Edelweiss Applied Science and Technology
ISSN: 2576-8484
Vol. 9, No. 3, 7-16
2025
Publisher: Learning Gate
DOI: 10.55214/25768484.v9i3.5105

The effect of secondary atmospheric parameters on radio wave propagation in a typical Sahel Savannah environment

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Abstract: The need for radio scientists and engineers to consider the atmospheric dynamics of a region is key in the design of communication links. This study was carried out over Katsina City, in the Sahel parts of Nigeria, using mean monthly atmospheric data covering 1980 to 2020. The data were retrieved from the European Centre for Medium-Range Weather Forecast ERA-5 Reanalysis. Refractivity at the surface, 100 m, and 250 m, refractivity gradient (G), and effective earth radius factor (k-factor) were determined using the International Telecommunications Union-Radio Study Group (ITU-R) Recommendation P.453-14, 2019. The data obtained were analyzed, and the results were compared with ITU-R standards. Results indicate higher values of refractivity and k-factor during the wet season compared to the dry season months, meaning there would be more attenuation of radio signals during the wet season compared to the dry season because studies have established a negative correlation coefficient (R) between these parameters and radio signals in Nigeria. Results further indicate a high negative (R) between k-factor and refractivity gradient (G) and a high positive (R) between k-factor and refractivity. The average refractivity for the surface, 100 m, and 250 m were 326.34, 316.39, and 305.07 (N-units) respectively, indicating that radio refractivity decreases with height. The mean k-factor for dry and wet seasons are 1.909 and 2.956 respectively, with an overall mean of 2.433, while the overall mean for (G) is -94.290 (N-units/km). By ITU-R standards, (G) and k-factor results indicate that radio wave propagation would experience a super-refractive effect over the Sahel environment. These results provide valuable applications in the design and reassessment of radio links for terrestrial and satellite communications over the study area or any similar environments in the Sahel region of Africa.

Keywords: *Quality of services and Sahel environment, Radio wave propagation, Radio link, Secondary atmospheric parameters.*

1. Introduction

The need for radio scientists and engineers to consider the atmospheric dynamics of a region is key in the design of communication links. Electromagnetic waves propagation in space is affected by the characteristics of the atmosphere [1]. The atmospheric variables can reflect, diffract, scatter and absorb the radio wave energy. The troposphere acts as the medium of propagation for terrestrial transmission, and the frequency and power of the signal are key determinants of the degree of the effects of the atmosphere. For instance, worse radio signal propagation conditions can cause higher fading on wireless communication links and lower receiver power levels [1]. Two sets of parameters should be analyzed to determine the effect of atmospheric variables on radio wave propagation because the signal strength of the electromagnetic wave between the receiver and transmitter depends on the signal's interaction with the propagation path amongst others; that is the link's performance [2]. These parameters are primary atmospheric variables of temperature, pressure, rainfall and relative humidity

History: Received: 19 December 2024; Revised: 31 January 2025; Accepted: 10 February 2025; Published: 1 March 2025
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amongst others. The secondary parameters include radio refractivity (N), gradient of refractivity (G) and k-factor [2, 3].

In the design of wireless communication links, secondary atmospheric parameters such (N), (G), and k-factor should be investigated to ensure the reliability of communication link [4-6]. For instance, understanding the values of k-factors in a local environment is essential in the design of antenna height necessary for effective radio wave propagation [3-5]. However, the k-factor depends on (G). The (G), can also be used to probe the bending of radio signals when propagating through different atmospheric layers. The effects of atmospheric variables can be noticed when the radio wave signal propagates through various routes (multi path propagation), to the targeted receiver and the time of arrival to the receiver also differs [7, 8]. This study used the latest ITU-R (2019) models of radio refractivity [9] to compute (G) and the k-factor for Katsina City. This is one of the advantages of this study over previous studies that deployed older ITU-R standards. The results were analyzed based on ITU-R standards to determine the effect of the secondary radio-climatic factors on radio wave propagation in the Sahel environment.

2. Basic Theory

Radio refractivity (N) is the measure in the changes of atmospheric refractive indices [2, 5, 6]. The refractive index n, and radio refractivity are as follows:

$$N = (n-1) \times 10^6 \quad (1)$$

N, can be further defined as:

$$N = 77.6\frac{p}{T} + \left[3.73 \times 10^5 \frac{e}{T^2}\right] \quad (2)$$

The independent parameters in (2) are Pressure P (hPa), temperature T (K) and water vapour pressure e (hPa) [9-11]. The water vapor pressure e can be determined using (3) where H is the relative humidity (%R.H). We have:

$$e = \frac{H}{dh} e_s \quad (3)$$

where e_s is the saturated vapor pressure at t(°C), which is expressed as (ITU-R, 2019):

$$e_s = EF \times 6.1121 \times \exp\left(\frac{\left(18.678 - \frac{t}{234.5}\right) \times t}{(t + 257.14)}\right) \quad (4)$$

and

$$EF = 1 + 10^{-4}\left[7.2 + P \times \left(0.0320 + 5.9 \times 10^{-6} \times t^2\right)\right] \quad (5)$$

2.1. Refractivity Gradient (G) and k-Factor

The atmosphere is dynamic, therefore N, changes from one atmospheric layer to another. The ITU-R offers a standard method for calculating the (G), [5, 6]:

$$G = \frac{dN}{dh} = \frac{N_2 - N_1}{h_2 - h_1} \quad \text{(N-Units/km)} \quad (6)$$

where N_1 and N_2 are the values of radio refractivity at heights h_1 and h_2.

Edelweiss Applied Science and Technology
ISSN: 2576-8484
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The radius of a hypothetical, spherical earth without an atmosphere delineates the k-factor using the heights and distances of the ground like those of a natural earth in the atmosphere with a constant vertical radio refractive gradient. The k-factor can be calculated using equation (7). Both (G) and k-factor can be used to predict anomalous propagations as presented in Table 1. We used equation (7) for the calculation of k-factor:

$$k = \frac{1}{1+\frac{\left(\frac{dN}{dh}\right)}{157}} \quad (7)$$

3. Materials and Methods

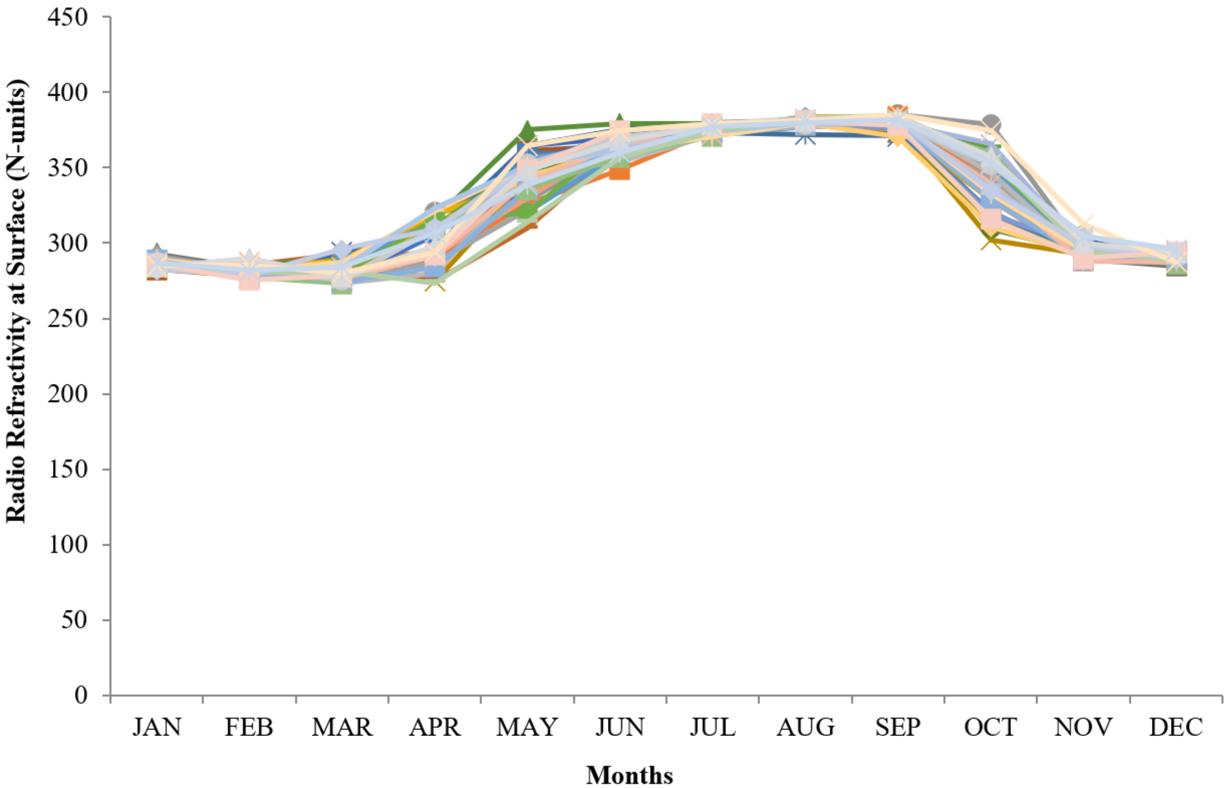
Monthly mean of 41 years' data sets covering (1980-2020) were retrieved from ECMWF ERA-5 [12] in the year 2021 at pressure levels of 1013, 1000 and 975 hPa corresponding to heights above ground level of surface, 100 and 250 m, respectively. They were used for computation and analysis. Equations (2) - (5) were used to calculate refractivity for the three atmospheric levels. Equations (6) and (7) were used to determine (G) and k-factor respectively. The overall mean annual values of the parameters were used for the analysis to obtain better results. ITU-R recommendations on the description of propagation effects with reference to the studied parameters were deployed [3, 9]. For the description of G, Table 1 presents the ITU-R standard. In addition, $k = {}^{4}/_{3}$ represents normal refraction, $k < {}^{4}/_{3}$ and $k > {}^{4}/_{3}$ represents sub and super refractive effects respectively [3-5].

Table 1.
ITU-R standards on refractivity gradient [1, 3, 10].

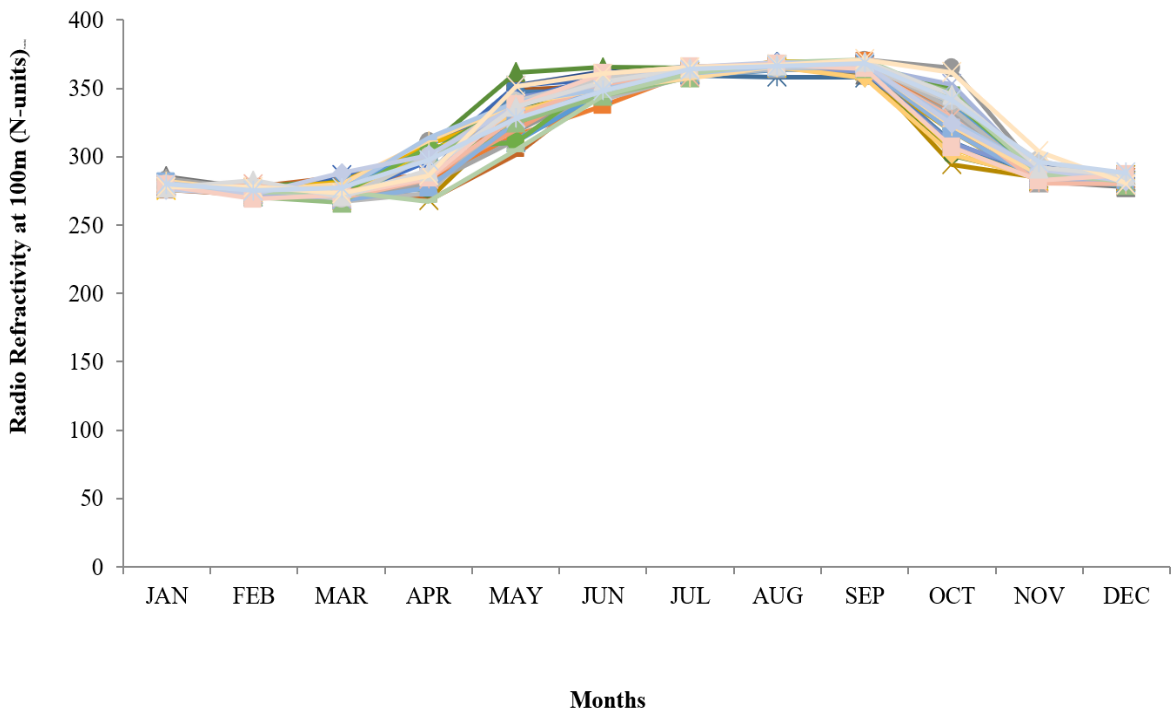
$G \approx -40$	$G > -40$	$G < -40$	$G < -157$
Normal: Standard atmosphere	Sub-refraction: Radiowaves could move away from the earth's surface causing the range of propagation to decrease.	Super-refraction: Transmitted radio waves can skip large distances due to multiple reflections	Ducting: Radio waves could be trapped between tropospheric layers with the signal exceeding free space value

4. Results and Discussion

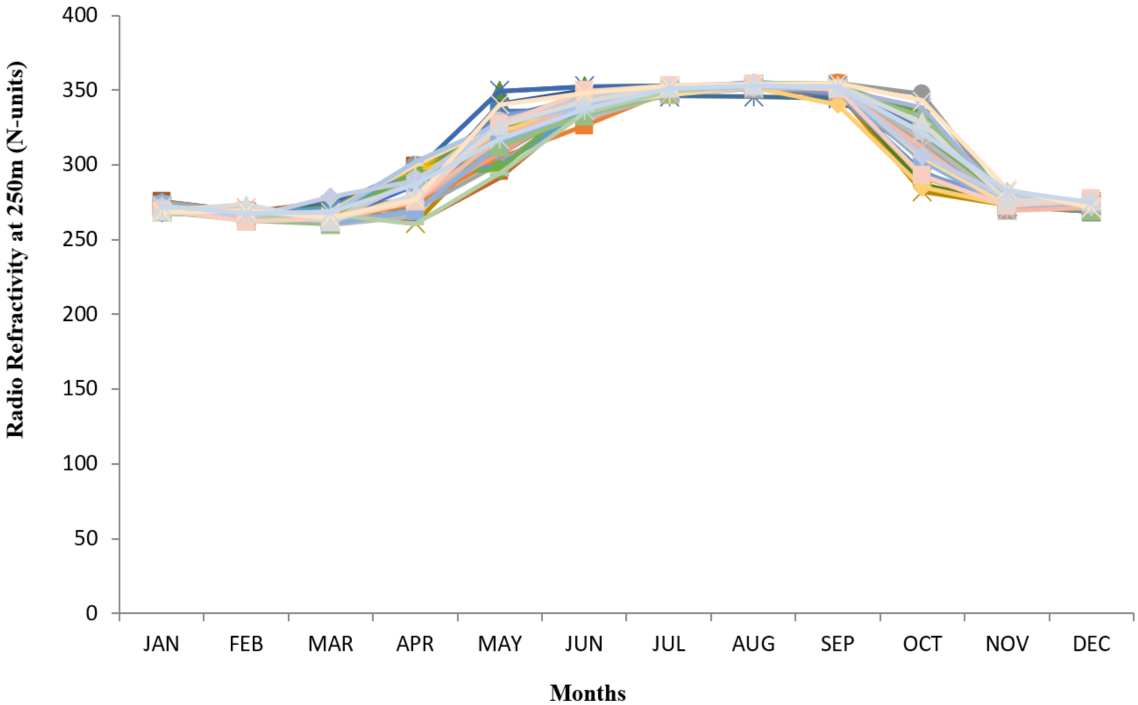
Figures 1a, 1b and 1c show the annual radio refractivity variations for forty-one years at the surface, 100 and 250 m. Higher values were obtained during the wet compared to dry season months. The average *N*, values for the surface, 100 and 250 m (AGL), are determined to be 326.345, 316.387 and 305.074 N-units respectively, meaning that (*N*) decreases with height. This result agrees very well with the results of Sabiru, et al. [4] and International Telecommunications Union [9]. The overall mean value of (*N*) for the three layers is 315.936 N-units.


Radio Refractivity at Surface (N-units)
450
400
350
300
250
200
150
100
50
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Months

(a)


Radio Refractivity at 100m (N-units)
400
350
300
250
200
150
100
50
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Months

(b)



(c)

Figure 1.
Mean annual variation of radio refractivity (N) for forty-one years (1980-2020) under study over Katsina at: (a) the surface, (b) 100 m and (c) 250 m

The forty-one-year annual mean variations comparison of (*N*) for the three heights under discussion is displayed in Figure 2. May-October (wet season months) recorded peak values than the dry season months of November-March. The implications of this are higher attenuation of radio signal during wet compared to the dry season's month because many literatures [13-15] have established a significant negative correlation coefficient between wireless signal and radio refractivity in Nigeria. Additionally, from Figure 2, it can also be observed that (*N*) decreases with increasing altitude. This implies that as a radio wave propagates from one atmospheric layer to the other, it will experience refraction, leading to attenuation that depends on the degree of the refractivity gradient.

Edelweiss Applied Science and Technology
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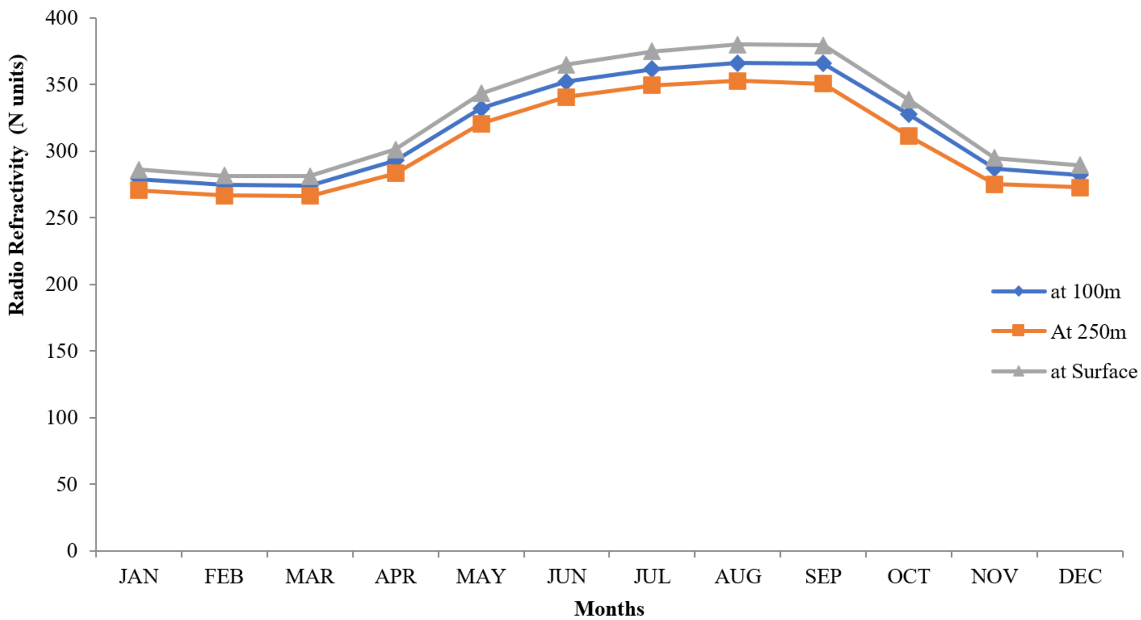

Figure 2.
Average Monthly Variations of Radio Refractivity for 41 years (1980-2020) at three different heights above the ground level.

Two refractivity gradients (G)values using the surface and 100 m and their respective refractivity values; as well as 100 and 250 m and their respective refractivity values were computed. They are presented in Figure 3. A close examination of Figure 3 revealed that the dry season months have greater values, and they decrease gradually during the wet season- months. Additionally, from Figure 3, it can be observed that the values increase with increasing altitude. The average computed (G) using height difference of; surface-100 m and 100-250 m and their corresponding (N) values are; -113.162 units/km and -75.418 units/km, respectively, with a total average of -94.290 units/km. Since this value is within the range; $-40 \leq -94.3 \leq -157$ (N-units/km), the interpretation is that radio propagation would experience super refraction according to ITU-R standards as defined in Table 1.

DOI: 10.55214/25768484.v9i3.5105

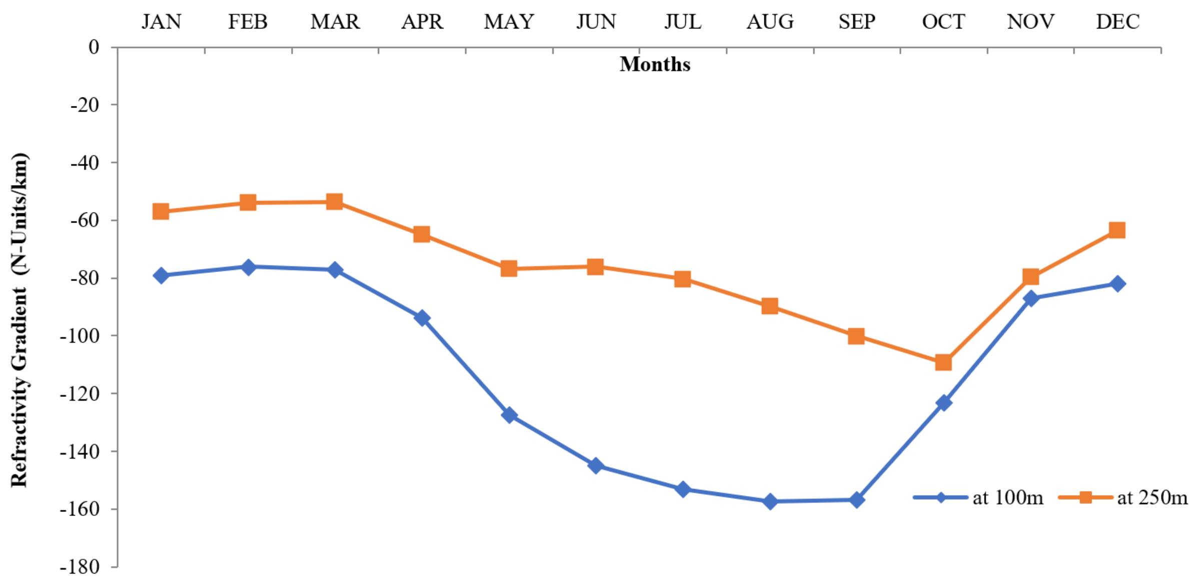

Figure 3.
Average Monthly Variations of (G) for the period of forty years (1980-2020)

The corresponding k-factor values for the period were determined and presented in Figure 4. It shows that the k-factor recorded the lowest values in the dry season months and gradually increased in the wet season months. In comparison to the wet season, the dry season months have less rainfall and a lower k-factor. From the obtained result, k-factor is inversely proportional to (G).

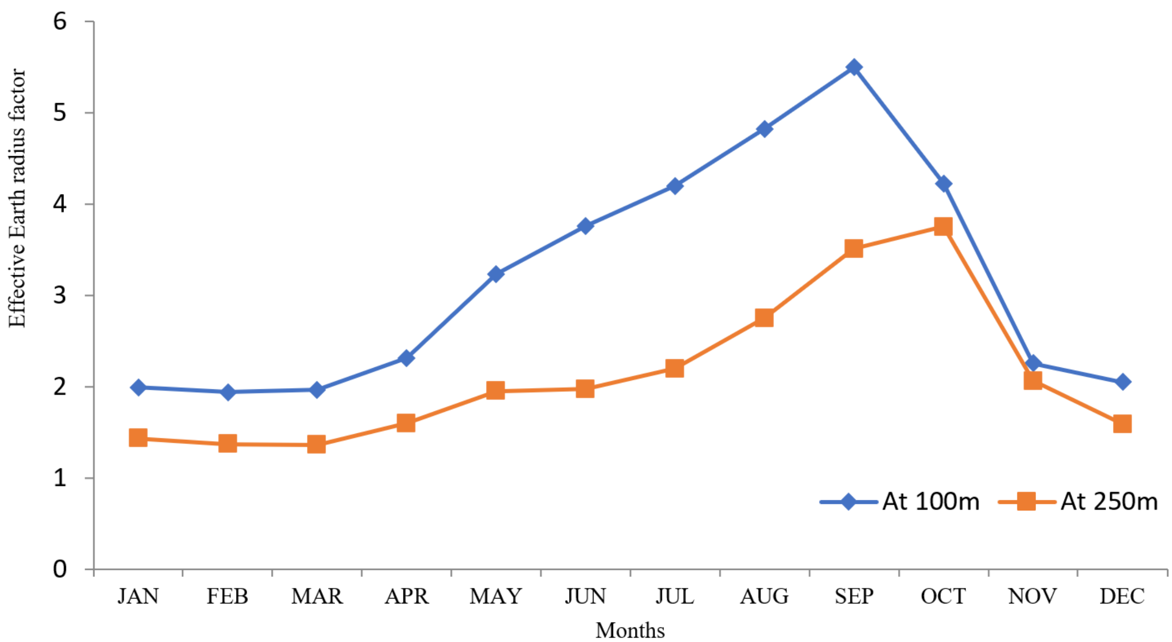

Figure 4.
Average Monthly Variations of k-factor for the period (1980-2020).

Edelweiss Applied Science and Technology
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The mean ranges of k-factor for the dry season months are 1.943 - 2.258 using the gradient computed from refractivity at the surface and 100 m and 1.365- 2.068 for the gradient computed from 100-250 meters. For the wet season months, it ranges from 1.961 - 4.505 for the gradient computed from refractivity at the surface and 100 m and 1.604-3.753 for the gradient computed from 100-250 m, respectively. The mean for dry and wet season are 1.909 and 2.956 respectively. The overall mean value of the k-factor for the two seasons using the two-height profiles is **2.433** for the years under consideration. This is higher than the recommended value for the normal atmosphere set at 1.33 (4/3) by the ITU-R. The implication is that radio wave propagation would experience super refraction.

For the correlation coefficient analysis, the overall mean values of the data (used in this study) presented in Table 2 were deployed in the analysis to determine the degree of relationship amongst all the parameters studied.

Table 2.
Evaluated monthly mean of secondary atmospheric parameters for the forty-one years (1980-2020) over Katsina City.

Month	N_surface (N-Units)	N_100 m (N-Units)	N_250 m (N-Units)	G (N-Units/km)	k-factor
Jan	285.51	278.59	270.30	-66.94	1.68
Feb	281.45	274.78	267.17	-63.24	1.62
Mar	281.95	275.12	266.94	-66.09	1.67
Apr	300.58	292.35	282.47	-79.71	1.95
May	351.72	339.91	328.99	-103.41	2.58
Jun	367.84	354.90	343.57	-111.29	2.89
Jul	378.57	364.84	351.79	-121.53	3.57
Aug	380.81	366.91	353.34	-124.22	3.82
Sep	379.49	365.69	350.06	-130.50	4.79
Oct	347.06	335.63	317.88	-124.08	4.86
Nov	299.42	291.48	279.47	-85.16	2.17
Dec	292.02	284.64	273.87	-77.81	1.99

Results show a high negative correlation coefficient (R) between the refractivity values with increasing heights using the surface as reference. In addition, high negative R, of -0.962, -0.963 and -0.945, exist between refractivity gradient and refractivity at surface, 100 and 250 m, respectively. Meaning that the higher the refractivity, the lower the refractivity gradient. Similarly, a high negative R of -0.929 exists between k-factor and (G) indicating they are inversely proportional. Lastly, high positive (R) of 0.815, 0.815 and 0.784 exist between the k-factor and refractivity at the surface, 100 and 250 m, respectively.

5. Conclusion

Atmospheric data obtained from three different height levels; surface (2m), 100 and 250 m, respectively, were used to determine and analyze the radio refractivity (N), refractivity gradient (G) and k-factor over Katsina City, Katsina State, Nigeria. The values obtained were used to investigate anomalous propagation of radio signals in the study area. The study reveals that (N) and k-factor have higher values in the wet compared to the dry season which is consistent with the works of Akinwunmi, et al. [16]; Ayantunji, et al. [17]; Oyedum, et al. [18]; Ajileye, et al. [19]; Mmahi, et al. [20]; Akpootu, et al. [21] and Lawal, et al. [22] while (G) has higher values in dry compared to the wet season months; the k-factor is inversely proportional to (N). A high negative correlation coefficient (R) exists between the refractivity values with increasing heights using the surface as reference, while a high negative R exists between (G) and (N), at various heights. In addition, a high negative R exists between the k-factor and (G) with a high positive R between it and refractivity at different heights. The overall mean values of radio refractivity, refractivity gradient and k-factor for Katsina City are 310.731 N-units, -94.290 units/km and 2.433 respectively. The implication is that propagated radio signals in the study location are prone to more attenuation during wet compared to dry season months because of the higher

Edelweiss Applied Science and Technology
ISSN: 2576-8484
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refractivity values. Similarly, going by the ITU-R standards, the refractivity gradient (Table 1) and k-factor results are consistent, showing that radio waves propagation over the study area will experience super-refractive anomalous propagation (super refractive attenuation effect). This result provides valuable practical applications in the design of transmission parameters and power budgets for reliable communications. The overall findings of this study would be of great importance to radio scientists and engineers in the design and re-assessment of communication's link over a typical Sahel Savanah in Nigeria or any similar environments in Africa.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

Acknowledgement:

Authors wish to acknowledge ECMWF ERA-5 Reanalysis as the source of Data for the study. This study is supported by Tshwane University of Technology, South Africa.

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