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Estimation of Refractivity Gradient and Geoclimatic Factor for Radio Link Design in Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Authors IE, BA and KDA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors IE and BA managed the analyses of the study. Author IE managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Accurate estimation of refractivity gradient and geoclimatic factor is highly necessary for radio signal propagation in clear air environment to cater for fade margin, essential for a reliable radio link. This is necessary because of the unstable nature of the environment the signal is traversing. These parameters were estimated from the meteorological parameters of surface air and dew temperature, temperature and relative humidity obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) archive during the period of 36 years. Point refractivity gradient at 100 m with refractive conditions were estimated for different locations across Nigeria in tropical region. The results show that the seasonal variation experience across the locations were influenced by the movement of inter tropical discontinuity. Values of geoclimatic factor also varies seasonally and geographically. Moderate association exist between β factor and latitude with correlation coefficient of 0.45 which is statistically significant as $p<0.05$. However, weak or non-relationship exist between β, μ, altitude and longitude as indicated by correlation coefficient.

Keywords: Meteorological parameters, propagation; geoclimatic; refractivity gradient.

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1. INTRODUCTION

The earth's atmosphere influence the propagation of electromagnetic waves around the earth. Earth's atmosphere is a dynamic medium. Its properties vary with temperature, pressure and humidity [1]. Variation in these atmospheric parameters is responsible for variability of tropospheric refractive index which is related to clear air propagation mechanism. It causes adverse effects on radio signal such as multipath fading, interference and attenuation [1]. These in turn impair the radio wave propagation and radar system performance [2,3]. The nonstandard troposphere conditions cause anomalous propagation which redirect radio rays to bend upwards (sub refraction) or downwards to the Earth surface (super refraction and ducting). These conditions significantly affects radio communication links and radar performance. The outages due to multipath fading depend on parameters such as frequency, hop length, terrain type and roughness, climatic conditions, and path clearance [4]. These effects give rise to the interest in detailed investigation of anomalous behaviour of radio wave propagation over tropic region in order to increase the communication and radar systems strength. Radio link systems must be well planned and designed to achieve good performance [5]. This however requires accurate estimation of refractivity gradient and geoclimatic factor value for all the locations where it may be needed across the country. The method for estimating percentage of time that a certain fades depth is exceeded is a function of frequency, path length and geoclimatic factor. Hence the need to determine the geoclimatic factor based on each location and region of interest is important. This work evaluate radio refractivity gradient and geoclimatic factor across some selected locations in Nigeria.

Nigeria is a tropical country with latitude 4 -14ºN and longitude 3-15ºE. It has an area of approximate 923300 km^2. Nigeria climate varied relatively than any other country in West Africa due to latitudinal range [6]. Nigeria climate is influenced by three main wind currents: the tropical maritime (mT) air mass, the tropical continental (cT) air mass and equatorial easterlies [6]. The mT air mass emanates from the southern high pressure belt located off the Namibian coast, cT air mass originates from the high pressure belt North of the Tropic of Cancer and picks up little dry moisture along its path. The two air masses meet along a slanting surface called Inter Tropical Discontinuity (ITD). The third air mass which is erratic cool comes from the East and flows in the upper atmosphere along the ITD [7]. Sixteen locations were selected across the country; grouped into four regions, namely: Coastal, Derived savannah, Guinea savannah and Arid regions as shown in Fig. 1.

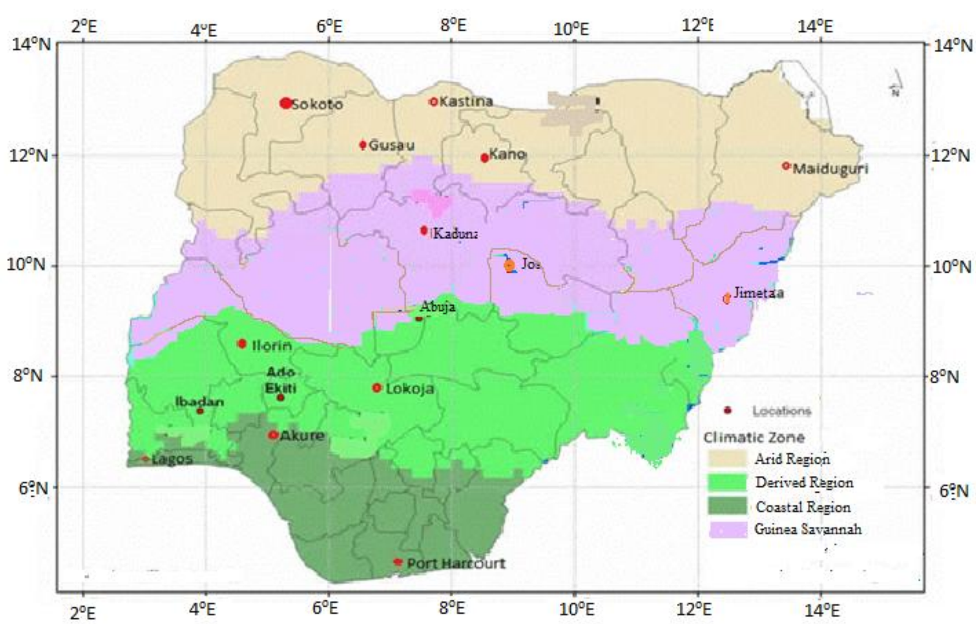


Fig. 1. Nigeria map with locations

Previous studies on radio refractivity and geoclimatic factor in some locations across Nigeria are available in [8-11]. Earlier work reveal that geoclimatic factor was only estimated for Akure in Nigeria [10]. Geoclimatic factor is important in determining multipath fading conditions and their impact on tactical LOS links [12].

2. METHODOLOGY

Long term Era – interim data of surface air and dew temperature , temperature and relative humidity at 1000 hPa with resolution of 0.25 × 0.25 from four daily ascents, nominally at 00:00, 06:00, 12:00 and 18:00 UTC covered the period of 36 years (1979 – 2014) have been used for this analysis. European Center for Medium Range Weather Forecast (ECMWF) Re-Analysis Interim (ERA-I) cover the time period of January 1979 to the present with horizontal resolution of about 80 km. The model and analysis (4 DVAR with a 12 hour window) uses 60 vertical levels between surface and 6 hours for the upper air fields [13].

2.1 Refractivity Gradient

Radio refractivity gradient of radio refractivity, G, in the lowest layer of the atmosphere is an important parameter for the estimation of path clearance and propagation effects such as ducting, surface reflection and multipath fading on terrestrial line of-sight links. Radio refractivity is of great interest to radio link engineer. The variation of refractivity gradients is a function of climate, season, and transient weather conditions across the day, clutter and terrain over the communication path [9, 14]. Negative value of G (beyond 100 N-unit/km) cause the radio signal to bend toward the earth and to traverse beyond the geometric horizon. When it becomes positive, it is known as sub-refraction and can cause diffraction loss. Refractivity (Surface refractivity or level refractivity) was obtained from meteorological parameters using equation 1[5,6].

$$N_s = \frac{77.6P_s}{T_s} + \frac{3.73\times10^5 e_s}{T_s^2} \tag{1a}$$

$$N_h = \frac{77.6P_h}{T_h} + \frac{3.73\times10^5 e_h}{T_h^2} \tag{1b}$$

where P_s, T_s, e_s and P_h, T_h, e_h are pressure (hPa), temperature (K) and water vapour (hPa) at surface (s) and height (h) respectively. Water vapour e_s and e_h is calculated using equation (2)

$$e = H \times 0.06112 \exp\left(\frac{17.502t}{t+240.97}\right) \tag{2}$$

where H and t are relative humidity (%) and temperature (ºC) for either surface (s) or height (h).

Refractivity gradient, G was obtained from surface refractivity, N_s corresponding to altitude, h_s and level refractivity, N_h corresponding to altitude h as shown in equation (3) [5,6,15]. Table 1 shows different refractive condition with corresponding refractivity gradient.

Table 1. Refractive conditions [16]

Refractive condition	Refractivity gradient
Sub refractive	G>-40
Super refractive	-40>G>-157
Ducting	G<-157

$$G = \frac{N_s - N_h}{h_s - h} \tag{3}$$

2.2 Geoclimatic Factor

Suitable fade margin which is a function of frequency, path length, geoclimatic factor etc. is necessary for a reliable radio link performance. The geoclimatic factor, K is an important parameter in fade depth estimation [17]. Unlike effective earth radius factor (k-factor) which has standard value of 1.44 for link design, K has no standard value [18]. Equation (4) show the relation between geoclimatic factor and the percentage of time p_w that fade depth A (dB) is exceeded in the average worst month [19].

$$p_W = Kd^{3.1}(1+|\eta|)^{-1.29} \times 10^{0.033f - 0.001h_L - A/10} \tag{4}$$

where η is path inclination, *f* is frequency (Hz), h_L is is the altitude of the lower antenna (meter) and d is path length (meter). The geoclimatic factor which is a measure of the climate and geographical condition of a terrain is calculated using the following ITU relation [4].

$$K = 10^{-4.2-0.0029\times dN_1} \tag{5}$$

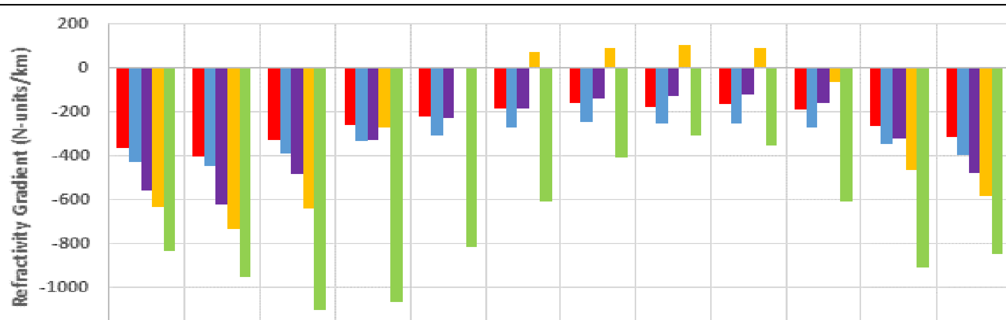
where dN_1 is point refractivity gradient in the lowest 100 m.

3. RESULTS

3.1 Refractivity Gradient and Anomalous Propagation

Fig. 2 shows the monthly variation of point refractivity gradient at 100 m and its statistics in six locations across Nigeria. Statistics of refractivity gradient at 100 m above ground is highly essential in terrestrial microwave links design. The figure revealed that point refractivity gradient varies seasonally in all the locations across the regions. The variation across the locations display two troughs with a crest discernable in July/August especially in coastal and derived region. This can be attributed to the fluctuations observed in atmospheric parameters in synchronism to the north – south movement of the Inter Tropical Discontinuity (ITD). The ITD reaches its maximum northward in July/August [7,10]. Refractivity gradient values are higher in rainy months (May – October) in all the locations than the dry months (November – April). During the dry season, value of refractivity gradient, G, oscillate between -266 ~ -399; - 335 ~ - 342; - 322 ~ - 620; - 461 ~ -635 and -830 ~ -1101 N-units/km at Coastal (Akure , Lagos); Derived Savannah (Ilorin); Guinea Savannah (Jos) and Arid (Sokoto) respectively.

Whereas, during the rainy season, it varies between -159 ~ -258, -247 ~ -335, -120 ~ -325, 90 ~ -268 and -309 ~ -814 N-units/km across the locations respectively. This variation however similar to the result obtained by earlier work [8,9]. The result can be attributed to the increase in the amount of water vapour in the atmosphere during this period, which limit temperature inversion. This will however cause radio wave to refract less. High variability observed in seasonal variation of refractivity gradient at Sokoto (arid region) can be linked to long dry season and short rainy season in the region [9]. This will result to high variability in the behaviour of radio wave propagation under super and ducting condition in this region. Long – term cumulative distribution function (CDF) of refractivity gradient G, over the period of thirty six years (1979 – 2014) is shown in Fig. 3. Cumulative distribution function of refractivity gradient, G, is important in estimating the probability of anomalous radio propagation conditions. The range of G at Arid and Guinea savannah varied between -1800 and 600 N-units/km. Values of G varies between -1400 ~ 200 N-units/km in Coastal and Derived savannah. The value of G for all the locations in Arid and Guinea savannah regions converge around 200 N –units/km except in Jos which converge around 400 N-units/km. It however converge around 100 N-units/km for all the locations in coastal and derived except in Lagos. The probabilities for the occurrence of sub refraction, super refraction and ducting in Arid and Guinea savannah regions varies between 5 - 35%, 2 – 5% and 50 – 88% respectively. Similarly, in Coastal and Derived savannah regions, the probabilities of occurrence ranges between 10 - 40%, 10 – 22% and 40 – 65% respectively.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Akure	-365.54	-399.77	-328.34	-258.17	-220.04	-180.26	-159.97	-176.53	-165.94	-189.64	-266.36	-315.43
Lagos	-425.83	-447.26	-386.86	-335.92	-308.17	-268.21	-247.16	-251.46	-253.39	-270.76	-342.64	-392.69
Ilorin	-558.88	-620.05	-484.85	-325.29	-223.57	-181.16	-140.41	-124.63	-120.84	-157.78	-322.1	-478.07
Jos	-629.52	-729.7	-635.99	-268.23	6.39188	70.929	90.3746	102.769	94.4253	-65.127	-461.22	-582.8
Sokoto	-830.26	-951.74	-1101.1	-1064.8	-814.64	-606.05	-408.83	-309.22	-351.83	-608.72	-909.15	-847.51

Fig. 2. Monthly distribution of refractivity gradient across Nigeria

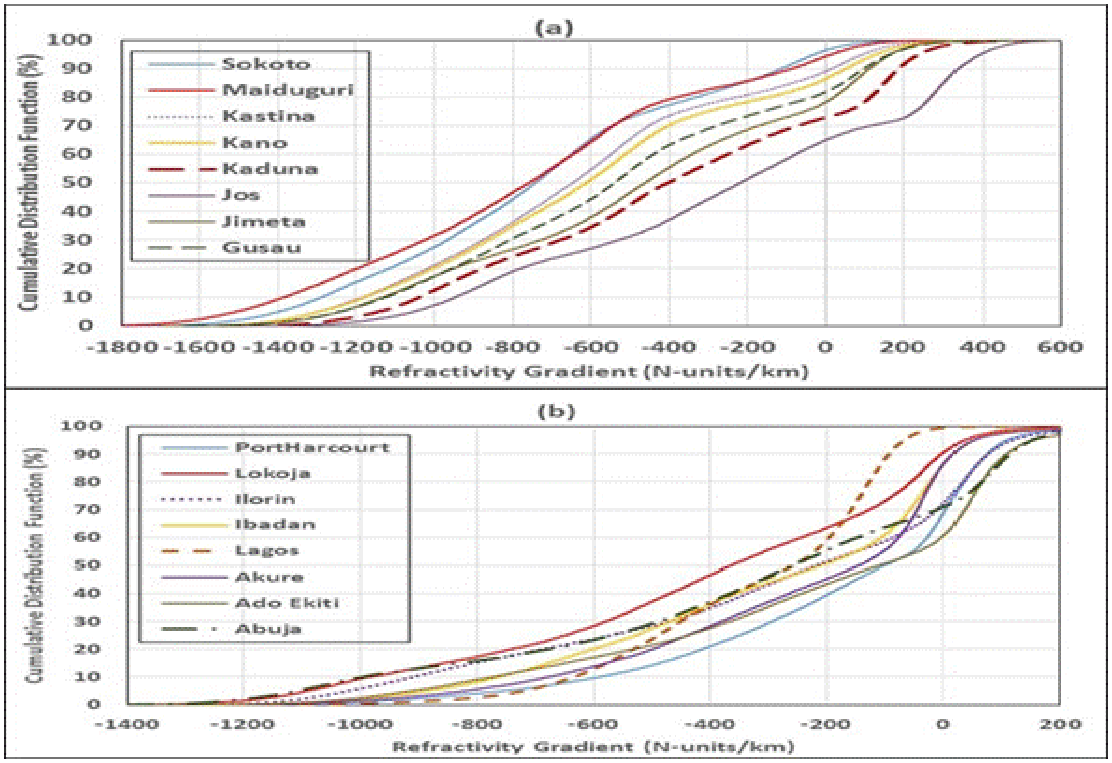


Fig. 3. Long-term cumulative distribution of refractivity gradient at (a) Arid and Guinea Savannah (b) Coastal and Derived Savannah

Table 1 summarizes the occurrence of anomalous propagation (β factor and sub refractive μ). β factor is the percentage of time refractivity gradient in the lowest 100m above the ground is less than -100 N - units/km. It encompass super refractive and ducting condition. Highest occurrence of β factor (90%) is obtained in Sokoto, while 50%, lowest value of β is observed in Port Harcourt. Maximum (39 %) and minimum (0.4 %) occurrence of μ are obtained in Ado Ekiti and Lagos respectively. Occurrence of ducting and super refractive in Arid region can be attributed to nocturnal radiation of heat which favour the growth of temperature inversion. Prevailing stable condition and low level moisture condition from the nearby ocean may cause the occurrence of ducting in the coastal region especially in the night. Under this condition radio wave propagation will be guided over distances far greater than the normal radio propagation range. Under sub refraction condition, radio ray refract upward, the bulge of the earth causes the direct path between the transmitter and receiver to be obscured, leading to the decrease in the received signal strength which may cause diffraction of radio propagation around the curvature.

Table 2. Occurrence of anomalous propagation

Locations	β factor (%)	Sub Refractive, μ (%)
Sokoto	90.79	3.45
Port Harcourt	50.03	31.53
Maiduguri	89.51	5.55
Lokoja	73.01	9.33
Kastina	84.27	10.99
Kano	81.63	13.47
Kaduna	68.81	26.95
Jos	58.29	34.95
Jimeta	73.06	21.65
Ilorin	58.70	27.61
Ibadan	60.96	13.75
Lagos	88.44	0.41
Akure	55.43	13.67
Ado Ekiti	50.73	39.46
Abuja	63.66	29.04
Gusau	77.38	18.25

To examine the variation of anomalous propagation (β factor and sub refraction, μ) with altitude, latitude and longitude, correlation coefficient (r) and p-value were determine for each of this element as shown in Table 2. The p-value is calculated to determine the level of correlation significant.

Table 3. Altitudinal, latitudinal and longitudinal variation of β_o factor, μ parameter

	Parameters	β_o	μ
Altitude	r	0.02	0.18
	p-value	0.59	0.11
Latitude	r	0.45	0.09
	p-value	0.00	0.11
Longitude	r	0.08	0.00
	p-value	0.30	0.92

From Table 3, the strength of association between β_o factor and latitude is moderate (r = 0.45), and that the correlation coefficient is statistically significantly with $p < 0.05$. Other relations between β_o factor, μ and longitude, altitude are poor and insignificant. The results revealed that μ which causes diffraction loss increase with altitude, while multipath fading which is a function of β_o significantly increases with latitude.

3.2 Geoclimatic Factor Distribution

Geoclimatic factor, K is an important parameter as it is directly proportional to the worst month outage probability P_w. It is used in the determination of the multipath fade depth at any point in radio communication link [4]. Table 4 shows the monthly distribution of geoclimatic factor, K, across Nigeria. Its values varies seasonally across Nigeria with minimum values observed in wet season. Though, K values increases northward across Nigeria, the distribution of K in all the locations shows lower values in the rainy months of April-October, whereas higher values occur in the dry months of November-March. In coastal and derived regions, values of K varies between 0.019 and 2.4E-04. It oscillate between 1.7E-01 and 3.5E-05 in guinea region, whereas in arid/semi-arid region it varies between 1.2 and 3.6E-04. Values of K (3.1E-04) obtained in July for Akure is the same as the one obtained in [10] using data from experimental site located at Akure.

Fig. 4 depict the latitudinal variation of geoclimatic factor at midnight, K_n, midday K_d and daily average, K_m. Strong significant variation exist between latitude and geoclimatic factor for K_n, K_d and K_m with p values equal to 0.009, 0.009 and 0.00009 respectively.

Table 5 shows correlation coefficient, r, p – value and slope Δ between latitude, longitude, altitude above sea level and geoclimatic factor. Good relationship with r = 0.64 exist between geoclimatic factor and latitude at 99 % significant level. However, insignificant relation exist between geoclimatic factor and longitude and altitude. The results shown that geoclimatic factor is a function of latitude of a location.

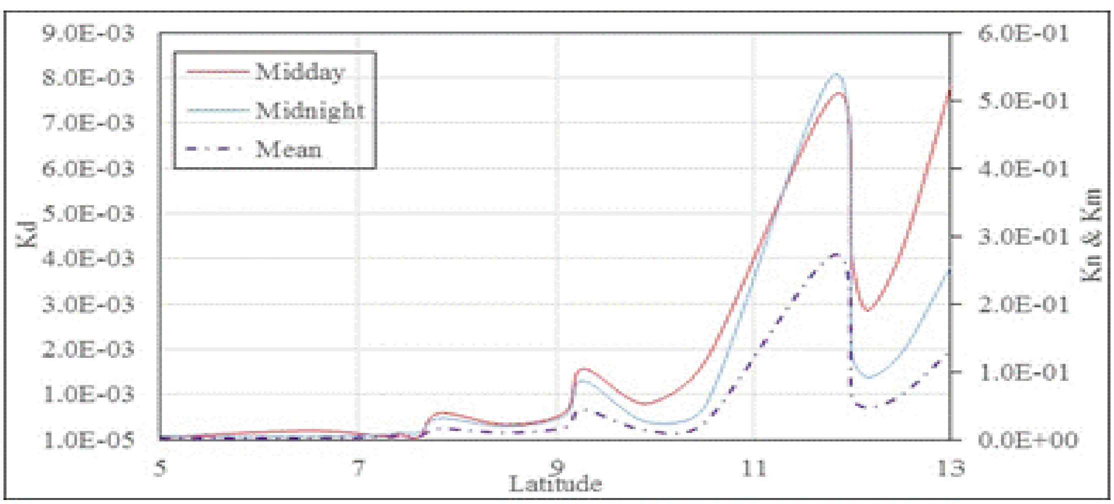


Fig. 4. Latitudinal variation of Geoclimatic factor across Nigeria

Table 4. Monthly distribution of Geoclimatic factor

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Portharcourt	7.2E-03	9.5E-03	3.4E-03	1.2E-03	6.3E-04	3.3E-04	2.4E-04	2.9E-04	2.5E-04	3.4E-04	1.1E-03	4.9E-03
Lagos	5.4E-03	7.5E-03	3.0E-03	1.5E-03	1.0E-03	6.9E-04	5.1E-04	5.6E-04	6.0E-04	7.9E-04	2.1E-03	3.6E-03
Akure	9.9E-03	1.4E-02	6.4E-03	1.5E-03	8.5E-04	4.6E-04	3.1E-04	4.0E-04	3.7E-04	5.5E-04	2.5E-03	6.9E-03
Ado Ekiti	1.3E-02	1.9E-02	1.2E-02	2.2E-03	7.2E-04	4.0E-04	2.6E-04	2.7E-04	2.6E-04	4.7E-04	3.9E-03	9.9E-03
Ibadan	1.2E-02	2.0E-02	1.3E-02	3.1E-03	1.4E-03	7.4E-04	4.7E-04	4.6E-04	5.0E-04	8.1E-04	4.4E-03	8.8E-03
Ilorin	2.3E-02	3.5E-02	2.6E-02	6.5E-03	1.3E-03	6.8E-04	3.7E-04	3.1E-04	3.2E-04	8.4E-04	8.3E-03	1.8E-02
Jimeta	5.1E-02	1.1E-01	1.7E-01	9.6E-02	9.3E-03	2.3E-03	8.5E-04	4.9E-04	7.9E-04	7.0E-03	4.4E-02	4.3E-02
Jos	1.7E-02	3.8E-02	5.2E-02	2.6E-02	9.1E-04	1.4E-04	4.7E-05	3.5E-05	1.1E-04	2.7E-03	1.3E-02	1.4E-02
Abuja	3.8E-02	6.4E-02	4.6E-02	6.3E-03	8.9E-04	4.0E-04	3.9E-04	1.8E-04	3.1E-04	2.0E-03	2.4E-02	3.5E-02
Kaduna	2.8E-02	6.5E-02	9.7E-02	6.1E-02	3.8E-03	6.3E-04	1.7E-04	1.1E-04	3.1E-04	5.2E-03	2.6E-02	2.5E-02
Lokoja	3.6E-02	5.6E-02	3.8E-02	1.2E-02	2.6E-03	1.3E-03	7.8E-04	7.2E-04	7.8E-04	1.7E-03	1.5E-02	2.9E-02
Gusau	2.7E-02	7.5E-02	1.7E-01	1.7E-01	2.6E-02	3.5E-03	7.9E-04	3.6E-04	8.1E-04	1.6E-02	4.8E-02	2.9E-02
Kano	2.2E-02	6.4E-02	1.7E-01	2.6E-01	9.0E-02	1.4E-02	2.2E-03	8.7E-04	2.6E-03	4.1E-02	6.1E-02	2.3E-02
Kastina	2.0E-02	5.8E-02	1.8E-01	2.8E-01	1.0E-01	1.5E-02	2.5E-03	1.1E-03	3.4E-03	5.1E-02	6.1E-02	2.2E-02
Maiduguri	5.4E-02	1.6E-01	5.1E-01	1.2E+00	7.2E-01	1.5E-01	1.5E-02	3.0E-03	2.1E-02	2.1E-01	1.9E-01	5.9E-02
Sokoto	4.8E-02	1.5E-01	4.3E-01	5.1E-01	1.3E-01	2.2E-02	4.4E-03	1.5E-03	3.7E-03	8.9E-02	1.5E-01	6.1E-02

Table 5. Altitudinal, latitudinal and longitudinal variation of Geoclimatic factor

	R	p – value
Latitude	0.64	0.01
Longitude	0.03	0.94
Altitude	0.03	0.91

4. CONCLUSION

Using thirty six years reanalysis data of European Centre for Medium-Range Weather Forecasts (ECMWF), refractivity gradient, and geoclimatic factor needed for radio links design have been estimated for sixteen locations across Nigeria. The result shows that the values of refractivity gradient and geoclimatic factor varies seasonally and geographically across Nigeria. Seasonal variation of these parameters is influenced by the migration of inter tropical discontinuity which reaches its maximum northward in July/August. High variability of refractivity gradient is observed in arid region of the country. Percentage of refractivity conditions which determine the behaviour of radio signal and radar performance in the atmosphere varies regionally across the country. The correlation of β factor with latitude was significantly positive across Nigeria with r = 0.45. Low values of geoclimatic factor is associated with midday which increases northward. It has been established that a good relationship exist between latitude and geoclimatic factor with correlation coefficient equal to 0.64 at 99 significant level. The results will be useful in terrestrial microwave links design.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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