# METEOROLOGICAL MODELS FOR DETERMINATION OF SURFACE RADIO REFRACTIVITY OVER NIGERIA

**Abstract**

The problem of quantifying surface refractivity in terms of atmospheric variables in different climatic scenarios is very complex because the meteorological variables required are neither perfectly correlated nor totally uncorrelated. The previous studies showed that linear meteorological expressions obtained were localized and could not be generally applied. It is therefore required that more locations should be investigated to deduce new linear meteorological models best suitable for estimation of surface refractivity.

Surface meteorological data, including pressure, temperature and relative humidity, was downloaded from Modern-Era Retrospective analysis for Research and Application (MERRA - 2) for six locations defined by different climatic conditions over Nigeria, namely Yenagoa, Abakaliki, Ibadan, Anyigba, Jalingo and Sokoto for a period of 40 years partitioned into two periods of 20 years each. The 1979 – 1998 dataset of atmospheric temperature, T (K), atmospheric pressure, P (hPa) and relative humidity, Rh (%) were extracted using text import wizard to calculate surface refractivity using existing model ($\mathrm{N_{itu-r}}$). Regression analysis was carried out to obtain new linear meteorological expressions as function of temperature ($\mathrm{N_t}$), relative humidity ($\mathrm{N_{Rh}}$), and combination of relative humidity and temperature ($\mathrm{N_{Rh,t}}$). The new expressions were tested using 1999 – 2018 meteorological dataset and the results of surface refractivity from the new linear expressions were compared with values from existing equations.

It was observed that high relative humidity and low temperature values prevalent in the three southern stations – Yenagoa, Abakaliki and Ibadan – significantly enhanced the suitability of $\mathrm{N_{Rh,t}}$ linear meteorological model for estimation of surface refractivity values comparable to $\mathrm{N_{itu-r}}$. Contrary to the observations in the southern stations, in the northern stations, relative humidity contributions ($\mathrm{N_{Rh}}$) had the best linear correlation of 0.96 at Anyigba, 0.98 at Jalingo and Sokoto. Estimation of surface refractivity from the new linear meteorological models was found to be best as a function of temperature and relative humidity in the south and a function of relative humidity in the north. Linear meteorological models as a function of relative humidity and temperature were best suitable for stations in the south with minimum correlation of 0.98 while linear expressions as a function of relative humidity only were best suitable for the stations in the north with minimum correlation of 0.96.

## 1.0 Introduction

Atmospheric refractivity has been well studied over the years and some mathematical expressions have been developed to estimate the value of refractivity (Amajama and Eshiet, 2016). However, most of the expressions are complex and involve some nonlinear expressions. The complexity makes it more difficult to integrate the refractivity expressions into other formula to develop simple closed-form mathematical expressions needed in wireless link design (Joseph, 2015). In recent years, researchers have tried to develop simple mathematical equations that can be used to estimate the radio refractivity from the atmospheric parameters (Jari and Ismo, 2015). Prediction of radio refractivity has been required since the early days of microwave radio links. Although one of the earliest prediction models is still in use, it is only valid for continental temperate climate (ITU – R, 2013).

In a study conducted by Stephen, *et al.,* (2014), radiosonde data from 65 stations covering parts of Australia, India, South Africa, Europe and North America, most of them with around 16 years of data, typically 1997–2012, were processed. A new prediction model for the distribution of refractivity gradient in the atmospheric surface layer, having better prediction accuracy than existing models, and using only data that can be obtained from surface weather stations, was obtained with rms error of 17 N-units per km, and correlation coefficient of 0.79

In the recent research conducted by Enyenihi, *et al*., (2019), radiosonde meteorological data for Cross River state, Nigeria was obtained from Nigerian Meteorological Agency (NIMET) for the twelve months in 2013. The study examined the correlation among radio refractivity and the meteorological parameters, namely atmospheric temperature (T), atmospheric pressure (P) and relative humidity (H). The correlation values from the results showed that there is a positive correlation between surface refractivity (N) and temperature (T) and pressure (P). However, there is a negative correlation between N and relative humidity (H) which indicated inverse proportionality between N and H. In all, T and products of TPH showed highest correlation values for the model training datasets; as such the two parameters were used in the development of the linear regression model that can be used to estimate the radio refractivity for the available meteorological dataset.

The model was developed using XURU online regression tool where the values of T was X1, TPH was X2 and N was Y. The dataset of T, TPH and N for the 12 months were pasted into the text box provided in Xuru Multiple Linear Regression (MLR) webpage and the model obtained from the Xuru MLR was given as;

$$\mathrm{N} = 2.38\mathrm{T} + 0.000051[(\mathrm{T})(\mathrm{P})(\mathrm{H})] + 198.38 \qquad 1.0$$

Two sample meteorological dataset from published articles were also used by Enyenihi, et al., (2019) to validate the model. The model gave a maximum absolute percentage error of 2.46 % for the first test meteorological dataset while it gave a maximum absolute percentage error of 1.25 % for the second test meteorological dataset. The results that was obtained from the new model showed that the model can estimate refractivity with a maximum prediction error of about ±3.35%.

In this study, a set of meteorological data measured over 20 years was used to deduce useful linear expressions for the estimation of surface refractivity adaptable to specific climatic features in six locations across Nigeria. The linear expressions were tested using meteorological data from another period of 20 years. The values of surface refractivity from the new linear expressions were compared with values from existing equations.

## 2.0 Theoretical Background

The refractive index of the troposphere is an important factor in predicting the performance of terrestrial radio links. Refractive index variations of the atmosphere affect radio frequencies above 30 MHz, although these effects become significant only at frequencies greater than about 100MHz especially in the lower atmosphere. The radio refractive index n of the troposphere deviates slightly from unity due to the polarisability of the constituent molecules by the incident electromagnetic field, and the quantum mechanical resonances at certain frequency bands (Ayantunji and Okeke, 2011). While molecular polarisability is independent of frequency up to millimeter waves, molecular resonance is totally frequency dependent, and n tends to be dispersive above approximately 50 GHz.

Radio refractivity N is a measure of deviation of refractive index n of air from unity which is scaled-up in parts per million to obtain more amenable figures. Thus, N is a dimensionless quantity defined as measured in N units (ITU-R, 2003).

$$\mathrm{N} = (\mathrm{n} - 1) \times 10^{6} \qquad 2.0$$

N depends on meteorological parameters of pressure P (hPa), temperature T (K) and water vapour pressure e (hPa), as given by the relation (ITU-R, 2013):

$$N_{itu-r} = \frac{77.6P}{T} + 3 \times 10^5 \frac{e}{T^2} \qquad 3.0$$

The vapour pressure is also related to the relative humidity H (%):

$$e = \frac{He_s}{100} \qquad 4.0$$

$e_s$ is the maximum (or saturated) vapour pressure at the given air temperature t $^0$C, and may be obtained from:

$$e_s = 6.11\exp\left[\frac{17.502t}{(t+240.97)}\right] \qquad 5.0$$

Generally P and e decrease rapidly with height while T decreases slowly with height (ITU-R, 2013).

Horizontal variation of refractive index is generally negligible in the lower troposphere compared to the large-scale vertical variation which has a median gradient of about –40 N/km near the surface in mid-latitude and most temperate regions. However, significant deviations can arise from local or mesoscale meteorological factors, especially in the tropics. This horizontal variation of refractive index is very significant over Nigeria because of the significant change in climatic condition from the coastal region in the extreme south to the semi-arid region in the extreme North.

## 3.0 Climate of the Study Area

The study area in this research spread across six geopolitical zone across Nigeria. Each locations has a diverse climatic pattern to ensure adequate representation of surface refractivity patterns. The locations are shown in figure 1 namely Yenagoa in south-south zone, Abakaliki in south-east zone, Ibadan in south-west zone, Anyigba in north-central zone, Jalingo in north-east zone and Sokoto in north-west zone. The climate at Yenagoa is tropical. Most months of the year are marked by significant rainfall. The short dry season has little impact. The average annual temperature is 26.7 °C in Yenagoa. In a year, the average rainfall is 2899 mm (Odjugo, 2013). The driest month is January, with 40 mm of rain. The greatest amount of precipitation occurs in September, with an average of 472 mm. March is the warmest month of the year. The temperature in March averages 28.0 °C (Abu, 2007). The lowest average temperatures in the year occur in July, when it is around 25.4 °C. There is a difference of 432 mm of precipitation between the driest and wettest months (Nwagbara, et al., 2009). The variation in temperatures throughout the year is 2.6 °C.

Abakaliki climate is classified as tropical. The average temperature in Abakaliki is 27.7 °C. Precipitation here averages 1918 mm (Maria, 2013). Precipitation is the lowest in December, with an average of 7 mm. Most precipitation falls in September, with an average of 291 mm. At an average temperature of 29.6 °C, March is the hottest month of the year (James, 2009). In August, the average temperature is 26.0 °C (Jagtap, 2007). It is the lowest average temperature of the whole year. Between the driest and wettest months, the difference in precipitation is 284 mm. The average temperatures vary during the year by 3.6 °C.

The climate is tropical in Ibadan. The average annual temperature is 26.5 °C in Ibadan. About 1311 mm of precipitation falls annually. The driest month is January. There is 6 mm of precipitation in January. In June, the precipitation reaches its peak, with an average of 190 mm (Ayoade, 2004). With an average of 28.6 °C, March is the warmest month. At 24.1 °C on average, August is the coldest month of the year. The precipitation varies 184 mm between the driest month and the wettest month. The variation in annual temperature is around 4.5 °C.

Anyigba has a tropical climate. The average temperature in Anyigba is 25.4 °C. The average annual rainfall is 1321 mm. The least amount of rainfall occurs in January. The average in this month is 7 mm. The greatest amount of precipitation occurs in September, with an average of 265 mm. The temperatures are highest on average in March, at around 27.9 °C (Nwafor, 2007). The lowest average temperatures in the year occur in August, when it is around 23.8 °C. The variation in the precipitation between the driest and wettest months is 258 mm. The variation in temperatures throughout the year is 4.1 °C.

The climate is tropical in Jalingo. The temperature here averages 27.3 °C. About 1053 mm of precipitation falls annually. The driest month is January. There is 0 mm of precipitation in January. In August, the precipitation reaches its peak, with an average of 224 mm. With an average of 30.6 °C, April is the warmest month (IPCC, 2007). At 25.2 °C on average, December is the coldest month of the year. The precipitation varies 224 mm between the driest month and the wettest month. The variation in annual temperature is around 5.4 °C.

The climate in Sokoto is referred to as a local steppe climate. There is little rainfall throughout the year. In Sokoto, the average annual temperature is 28.4 °C (Ayuba et al., 2007). The average annual rainfall is 629 mm. The least amount of rainfall occurs in January. The average in this month is 0 mm. The greatest amount of precipitation occurs in August, with an average of 211 mm. The temperatures are highest on average in April, at around 33.2 °C. The lowest average temperatures in the year occur in January, when it is around 24.5 °C. The variation in the precipitation between the driest and wettest months is 211 mm. The variation in temperatures throughout the year is 8.7 °C.

## 4.0 Data Source and Analysis

Surface meteorological data, including pressure, temperature and relative humidity, was downloaded from Modern-Era Retrospective analysis for Research and Application (MERRA - 2). The data project was stimulated by the recognition that various aspects of the hydrologic cycle represented in previous generations of re-analyses were not adequate for climate and weather studies. MERRA – 2 offered an improvement upon the water cycle as a contribution to the science community and reanalysis research (Colarco, *et al*., 2010).

MERRA uses a three-dimensional variation (3D-Var) analysis algorithm based on the Grid-point Statistical Interpolation scheme. Like other current re-analyses, it makes extensive use of satellite radiance information, including data from hyper-spectral instruments such as the Atmospheric Infrared Sounder (AIRS) on Aqua (Bacmeister, 2006). MERRA was processed in three separate streams, each spun-up in two stages: Stream 1 for 1 January 1979 to 31 December 1992, followed by Stream 2 for 1 January 1993 to 31 December 2000, and then continues with Stream 3 for 1 January 2001 to the present.

The MERRA meteorological data for six locations defined by different climatic conditions over Nigeria, namely Yenagoa, Abakaliki, Ibadan, Anyigba, Jalingo and Sokoto, were downloaded for two periods of 20 years, 1979 – 1998 and 1999 – 2018, on monthly averages. The dataset of atmospheric temperature, T (K), atmospheric pressure, P (hPa) and relative humidity, Rh (%) were extracted using text import wizard and appropriate delimited options to prepare excel spreadsheet format for data manipulations. Radio refractivity (N) was computed from a set of T, Rh and P on monthly basis within the period of 1979 – 1998 using ITU-R equation 3.0 with a view to deduce monthly averages for 20 years. Monthly values of t ($^0$C), Rh and P were also separately estimated for the period covering 1979 – 1998 as shown in tables 1 - 3.

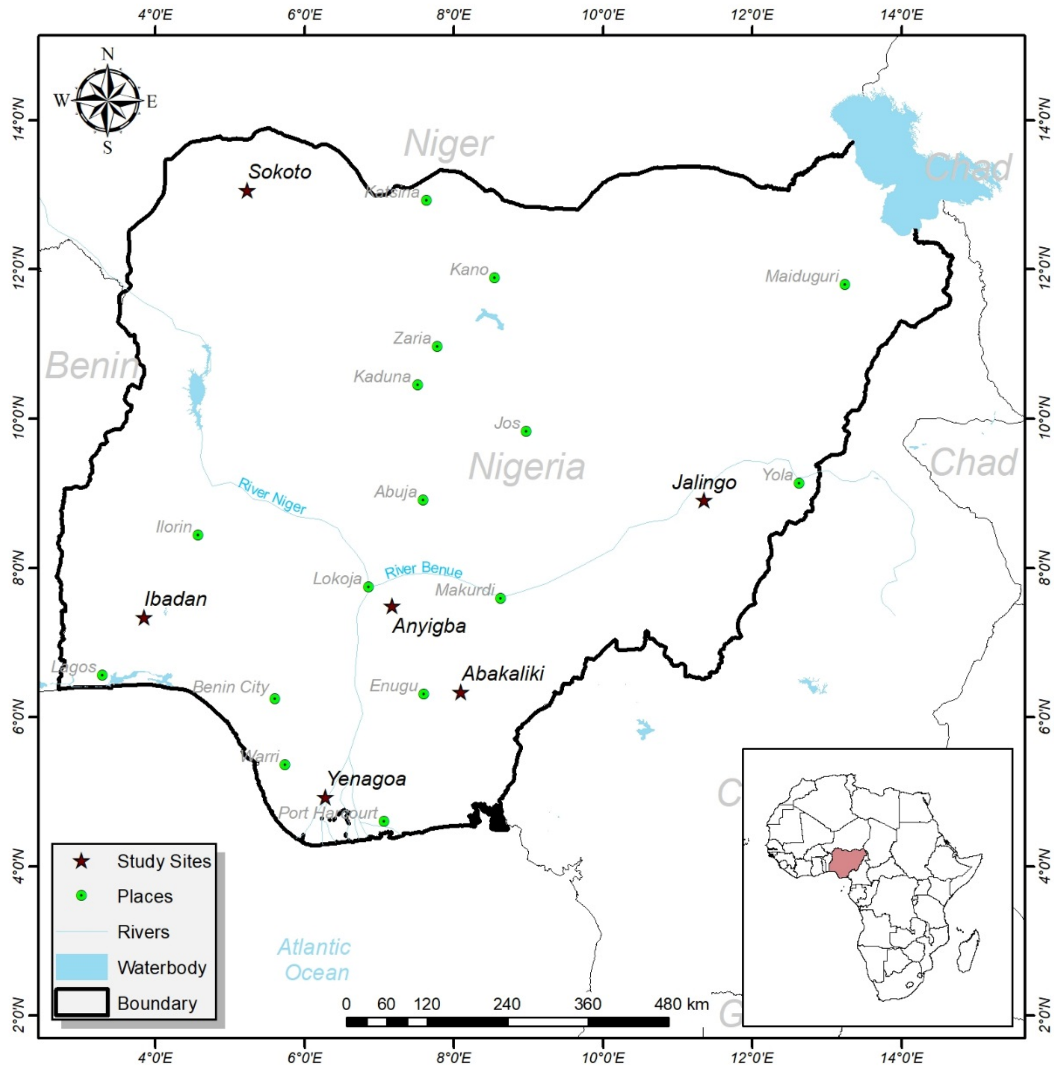


Figure 1: Map showing the Six Locations of the Study Areas over Nigeria

Multiple linear regression was developed for each location to estimate radio refractivity directly from meteorological parameters. This was carried out using scattered plots of N and t ($^0$C); N and Rh; N and Rh, t ($^0$C) with the aid of Origin graphing software to obtain a linear relationship between N and other meteorological parameters for different climatic zones across Nigeria. The linear expressions obtained for N from different regression analysis in the six climatic locations (as a function of t, Rh and t, Rh) and the ITU-R equation were applied on new set of monthly averages of meteorological data within a period of 1999 – 2018. Values of N obtained from linear regressions from each location were compared with values of N estimated from ITU-R equations. Correlation between radio refractivity values evaluated from linear expressions and ITU-R equation were computed to determine the degree of agreement and suitability of the new empirical relationships.

Table 1: Temperature (K) at 2 m above ground averaged monthly over a period of 1979 – 1998)

| Months | Yenagoa | Abakaliki | Ibadan | Anyigba | Jalingo | Sokoto |
|---|---|---|---|---|---|---|
| 1 | 299.46 | 297.01 | 298.45 | 299.28 | 299.00 | 297.92 |
| 2 | 300.06 | 300.32 | 299.12 | 300.44 | 299.87 | 298.30 |
| 3 | 300.19 | 300.16 | 299.82 | 302.05 | 303.53 | 302.55 |
| 4 | 300.13 | 300.05 | 299.62 | 300.75 | 303.06 | 306.18 |
| 5 | 299.85 | 299.83 | 299.28 | 299.88 | 300.32 | 306.32 |
| 6 | 299.03 | 298.79 | 298.58 | 299.12 | 299.86 | 303.22 |
| 7 | 298.13 | 298.42 | 297.63 | 298.10 | 298.18 | 300.68 |
| 8 | 297.84 | 298.34 | 297.38 | 297.93 | 297.75 | 299.38 |
| 9 | 298.21 | 298.73 | 297.91 | 298.15 | 298.46 | 300.22 |
| 10 | 299.04 | 298.90 | 298.63 | 298.94 | 299.49 | 299.95 |
| 11 | 299.38 | 299.87 | 298.58 | 298.78 | 299.53 | 298.77 |
| 12 | 299.67 | 298.65 | 298.16 | 298.47 | 299.01 | 297.25 |
| **Monthly Mean** | **299.25** | **299.09** | **298.59** | **299.32** | **299.84** | **300.89** |

Table 2: Atmospheric Pressure (hPa) at ground level averaged monthly over a period of 1979 – 1998)

| Months | Yenagoa | Abakaliki | Ibadan | Anyigba | Jalingo | Sokoto |
|---|---|---|---|---|---|---|
| 1 | 1008.29 | 1001.57 | 989.87 | 985.05 | 985.05 | 979.13 |
| 2 | 1007.86 | 999.28 | 989.53 | 984.69 | 984.69 | 979.52 |
| 3 | 1007.43 | 1000.41 | 988.88 | 983.80 | 983.8 | 976.51 |
| 4 | 1007.77 | 1000.42 | 989.25 | 984.28 | 984.28 | 975.40 |
| 5 | 1009.13 | 1001.31 | 990.66 | 985.68 | 985.68 | 976.39 |
| 6 | 1010.04 | 1003.09 | 991.51 | 986.48 | 986.48 | 977.88 |
| 7 | 1011.85 | 1003.61 | 993.03 | 988.04 | 988.04 | 979.54 |
| 8 | 1010.93 | 1003.60 | 992.10 | 987.08 | 987.08 | 978.78 |
| 9 | 1010.58 | 1001.75 | 991.83 | 986.91 | 986.91 | 978.88 |
| 10 | 1009.39 | 1001.49 | 990.83 | 985.81 | 985.81 | 978.54 |
| 11 | 1008.50 | 1000.43 | 990.10 | 985.19 | 985.19 | 978.68 |
| 12 | 1008.30 | 1001.80 | 990.07 | 985.28 | 985.28 | 979.60 |
| **Monthly Mean** | **1009.17** | **1001.56** | **990.64** | **985.69** | **976.01** | **978.24** |

Table 3: Relative humidity (%) at 2 m above ground averaged monthly over a period of 1979 – 1998)

| Months | Yenagoa | Abakaliki | Ibadan | Anyigba | Jalingo | Sokoto |
|---|---|---|---|---|---|---|
| 1 | 82.31 | 54.61 | 76.42 | 58.85 | 38.77 | 18.94 |
| 2 | 80.13 | 75.93 | 76.77 | 45.73 | 21.27 | 11.03 |
| 3 | 86.59 | 80.79 | 82.67 | 64.66 | 26.1 | 13.15 |
| 4 | 86.85 | 81.80 | 85.16 | 73.63 | 55.25 | 20.31 |
| 5 | 87.69 | 82.89 | 87.26 | 81.23 | 76.07 | 42.54 |
| 6 | 89.43 | 86.18 | 87.35 | 82.80 | 76.1 | 56.97 |
| 7 | 89.20 | 86.25 | 88.52 | 84.86 | 83.91 | 70.96 |
| 8 | 89.67 | 85.61 | 88.49 | 85.79 | 85.97 | 79.72 |
| 9 | 89.67 | 85.76 | 87.97 | 85.81 | 83.24 | 74.31 |
| 10 | 88.04 | 85.96 | 87.02 | 82.62 | 70.67 | 46.15 |
| 11 | 85.66 | 79.24 | 83.09 | 74.25 | 49.28 | 24.15 |
| 12 | 81.55 | 64.03 | 76.31 | 62.47 | 35.25 | 24.78 |
| **Monthly Mean** | **86.40** | **79.09** | **83.92** | **73.56** | **58.49** | **40.25** |

## 5.0 Results and Discussion

### 5.1 Derivation of Linear Meteorological Models for Surface Refractivity Estimation

The surface radio refractivity values estimated from existing ITU-R equation (quoted in equation 3) for six locations across Nigeria were presented in table 4. The results showed monthly averages of surface refractivity a period of 1979 – 1998. The spatial trend showed a significant decrease in monthly average of surface refractivity from southern location to the northern locations with the highest value of 383.41 N-Unit in Yenagoa and the least value of 314.81 N-Unit in Sokoto. Monthly distributions of refractivity values showed that high values were attained from March to October for Yenagoa, Abakaliki and Ibadan while high values were attained from May to October for Anyigba and Jalingo. Sokoto attained its high values from June to September.

The distributions were greatly influenced by wide variations in meteorological parameters most especially temperature (T) and relative humidity (Rh) along the latitudes across Nigeria. Temperature values reduced on monthly average in the south from 299.25 K in Yenagoa to 298. 59 K at Ibadan while it increased in the north from 299.32 K at Anyigba to 300.89 K at Sokoto. Atmospheric pressure reduced south – north on monthly average from 1009.17 hPa at Yenagoa to 978.24 hPa at Sokoto. Also, relative humidity on monthly average reduced south – north from 86.40 % at Yenagoa to 40.25 % at Sokoto.

Linear regression analysis between the N values obtained from ITU-R in table 4 and meteorological parameters measured within the same period were carried out to obtain new expressions in terms of t ($^0$C) and Rh for the six locations identified over Nigeria. Linear expressions 6a – 6c were obtained for Yenagoa as possible empirical models for estimating surface refractivity expressed in terms of relative humidity and temperature only (Eq. 6a); in terms of temperature only (Eq. 6b) and in terms of relative humidity only (Eq. 6c).

The regression analysis was repeated for other locations namely Abakaliki, Ibadan, Anyigba, Jalingo and Sokoto. The resulting linear expressions are presented subsequently. Linear expressions for Abakaliki were presented in equations 7a – 7c; expressions for Ibadan were presented in equations 8a –

8c; expressions for Anyigba were presented in equations 9a – 9c; expressions for Jalingo were presented in expressions 10a – 10b; expressions for Sokoto were presented in 11a – 11c respectively.

Table 4: Surface Refractivity (N-Units) estimated from ITU-R Equation ($N_{itu-r}$) averaged over a period of 1979- 1998

| Months | Yenagoa | Abakaliki | Ibadan | Anyigba | Jalingo | Sokoto |
|---|---|---|---|---|---|---|
| 1 | 378.55 | 360.38 | 360.62 | 338.47 | 307.18 | 279.92 |
| 2 | 378.44 | 351.45 | 364.15 | 322.90 | 283.39 | 269.60 |
| 3 | 388.58 | 379.52 | 375.96 | 358.10 | 294.80 | 272.44 |
| 4 | 388.71 | 380.79 | 378.56 | 366.16 | 344.21 | 287.97 |
| 5 | 388.66 | 383.41 | 380.02 | 373.36 | 365.51 | 333.31 |
| 6 | 386.68 | 380.93 | 376.51 | 371.80 | 363.46 | 348.79 |
| 7 | 381.86 | 377.73 | 373.42 | 369.75 | 366.35 | 360.53 |
| 8 | 380.69 | 377.50 | 371.84 | 369.86 | 366.65 | 366.80 |
| 9 | 382.59 | 379.08 | 373.85 | 370.97 | 366.61 | 363.17 |
| 10 | 384.63 | 379.98 | 376.16 | 370.44 | 353.74 | 320.61 |
| 11 | 382.94 | 370.70 | 370.35 | 357.95 | 323.21 | 287.38 |
| 12 | 378.57 | 355.28 | 359.21 | 340.65 | 302.34 | 287.15 |
| **Monthly Mean** | **383.41** | **373.06** | **371.72** | **359.20** | **336.45** | **314.81** |

The expressions showed linear dependence of surface refractivity on temperature and relative humidity. It was observed that the expressions had a pattern of highly varied numerical constants which makes the expressions significantly dependent on weather characteristics at specific location. The linear meteorological models are listed as follows:

$N_{Rh,t(Yenagoa)} = 335.32 + 0.33Rh + 0.75t$ 6a

$N_{t(Yenagoa)} = 344.07 + 1.50t$ 6b

$N_{Rh(Yenagoa)} = 326.57 + 0.66Rh$ 6c

$N_{Rh,t(Abakaliki)} = 251.0 + 0.69Rh + 1.78t$ 7a

$N_{t(Abakaliki)} = 280.27 + 3.55t$ 7b

$N_{Rh(Abakaliki)} = 261.73 + 1.37Rh$ 7c

$N_{Rh,t(Ibadan)} = 285.68 + 0.6Rh + 1.39t$ 8a

$N_{t(Ibadan)} = 300.25 + 2.79t$ 8b

$N_{Rh(Ibadan)} = 271.1 + 1.2Rh$ 8c

$N_{Rh,t(Anyigba)} = 358.18 + 0.66Rh + 1.67t$ 9a

$N_{t(Anyigba)} = 446.8 - 3.33t$ 9b

$N_{Rh(Anyigba)} = 269.56 + 1.22Rh$ 9c

$N_{Rh,t(Jalingo)} = 381.84 + 0.67Rh - 3.15t$ 10a

$N_{t(Jalingo)} = 505.25 - 6.29t$ 10b

$N_{Rh(Jalingo)} = 258.43 + 1.33Rh$ 10c

$N_{Rh,t(Sokoto)} = 381.84 + 0.67Rh - 3.15t$ 11a

$N_{t(Sokoto)} = 505.25 - 6.29t$ 11b

$N_{Rh(Sokoto)} = 258.43 + 1.33Rh$ 11c

### 5.2 Performance of Linear Meteorological Model in Estimation of Surface Refractivity

The results of monthly estimates of surface refractivity from new set of meteorological data for a period of 1999 – 2018 using equations 3, 6, 7, 8, 9, 10 and 11 are shown in tables 5 – 10. The values of surface refractivity averaged on monthly basis within the period of 20 years showed that surface refractivity had highest linear dependence on relative humidity in five out of the six locations. The five locations include Yenagoa, Abakaliki, Anyigba, Jalingo and Sokoto. Surface refractivity estimated from ITU-R equation was compared with values from linear meteorological models in equations 6 – 11 to determine the suitability of the expressions.

The mean values of surface refractivity from different linear meteorological models for the six locations are presented in table 11. In Yenagoa, ITU-R had a monthly average value of 381.87 N-Units while $N_{Rh}$ had the closest value of 383.16 N-Units. In Abakaliki, ITU-R had a monthly average value of 370.75 N-Units while $N_{Rh}$ had the closest value of 369.35 N-Units. In Ibadan, ITU-R had a monthly average value of 370.02 N-Units while $N_t$ had the closest value of 370.89 N-Units. In Anyigba, ITU-R had a monthly value of 358.74 N-Units while $N_{Rh}$ had the closest value of 359.58 N-Units. In Jalingo, ITU-R had a monthly value of 338.77 N-Units while $N_{Rh}$ had the closest value of 337.09 N-Units. In Sokoto, ITU-R had a monthly value of 319.09 N-Units while $N_{Rh}$ had the closest value of 319.61 N-Units. The temporal and spatial difference in surface refractivity values estimated from linear meteorological models with highest dependence is given as ±1.12 N-Units when compared with values from ITU-R.

Table 5: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Yenagoa for a period of 1999 – 2018

| Months | $N_{itu-r}$ | $N_{Rh,t(Yenagoa)}$ | $N_{t(Yenagoa)}$ | $N_{Rh(Yenagoa)}$ |
|---|---|---|---|---|
| 1 | 363.77 | 379.11 | 382.64 | 375.58 |
| 2 | 383.28 | 383.13 | 384.86 | 381.41 |
| 3 | 386.42 | 383.99 | 384.23 | 383.75 |
| 4 | 386.54 | 384.03 | 384.17 | 383.90 |
| 5 | 386.89 | 384.23 | 383.72 | 384.75 |
| 6 | 385.46 | 384.21 | 382.62 | 385.81 |
| 7 | 382.87 | 383.80 | 381.99 | 385.60 |
| 8 | 380.17 | 383.30 | 381.54 | 385.05 |
| 9 | 383.83 | 384.07 | 382.19 | 385.96 |
| 10 | 385.49 | 384.17 | 383.01 | 385.32 |
| 11 | 386.98 | 384.06 | 384.39 | 383.73 |
| 12 | 370.75 | 380.45 | 383.85 | 377.05 |

| | | | | |
|---|---|---|---|---|
| **Monthly Mean** | **381.87** | **383.21** | **383.27** | **383.16** |

Table 6: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Abakaliki for a period of 1999 – 2018

| Months | $\mathbf{N_{itu-r}}$ | $\mathbf{N_{Rh,t(Abakaliki)}}$ | $\mathbf{N_{t(Abakaliki)}}$ | $\mathbf{N_{Rh(Abakaliki)}}$ |
|---|---|---|---|---|
| 1 | 330.03 | 331.42 | 365.51 | 335.82 |
| 2 | 371.35 | 352.02 | 377.26 | 365.02 |
| 3 | 378.02 | 355.09 | 376.69 | 371.68 |
| 4 | 378.92 | 355.59 | 376.30 | 373.07 |
| 5 | 379.55 | 355.95 | 375.52 | 374.56 |
| 6 | 379.05 | 356.37 | 371.82 | 379.07 |
| 7 | 377.31 | 355.76 | 370.51 | 379.16 |
| 8 | 376.03 | 355.18 | 370.23 | 378.29 |
| 9 | 377.81 | 355.97 | 371.61 | 378.49 |
| 10 | 378.93 | 356.41 | 372.22 | 378.77 |
| 11 | 374.23 | 353.50 | 375.66 | 369.56 |
| 12 | 347.73 | 340.84 | 371.33 | 348.72 |
| **Monthly Mean** | **370.75** | **352.01** | **372.89** | **369.35** |

Table 7: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Ibadan for a period of 1999 – 2018

| Months | $\mathbf{N_{itu-r}}$ | $\mathbf{N_{Rh,t(Ibadan)}}$ | $\mathbf{N_{t(Ibadan)}}$ | $\mathbf{N_{Rh(Ibadan)}}$ |
|---|---|---|---|---|
| 1 | 342.73 | 359.37 | 366.68 | 352.28 |
| 2 | 371.04 | 371.00 | 373.52 | 368.73 |
| 3 | 375.60 | 372.78 | 373.65 | 372.15 |
| 4 | 377.65 | 373.71 | 373.49 | 374.18 |
| 5 | 377.85 | 374.16 | 372.12 | 376.45 |
| 6 | 375.43 | 373.55 | 370.33 | 377.01 |
| 7 | 373.73 | 373.06 | 369.41 | 376.94 |
| 8 | 371.97 | 372.69 | 368.21 | 377.40 |
| 9 | 375.22 | 373.81 | 369.80 | 378.06 |
| 10 | 376.35 | 373.69 | 371.59 | 376.03 |
| 11 | 371.36 | 371.24 | 372.71 | 370.03 |
| 12 | 351.26 | 362.97 | 369.16 | 357.01 |
| **Monthly Mean** | **370.02** | **371.00** | **370.89** | **371.36** |

Table 8: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Anyigba for a period of 1999 – 2018

| Months | $N_{itu-r}$ | $N_{Rh,t(Anyigba)}$ | $N_{t(Anyigba)}$ | $N_{Rh(Anyigba)}$ |
|---|---|---|---|---|
| 1 | 310.60 | 346.72 | 367.68 | 321.72 |
| 2 | 354.19 | 355.95 | 354.96 | 350.57 |
| 3 | 363.88 | 359.09 | 354.09 | 357.18 |
| 4 | 364.82 | 359.42 | 354.03 | 357.86 |
| 5 | 368.71 | 364.15 | 356.72 | 364.10 |
| 6 | 370.20 | 370.81 | 361.79 | 371.71 |
| 7 | 369.46 | 372.34 | 363.35 | 373.10 |
| 8 | 369.19 | 372.73 | 363.75 | 373.44 |
| 9 | 370.60 | 372.72 | 363.02 | 374.10 |
| 10 | 371.87 | 370.76 | 360.95 | 372.39 |
| 11 | 361.19 | 363.48 | 359.02 | 360.73 |
| 12 | 330.12 | 353.96 | 364.45 | 338.10 |
| **Monthly Mean** | **358.74** | **363.51** | **360.32** | **359.58** |

Table 9: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Jalingo for a period of 1999 – 2018

| Months | $N_{itu-r}$ | $N_{Rh,t(Jalingo)}$ | $N_{t(Jalingo)}$ | $N_{Rh(Jalingo)}$ |
|---|---|---|---|---|
| 1 | 283.17 | 321.98 | 355.74 | 288.24 |
| 2 | 307.86 | 312.42 | 319.95 | 304.85 |
| 3 | 322.58 | 312.11 | 310.83 | 313.29 |
| 4 | 341.74 | 320.35 | 312.27 | 328.20 |
| 5 | 359.84 | 341.17 | 329.70 | 352.21 |
| 6 | 362.29 | 348.49 | 337.31 | 359.18 |
| 7 | 365.60 | 357.57 | 345.92 | 368.63 |
| 8 | 364.25 | 358.98 | 348.25 | 369.13 |
| 9 | 366.15 | 357.76 | 345.61 | 369.34 |
| 10 | 362.14 | 348.04 | 336.68 | 358.91 |
| 11 | 327.98 | 330.85 | 334.67 | 326.79 |
| 12 | 301.62 | 328.06 | 349.64 | 306.36 |
| **Monthly Mean** | **338.77** | **336.48** | **335.55** | **337.09** |

Table 10: Monthly Estimates of Surface Refractivity from Linear Meteorological Models at Sokoto for a period of 1999 – 2018

| Months | $N_{itu-r}$ | $N_{Rh,t(Sokoto)}$ | $N_{t(Sokoto)}$ | $N_{Rh(Sokoto)}$ |
|---|---|---|---|---|
| 1 | 276.13 | 289.67 | 300.32 | 278.81 |
| 2 | 283.63 | 300.08 | 314.14 | 285.76 |
| 3 | 273.52 | 297.91 | 320.64 | 274.88 |
| 4 | 290.79 | 306.81 | 326.21 | 287.09 |
| 5 | 331.74 | 321.98 | 326.31 | 317.33 |
| 6 | 347.40 | 329.10 | 320.51 | 337.40 |
| 7 | 355.37 | 334.67 | 315.33 | 353.74 |
| 8 | 363.85 | 341.26 | 311.48 | 370.79 |
| 9 | 365.93 | 342.13 | 311.97 | 372.04 |
| 10 | 353.01 | 334.84 | 313.03 | 356.39 |
| 11 | 298.71 | 306.43 | 307.20 | 305.44 |
| 12 | 289.03 | 299.13 | 302.38 | 295.66 |
| **Monthly Mean** | **319.09** | **317.00** | **314.13** | **319.61** |

Table 11: Mean Surface Refractivity Values from ITU-R and Linear Meteorological Models for a period of 1999 - 2018

| Stations | $N_{itu-r}$ | $N_{Rh,t}$ | $N_t$ | $N_{Rh}$ |
|---|---|---|---|---|
| Yenagoa | 381.87 | 383.21 | 383.27 | 383.16 |
| Abakaliki | 370.75 | 352.01 | 372.89 | 369.35 |
| Ibadan | 370.02 | 371.00 | 370.89 | 371.36 |
| Anyigba | 358.74 | 363.51 | 360.32 | 359.58 |
| Jalingo | 338.77 | 336.48 | 335.55 | 337.09 |
| Sokoto | 319.09 | 317.00 | 314.13 | 319.61 |

## 5.3 Validation and Comparison of Linear Meteorological Models with ITU-R Equation

The results of surface refractivity estimated from different linear meteorological models were compared in scattered plots to establish levels of disparity in the values obtained. The graphs are presented in figures 2 – 7 showing the line of best fit. Surface refractivity values from $N_{itu-r}$ was compared with values obtained from $N_{Rh}$, $N_t$ and $N_{Rh,t}$ being the contributions of relative humidity, temperature and combination of relative humidity and temperature to linear meteorological models. This was to determine the correlation coefficient and the standard deviation of the surface refractivity from ITU-R results at six locations – 3 from the south and 3 from the north – over Nigeria and the results are shown in table 12.

In Yenagoa, contributions of Rh and t ($N_{Rh,t}$) had the best linear correlation of 0.98 and standard deviation of ±0.32 while temperature contribution ($N_t$) had the least correlation of 0.23 and standard deviation of ±1.09. The contributions of relative humidity ($N_{Rh}$) had a dominance on temperature with correlation of 0.88 and standard deviation of ±1.73. Results from Abakaliki and Ibadan were similar to that of Yenagoa, correlation of $N_{Rh,t}$ with $N_{itu-r}$ was 0.99 at Abakaliki and Ibadan while the standard deviation was ±0.44 and ±0.49 respectively. Similarly, $N_{Rh}$ had a dominance over $N_t$ having correlation of 0.97 and 0.95 at Abakaliki and Ibadan while $N_t$ had correlation of 0.62 and 0.65 respectively. High relative humidity and low temperature values observed in the 3 southern stations – Yenagoa, Abakaliki and Ibadan – significantly enhanced the suitability of $N_{Rh,t}$ linear meteorological model for estimation of surface refractivity values comparable to $N_{itu-r}$.

The remaining 3 stations in the north – Anyigba, Jalingo and Sokoto – had divergent trend from the southern stations. Surface refractivity values obtained from the contributions of temperature ($N_t$) was extremely low and mostly negative. Results from $N_t$ at Anyigba, Jalingo and Sokoto had correlation -0.46, -2.99 and 0.17 while the standard deviation was ±4.21, ±15.53 and ±8.64 respectively. Contrary to the observations in the southern stations, in the northern stations, relative humidity contributions ($N_{Rh}$) had the best linear correlation having 0.96 at Anyigba, 0.98 at Jalingo and Sokoto. Standard deviation was given as ±4.71 at Anyigba, ±6.39 at Jalingo and ±7.17 at Sokoto. The trend in the north was as result of low relative humidity and high temperature.

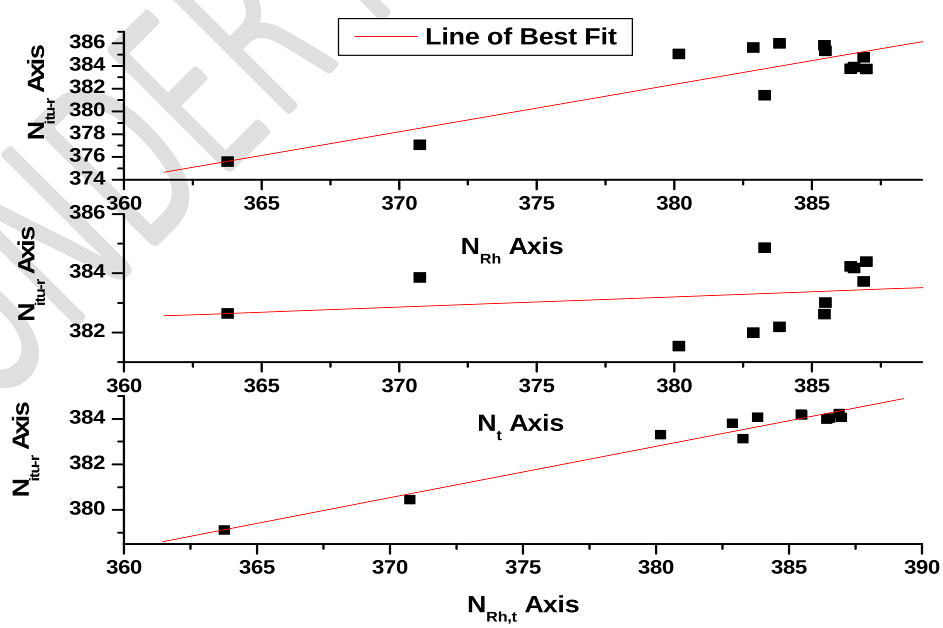

Figure 2: Correlation between ITU-R and Linear Meteorological Models Values for Yenagoa

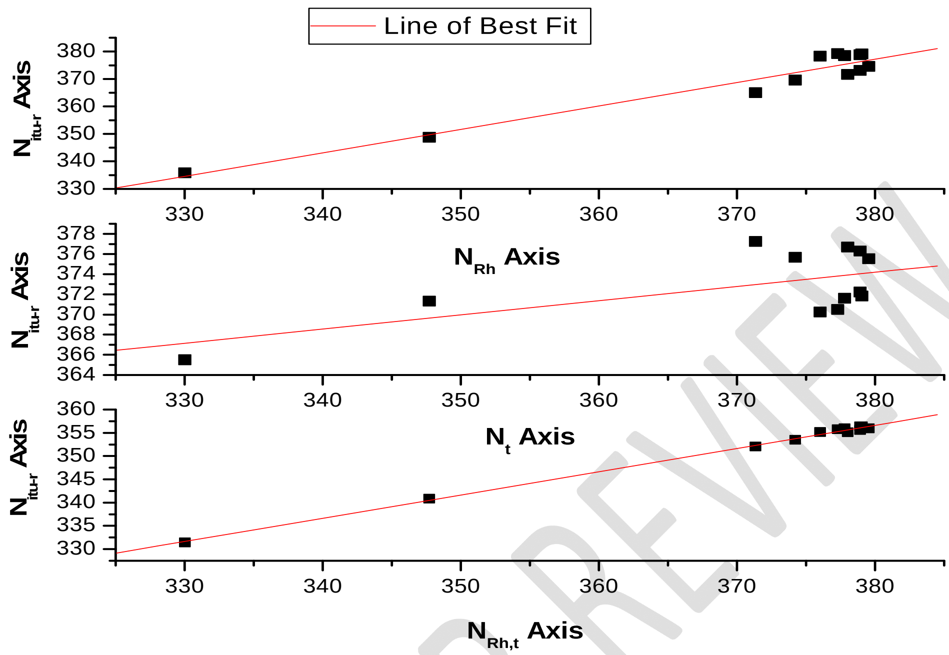


Figure 3: Correlation between ITU-R and Linear Meteorological Models Values for Abakaliki

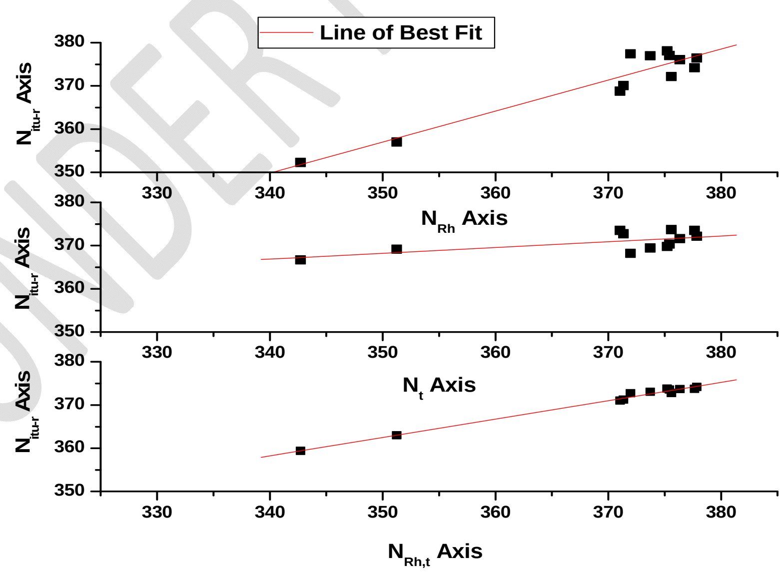


Figure 4: Correlation between ITU-R and Linear Meteorological Models Values for Ibadan

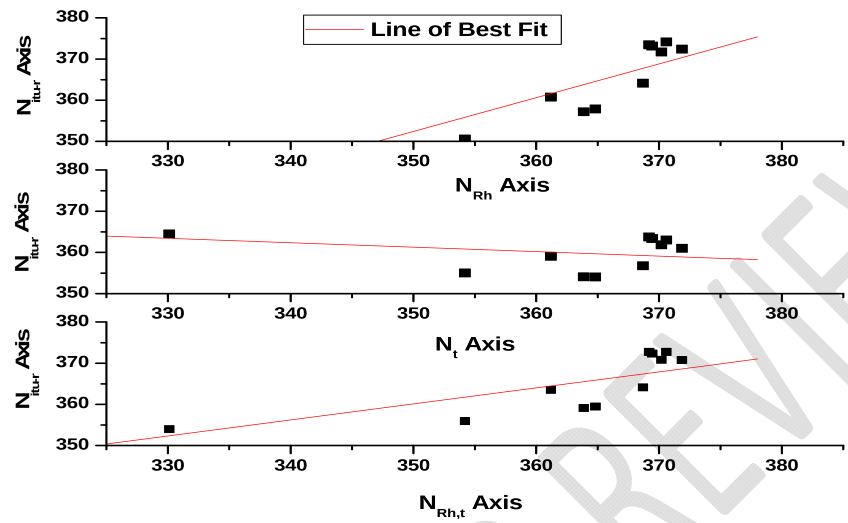


Figure 5: Correlation between ITU-R and Linear Meteorological Models Values for Anyigba

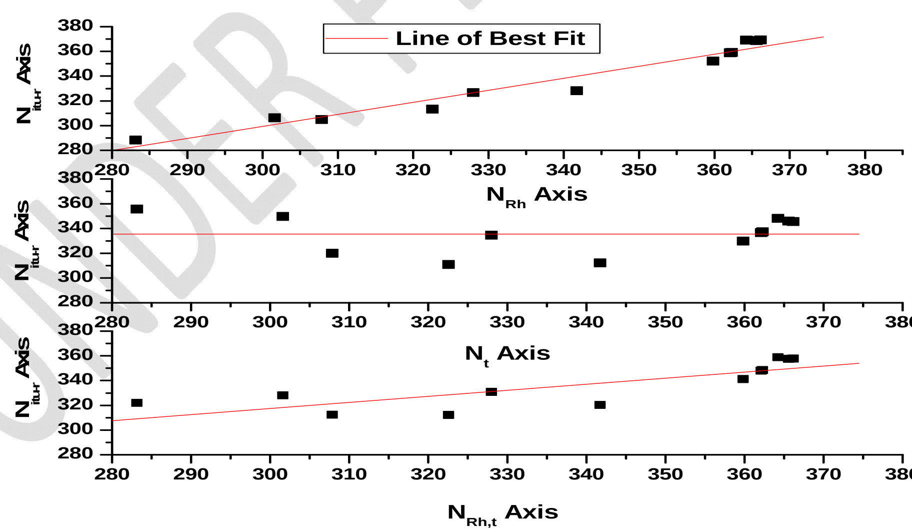


Figure 6: Correlation between ITU-R and Linear Meteorological Models Values for Jalingo

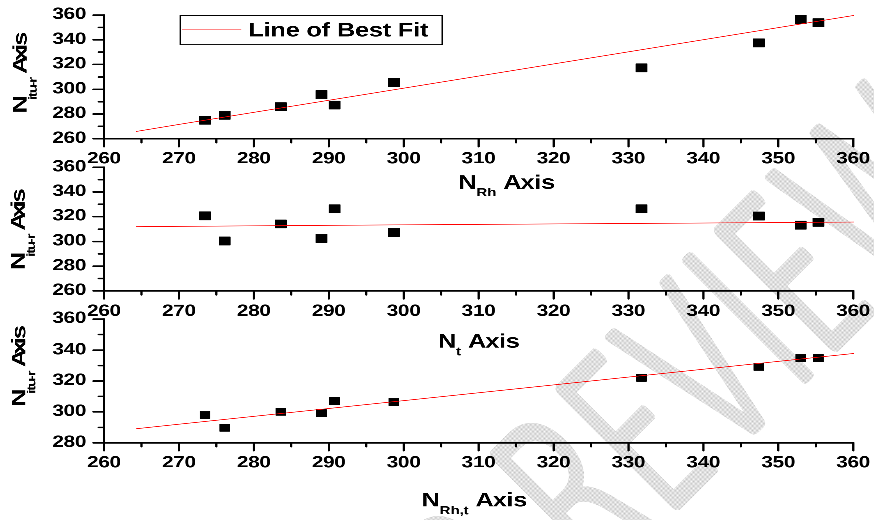


Figure 7: Correlation between ITU-R and Linear Meteorological Models Values for Sokoto

Table 12: Correlation Coefficient (r) and Standard Deviation (σ) between Surface Refractivity Values estimated from ITU-R and Linear Meteorological Models

| Stations | $N_{Rh,t}$ | | $N_t$ | | $N_{Rh}$ | |
|---|---|---|---|---|---|---|
| | r | σ | r | σ | r | σ |
| Yenagoa | 0.98 | 0.32 | 0.23 | 1.09 | 0.88 | 1.73 |
| Abakaliki | 0.99 | 0.44 | 0.63 | 2.83 | 0.97 | 3.52 |
| Ibadan | 0.99 | 0.49 | 0.65 | 1.84 | 0.95 | 2.78 |
| Anyigba | 0.86 | 4.64 | -0.46 | 4.21 | 0.96 | 4.71 |
| Jalingo | 0.81 | 10.83 | -2.99 | 15.53 | 0.98 | 6.39 |
| Sokoto | 0.99 | 2.91 | 0.17 | 8.64 | 0.98 | 7.17 |

## 6.0 Conclusion

The problem of quantifying surface refractivity as a function of atmospheric variables in various climatic situations is very complex because the three meteorological variables involved are neither perfectly correlated nor totally uncorrelated. In this study, new sets of linear expressions were obtained in terms of meteorological parameters from six locations across Nigeria as alternate means of estimating surface refractivity. The linear expressions were validated using data obtained for a period of 20 years and compared with results from existing equations. Linear expressions as a function of relative humidity and temperature were best suitable for stations in the south with minimum correlation of 0.98 while linear expressions as a function of relative humidity only were best suitable for the stations in the north with minimum correlation of 0.96.

The sensitivity of the parameters showed that surface refractivity is much more likely to vary due to moisture changes in the atmosphere than temperature changes. In the northern Nigeria, relative humidity changes near the surface have more than twice the impact on refractivity as temperature changes. This is partly a result of the high variability of humidity and partly due to the inherent sensitivity of refractivity to moisture in the additional wet term, which is also a maximum in wet months.

At low temperatures, surface refractivity varies very little with relative humidity because the saturation vapour pressure is low: as air temperatures increase, the saturation vapour pressure rises, expanding the range of possible refractivity values. Hence, estimation of surface refractivity from linear meteorological models is mainly a function of low temperature and high relative humidity in the south and a function of relative humidity in the north.

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