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Article

Effect of Weather Condition on QoCS Beam of Downlink Microwave Radio Signals for High-Definition Digital Terrestrial Link over Abuja, Nigeria

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***Abstract*— High-Definition Digital Terrestrial Television (HDDTT) replaces analogue, requiring further research on propagation links due to atmospheric variables potentially disrupting signals during uplink and downlink reception. This study examines the impact of surface meteorological parameters on the downlink Receive Signal Strength (RSS) of an HDDTT station in a tropical location-Abuja, Nigeria. The impact of k-factor, Radio Refractivity (RaR), refractivity gradient, and Radio Horizon distance (dRH) on HDDTT RSS are also investigated. The assessments were based on an experimental setup over 12-months (Jan.–Dec., 2020). The RSS link values showed strong negative correlations with temperature, pressure, and water vapor during the day, while weak negative correlations were observed with relative humidity. A very weak correlation was also observed between RSS link and RaR, which implies a significant influence of RaR on the RSS under clear weather. With average peak and lowest values of about 364.73 and 271.91 (N-units), respectively, RaR values are slightly higher during the rainy periods, with the dry component accounts for more than 69.70% of the total values. The mean monthly k-factor and dRH are 1.39 and 133.17 km, respectively. This information will assist radio engineers in enhancing HDDTT broadcast signals, ensuring high-quality service, and fostering customer service agreements.**

***Index Terms*—** HDTTT, Microwave propagation, QoCS of Downlink link, Weather variables.

I. INTRODUCTION

Meteorological parameters are useful for the prediction of the spatial distribution of refractivity, identified as one of the major causes of the anomalous behaviour of radio waves propagating through the atmosphere [1]. Radio waves are characterized by their wavelengths, distinguishable as short, medium, or millimeter waves, such that with higher frequency (f), there is significant reduction in the wavelength (λ) and bandwidth efficiency [2]. This makes them susceptible to fading and scattering when impinged by meteorological variables.

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The transmission path is usually a significant cause of signal clarity impairment when radio signals traverse across long distances [3]. The lowermost portion of the atmosphere encompassing the earth, described as the troposphere, is made up of about 99% of volume of water vapour in the atmosphere and is used as a medium for conveying radio communications. Thus, the quality of radio signal received is impinged by fluctuations in weather variables [4]. Relative humidity, the measure of water content of the atmosphere, is one of the most important radio-climatic parameters that characterize the troposphere and determines the permittivity and permeability of the atmosphere because water volume has variations in these factors in free space and between different mediums. Thus, the porosity and permissiveness of the environment through which electromagnetic waves travel influence their ability to propagate which underpins the importance of investigating the anomalous conditions experienced along the path of a radio link propagating through the troposphere due to changes in climatological parameters [5].

When designing radio communication systems operating above 30 MHz which are highly susceptible to distortions, radio engineers use statistical analysis of atmospheric refractive index data and its derivatives to predict the systems performance [6]. Radio refractivity (RaR) is used to study how the troposphere interacts with propagating radio links, assessing its quality and the characterization of propagation mode [7].

The study and measurement of atmospheric parameters has aroused considerable interest primarily on weather forecast, flood prediction, and agricultural purposes and, to a lesser extent, on radio-wave communication because of its influence in the lower atmosphere. Over the years, attention has been diverted to the influence of atmospheric variables on radio propagation studies as reported in the works of [6], [8]-[17]. In all the aforementioned reports, studies on radio refractivity have mostly been focused on anomalous behaviour and few on influences on mobile networks. More recently, however, efforts have been made to assess the impact of atmospheric variables on television broadcasting signal receptions; this includes the work of [17]-[25], to mention but a few. The aforementioned works only concentrated on the influence of atmospheric variables on UHF and VHF signals, which are basically analogues. Although [4] investigated the impact of atmospheric parameters and noise temperature on digital terrestrial television signal strength over Abuja (the same location under study), only time series analysis was considered over many broadcasting stations without significant emphasis on correlations. Also, [26] carried out a statistical analysis of atmospheric parameters, noise temperature, and digital terrestrial television signal strength over Jos metropolis, Plateau State, Nigeria. However, the location is different from the present study area, and radio refractivity due to clear effect was not considered.

The transition of terrestrial broadcasting to digital technology and the changing nature of atmospheric variables as a consequence of climate change highlight the need for this study, which calls for advanced research requiring reliable and accurate models for planning and execution. Consequently, by offering comprehensive information particularly tailored to a geographical region with high demand for HDDTT services, the current study significantly advances the field of HDDTT systems. The research addresses a significant knowledge gap about how weather conditions affect terrestrial broadcasting signal propagation in these regions by examining the specific influence of weather-related factors on HDDTT signals. This is especially crucial for the efficient implementation of HDDTT networks in tropical regions around the world.

Instead of using data from satellites, this study uses measurements of atmospheric variables taken on the ground. This makes it a better fit for looking at how the changes directly affect the quality of signals received by HDDTT in the study area. Thus, this study comprises an evaluation of the daily and seasonal fluctuations of the surface radio refractivity and their effect on the downstream Africa Independent Television (AIT) broadcast signal propagating over Abuja, as well as the results of an on-site assessment of the temperature, pressure, humidity, and AIT (535.2 MHz) received signals obtained from January 1 to December 31, 2020.

II. METHODOLOGY

A. *Study Area*

Fig. 1 shows where the study is being conducted, while the geographical location of the GW and distance of the measurement site and the distance from the HDDTT station are shown in Fig. 2. The study was carried out in Abuja (9°326 N, 7°2923 E) the Federal Capital Territory of Nigeria. As a tropical location that belongs to the central northern portion of Nigeria, it receives intense heat within the non-rainy months and humid, warm conditions within the rainy months, attributable to the Inter-tropical Convergence Zone (ITCZ). The ITCZ is the convergence point of easterly trade winds that shift with the position of heavy precipitation, originating from both the northern and southern hemispheres [27]. There are two main seasons in this location: the rainy/wet and the dry. The wet months are marked by sporadic rainfall between March and October, while the dry months are characterized by little to no rainfall and a brief period of dry, dusty air between November and February each year. The site was selected because of its commercial significance and it's being the administrative capital of the country, which allows for the reception of numerous radios propagation channels.

B. *Instrumentation and Measurements*

The setup is composed of a weather station (automatically controlled-type) that monitors the humidity and atmospheric pressure simultaneously from January 1 to December 31, 2020, and a CATV signal strength meter linked to a Yagi antenna over a 5 m high pole that measures the signal strength of African Independent Television, Abuja (AIT) operating at 535.2 MHz. Every minute at an interval (integrated over a 24-hour period), the relative humidity, pressure level, and temperature are obtained in conjunction with the daily received signal level of Africa Independent Television. The data is then saved on a personal computer. The setup at the location is shown in Fig. 3.

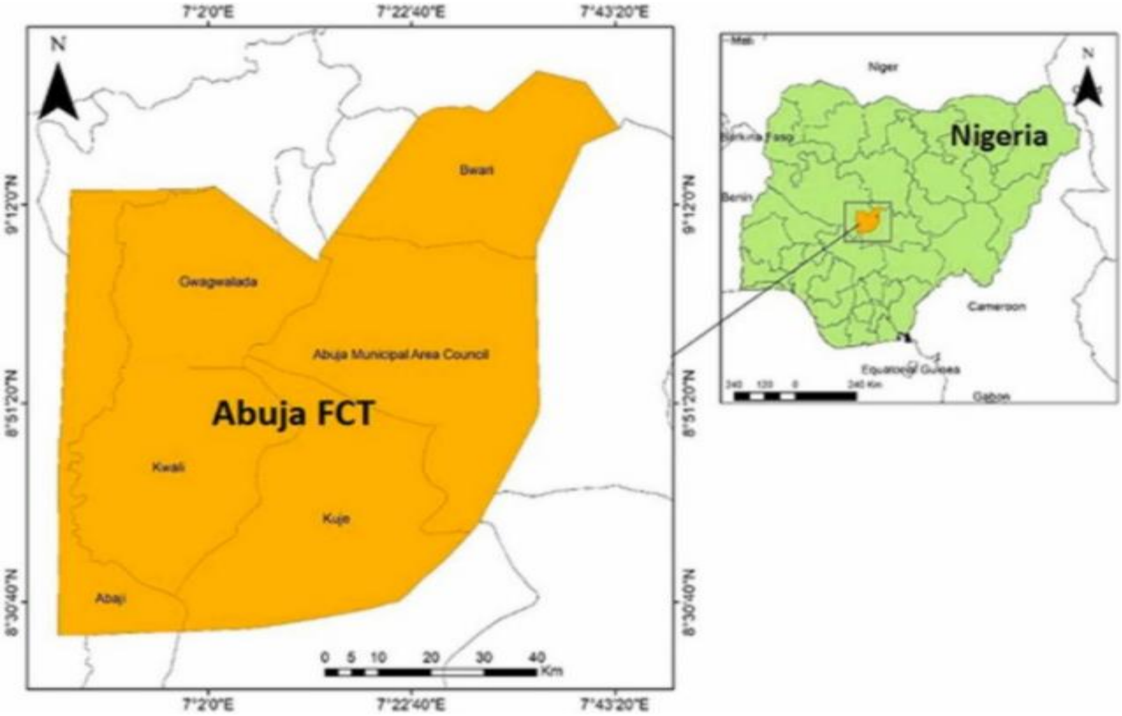

Fig. 1. Map of Abuja and Nigeria showing the location of Abuja (North Central Region of Nigeria).

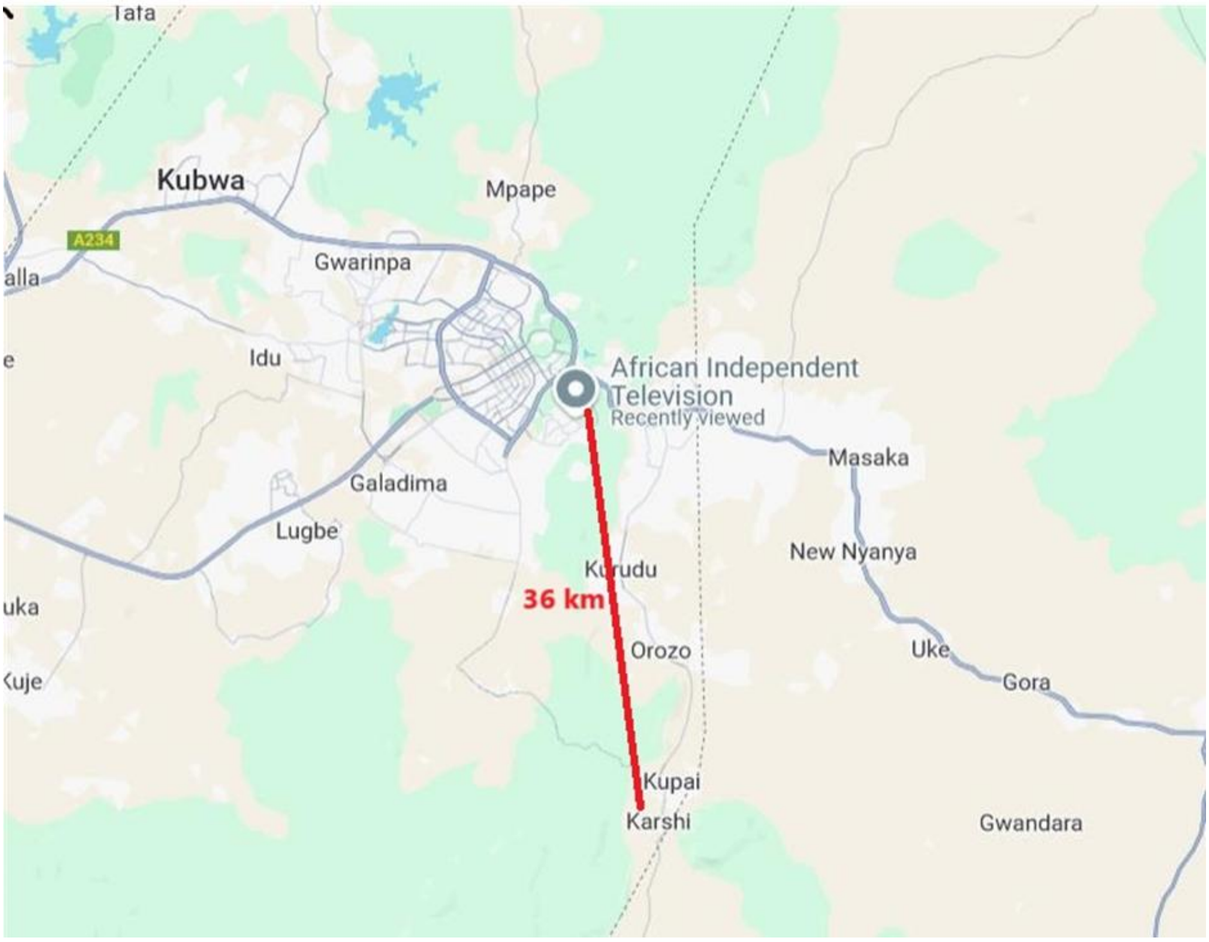

Fig.2. Location of AIT and Karshi –Measurement site

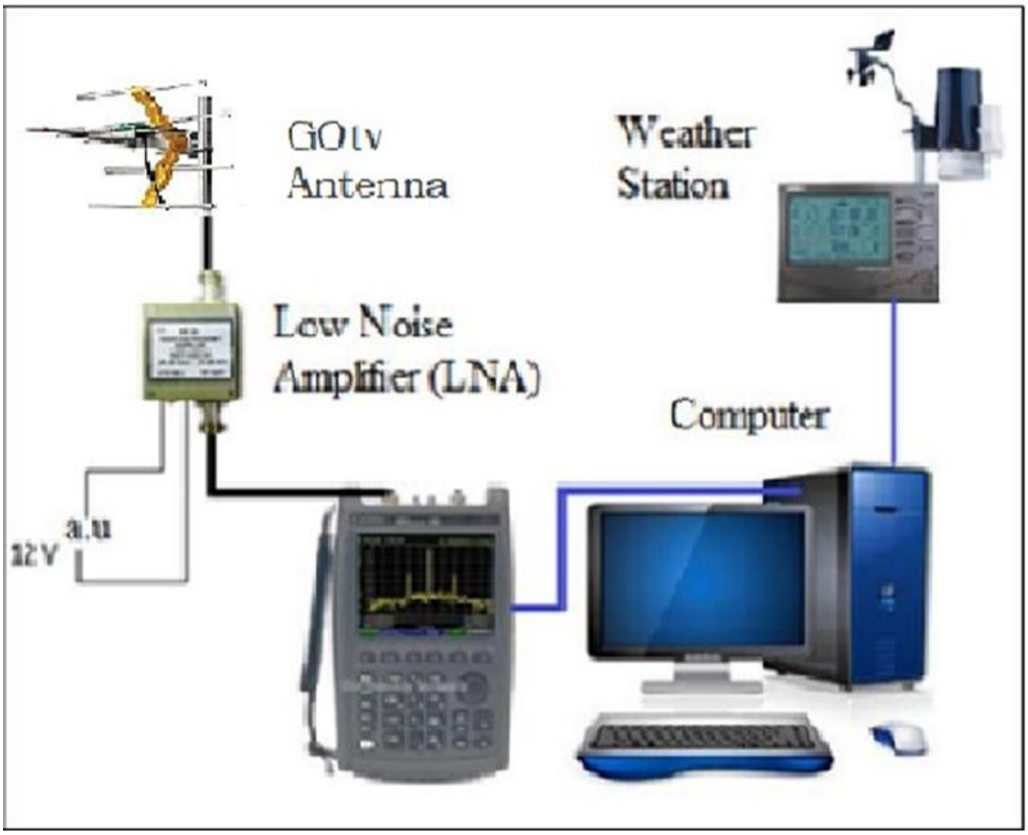

Fig. 3. The set up at the experimental site

C. Theoretical Background

Wireless communication has become a vital aspect of our lives with the emergence of 5G networks and the switch from analogue to digital broadcasting. Therefore, designing and enhancing wireless communication networks in order to achieve acceptable levels of reliable signals requires an understanding of the way radio frequency waves travel through the atmosphere. The conventional approach of illustrating the activities of satellite connectivity based on bent-pipe transponders is to employ the carrier-to-noise ratio (C/N), which demonstrates the level of signal that is received for the analogue and digital transmissions and symbolizes the dB (disparity at the receiver between the wanted carrier signal power and the unwanted noise level). The C/N ratio is usually referred to as the budget of the link power in satellite network systems. The C/N estimation in decibel is expressed as [28]-[29]:

$$\left.\frac{C}{N}\right|_{dB} = \left(G_t + G_r + P_t - L_p - A\right) - \left(T_n + B + K\right) - L_s. \quad (1),$$

where P_t = transmitted power (dB), G_t and G_r are the transmitting and receiving gain of the antenna; L_p represents the path loss in (dB), A is the attenuation due to rain as measured in dB, The transmission distance is denoted as R and measure in meter, λ is the wavelength. Also, B is the noise bandwidth in dBHz and K is the Boltzmann constant. Other negligible losses (L_s) are antenna pointing losses, atmospheric gaseous losses and the link margin (not considered).

Radio wave propagation can be affected by fluctuations in the refractive index (n) of the air in the lower atmosphere, which can be affected by temperature, humidity, and atmospheric pressure. Very close to the surface of the earth, *n* approaches unity, with values ranging from 1.000250 to 1.000400. Fluctuations in this value across time and space are insignificant, and they have correlations with n as [29-30]:

$$n = 1 + N \times 10^{-6}. \tag{2}$$

The refractivity N, defined in terms of meteorological variables that have been measured, is expressed as:

$$N_{dry} + N_{wet} = N = 77.6\frac{p}{T} + 3.73 \times 10^{5}\frac{e}{T^{2}}. \tag{3}$$

where N_{dry} is the component that represents $= 77.6\frac{p}{T}$ and N_{wet} represents $3.73 \times 10^{5}\frac{e}{T^{2}}$, p is the atmospheric pressure in hPa, e is the water vapour pressure while T denotes absolute temperature in Kelvin. The non-polar nitrogen and oxygen molecules are the reason behind the N_{dry}. It coincides with air density because it is comparable to pressure (hpa). On the other hand, the N_{wet} is influenced by the polar water concentrations in the lower atmosphere and corresponds to the vapour pressure.

Equation (3) is applicable up to 100 GHz when applied to radio frequencies application. The equation also has a permissible error of about 0.5% [31]. The water vapour pressure *e* in equation (3) is related to RH as:

$$e = \frac{RHe_{s}}{100} \tag{4}$$

The e_s in equation (4) is related with some parameters and *t* as

$$e_{s} = a\exp\left(\frac{bt}{t + c}\right) \tag{5}$$

where, RH is expressed in %, e_s denotes the saturation vapour pressure (hpa) and the temperature in °C is denoted as *t*. Other constants *a, b* and *c* are 6.1121, 17.502 and 240.97, respectively. These values are valid between -20°C and +50°C with an effectiveness of around ±0.20% [31]. Since RaR, and N decreases within the lower atmosphere with height, it can be represented as:

$$N = N_{s}\exp\left(\frac{-h}{H}\right) \tag{6}$$

N in equation (6) denotes the RaR at specific height *h* (km) above the sea level while N_s is the value at the lower earth surface and *H* is the scale height (km). Reference [31] reported average values for *H* and N_s at mid-latitude as 7.35 km and 315 km, respectively. Hence, RaR as related to height h (km) can be represented as:

$$N = 315\exp^{-0.136h} \tag{7}$$

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Thus, the gradient of RaR can be deduced using the differential algorithm on equation (7) as related to *h* resulting into:

$$\frac{dN}{dh} = -\frac{N_s}{H}\exp\left(\frac{-h}{H}\right) \quad (8).$$

Equation (8) can be used to quantify the behaviour (anomaly) of the atmospheres as thus [6, 9, 31]:
−39 N-units/km for h < 1 km represents a standard atmosphere, > -40 symbolizes the sub refraction, <-40 indicates the super refraction, and <-157 represents ducting.

Refractive environments such as standard atmosphere, sub-refraction, super-refraction, and/or ducting may also be explained using the effective earth radius factor k; they can be defined in terms of the gradient of the RaR according to as [31]:

$$k \approx \left[1 + \left(\frac{\partial N/\partial h}{157}\right)\right]^{-1} \quad (9).$$

At the lowest portion of the surface of the earth, the gradient of RaR (−39 N-units/km) also conforms to an effective earth radius variable of about $4/3 = 1.333$ indicating when radio links transverse through a line of sight across the lowest level of the earth. Hence, $4/3 > k > 0$ translates to sub-refraction, indicating that radio waves irregularly traverse beyond the lowest level of the earth. If $\infty > k > 4/3$ it meant super-refraction happens and radio waves unusually depart along the surface of the earth, thereby expanding the radio horizon and when $-\infty < k < 0$, waves suffer ducting and curve downward with a larger bend than the lowest level of the earth [31]:

The Field Strength Variation is also given as:

$$FSV = (N_{s\max} - N_{s\min}) \times 0.2dB \quad (10),$$

$N_{s\min}$ and $N_{s\max}$ denotes minimum the and maximum amount of RaR, respectively.

Conversely, Radio Horizon Distance can be obtained as follows:

$$d_{RH} = \sqrt{(2R_e h)} \quad (11),$$

where R_e is the approximate earth's radius (6370 km) and h represents height of transmitting antenna in m. Hourly mean of RSS values were obtained using:

$$\overline{RSS}_{1hr} = \frac{1}{n}\sum RSS_{1hr} \quad (12).$$

III. Discussion of the Results

A. Correlation of RSS with Meteorological Variables

Scatter plots of correlations between the variation of RSS with temperature, relative humidity, pressure and water vapour over the period of study are shown in Figs 4 (a), 4 (b), 4 (c), and 4 (d), respectively. The results indicate a consistent pattern with RSS link values showing weak positive correlations with atmospheric temperature as presented in Fig. 4 (a) and water vapour (Fig. 4 (d)) during the day, while the link shows very weak positive correlations with relative humidity as in Fig. 4 (b) and pressure as presented in Fig. 4 (c). The weak positive correlations experienced between RSS and atmospheric variables—temperature and water vapour—show correlation coefficients of about 0.16 and 0.14, respectively, while the very weak relations between RSS, RH, and pressure show a correlation coefficient of about 0.04 and 0.03, respectively. The results also show that while temperature shows linear relations with RSS, RH and pressure shows poor fit for the data and water vapour shows a quadratic polynomial relation of two orders. This implies that while temperature has a direct link with RSS, RH and pressure show relatively weak positive relations, and water vapour has complex relations with RSS, that can only be approximated. The relationship between RSS, temperature, RH, pressure, and water vapour also shows that lower values of RSS are available at low temperatures, while signals are available at both lower and higher values of RH, pressure, and water vapour. Overall, the positive correlations might be due to the tropospheric influences that were prevalent in the study location and RSS is affected by combinations of the variables.

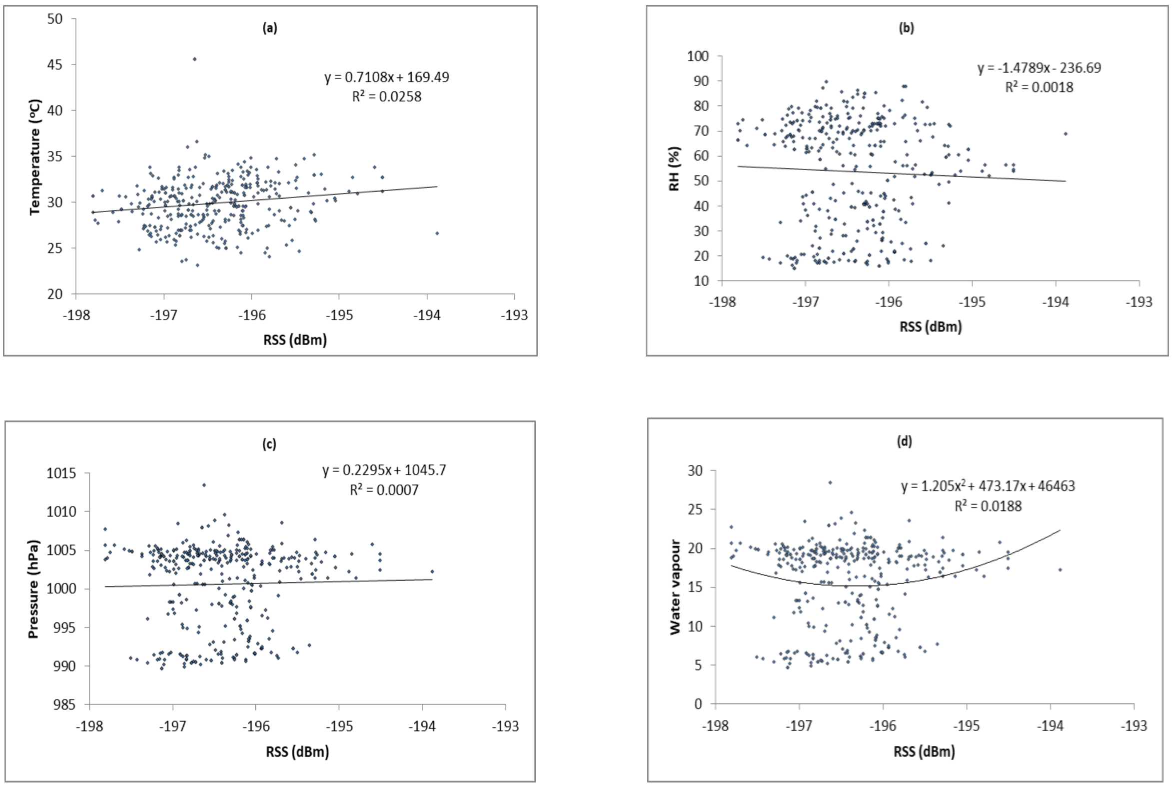

Fig. 4. Variation of RSS with atmospheric variables (a) Temperature, (b) Relative humidity, (c) Pressure and (d) Water vapour

B. Monthly Influence of Ndry and Nwet Components on RaR and RSS

Both the dry and wet components influence the behaviour of RaR and can lead to different anomaly in microwave propagation. The dry term (Ndry) arises from oxygen contents and the non-polar nitrogen in the atmosphere, representing refractivity due to the non-humid components of the air. On the other hand, the wet term (Nwet), results from the presence of polar water molecules in the

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troposphere which accounts for the refractivity associated with humidity and water vapor content. The wet term plays a crucial role in radio propagation, especially in regions with varying humidity levels. Fig. 5 displays that the wet Nwet, which adds significantly to its variation, has higher values (10-11%) recorded in the rainy period between March and October as compared to November to February (3-8%). The Ndry accounts for over 69.70% of the total estimated RaR value. Fig. 6 (a) show a correlation of RSS with the components of Ndry while 6 (b) presents a curve fit for Nwet with Nwet showing a weaker positive pearson correlation than Ndry. It is important to remember that water vapour, a significant component of Nwet, causes higher signal refraction in clear air conditions. An inverse relationship therefore exists between RSS and Ndry showing relatively weak correlation. This result conforms to the work of [32] in which the signal strength recorded was found to be inversely proportional to temperature, water vapour and atmospheric pressure. Also, RSS values are associated with higher values of Ndry, while low values of RSS are associated with both lower and higher values of Nwet. The variation of RSS with Ndry and Nwet is also presented in Fig. 7. The inverse relationship between Nwet and RSS is conspicuously shown especially between January and March as well November and December. These months are known as dry periods with little or no rain but of more water vapour and high temperature, while Ndry continue to show lesser influence over the year.

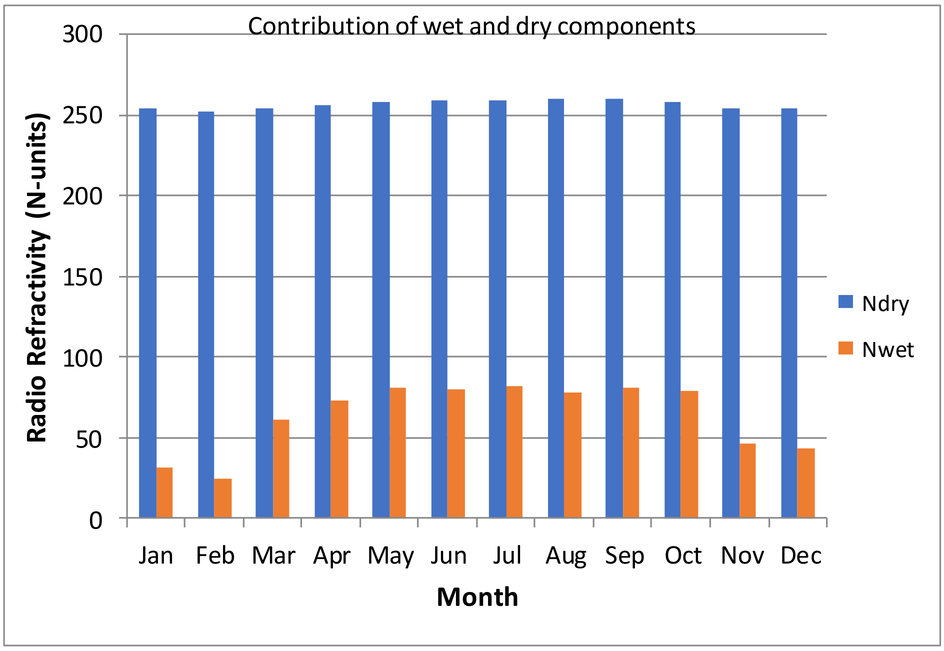

Fig. 5. Contributions of atmospheric components on RaR

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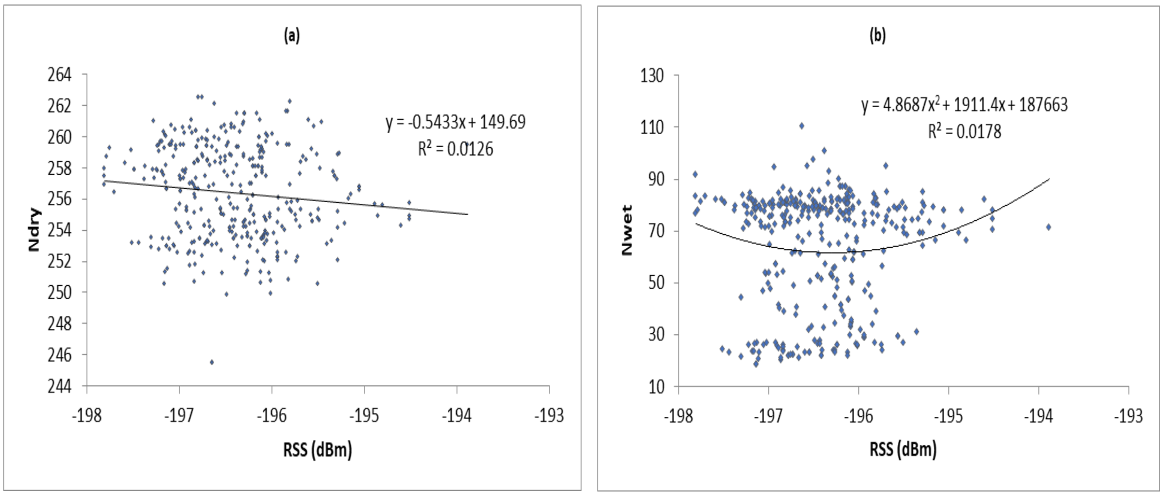

Fig. 6. Correlations between atmospheric components and RaR with (a) N_{dry} and (b) N_{wet}

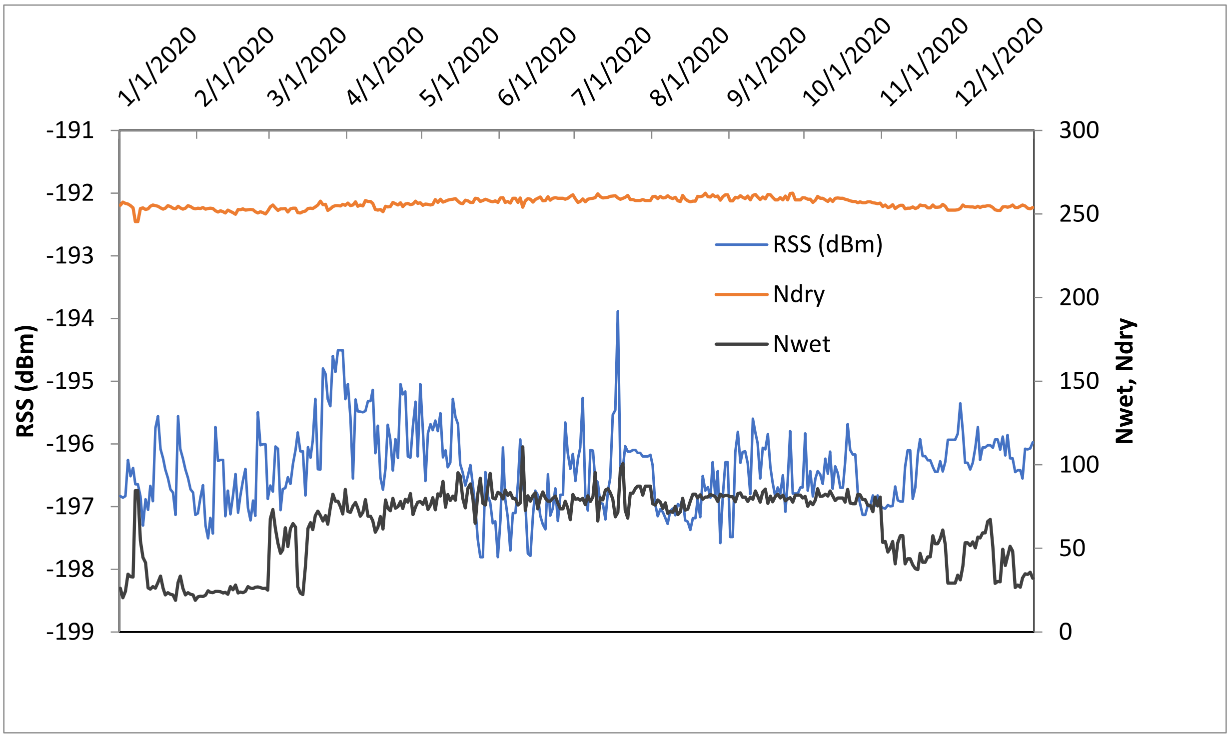

Fig 7. Influence of the N_{wet} and N_{dry} components on RaR

C. Influence of RaR and other atmospheric variables on the levels of the signal received

Fig. 8 also depicts correlations between the RSS and RaR with stronger negative correlations. This should be expected since the components that contributed to RaR also shows negative correlation. It is therefore evident that HDDTT are prone to signal disruption during clear air effect. Mitigation measure should therefore be provided to assure good reception of signal at the customer end. This can be achievable by adopting power mitigation or frequency mitigation technique. However, further study is needed to ascertain such measure. The monthly variation of propagating HDDTT signal with radio reactivity (N-units) and its components over the study location and period is also presented in Fig. 9. Thus, indicating the strength of the signal received reduces as the corresponding relative humidity increases, temperature, atmospheric pressure, and RaR but to varying degrees. The peak and minimum level (-193 and -198 dBm, respectively) of the signal received for the selected link were recorded in July and May, respectively. Atmospheric pressure was constantly ahead while other parameters show more negative relations with RSS. The findings demonstrate that RaR increases gradually, reaching its highest level of about 364.734 N-units in June while beginning at a low value of about 271.908 N-units in January. This demonstrates the drastic shift from the dry to the wet months. Earlier report by [21] and [33] had confirmed that RaR values are higher in wet months than dry months. As demonstrated by the obvious pattern of variation, RaR approaches a peak value during the wet period of the year attaining average value of about 334.745 N-units and lowest value within the dry period with an average value of about 290.021 N-units. Due to the much higher relative humidity values brought on by the moisture-laden tropical marine air arising from the constant migration of inter-tropical discontinuity (ITD) with the sun, the high radio refractivity figures recorded during the period of rain (March - October) can be explained. Consequently, the dry Harmattan period begins in December when the dusty, dry north-east winds take center stage, leading to decreased RaR levels. The radio refractivity values and their fluctuations in Abuja correspond with the outcomes reported by [4].

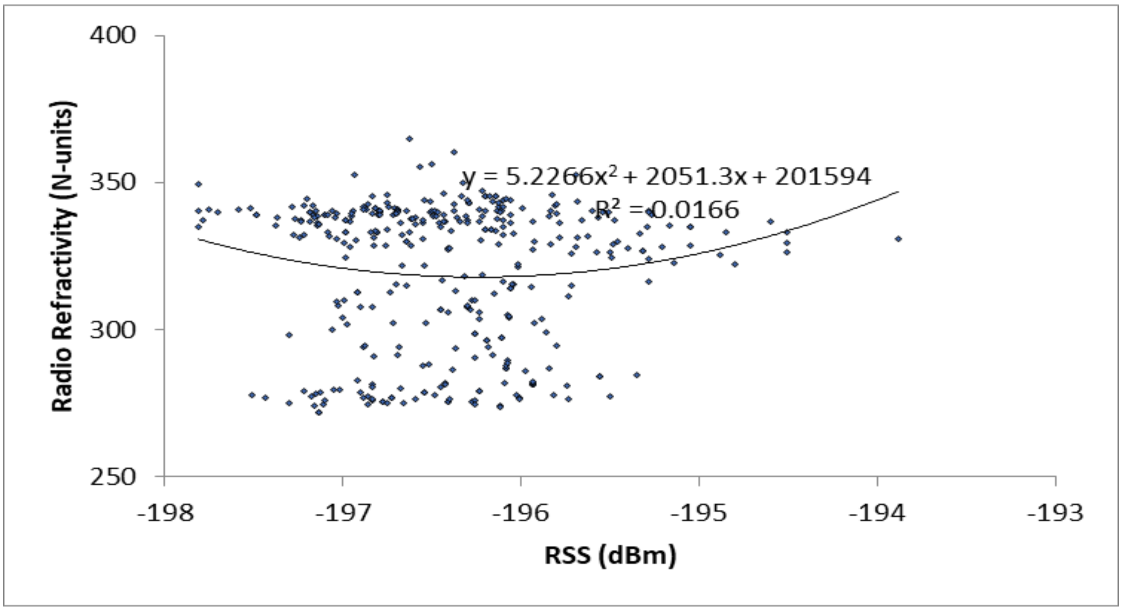

Fig. 8. Correlations between RaR and RSS

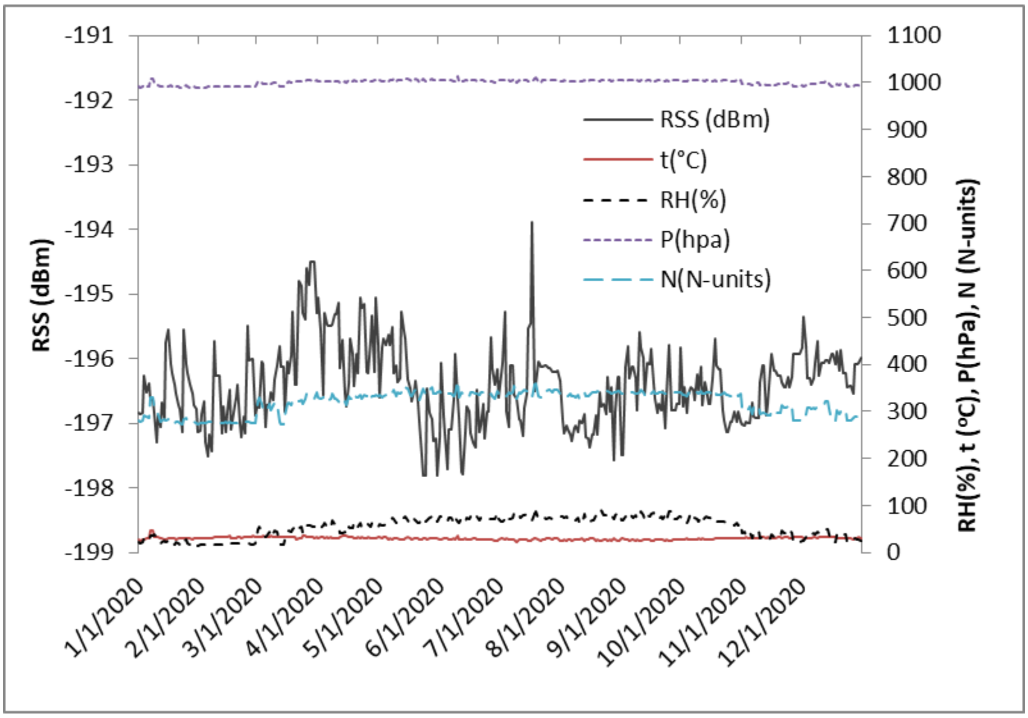

Fig. 9. Variation of RaR (N-units) and other meteorological parameters with RSS

D. Influence of k-Factor, Radio horizon, Gradient to RaR on the Signal Received Level

The average k-factor of the study location has been estimated as 1.393, which indicates that super-refractive signal transmission is the most frequent mode [34]. Meteorological conditions that produce super refraction comprise temperature inversions, which are defined by an upward trend in temperature with increasing height, and dielectric constant variations, which are triggered by a significant reduction in total moisture content in the air. The turbulent flow of warmer air across a chilled body of water is one of the reasons that could lead to a sporadic refraction. Furthermore, water evaporation might increase the degree of moisture and lowering the temperature at the lowest level of the earth, which may contribute to a temperature inversion. The unusual diversion of the microwave path is triggered by more than just the inversion of the temperature itself, nevertheless. This impact is made even worse at the surface by a substantial rise in the dielectric constant and, consequently, the water vapour content [29]. The maximum distance to receive a good quality HDDTT is also needed as it may be affected by antenna height, terrain, as well as atmospheric conditions. It is therefore an important concept to be considered so that appropriate mitigation measures can be adopted. Refractivity gradient that can lead to bending, ducting and refraction is also a factor to be considered to enhance good quality HDDTT. Figure 10 therefore presents the influence of radio horizon, k-factor and refractivity gradient on RSS of HDDTT. It is observed that the gradient of refractivity shows strong inverse relation with RSS, while the k-factor shows little significant impact on the RSS. The inverse relation of the gradient of refractivity with RSS may be attributed to the fact that most of the components of the gradient already show negative correlations as earlier pointed out. It can also be shown that during the period of clear air scenario, no value of RSS below -198 dBm indicating that the attenuation is 0 dB.

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Radio horizon distance continues to show significant impact on RSS especially during the intense rainy period (April and October). Also the impact may be as a result of the distance of the HDDTT to the site, since the inverse-square rule indicates that the intensity of electromagnetic radiation rapidly declines with increasing distance from the source. Figure 11 illustrates that the FSV, which has a mean range of 4.2-12.6 dB throughout the period of the study, was found to be higher within the non-rainy period and lower within the period of rain. This information is significant for establishing receiver antennas that would provide continuous signal reception especially in bad weather period.

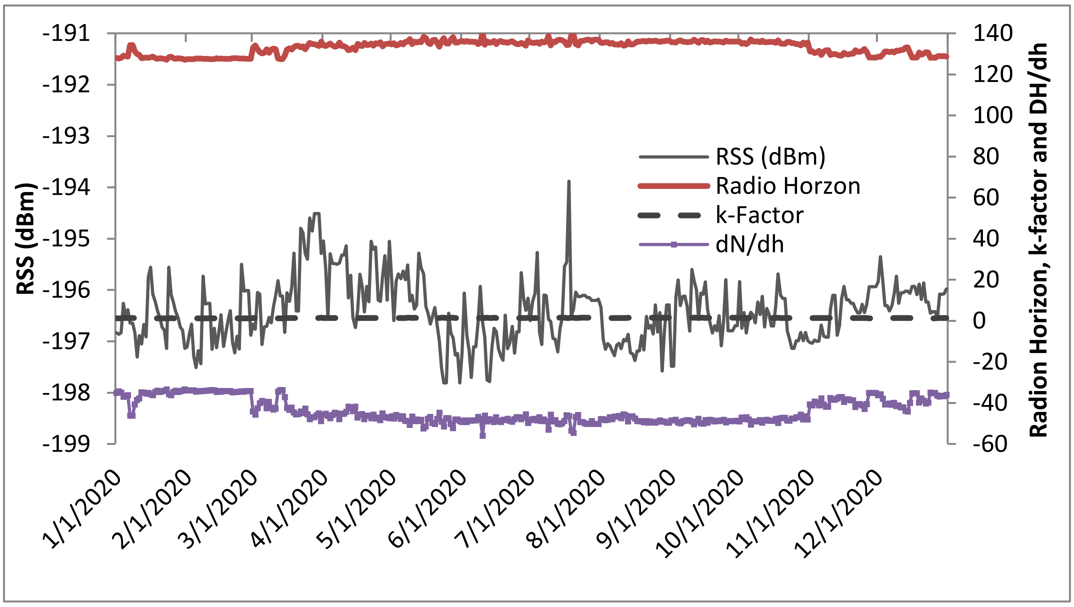

Fig. 10. Influence of k-Factor, Radio horizon, gradient to RaR on the signal received level

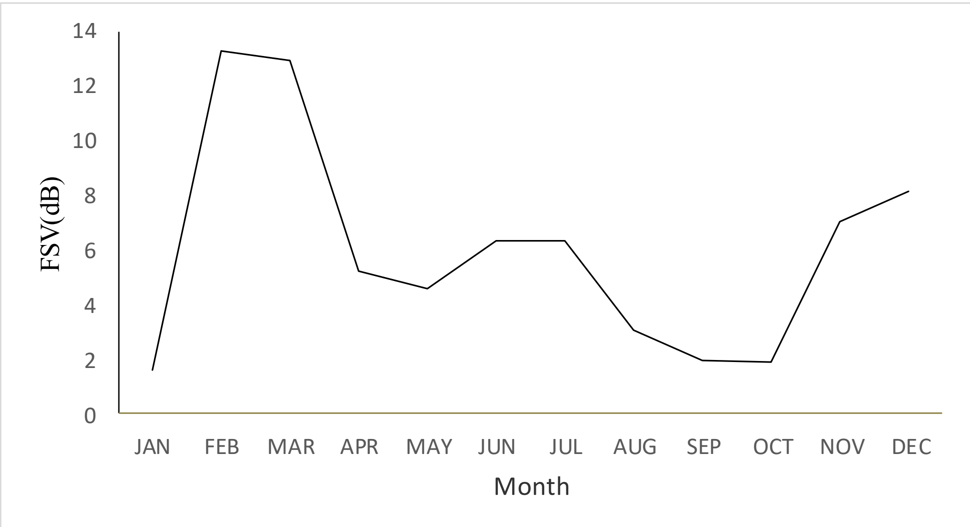

Fig. 11. Monthly Field Strength Variability

IV. CONCLUSION

The fluctuation and weather-related effects based on the HDDTT link were presented in this study. The analyses of the impact of atmospheric temperature, relative humidity, and water vapour, k-factor and radio horizon distance on the HDDTT signal link were provided. The findings reveal that RSS link values showing strong negative correlations with atmospheric temperature, pressure, and water vapour during the day, while the link shows weak negative correlations with the relative humidity. Further findings revealed that radio refractivity becomes greater in the study area within the period of rain than the non-rainy period, with the dry term contributing more than 69.70% of the total radio refractivity during both seasons. The mean value of 334.744 N-units and 290.635 N-units, respectively, were found during both seasons of the year. Furthermore, the finding indicates that the average refractive index (n) for the research area is greater than unity, which can be attributed to the continuous variations in temperature, relative humidity, and air pressure associated with the area. An increase in n usually leads to super refraction propagation impairment that predominantly impacts radio signals and eventually causes interference to the signal with an average observed refractivity gradient and k-factor of -43.989 N-units/km and 1.393, respectively. The ITU-Recommendation indicates that a rise in N will ultimately result in super refraction, a propagation defect that mostly affects radio signals while triggering signal interference. The results of the study will provides valuable results as a reference for radio engineers in designing HDDTT link budgets in Nigeria.

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