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Evaluation of Some Secondary Radio Meteorological Variables for Line-of-Sight Applications over Some Locations in Nigeria

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Abstract:

Reliable data on radio propagation is required to suggest useful models for radio-climatic study. Computation of some secondary radio parameters across ten locations in Nigeria was done to deduce their effects on Line-of-Sight links. ERA-5 data obtained from the archive of European Centre for Medium-Range Weather Forecast (ECMWF) comprising of surface air and dew temperature, atmospheric pressure and relative humidity covering eight years (January 2010 – December 2017) was utilized. The results show that average radio refractivity values during the wet season (343.4 N-units) was higher than the dry season (273 N-units) and radio refractivity gradient values increase as the wet season progresses. Mean effective earth radius factor (*k*-factor) for the period of study were 1.38, 1.34, 1.67 and 1.72 for the rainforest, mangrove swamp, Sudan and guinea savannah regions respectively. It was also observed that a distinct relationship exists between the geo-climatic factor (K) and the seasons of the year with a range of 2.2×10^{-5} to 1.0×10^{-4}.

1. INTRODUCTION

The extent to which radio signal will travel within a certain medium is determined by some weather parameters which dictate the medium's refractive index. Temperature, pressure and humidity are the major atmospheric parameters that determine the value of the radio refractive index in the troposphere. The variations in the vertical profiles of the radio refractive index, its gradients and the effective earth radius factor (k-factor) are responsible for the curvature in the trajectory of the radio waves as it traverses the troposphere. When designing a radio link within the tropospheric region in a geographical location; it is important first, to determine the local effective earth radius factor (k-factor) so that a propagated radio signal would not bend excessively towards or away from the Earth. Excessive bending towards or away from the earth could lead to abnormal propagation such as sub-refraction, super-refraction and ducting.

Over the years, some radio-climatic variables like the effective earth radius factor (k) and refractivity gradient (dN/dh) have been examined by some researchers in Nigeria. Examples of such studies are: [1-13, 26] and so on. However, most of these studies did not compute the geo-climatic factors, and the scope of the studies was limited to few locations across Nigeria. Since atmospheric variables that control line-of-sight (LOS) communication are known to be dynamic in nature, a combined effect of these secondary parameters on line-of-sight communication over the selected locations in Nigeria was examined in the present work. The secondary radio-climatic variables investigated are: Radio refractivity, Radio refractivity gradient, Effective earth radius factor, Geo-climatic factor and Point refractivity gradient. This work also determines the variation of radio refractivity for different season of the year at different heights over specific locations in Nigeria.

2. RELEVANT THEORY

The ratio of the velocity of radio waves in free space to that in the medium is called refractive index, n. According to [14], the propagation of radio wave signal in the troposphere is affected by many processes such as the changes of meteorological parameters of temperature, pressure and humidity. In other words, the changes in these parameters or any of these parameters will result in enhancing or weakening of the propagated radio signal. The atmospheric radio refractive index depends on air temperature, humidity, atmospheric pressure and water vapour pressure. Thus, in radio propagation studies, the parameter; radio refractivity, N which is related to refractive index, n is often used. Thus, n is related to N as [15];

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

while the radio refractivity, *N*, is:

$$N - 77.6\frac{P_d}{T} + 72\frac{e}{T} + 3.75\times10^{5}\frac{e}{T^2} \tag{2}$$

with the dry term of radio refractivity N_{dry} given as:

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

and the wet term as:

$$N_{wet} = 72\frac{e}{T} + 3.75\times10^{5}\frac{e}{T^2} \tag{4}$$

where P_d is the dry atmospheric pressure (hPa), P is the total atmospheric pressure (hPa), e is the water vapour pressure (hPa), T is the absolute temperature (K)

and

$$P = P_d + e \tag{5a}$$

i.e

$$P_d = p - e \tag{5b}$$

From equation (5b), equation (2) can be written as:

$$N = 77.6\frac{P}{T} - 5.6\frac{e}{T} + 3.75\times10^{5}\frac{e}{T^2} \tag{6}$$

Equation (6) is approximated with reduced accuracy as:

$$N = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \tag{7}$$

The relationship between saturated water vapour pressure, e and relative humidity, H is given by:

$$e = \frac{H.e_s}{100} \tag{8}$$

with

$$e_s = EF.aexp\left[\left(\frac{b - \frac{t}{d}}{t+c}\right).t\right] \tag{9}$$

and

$$EF_{water} = 1 + 10^{-4}[7.2 + P(0.0320 + 5.9 \times 10^{-6} t_2)] \quad (10a)$$

$$EF_{ice} = 1 + 10^{-4}[2.2 + P(0.0383 + 6.4 \times 10^{-6} t^2)] \quad (10b)$$

where; t is temp (°C), P is total atmospheric pressure (hPa), H is relative humidity (%) e_s is saturated vapour pressure (hPa) at temperature, t (°C) and the coefficients a, b, c and d are:

For water: a = 6.1121, b = 18. 678, c = 257.14, d = 234. 5 (valid between -40° to +50°) and

For ice a = 6.1115, b = 23. 036, c = 279.82, d = 333.7 (valid between -80° to +0°)

Refractivity gradient occurs whenever there is a change in the atmospheric air density, leading to a change in atmospheric air refractive index. The change in atmospheric density and refractive index is due to a change in the temperature of the air medium. The vertical gradient of refractivity in the lower layer of the atmosphere is an important parameter in estimating path clearance and propagation effects such as sub-refraction, supper refraction and ducting [16] and [3].

The refractivity gradient, which is a measure of how radio refractivity varies with increasing height is determined by [17]:

$$\frac{dN}{dN} = \frac{N_2 - N_1}{h_2 - h_1} \quad (11)$$

Where N_1 and N_2 are refractivity at heights 2 m and 100 m respectively.

The effective earth radius factor (k) is the radius of a hypothetical spherical Earth, without atmosphere, for which propagation paths follow straight lines while the heights and ground distance being the same for the actual Earth with atmosphere and constant vertical gradient of refractivity [18]. This 'k' can also be used to characterize refractive conditions but its main application in radio link design is to calculate the antenna height requirement and for diffraction fading estimate. It can be estimated according to [19]:

$$k = \left(1 + \left(\frac{dN}{dh}\right) \div 157\right)^{-1} \quad (12)$$

Another parameter used to calculate the link availability on terrestrial line-of-sight links is the geo-climatic factor K. It is a measure of the climatic and geographic condition of a terrain/location. Microwave links are known to be subject to deterioration due to environmental propagation conditions (rain, snow, fog, and so on). These conditions cause digital signal distortion and may lead to total outage on the communication link. The frequency of occurrence of these events and their duration depends on the link length and the frequency of operation for given climatic conditions. Similarly, link outage can vary with climatic conditions for a given link distance and a given frequency of operation. According to the [20], the impact of climate on link unavailability is incorporated in the geo-climatic factor. This factor is related to the climate through the gradient of refractivity, which depends on pressure, temperature and humidity. All of these parameters are subject to seasonal variations and over time, to climate change. Therefore, to take into account the climatic variation, either seasonal or over long periods of time, one must focus on these factors.

The geo-climatic factor is expressed as [20]:

$$K = 10^{-4.2 - 0.0029 dN_1} \quad (13)$$

where dN_1 is the point refractivity gradient from the scaling of the atmosphere. The point refractivity gradient is obtained from two refractivity values Ns (surface refractivity) and N_1 (refractivity within 1 km height above the ground). It is estimated from [21]:

$$dN_1 = \frac{N_s - N_1}{h_s - h_1} \quad (14)$$

3. MATERIALS AND METHODS

Nigeria is located within the Equator and the Tropic of Cancer. The climatic condition varies in most parts of the country; in the north, the climatic condition is arid, and to the south, there is an equatorial type of climate. The weather condition can be generally characterized into two seasons: Wet season (April to October) and Dry season (November to March of the succeeding year) in most parts of the country. The overall changes in meteorological parameters determine the changes in climate over the country each year. Ten locations were selected across the country, grouped into four main climatic regions: Sudan savannah, Guinea savannah, Rainforest, and Mangrove swamp [22] and [12]. Figure **1** shows the map of Nigeria showing the study locations while Table **1** gives the summary of the characteristics of the locations used for this study.

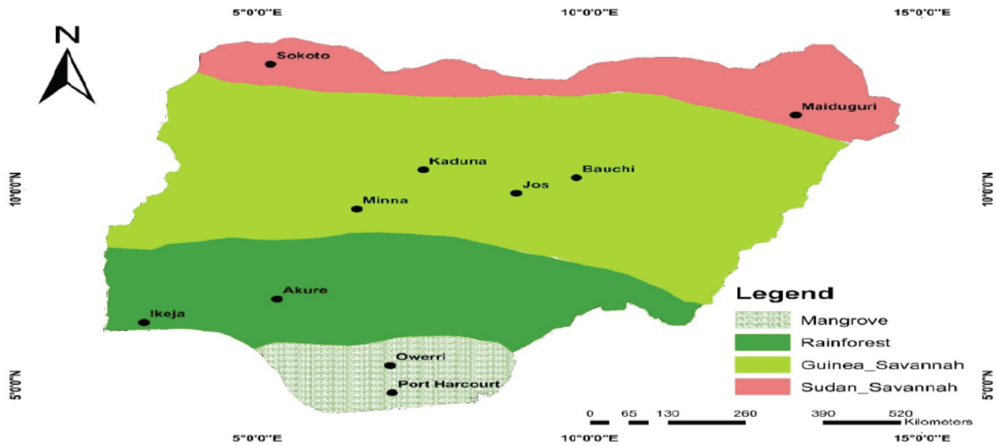


Figure 1: Map of Nigeria showing study locations.

Table 1: Summary of the Characteristics of the Study Locations

S/N	Location	Geographic Coordinates	Altitude (m)	Climatic Region	Average Temp. (°C)
1	Sokoto	13°2'N, 5°16'E	318	Sudan Savannah	28.3
2	Maiduguri	12°0'N, 13°20'E	320	Sudan Savannah	25.8
3	Bauchi	10°22'N, 9°48'E	628	Guinea Savannah	28.5
4	Kaduna	6°30'N, 7°21'E	250	Guinea Savannah	28
5	Minna	9°37'N, 6°30'E	243	Guinea Savannah	27.5
6	Jos	9°53'N, 8°51'E	1,217	Guinea Savannah	22.8
7	Ikeja	6°36'N, 3°20'E	39	Rainforest	26.8
8	Akure	7°15'N, 5°5'E	350	Rainforest	26.7
9	Owerri	5°29'N, 7°2'E	73	Fresh Water swamp	26.4
10	Port Harcourt	4°40'N, 7°10'E	463	Fresh Water swamp	26.4

For the purpose of this study, ERA-5 satellite data obtained from the archive of European Centre for Medium-Range Weather Forecast (ECMWF) was used. ERA-5 is a dataset showing results of a global climate re-analysis from 1979 to date. ECMWF has global spatial coverage with a horizontal resolution of about 80 km. The model and analysis (4 DVAR with a 12 hour window) use 60 vertical levels between surface and 6 hours for the upper airfields [23]. The data collected were that of surface air and dew temperature, temperature and relative humidity at 2 m and 100 m with a resolution of $0.25^o \times 0.25^o$ covering a period of eight (8) years.

4. RESULTS AND DISCUSSION

4.1. Seasonal Variation of Radio Refractivity over Nigeria

Figures **2a-d** and **3a-d** presents the seasonal variation of radio refractivity at 100 m and 2 m, respectively. Results obtained show that radio refractivity values at 100 m are lower than at 2 m. Also, values of radio refractivity are lower in the dry months than in the wet months.

Figure **2a** shows the seasonal variation of radio refractivity at 100 m in the Guinea Savannah region. The values of radio refractivity were lower in the dry months, with the lowest value of 198.8 N-units in Jos in the month of March. Average radio refractivity values during the dry season is 273.0 N-units which is lower than refractivity values during the wet season. The average value of radio refractivity during the wet months is 343.4 N-units.

In Figure **2b**, the radio refractivity values show a continuous increase during the wet season until it reaches a peak value of 380.5 N-units in August. This could be attributed to the heavy rainfall during this period. During the onset of dry season in November, the values of radio refractivity start to fall until it

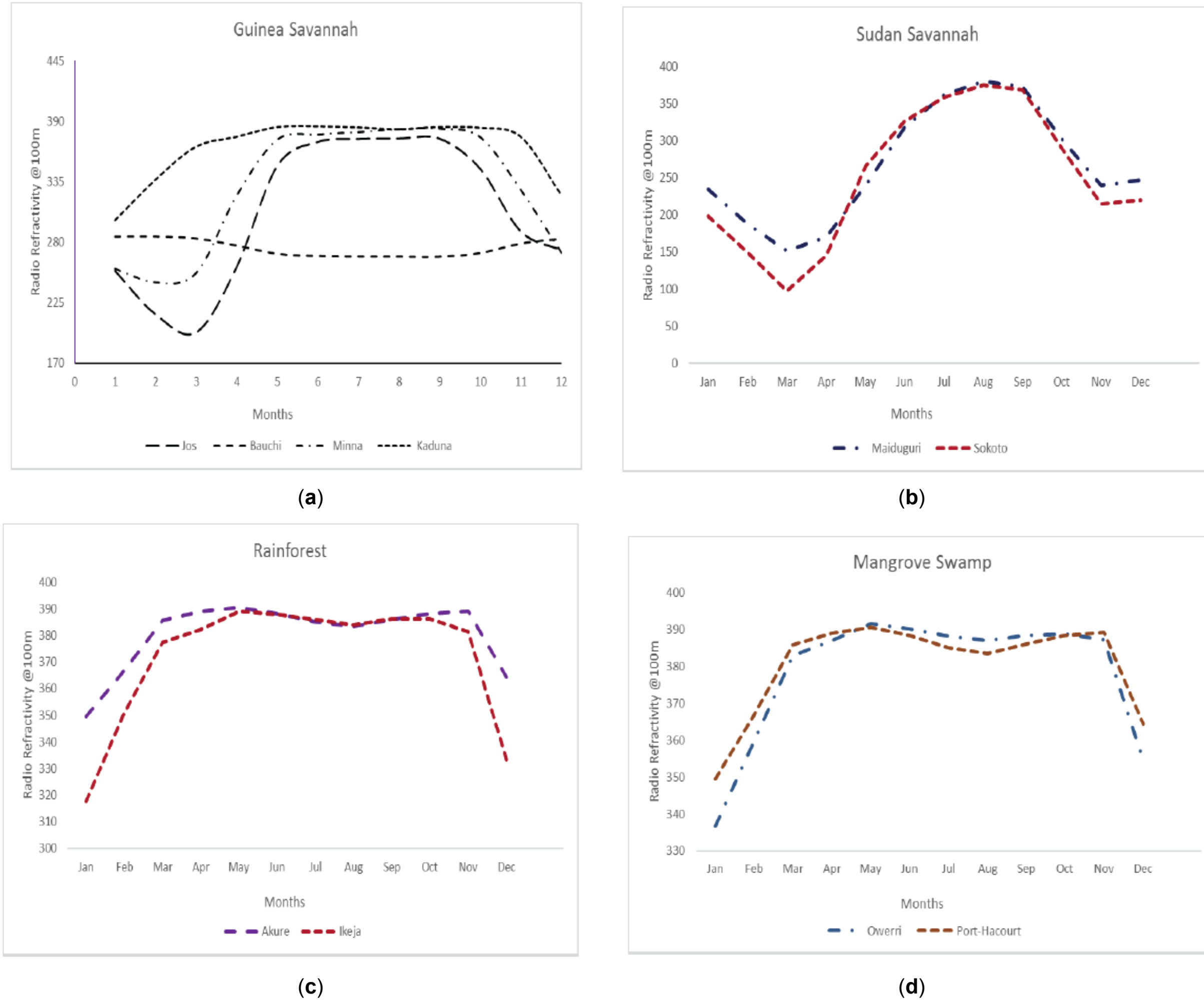


Figure 2: Seasonal Variation of Radio Refractivity at 100 m over Nigeria in: (**a**) Guinea Savannah, (**b**) Sudan Savannah, (**c**) Rainforest and (**d**) Mangrove Swamp.

reaches its lowest value at 97.9 N-units in March. Radio refractivity values are higher in the Rainforest and Mangrove swamp regions with average values of 386.6 N-units and 387.9 N-units, respectively, as seen in Figures **2c** and **d**. These results are in line with the works of previous researchers such as [24, 25]. Hence, following from these results; consideration must be given to these variations when planning terrestrial radio links in those regions.

Figure **3** shows a slight increase in values of radio refractivity at 2 m. Average values of radio refractivity are also higher in the wet months in comparison with the dry months. The Guinea Savannah and Sudan Savannah regions as shown in Figures **3a** and **b** record an average refractivity value of 312.4 N-units and 293.3 N-units respectively in the dry months while the Rainforest and Mangrove Swamp regions in Figures **3c** and **d** record an average refractivity value of 381.9 N-units and 379.1 N-units respectively in the dry months.

Generally, values of radio refractivity increases as the moisture content or water vapour in the atmosphere increases and as the dry season approaches, a gradual decrease in the values of radio refractivity was observed.

4.2. Seasonal Variation of Radio Refractivity Gradient over Nigeria

Figures **4a-d** presents the seasonal variation of radio refractivity gradient over the study locations. These show that propagation conditions over the study locations have varying degree of occurrence. It was also observed that refractivity gradient values are more negative in the dry months in comparison with the wet months. These values are, however, dependent on the location as no two locations have the same values. Factors such as change in temperature, longitude and difference in altitude can be attributed to the differences in refractivity gradient values and

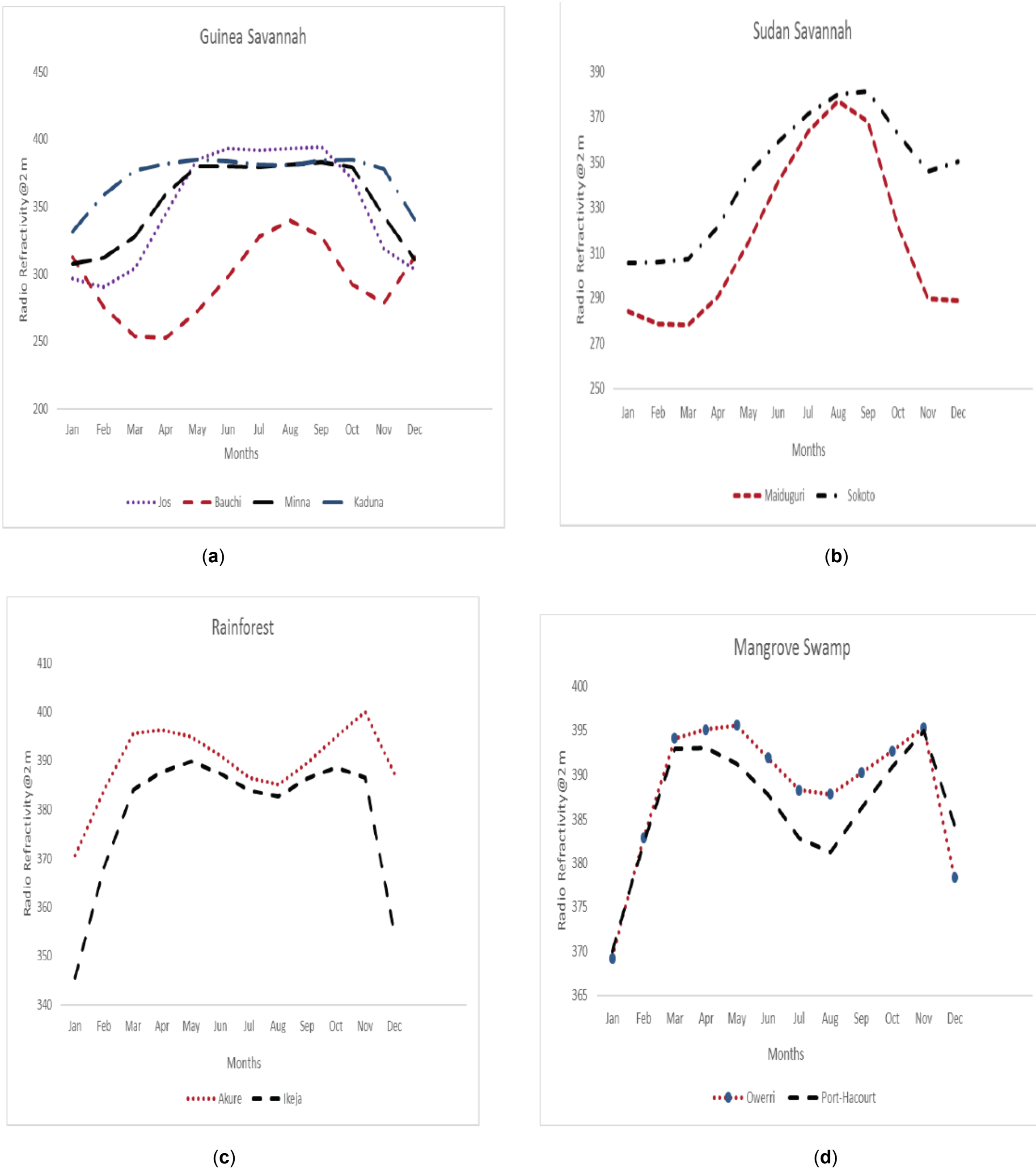


Figure 3: Seasonal Variation of Radio Refractivity at 2 m over Nigeria in: (**a**) Guinea Savannah, (**b**) Sudan Savannah, (**c**) Rainforest and (**d**) Mangrove Swamp.

consequently, the difference in propagation conditions of the different locations.

Guinea Savannah zone (Figure **4a**), is characterized by super-refraction in April which is the onset of the wet season with an average refractivity gradient value of -104 N units/km. Refractivity gradient values in the Sudan Savannah are largely negative, with an average value of -409.5 N-units/km, as shown in Figure **4b**. The Rainforest and Mangrove swamp is mainly characterized by normal refraction with an average value of -23.9 N-units/km and -24.9 N-units/km, respectively, (Figures **4c** and **d**).

The values of refractivity gradient increase as the wet season progresses. During the peak of the wet season in July, the Guinea Savannah (Figure **4a**) has an average refractivity gradient value of -85.2 N-units/km. Hence, the propagation condition is said to be super-refractive according to ITU recommendations. In Figure **4b**, the Sudan Savannah has an average refractivity

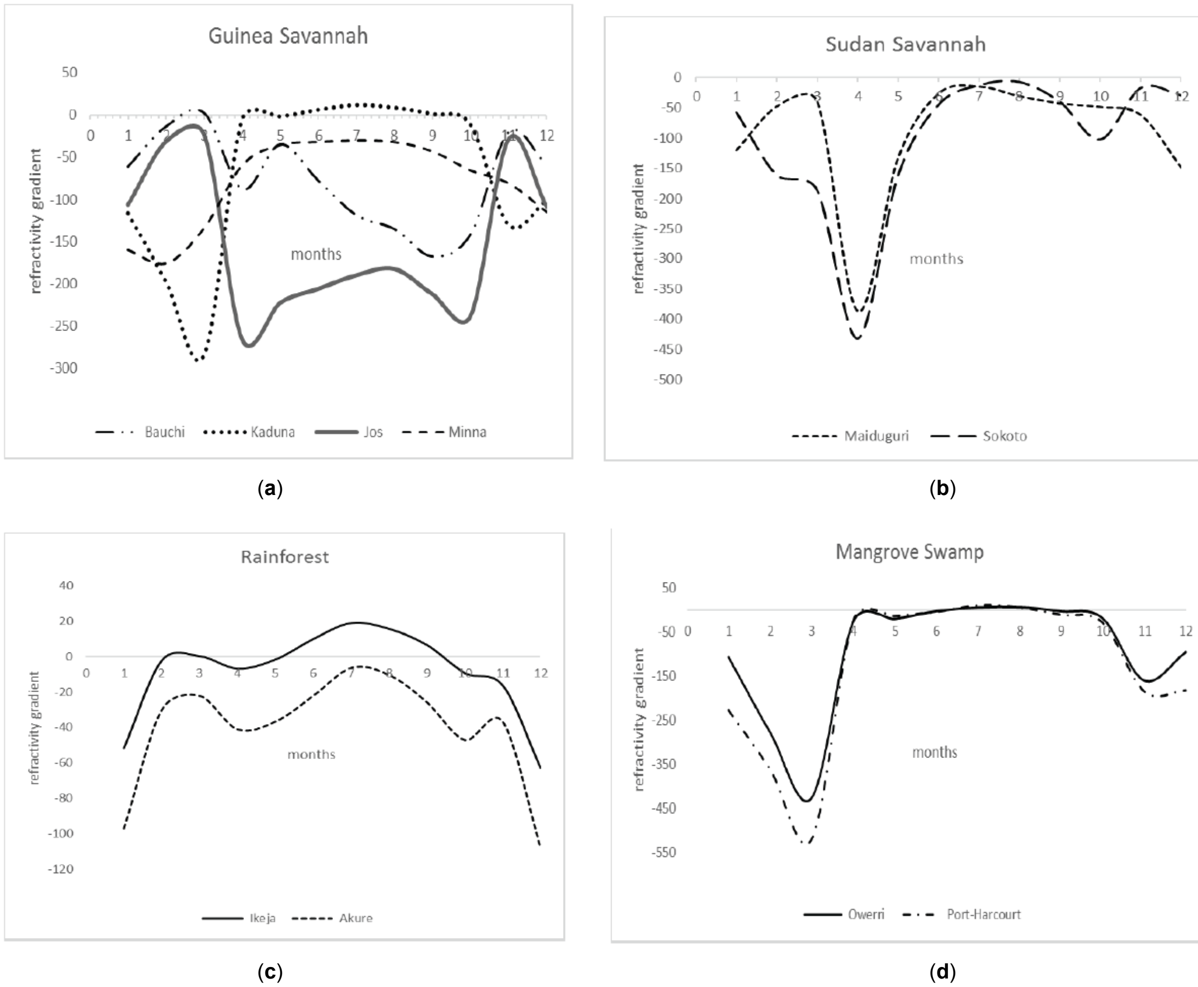


Figure 4: Seasonal Variation of Radio Refractivity Gradient Over Nigeria for: (**a**) Guinea savannah (**b**) Sudan savannah (**c**) Rainforest (**d**) Mangrove swamp.

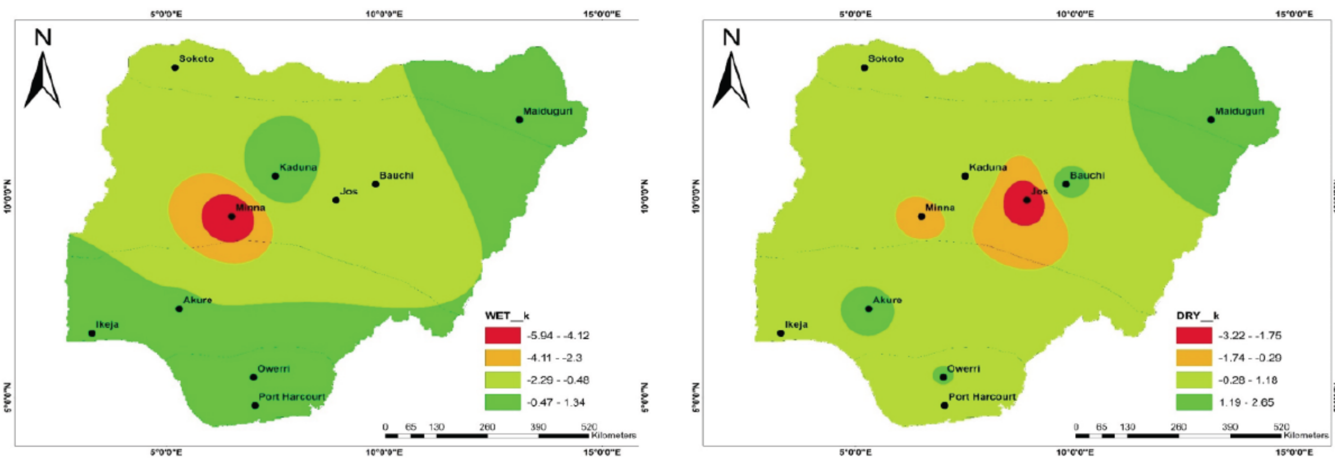
gradient value of -19.3 N-units/km; hence, the propagation condition is normal. The Rainforest and Mangrove swamp as depicted by Figures **4c** and **d** are sub-refractive because average refractivity gradient values are 2.6 N-units/km and 5.9 N-units/km. Sub-refraction is a condition in which radio beams travelling is refracted upward and hence, the portion of the wave-front that is received will travel close to the ground than usual. This leads to signal degradation (attenuation).

During the dry season months which runs from November to March of the following year, conditions of radio signal propagation are super refractive for Jos and Minna in the Guinea savannah, (Figure **4a**) with an average refractivity gradient value of -129.6 N-units/km and -82 N-units/km, respectively. Propagation condition in the Sudan Savannah, (Figure **4b**) is mainly ducting phenomena as an average value of -172.8 N-units/km was observed. Propagation condition is normal in Kaduna and Bauchi as an average value of -56 N-units/km was observed. The Rainforest and Mangrove swamp as shown in Figures **4c** and **d**, have normal-refraction as an average refractivity gradient value of -38.5 N-units/km was recorded for Kaduna and Bauchi respectively.

These variations could be attributed to a number of factors ranging from variation in altitude, inter-tropical discontinuity, longitudinal differences, variation in temperature and relative humidity, the difference in the terrain of different locations and so on.

4.3. Spatial Variation of Effective Earth Radius Factor over Nigeria

Figures **5a-b** shows spatial variation of the k-factor over Nigeria for wet and dry seasons respectively. Results show that values of the k-factor are location-dependent for both the wet and dry seasons. During the wet season (Figure **5a**), average k-factor values



(**a**) (**b**)

Figure 5: Spatial Variation of Effective Earth Radius Factor over Nigeria for: (**a**) Wet Season and (**b**) Dry Season.

range between -0.47 to 1.34 for the Rainforest, mangrove swamp, Kaduna and Maiduguri. This indicates that the conditions of radio signal propagation will vary between normal-refraction and sub-refraction. The other locations in the Guinea savannah (Jos and Bauchi) and Sokoto (Sudan savannah) have an average k-factor value ranging between -2.29 to -0.48. The propagation condition here is ducting.

The prevailing propagation condition during the dry season is ducting for Sokoto, Kaduna, Ikeja and Port-Harcourt with average k-factor values ranging between -0.28 to 1.18 as seen in Figure **5b**. For Akure, Bauchi, Maiduguri and Owerri, propagation conditions vary between normal and sub-refraction with k-factor values ranging between 1.19 to 2.65. These results show that propagation conditions are dependent on individual locations as no two locations studied had the exact same values.

4.4. Seasonal Variation of Geo-Climatic Factor over Nigeria

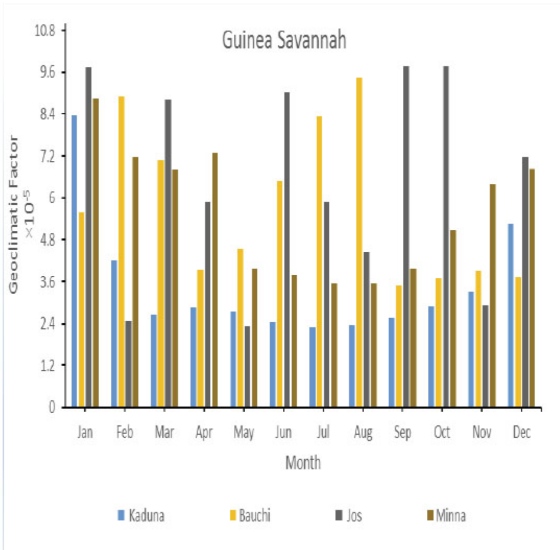
The main application of the geo-climatic factor is in the estimation of fade depth needed in radio link design. Figures **5a-d** presents the dependence of the average value of geo-climatic factor on the seasons for the year over the study locations. Results show that geo-climatic factor values are higher in the wet months than in the dry months. This can be attributed to high rainfall and relative humidity experienced in the wet months. It could be observed that a distinct relationship exists between the geo-climatic factors (K) and the season of the year. For example, Akure recorded average minimum mean value of the geo-climatic factor of about 3.9×10^{-5} for the month of March. The same trend could also be observed in other locations, although with different months recording the minimum and maximum geo-climatic factor K value.

It is important to estimate the correct value of the geo-climatic factor in order to cater for the adequate fade margin necessary for a reliable radio link performance. The percentage of time that a fade depth A(dB) is exceeded can then be estimated using the data from seasonal variations (Figures **6a-d**) of the geo-climatic factor K for multipath fading prediction in the study locations.

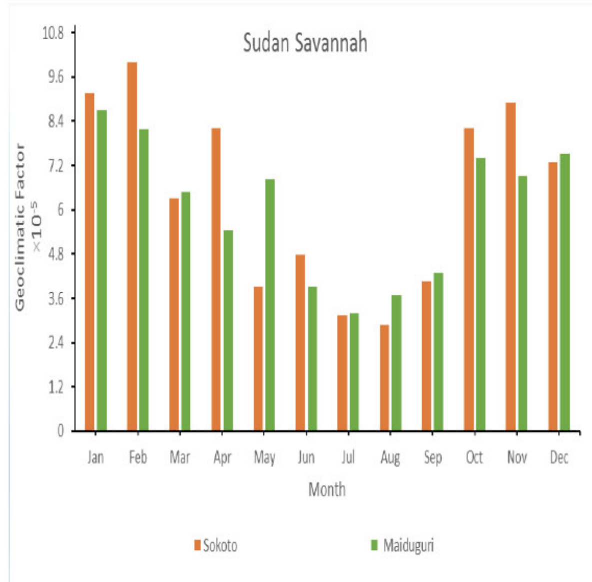
5. CONCLUSION

Computation and analysis of some secondary radioclimatic variables (radio refractivity, refractivity gradient, k-factor, Geo-climatic factor and point refractivity gradient) across ten locations in Nigeria were carried out using long term ERA-5 data of surface air and dew temperature, atmospheric pressure and relative humidity covering a period of 8 years (2010 – 2017). However, the main findings are:

- Average radio refractivity values over the study locations during the wet season (343.4 N-units) was higher than the dry season (273 N-units).
- Radio refractivity gradient values increase as the wet season progresses.
- Conditions of signal propagation in the Rainforest and Mangrove swamp are mainly sub-refractive in the wet season with an average refractivity gradient value of 2.64 N-units/km and 5.98 N-units/km respectively.



(**a**)



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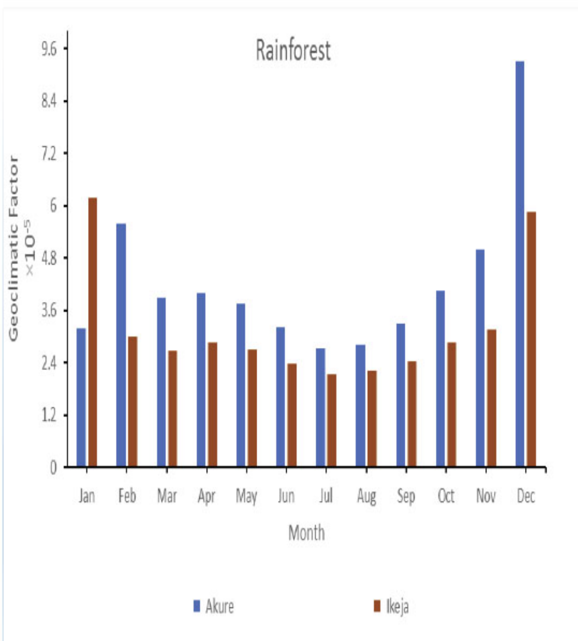

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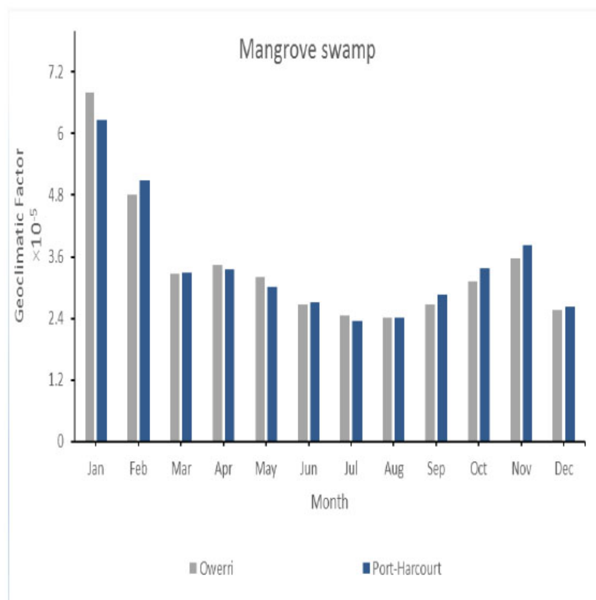

(**d**)

Figure 6: Seasonal Variation of Geo-Climatic Factor over Nigeria for: (**a**) Guinea savannah (**b**) Sudan savannah (**c**) Rainforest (**d**) Mangrove swamp.

- Mean *k*-factor value for the 8 years period of the study were 1.38, 1.34, 1.67 and 1.72 for locations in the rainforest, mangrove swamp, Sudan and guinea savannah regions respectively.
- A distinct relationship exists between the geo-climatic factor (K) and the seasons of the year with a range of 2.2×10^{-5} to 1.0×10^{-4}.

The main application of the effective earth radius factor (k-factor) in radio link design is to calculate the antenna height requirement and for diffraction fading estimate, while the geo-climatic factor, on the other hand, finds useful application in fade depth calculation. Hence, there is the need to estimate the correct value of the geo-climatic factor in order to cater for the adequate fade margin necessary for a reliable radio link performance. It could be observed, from the results, that the secondary radio-climatic variables show a seasonal type dependence and location dependent as no two stations studied have the same value.

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AUTHOR STATEMENT

This article is a product of research work carried out by the listed authors in Nigeria tropical region. Adediji A. T. is the main author of the work and he actually supervised the data collection. Ajewole M. O and Okunwa P. N. helped in the analysis of the plots while Tomiwa A. C. was the one that sorted all the data obtained and also serves as the corresponding author.

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