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Radioclimatic Variable Characterization for Tropical Microwave Link Applications

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Abstract: One of the main factors impairing radio wave propagation is atmospheric refraction. To ensure a reliable radio link, accurate estimates of the refractivity gradient and geoclimatic factor are essential for determining the fade margin, a crucial component of radio-wave signal transmission. In this study, three years of data from 2019 to 2021, collected from six distinct locations in Nigeria, were utilized to analyze the radio-climatic variables in order to determine their influences on microwave linkages. The obtained values for surface refractivity show seasonal variation, with higher values during the wet season and lower values during the Harmattan. Makurdi, located in the north of the country, is mostly impacted by sub-refraction, whilst Lagos and Port-Harcourt, in the south, are impacted by super-refraction. The average refractivity gradient values for Makurdi and Yola are -35.2 and -30.62 N-units/km, respectively, with k factors of 1.30 and 1.32. In contrast, Lagos and Port Harcourt recorded values of -81 and -93. with k factors of 1.42 and 1.51. The findings also show that the shift of the intertropical discontinuity influences seasonal variations across the studied locations. Geoclimatic factor values vary seasonally and spatially. The results provide valuable insights for designing microwave wireless links in Nigeria.

Keywords: Fade margin, Geoclimatic factor, Microwave links, Propagation, Surface refractivity.

Introduction

The most accessible method for efficient propagation and communication involves using radio links in the microwave frequency region [1]. These links are utilized for transmitting a large number of high-definition television (HDTV) channels with excellent audio and video output. Although operated at a greater operating frequency definition than television channels, this radio broadcast is nonetheless affected by a number of atmospheric factors [2]. It has been determined that the problem of climate change and rising global warming is caused by a net imbalance in the energy radiation of the earth [3].

In order to transmit high-quality messages, radio links must operate reliably and efficiently in light of the increased bandwidth demand that recent advancements in radio communication technology can support [4]. The troposphere has an impact on how radio waves travel between radio link terminals when using a wireless medium. When there are poor propagation conditions, the output signal will fluctuate, which will cause microwave links to fade [5]. Because of the extreme concentration of aerosol particles and other pollutants in industrial and heavily populated areas, the pollution in the atmosphere calls for attention [6]. The most

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frequent adverse impact on satellite communication lines at higher frequency bands is attenuation brought on by precipitation, especially in the tropical and equatorial regions [7].

In the modern era, where radio communications are heavily influenced by everything from mobile telephony to terrestrial digital broadcasting to the propagation of satellite radio signals through the troposphere, the behavior of radio waves in the tropospheric layer of the Earth's atmosphere is extremely important. The troposphere can cause radio waves to bend upward, leading to sub-refraction, or downward toward the Earth's surface, resulting in abnormal propagation phenomena such as super-refraction and ducting [8]. These effects have significant implications for the performance of radio communication systems and radar operations [9][10].

Refractivity is one of the main challenges of radio propagation due to the non-uniform medium of the atmosphere [11]. To maximize the effectiveness of a microwave link, some parameters such as the effective earth radius factor (k), and the point refractivity gradient must be carefully tuned. Variations in atmospheric weather parameters, including temperature, relative humidity, and dew point, lead to changes in the geoclimatic factor, which varies over time and space. A measurement of a terrain's climatic and geographic conditions is called the geoclimatic factor (K) [12]. The geoclimatic factor plays a vital role in calculating the percentage of time that a particular fade depth is exceeded. The effective earth radius (k factor), along with the changes to the geoclimatic factor, causes radio signals to refract in diverse routes over the curvature of the earth causing multipath fading of the radio signal [13]. The frequency, hop length, type and roughness of the terrain, weather, and path clearance are factors that affect multipath fading outages [14]. Determining the geoclimatic factor for each site and region of interest is crucial for accurate planning, ensuring that terrestrial radio links successfully transport radio waves.

Various methods have been suggested by numerous authors to address this issue with radio propagation in various parts of the world. The radio propagation data of the relevant locations were used to create these strategies [15–18]. These studies highlight the critical role of the geoclimatic factor in capturing both the geographical and climatic aspects of a region [15].

The radio refractivity index N is defined by the International Telecommunication Union (ITU) in [19] as N (p, e, T), where p is the total atmospheric pressure, e is the vapor pressure, and T is the ambient temperature [19]:

$$N = 77.6\frac{p}{T} + 3.75\ X\ 10^5\frac{e}{T^2} - 5.6\frac{e}{T} \quad (1)$$

T is measured in Kelvin, while p and e are measured in hPa. As can be seen from Eq. (1), the amount of moisture in the atmosphere has a significant impact on atmospheric radio refractivity. It should also be emphasized that Eq. (1) is accurate and dependable for calculating the refractivity of a wide range of frequencies, including those up to 100 GHz [20, 21], making it a typical model for calculating radio refractivity.

The effective earth radius factor, also known as the k-factor, is used to classify radio refractivity into categories such as normal or standard refraction, sub-refraction, super-refraction, and ducting. The k-factor is calculated as [22]:

$$k = \left(1 + \frac{\frac{dN}{dh}}{157}\right)^{-1} \quad (2)$$

where $\frac{dN}{dh}$ is the refractivity gradient

$$\frac{dN}{dh} = \frac{N_s - N_h}{h_2 - h_1}$$

Refractivity gradients vary with climate, season, transient weather conditions, time of day, congestion, and terrain along the communication path [23]. The radio signal bends toward the ground and travels beyond the geometric horizon when refractivity gradient is negative (beyond 100 N-unit/km).

The aim of this study is to characterize the radioclimatic variables, including surface refractivity, radio refractivity gradient, effective earth radius, and geoclimatic factor in six selected locations in Nigeria. As a tropical country, Nigeria experiences extreme weather conditions during the rainy and dry seasons, creating an unpredictable environment for radiowave propagation. This necessitates an investigation.

Nigeria Climate

Nigeria is situated between latitudes 4° and 14° N and longitudes 2° and 15° E. The country is close to both the equator and the Tropic of Cancer. In general, Nigeria has an equatorial and tropical continental climate. Nigeria's climate is truly tropical, with average temperatures ranging from 24°C to 27°C. The annual mean temperature is 27°C in the tropical rainforest region to the south, with slightly higher mean values observed in the sub-Sahel to the north. This is due to the movement of the Intertropical Discontinuity (ITD) combined with aspects of ocean-atmosphere coupling. Table 1 outlines the climatic zone characteristics of the study locations. In the northern region, a long dry season extends from October to mid-May, followed by a brief rainy season from June to September, with an annual mean rainfall of approximately 50 cm. In contrast, the southern region experiences a prolonged wet season from March to October, with peak rainfall occurring in June or July.

TABLE 1. Geographic and climatic characteristics of study areas.

Stations	Longitude	Latitude	Annual Mean Precipitation (mm)	Average Temperature (°C)	Climatic Region
Makurdi	8.92° E	7.75"N	1,290	28.26182	Guinea Savanna
Lagos	3°26'1.19"E	6°48'3.77"N	1,540	26.62534	Tropical
Port-Harcourt	6°54'2.58"E	4°43'6.18"N	2,719	26.98320	Tropical Monsoon
Yola	12°28'4.47"E	9°12'3.30"N	114.29	30.53711	Tropical Savanna
Ayingba	7°10'2.10"E	7°29'3.12"N	654.21	26.79148	Tropical Hinterland
Osogbo	4°32'3.59"E	7°46'5.61"N	1,361	26.58866	Tropical Savanna

Yola is located in Nigeria's northeast and exhibits some Sahel savannah characteristics. The area has two different seasons: the dry season and the rainy season. The wet season typically begins in early June and lasts through early October, with the dry season starting around November and ending around May. Despite the brief duration of the rainy season, it is marked by heavy rainfall. Due to the north-easterly wind coming from the Sahara Desert, the area also gets Harmattan dust between December and February.

Lagos, in southwestern Nigeria, has a tropical climate, while Port Harcourt, in the South-South, experiences a tropical monsoon climate, which is similar to Lagos. Both cities experience precipitation almost year-round, with temperatures remaining fairly consistent throughout the year. The Harmattan is less pronounced in these metropolises, though it still significantly impacts weather patterns across West Africa.

Makurdi, situated within the Guinea savannah region, is known for its hot climate. The wet season lasts from April to early October, while the dry season occurs from November to April. Between late December and early February, the region is also affected by Harmattan dust.

Ayingba experiences a tropical hinterland climate characterized by a small diurnal temperature range, high humidity, and increasing cumulus cloud cover from March to early April. Rainfall occurs as brief, intense showers accompanied by thunderstorm activity, signaling the onset of the rainy season.

Oshogbo has a tropical savannah climate. The city experiences two primary seasons—dry and wet—typical of the monsoon climate in West Africa, marked by a distinct seasonal shift in wind patterns. From March to October, the moist maritime southwest monsoon breeze from the Atlantic Ocean dominates, while the dry season, from November to February, is influenced by dusty winds from the Sahara

Desert. The strongest Harmattan winds, dry and dusty, are observed between December and January.

Methods

As shown in Table 1, the places considered for this study include the various climate zones in Nigeria. Data spanning three years (2019 to 2021) were collected for this work and included measurements of key meteorological parameters such as atmospheric pressure, temperature, water vapor, and relative humidity. These measurements were obtained from six stations in Nigeria, shown in Fig. 1: Makurdi, Lagos, Port-Harcourt, Yola, Ayingba, and Oshogbo, all situated up to 100 m above sea level, using the ERA5 satellite. The data were validated using the meteorological data from the Tropospheric Observatory Data Network (TRODAN) of Nigeria.

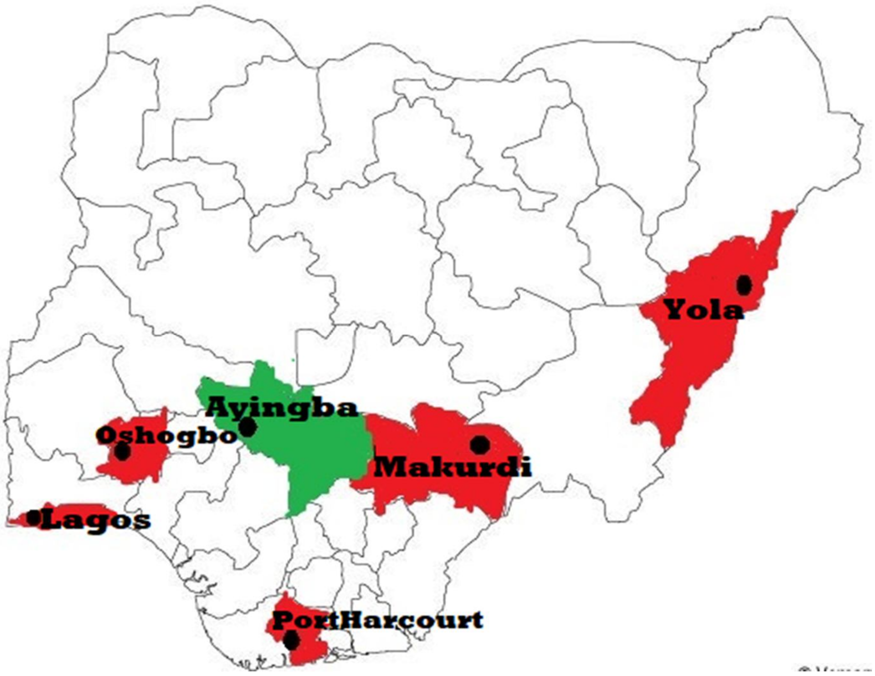


FIG. 1. Map of Nigeria showing selected locations.

Equation 1 was used to calculate the surface refractivity. The surface refractivity, which corresponds to altitude h_s, and level refractivity, N_h (100 m), which corresponds to altitude h, were combined to estimate the refractivity gradient $\frac{dN}{dh}$. As a result, the radio refractivity gradient which is often given in units/km, is expressed by [24]:

$$\frac{dN}{dh} = \frac{N_s - N_h}{h_2 - h_1} \tag{3}$$

N_s and N_h are radio refractivity values at heights h_2 and h_1, respectively.

The geoclimatic factor was calculated using the relation provided in [24]:

$$K = 10^{-4.2-0.0029(\frac{dN_1}{dh})} \tag{4}$$

Result and Discussion

The results of the collected data from 2019 to 2021 are presented in Table 2, which shows the estimated monthly average values of the geoclimatic factor and the effective factor of the earth radius (k) over the study period for the six selected stations. The graphs of annual fluctuations of surface refractivity on a monthly basis for Makurdi, Oshogbo, Yola, Lagos, Ayingba, and Port Harcourt are shown in Figs. 2-6.

Figure 2(A) shows the estimated monthly surface refractivity values for Lagos during the years 2019–2021. The refractivity values range from 317 to 378 N-units. Lagos refractivity values for the Harmattan months (November, December, January, and February,) are between 305 and 338 N-units. During the wet season months (March to October), the refractivity values range from 321 to 378 N-units.

Figure 2(B) demonstrates that, throughout the examined years in Makurdi, surface refractivity typically grew progressively from January to May. A steady rise was observed in October, followed by a sharp decline in December. The lowest refractivity value of 290 N-units was recorded in December 2020, while the highest value of 379 N-units was recorded in July 2021, a typical month during Nigeria's rainy season.

Surface refractivity was generally higher between April and October, coinciding with the rainy season. This trend might be attributed to the high relative humidity recorded in Makurdi during this period. The south-to-north movement of the inter-tropical discontinuity (ITD) with the Sun likely influenced Makurdi by bringing moist tropical marine air during this time.

In contrast, surface refractivity values decreased in December due to the prevalence of dry harmattan conditions and dominant northeasterly winds. This explains the lower refractivity values observed in January and February. However, from April to October, widespread rainfall led to an increase in atmospheric moisture, which raised relative humidity and, consequently, surface refractivity, peaking at 383 N-units in May.

TABLE 2. Estimated monthly average values of geoclimatic factor and effective earth radius k over the study period across Yola, Makurdi, and Oshogbo based on meteorological data.

	Yola		Makurdi		Oshogbo	
Months	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*
Jan	3.56	2.1957	3.86	1.8816	4.31	1.5702
Feb	4.89	1.3202	3.09	3.1339	2.19	5.3641
Mar	3.58	2.1768	4.70	1.3899	3.21	2.8124
May	4.74	1.3758	4.57	1.4405	4.37	1.5407
Jun	4.57	1.4426	4.52	1.4651	3.23	2.7745
Jul	4.53	1.4609	3.67	2.0639	3.99	1.7797
Aug	4.67	1.4009	4.50	1.4734	4.43	1.5092
Sept	4.54	1.4558	4.50	1.4740	4.43	1.5079
Oct	3.7	2.0334	3.66	2.0734	2.65	5.8405
Nov	3.34	2.5369	4.24	1.6105	4.13	1.6802
Dec	4.69	1.3951	4.46	1.4913	4.39	1.5298

TABLE 2 (cont.). Estimation of monthly average values of geoclimatic factor and effective earth radius k over the study period across Port Harcourt, Lagos, and Ayingba.

	Port-Harcourt		Lagos		Ayingba	
Months	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*	*Geoclimatic Factor, K* ($\times 10^{-5}$)	*Effective radius, k factor*
Jan	3.72	2.0080	2.89	3.9169	3.93	1.8230
Feb	3.03	3.3067	2.65	5.7569	4.63	1.4195
Mar	2.46	9.5649	3.29	2.6307	2.76	4.7312
May	3.73	1.9971	4.49	1.4792	4.58	1.4400
Jun	3.37	2.4859	4.48	1.4847	4.67	1.4026
Jul	3.68	2.0479	4.48	1.4832	4.54	1.4569
Aug	3.73	2.0011	2.69	5.3345	4.56	1.4484
Sept	2.47	9.3591	3.67	2.0676	2.46	9.6962
Oct	3.03	3.3087	4.49	1.4785	4.5	1.4752
Nov	3.73	1.9972	4.32	1.5629	3.71	2.0236
Dec	3.39	2.4533	4.48	1.4814	3.63	2.1141

Port Harcourt is shown in Fig. 3(A) as having monthly refractivity fluctuation from 2019 to 2021. The refractivity values are between 328 and 348 N-units in the stations' Harmattan months (January, February, November, and December) which are the low refractive values of the observation period. However, other seasonal fluctuations of refractivity are also seen, as the average monthly refractivity values recorded for the rainy season are 377 and 388 N-units.

Figure 3(B) depicts the change in Yola's monthly surface refractivity during the study. Following the analysis and presentation of the fluctuations in surface refractivity over Yola for three years, the refractivity values during the non-rainy months of January, February, November, and December are low, ranging from 292 N-units to roughly 295 N-units. The statistics for these months show the substantial influence of the dry continental air mass that dominates throughout the dry season as a result of ITD's North-South migration; as a result, these months show pronounced variance. Low moisture content results from a combination of low humidity and high-temperature values, which lowers refractive values. Refractive index values between 375 and 358 N units are seen during the wet (rainy) season, which runs from March to October, compared to those for the Harmattan months. It has been noted that the refractivity values are higher than those recorded for the Harmattan season.

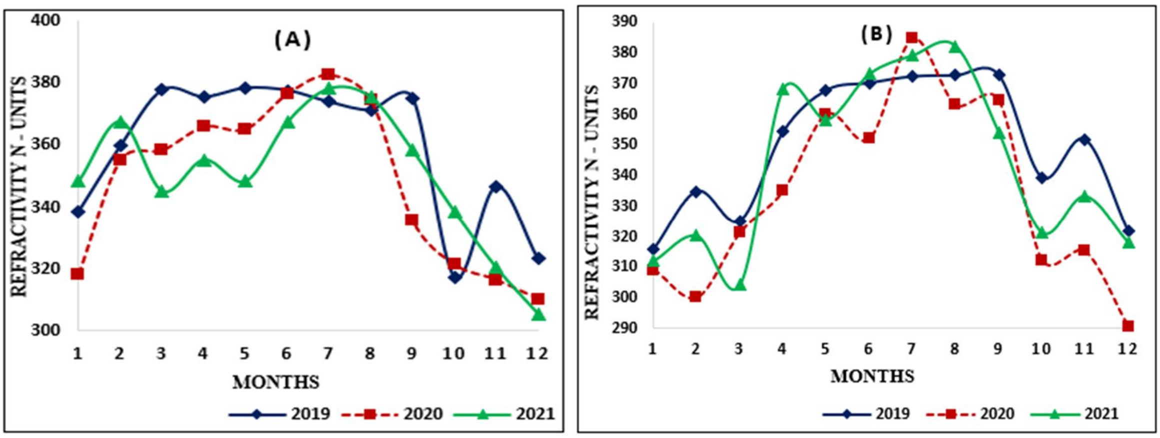


FIG. 2. Surface refractivity in (A) Lagos and (B) Makurdi

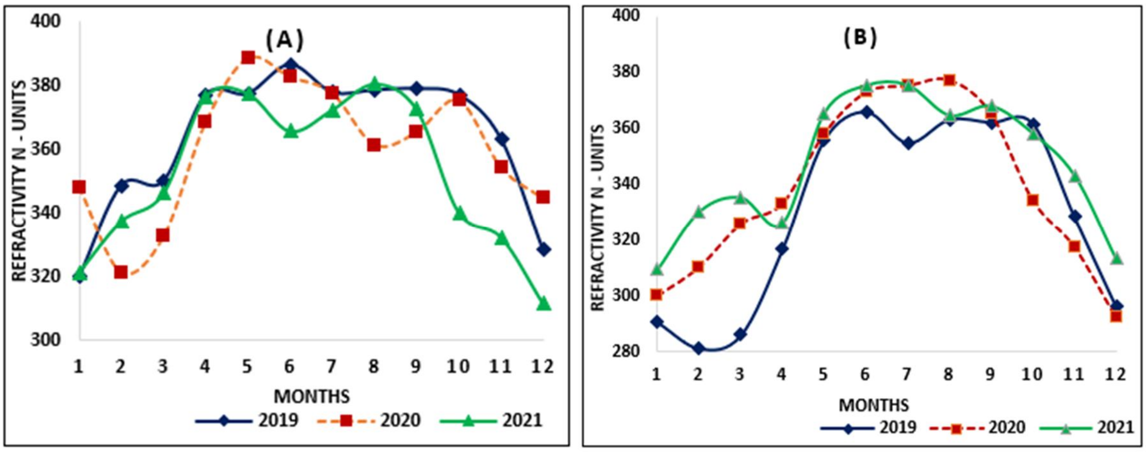


FIG. 3. Surface refractivity in (A) Port Harcourt and (B) Yola.

Figure 4(A) depicts the average monthly fluctuation in refractive index for the years 2019 to 2021 in Ayingba, which is 385 meters above sea level. Again, a similar pattern of seasonal fluctuations is observed, with the Harmattan months of January, February, November, and December having the lowest refractive indices in a 298–315 N-unit range of the refractivity values. In March 2020, a considerable increase was seen, with a refractivity value of 300 to 356 N-units. The refractivity values are increasing for the wet season months of April, May, June, July, August, September, and October, ranging from 363 to 380 N-units.

The mean monthly Ns variations in Oshogbo, which is located 320 meters above sea level, are shown in Fig. 4(B) for the years 2019 to 2020. The dry (non-rainy) season months of January, February, November, and December had the lowest refractivity values, ranging between 320 and 342 N-units. In contrast, the wet season months (May, June, July, August, September, and October) displayed higher refractivity values, ranging from 378 to 381 N-units. These findings suggest that both stations experience similar meteorological conditions influenced by the North-South migration of the Inter-Tropical Discontinuity (ITD) [25].

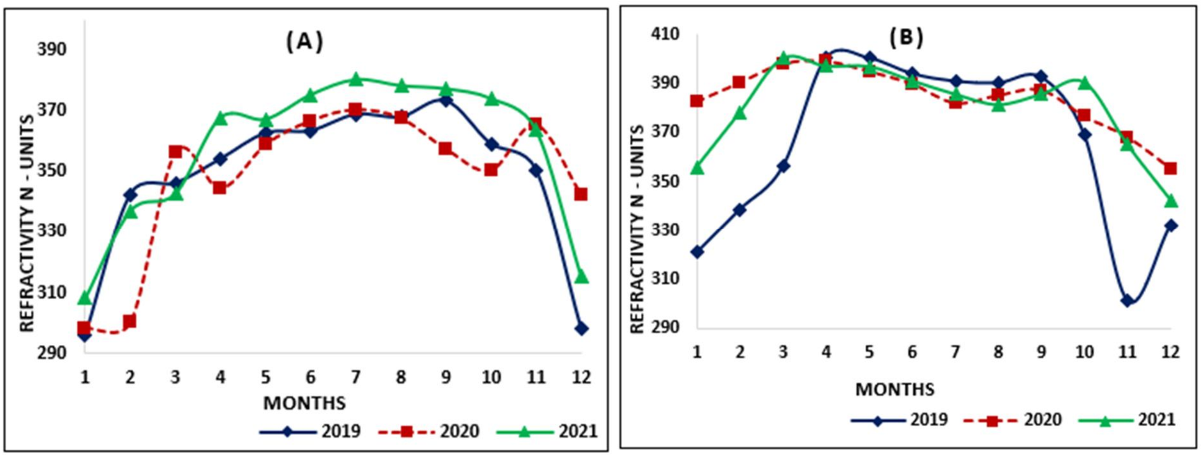
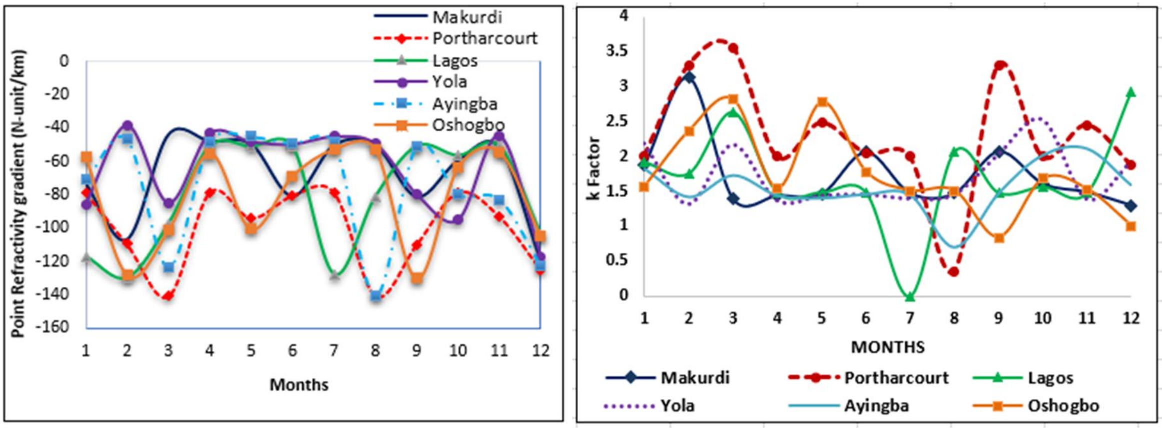


FIG. 4. Surface refractivity in (A) Ayingba and (B) Oshogbo.

The spatial distribution of the average radio refractivity gradient and the k factor are shown in Figs. 5 and 6. Figure 5 shows that the atmosphere of Nigeria is dominated by two main types of refraction. The first is sub-refraction, which occurs when the radioactivity gradient is greater than 40 N-units/km or infinity less than the k factor and less than 1.33. The second is super-refraction, which occurs when the radioactivity gradient is less than 40 N-units/km or zero greater than the k factor and more than 1.33. While Lagos and Port Harcourt located in the southern part of Nigeria, are predominantly affected by super-refraction. In contrast, Makurdi, situated in the northern region, is primarily influenced by sub-refraction.



(a) (b)

FIG. 5. (a) Refractivity gradients and (b) Effective earth radius factor across study locations.

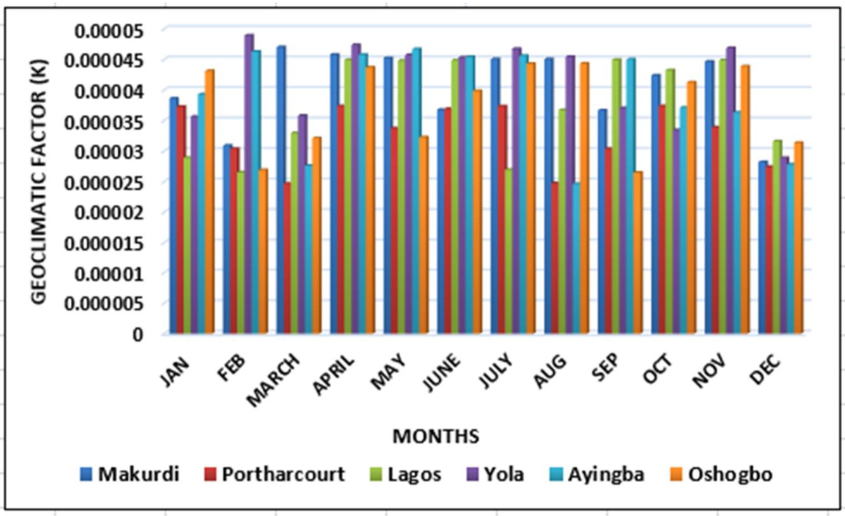


FIG. 6. Mean monthly values of geoclimatic factor across the studied locations.

As shown in Fig. 5, Makurdi and Yola have average refractivity gradient values of -35.2 and -30.62 N-units/km, with corresponding *k* factors of 1.30 and 1.32, respectively. The average refractivity gradient values for Lagos, Port Harcourt, Oshogbo, and Ayingba are -81, -93, -68, and -70 N-units/km, with *k* factors of 1.42, 1.51, 1.73, and 1.50, respectively.

Moreover, Fig. 5(B) indicates that the *k* factor increases, while the refractivity gradient decreases during the wet season, in line with seasonal variations in atmospheric moisture. It is also evident from the figure that sub-refraction predominantly occurs at higher latitudes in Nigeria, as seen in Yola and Makurdi (Table 1), while super-refraction is more common at lower latitudes.

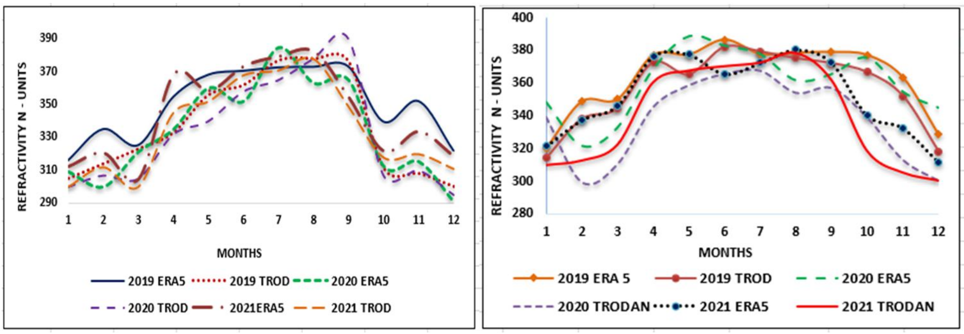
When designing terrestrial line-of-sight systems, it is essential to incorporate a fade buffer to account for multipath fading. The International Telecommunication Union (ITU-R) recommendations [12] consider factors such as operating frequency, path length, path inclination, and the geo-climatic characteristics of the location under study. The geo-climatic factor has a direct impact on the fade margin, and using locally derived *K* values, as per ITU-R, provides an accurate estimate of multipath fading.

Knowing the geo-climatic factor (*K*) value during months of poor radio signal reception is critical for determining the multipath fade margin. The highest *K* value typically corresponds to periods of increased signal fading. Figure 5 illustrates the monthly variation of the geo-climatic factor for the six cities studied.

In Markudi, the highest K values occur in March and April, peaking at *K = 0.000047* in March. In Lagos, the months of April and October have the highest K values, totaling K = 0.000044. Between July and October, Port Harcourt experiences its highest K values, with a peak of K = 0.000038. Between February and November, Yola experiences its highest K values, with a peak of K = 0.000048 in February. Additionally, K levels in Ayingba are high in February and May, with the greatest value of K being 0.000047 in May. The high K values for Oshogbo were between April and August. having the highest value of 0.000044 occurring in April. Among all the locations studied, Yola exhibits the highest geo-climatic values, which suggests it experiences the most significant multipath fading.

Figure 7(A) shows the comparison of the surface refractivity using ERA5 satellite data and the TRODAN ground data in Makurdi. The plot shows that both TRODAN and ERA5 predict lower refractivity values during the dry season, while higher values are observed during the rainy season (from March to September). In January 2019, data from ERA5 predicted 315 N units, compared to 309 N-units from TRODAN. ERA5 data predicted 309 N-units, while TRODAN recorded 300 N-units in January 2020. 312 N-units were obtained from ERA5 satellite data in 2021, while 300 N-units were predicted from TRODAN data. Generally, in Makurdi, ERA5 data predicted a little higher than the ground data except for September. in September. This month, the refractivity value from TRODAN data peaked at 390 N-units, surpassing the 369 N-units predicted by ERA5.

In Fig. 7(B), a similar trend is observed in Port Harcourt. In 2020, the refractivity values reached as high as 340 N-units from ERA5 data, while the ground data recorded 321 N-units. Surface refractivity was observed to be low during the dry season from 2019 to 2021 in both ERA5 and TRODAN data. However, it gradually increased thereafter, reaching its peak in August.



(a) (b)

FIG. 7. Validation of the surface refractivity using ERA5 satellite data and the in-situ TRODAN ground data in (a) Makurdi and (b) Port Harcourt.

Conclusion

In this study, the surface refractivity, refractivity gradient, geoclimatic factor (K), and associated k-factor—crucial radioclimatic variables for planning radio links—were estimated for six stations in Nigeria. The findings indicate that surface refractivity values vary with the seasons, with higher values observed during the rainy season and lower values during the Harmattan season. Additionally, it was observed that as the refractivity gradient becomes more negative, the geoclimatic factor increases.

The ERA5 satellite data was validated using TRODAN ground data, and the results show good agreement between the two data sources in predicting radioclimatic variables in the studied locations.

These findings will be valuable for determining location-dependent fade margins required for radio propagation, both for terrestrial and satellite communication, in the studied areas of Nigeria.

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