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Comparative Analysis of Surface Refractivity Variations in the Sahel and Coastal Zones of Nigeria

Yusuf Babatunde Lawal[1, *], Joseph Babatunde Dada[2]

[1]Department of Physics, University of Africa, Toru-Orua, Nigeria
[2]Department of Physical and Chemical Sciences, Elizade University, Ilara-Mokin, Nigeria

Email address:

lawalyusuf.b@gmail.com.com (Yusuf Babatunde Lawal), dor4jos@gmail.com (Joseph Babatunde Dada)
[*]Corresponding author

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Abstract: Variation in Surface Refractivity N is largely influenced by changes in some meteorological parameters such as air temperature, relative humidity, and pressure. These parameters are more accurate when measured locally due to their temporal and spatial variations. The research studies and verifies the contributions of the dry and wet term components of surface radio refractivity. The research focuses on the comparison of surface refractivity variations in two geoclimatic zones of Nigeria. The study reveals that the Sahel and Coastal zones have dissimilar distinct weather conditions and consequently diverse variational pattern of their surface refractivities diurnally and seasonally. The diurnal values of surface refractivity vary moderately on typical sunny days with average values of about 345-391 N-units and 275-314 N-units in the Coastal and Sahel respectively. Wider daily variations were observed during the rainy season in both geoclimatic zones due to frequent rainfalls, especially in the Coastal Stations. The average daily refractivity in the Coastal and Sahel during the rainy seasons are 339-390 and 311-384 N-units respectively. Analysis of the results obtained indicates that the annual mean of the ITU-R recommendation underestimates surface refractivity by 11-15% across the coastal stations and by 5-10% across the Sahel zone. The derived values for each station would be useful for radio engineers in the design and optimization of terrestrial radio links.

Keywords: Surface Refractivity, Geoclimatic Zones, Sahel Zone, Coastal Zone

1. Introduction

The principle of rectilinear propagation of light states that light (waves) travel in continuous straight lines in a homogeneous medium of uniform refractive index. However, bending of waves as it travels through the layers of the atmosphere has been reported over the years [1]. This is due to the variation in the vertical profile of the refractive index occasioned by changes in density and constituents of the gases and other matter that make up the stratified layers of the atmosphere. This implies that there is gradual bending of radio propagation path as it transverses the atmosphere. This phenomenon is generally called Refractivity. Proper knowledge of refractivity, its effects, and estimation is important in the design of radio links such as point-to-point (P2P) and point-to-multipoint (P2MP) links. For instance, a radar may miss its intended target as a result of rapid changes in atmospheric propagation conditions if the changes are not taken into consideration. Details about the classification of propagation conditions and their implications on radiowaves can be found in the work of Anderson [2].

Refractivity is the modified form of refractive index commonly applied in the analysis of radio wave propagation. It is a scaled-up term for expressing the refractive index in a bigger unit. The relationship between refractivity N and refractive index n is given by equation (1) [3].

$$N = (n - 1) \times 10^6 \tag{1}$$

Refractivity varies with respective to altitude due to variations in the vertical profile of the atmospheric constituents. The value of refractivity near the ground surface is known as surface refractivity. The extent to which a radio signal curves is a function of meteorological parameters such as temperature, relative humidity and pressure. Temporal and spatial variations in these parameters have a great effect on propagation conditions [4].

Although, the Radio Section of the International Telecommunication Union (ITU-R) recommended surface refractivity for different regions of the world on a contour map [5], several kinds of research have revealed that wide variations exist between the recommended and the locally measured refractivity. It is imperative to compute surface refractivity using local parameters. Surface refractivity is a localized radio parameter, hence, its accuracy can be greatly improved by utilizing local meteorological parameters in the computation.

2. Methodology

2.1. Data Acquisition and Research Locations

The data employed for this study are meteorological satellite data retrieved from the archive of the European Centre for Medium-Range Weather Forecast (ECMWF). It is an ERA-5 reanalysis data which consists of temperature, relative humidity and pressure measured hourly near the earth's surface. The data has a grid and temporal resolutions of 0.25◦ by 0.25◦ lat/long and 24 hours respectively [6]. The data span between 2012-2021 (10 years) covering eight selected stations from the Coastal and Sahel geoclimatic zones of Nigeria. Although Nigeria is a tropical region characterized by higher precipitation when compared with the temperate region, the distribution of rainfall in the entire region is not uniform [7]. The coastal stations are Lagos, Warri, Port Harcourt (PH), Calabar while the Sahel stations are Kano, Maiduguri, Katsina and Sokoto. Table 1 shows the study stations, the features, as well as their ITU-R, recommended surface refractivity values according to equation (2) [5, 8].

$$N = 315\exp(-0.136h) \quad (2)$$

Where *h (km)* is the refractivity at the ground surface above the mean sea level.

Table 1. *The study Areas and their Geoclimatic Classifications [9-10].*

Station	Latitude (°N)	Longitude (°E)	Height Above Sea Level (m)	Rec. ITU-R Annual Surface Refractivity (N-Units)	Geoclimatic Zone	Geoclimatic Feature
Sokoto	13.006	5.248	318	301.66	Sahel	The tropical continental (cT) air mass predominates and the Tropical maritime (mT) air mass invades for between 3 and 5 months every year
Katsina	12.514	7.611	519	293.53		
Maiduguri	11.831	13.151	320	301.56		
Kano	12.002	8.592	488	294.77		
Lagos	6.524	3.379	41	313.25	Coastal	The zone is dominated by mT air for most of the year
Warri	5.554	5.793	6	314.74		
Calabar	4.976	8.341	32	313.63		
PH	4.745	6.823	65	312.23		

2.2. Calculation Procedure

The Saturated Water Vapor Pressure *e* and Water Vapour Pressure e_s were computed using equations (3) and (4) respectively [11].

$$e = RH \times \frac{e_s}{100} \quad (3)$$

$$e_s = 6.1121 \times \exp\frac{17.502t}{(t+240.97)} \quad (4)$$

Where RH is the relative humidity (%), e_s is the saturation water vapor pressure of water (hPa), and t is the temperature (° C).

The surface refractivity is determined from the retrieved meteorological parameters and the derived water vapour pressure according to equation (5) [12].

$$N = \frac{77.6}{T}[P + \frac{4810e}{T}] \quad (5)$$

Where P is the ground surface pressure (hPa), T is the absolute temperature (K) and *e* is the water vapor pressure. Equation (5) can be split into two components as expressed in equation (6).

$$N = \frac{77.6P}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (6)$$

Where $\frac{77.6P}{T}$ and $3.73 \times 10^5 \frac{e}{T^2}$ are referred to as dry and wet terms respectively. The hourly values were processed statistically to determine the daily and monthly values of surface refractivity. The results obtained were utilized for the comparative studies of the diurnal and seasonal variations of surface refractivity across the stations and geoclimatic zones.

3. Results and Discussion

3.1. Influence of Atmospheric Parameters on Surface Refractivity Variation

The processed data was applied to study the contributions of wet and dry term components of radio refractivity. Analysis of the data reveals that while the dry term is responsible for the high magnitudes of N, the wet term is largely responsible for the wide fluctuations in the values of N. This was observed throughout the study period in all stations. Typical plots of these observations are presented in Figures 1 and 2. About 70% of N values is made up of the dry term while the wet term contributes only 30%. However, the trend of changes in the N aligns perfectly with that of the wet term as depicted in Figure 2. Similar results were obtained for all the study locations with coefficients of correlation between 0.92 and 0.98. This observation is in consonant with some previous reports across Nigeria and beyond [13-15]. The high value of the dry term is due to the atmospheric pressure and the wide variations in the wet term is the consequence of the polar nature of water vapour molecules.

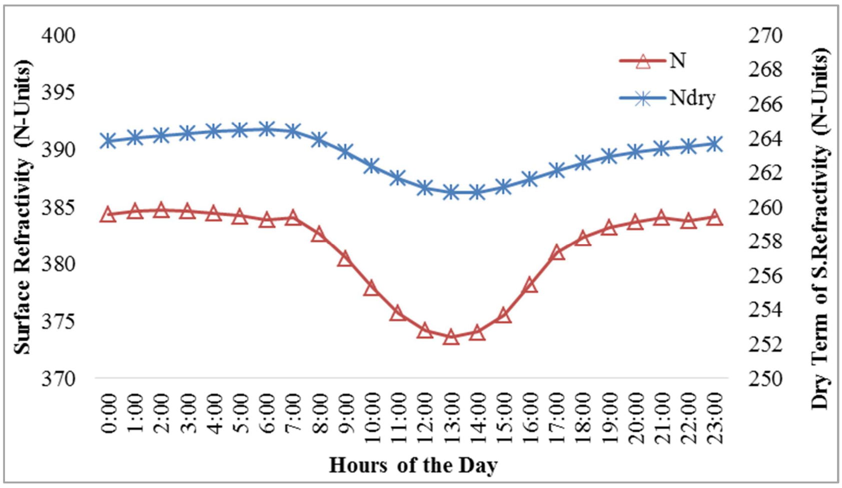

Figure 1. *Comparison of Surface Refractivity N and its Dry Term Component* N_{dry}.

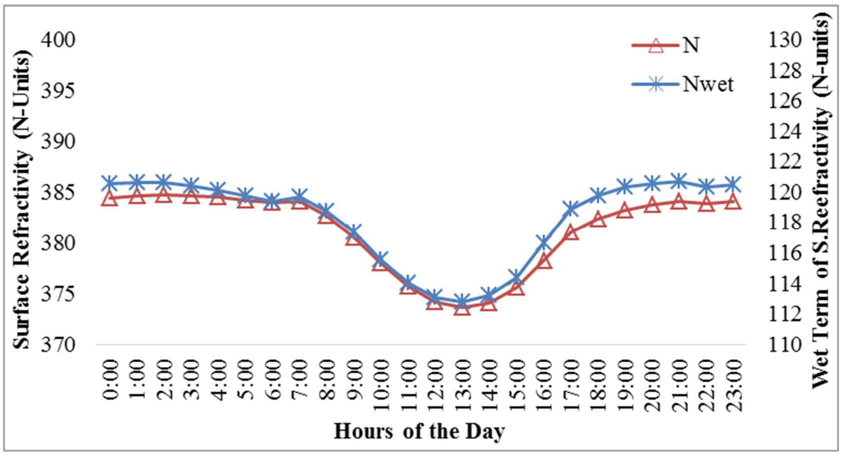

Figure 2. *Comparison of Surface Refractivity N and its Wet Term Component* N_{wet}.

3.2. Diurnal Variation of Surface Refractivity

The diurnal variation of surface refractivity in the study stations was also investigated between 2012 and 2021. Generally, N is fairly steady during the early hours (00:00 – 6:00) of the day across all the stations. The N values in the Coastal stations (Calabar, Lagos, PH and Warri) are generally higher than those of the Sahels (Katsina, kano, Maiduguri and Sokoto).

In the Sahel stations, N reduces gradually as the sun rises and attains its minimum values between 12:00 and 15:00 as depicted in figures 3-6. This is caused by the increase in temperature which lowers both the dry and wet terms as shown in equation (6). As the temperature begins to fall at about 16:00 due to reduction in solar radiation, N rises gradually and becomes fairly stable at the late hours. Similar observations were observed in the Coastal zone but only during the dry season. On rainy days, the value of N in the afternoon rises rapidly higher than the early hour values due to massive water vapour content in the atmosphere in the coastal stations.

For instance, on the 27th of September 2021, a rainy day in Calabar, N increases from about 353.7 N-units at 8:00 to reach a peak value of about 389.1 N-units at 15:00 as shown in Figure 6. Lagos also with a peak value of about 394.5 at 21:00 due to late night rainfall. The plots of the rainy days presented in Figures 5 and 6 have shown that the wet term has great influence on the variation of N when compared with typical dry days in Figures 3 and 4. Similarly, on the 10th of July 2014, a rainy day in some Sahel stations, Sokoto, Maiduguri, Katsina and Kano recorded maximum N of 377.2 N-units, 382.5 N-units, 388.3 N-units and 386.7 N-units respectively at 0:00 hours as presented in figure 5.

These values are higher than the corresponding coastal station values due to absence of rainfall in the coastal zone. Figures 3 and 4 which represent typical dry days possess a uniform trend pattern with minimal fluctuations as a result of low steady water vapour content during the dry season in all the stations. The effect of the wet term is minimal during the dry season. This account for the smooth pattern of refractivity especially in the Sahel as depicted in Figures 3 and 4.

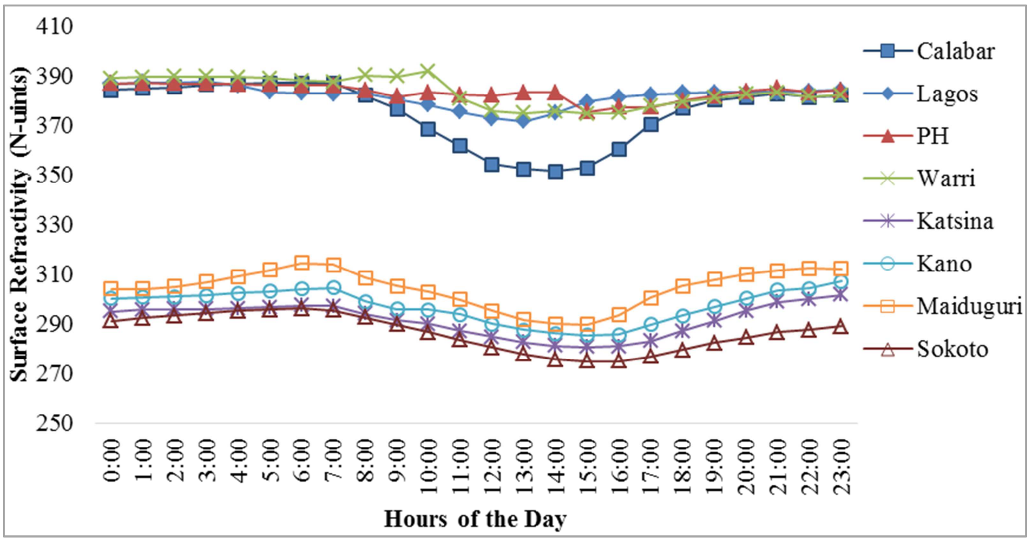

Figure 3. *Diurnal Variation of Surface Refractivity on a typical sunny Day (15, January 2021).*

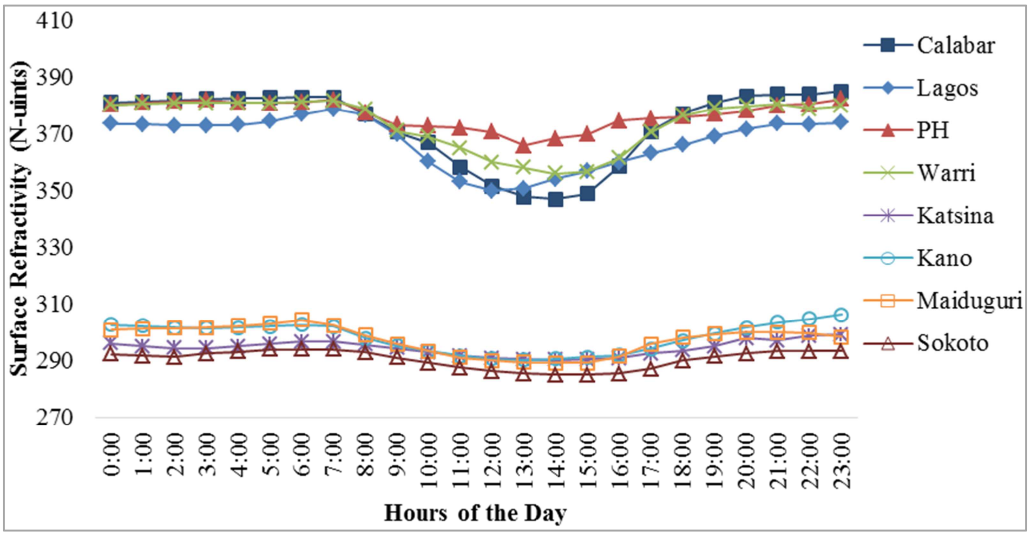

Figure 4. *Diurnal Variation of Surface Refractivity on a typical sunny Day (28, February 2014).*

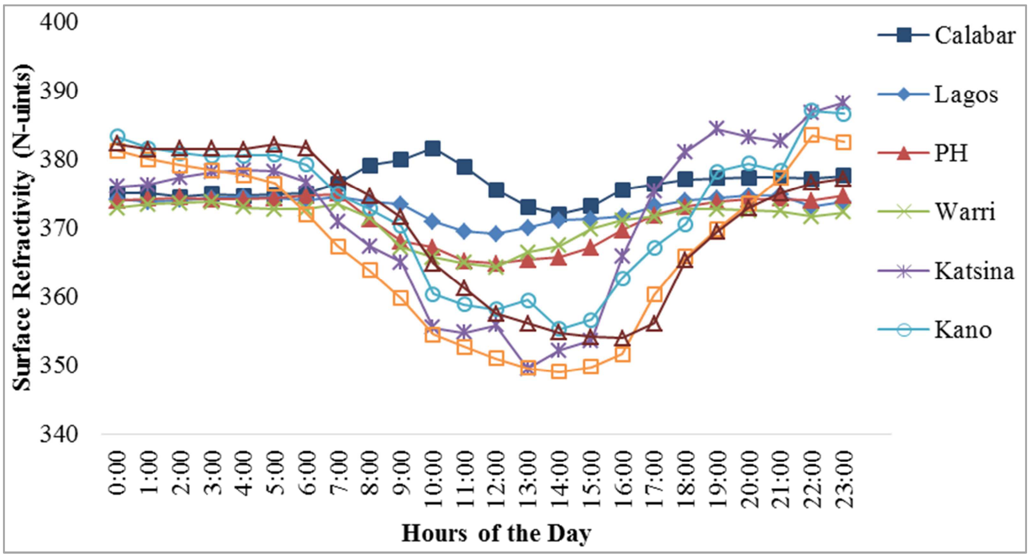

Figure 5. *Diurnal Variation of Surface Refractivity on a typical rainy Day (10, July 2014).*

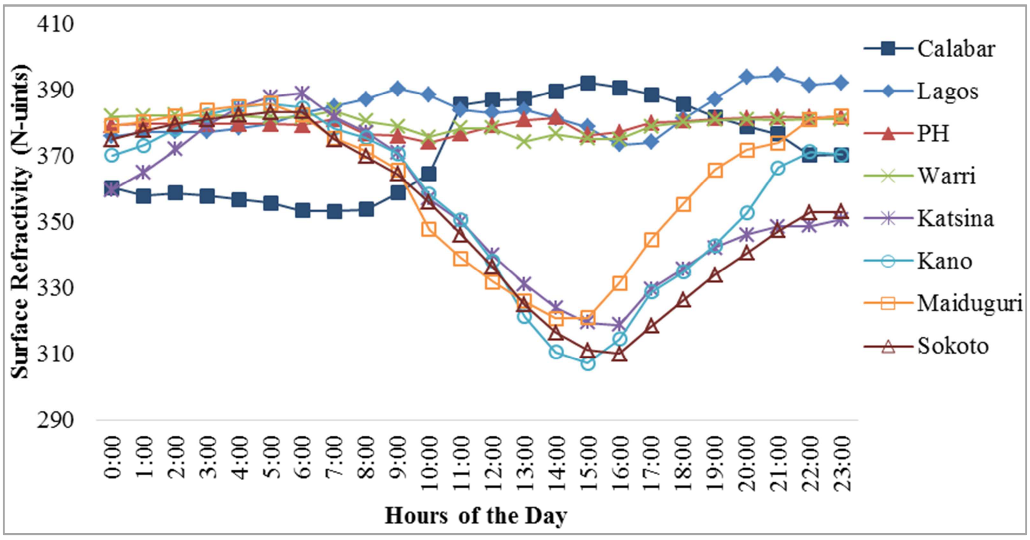

Figure 6. *Diurnal Variation of Surface Refractivity on a typical rainy Day (27, July 2021).*

3.3. Seasonal Variation of Surface Refractivity

The Coastal and the Sahel zones are the Southernmost and Northernmost parts of Nigeria respectively. The transition of the Inter-Tropical Discontinuity (ITD) between the former zone bounded by the Atlantic Ocean and the latter zone bounded by the Sahara Desert is responsible for the occurrence of dry and wet seasons experienced annually [16-17]. The wet season runs from March till late October while the dry season reigns between November to March [18].

In the Sahel zone, N is fairly stable throughout the dry season with minimal fluctuations between 275 and 289 N-units in all the stations. The slight increase from November and December signifies the commencement of harmattan, a short period characterized with low humidity and cloud cover which prevents rain formation. The harmattan period is followed by intense solar radiation which results in lower N between January and March as shown in Figures 7 – 10. At the onset of wet season, Surface refractivity increases rapidly from March and attains its peak in August across all the four stations of the Sahelian zone throughout the study period. Precisely, the average maximum surface refractivity for Katsina, Kano, Maiduguri, and Sokoto are 359, 355.5, 358.3, and 358 N-units respectively. The values are fairly stable with minimal fluctuations between July and September. The refractivity values decline greatly from September to November signifying the end of wet season and the onset of the dry season i.e October/November.

The seasonal variation of refractivity in the coastal zone follows a similar trend in Lagos and Port Harcourt only as depicted in Figures 13 and 14. On the contrary, two dips were observed in Calabar and Warri between May and September as shown in Figures 11 and 12. The first dip is due to the sudden rise in temperature in the month of May in the two stations occasioned by frequent cool wind and light showers as reported by Taiwo *et. al.* [19].

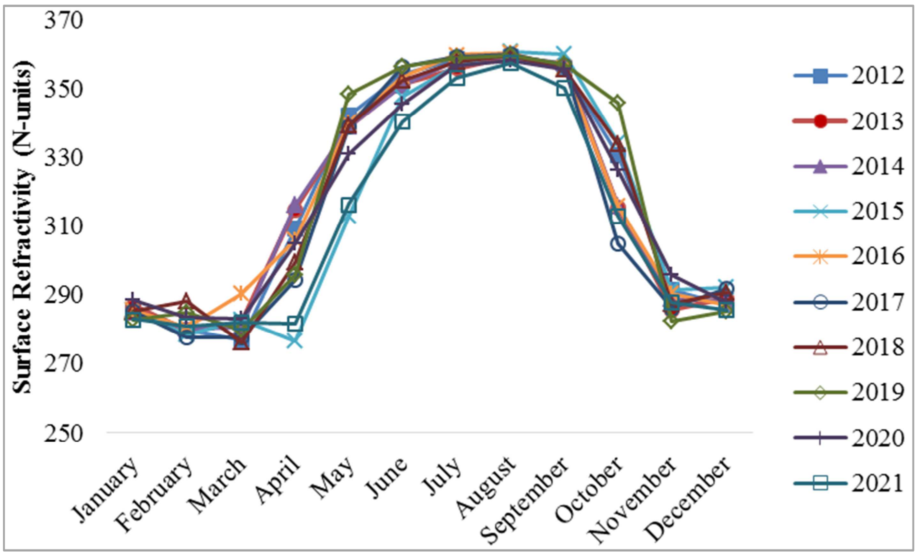

Figure 7. *Seasonal Variation of Surface Refractivity over 10 years in Katsina.*

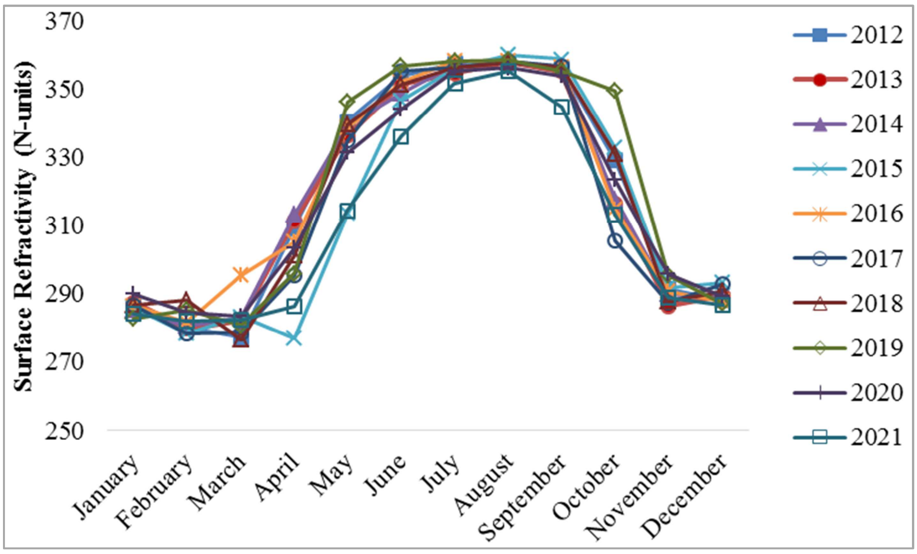

Figure 8. *Seasonal Variation of Surface Refractivity over 10 years in Kano.*

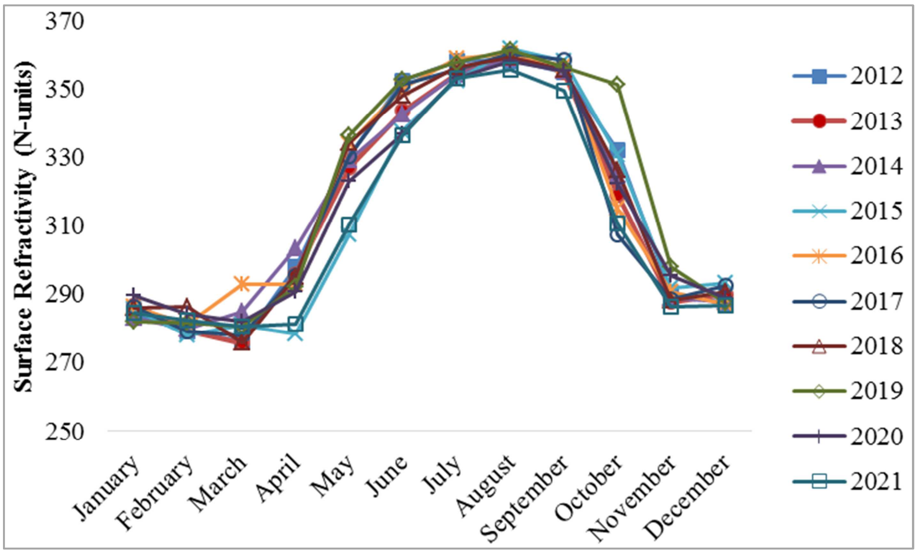

Figure 9. *Seasonal Variation of Surface Refractivity over 10 years in Maiduguri.*

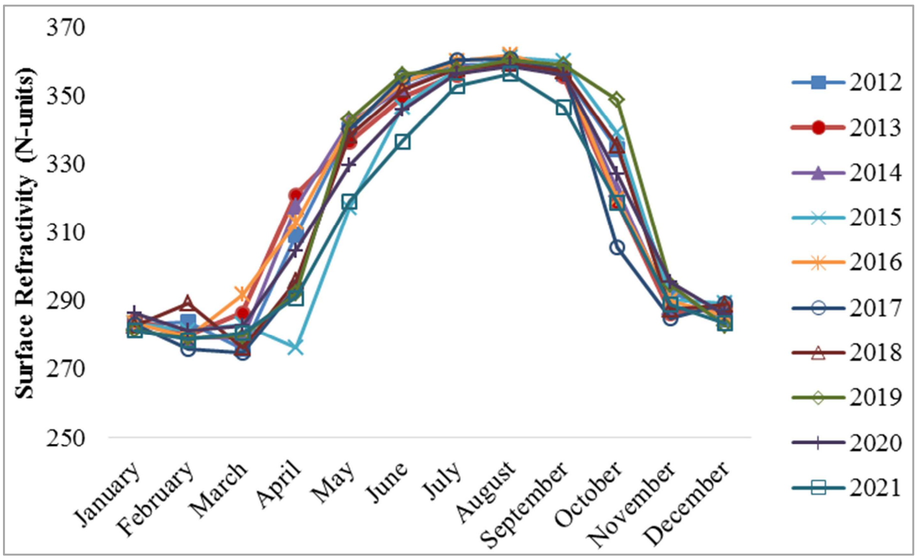

Figure 10. *Seasonal Variation of Surface Refractivity over 10 years in Sokoto.*

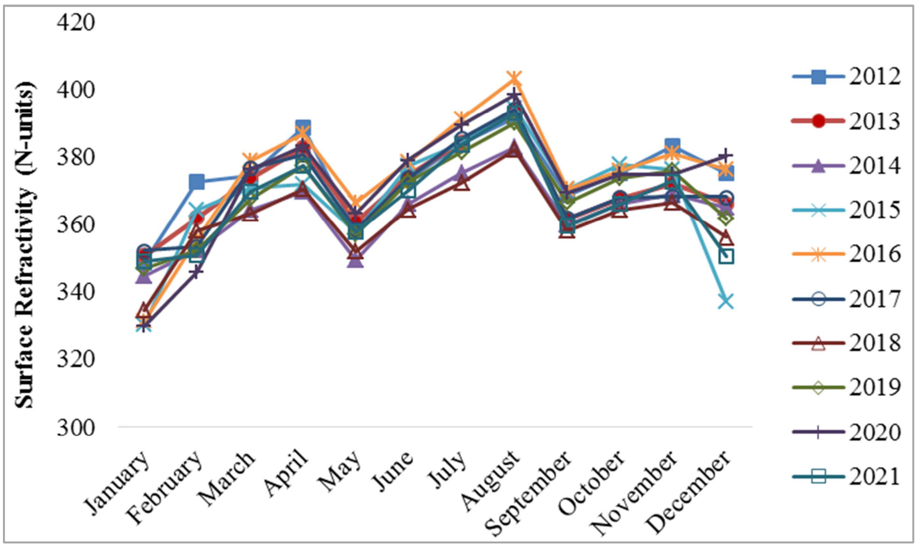

Figure 11. *Seasonal Variation of Surface Refractivity over 10 years in Calabar.*

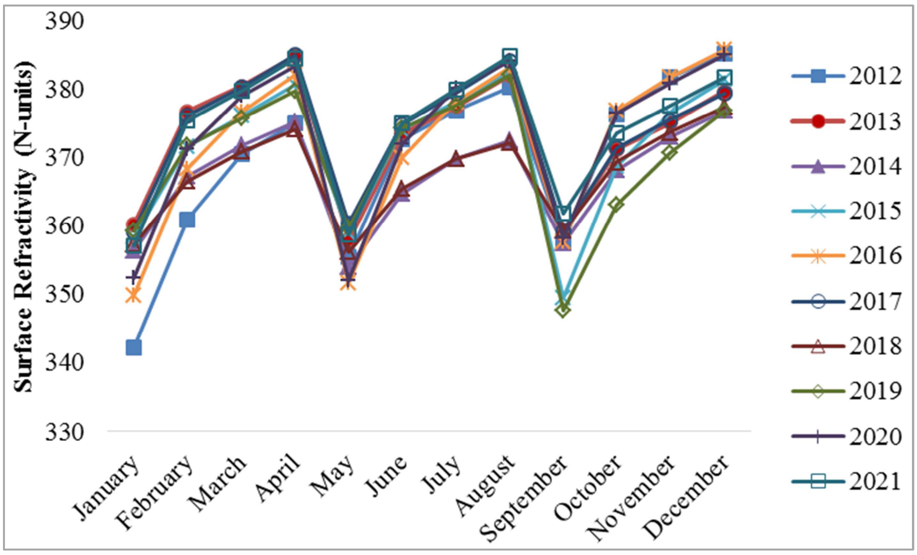

Figure 12. *Seasonal Variation of Surface Refractivity over 10 years in Warri.*

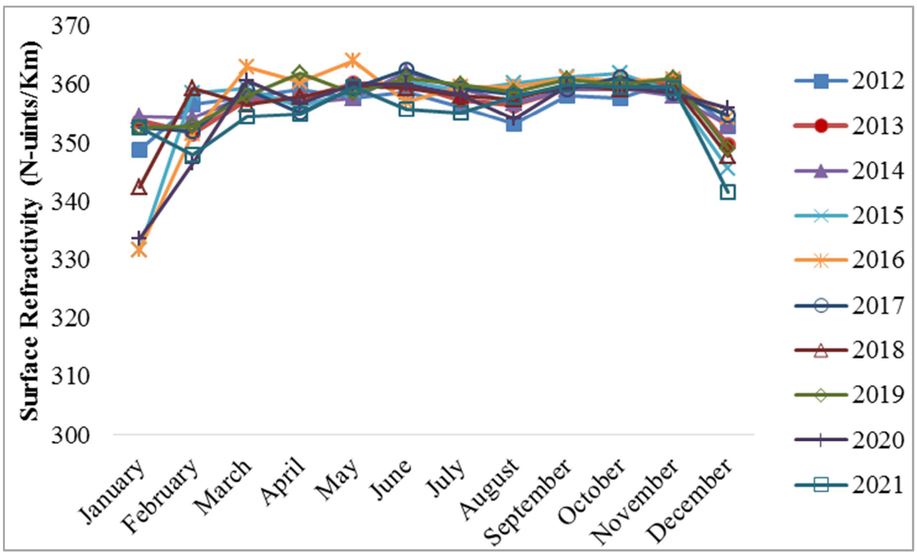

Figure 13. *Seasonal Variation of Surface Refractivity over 10 years Port Harcourt.*

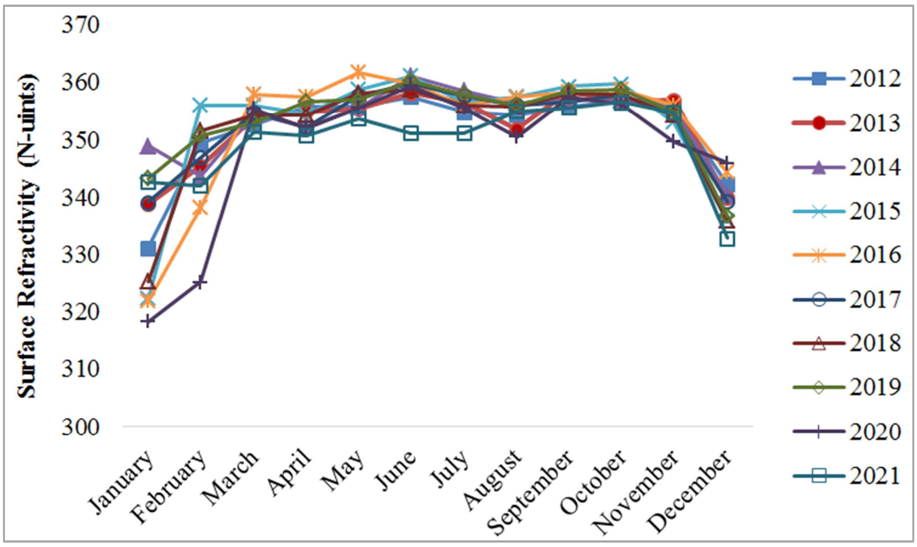

Figure 14. *Seasonal Variation of Surface Refractivity over 10 years Lagos.*

The following months are usually accompanied with heavy down pour which is a consequence of high humidity and cloud formation. The peak value of Refractivity recorded in August is the consequence of precipitation which climaxed in the same month as reported by Weather spark [20]. This leads to corresponding increase in refractivity. The second dip is caused by a fall in water vapour content after rainfall has climaxed in August. The average maximum refractivities in Calabar, Warri, PH and Lagos are 394.2 (August), 383 (August), 361 (May), 362.6 (August) respectively.

The average annual surface refractivities of the study locations were computed and compared with the ITU-R recommended values. Table 2 shows surface refractivity was under-predicted by the ITU-R model in all the locations. The Sahel station values were underestimated by less than 10% in all the stations while the Coastal station values were grossly underestimated by over 10% in all the stations as depicted in Table 2.

Table 2. *Comparison of Computed and ITU-R Recommended Annual Mean of Surface Refractivities.*

Study Locations	Rec. ITU-R Surface Refractivity (N-Units)	Computed Annual Surface Refractivity (N-Units)	Percentage Difference (%)
Sokoto	301.66	317.45	4.97
Katsina	293.53	317.41	7.52
Maiduguri	301.56	315.58	4.44
Kano	294.77	317.28	7.09
Lagos	313.25	351.87	10.98
Warri	314.74	371.22	15.21
Calabar	313.63	369.21	15.05
PH	312.23	356.64	12.4

4. Conclusion

The research reveals that the dry and wet term components play a significant role in the value of surface radio refractivity. The dry component is responsible for the high values of N while the wet component influences the variation between its average minimum and maximum. A study of the diurnal variation shows that N is generally low during the active solar radiation period (9:00 – 16:00) in all the stations except on rainy days. The daily variation of N in the Sahel is between 275 and 315 N-units but could be as high as 384 N-units on heavy rainy days. The margin of variation is wider in the Coastal zone due to frequent rainfalls resulting in a sudden decrease in temperature and increases in humidity. The annual variational pattern of surface refractivity in the Sahel is more consistent than that of the Coastal zone over the last ten years. N varies between 275 and 384 N-units in the Sahel whereas it varies between 339 and 391 N-units in the Coastal stations during the dry season. The recommended geoclimatic zonal surface refractivities for the Coastal and Sahel are 362 and 317 N-units respectively.

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