

Regression-Based Modeling and Contour Mapping of Radio Refractivity in Nigeria For Improved Link Budget Design

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Abstract: The performance of radio signals propagating through the lower atmospheric layers is influenced by their refractive conditions. To ensure that the effects of propagation do not compromise the strength of signals transmitted, link budgets must be carefully designed. The International Telecommunication Union (ITU) model is the globally accepted standard for estimating radio refractivity. However, due to climate variability, researchers have reported overestimations and underestimations of radio refractivity by the ITU model in tropical climates. In response, this study introduces a novel modeling approach by developing a new empirical model for estimating radio refractivity and generating contour maps to enhance existing link budgets in Nigeria. Ten years of atmospheric parameter data from twelve locations across different climatic regions of Nigeria were obtained from the Center for Atmospheric Research (CAR), Anyigba, Nigeria. Using these data, a new refractivity model was developed and statistically validated with R-squared and Root Mean Squared Error (RMSE) metrics. Subsequently, refractivity contour maps for Nigeria were created using Surfer 16 software. The analysis revealed that the proposed model achieved R-squared and RMSE values of 0.99 and 0.27, respectively. Additionally, annual refractivity contour maps indicated a progressive increase in refractivity values from the northern (dry) regions of Nigeria to the southern (coastal) region. The study also demonstrated that refractivity values vary across climatic regions. Thus, this work can be employed for the quick and precise link budgets estimation in the design and planning of radio links in Nigeria and other regions with comparable climatic conditions.

Keywords: Refractivity, empirical model, climate, ITU model.

I. Introduction

The growing reliance on radio communication in Nigeria, facilitated by technologies like laptops, smartphones, and computers, has streamlined daily activities, enhancing business operations and social interactions. This includes advancements in internet banking, online shopping, access to news accessibility and accessing the social media platforms [1]. Despite these benefits, users frequently encountered poor network services that disrupt their daily activities. These challenges may be links to numerous factors, including the height of an antenna and network congestion with tropospheric conditions contributing significantly [2].

Troposphere is an essential part of the Earth's space environment, represent the Earth's atmosphere's lowest layer, contained about (75 - 80%) of the entire mass of the atmosphere and almost all weather activities occur within this layer. It is characterized by fluctuations in various atmospheric parameters, such as the temperature, pressure, and humidity, which may vary depending on geographic location, time of the day and solar cycle [3], [4]. Studying how weather affects radio waves helps us understand how well radio signals travel. We look at these three main weather parameters to figure this out. These parameters change a lot with time of the day and with the seasons, especially in tropical areas. To make sure our radio systems work well, we need to know exactly how these weather parameters change [5], [6], [7], [8].

Radio refractivity refers to how radio signal bends as it passes through the atmosphere. There are several existing radio refractivity models. Among these, is the ITU model [9], which is the globally accepted model for estimating radio refractivity. However, due to the changing climate, researchers have reported that the ITU model over estimate or underestimate radio refractivity [10], [11], [12]. Overestimation will squander power resources, whilst underestimation could cause signal loss, ultimately degrading service quality. In many cases, models developed from data analysis in temperate regions are used to establish link margins and budgets for network planning and implementation in tropical regions. However, these models are often applied without prior evaluation or characterization of the region's signal path losses and attenuations, which are influenced by variable parameters. This lack of region-specific analysis is one of the main reasons for poor network performance, particularly in terms of signal quality during transmission and reception in tropical areas [13].

Estimating radio refractivity in tropical regions has been the focus of various studies due to the distinct atmospheric conditions characterized by high humidity, temperature, and pressure variations. While International Telecommunication Union (ITU-R) model is globally accepted for its applicability, however, its performance in tropical climates frequently requires validation or adjustment due to deviations caused by distinct local weather patterns. Researchers in tropical regions have developed empirical models fitted to these conditions to improve prediction accuracy. Some of the notable models are: [10], the model was developed using meteorological data from Oshogbo, Nigeria. It focuses on the relationship between refractivity and weather variables such as temperature, relative humidity, and pressure. The model aims in addressing the ITU's overestimation and underestimation

tendencies by refining the empirical coefficients for tropical climates. [14], the study introduced an empirical linear regression model for the estimation radio refractivity using temperature, pressure, and humidity as primary parameters. The model was based on data from Cross River State, Nigeria, and achieved high accuracy with a maximum absolute percentage error of 3.22%. Validation on datasets from other regions showed errors of 2.46% and 1.25%, indicating its broader applicability. The model simplifies refractivity estimation, making it suitable for automated wireless network designs. [15], Developed a vertical profile model emphasizing altitude-related refractivity variations, achieving remarkable accuracy (maximum error of 0.0176%) but limited to applications requiring altitude-dependent data.

The existing radio refractivity models are limited by their geographical specificity, simplistic parameterization, narrow scope of application, and inadequate consideration of seasonal and climatic variations, necessitating a comprehensive, adaptable model for diverse tropical conditions. The development of the new regression model was driven by the need to overcome the aforementioned lapses in the existing models, thereby achieving superior accuracy, broader applicability, and adaptability to diverse climatic conditions, so as to serve as a valuable tool for predicting refractivity in tropical regions. The empirical model proposed in this study was based on meteorological data collected over twelve locations cut across different climatic region and cross-validated with atmospheric data from one location in each of the four major geo-climatic region of Nigeria. Eventually, annual radio refractivity contour map was developed. The new modelling approached presented in this paper would be used in upgrading the existing links budget and sufficiently improve Quality of Service (QoS) in Nigeria.

II. Methodology

Atmospheric temperature (T), relative humidity (H), and atmospheric pressure (P) data for twelve locations—namely Gusau (12.17°N, 6.66°E), Sokoto (13.06°N, 5.24°E), Maiduguri (11.84°N, 13.27°E), Makurdi (7.73°N, 8.54°E), Enugu (6.46°N, 7.51°E), Lagos (6.52°N, 3.37°E), Port Harcourt (4.81°N, 7.05°E), Akure (7.25°N, 5.20°E), Jos (9.93°N, 8.89°E), Yola (9.20°N, 12.48°E), Minna (9.61°N, 6.56°E), and Ogbomoso (8.13°N, 4.25°E) in Oyo State—were sourced from the Centre for Atmospheric Research (CAR) in Anyigba, Kogi State, Nigeria. the data were obtained using a Davis Wireless Vantage Pro2 automatic weather station. This system includes an Integrated Sensor Suite (ISS), a solar panel with a backup battery, and a console. The ISS collects external weather information and send to a Vantage Pro2 console. The standard model of the ISS is equipped with a rain gauge, temperature and humidity sensors, an anemometer, a solar radiation sensor, and a UV sensor. The temperature, pressure, and humidity Sensors are housed within a passive radiation shield to minimized the effects of solar radiation on their measurements.

A. Calculation of Radio Refractivity

The radio refractivity, N, is related to refractive index of air [9] as follows;

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

where N is radio refractivity expressed by:

$$N = 77.6 \frac{P_d}{T} + 3.75 \times 10^5 \frac{e}{T^2} \quad (\text{N-Units}) \quad (2)$$

with the 'dry term' of radio refractivity given by:

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

and the 'wet term' given by:

$$N_{wet} = 3.732 \times 10^5 \frac{e}{T^2}, \quad (4)$$

$$N = N_{dry} + N_{wet} = \frac{77.6}{T} \left(P + 4810 \frac{e}{T} \right), \quad (5)$$

With, P is atmospheric pressure (hPa), e is water vapor pressure (hPa), and T is absolute temperature (K).

Equation (5) produces values of N that is within 0.02 percent obtained from those of equation (2) for temperature ranging from -50°C to +40°C. Additionally, water vapor pressure, e, can be obtained from relative humidity.

$$e = \frac{H e_s}{100}, \quad (6)$$

with,

$$e_s = a \exp \left\{ \frac{bt}{t+c} \right\}, \quad (7)$$

with, t , is temperature measured in Celsius, $a = 6.1121$, $b = 17.502$ and $c = 240.97$ [9].

B. Development of Empirical Model for Estimation Radio Refractivity

The ITU-R model was employed to calculate radio refractivity (N) based on meteorological parameters obtained from the instrument. The correlation among the parameters N , T , H , P and THP , which is the product of T , H and P was computed. From the correlation values, H and THP have the highest correlation values with respect to N in all the region considered. A multiple linear regression model was created to estimate radio refractivity (N) using the mean hourly values of relative humidity (H) and THP . The model was created using the Origin-Pro software, with H and THP serving as the independent variables and N as the dependent variable.

C. Model Validation

In order to validate and evaluate the effectiveness of the proposed model, atmospheric parameters data from four stations cut across each of the climatic region under consideration were used. Comparative analysis techniques were employed and the results from the two models were compared.

D. Development of Refractivity Contour Maps

To enable a climatic map of radio refractivity in Nigeria to be drawn, it is necessary that the stations be well distributed over the whole country, for this reason, meteorological data from the twelve meteorological stations cutting across different climatic zones in Nigeria where long-term measurement are available was obtained. A contour map represented by three variables, with the first two (X and Y) representing spatial coordinates (longitude and latitude) of a location, and the third (Z) representing refractivity values. These refractivity values are shown as contour lines, which connect points of equal value across the map's area. The refractivity contour map for Nigeria was created using Surfer 16 software.

III. Result and Discussions

A. Empirical Model for Estimation Radio Refractivity

To develop a model that precisely estimates the radio refractivity, multiple linear regression between radio refractivity and atmospheric parameters was performed and an empirical model was obtained, equation (5).

$$N = 0.000061THP - 0.22438H + 259.63, \quad (8)$$

where N is the radio refractivity, T represents the temperature in degrees Celsius, H denotes the relative humidity as a percentage, and P refers to the atmospheric pressure in (hPa).

The model parameters presented in Table 1 and the correlation coefficient derived from the scatter plot in Figure 1 are nearly equal to one (1). This indicates a strong correlation between radio refractivity and atmospheric parameters. Therefore, the derived model is highly accurate and can be reliably employed in estimating the radio refractivity for any location in the country, provided that the temperature, pressure, and relative humidity of the area are known.

Table 1: Optimal values of the fitting parameters in the model equation.

Model Parameters	Values
RMSE	0.27
P Value	1.6×10^{-24}
Error C	4.1057
Error THP (X1)	4.1×10^{-06}
Error in H (X2)	0.043
R^2 value	0.99

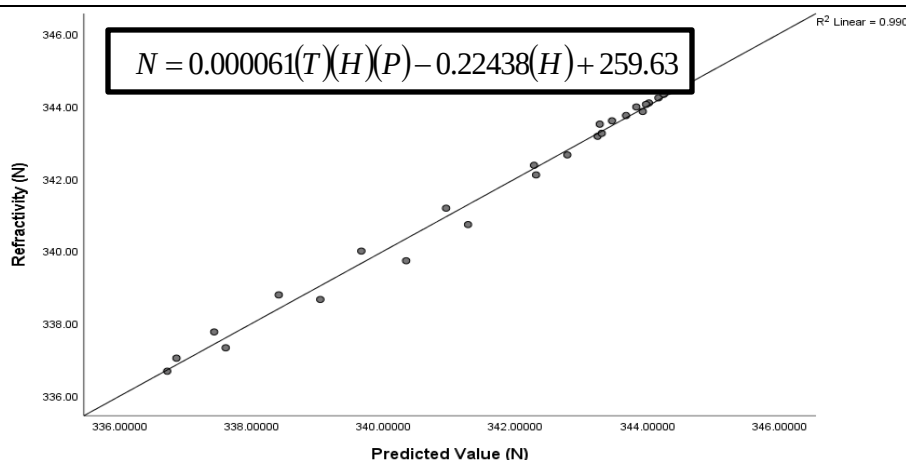


Figure 1: Multiple Regression Scattered Plot

B. Model Validation

The data of meteorological parameters for four station that cuts across each of the climatic region were used to estimates refractivity using ITU-R model and empirical model developed in this study. Results from the two models were compared. Figures 2 to 5 show the comparison between the ITU-R model and radio refractivity model for Gusau, Akure, Ogbomoso and Yola, Nigeria. The two models are the same in structure and differ in magnitude over all locations. However, the analysis of the two models in term of MPE, the results showed that the estimated model and ITU-R model shows some level of disparity with the following MPE values; Gusau 7.5%, Yola 16.4%, Ogbomoso 9.26%, and Akure 8.87%. The empirical regression models identified as effective for accurately calculating diurnal and monthly radio refractivity in Nigeria and its surrounding areas, based on the available meteorological parameters.

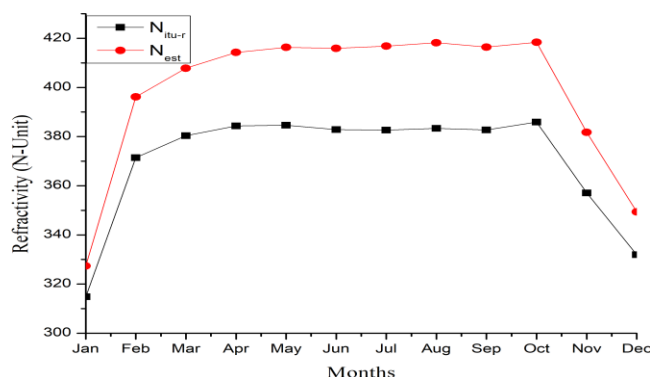


Figure 2: Comparative refractivity over Gusau

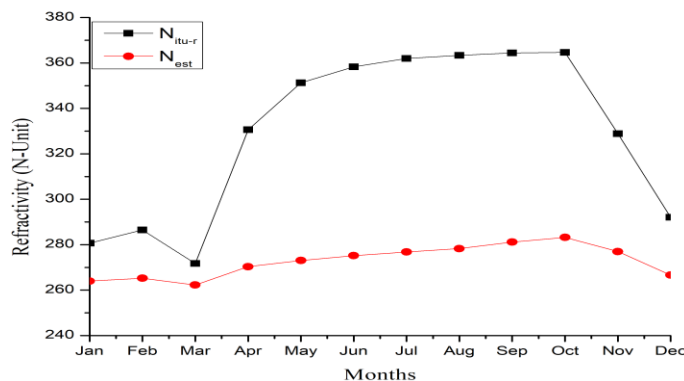


Figure 3: Comparative refractivity over Yola

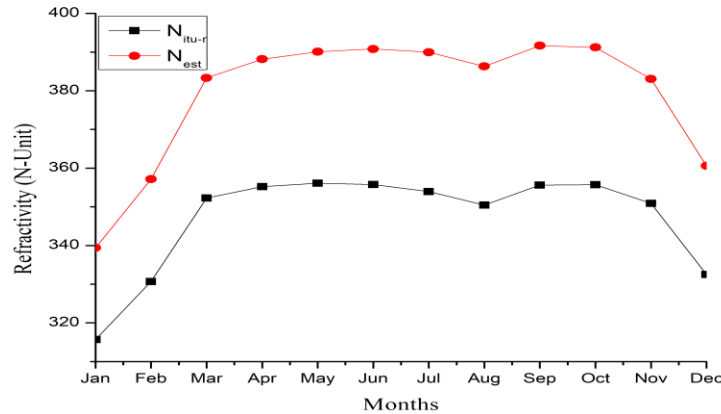


Figure 4: Comparative refractivity over Ogbomoso

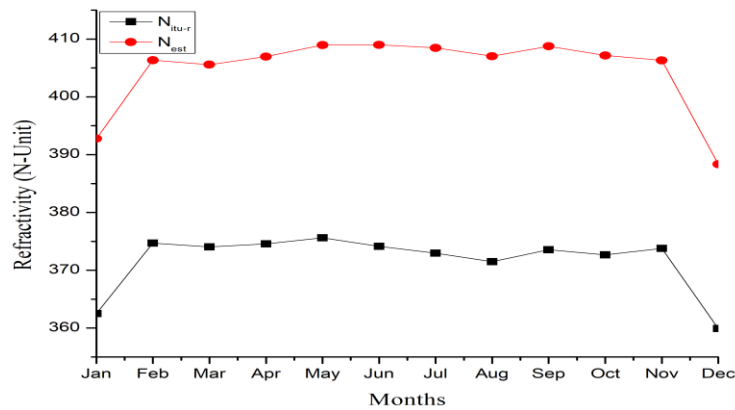


Figure 5: Comparative refractivity over Akure

C. Analysis of Deviations from the ITU Model

Deviations between the ITU-R model and the proposed model primarily arise from differences in how they handle local atmospheric conditions. The ITU model tends to overestimate refractivity during the wet season due to its simplified approach [16], while the proposed model, which accounts for local variations in temperature, humidity, and pressure, provides more accurate predictions. Additionally, the ITU model underestimates refractivity in areas with significant altitude or diurnal temperature variations [15], while the proposed model incorporates these factors. Overall, the proposed model offers improved accuracy, particularly in tropical regions with variable weather patterns and topography.

D. Comparative Analysis with Existing Tropical Models

Estimating radio refractivity in tropical regions has been the focus of various studies due to the distinct atmospheric conditions characterized by high humidity, temperature, and pressure fluctuations. While the International Telecommunication Union (ITU-R) model is globally recognized for its applicability, its performance in tropical climates often requires validation or modification due to deviations caused by unique local weather patterns. Researchers in tropical regions have developed empirical models tailored to these conditions to improve prediction accuracy. Some of the existing tropical model and their performance metrics are presented in table below.

Table 2: Comparative Performance of Refractivity Models for Tropical Regions

Model	Focus/Scope	Key Parameters Used	Validation Location(s)	Performance Metrics	Limitations
[15]	Vertical refractivity profile	Temperature, Pressure, Humidity, Altitude	Akure, Nigeria	Max Error: 0.0176% (Cross River); 0.0849% (Akure)	Focused on vertical profiling; less suitable for surface-level predictions

[10]	Surface refractivity for Osogbo, Nigeria	Temperature, Pressure, Humidity	Osogbo, Nigeria	Improved ITU accuracy for Osogbo	Region-specific coefficients limit broader applicability
[14]	Linear regression model for refractivity	Temperature, Humidity, Pressure, TUP	Cross River, Nigeria; datasets from other regions	Max Error: 3.22% (Cross River), 2.46%/1.25% (validation datasets)	Primarily focused on linear relationships; complex nonlinear dynamics excluded

The proposed model surpasses the existing tropical refractivity models in accuracy, with an RMSE of 0.27 and R^2 of 0.99, making it suitable for surface refractivity estimation across diverse climatic zones in Nigeria. Unlike models like [15] and [10], which focus on specific locations or vertical profiles, the proposed model offers broader applicability. However, it requires calibration for non-tropical climates, limiting its global use.

E. Refractivity Contour Map for Nigeria.

The newly developed empirical model was applied to create an average annual radio refractivity contour map for Nigeria, utilizing ten years' worth of average temperature, pressure, and relative humidity data. The maps Figure 6, revealed that lower radio refractivity values occurred over December, January, February, and March, aligning with dry season. High values refractivity were recorded during June, July, August, September, and October, which corresponded with the wet season, consistent with the findings of (Agunlejika and Raji, 2010; Ayantunji et al., 2011). Similarly, Figure 6 shows the average annual values of refractivity increase across different regions; the Coastal region ranges from 356-N to 378-N, the Derived Savanna from 349-N to 353-N, the Guinea Savanna from 312-N to 331-N, and the Arid region from 321-N to 323-N. These findings are consistent with the work of (Adewumi and Kehinde, 2018; Ayantunji and Okeke, 2011). Higher refractivity values in the coastal region occur due to the frequent presence of water vapor in the atmosphere, influenced by the Atlantic Ocean. This, in turn, raises air humidity, air pressure, and water vapor levels, resulting in a denser troposphere that enhances radio refractivity in the area.

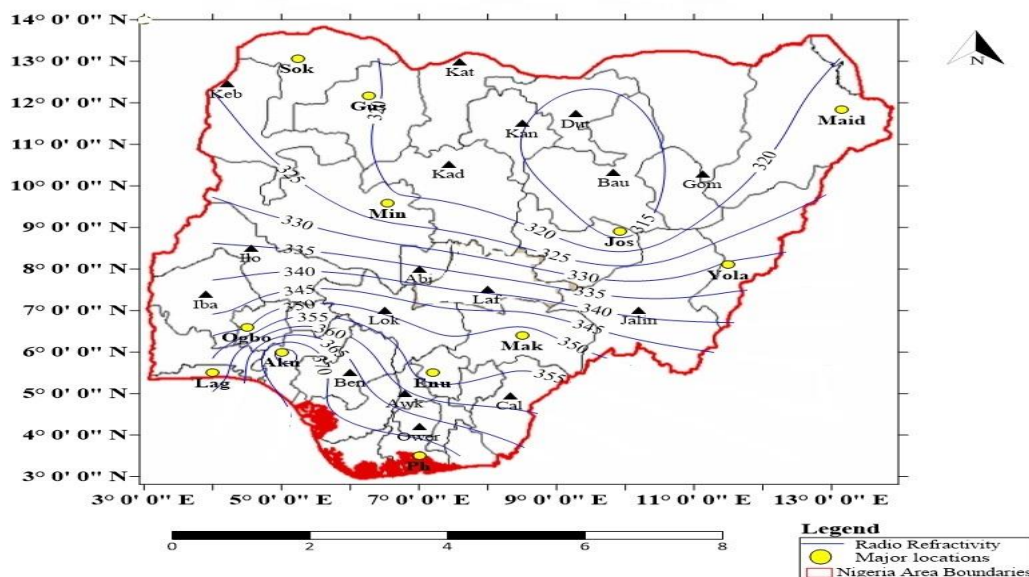


Figure 6: Average Annual Radio Refractivity Contour Map across Nigeria.

IV. Conclusion

A linear regression model was developed to estimate atmospheric refractivity based on fundamental atmospheric parameters such as temperature, pressure, and relative humidity. Additionally, the model's parameters and a scatter plot were successfully generated. The model's validity was assessed using statistical tools. Regression analysis of the two models showed a strong correlation. However, a graphical comparison of the two models revealed that the estimated model closely follows the structure of the ITU-R model. The radio refractivity model developed was determined to be effective for estimating radio refractivity over Nigeria, as well as in other regions with similar climatic conditions. The contour maps ultimately showed that radio refractivity values at the surface rise from the dry northern regions to the more humid southern coastal areas. Additionally, surface refractivity values were found to be higher during the wet season compared to the dry season across all regions.

Eventually, the empirical model is robust for current climatic conditions but will require recalibration to account for projected changes in temperature, humidity, and pressure due to climate change. Integrating predictive climate data and testing under various scenarios will ensure its continued relevance for Nigeria and other tropical regions.

V. Recommendation

The following recommendations are proposed for future work

Considering potential for changing climate, it is recommended that the proposed empirical model be periodically recalibrate to account for variation in temperature, humidity and pressure.

Integrating real-time meteorological data from local weather stations and satellite sources such as NIMET and NOAA, so as improve the model's accuracy. This will provide up-to-date atmospheric parameters for more precise refractivity predictions in dynamic conditions.

Its recommended to include parameters that account extreme weather event such as heatwaves and storms. This will assist in improve the predictions under unusual atmospheric conditions, which are becoming more often due to climate change.

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