371.73	-50.233	1.47131
2003	375.22	-50.704	1.47749
2004	375.27	-50.711	1.47755
2005	376.51	-50.879	1.47991
2006	375.79	-50.781	1.47853
2007	373.49	-50.471	1.47443
2008	372.00	-50.269	1.47162
2009	376.22	-50.839	1.47923
2010	376.50	-50.878	1.47989
2011	373.48	-50.469	1.47434
2012	374.98	-50.673	1.47697
2013	376.65	-50.898	1.48003
2014	375.23	-50.706	1.47745
2015	372.90	-50.392	1.47341
2016	373.84	-50.518	1.47519
2017	375.85	-50.789	1.47865
2018	373.58	-50.483	1.47457
2019	374.57	-50.617	1.47637
2020	371.79	-50.242	1.47126
2021	374.71	-50.636	1.47641
2022	375.23	-50.706	1.47745

season, the lowest K value is 1.433 in January, which is 7.5% higher than the standard. The highest K value is 1.494 in May during the wet season, 12.1% higher than the standard. The difference between the highest and lowest K values is 0.061, implying that the effective Earth radius changes by about 388 km throughout the year. For microwave-link design in the Otukpo area, K = 1.433 is recommended for dry-season calculations to ensure obstacle clearance, and K = 1.494 is recommended for wet-season calculations to minimise interference, rather than relying solely on the standard 4/3 value.

3.6. Annual variation and trend of propagation parameters over Otukpo

Annual mean values were computed by averaging all daily values within each calendar year from 2000 to 2022. Table 2 presents the complete 23-year annual mean series, and Figures 11–13 display the interannual variability with fitted trend lines.

Figure 11 and Table 2 show that surface N_s varied from year to year. The lowest annual mean was 369.84 N-units in 2000, and the highest was 376.65 N-units in 2013, giving a range of 6.81 N-units. Over the 23-year period, N_s increased slightly, with a fitted trend of about 0.069 N-units per year. Although small, this trend suggests increasing atmospheric moisture over Otukpo with time. Similar tendencies have been observed in other parts of tropical West Africa [24]. The annual values for 2010–2022 are generally higher than those for 2000–2009, consistent with this trend.

Figure 12 and Table 2 show that annual mean RRG ranged from −49.978 N-units km^{-1} in 2000 to −50.898 N-units km^{-1} in 2013, mirroring the interannual pattern of surface N_s. The interannual range of RRG is less than 1 N-unit km^{-1}, indicating a climatologically stable super-standard refractive regime across all 23 years. The annual mean RRG is more negative than the ITU-R standard of −40 N-units km^{-1} in all 23 years without exception.

Figure 13 and Table 2 show that annual mean K ranged from 1.46764 in 2000 to 1.48003 in 2013, spanning an interannual range of only 0.012. This very small variability confirms the robustness and stability of the super-standard refractive regime at Otukpo across all years. In all 23 years, the annual mean K exceeds the ITU-R standard of 1.333, with the lowest annual value (K = 1.468 in 2000) still 10.1% above the standard. The grand mean K = 1.4757 is the recommended design value for microwave path analysis in this corridor.

3.7. Correlation analysis

Pearson product-moment correlation analysis was performed between daily surface refractivity N_s and each of the three input meteorological variables—relative humidity, atmospheric temperature, and surface pressure—across all $n = 8{,}395$ daily observations. The results are presented in Table 3 and Figure 14.

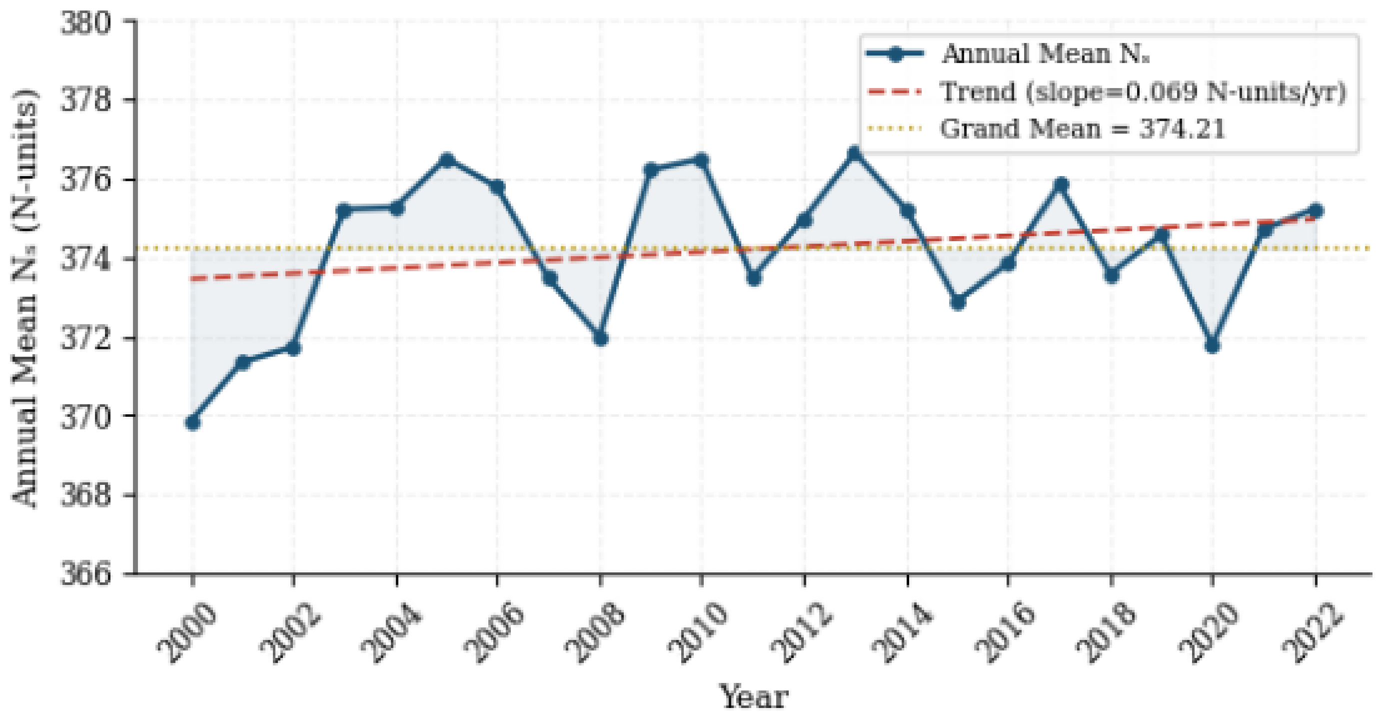

Figure 11: Annual mean surface radio refractivity (N_s) over Otukpo (2000–2022).

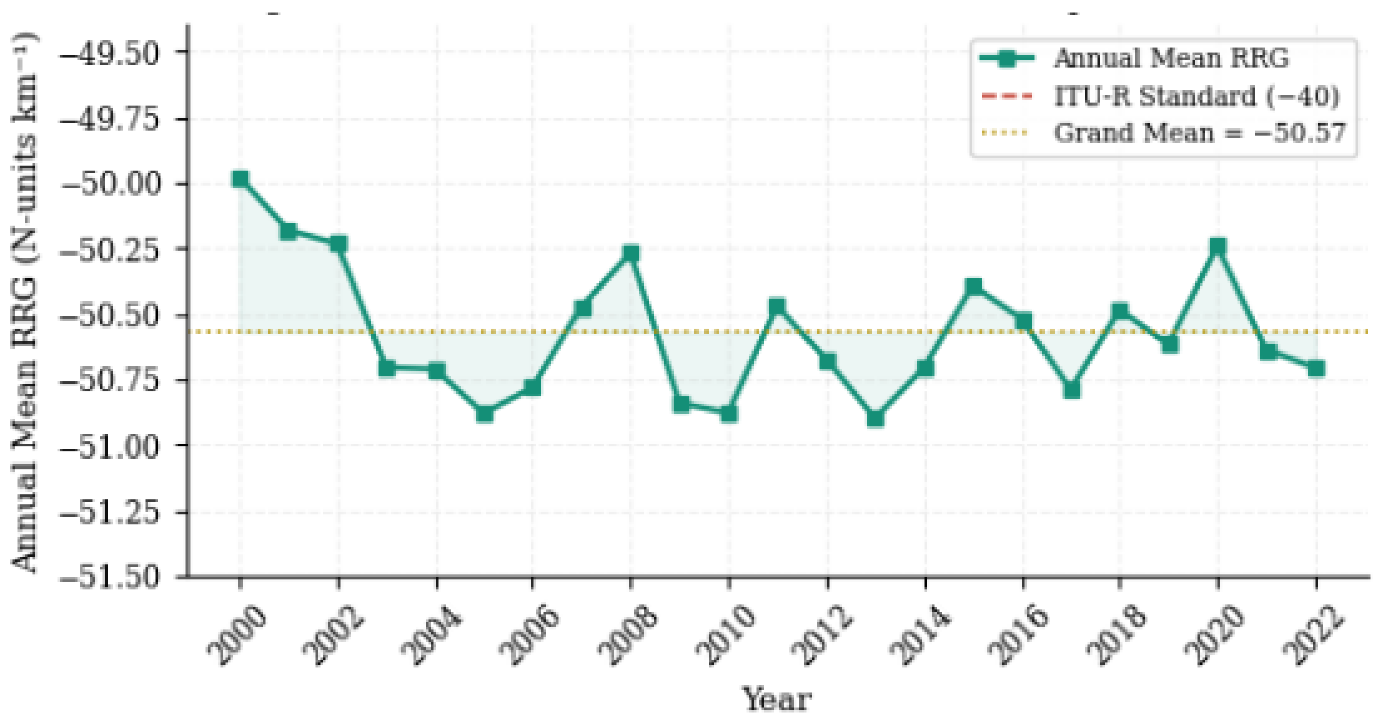

Figure 12: Annual mean RRG at 100 m over Otukpo (2000–2022).

The data in Table 3 and Figure 14 show that relative humidity is the main factor affecting the variability of surface radio refractivity at Otukpo. The correlation between relative humidity and surface radio refractivity is very strong, with a Pearson correlation coefficient of 0.9243 and significance at $p < 0.001$. Relative humidity alone explains about 85.4% of the day-to-day changes in surface radio refractivity based on 8,395 observations. This is expected because the wet refractivity term is directly related to water-vapour pressure, which is related to relative humidity at a given temperature. In a humid tropical climate such as Otukpo, changes in

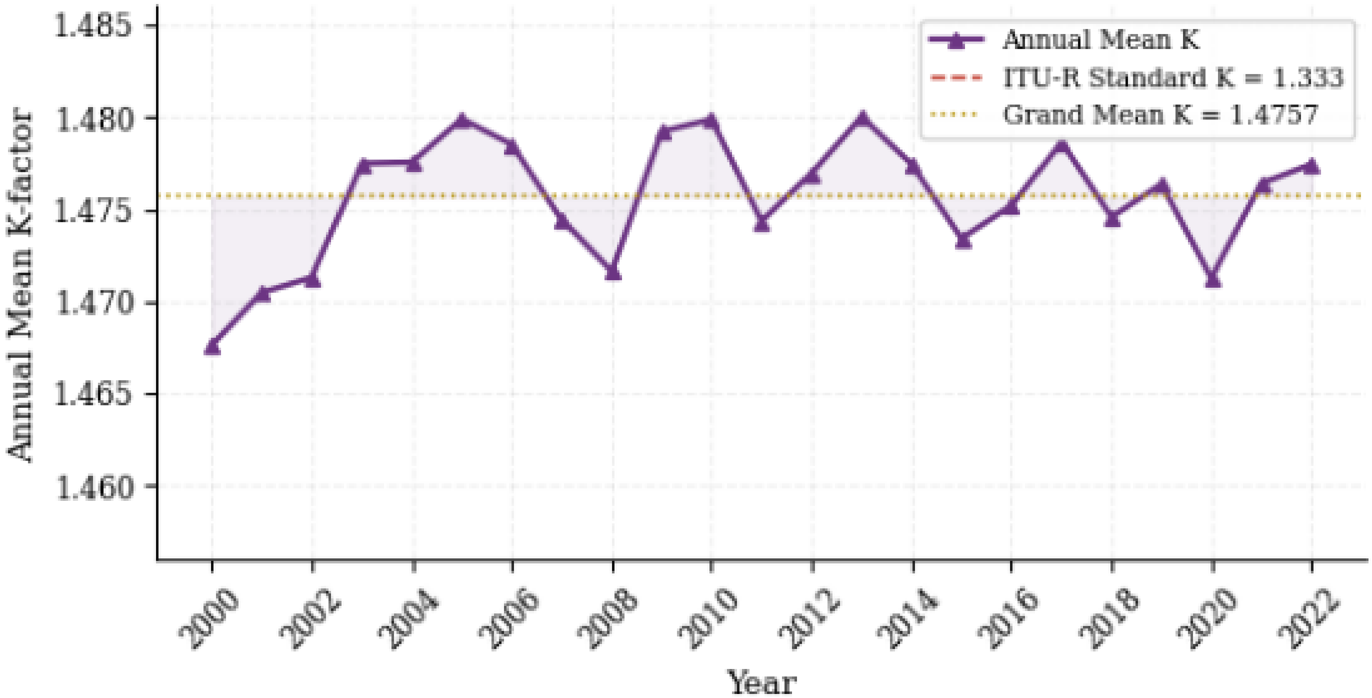

Figure 13: Annual mean K-factor at 100 m over Otukpo (2000–2022).

Table 3: Pearson correlation between N_s and meteorological variables (n = 8,395; Otukpo, 2000–2022).

Variable	Pearson r	r^2 (% variance explained)	p-value	Interpretation
Relative humidity (RH)	0.9243	85.4%	< 0.001	Very strong positive
Atmospheric temperature (T)	0.5935	35.2%	< 0.001	Moderate positive
Atmospheric pressure (P)	0.5956	35.5%	< 0.001	Moderate positive

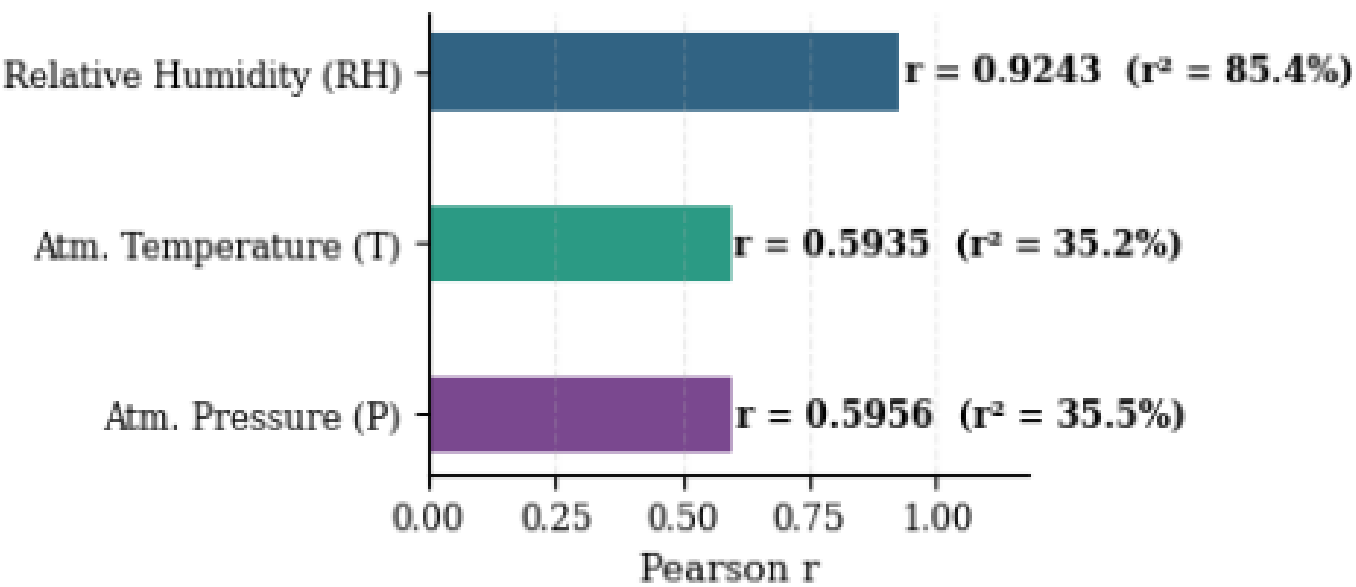

Figure 14: Pearson correlation coefficients between meteorological variables and surface N_s for Otukpo (n = 8,395; 2000–2022).

Table 4: Comparison of Otukpo propagation parameters with ITU-R standards and Nigerian literature.

Parameter	ITU-R standard	Otukpo	Literature	Reference
Mean N_s (N-units)	315 (sea level); ≈ 313 at 91 m	374.21	360–395 (Guinea Savannah)	Bello *et al.* (2024)
Mean RRG (N-units km^{-1})	-40	-50.57	-77 to -110 (North-Central)	Usman *et al.* (2024)
Mean K-factor	1.333 (4/3)	1.4757	> 1.333 (all Nigerian stations)	Omotosho & Mandeep (2011)
Effective Earth radius	8,495 km	≈ 9,402 km	—	—
Primary driver of N_s	—	RH (r = 0.9243)	Humidity dominant	Adediji *et al.* (2015)
Seasonal amplitude of N_s	—	33.88 N-units	—	—

atmospheric moisture content from day to day and season to season have a strong impact on surface radio refractivity. Atmospheric temperature and surface pressure are moderately correlated with surface radio refractivity, with coefficients of 0.5935 and 0.5956, respectively. These correlations are likely linked to their seasonal covariation with relative humidity through the ITCZ-driven annual cycle rather than to a wholly independent effect. This finding is consistent with results from other stations in tropical Nigeria Refs. [3, 15, 17, 22]. Overall, the results suggest that relative humidity is the key driver of surface radio refractivity variability at Otukpo, while temperature and pressure play secondary roles.

3.8. Comparison with ITU-R standards and related literature

Table 4 compares the principal propagation parameters computed in this study with the ITU-R standard reference atmosphere and with representative values reported from other Nigerian stations in the literature.

The results show that the atmosphere over Otukpo is more super-standard than typically assumed under the ITU-R reference atmosphere. On average, N_s is 374.21 N-units, about 61 N-units higher than the adjusted reference value of approximately 313 N-units. The RRG value is also more negative than the standard, at −50.57 N-units km^{-1}, which is 10.57 N-units km^{-1} lower than the standard. In addition, the K-factor is 1.4757, 10.7% higher than the standard value of 4/3. This condition persists in every year and every month of the 23-year period. Compared with other stations in North-Central Nigeria, Otukpo's RRG value is not as negative as values reported for Makurdi, Abuja, and Jos. This difference is mainly due to the methods used for data collection: the other study used radiosonde data that could detect sharp near-surface temperature changes, while this study considered the gradient from the surface to 100 m. Nevertheless, the high values at Otukpo are consistent with expectations for the Guinea Savannah region, as reported by Ref. [15]. The comparison indicates that the lower troposphere over Otukpo is more super-standard than reference conditions, with implications for regional climate characterisation and radio-propagation planning.

4. Conclusion and recommendations

4.1. Conclusion

The objectives of this research were accomplished using ITU-R P.453-14 and P.530-18 formulae. Daily relative humidity showed a strong bimodal seasonal pattern (wet season: RH > 80–95%; Harmattan: RH = 40–60%), confirming it as the dominant propagation driver (r = 0.9243, r^2 = 0.854). Surface pressure was stable (1,002–1,006 hPa), while temperature ranged from 20 °C to 37 °C. The grand mean N_s = 374.21 N-units (SD = 15.43) exceeded the altitude-adjusted ITU-R reference by approximately 61 N-units, with a seasonal amplitude of 33.88 N-units. The grand mean RRG of −50.57 N-units km^{-1} was more negative than the ITU-R standard (−40 N-units km^{-1}) in all 23 years and all 12 months, confirming persistent super-standard refraction. The grand mean K-factor of 1.4757 exceeded the standard 4/3 ≈ 1.333 throughout the record, corresponding to an effective Earth radius of approximately 9,402 km. This study provides the first radio-climatic baseline that combines surface and 100 m refractivity, RRG, and K-factor in one framework for the Otukpo study area, based on long-term daily data. The annual and seasonal propagation parameters obtained for the local environment are useful for improved microwave-link planning, path-clearance assessment, and reliable communication-system design in Otukpo and other tropical inland environments.

4.2. Recommendations

To improve the accuracy of path analysis in the Otukpo–Benue Valley corridor, the standard ITU-R value of $K = 4/3$ should be replaced with locally derived values: $K = 1.4757$ for annual analysis, $K = 1.4329$ for dry-season calculations, and $K = 1.4943$ for wet-season calculations. These local values will improve path-analysis precision in the area.

The value RRG = −50.57 N-units km^{-1} should be used in fade-depth and multipath-fading calculations according to ITU-R P.530-18, and wet-season K values (April–October) should be applied when computing fade margins for high-availability links (≥ 99.99%).

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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