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QUARTERLY VARIATION IN TROPOSPHERIC SURFACE REFRACTIVITY IN ILORIN, NIGERIA

M.S Otto[1a], O.J Abimbola[2a], O.A Falaiye[3b], F.U.Muhammad[4a], A.A Sule[5a]

Abstract: Refractivity impacts radio communication systems that are above the atmosphere. It is thus necessary to understand variations in refractivity to improve the effectiveness of cellular networks and navigation and surveillance systems. The purpose of this study is to measure seasonal changes in tropospheric surface refractivity in Ilorin, Kwara, Nigeria. During the dry (first quarter) and rainy (third quarter) seasons from 2000 to 2002, refractivity was calculated using meteorological data obtained from the Nigerian Meteorological Agency, Ilorin. Average surface refractivity of 243.34 N-units was recorded in the third quarter (July–September) of 2000; it was 212.86 N-units in the first quarter (January–March). Refractivity was measured at 240.25 N-units and 212.73 N-units in the third and first quarters of 2001, respectively. Finally, refractivity was measured at 242.83 N-units and 216.51 N-units in the third and first quarters of 2002, respectively. These results show that tropospheric surface refractivity differs in the dry and rainy seasons; higher surface refractivity was observed during the rainy season than during the dry season over a three-year period. This is attributed primarily to water content in the atmosphere (troposphere), which is higher during the rainy season than the dry season.

Keywords: *Refractivity, atmosphere, troposphere, meteorological parameters*

1. Introduction

Variations in meteorological parameters, particularly in the troposphere, can change the composition of the atmosphere, which has a profound effect on the propagation of electromagnetic waves in the atmosphere (specifically in the troposphere) (Korak, 2003). Variations in meteorological parameters such as temperature, pressure, and relative humidity impact the index of refraction of the air within this layer. Solar radiation influences all meteorological parameters, either directly or indirectly, causing typical daily or yearly trends. To measure these trends, it is necessary to calculate the mean values of multiple measurements taken over a specific period (Bean & Horn, 1959). However, the daily cycles of some meteorological parameters are quite easy to measure.

Variations in meteorological parameters such as clouds and rain have a stronger impact on radio wave propagation in the lower atmosphere, particularly in the troposphere (Hall, 1979). In the tropics, these variables vary every quarter hour, as well as hourly, daily, and seasonally. Radio communication (terrestrial and satellite) systems must account for variations in refractivity. Radio refractivity, which is impacted by these three parameters (temperature, pressure, and relative humidity), affects the propagation of radio waves at various frequencies, such as ultra-high frequencies and microwave frequencies. Radio refractivity is influenced by the meteorological variables of temperature, pressure, and relative humidity (Bean & Horn, 1959). Distribution studies of refractivity can help address the challenges that arise due to unexpected path loss and uncharacteristic propagation of radio waves, which obstruct radio signal performance in cellular networks and in surveillance and navigation systems (Ukhurebor & Nwankwo, 2020).

Many researchers have made significant contributions to this field, including Ukhurebor and Nwankwo (2020), who used an inexpensive, portable, self-implemented meteorological monitoring device to estimate the refractivity gradient from basic climate variables in Iyamho-Auchi, Edo State, South-South Region of Nigeria over a one-year period (2018). They concluded that refractivity gradient values are higher during months with lower relative humidity. Abimbola et al. (2021) estimated radio refractivity from a decade of satellite meteorological data for West Africa and discovered a seasonal pattern in refraction variation across the West African region, with super-refraction dominating the coastal area during the wet season and sub-refraction dominating during the dry season. In 2017, Ukhurebor et al. (2018) used a portable weather monitoring system to estimate atmospheric refractivity over Auchi town (Edo State), Nigeria, and found that air temperature impacts refractivity more than relative humidity or atmospheric pressure. Edet et al. (2017) investigated monthly variations in radio refractivity in Calabar, Nigeria, in 2016 and found that radio refractivity patterns varied

Authors information:
[a]Department of Physics, Federal University of Lafia, NIGERIA. E-mail: o.muhammed@science.fulafia.edu.ng[1]; abimbola.oladiran@science.fulafia.edu.ng[2]; faisal.usman@science.fulafia.edu.ng[4]; ahmedsule0104@gmail.com[5]
[b]Department of Physics, University of Ilorin, NIGERIA. E-mail: sesantayo2001@yahoo.com[3]
*Corresponding Author: o.muhammed@science.fulafia.edu.ng

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only slightly due to Calabar's nearly uniform weather conditions (i.e., a small observed increase in tropospheric temperature and humidity). Ikeh and Okeke (2016) found that, over a two-year period, surface refractivity over Awka, South East Nigeria, varied most during the rainy season and least during the dry season. Bawa et al. (2015) examined average hourly variations in radio refractivity in several Nigerian cities: Yola (9° 11' N, 12° 30' E), Anyigba (7° 45' N, 6° 45' E), Lagos (6° 27' N, 5° 12' E), and Port-Harcourt (40° 48' N, 7° E). This study found that average hourly variations in refractivity during the dry season are due primarily to variations in humidity, while refractivity varies during the rainy season due to changes in both dry (pressure) and wet components (humidity). Ali et al. (2011) also examined seasonal variations in radio refractivity, using measurements taken at a height of 10 km over Minna (9° 37' N, 6° 30' E). They found that the atmosphere over Minna was super-refractive during the wet season and sub-refractive during the dry season. Adediji et al. (2013) computed radio refractivity using measurements of atmospheric parameters taken by weather stations in Akure, Nigeria (2007–2011) (Davies 6162 wireless vantage Pro2 specs), at different altitudes. They found that, at all levels, water vapour pressure impacts radio refractivity more than any other parameter. Igwe and Adimula (2009) used the University of Ilorin Atmospheric observatory to obtain data from the radiometric network of the Baseline Surface Radiation Network (BSRN) and computed surface-level monthly variations in the radio refractive index over Ilorin (8° 32' N, 4° 34' E) over a period of five years (2000–2004). Okoro and Agbo (2012) investigated the effect of diurnal variations in meteorological parameters on tropospheric radio refractivity during the dry and rainy seasons in Minna in 2008. They found that variations in meteorological parameters, such as humidity and temperature, in the lower troposphere caused radio refractivity to vary throughout the day; this impact was more significant during the rainy season than the dry season. Agbo et al. (2013) evaluated atmospheric refractivity on disturbed and quiet days in Abuja during the dry and rainy seasons and found that refractivity is impacted by changes in weather variables. Other similar studies include Willoughby et al. (2002), Adeyemi (2004), Falodun (2006), Adedeji (2008), Ekpe et al. (2010), Igwe et al. (2011), Daniel et al. (2015), Falaiye et al. (2016), and Ukhurebor and Azi (2019). However, none of the reviewed studies have computed quarterly surface refractivity in Ilorin, Kwara State, North-Central Nigeria, despite this region's unique climate (tropical savanna).

Because changes in the index of refraction play such a large role in radio wave propagation in the troposphere, it is convenient to use refractivity (N) when modelling atmospheric variation in the index of refraction (Bean, 1966; Thayer, 1974). Refractivity (N) is related to the index of refraction, n, as shown in Eq. 1:

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

Refractivity is also related to meteorological parameters (Willoughby et al., 2002):

$$\begin{aligned} \mathrm{N} &= \frac{77.6}{\mathrm{T}}\left(\mathrm{P} + 4810\frac{\mathrm{e}}{\mathrm{T}}\right) \\ &= 77.6\frac{\mathrm{P}}{\mathrm{T}} + \left(3.732 \times 10^5 \frac{\mathrm{e}}{\mathrm{T}^2}\right) \end{aligned} \tag{2}$$

where T = Absolute temperature in Kelvin, P = Barometric pressure in millibars, e = Partial pressure of water vapor in millibars, and e_s = Saturated vapor pressure in millibars.

$$\mathrm{e_s} = 6.11 \times \exp(\mathrm{x}) \tag{3}$$

$$\mathrm{x} = \frac{17.2694(\mathrm{T} - 273.15)}{\mathrm{T} - 35.85} \tag{4}$$

$$\mathrm{e} = \frac{\mathrm{RH}}{100}\mathrm{e_s} \tag{5}$$

The present paper aims to measure and compare quarterly variations in refractivity in Ilorin, Nigeria, and to measure the relationships of these variations with the aforementioned meteorological parameters.

2. Methodology

Ilorin (4.542 °E, 8.497 °N; altitude 303 m), the research location of the present study, is the capital city of Kwara State, Nigeria. It has a population of about 777,667 and a Köppen climate classification of Aw, tropical savanna. The average climatic data for Ilorin is as follows: temperature: 32.5 °C; total annual rainfall: 1,185 mm; average annual rainy days: 88; average relative humidity: 51.1%. Figure 1 shows Ilorin on a map of Nigeria. The data used in this study were recorded over a period of three years and provided by the Nigerian Meteorological Agency (NIMET). The station uses a dry bulb thermometer to measure temperature, a barometer to measure atmospheric pressure, and a hygrometer to measure relative humidity.

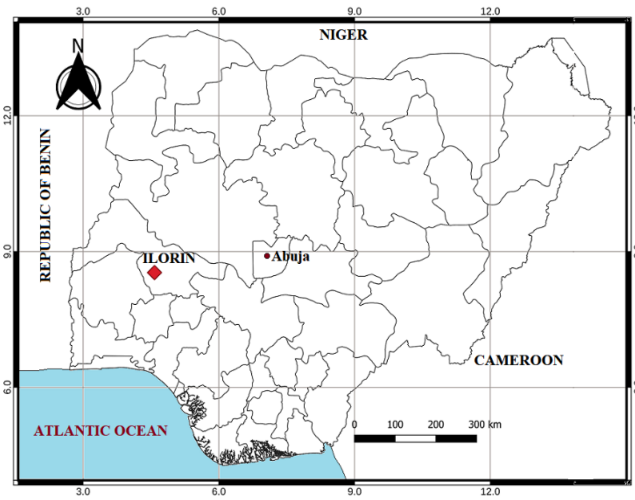

Figure 1. Research location (Ilorin) on a map of Nigeria.

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To compute the seasonal surface refractivity, the quarterly values of each of the three meteorological parameters (temperature, pressure, and relative humidity) from 2000 to 2002 were determined by averaging the values for the same three months of each of the three measured years. The first quarter includes the average values for January to March, the second quarter includes those from April to June, the third quarter includes those from July to September, and the fourth quarter includes those from October to December. All temperature, pressure, and relative humidity measurements were entered separately into a Microsoft Excel document and then input into the formula shown in Eq. 2. Graphs were also plotted to compare quarterly variations in surface refractivity from 2000 to 2002.

3. Results and Discussions

Quarterly variations in tropospheric surface refractivity were computed based on meteorological data. The extreme dry season is the first quarter (January–March), while the moderately rainy season is the second quarter (April–June), the extreme rainy season is the third quarter (July–September), and the moderately dry season is the fourth quarter (October–December) in Ilorin. During the extreme rainy season (the third quarter), average surface refractivity was 243.34 N-units. During the extreme dry season (the first quarter), it was lower, only 212.86 N-units, as shown in Figure 2. This is due to higher atmospheric water content during the extreme rainy season. The standard deviation (SD) in surface refractivity for each quarter was also calculated; the third quarter has the highest surface refractivity (243.34 N-units) and the lowest SD (4.86) (first quarter: 212.86 N-units, SD = 8.22; second quarter: 227.02 N-units, SD = 9.00; fourth quarter: 223.26 N-units, SD = 12.72).

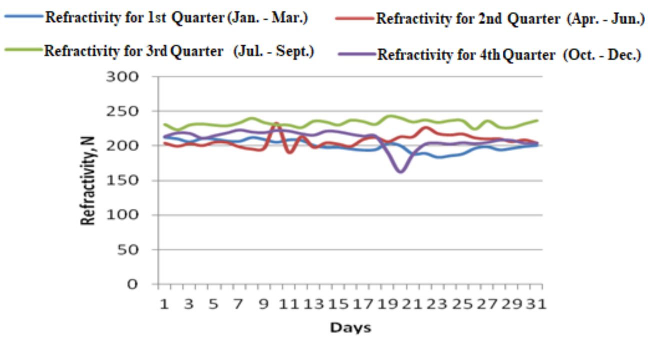

Figure 2. Quarterly refractivity for all quarters of 2000.

Figures 3 and 4 show that, during the first and third quarters, seasonal surface refractivity responds more to changes in relative humidity than in other parameters.

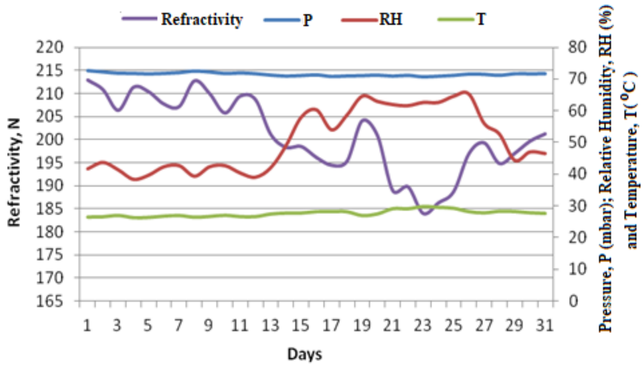

Figure 3. First-quarter (dry season) seasonal refractivity in 2000.

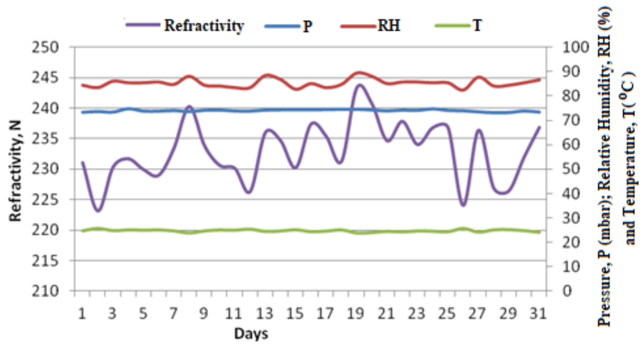

Figure 4. Third-quarter (rainy season) seasonal refractivity in 2000.

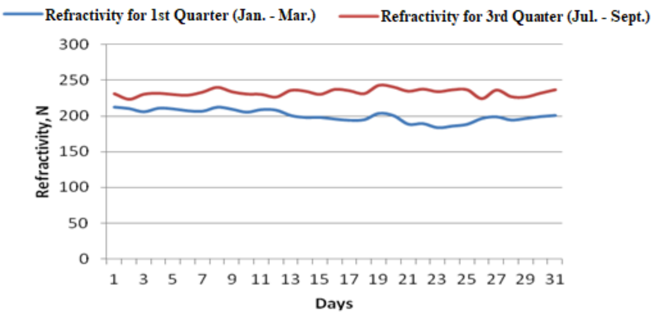

Figure 5. Quarterly refractivity for the first and third quarters of 2000.

Figure 6 shows that in 2000, surface refractivity was higher during the extreme rainy season (third quarter; 240.25 N-units) than during the extreme dry season (first quarter; 212.73 N-units). This is due to the higher atmospheric water content during the extreme rainy season. The third quarter has the highest surface refractivity (240.25 N-units) and the lowest SD (3.39) (first quarter: 212.73 N-units, SD = 7.26; second quarter: 224.78 N-units, SD = 5.96; fourth quarter: 244.36 N-units, SD = 9.70).

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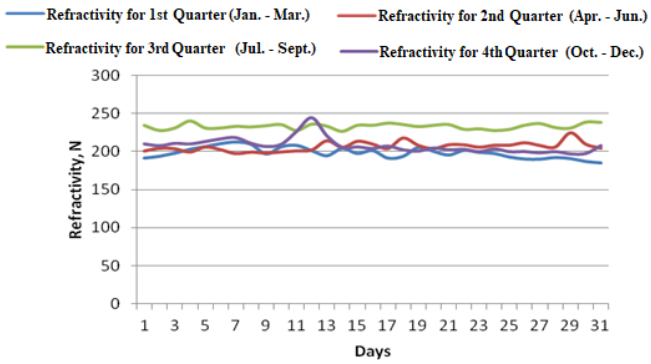

Figure 6. Quarterly refractivity for all quarters of 2001.

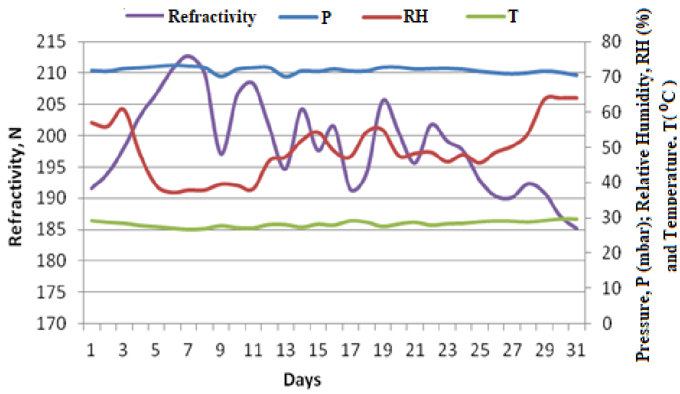

Figure 7. First-quarter (dry season) seasonal refractivity in 2001.

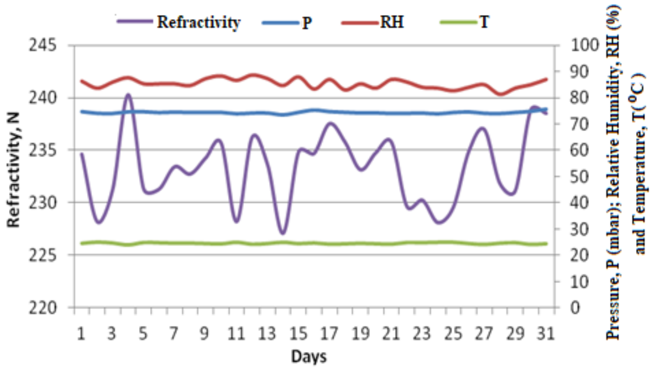

Figure 8. Third-quarter (rainy season) seasonal refractivity in 2001.

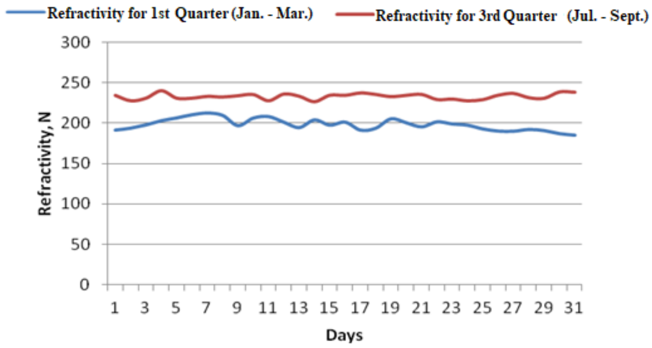

Figure 9. Quarterly refractivity for the first and third quarters of 2001.

As shown in Figure 10, surface refractivity during the extreme rainy season of 2001 was 242.83 N-units, higher than refractivity during the extreme dry season (216.51 N-units). In 2001, the third quarter had the highest surface refractivity (242.83 N-units) and the lowest SD (4.20) (first quarter: 216.51 N-units, SD = 9.25; second quarter: 222.91 N-units, SD = 7.82; fourth quarter: 223.56 N-units, SD = 5.27).

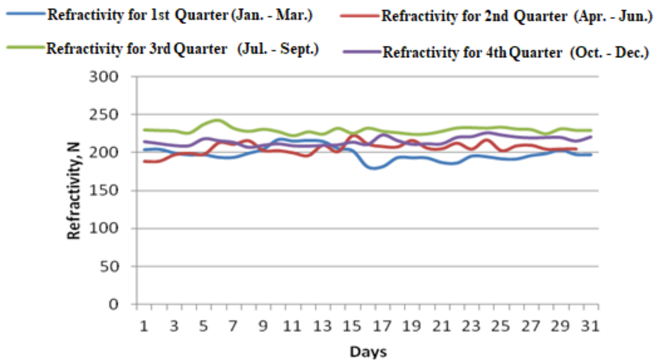

Figure 10. Quarterly refractivity for all quarters of 2002.

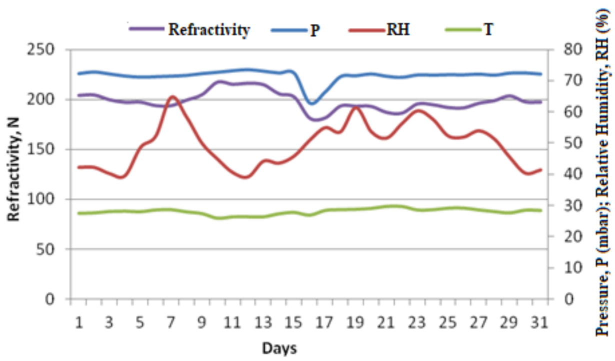

Figure 11. First-quarter (dry season) seasonal refractivity in 2002.

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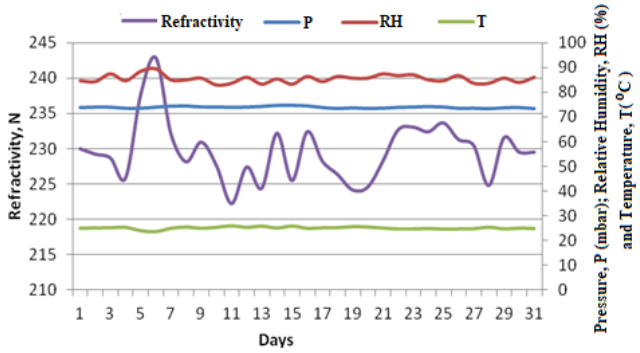

Figure 12. Third-quarter (rainy season) seasonal refractivity in 2002.

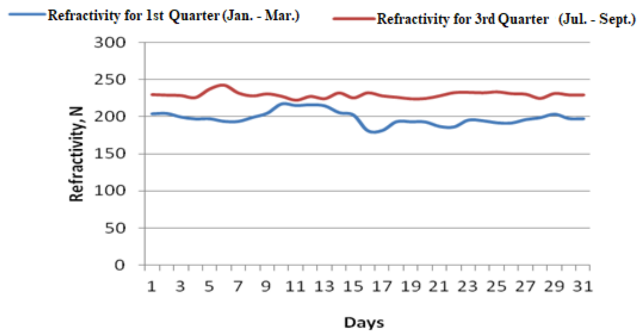

Figure 13. Quarterly seasonal refractivity for the first and third quarters of 2002.

Table 1. Correlation coefficients of the weather parameters for the dry and wet seasons in Ilorin over a period of three years.

VARIATION	YEAR	PRESSURE, P (millibars)	RELATIVE HUMIDITY, RH (%)	TEMPERATURE, T (°C)
First quarter (dry season) refractivity	2000	0.84	-0.81	-0.99
	2001	0.76	-0.72	-0.97
	2002	0.68	-0.59	-0.78
Third quarter (rainy season) refractivity	2000	0.42	0.76	-0.96
	2001	0.62	0.42	-0.95
	2002	0.14	0.64	-0.95

As shown in Table 1, in 2000, dry season refractivity in Ilorin correlated with pressure (correlation coefficient: 0.84 at the 5% significant level). This indicates that these factors increase together. Thus, based on pressure, it can be predicted that refractivity in Ilorin during the dry season is 84%. Relative humidity and temperature have very high negative correlation coefficients with surface refractivity (-0.81 and -0.99), indicating that these factors have an inverse relationship with surface refractivity during the dry season.

In contrast, during the rainy season in Ilorin, refractivity has a small or insignificant correlation with pressure, but it has a positive correlation coefficient with relative humidity and a very high negative correlation coefficient with temperature. This suggests that, during the rainy season, daily surface refractivity in Ilorin increases due to other parameters (an increase in relative humidity leads to a decrease in temperature), while pressure has no or little impact on tropospheric surface refractivity in Ilorin during the rainy season. More research is needed to confirm these findings.

Quarterly tropospheric surface radio refractivity (N) in 2000 can be predicted based on relative humidity (RH) and temperature (T) using multiple regression equations:

$$N = 420.39 - 0.07RH - 7.80T \text{ (dry season)} \tag{6}$$

$$N = 480.28 - 0.02RH - 9.95T \text{ (rainy season)} \tag{7}$$

Radio refractivity (N) in 2000 can be predicted based on three parameters (pressure [P], relative humidity [RH], and temperature [T]) using the following equations:

$$N = 178.69 - 0.005RH - 6.99T + 3.02P \quad \text{(dry season)} \tag{8}$$

$$N = 230.66 + 0.02RH - 9.36T + 3.12P \text{ (rainy season)} \tag{9}$$

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5. Conclusion

This study has used meteorological parameters recorded in Ilorin from 2000 to 2002 to investigate quarterly variations in tropospheric surface refractivity. The results show that surface refractivity was high during the extreme rainy season (third quarter, July–September) and low during the extreme dry season (first quarter, January–March) during the study period (2000–2002). It can be stated unequivocally that tropospheric surface refractivity varies seasonally (dry and rainy); it is higher during the rainy season and lower during the dry season. Furthermore, during the rainy season, refractivity correlates positively with relative humidity and negatively with temperature, while during the dry season, refractivity correlates negatively with both temperature and relative humidity.

Future studies should use data from a broader spatial region, such as satellite data, which could enable a vertical study of refractivity in Ilorin. This will provide a better picture of the spatio-temporal variation in radio refractivity, which will support decisions about systems that use radio signals.

5. Acknowledgement

We would like to thank the Nigerian Meteorological Agency (NIMET) in Ilorin for allowing us to use their data. In addition, the success of this study is due to teamwork, so we would like to express our heartfelt appreciation to everyone who has helped during any phase of the study.

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