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Characterization of secondary radioclimatic variables for microwave and millimeter wave link design in Nigeria

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A reliable radio propagation data is required in other to propose a well-founded model for radioclimatic study in any area. The two major types of radio propagation data needed are the primary and secondary propagation data. The primary data include temperature, pressure and relative humidity or water vapour pressure, while the secondary radioclimatic data are radio refractivity gradients, geoclimatic factor (K-factor) and the effective earth radius factor (k-factor). In this paper, analyses of the secondary data are carried out instead of the usual primary variables in order to deduce the influences on the Terrestrial line-of-Sight (LOS) based on 5 years data (2009-2013) obtained from five different regions of Nigeria (Akure, Enugu, Minna, Jos and Sokoto). The *k*-factor values at the surface across the study locations are higher than the prescribed value of 1.33 by the ITU. The same trend could also be observed for the geoclimatic factor K. The overall result will be a very good tool for microwave wireless link design in Nigeria.

Keywords: Radio climatology, Geoclimatic factor, Refractivity, Effective earth radius (k) factor, Microwave and millimeter wave link design

1 Introduction

Any communication system can be generally divided into three parts, namely: the transmitter system, the propagation medium and receiver system. The integrity of the information at the receiver depends on how much the signal is distorted in the medium. Hence, the propagation medium is very important in any communication system. The propagation medium could be fiber optics, coaxial cable, the troposphere, and so on. The properties of channels can be modified by the designer of the system to yield the desired response. In case of transmission through the troposphere, the properties [illegible] adequate understanding of the response of the radio signals to variation of the tropospheric conditions[1]. This study revolves within the tropospheric region of the atmosphere. If the troposphere is homogenous and turbulence free, any wave propagated into the troposphere parallel to the earth surface will follow the earth's curvature. If the wave is transmitted at an angle to the earth surface it will never come back to the earth surface again. However, due to the in-homogeneity of the troposphere, wave propagated in the troposphere undergo bending depending on the tropospheric condition which also depends on the temperature pressure and humidity of the environment[2].

According to ITU-R Recommendation ITU-R.P.530-16[3] the propagation loss on a terrestrial line of sight path relative to free space loss is the sum of different contributions, including the following: attenuation due to atmospheric gases, diffraction, fading due to obstruction or partial obstruction of the path, fading due to multipath and attenuation due to precipitation. Each of this contribution depends on the frequency, path length and geographical location. The [illegible] gy variables have been studied by many authors in Nigeria[4-7] to mention but a few. The main focus of this paper is on the estimation of the secondary variables in Nigeria and their applications to the design of terrestrial LOS link for optimum performance.

2 Theoretical Background on the Secondary Radioclimatic Variables

This section discusses about the theoretical background of the variables used in the computation. The dynamics of the atmosphere leads to the refractive index of the troposphere to vary as the height increases from sea level[8] and this consequently

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*Corresponding author (E-mail: josnno@yahoo.com) has a significant effect on radio signal. ITU-R provided step-by-step procedure for determining the variation of the refractive index of the troposphere with height.

The refractivity gradient is a measure of how the refractive index varies with increasing height. This is given as[9]:

$$\frac{dN}{dh} = 77.6\frac{1}{T}\frac{dp}{dh}\left(\frac{77.6}{T^2} + \frac{746512e}{T^3}\right)\frac{dT}{dh} + \frac{373256}{T^2}\frac{de}{dh} \qquad \ldots (1)$$

where p is the pressure (hpa), T is the temperature (K), e is the water vapor pressure (hpa) and h is the height (m).

Since the water vapor pressure, e cannot be measured directly; the parameter is related to the relative humidity, H (%) by:

$$e = \frac{He_s}{100} \qquad \ldots (2)$$

where e_s is the saturated vapour pressure at the given air temperature t (^{o}C), and can be obtained from:

$$e_s = 6.112\exp\left[\frac{17.502t}{(t + 20.97))}\right] \qquad \ldots (3)$$

The effective earth radius factor (k-factor) can also be determined by[10,11]:

$$k = \left[1 + \left(\frac{dN}{dh}\right)/157\right]^{-1} \qquad \ldots (4)$$

Although, a typical design value of 4/3 is often assigned for k-factor in line of sight link design especially where information about the actual value of k for that location is not available ITU-R P. 530-16[3]. However, recent study revealed that k-factor is location dependent and should not be assumed constant in any location under study[6,11]. The significance of the parameter k is that it permits the simplification of practical problems encountered in tropospheric communications and radio engineering.

Another secondary variable is the geoclimatic factor, K, which is a measure of the climatic and geographical condition of a terrain and is given as[12]:

$$K = 10^{-4.2 - 0.0029 \times dN_1/dh} \qquad \ldots (5)$$

where dN_1/dh is the point refractivity gradient in the lowest 65 m of the atmosphere not exceeded for 1% of the average year. In order to deduce dN_1/dh, a probability distribution curve should be plotted to deduce dN_1 at each of the location under study.

Hence, the secondary radioclimatic variables in all the selected locations in Nigeria are estimated using Eqs (1)-(5). Although, some of these variables like k-factor and refractivity gradient have been examined by some investigators in Nigeria (for instance, parameters such as k-factor was studied in Nigeria by Adediji *et al.*[6] Ayantunji[13] to mention but few, while refractivity gradient was examined by many investigators in Nigeria among are the work of Falodun and Ajewole[5], Adediji *et al.*[6], Ayantunji[13] and Ajayi[14] to mention but few. However, most of these investigators studied and modeled separately in all cited situations with few or no reference to the geoclimatic factor. In this study, we intend to look at the combined effect of these secondary parameters on radio signal propagation over the selected locations in Nigeria.

3 Site, Instrumentation and Data Analysis

3.1 General overview of Nigeria climate and data source

Nigeria lies between latitude 4^{o}N and 14^{o}N and longitude 2^{o}E and 15^{o}E respectively with a total area of 923,768 square kilometer. The country is located within the Equator and the Tropic of Cancer. The latitude of Nigeria falls within the tropical zone but the climatic conditions are not entirely tropical in nature. 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. From April to October is the wet season; while from November to March in the succeeding year is the dry season in most parts of the country. The overall changes in meteorological parameters determine the changes in climate in the country each year.

The secondary variables are derived from the in-situ measurement taken over some locations in Nigeria; Akure, Enugu, Minna, Jos and Sokoto which are in 358 m, 223 m, 281 m, 1400 m and 500 m above sea level respectively using Davis 6162 Wireless Pro2 equipped with the Integrated Sensor Suite (ISS).

3.2 Criteria for choosing sites

In addition to the availability of the instrument for measurement placed up to 100 m height, the selected areas for this study were also chosen to cover the main climatic regions in Nigeria with more emphasis given to the land mass of each region.

Sokoto falls within the Sudan savannah with some characteristic of Sahel savannah. Hence, the reason for choosing Sokoto is to represent this region in this work. In addition, the region experiences two distinct seasons: dry and rainy season. The dry season commences around November to around May while the rainy season usually starts around early June and ends around October. Though the rainy season is very short, the rain within this period is always very heavy. The region also experiences Harmattan dust between December and February due to the North-easterly wind blowing from the Sahara desert. The instrument for the measurement was installed on a 300 m abandoned Nigeria Television Authority (NTA) mast about 30 km from the metropolis.

Minna, located within the guinea savannah region was chosen because of the peculiar nature of this region. Minna is very hot while Jos is very cold due to the plateaus around the region. The rainy season within this region commences around April and ends around early November. The dry season is from November to April. This region is also covered with Harmattan dust from late December to early February.

The station at Jos is located inside the University of Jos while the station at Minna is located on the surface and at 100 m on NTA mast located inside the premises of NTA Minna about 10 km from Federal University of Technology, Minna.

Nsukka and Akure were chosen within the rain forest. The station at Nsukka is installed on NITEL mast at the surface and at 100 m while the station at Akure is installed on abandoned NTA mast at Iju, about 17 km from the campus of the Federal University of Technology, Akure. The mast at Akure is about 250 m high and weather stations are mounted at the surface, and at 50 m, 100 m, 150 m and 200 m to provide vertical variation of the weather variables. Figure 1 depicts the map of Nigeria showing the locations where data were collected while Table 1 displays the summary of the characteristics of each of the study locations.

3.1 Instrumentation and scope of the data used

The major equipment used for the measurement in each of the sites is the Davis 6162 Wireless Pro2 equipped with the Integrated Sensor Suite (ISS), a solar panel (with an alternative battery source) and the wireless console. The ISS collects outside weather data and sends the data to a vantage Pro2 console. The standard version of the ISS contains a rain collector, temperature sensor, humidity sensor and anemometer. It also adds a solar radiation sensor and a ultra-violet (UV) sensor. Temperature and humidity sensors are mounted in a passive radiation shield to minimize the impact of solar radiation on the sensor readings. The anemometer measures wind speed and direction and can be installed adjacent to the ISS or away from it. The solar and UV sensors are mounted next to the rain collector cone. The ISS houses the sensors for pressure, temperature, relative humidity, UV index and dose, solar radiation among others and the sensor interface module (SIM). Detailed descriptions of this equipment are available in the work of Ojo *et al.*[15] and are not re-iterated here for paucity sake. The block diagram of equipment set up is as shown in Fig. 2.

In each of the sites, the fixed measuring method by a high tower was employed for the measurement with one sensor each placed at the ground level for the surface measurement and the others at different

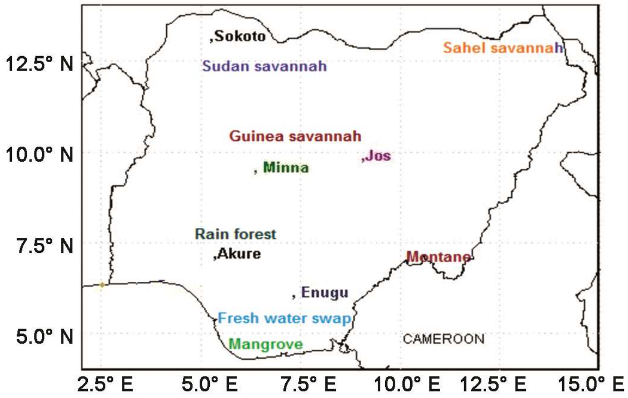

Fig. 1 — Map of Nigeria showing the locations, altitudes and vegetation of the study sites

Table 1 — Summary of the characteristics of each of the study locations

Location	Climatic region	Coordinate (°)	Altitude (m)	Annual mean precipitation (mm)	Average temperature (°C)
Akure	Rain forest	5°.12″E, 7°.15″N	358	1485.57	27.1
Enugu	Fresh water swap mangrove	7°.27″E, 6°.25″N	223	1876.30	26.7
Minna	Guinea savannah	6°.33″E, 9°.36″N	281	1196.75	27.0
Jos	Guinea savannah	8°.53″E, 9°.55″N	1400	1186.89	23.0
Sokoto	Sudan savannah	5°.13″E,13°.04″N	500	567.21	28.3

altitudes (depending on the location) on the tower for continuous measurement. The method provided an accurate measurement of the parameters required for the estimation of refractive index at a fixed height without interference. Based on this method, only the sensors are positioned aloft while all other auxiliary devices are on the ground[15-17]. Calibrations are carried out based on the manufacturer specification. For the purpose of this study only the data obtained from the surface and at 100 m height are used in the analysis.

Five years of data spanning 2009-2013 are used in this work. In order to extract the stored data in the data logger, the console is connected to a computer, through which the stored data are collected. The error margin of the ISS device for temperature, pressure and relative humidity are ±0.1 ^{o}C, ±0.5 hPa and ±2 %, respectively. The records cover 24 hours each day from 00 hours to 2300 hours local time at intervals of 30 min except for some few days when system are shut down due to maintenance. Hence, the availability of the equipment is about 96%, 92%, 90%, 90% and 89% at Akure, Enugu, Minna, Jos and Sokoto, respectively.

As earlier mentioned, the secondary radioclimatic variables in all the selected location in Nigeria are estimated using Eqs (1)-(5).

4 Results and Discussion

The values of the refractivity gradient dN/dh have been determined using Eqs. (1) to (3), while the values of k-factors were also obtained using equation (4). The values of the geomagnetic factor (K) were also obtained using equation (5).

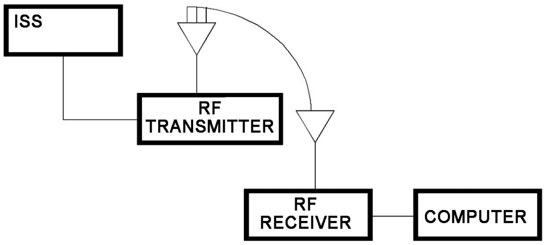

Fig. 2 — Block diagram of the equipment setup

4.1 Influence of refractivity gradient on the season of the year

Figure 3 presents the dependence of the average value of radio refractivity gradient on the seasons of the year (2009-2013) over the study locations. The result shows that a very large negative value of about-170 N-units/km for the month of October could be observed, which is the commencement of dry season in Sokoto, followed by Minna with point refractivity gradient of about-152 N-units/km while the lowest point refractivity gradient of about-100 N-units/km occurred in the month of November in Jos. The value later becomes less negative in the other locations. This result is in agreement with what was observed by Ajayi and Okeke[7]. In the report, it was observed in Enugu that the refractivity gradient becomes less negative at some specific values.

4.2 Influence of *k*-factor on the season of the year

The mean values of the *k* factor over the study locations during the dry season months and wet months are also presented in Figs 4a and 4b,

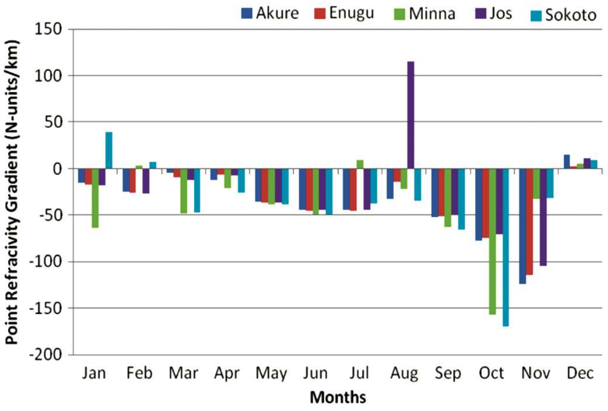

Fig. 3 — Average values of radio refractivity gradient on the seasons of the year (2009-2013) over the study locations

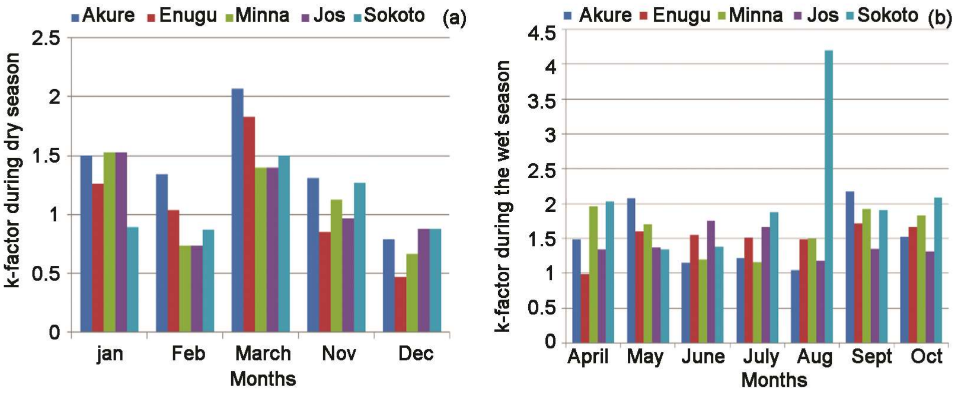

Fig. 4 — The mean values of *k*-factor during (a) the dry season months and (b) wet season months over each of the study locations

respectively. It could be seen that irrespective of the location, the *k*-factor shows seasonal type dependence. For example, during the dry months (Fig. 4a), results reveal that the mean *k*-factor value in Akure range from 0.79 to 2.07 with maximum value in the month of March and minimum in the month of December. The average value of *k*-factor during the dry season for the 5 years of this report is about 1.40. This implies that, for microwave propagation in the Akure environ, the propagation condition could be largely super-refractive during this season[7] Also in Sokoto, the value ranges from 0.87 to 1.5 with maximum value in the month of March and minimum in the month of December. The average value of *k*-factor during the dry season for the 5 years of this report is about 1.1. The propagation condition could also be largely sub-refractive during this season. The same trend could be observed in other locations although with different values of mean *k*-factor.

The mean values of the *k*-factor over the study locations during the wet season months as presented in Fig. 4b also shows that *k*-factor is generally higher in the rainy season months than in the dry season months. This result is in agreement with the observation by Kolawole[16] although their results underestimated the *k*-factor values when compare with the present results, this might be due to lack of temporal and spatial resolution of the data used in their work.

To be precise the results of the *k*-factor in Akure revealed that, the value ranges from 1.04 to 2.17 with maximum value in the month of September and minimum in the month of August.

The average value of *k*-factor during the wet season for the 5 years of this report is about 1.52. This implies that, for microwave propagation in the Akure environ, the propagation condition could also be largely super-refractive during this season[16-18]. The *k*-factor in Sokoto also ranges from 1.34 to 4.2; this value is unusually high due to the climatic nature of the region which is purely arid. The maximum value occurred in the month of August while the minimum value is in the month of May. The average value of *k*-factor during the wet season for the 5 years of this report is about 2.17. Based on this result, the propagation condition in Sokoto could be largely due to ducting during this season. The same trend could also be observed in other locations, although with different values of *k*-factor and with different associated propagation phenomena.

It must also be noted that the experimental *k*-factor presents a large variability from 1.04 to 4.18. This implies that the result from the study sometimes underestimates or overestimates the prescribed value of 1.33 recommended by the ITU.

4.3 Influence of geoclimatic factor on the season of the year

The main application of the geoclimatic factor is in the estimation of fade depth needed in the radio link design. Figure 5 presents the dependence of the average value of geoclimatic factor on the seasons of the year (2009-2013) over the study locations. It could be seen that distinct relationship exists between the geoclimatic factors (*K*) and the season of the year. For example, Akure recorded averaged minimum mean value of geoclimatic factor of about 8.05 E-05 for the month of May whereas the observed averaged maximum value of geoclimatic factor *K* was 7.44 E-04 in the month of October. The same trend could also be observed in other locations although with different months recording the minimum and maximum geoclimatic factor *K* value. The summary of the geoclimatic factor *K* and the corresponding *k*-factor for different months for each of the study locations is presented in Table 2.

As earlier mentioned 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 geoclimatic factor on the other hand finds useful application in fade depth calculation. Hence, the need to estimate the correct value of geoclimatic factor in order to cater for 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 Table 2.

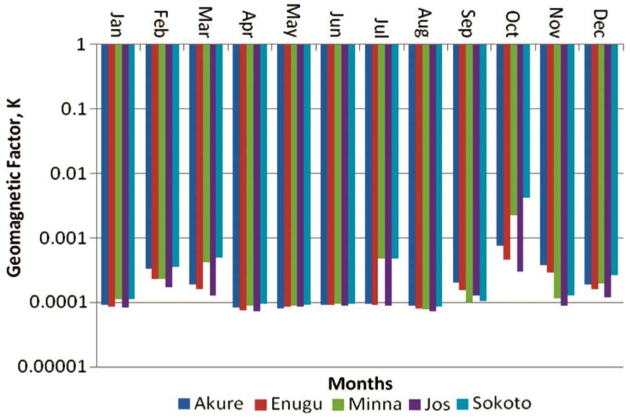

Fig. 5 — Seasonal and spatial variability of geoclimatic factor *K* for multipath fading prediction in the study locations

Table 2 — The geoclimatic factor, *K* and *k*-factor variability for different months using 5 years data

	Akure		Enugu		Minna		Jos		Sokoto	
Month of the Year	*k*-factor	Geoclimatic factor, *K*	*k*-factor	Geoclimatic factor, *K*	*k*-factor	Geoclimatic factor, *K*	*k*-factor	Geoclimatic factor, *K*	*k*-factor	Geoclimatic factor, *K*
Jan	1.504	9.04E-05	1.261	8.63E-05	1.525	0.000111	1.525	8.33E-05	0.893	0.000111
Feb	1.343	3.28E-04	1.033	0.000228	0.739	0.000234	0.739	0.000172	0.872	0.000351
Mar	2.068	1.87E-04	1.825	0.00016	1.401	0.00041	1.401	0.000129	1.503	0.000489
Apr	1.490	8.23E-05	0.989	7.45E-05	1.968	8.74E-05	1.343	7.36E-05	2.030	9.44E-05
May	2.081	8.05E-05	1.601	8.7E-05	1.702	8.9E-05	1.368	8.6E-05	1.345	9.06E-05
Jun	1.154	9.06E-05	1.550	9.04E-05	1.204	9.41E-05	1.756	8.9E-05	1.383	9.49E-05
July	1.222	9.32E-05	1.519	9.1E-05	1.158	0.000468	1.671	8.94E-05	1.877	0.000477
Aug	1.048	8.91E-05	1.485	8.05E-05	1.496	7.66E-05	1.184	7.16E-05	4.202	8.47E-05
Sept	2.171	2.04E-04	1.716	0.000153	1.923	0.000102	1.354	0.000126	1.904	0.000106
Oct	1.529	7.44E-04	1.665	0.000453	1.833	0.002252	1.312	0.000304	2.086	0.004134
Nov	1.306	3.75E-04	0.849	0.00029	1.127	0.000114	0.968	8.73E-05	1.268	0.000128
Dec	0.789	1.91E-04	0.470	0.00016	0.670	0.000193	0.878	0.000121	0.883	0.000264

Table 3 — Comparison of geoclimatic factor *K* and *k*-factor from some locations with the present study

Source	No of Year	Station	Geoclimatic factor	k-factor
Odedina and Afullo[9] Asiyo and Afullo[21]	3-year	Durban, South Africa	4.48 E-04	1.475
	3-year	Cape Town, South Africa	4.21 E-04	1.528
	3-year	Bloemfontein	3.25 E-04	1.812
	3-year	Pretoria	8.58 E-04	*Not provided*
	3-year	Polokwane	3.07 E-04	*Not provided*
Chaudhary *et al.*[22]	1-year	Indian Semi desert	*Not provided*	1.400- 1.570
Abdulhadi and Kifah[23]	NAN	Abu Dhabi UAE	*Not provided*	1.430-3.170
Present study	5-year	Akure	2.13 E-04	1.476
		Enugu	1.53 E-04	2.730
		Minna	3.53 E-04	1.940
		Jos	1.19 E-04	1.860
		Sokoto	5.35 E-05	1.287

Table 3 finally presents the comparison of the estimated geoclimatic factor *K* and the corresponding *k*-factor for different stations in the tropical and subtropical regions of the world. The result obtained shows good agreement with the earlier results from other tropical regions. However, no single location shows the same result except the value of *k*-factor in Durban that is similar to the value obtained in Akure. This might be due to the climatic nature of the two locations. Durban is noted to be the wettest part of South Africa[19, 20], while Akure is also a high rainfall location as well.

4.3 Development of contour maps for k-factor and geoclimatic factor over Nigeria

In order to make the contour map to cover a wide area over Nigeria, some other locations within the geographical zones studied were also incorporated. The contour lines were developed using the Kriging method in a MATLAB program.

For application in antenna height design and fade depth calculations needed in radio link design, contour maps were also developed for *k*-factor and geoclimatic factor. Figures 6 and 7 present the contour map for the average *k*-factor and geoclimatic factor over Nigeria, respectively. These parameters also decrease from the coastal region to the arid region of the country.

Generally, the *k*-factor values at the surface across the study locations are higher than the prescribed value of 1.33 by the ITU. The same trend could also be observed for the geoclimatic factor *K*. The cluster patterns are also clearly noticed in the two figures towards the south, this may have resulted from gas flaring activities from oil exploration in the region. The gas flaring that is taking place in the environment brings with it emission of carbon dioxide and sulphur output into the atmosphere at a height close to 100 m. The effect of these activities is shown clearly in the

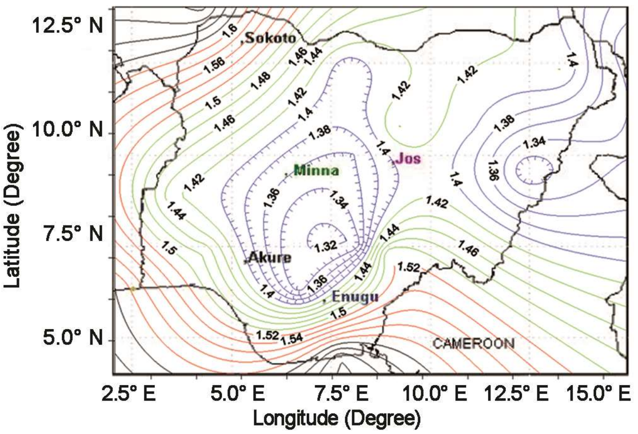

Fig. 6 — The contour map for average *k*-factor at the surface level over Nigeria

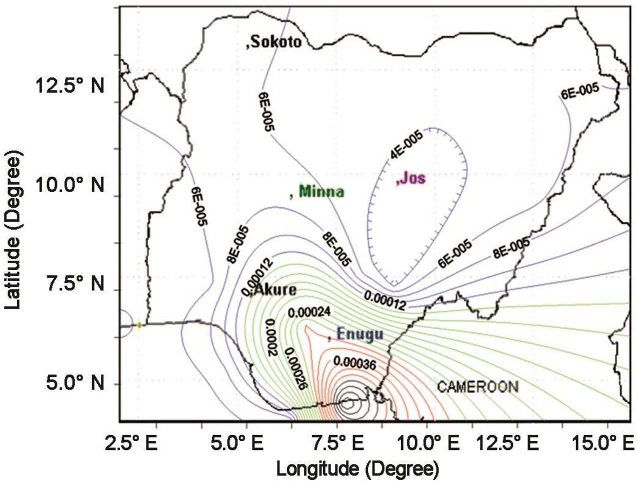

Fig. 7 — The contour map for average geoclimatic factor over Nigeria

figure. The overall information from these maps will be a very good tool for wireless link design over Nigeria.

5 Conclusions

Five years (2009-2013) of data from the in-situ measurement was employed to study the influences of secondary radioclimatic variables on the LOS link design over some selected locations in Nigeria. It could be observed that the secondary radioclimatic variables show seasonal type dependence. The result also shows that the secondary radioclimatic variables are location dependent with no two stations studied having the same value. Comparison of the estimated geoclimatic factor K and the corresponding k-factor for different stations in the tropical and subtropical regions of the world shows good agreement with the earlier results from other tropical regions. However, no single location shows the same result except the value of k-factor in Durban that is similar to the value obtained in Akure. Comparison of the k-factor with the predicted value by the ITU-R shows that k-factor values at the study locations are higher than the prescribed value of 1.33. The overall result will be useful in estimating location dependent fade margins required for user availability of satellite and terrestrial line of sight communication links for this region.

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