Assessment of Tropospheric Radio Refractivity and its Variation with Climatic Variables in the Guinea Savannah Region of Nigeria

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Abstract:

In studies involving terrestrial atmospheric electromagnetic propagation, such as point-to-point microwave communication, terrestrial radio, television radio, television broadcast, and mobile communication systems, radio refractivity—the bending of a radio signal as it propagates through media—is crucial. In this study, the seasonal tropospheric radio refractivity was estimated and its variations with other meteorological parameters and refractive index were investigated using the measured monthly climatic data of atmospheric pressure, relative humidity, and temperature obtained from the National Aeronautic and Space Administration (NASA) for Makurdi and Ibadan during the period of forty-two (42) years (1981 to 2022). The refractivity gradiant, effective earth radius, and percentage contribution of the dry and wet term radio refractivity were examined. The findings indicated that for the two locations, high values of radio refractivity were observed during the rainy season and low values during the dry season. The maximum and minimum average values of radio refractivity observed for Makurdi and Ibadan during the rainy and dry seasons are, respectively, 380.0641 N-units in the month of May, 331.9776 N-units in January, and 379.9479 N-units in the month of May, 352.2143 N-units in January. The dry term (N_{dry}) contributes 70.8764 % and 69.4504 % to the total value of radio refractivity, while the wet term (N_{wet}) contributes to the major variation with 29.1236 % and 30.5496 % for Makurdi and Ibadan, respectively. The study areas under investigation yielded average refractivity gradients of -43.8583 and -43.1480 N-units/km. Additionally, the average effective earth radius (k – factor) for Makurdi and Ibadan was found to be 1.3876 and 1.3790, respectively. These values align with the conditions of super refraction propagation.

Keywords: *Dry term, Guinea Savannah, radio refractivity, refractivity gradient, wet term.*

Introduction

The composition of the atmosphere has a significant impact on radio wave signal transmission in the lower atmosphere, or troposphere (Korakshaha, 2003). The dynamics of climatic elements like temperature, pressure, and relative humidity are what cause it to happen. At the poles and the equator, the troposphere rises to a height of roughly 10 km

and 17 km, respectively, from the earth's surface (Hall, 1979).

The most significant impact of the earth's atmosphere on radio wave propagation, especially at frequencies greater than 30 MHz, is refraction (Bean and Thayer, 1959). As radio waves pass through various layers of the atmosphere, their refractivity may vary. This variance is determined by meteorological elements, mainly temperature and humidity, which are highly variable based on location and season. The radio refractive index of the troposphere plays a critical role in forecasting the performance level of terrestrial radio communications. Frequencies in the troposphere over 100 MHz are significantly affected by changes in the tropospheric radio refractive index. This effect is noticeable even at lower frequencies than 30 MHz (Ayantunji *et al.*, 2011).

Various components of the atmosphere can scatter, absorb, refract, and reflect radio waves (Chinelo and Chukwunike, 2016). However, the frequency, power, and condition of the troposphere—through which radio waves propagate—are the primary determinants of the extent to which atmospheric factors affect radio signals. For radio communications, aircraft, environmental monitoring, disaster predictions, and other fields, the characterisation of tropospheric variability is extremely important. The performance and dependability of the links have a major impact on the quality of radio wave propagation that reaches a receiving antenna (Serdege and Ivanovs, 2007).

The various components that make up the atmosphere have a major impact on the electromagnetic waves that propagate in the lower atmosphere. This is due to variations in air temperature, atmospheric pressure, and relative humidity, among other meteorological variables, which caused the refractive index of the lower atmosphere's air to vary geographically (Korak-Shaha, 2003; Agbo *et al.*, 2013; Ukhurebor and Azi, 2018; Ukhurebor *et al.*, 2018). Due to the non-homogeneous spatial distribution of the refractive index of air, the electromagnetic waves' path bends, resulting in attenuation from

diffraction on obstacles in the terrain, also referred to as radio holes, and multipath fading and interference (Martin and Vaclav, 2011; Ukhurebor *et al.*, 2018). Meteorological variables influence the fluctuation in refractivity in the lower atmosphere (Ayantunji *et al.*, 2011). Since meteorological variables have an impact on radio wave communication links, it is important to take into consideration the transmission medium in order to have a better signal from the radio communication network (Adediji *et al.*, 2011; Ukhurebor and Azi, 2018).

Using measured local meteorological data from Nigeria and other parts of the world, a number of researchers, including Agbo (2011), Ayantunji et al. (2011), Zilinskas et al. (2011), Emmauel et al. (2013), Akpootu and Iliyasu (2017a), Adediji et al. (2017), Akpootu et al. (2019a), and Akpootu et al. (2021a), have conducted investigations on radio refractivity for different locations and climates. Their study's findings demonstrated that the local climate has a significant impact on radio refractivity, which in turn affects radio signals that are sent.

In the Guinea savannah region of Nigeria, the study's goal is to quantify the seasonal tropospheric radio refractivity and look at how it varies with meteorological parameters and radio refractive index over Makurdi and Ibadan. The study will also compute the effective earth radius and refractivity gradient for the locations, as well as look into the seasonal change and percentage contribution of the dry and wet components radio refractivity.

Methodology

The measured monthly climatic data of atmospheric pressure, relative humidity and temperature utilized in this study were obtained from the National Aeronautic and Space Administration (NASA). The study areas under investigations are Makurdi and Ibadan. The period under focus is forty-two (42) years (1981 to 2022).

The atmospheric refractive index (n) depends on three (3) factors, these are the atmospheric pressure, temperature and humidity (water

vapour content). The values of refractive index (n) is varied between 1.000250 and 1.0004000 showing that, it is very close to unity at or near the earth's surface and changes in this value is very small based on time and space. To make this values visible, the refractive index (n) of air are usually measured by a parameter called the radio refractivity (N) and is related to the refractive index (n) through the equation (ITU-R 2003; Freeman, 2007).

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

The radio refractivity (N) is a unitless quantity, it is expressed in N-units. Thus, from equation (1), one can deduce that N typically ranges between 250 N – units and 400 N-units. In terms of measured meteorological parameters, the International Telecommunication Union (ITU) has recommended the radio refractivity, N, to be expressed as; (ITU-R, 2003).

$$N = \frac{77.6}{T} \left(P + 4810 \frac{e}{T} \right) = N_{dry} + N_{wet} \qquad (2)$$

where the radio refractivity of the dry term is given by equation (3) through expansion of equation (2) (Akpootu and Rabiu, 2019; Akpootu et al., 2024).

$$N_{dry} = 77.6 \frac{P}{T} \qquad (3)$$

and the radio refractivity of the wet term is given by equation (3) through expansion of equation (2) (Akpootu and Rabiu, 2019; Akpootu et al., 2024).

$$N_{wet} = 3.73 \times 10^5 \frac{e}{T^2} \qquad (4)$$

where P is the atmospheric pressure (hPa), e is the water vapour pressure (hPa) and T is the temperature (K). The dry term is a result of the non polar nitrogen and oxygen molecules. It is proportional to pressure (P) and therefore related to the air density. The wet term is proportional to vapour pressure and dominated by polar water contents in the troposphere of the atmospheric layer.

ITU-R (2003) and Freeman (2007), reported that equation (2) may be used for all radio frequencies; for frequencies up to 100 GHz, the error is less than 0.5% and at sea level, the average value of N= 315 will be used (ITU-R, 2003).

The relationship between the water vapour pressure, e, and relative humidity is expressed as (ITU-R, 2003; Akpootu et al., 2019b; Akpootu et al., 2021b,c; Iliyasu et al., 2023; Akpootu et al., 2023a).

$$e = \frac{He_s}{100} \qquad (5)$$

where e_s is given by

$$e_s = a \exp\left(\frac{bt}{t+c}\right) \qquad (6)$$

where H is the relative humidity (%), t is the Celsius temperature (°C) and e_s is the saturation vapour pressure (hPa) at temperature (°C). The values of the coefficients a, b and c (water and ice) was presented in (ITU-R. 2003), The values for water was adopted in this study and are given as a = 6.1121, b = 17.502 and c = 240.97 and are valid between -20⁰ to +50⁰ with an accuracy of ±0.20%. The radio refractivity, N, decreases exponentially in the troposphere with height (ITU-R, 2003).

$$N = N_s \exp\left(\frac{-h}{H}\right) \qquad (7)$$

where N is the refractivity at the height h (km) above the level where the refractivity is N_s and H is the applicable scale height. ITU-R (2003)

recommended that at average mid-latitude; N_s and H are 315 km and 7.35 km respectively. Hence, N as a function of height N (h) is expressed by

$$N = 315\exp^{-0.136h} \qquad (8)$$

According to Agunlejika and Raji (2010), revealed that the model using the scale height of 7.35 km and 7 km are recommended for global environment ITU- R (2003) and tropical environment (John, 2005) respectively gave appreciable precise results for the refractivity at the altitude of 50 m and 200 m for seven (7) out of the twelve (12) months of the year. Although the scale height of 7 km tends to give a better result at 50 m altitude while 7.35 km scale height was found to perform better at 200 m.

The refractivity gradient is obtained by differentiating equation (7) with respect to *h*, therefore, the refractivity gradient is given by (Akpootu *et al.*, 2019).

$$\frac{dN}{dh} = \frac{-N_S}{H} \exp\left(\frac{-h}{H}\right) \qquad (9)$$

For a standard atmosphere, the refractivity gradient is -39 N-units/km. According to John (2005) when h < 1 km, refractivity gradient is well approximated by its value in a standard atmosphere. In this study typical values for a standard atmosphere John (2005) was employed and the refractivity of a standard atmosphere is therefore, $N_S = 312$ N-units

The vertical gradient of refractivity in the troposphere is an important parameter in estimating path clearance and propagation effects such as sub-refraction, 'super-refraction or ducting as reported by Adediji and Ajewole (2008).

(i)   Sub-refraction: $\frac{dN}{dh} > -40$

Since refractivity, or N, rises with height, radio waves in this situation (sub-refraction) migrate away from the surface of the earth, resulting in a decrease in both the line of sight and propagation ranges.

(ii)   Super-refraction: $\frac{dN}{dh} < -40$

Electromagnetic waves are bent downward towards the surface of the earth when there is super refraction. Its degree of bending depends on how strong the super-refractive state is. Since the ray path's radius of curvature is smaller than the radius of the earth, any rays that emerge from the transmitting aerial at tiny angles of elevation must first undergo complete internal reflection in the troposphere before returning to the earth at a certain distance from the transmitter. The waves can skip great distances after being reflected from the earth's surface, giving rise to irregular wide ranges beyond the line of sight as a result of numerous wave reflections.

(iii)   Ducting: $\frac{dN}{dh} < -157$

The waves bend downward throughout the ducting process with a curvature larger than the earth's. The radio radiation that is bent downward can be absorbed either between two boundaries in the troposphere (elevated duct) or between a boundary or layer in the troposphere and the surface of the earth or the sea (surface duct). extremely high signal intensities are obtained at extremely long ranges (far beyond line-of-sight) in this wave guide-like propagation, and the signal strength may exceed its free-space value.

The effective earth radius factor k was used to characterize refractive conditions as normal refraction or standard atmosphere, sub-refraction, super-refraction and ducting respectively. Thus, k are expressed in terms of refractivity gradient, *d*N / *dh* as (Hall, 1989; Afullo *et al.*, 1999; Maintham and Asrar 2003; Freeman, 2007) based on the equation.

$$k = \left[1 + \frac{\left(\frac{dN}{dh}\right)}{157}\right]^{-1} \qquad (10)$$

Near the earth's surface, $\frac{dN}{dh}$ is about -39 N-units/km which gives an effective earth radius factor, when k $= \frac{4}{3}$. This is referred to as normal refraction or standard atmosphere. Here, radio signals tend to travel on a straight line path along the earth's surface and go out to space undisturbed. If $\frac{4}{3} > k > 0$ Sub-refraction occurs, implying that radio waves propagate abnormally away from the surface of the earth.

When $\infty > k > \frac{4}{3}$ in this situation, Super-refraction occurs and radio waves propagate abnormally towards the earth's surface therefore extending the radio horizon. Consequently,

If - $\infty < k < 0$ waves bend downwards with a curvature greater than that of the earth and therefore ducting occurs.

Results and Discussion

Radio Refractivity and Its Variation with Meteorological Parameters for Makurdi
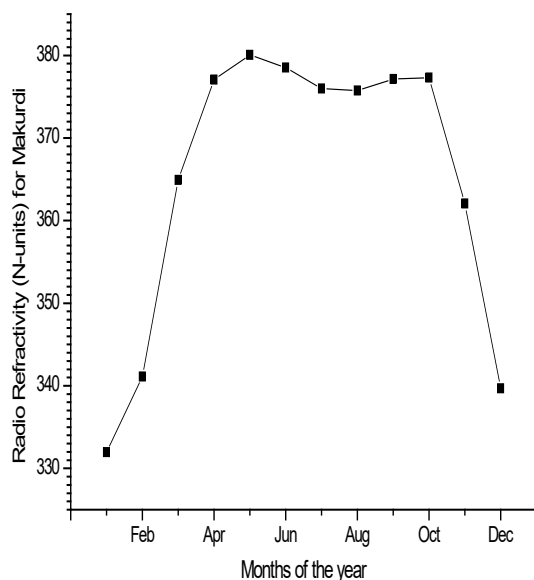

Figure 1. Seasonal Radio Refractivity Variation over Makurdi, Nigeria

The seasonal fluctuation in radio refractivity for Makurdi over a 42-year period is seen in Figure 1. At Makurdi, Benue State, Nigeria, radio refractivity increased gradually from a minimum of 331.9776 N-units in January to a peak value of 380.0641 N-units in May. Thereafter, the value gradually decreased until it reached 375.7558 N-units in August, after which it suddenly increased to 377.3148 N-units in October and decreased to 339.6738 N-units in December. The figure makes it evident that the radio refractivity value drops sharply and steadily as the dry harmattan season begins in November and continues until January, when the lowest value was recorded. In Makurdi, radio refractivity has been measured at maximum average values of 380.0641 N-units in May and minimum values of 331.9776 N-units in January, respectively, during the rainy and dry seasons. As per the results, radio refractivity exhibited high values during the wet season, averaging 377.4075 N-units, and low values during the dry season, averaging 377.9513 N-units. The figure made it clear that the variation pattern resembles that of the studies conducted by Emmaual *et al.*, (2013).
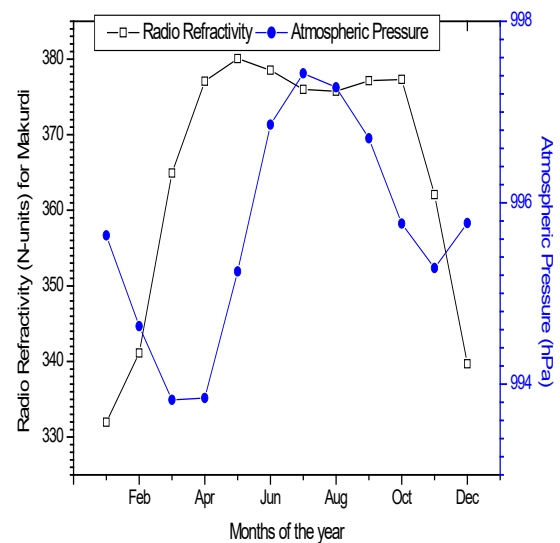

Figure 2. Seasonal Variation of Radio Refractivity with Atmospheric Pressure over Makurdi

Throughout the study period, Figure 2 shows how radio refractivity varied seasonally with

atmospheric pressure over Makurdi. The atmospheric pressure gradually decreases in January, reaches its lowest value of 993.8262 hPa in March, increases slightly in April, and then rises sharply in May, reaching its highest value of 997.4262 hPa in July. From July to November, it gradually decreases again, and in December, it rises to a value of 995.7762 hPa. From a minimum value of 331.9776 N-units in January to its peak value of 380.0641 N-units in May, the radio refractivity increases gradually. It then gradually decreases until it reaches 375.7558 N-units in August, when it suddenly increases again to reach another maximum value of 377.3148 N-units in October, and finally drops to 339.6738 N-units in December. The figure showed that from March to July, atmospheric pressure rises in tandem with a drop in radio refractivity from May to August. Additionally, it illustrates how the radio refractivity value sharply and steadily decreases when the dry harmattan season begins in November and reaches its lowest point in January, coinciding with the above-mentioned increase in atmospheric pressure. This observation, however, is consistent with the research conducted for Ikeja by Akpootu and Iliyasu (2017) and for Osogbo, Nigeria, by Akpootu *et al.* (2019). According to the results, there are high values of radio refractivity during the rainy season (average value: 377.4075 N-units) and low values (average value: 347.9513 N-units) during the dry season. Similarly, there are high values of atmospheric pressure during the rainy season (average value: 996.1605 hPa) and low values during the dry season (average value: 995.0319 hPa). In addition, radio refractivity measurements for Makurdi show a maximum average value of 380.0641 N-units in May and a minimum value of 331.9776 N-units in January, respectively, throughout the rainy and dry seasons. In the rainy and dry seasons, respectively, the maximum average value of atmospheric pressure was recorded in the month of July at 997.4262 hPa, and the lowest value was recorded in the month of March at 993.8262 hPa.
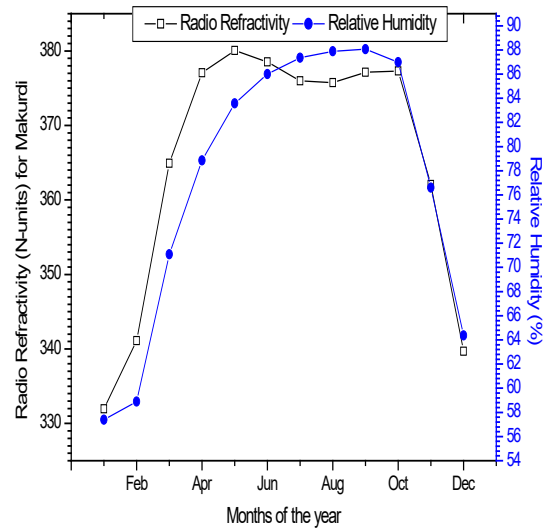

Figure 3. Seasonal Variation of Radio Refractivity with Relative Humidity over Makurdi

The seasonal change of Makurdi's radio refractivity with relative humidity is depicted in Figure 3. While the radio refractivity increases until it reaches its maximum value of 380.0641 N-units in May and then gradually decreases until it reaches 375.7558 N-units in August, it suddenly increases to October and drops in December, the relative humidity and radio refractivity both rise from their minimum values of 331.9776 N-nits and 57.3933% in January. On the other hand, the relative humidity increases somewhat in January and February before rising dramatically until September, when it reaches its highest value of 88.565 percent, and then steadily declining until December. The figure also demonstrates a sharp decline in the relative humidity and radio refractivity values from October to December. This may be because of high solar irradiance in December, which decreased the amount of humidity in the atmosphere and, as a result, the tropospheric radio refractivity. It was observed that the radio refractivity shows a slight dip downward in August. In the rainy and dry seasons, respectively, the maximum and minimum values of relative humidity were recorded as 88.0655 % and 57.3933 % in the months of September and January, respectively. The maximum average

value of radio refractivity was recorded as 380.0641 N-units in the month of May, and the lowest value as 331.9776 N-units in January. The results showed that while relative humidity has high values of 85.5309 % and low values of 65.6639 % which are observed during the rainy and dry seasons, respectively, radio refractivity had high values during the rainy season with an average value of 377.4075 N-units and low values during the dry season with an average value of 347.9513 N-units.
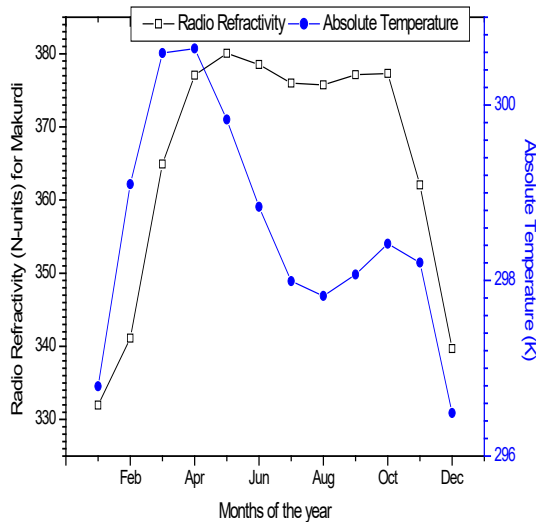

Figure 4. Seasonal Variation of Radio Refractivity with Absolute Temperature over Makurdi

Figure 4 displays the seasonal change of Makurdi's absolute temperature and radio refractivity. Absolute temperature readings rise with radio refractivity from 296.7950 K in January to March, then somewhat increase and reach their peak of 300.6445 K in April, after which they begin to decline from April to August. From August through October, it grows even more before progressively declining until December, when it reaches its lowest value of 296.4893 K. However, radio refractivity increased gradually from a minimum of 331.9776 N-units in January to a maximum of 380.0641 N-units in May. It then gradually decreased until it reached 375.7558 N-units in August, when it suddenly increased to a further maximum of 377.3148 N-units in October, and

finally dropped to 339.6738 N-units in December. The figure makes it evident that the radio refractivity and absolute temperature values decrease sharply and steadily when the dry harmattan season begins in November. These values peak in January and December, respectively. Additionally, it was noted that there is a slight decline in radio refractivity and absolute temperature in August. The average value of radio refractivity was found to be lowest during the dry season (347.9513 N-units) and to be highest during the rainy season (377.4075 N-units). Additionally, it was discovered that, within the wet and dry seasons, the highest average absolute temperature was 300.6445 K in April and the lowest value was 296.4893 K in December. Absolute temperature reaches its maximum during the rainy season (298.8033 K on average), and its lowest value (298.2352 K on average) during the dry season. Dust and aerosol particles suspended in the atmosphere, which reduce the temperature and amount of solar radiation that reaches Earth, are the reason of the high temperatures during the rainy season. This finding is consistent with the research that Akpootu and Iliyasu (2017b); Akpootu et al. (2023b) presented. The closeness of the absolute temperature result achieved during the inquiry period suggests that the region's temperature was relatively stable throughout the year.
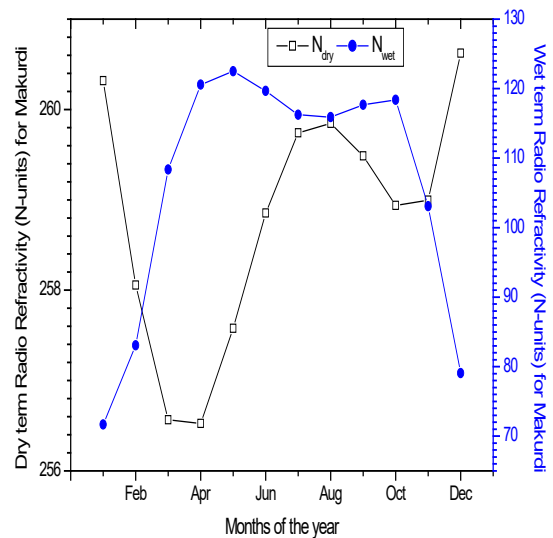

Figure 5. Seasonal Variation of Dry and Wet Terms Radio Refractivity over Makurdi

The seasonal change of Makurdi's wet term radio refractivity (Nwet) and dry term radio refractivity (Ndry) over the course of the inquiry is shown in Figure 5. The wet term radio refractivity, or Nwet, increased gradually over time, starting in January at a minimum of 71.6582 N-units and peaking at 122.4863 N-units in May. It then gradually decreased until reaching 115.9115 N-units in August, after which it suddenly increased to 118.3776 N-units in October and fell sharply to 79.0498 N-units in December. Conversely, the dry term radio refractivity falls from 260.3195 N-units in January to March, then marginally drops to 256.5241 N-units, its lowest value, in April, then rises to August and then falls to October. From October to November, it grows somewhat more before rising quickly to reach its peak value of 260.6240 N-units in December. The figure showed that the dry term radio refractivity's greatest value of 260.6240 N-units was recorded in December during the dry season, while the lowest value of 256.5241 N-units was recorded in April during the wet season. The wet term radio refractivity had its lowest value of 71.6582 N-units in January during the dry season, and its highest value of 122.4863 N-units in May during the rainy season. The outcome demonstrated that while the wet term radio refractivity contributes to the significant fluctuation of the radio refractivity, the dry term radio refractivity is a large contribution to the overall value of the refractivity.

The seasonal change of Makurdi's radio refractivity with radio refractive index is depicted in Figure 6. The figure unequivocally demonstrates that the patterns of variation indicated by the radio refractivity values and the radio refractive index are similar. However, the highest average radio refractive index value recorded between March and November was 1.0004, indicating that the months of March through November fall under the dry season, whereas the months of April through October fall under the rainy season. Moreover, the dry season months of January, February, and December had the lowest figure of 1.0003 being recorded. During the rainy and dry seasons, respectively, the maximum average value of

radio refractivity observed is 380.0641 N-units in May, while the lowest value is 331.9776 N-units in January. With an average value of 377.4075 N-units during the wet season and 347.9513 N-units during the dry season, respectively, high and low levels of radio refractivity are recorded. The chart shows that during the wet season, the radio refractive index has a high average value of 1.0004 and a low average value of 1.0003 during the dry season.
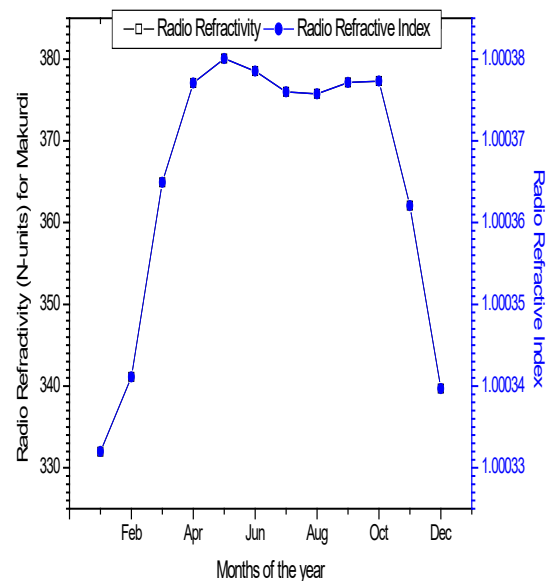

Figure 6. Seasonal Variation of Radio Refractivity with Radio Refractive Index over Makurdi

Refractivity Gradient for Makurdi

The refractivity gradient for Makurdi was calculated using equation (9) and the result is -43.8583 N-units/km. This suggests that Makurdi propagation is mostly super-refractive, meaning that electromagnetic waves are curved in the direction of the earth. The strength of the super-refractive state determines the level at which the bending happened. The wave path's curve gets closer to the earth's radius of curvature as the refractivity gradient continues to drop. When the bending of a radio wave's trajectory towards the ground is more than it would be in a typical

positive refraction scenario, super refraction occurs.

Effective Earth Radius for Makurdi

Equation (10) yielded the effective earth radius, or k - factor, of 1.3876. This suggests that super refractive propagation is predominant in Makurdi. Meteorological factors such as temperature inversion, or a drop in the air's overall moisture content, can lead to a fall in the dielectric constant gradient with height and consequently, super refraction. When this occurs, the K-factor rises, thus flattening the corresponding curvature of the globe. Warm air passing over a cool body of water is a common scenario that might result in this type of irregular refraction. Water evaporation can raise the moisture content and lower the surface temperature, which can lead to a rise in temperature inversion. However, the aberrant bending of the microwave beam is not primarily caused by the temperature inversion. This effect is continuously increased approaching the surface due to the significant increase in the dielectric constant and water vapour content.

Percentage Contribution Analysis

Table 1. Monthly Variation of the Percentage Contribution of Ndry and Nwet for Makurdi

Month	Ndry-Nwet	%CNdry	%CNwet
Jan	188.6613	5.9412	1.6354
Feb	174.9983	5.8895	1.8956
Mar	148.2105	5.8555	2.4729
Apr	135.9685	5.8546	2.7514
May	135.0915	5.8786	2.7955
Jun	139.1801	5.9078	2.7313
Jul	143.5111	5.9280	2.6527
Aug	143.9328	5.9303	2.6454
Sep	141.8335	5.9222	2.6852
Oct	140.5597	5.9096	2.7017
Nov	155.9207	5.9110	2.3525
Dec	181.5742	5.9481	1.8041
Total		**70.8764**	**29.1236**

Table 1 displays the monthly variation of the percentage contributions to the overall radio refractivity for both the wet term and dry term radio refractivity. As can be observed, throughout the study time, Makurdi's wet term radio refractivity was 29.1236%, while the dry term radio refractivity contributed 70.8764% to the total radio refractivity. Naturally, the month of December has the highest monthly contribution for the dry term (5.9481%), while the month of April has the lowest monthly contribution (5.8546%). Similarly, the month of May has the highest monthly contribution (2.7955%) for the wet term, while the lowest monthly contribution (1.6354%) occurs in the month of January.

Radio Refractivity and Its Variation with Meteorological Parameters for Ibadan
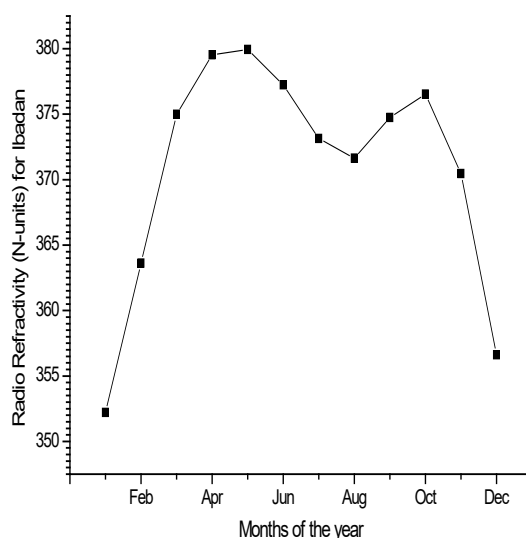

Figure 7. Seasonal Radio Refractivity Variation over Ibadan

The seasonal fluctuation in radio refractivity for the study area and time period under investigation is shown in Figure 7. From a minimum value of 352.2143 N-units in January to a climax of 379.9479 N-units in May, the radio refractivity at Ibadan showed gradual increases. It then gradually decreased until it reached 371.6408 N-units in August, then suddenly

increased until it reached another peak value of 376.5407 N-units in October, and finally dropped to 356.6204 N-units in December. In the research area, radio refractivity has been measured at maximum average values of 379.9479 N-units in May and minimum values of 352.2143 N-units in January. These values correspond to the rainy and dry seasons, respectively. The figure makes it evident that there is a decrease in radio refractivity value in August, which may be related to August break, a brief period of dry weather. Additionally, it shows that the radio refractivity value drops sharply and steadily when the dry harmattan season begins in November and continues until January, when the lowest value was recorded. The outcome demonstrated that radio refractivity has low values during the dry season, averaging 363.5790 N-units, and high values during the wet season, averaging 376.1149 N-units. Additionally, Emmanuel *et al.* (2013) investigation revealed similar observations.
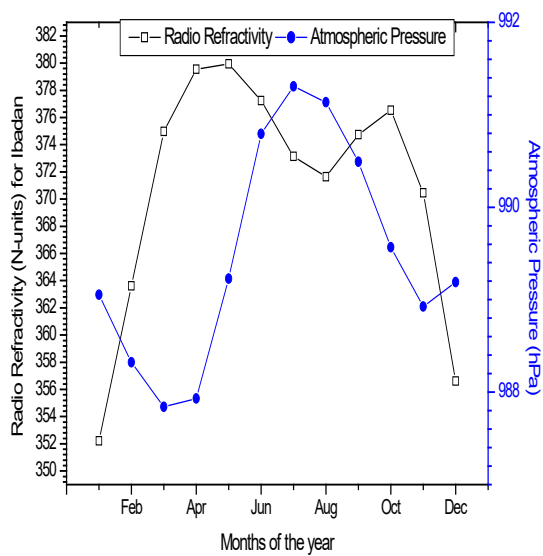

Figure 8. Seasonal Variation of Radio Refractivity with Atmospheric Pressure over Ibadan

For the study area and time period under examination, Figure 8 displays the seasonal fluctuation of radio refractivity with atmospheric pressure over Ibadan. From January until its lowest value of 987.8405 hPa in March, the

atmospheric pressure declines steadily. It then slightly climbs in April, increases rapidly in May, and reaches its peak value of 991.3071 hPa in July. Finally, it abruptly decreases in November and increases in December. From a minimum value of 352.2143 N-units in January to a peak of 379.9479 N-units in May, the radio refractivity increased gradually. It then gradually decreased until it reached 371.6408 N-units in August, then abruptly increased until it reached another peak value of 376.5407 N-units in October, and finally dropped to 356.6204 N-units in December. According to the chart, August break—a brief period of dry weather—may be the cause of the decrease in radio refractivity values in August. Additionally, it notes that atmospheric pressure rises until December as the dry harmattan season begins in November, and that the radio refractivity value falls sharply and steadily until January, when the lowest value was recorded. Comparable findings were observed in the research conducted by Akpootu and Iliyasu (2017) for Ikeja, Nigeria, and Akpootu et al., (2019) over Osogbo. In the research region, radio refractivity has been measured at maximum average values of 379.9479 N-units in May and minimum values of 352.2143 N-units in January, respectively, during the rainy and dry seasons. The maximum average atmospheric pressure value recorded during the wet season is 991.3071 hPa in July, while the lowest value was 987.8405 hPa in the dry season of March. According to the results, radio refractivity peaks during the rainy season (average value: 376.1149 N-units) and troughs (average value: 363.5790 N-units) during the dry season. Conversely, high average levels of atmospheric pressure (990.0650 hPa) are recorded during the rainy season, while low average values (988.5667 hPa) are noted during the dry season.

The seasonal change of Ibadan's radio refractivity with relative humidity is depicted in Figure 9. From their lowest values of 352.2143 N-units and 72.7748% in January to May, when the radio refractivity reached its peak value of 379.9479 N-units, the radio refractivity and relative humidity increased simultaneously. However, the relative humidity increased steadily until July, then slightly decreased in

August, then increased again and reached its peak value of 89.9345% in September, before gradually declining to December. The radio refractivity falls in May and reaches a maximum value of 371.6408 N-units in August. It then abruptly climbs and drops in December, reaching a new maximum value of 376.5407 N-units in October. Both the radio refractivity and the relative humidity showed a slight decline in August, although the radio refractivity's decline was more pronounced than the relative humidity's. The figure also demonstrated the steep decline in December's relative humidity and radio refractivity values. This may be attributed to strong solar irradiation in December, which lowers the amount of humidity in the atmosphere and, in turn, lowers radio refractivity. In the rainy and dry seasons, respectively, the highest average relative humidity value recorded was 89.9345% in September and the lowest value was 72.7748 % in January.
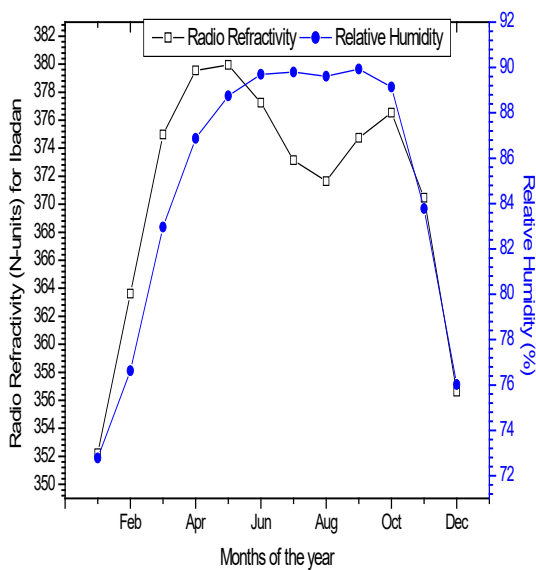

Figure 9. Seasonal Variation of Radio Refractivity with Relative Humidity over Ibadan

During the rainy season, in May, the highest average value of radio refractivity was recorded at 379.9479 N-units, while in the dry season, in

January, the lowest value was recorded at 352.2143 N-units. The findings indicate that high relative humidity values (89.1153%) are recorded during the rainy season, and low relative humidity values (78.4306%) are recorded during the dry season. On the other hand, radio refractivity is found to be highest during the wet season (379.1149 N-units on average) and lowest during the dry season (363.5790 N-units on average).
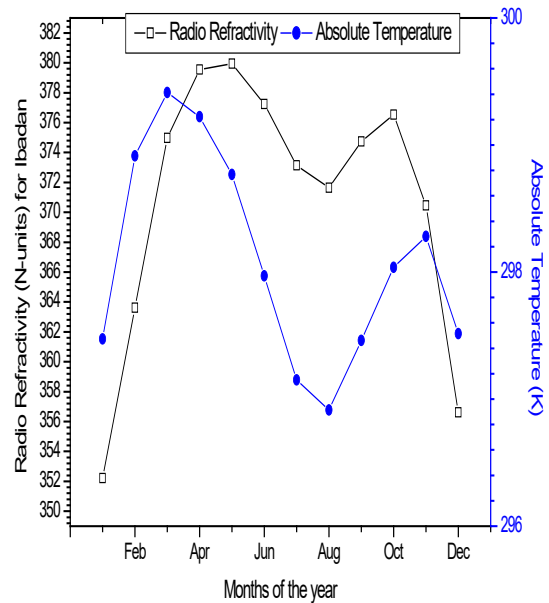

Figure 10. Seasonal Variation of Radio Refractivity with Absolute Temperature over Ibadan

The seasonal change of radio refractivity over Ibadan with absolute temperature is depicted in Figure 10. The absolute temperature starts to rise in January, reaches its highest value of 299.4140 K in March, and then starts to fall until it reaches its lowest value of 296.9136 K in August. Additionally, the temperature values rise gradually from August to November, when they reach 298.2805 K, and subsequently decline until December. Conversely, the radio refractivity exhibited a gradual increase starting in January and reaching its maximum value of 379.9479 N-units in May. After that, it gradually decreased until it reached 371.6408 N-units in August, then

suddenly increased until it reached another peak value of 376.5407 N-units in October and dropped in December. The figure shows that in August, both the absolute temperature and radio refractivity show a slight decline; additionally, in November, when the dry season arrives, there is a dramatic and continuous decline in both the absolute temperature and radio refractivity values in December. The outcome shows that while absolute temperature is highest during the dry season with an average value of 298.3193 K and lowest during the rainy season with an average value of 297.9319 K, radio refractivity is highest during the rainy season with an average value of 376.1149 N-units and lowest during the dry season with an average value of 363.5790 N-units. Nonetheless, during the wet and dry seasons, respectively, the highest average value of radio refractivity measured was 379.9479 N-units in May and the lowest value was 352.2143 N-units in January. Likewise, the month of March saw the highest average temperature of 299.4140 K during the dry season, while the month of August saw the lowest average temperature of 296.9136 K during the wet season.
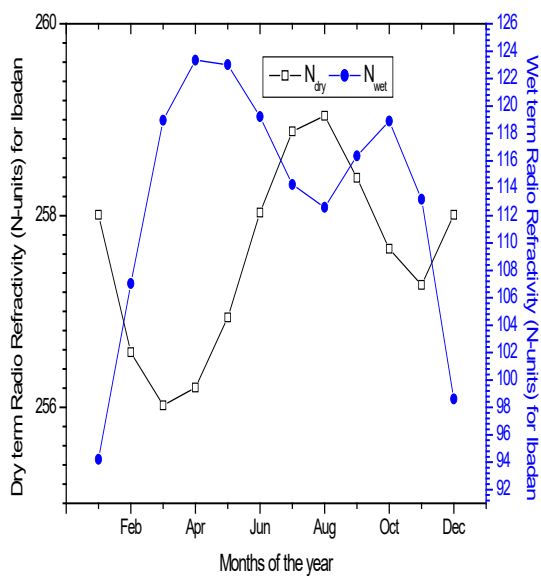

Figure 11. Seasonal Variation of Dry and Wet Terms Radio Refractivity over Ibadan

The seasonal change of Ibadan's wet term radio refractivity (N$_{wet}$) and dry term radio refractivity (N$_{dry}$) over the course of the inquiry is shown in Figure 11. From its lowest value of 94.2065 N-units in January to its peak point value of 123.3338 N-units in April, the wet term radio refractivity grows dramatically. From there, it begins to decline until it reaches 112.6021 N-units in the month of August. After that, it continues to rise through August, reaching a peak of 118.8866 N-units in October before abruptly declining to 98.6118 N-units in December. On the other hand, the dry term radio refractivity falls in January, achieves its lowest value of 256.0215 N-units in March, then steadily rises to reach its highest value of 259.0388 N-units in August, falls in November, and then rises once again to December. The wet term radio refractivity values measured in the months of April and January had a maximum average value of 123.3338 N-units and a minimum value of 94.2065 N-units, respectively, during the rainy and dry seasons. The highest and lowest values of radio refractivity during the dry term, which are 259.0388 N-units in August and 256.0215 N-units in March, respectively, fall within the wet and dry seasons. The outcome shows that while the wet term radio refractivity contributes to the significant variance of the radio refractivity, the dry term radio refractivity is a large contribution to the overall value of the refractivity.
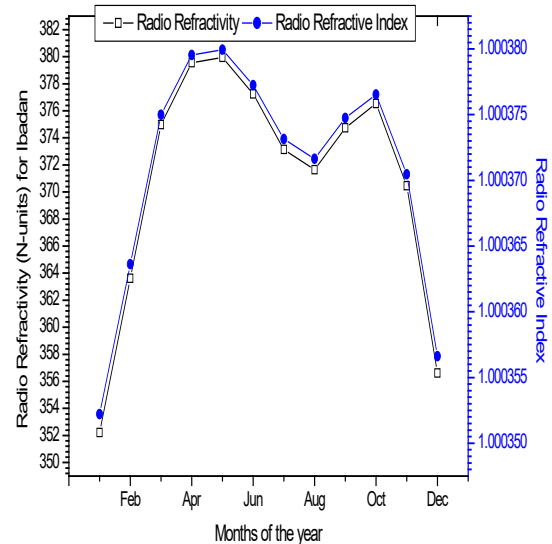

Figure 12. Seasonal Variation of Radio Refractivity with Radio Refractive Index over Ibadan

The seasonal change of radio refractivity with radio refractive index for Ibadan is displayed in Figure 12. The outcome showed that the patterns of variation for radio refractivity values and radio refractive index are similar. However, during the dry and wet seasons, from January to December, the average radio refractive index value was 1.0004 at both the maximum and lowest values. In the rainy and dry seasons, respectively, the highest average value of radio refractivity measured was 379.9479 N-units in May, while the lowest value was 352.2143 N-units in January. The figure also indicates that radio refractivity is highest during the rainy season (average value: 376.1149 N-units) and lowest (average value: 353.5790 N-units) during the dry season. Conversely, during the rainy and dry seasons, the radio refractive index has an identical high and low average value of 1.0004, respectively.

Refractivity Gradient for Ibadan

The refractivity gradient for Ibadan was calculated using equation (9) and the result is -43.149 N-units/km. This suggests that the electromagnetic waves are bent downward towards the earth in the case of Ibadan, implying that the propagation is mostly super-refractive. The strength of the super-refractive state determines the level at which the bending happened. The wave path's curve gets closer to the earth's radius of curvature as the refractivity gradient continues to drop. When the bending of a radio wave's trajectory towards the ground is more than it would be in a typical positive refraction scenario, super refraction occurs.

Effective Earth Radius for Ibadan

Equation (10) yielded the effective earth radius, k – factor of 1.3790. This suggests that super refractive propagation is predominant in Ibadan. Meteorological factors such as temperature inversion, or a drop in the air's overall moisture content, can lead to a fall in the dielectric constant gradient with height and consequently, super refraction. When this occurs, the K-factor rises, thus flattening the corresponding curvature of the globe. Warm air passing over a cool body of water is a common scenario that might result in this type of irregular refraction.

Water evaporation can raise the moisture content and lower the surface temperature, which can lead to a rise in temperature inversion. However, the aberrant bending of the microwave beam is not primarily caused by the temperature inversion. This effect is continuously increased approaching the surface due to the significant increase in the dielectric constant and water vapour content.

Percentage Contribution Analysis

Table 2. Monthly variation of the percentage contribution of N_{dry} and N_{wet} for Ibadan

Month	N_{dry}-N_{wet}	$\%CN_{dry}$	$\%CN_{wet}$
Jan	163.8014	5.7970	2.1167
Feb	149.5324	5.7648	2.4051
Mar	137.0608	5.7524	2.6729
Apr	132.8741	5.7566	2.7711
May	133.9252	5.7729	2.7639
Jun	138.8188	5.7975	2.6785
Jul	144.6113	5.8166	2.5674
Aug	146.4367	5.8202	2.5300
Sep	142.0396	5.8057	2.6143
Oct	138.7675	5.7891	2.6712
Nov	144.0929	5.7806	2.5431
Dec	159.3968	5.7970	2.2156
Total		**69.4504**	**30.5496**

Table 2 displays the monthly variation of the percentage contributions to the overall radio refractivity for both the wet term and dry term radio refractivity. As can be shown, throughout the study time, Ibadan's wet term radio refractivity had 30.5496 %, while the dry term radio refractivity had 69.4504 %, contributing significantly to the total radio refractivity. On the other hand, the dry term's monthly maximum contributor is 5.8202 % in August, while the wet term's monthly minimum is 2.1167 % in January. Similarly, the dry term's monthly maximum contributor is 2.7711 % in April and the minimum is 5.7524 % in March.

Table 3. Comparison of Average Values of Radio Refractivity for Makurdi and Ibadan

Average Values	Makurdi	Ibadan
Rainy	377.4075 N-units	376.1149 N-units
Dry	347.9513 N-units	363.5790 N-units
Maximum	380.0641 N-units	379.9479 N-units
Minimum	331.9776 N-units	352.2143 N-units

The average radio refractivity values for the wet and dry seasons, as well as the maximum and minimum values for Makurdi and Ibadan, are compared in Table 3. The findings indicate that Makurdi's average radio refractivity value is higher than Ibadan's during the rainy season, whereas Ibadan's value is higher than Makurdi's during the dry season. On the other hand, Makurdi's radio refractivity maximum average value of 0.1162 N-units is higher than Ibadan's, while Ibadan's minimum average value of 20.2367 N-units is higher than Makurdi's.

Table 4. Comparison of Refractivity Gradient and k-factor for Makurdi and Ibadan

Average Values	Makurdi	Ibadan
Refractivity gradient	- 43.8583 N-units/km	- 43.148 N-units/km
k-factor	1.3876	1.3790

The refractivity gradient and k-factor comparison between Makurdi and Ibadan is displayed in Table 4. The findings indicate that Ibadan has a stronger refractivity gradient than Makurdi, while Makurdi has a higher k-factor than Ibadan. Nonetheless, both sites demonstrate that the Guinea savannah region of Nigeria is primarily the site of super-refractive propagation.

Table 5. Comparison of Dry and Wet term Radio Refractivity for Makurdi and Ibadan

Average Values	Makurdi	Ibadan
Dry term	70.8764 %	69.4504 %
Wet term	29.1236 %	30.5496 %

The comparison of the dry and wet term radio refractivity for Makurdi and Ibadan is displayed in Table 5. With 1.4260%, Makurdi's dry term radio refractivity is higher than Ibadan's, and Ibadan's wet term radio refractivity is higher than Makurdi's with the same value. It is clear from both sites that the wet term adds to the radio refractivity variation pattern, whereas the dry term contributes mostly to the overall tropospheric radio refractivity.

Conclusion

In this study, the tropospheric radio refractivity is estimated and investigated along with other pertinent parameters over two locations in Nigeria's Guinea savannah climatic zone: Makurdi (Latitude 7.73 °N, Longitude 8.53 °E, and altitude 112.9 m) and Ibadan (Latitude 7.43 °N, Longitude 3.90 °E, and altitude 227.2 m above sea level). Using measured monthly meteorological parameters of temperature, relative humidity, and atmospheric pressure from the National Aeronautic and Space Administration (NASA), the International Telecommunication Union (ITU) recommended procedure was used to evaluate tropospheric radio refractivity for the locations over a 42-year period (1981 to 2022). According to the findings, radio refractivity was highest during the rainy season (377.4075 N-units and 376.1149 N-units on average) and lowest during the dry season (347.9513 N-units and 363.5790 N-units on average) for Makurdi and Ibadan, respectively. For Makurdi and Ibadan throughout the wet and dry seasons, respectively, the maximum and lowest average values of radio refractivity were 380.0641 N-units and 379.9479 N-units in May and 331.9776 N-units and 352.2143 N-units in January. During the investigation period, it was

discovered that the wet term radio refractivity contributed to the major variations with 29.1236% and 30.5496 % for Makurdi and Ibadan, respectively, while the dry term radio refractivity was a major contributor to the total radio refractivity with 70.8764% and 69.4504%. The study areas under investigation yielded average refractivity gradients of -43.8583 and -43.148 N-units/km. Additionally, the average effective earth radius (k – factor) for Makurdi and Ibadan was found to be 1.3876 and 1.3790, respectively. These values align with the conditions of super refraction propagation in the climatic zone of the Guinea savannah in Nigeria.

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Conflict of Interests

Authors declared no conflict of interest.

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