International Journal of Physical Research, 12 (2) (2024) 116-122

International Journal of Physical Research

Website: www.sciencepubco.com/index.php/IJPR

Research paper

Investigating tropospheric radio refractivity variation with weather parameters in Kampala, Uganda: implications for communication systems

Musa Bawa [1] *, Afam Uzorka [1], Living Ounyesiga [1],Rabiu Tukur[2]

[1] *Department of Physical Science, School of Natural and Applied Sciences, Kampala International University, Kampala, Uganda*
[2] *Department of Geography, Faculty of Arts and Social Sciences, Islamic University in Uganda, Main Campus Mbale, Uganda*
**Corresponding author E-mail: musa.bawa@kiu.ac.ug*

Abstract

The tropospheric radio refractivity plays an important role in the propagation of radio waves and significantly affecting the performance of radio communication systems. This study aims to investigate the influence of weather parameters on tropospheric radio refractivity variation and the implication for communication system in Kampala, Uganda. Through a comprehensive dataset of temperature, humidity and pressure obtained from the National Aeronautics and Space Administration (NASA) archives for Kampala over a period of one year (January 2023 to December 2023). Using the International Telecommunication Model (ITU-R model), radio refractivity was computed from the collected weather parameters, and subsequently correlate with weather parameters. The analyses of the results showed that, radio refractivity displayed seasonal variability with high values in the wet season with a peaks points observed in April and October (339N and 338N) and a low value during dry season, July and January (328N and 324). It was also observed that the Relative humidity and Temperature are the main force driven the variations of radio refractivity. Hence, the work could be used for rapid and precise estimation of link budgets while planning and designing radio links budget in Kampala and regions of similar climatic characteristics.

Keywords: *Tropospheric Radio Refractivity; Weather Parameters; Communication Systems.*

1. Introduction

The influence of tropospheric radio refractivity variation on communication through troposphere have been well known for some time [1], [2], [3]. Radio refractivity of the Troposphere is a critical factor in the propagation of radio waves, which significantly affecting the reliability and quality of communication systems [4]. Radio refractivity is the measure of the deviation of refractive index, n, of the air from unity. Upon deviation from standard condition, anomalous propagations are usually experienced within the atmosphere. Changes in climatic condition, such as temperature inversion and high humidity, are thought to be responsible for these anomalies [5]. The refractive index varies with altitude, humidity, temperature, and pressure, which lead to the decreased in radio signal strength and quality [6]. The significance of understanding and estimating these variations cannot be overemphasized, particularly for the design and operation of terrestrial communication systems. Therefore, quantitative knowledge of radio refractivity is essential in order to be able to design reliable and efficient radio communication (terrestrial and satellite) system [7].

Radio wave propagation in the troposphere is essentially defined as propagation within a non-ionized medium. This is a region where meteorological phenomena like wind and rain occur, which are influenced by air pressure, temperature, and relative humidity [8]. The proportional significance of radio wave propagation in space communications is determined by the frequency of operation, local climatology, topography, transmission type, and satellite elevation angle. To keep a communication link reliable, the transmission medium often affects signal quality. When this medium includes the troposphere, it’s crucial to ensure the signal can handle troposphere-induced issues. These issues are caused by changes in temperature, humidity, air pressure, rain, and atmospheric gases [7].

Kampala, Uganda's capital, experiences a tropical rainforest climate with significant year-round variation. Two main rainy seasons were experiences in the city; from March to May and from September to November, which bring high humidity levels and significant temperature fluctuations [9]. These climatic conditions made Kampala an ideal location for studying the impact of weather parameters on tropospheric radio refractivity. Kampala's fast urbanization and expansion of communication infrastructure necessitate a full understanding of how local weather conditions influence radio wave propagation. Effective communication networks are critical to the city's growth, supporting emergency services, business operations, and personal communications. This study intends to provide insights that will help in the planning, deployment, and maintenance of communication networks in the Kampala city and other region with similar weather condition. Furthermore, the research will not only benefit local telecommunication operators and broadcasters but also provide valuable data for policymakers and engineers working to enhance Uganda's overall communication infrastructure.

Several studies across different locations around the globe have explored the relationship between atmospheric parameters and radio wave propagation, providing a comprehensive understanding of how atmospheric parameters influenced the variation radio refractivity and consequently affected the propagation of radio wave. Studies by [4], [5], [7], [10], [11], [12], [13], [14], [15], [16] shows that refractivity values are higher during the rainy season compared to the dry season. These values also vary across different climate zones and depend on local weather conditions. The researchers found that relative humidity has the greatest impact on radio refractivity, followed by temperature and pressure.

Furthermore, studies in areas with similar weather patterns to Kampala, such as tropical region, provide an important insight into the impact of meteorological conditions on tropospheric radio refractivity. [11], [17], [18], [19], [20] carried out comprehensive research on the impact of atmospheric variables on tropospheric radio refractivity in tropical region. Their findings revealed that high humidity and temperature variations significantly influenced the radio refractivity and consequently affecting radio signal propagation. Despite these development, there remains a gap in lack of localized climatic data for Kampala. Existing refractivity models often rely on climatic data obtained from temperate region of the world, which may not accurately reflect the specific weather conditions in Kampala. The unique combination of high humidity, frequent rainfall, and varying topography in Kampala necessitates comprehensive research to accurately estimate and predict radio wave behavior under its specific climatic conditions.

As a result, this research estimate and investigate the tropospheric radio refractivity variation with weather parameters using measured average daily temperature, relative humidity, and atmospheric pressure for a period one-year of (January 2023 to December 2023) obtained from the National Aeronautics and Space Administration (NASA) archives for Kampala (0.3152 °N, 32.5816 °E), Uganda. The experiments presented involve an indirect measurement, in which the value of refractivity is calculated from the atmospheric pressure, temperature, and water vapor pressure using an empirical formula provided by the International Telecommunication Union [21].

2. Theoretical background

The troposphere is the layer of the atmosphere that extends from the Earth's surface up to about 10-14 km. This region is dense with gases, mainly molecular nitrogen (N2) and molecular oxygen (O2). All weather-related phenomena occur in the troposphere, which contains over 75% of the Earth's atmospheric mass and 99% of its water vapor [22]. This layer influences electromagnetic wave propagation due to elements like rain, clouds, vapor, and gases. Additionally, the temperature in the troposphere gradually decreases with height.

2.1. Temperature

This is the variation in the atmospheric conditions that can be subjectively described in terms of relative concepts of coldness or hotness. The objective quantity corresponding to this concept is the temperature which is measured either in degrees Celsius (^oC) or in Kelvin (K). The temperature in Celsius is converted to the temperature in Kelvin by the expression:

$$T = 27315 + t\,(\text{K}), \tag{1}$$

where T is temperature in degree Kelvin and t is temperature in degree Celsius [23].

2.2. Pressure

Atmospheric pressure is the force exerted by the atmosphere on a surface due to its weight. It is the weight of a column of air above a unit area, extending to the outer edge of the atmosphere [24]. Under normal atmospheric conditions, the atmospheric pressure decreases with increasing altitude. The variation of pressure with height in the atmosphere can be expressed by the hydrostatic equation,

$$\frac{dp(z)}{dz} = -\rho(z)g, \tag{2}$$

Where ρ(z) is the mass density of air at height p, z and g is the pressure and acceleration due to gravity respectively.
From ideal gas law,

$$\rho(z) = \frac{M_{air}\,p(z)}{RT(z)}\ (\text{kg/m}^3), \tag{3}$$

Where M_{air} is the average molecular weight of air (28.97 mol^{-1}), T is the absolute temperature in Kelvin and R is the ideal gas constant. Substituting equation 3 in equation 2 and solving for ρ, then,

$$\rho(z) = \rho_o e^{-\frac{z}{H}}\ (\text{kg/m}^3), \tag{4}$$

Where H is called scale height and equal to 8 km in the lower atmosphere when $T = 273$K
H is defined as:

$$H = \frac{RT}{M_{air}\rho_o g} \text{ (km).} \tag{5}$$

2.3. Relative humidity

Humidity is the amount of water vapor in the atmosphere, measured as vapor density or vapor pressure. Relative humidity (H) is expressed as a percentage. When it reaches 100%, the air is saturated, and water vapor condenses into liquid droplets, forming rain, fog, and clouds [25].

2.4. Saturation vapour pressure

The saturation vapour pressure, e_s, is the vapour pressure the air would have if it were saturated.

$$e_s = a\exp\left\{\frac{bt}{t+c}\right\}, \tag{6}$$

Where, t, is temperature in Celsius, $a = 6.1121$, $b = 17.502$ and $c = 240.97$[21].
The water vapour partial pressure, e, can be determined from the relative humidity, H, expressed in percentages, and from the saturated water vapour pressure, e_s, expressed in hPa using the expression [21]:

$$e = \frac{He_s}{100}. \tag{7}$$

3. Refractive index and refractivity of the troposphere

The radio refractive index is the ratio of the speed of radio waves in a vacuum to their speed in a specific medium. In the troposphere, the refractive index is about 1.0003, very close to that of free space (n = 1.0). To simplify, we use refractivity (N), which measures the deviation of the refractive index from 1, scaled up to parts per million for easier figures. Thus, N is a dimensionless quantity measured in N-units [26].
The Refractivity, N, is related to refractive index of air [21] as follows;

$$N = (n-1)\times 10^{-6}, \tag{2.8}$$

Where N is radio refractivity expressed by:

$$N = N_{dry} + N_{wet} = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right), \tag{2.9}$$

With the ‘dry term’ of radio refractivity given by:

$$N_{dry} = 77.6\frac{P}{T}, \tag{2.10}$$

And the ‘wet term’ given by:

$$N_{wet} = 3.732\times 10^{5}\frac{e}{T^2}, \tag{2.11}$$

Where P is atmospheric pressure (hPa), e is water vapor pressure (hPa), and T is absolute temperature (K).
This expression can be used for all radio frequencies up to 100 GHz, with an error of less than 0.5%, for typical profiles of temperature, pressure, and water vapor pressure. The water vapor pressure, e, can be calculated from relative humidity using equation (7).

4. Methodology

The location of the study is showed in Figure 1. Kampala city the capital of Uganda, situated in the central part of the country, on the northern shores of Lake Victoria. It lies between latitudes 0.3° and 0.4° N and longitudes 32.5° and 32.6° E, it covers an area of approximately 189 square kilometers, with an elevation ranges between 1,150 meters and 1,300 meters above sea level, which contributes to its unique climatic conditions. In this research, monthly average daily data for atmospheric pressure, relative humidity, and temperature from the National Aeronautics and Space Administration (NASA) were used to estimate tropospheric radio refractivity and study its variation with other meteorological parameters for the period from January 2023 to December 2023. The average hourly data for each month was further averaged to obtain a single data point per month. This data was then used to determine the seasonal variation of radio refractivity using an empirical formula provided by the International Telecommunication Union [21]. The collected weather parameters and radio refractivity computed values undergo rigorous statistical analysis to identify the patterns, trends, and quantify the correlations between weather parameters and tropospheric radio refractivity. Microsoft Excel (2016) is used for the data analysis.

Fig. 1: Map of the Area of Investigation.

5. Results and discussions

5.1. Average seasonal variations of surface radio refractivity

Figure 2 depict the average seasonal variations of surface radio refractivity variations for Kampala for the period of one year (January 2023 to December 2024). As observed from the plot, there is a gradual increase in the value of radio refractivity from January (323N) to a peak in April (339N). Following the peak in the month of April, decreases steadily through May, attained a low point in July around (327N), before starting to rise again in August to September. Furthermore, radio refractivity increases again from September to attaining another peak in October (338N-339N), and then slightly decreases towards December.

The peaks points observed in April and October, these months coincided with wet season in Kampala city. During wet season, the atmosphere is mostly dominated by moist content of water vapor which increases the humidity in the atmosphere and consequently the surface radio refractivity. These results agree with the work of [13], [27], [28], [29]. Furthermore, the lower values observed in July and January correspond to dry season months in Kampala city, during the period higher temperature is observed which leads to an extreme reduction of water vapor content of the atmosphere and consequently the observed low values of radio refractivity in the city.

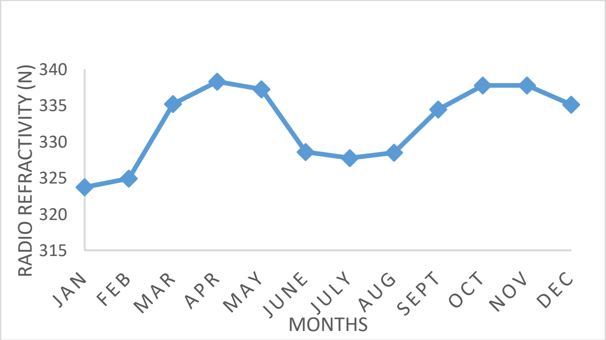

Fig. 2: Average Seasonal Variation of Radio Refractivity for Kampala.

5.2. Variations of radio refractivity with relative humidity

Figure 3 depicts the monthly mean variations of radio refractivity with Relative Humidity. As observed from the graph, radio refractivity shows strong dependence on the wet term (Humidity). This is evidence as the peaks in radio refractivity align with higher relative humidity, indicating a direct influence of humidity on refractivity. This is noticeable particularly during the months of April and October. The regression analysis between radio refractivity with relative humidity gave a strong positive correlation value of 0.88. This confirms the prediction that relative radio refractivity is directly proportional to relative humidity [30], [31].

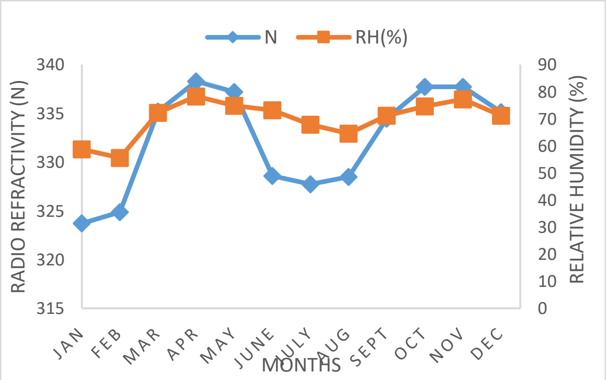

Fig.3: Monthly Mean Variation of Radio Refractivity with Relative Humidity.

5.3. Variations of radio refractivity with temperature

Figure 4 depicts the monthly mean variations of radio refractivity with Temperature. As observed from the graph, the variation pattern of the two parameter showed an opposite trend. As the temperature increases the radio refractivity decreases. The regression analysis between radio refractivity with temperature gave a strong negative correlation value of -0.63. This showed that while temperature is a key factor, other parameters like relative humidity and pressure also play crucial roles in the variation of radio refractivity [13], [27].

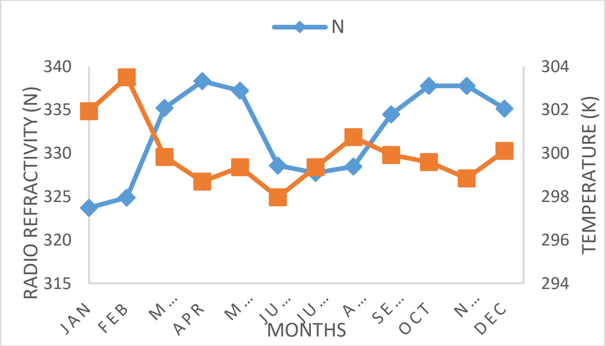

Fig. 1: Monthly Mean Variation of Radio Refractivity with Relative Temperature.

5.4. Variations of radio refractivity with pressure

Figure 4 depicts the monthly mean variations of radio refractivity with Pressure. As observed from the graph, the variation pattern of the two parameter showed some level of disparity with weak correlation value of -0.18 suggesting that other factors, such as temperature and humidity, play more significant role. This confirmed the results by [7] that other factors, such as temperature and humidity, play more significant role in the variation of radio refractivity.

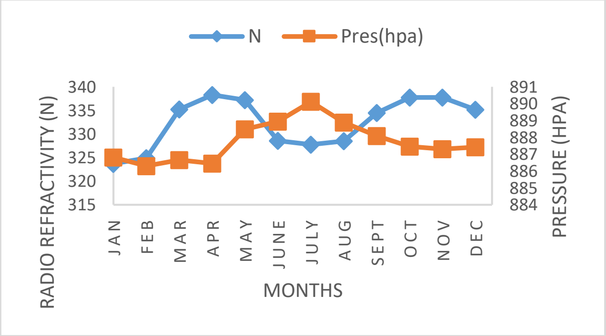

Fig. 2: Monthly Mean Variation of Radio Refractivity with Pressure.

5.5. Implication of the result

Hence, the implications of the results for communication systems is that, high radio refractivity values in the months (April and October), radio waves might experience more bending, leading to an extended communication ranges as well as more interference and signal degradation. However, low radio refractivity values observed in (July and January), communication ranges might be shorter, but more steady, with less signal bending [7]. To mitigate signal degradation, the communication systems should be designed with adaptive modulation and coding schemes, also additional repeaters or relay stations should be deployed so as to ensure signal integrity during these high refractivity variation periods.

6. Conclusion

This study determined the variations in radio refractivity with Weather parameters and their implications for communication systems over Kampala city, Uganda. One year (January 2024 to December, 2024) weather parameters data obtained from National Aeronautics and Space Administration (NASA) archives for Kampala were used for the study. The major findings of this study are as follows:

- Radio refractivity displayed seasonal variability with high values in the wet season and low values during dry season.
- Radio refractivity shows strong dependence on the wet term (Humidity) with a strong positive correlation value.
- Radio refractivity decreases with the increase in temperature with a strong negative correlation value.
- Atmospheric pressure has less effect in the variation of radio refractivity.
- Relative humidity and Temperature are the main force driven the variations of radio refractivity.
- Radio refractivity is a function of local climatology.

7. Recommendation

The following recommendations are made for future work

1) In-situ measurement of weather parameters should be carried out using weather station in Kampala city, as it provides a high precision and detailed temporal resolution crucial for local and real-time applications.

2) Long time measurement and prediction of radio refractivity in Kampala city should be carried out so as to validate the present research.
3) More measurement and prediction of radio refractivity should be carryout in other part of Uganda with different geographic climatic condition.

Competing interests

None

Funding

None

Ethical approval

Not applicable

Consent to participate

Not applicable

Availability of data and material

All data used will be made available on request.

Code availability

Not applicable

Author contributions

B.M. contributed to the study conception. B.M., A.U., L.O., T.R. contributed to the study, design, and all aspect of the manuscript. The first draft of the manuscript was written by B.M., A.U., L.O., T.R., and B.M., A.U., L.O., T.R. read and approved the final manuscript.

Consent to publish

The authors hereby grant consent for the publication of the work.

References

[1] M. G. Hamza, L. A. Latiff, E. M. Mustafa, and W. M. Gasim, “Radio propagation and troposphere parameters effect for Microwave links in Sudan,” Proc. - 2017 Int. Conf. Commun. Control. Comput. Electron. Eng. ICCCCEE 2017, pp. 0–4, 2017, doi: 10.1109/ICCCCEE.2017.7867670.

[2] R. Mat, N. H. Sabri, R. Umar, and S. Ahmad, “Effect of Humidity on Tropospheric Received Signal Strength (RSS) in Ultra-High Frequency (UHF) Band Effect of Humidity on Tropospheric Received Signal Strength (RSS) in Ultra-High Frequency (UHF) Band,” 2020, doi: 10.1088/1742-6596/1529/4/042048.

[3] A. T. Adediji, M. O. Ajewole, and S. E. Falodun, “Distribution of radio refractivity gradient and effective earth radius factor (k-factor) over Akure, South Western Nigeria,” J. Atmos. Solar-Terrestrial Phys., vol. 73, no. 16, pp. 2300–2304, 2011, doi: 10.1016/j.jastp.2011.06.017.

[4] M. M. Tanko, M. S. Liman, W. L. Lumbi, U. S. Aliyu, and M. U. Sarki, “Field Strength Variability Mapping of Nigeria,” J. Niger. Soc. Phys. Sci., vol. 4, no. 3, pp. 1–6, 2022, doi: 10.46481/jnsps.2022.746.

[5] K. O. Suleman, S. B. Suleiman, L. A. Sunmonu, and A. L. Sheu, “Estimation of Refractivity Gradients and Effective Earth Radius Factor (K-Factor) In the Lowest 100 m of the Atmosphere over Ogbomoso , South western Nigeria,” J. Eng. Technol. Ind. Appl., vol. 10, no. 46, pp. 27–32, 2024.

[6] K. E. Ukhurebor, O. S. Akinola, and W. Nwankwo, “Evaluation of the Effects of some Weather Variables on UHF and VHF Receivers within Benin City , South-South Region of Nigeria Evaluation of the Effects of some Weather Variables on UHF and VHF Receivers within Benin City , South-South Region of Nigeria,” J. Phys. Conf. Ser. Pap., no. August, 2019, doi: 10.1088/1742-6596/1299/1/012052.

[7] B. G. Ayantunji, F. D. Chizea, B. Musa, and A. S. Adewumi, “An Empirical Analysis of Atmospheric Radio Refractivity Effect on Signal Quality at UHF Band in a Tropical Environment,” Int. J. Appl. Phys. (SSRG- IJAP), vol. 6, no. 1, pp. 7–16, 2019.

[8] Sa’adu, L., Bawa, M., and Bello, M., “A Review on the Effects of Radio Refractivity and Atmospheric Parameters on Signal Quality at Ultra High Frequency (UHF),” Int. J. Sci. Glob. Sustain., vol. 6, no. 2, p. 9, 2020, doi: 10.57233/ijsgs.v6i2.112.

[9] Uganda National Meteorological Authority., Climate of Uganda. 2020.

[10] A. T. Adediji, M. Ismail, and J. S. Mandeep, “Variation of radio fi eld strength and radio horizon distance over three stations in Nigeria,” J. Atmos. Solar-Terrestrial Phys., vol. 109, pp. 1–6, 2013, doi: 10.1016/j.jastp.2013.12.006.

[11] S. Ali, S. A. Malik, K. S. Alimgeer, S. A. Khan, and R. L. Ali, “Statistical estimation of tropospheric radio refractivity derived from 10 years meteorological data,” J. Atmos. Solar-Terrestrial Phys., vol. 77, pp. 96–103, 2012, doi: 10.1016/j.jastp.2011.12.001.

[12] B. G. Ayantunji, P. N. Okeke, and J. O. Urama, “Seasonal variation of surface refractivity over Nigeria,” Adv. Sp. Res., vol. 48, no. 12, pp. 2023–2027, 2011, doi: 10.1016/j.asr.2011.08.025.

[13] G. S. M. Bawa, M., Galadanci, B. G. Ayantunji, M. T. Muhammad, and I. Umar, “Variation Of Meteorological Parameters And Its Effect On Refractive Index Of Air Over Lagos Nigeria,” Bayero J. Pure Appl. Sci., vol. 10, no. 2, pp. 222–225, 2017.

[14] and M. M. . Musa, B., Galadanci G.S.M, Ayantunji B.G, Mai-Unguwa H, “Study of Average Seasonal Variations of Surface Radio Refractivity Across Some Selected Cities In Nigeria,” Bayero J. Pure Appl. Sci., vol. 10, no. 2, pp. 251–255, 2017.

[15] O. S. Macaulay and E. K. Makama, “Characteristics of Tropospheric Scintilation for Satellite Applications In Jos,” IEEE Xplore, no. September, pp. 5–8, 2020.

[16] A. A. Segun, A. M. Olusope, and A. H. Kofoworola, “Influence of Air Temperature, Relative Humidity and Atmospheric Moisture on UHF Radio Propagation in South Western Nigeria,” 2013. [Online]. Available: www.ijsr.net

[17] Z. Akpootu, D. O., 1Aminu, M. Nouhou, I., Yusuf, A., Idris, and O. E. Aliyu, M. A. Salifu, S. I., Kola, T. A and Agidi, “Assessment of Tropospheric Radio Refractivity and Its Variation with Climatic Variables Over Zaria , Nigeria,” Dutse J. Pure Appl. Sci. (DUJOPAS), vol. 10, no. 1, pp. 243–255, 2024.

[18] D. O. Akpootu et al., “Performance Analysis of Tropospheric Radio Refractivity on Radio Field Strength and Radio Horizon Distance and Its Variation with Meteorological Parameters over Osogbo, Nigeria,” Int. J. Adv. Sci. Res. Eng., vol. 05, no. 10, pp. 81–97, 2019, doi: 10.31695/ijasre.2019.33545.

[19] A. A. Segun, A. D. Kehinde, and A. A. Adebambo, “Analysis of Radio Refractivity Variations Across Geographical Coordinates of Nigeria,” J. Inf. Eng. Appl., vol. 8, no. 3, pp. 1–6, 2018.

[20] D. O. A. and M. I. Iliyasu, “Estimation of Tropospheric Radio Refractivity and Its Variation with Meteorological Parameters over Ikeja , Nigeria,” J. Geogr. Environ. Earth Sci. Int., no. January 2017, 2019, doi: 10.9734/JGEESI/2017/32534.

[21] ITU – R., “The refractive index: its formula and refractivity data,” in Recommendation 203/1, 2015, pp. 253–9.

[22] H. Zell, “Earth’s Atmospheric Layers,” NASA.

[23] H. Chang, “’Theory, Measurement, and Absolute Temperature,” in Measurement and Scientific Progress, Online., New York, 2004, pp. 159–219. doi: https://doi.org/10.1093/0195171276.003.0004.

[24] Sizum H., Radio wave propagation for communication applications. 1997.

[25] S. E. Schulze, “South African atlas of Agrohydrology and Climatology,” pp. 16–22, 1997.

[26] K. A. Hughes, “Radio Propagation Data from Tropical Regions,” in A Brief Review of a seminar on Radio Propagation in Tropical Regions, 1993.

[27] B. Musa, B. G. Ayantunji, G. S. M. Galadanchi, and S. Idris, “Study of Average Hourly Variations of Radio Refractivity Variations across Some Selected Cities in Nigeria,” J. Appl. Phys., vol. 7, no. 6, pp. 37–43, 2015, doi: 10.9790/4861-07613743.

[28] A. T. Adediji and M. O. Ajewole, “Journal of Atmospheric and Solar-Terrestrial Physics Microwave anomalous propagation (AP) measurement over Akure South-Western Nigeria,” J. Atmos. Solar-Terrestrial Phys., vol. 72, no. 5–6, pp. 550–555, 2010, doi: 10.1016/j.jastp.2010.02.008.

[29] A. A. Willoughby, T. O. Aro, and I. E. Owolabi, “Seasonal variations of radio refractivity gradients in Nigeria,” J. Atmos. Solar-Terrestrial Phys., vol. 64, pp. 417–425, 2002.

[30] B. G. Ayantunji, B. Musa, L. A. Sunmonu, A. S. Adewumi, L. Sa, and A. Kado, “Atmospheric Humidity and Its Implication on UHF Signal over Gusau, North West, Nigeria,” Int. J. Sci. Eng. Res., vol. 9, no. 3, pp. 599–611, 2018.

[31] J. Amajama, “Impact of Weather Components on (UHF) Radio Signal,” Int. J. Eng. Res. Gen. Sci. ·, vol. 4, no. 3, pp. 481–495, 2016, [Online]. Available: https://www.researchgate.net/publication/303882242