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Research Article

Analysis of Field Strength Variability at Ultra-High Frequency and Maximum Angle of Incidence across the Sahelian and Midland Regions of Nigeria

[1,3]*Davidson Odafe Akpootu., [2]Gazali Bello., [3]Isah Ibrahim Garba., [4]Mudassir Na-Allah., [1]Jabir Muhammad., [5]Maryam Balarabe., [6]Abdulsemiu Oluwatoyin Aina and [1]Abba Babagana

[1]Department of Physics, Usmanu Danfodiyo University, Sokoto, Nigeria

[2]Sultan Abdurrahaman College of Health Technology Gwadabawa, Sokoto State, Nigeria

[3]Department of Physics with Electronics, Federal University, Birnin Kebbi, Nigeria

[4]Department of Physics, Abdullahi Fodiyo University of Science and Technology, Aliero

[5]Nigerian Postal Service No 10, Maputo Street Wuse Zone 3, Abuja

[6]Department of Physics and Materials Science, Kwara State University, Malete, Nigeria

***Corresponding author's Email**: davidson.odafe@udusok.edu.ng, doi.org/10.55639/607.02010071

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ABSTRACT

Ultra-High Frequency (UHF) is the International Telecommunications Union (ITU) designation for radio frequencies between 300 MegaHertz (MHz) and 3 GigaHertz (GHz). In this study, the Field Strength Variability (FSV) at UHF and the maximum angle of incidence was estimated using the measured monthly climatic data obtained from the National Aeronautic and Space Administration (NASA) during the period of forty-two (42) years (1981 to 2022). The two climatic zones considered in this study are the Sahelian and Midland regions with two locations in each; Sokoto and Maiduguri, in the Sahelian region; Bauchi, and Jos in the Midland region. Using equation (8), the evaluated average radio refractivities at the operating frequency of 315.9 MHz were obtained to be 314.2398 N – units, 307.9401 N – units, 311.2480 N – units and 296.6702 N – units respectively. The findings indicated that for the four locations, the maximum average values of FSV at UHF obtained were 0.5583 dB, 0.3592 dB, 0.4654 dB and 0.0126 dB, which occurred in the rainy season, the positive values observed indicate a strong signal with good reception quality while the maximum average values of angle of incidence measured were 0.6204º, 0.6266º, 0.6592º, and 0.5820º for Sokoto, Maiduguri, Bauchi, and Jos respectively. The average maximum angles of incidence were found to be 0.5749º, 0.5243º, 0.6404º and 0.5696º for the locations during the studied period and are within the range of reported values (0.5º - 1º). The optimal angle of incidence values obtained in this study suggests enhanced signal strength and broader coverage areas for the four locations under investigation.

Corresponding author: Davidson Odafe Akpootu, **Email:** davidson.odafe@udusok.edu.ng
Department of Physics, Usmanu Danfodiyo University, Sokoto, Nigeria

INTRODUCTION

Tropospheric radio wave signals experience loss due to multipath effect, scattering and other forms of attenuation through the atmospheric medium, primarily due to variations in weather conditions with time. The knowledge of surface refractivity profile is important for optimal planning of Very High Frequency/Ultra High Frequency (VHF/UHF) terrestrial radio links in a region (Ladan *et al.*, 2021). Telecommunications have become an integral part of our life; providing services that range from phone connection, entertainment, information and learning over a broad range of media. This wireless technology relies upon an extensive network of fixed antennae, or base stations, relaying information via radio frequency waves or signals that travel at the speed of light. The frequency of a radio wave is a function of its propagating characteristics through various media. UHF band has its propagation characteristics hinged on space wave exclusively. It can be applied in Global Positioning System (GPS), Microwave links, Wireless Personal Communication Systems, etc. (Agbo and Marconi, 2004).

Radio communications use electromagnetic waves propagation through the earth's atmosphere to send information over long distances without the use of wires (Agbo and Marconi, 2004). Tropospheric radio signal transmissions at frequencies above 30 MHz are prone to the effect of fluctuations of weather and climate, because of water vapour molecules with their permanent electric dipoles account for the atmosphere having a complex dielectric constant and a complex refractive index (Adebanjo, 1977). In order to have a good communication link for radio wave, the transmission medium need to be considered in order to have a better signal from the radio communication network, since the radio wave communication links are influenced by meteorological variables (Adediji *et al.,* 2011; Ukhurebor and Azi, 2018). The attitude and phase scintillations, absorption, scattering of radio wave network signals and other numerous complex mechanisms that occur in the lower atmosphere are caused by the random changes in the surface and vertical refractivity which can cause transmission signals lost and co channel interference. The effect of interference as a result of refractivity difference in the lower atmosphere is much in the humid climate than in the temperate climate regions due to the occurrence of high intensity humid rainfall (Adediji *et al.,* 2011; Ukhurebor and Umukoro, 2018). Angle of incidence of a ray is the angle between the incoming ray (incident) and a line perpendicular to the surface it strikes, called the normal at the point of incidence. Essentially, it is the angle at which a ray hits a surface measured from the normal line to the ray itself. Ultra-High Frequency (UHF) is the part of the radio waves from the electromagnetic spectrum, which frequencies are from 300 MHz to 3 GHz (Iloke *et al.,* 2022). The range of all types of electromagnetic radiation is termed as the electromagnetic spectrum (Iloke *et al.,* 2022).

The Sahelian and Midland regions of Nigeria represent distinct climatic zones that exhibit unique atmospheric conditions impacting radio wave propagation, particularly in the ultra-high frequency (UHF) range. Despite the significance of these variables in telecommunications, broadcasting, and wireless communications, there exists a notable research gap pertaining to the variability of field strength at UHF and the maximum angle of incidence in these regions. Understanding field strength variability is crucial for designing effective communication systems, optimizing signal coverage, and minimizing interference. The Sahelian region is characterized by arid conditions and high temperatures, while the Midland zone features more temperate climates with increased humidity. These differing atmospheric characteristics can significantly affect radio wave propagation. This study focused is limited to considering two locations out of the several locations in each of the Sahelian and Midland zones, this is due to similar climatic characteristics in each of the climatic zones.

Current literature has explored aspects of radio wave propagation in various climates using measured local meteorological data from Nigeria and other parts of the world, a number of researchers, including Ayantunji *et al.* (2018), Ukhurebor and Umukoro (2018), Mat *et al.* (2018), Raji (2020), Iloke *et al.* (2022) and Emeruwa (2023). However, specific studies focusing on UHF field strength and the maximum angle of incidence in the Sahelian and Midland regions of Nigeria are limited. The absence of detailed empirical data restricts the ability to make informed decisions about infrastructure development and technological advancements in these areas; hence, the motivation of the study.

2. METHODOLOGY

2.1 Data Collection

The measured monthly meteorological data of temperature, relative humidity, and atmospheric pressure for four (4) distinct locations over a forty-two (42) year period (from 1981 to 2022) spread across two (2) climatic zones in Nigeria were obtained from the National Aeronautics and Space Administration (NASA) with resolution of $0.5 \times 0.625°$. The yearly data was averaged into monthly data. The quality assurance of the meteorological measurements was determined by checking the overall consistency of the monthly average of the climatic parameters used in the study locations. The computation for this study was done using Excel while the graphs were plotted using Origin software. Table 1 presented the state, along with each location's latitude, longitude, and elevation for the locations under investigation.

Table 1: Latitude, longitude and elevation of the studied locations

Climatic Zone	Locations	Latitude	Longitude	State	Elevation (m)
Sahel	Sokoto	13.02 ºN	5.25ºE	Sokoto	276.16
Savannah	Maiduguri	11.85 ºN	13.08ºE	Borno	318.25
Midland	Bauchi	10.28 ºN	9.82ºE	Bauchi	518.79
Zone	Jos	9.87 ºN	8.75ºE	Plateau	980.85

The refractive index (n) of air is typically measured using a quantity known as the radio refractivity (N), which is related to the refractive index (n) by the equation (Freeman, 2007; Akpootu and Iliyasu, 2017; ITU-R 2019).

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

The radio refractivity (N) is measured in units called N-units. Equation (1) indicated that N usually falls between 250 and 400 N-units. The radio refractivity, N, was represented as follows in terms of measured meteorological factors, according to the International Telecommunication Union (ITU) (ITU-R, 2019).

$$N = \frac{77.6}{T}\left(P + 4810\,\frac{e}{T}\right) \quad (2)$$

where the radio refractivity of the dry term and wet term are given by equation (3) and (4) according to ITU-R (2019) through expansion of equation (2) (Akpootu and Rabiu, 2019; Akpootu *et al.*, 2024a, b).

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

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

where e is the water vapour pressure (hPa), T is the temperature (K), and P is the atmospheric pressure (hPa). The temperature in ℃ was converted to Kelvin, by adding 273 to the temperature in ℃

According to ITU-R (2003) and Freeman (2007), equation (2) can be used for all radio frequencies; the inaccuracy is less than 0.5% for frequencies up to 100 GHz, and John (2005) discovered that the average value of N = 315 was utilized at sea level.

The relationship between the water vapour pressure, e, and relative humidity is expressed as (ITU-R, 2003; Akpootu *et al.*, 2019; Akpootu *et al.*, 2021a,b; Iliyasu *et al.*, 2023; Akpootu *et al.*, 2023; Abdullahi *et al.*, 2024a,b).

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

where e_s is given by

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

where H is the relative humidity (%), *t* is the Celsius temperature (°C) and e_s is the saturation vapour pressure (hPa) at temperature (°C). The values of the coefficients a, b and c (water and ice) was presented in ITU-R (2003). The water values and level of accuracy used in this investigation are contained in ITU-R (2003).

The field strength variability in decibels at Ultra-High Frequency (UHF) in terms of radio refractivity was obtained using the formula (Balanis, 2005):

$$FSV\ at\ UHF\ (dB) = 20 \times log_{10}\left(\frac{u}{u_o}\right) \quad (7)$$

where *FSV* is the field strength variability at UHF, is the variability of the field strength in decibels (dB), u is the radio refractivity at the operating frequency in N-units, and u_0 is the reference radio refractivity at the standard frequency of 315.9 MHz

The radio refractivity at the operating frequency was obtained using (Balanis, 2005):

$$u = \frac{77.6 \times p}{T} + 3.73 \times e \quad (8)$$

where p is the atmospheric pressure in millibars, T is the atmospheric temperature in Kelvin and e is the vapor pressure in millibars.

A ducting layer is known to trap radio waves if certain geometrical constraints apply. For coupling of electromagnetic energy into a duct, the angle of incidence of the radio wave at the layer boundary must be very small. According to Barclay (2003), using the total-internal-reflection condition of geometrical-optics, the maximum angle of incidence (degrees) is related to the change in refractivity ΔN (N-units) across the layer by

$$\theta_{imax} = 0.081\sqrt{|\Delta N|} \quad (9)$$

As reported by Sikka and Gadgil, (2003); and Dairo and Kolawole (2017), ΔN rarely exceeds 100 N-units, θ_{imax} is limited to 0.5° - 1°. The geometrical consideration of the Earth's curvature shows that the angle of incidence of a wave propagated horizontally intercepting an elevated layer is nonzero. The implication is that terrestrial radio links will not be significantly affected by the occurrence of ducting layers at altitudes higher than about 1 km (Sikka and Gadgil, 2003; and Dairo and Kolawole, 2017).

3. RESULTS AND DISCUSSION

3.1 FSV at UHF and Angle of Incidence in the Sahelian Savannah Zone

3.1.1 Field Strength Variability at UHF for Sokoto

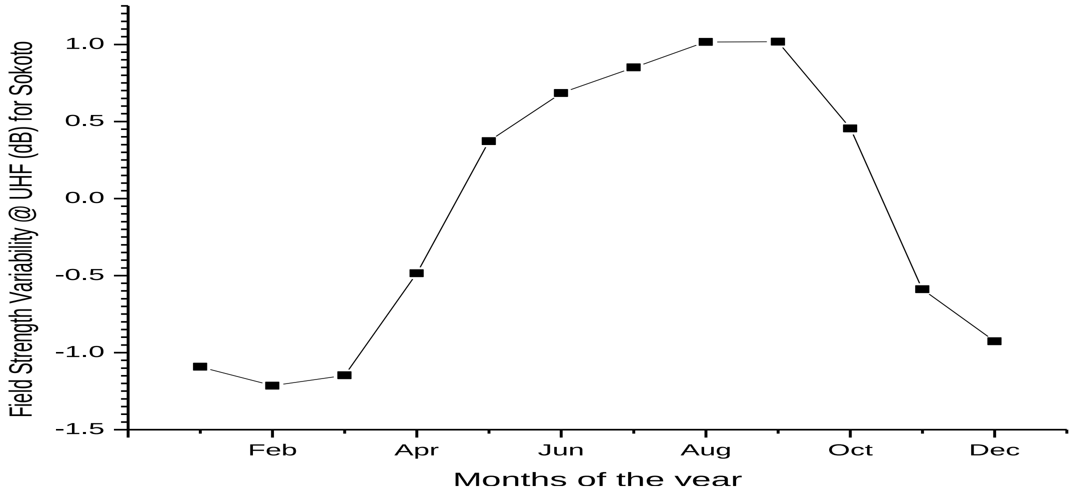

Figure 1. Seasonal Field Strength Variability at UHF Variation for Sokoto

Figure 1 depicts the seasonal variation of field strength variability at UHF for Sokoto during the period under investigation. The figure showed gradual decrease from January to a minimum value of -1.2152 dB in February during the dry season then slightly increase to March, it further increases gradually until it gets to its peak value of 1.0171 dB in the month of September within the rainy season, and then decreases gradually to December. However, the result from the analysis as indicated from the figure revealed that the maximum average value of FSV at ultra high frequency for Sokoto was obtained during the rainy season (April to October) with 0.5583 dB while the minimum average value with -0.9940 dB was obtained within the dry season (November to March). In addition to this, the positive result observed in the rainy season indicate a strong signal with good reception quality and the negative result obtained during the dry season signify a weak or disrupted signal with poor reception, meaning that the signal strength is low in the dry season.

3.1.2 Maximum Angle of incidence for Sokoto

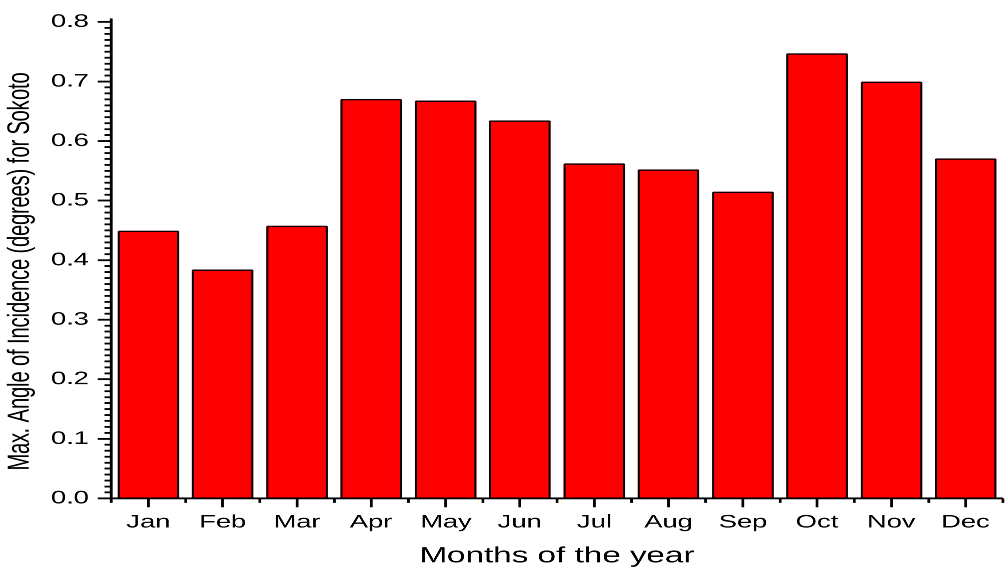

Figure 2: Monthly Variation of Maximum Angle of incidence for Sokoto

Figure 2 depicts the monthly change of angle of incidence for Sokoto during the study period (1981- 2022). The outcomes of the result showed that the highest value of angle of incidence occured in the month of October with 0.7462º, while the least value was obtained in the month of February with 0.3830º, which was slightly less than the reported value (0.5º - 1º) by Dairo and Kolawole (2017), this could be as a result of the low value of change in radio refractivity in the month of February which was obtained to be 22.3630 N-units. However, the result also indicates that the highest value of angle of incidence fall within the rainy season and the least value occurred during dry the season. Other months which are much closed to the peak value and as well to each other include April, May and November with 0.6695º, 0.6671º and 0.6988º that occur during the rainy and dry seasons respectively. The figure also revealed that the maximum average value of angle of incidence obtained was 0.6204º during the rainy season, while the minimum average value of angle of incidence was obtained within the dry season with 0.5113º. The average maximum angle of incidence for Sokoto during the studied period is 0.5749º which falls within the range of values reported by Dairo and Kolawole, (2017).

3.1.3 Regression Analysis between FSV@UHF with Meteorological Parameters for Sokoto

The multivariate regression equation is for Sokoto is given by

$$FSV@UHF = -199 + 0.139\ T + 0.198\ P + 0.0329\ RH \quad (R^2 = 99.4\%) \qquad (10)$$

Equation (10) shows the regression equation between the Field Strength Variability at Ultra High Frequency (FSV@UHF) with the meteorological parameters of Temperature (T) in ℃, pressure (P) in hPa and relative humidity (RH) in %. The result shows strong correlation with coefficient of determination of 99.4%.

3.1.4 Field Strength Variability at UHF for Maiduguri

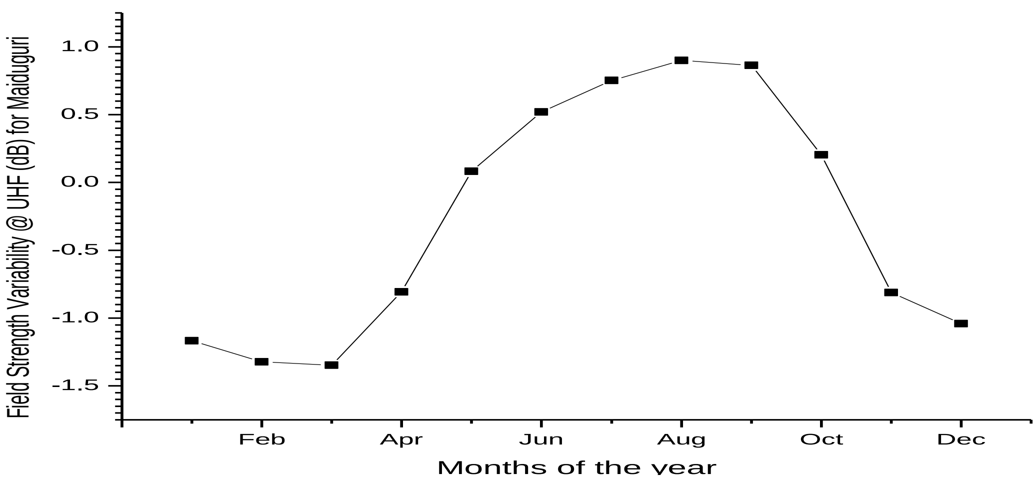

Figure 3: Seasonal Field Strength Variability at UHF Variation for Maiduguri

Figure 3 illustrate the seasonal variation of field strength variability at UHF for Maiduguri during the study period. The FSV at UHF decreases steadily in the month of January and attained its minimum value of -1.3474 dB in March during the dry season and then increases gradually until it reaches its maximum value of 0.8993 dB in August within the rainy season, which decreases slightly in September with 0.8640 dB then decreases sharply to December. Furthermore, the result revealed that the maximum average value of FSV at UHF for Maiduguri was observed during the rainy season with 0.3592 dB while the minimum average value with -1.1378 dB was obtained in the dry season. The positive result shows a strong signal in the rainy season while the negative result obtained during the dry season signifies that the signal strength is low during the period in the region.

3.1.5 Maximum Angle of incidence for Maiduguri

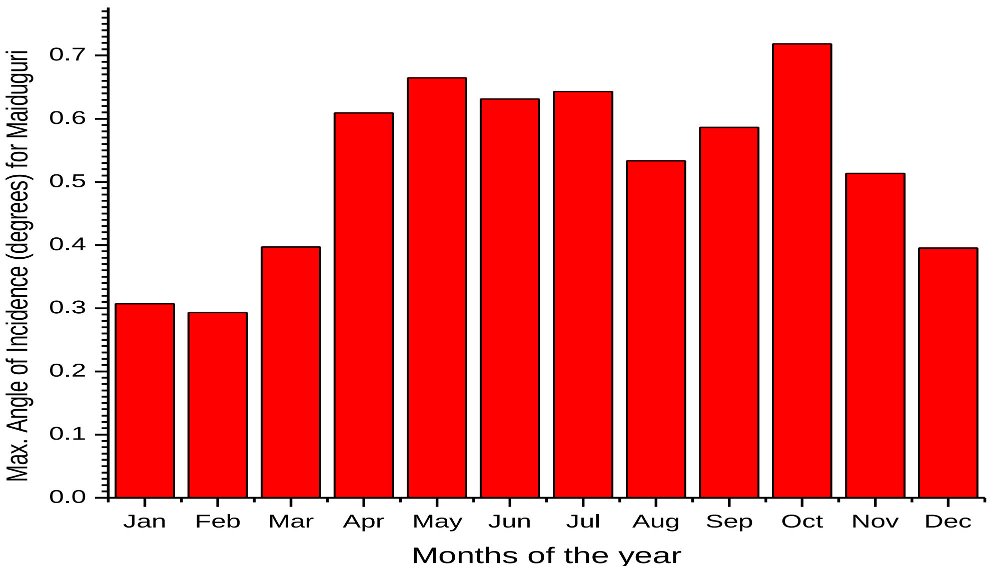

Figure 4: Monthly Variation of Maximum Angle of incidence for Maiduguri

The monthly change of angle of incidence for Maiduguri over the research period (1981- 2022) is depicted in figure 4. Based on the result, the month of February had the lowest angle of incidence value, measuring 0.2931º, which is less than the reported value (0.5º - 1º) by Dairo and Kolawole (2017), this could be as a result of the low value of change in radio refractivity in the month of February which was obtained to be 13.0942 N-units, while the month of October had the highest angle of incidence value, measuring 0.7186º. The outcome also shows that the highest angle of incidence value happened during the rainy season, while the lowest angle of incidence value occurred during the dry season. Nevertheless, May has angle of incidence value of 0.6647º which is significantly closer to the maximum value. The result also revealed that the maximum average value of angle of incidence obtained for Maiduguri was 0.6266º during the rainy season, while the minimum average value of angle of incidence was obtained within the dry season with 0.3811º. The average maximum angle of incidence for Maiduguri during the studied period is 0.5243º which falls within the range of values reported by Dairo and Kolawole (2017).

3.1.6 Regression Analysis between FSV@UHF with Meteorological Parameters for Maiduguri

The multivariate regression equation is for Maiduguri is given by

FSV@UHF = - 259 + 0.171 T + 0.259 P + 0.0335 RH (R^2 = 99.6%) (11)

Equation (11) shows the regression equation between the Field Strength Variability at Ultra High Frequency (FSV@UHF) with the meteorological parameters of Temperature (T) in ℃, pressure (P) in hPa and relative humidity (RH) in %. The result shows strong correlation with coefficient of determination of 99.6%.

3.2 FSV at UHF and Angle of Incidence across the Midland Zone

3.2.1 Field Strength Variability at UHF for Bauchi

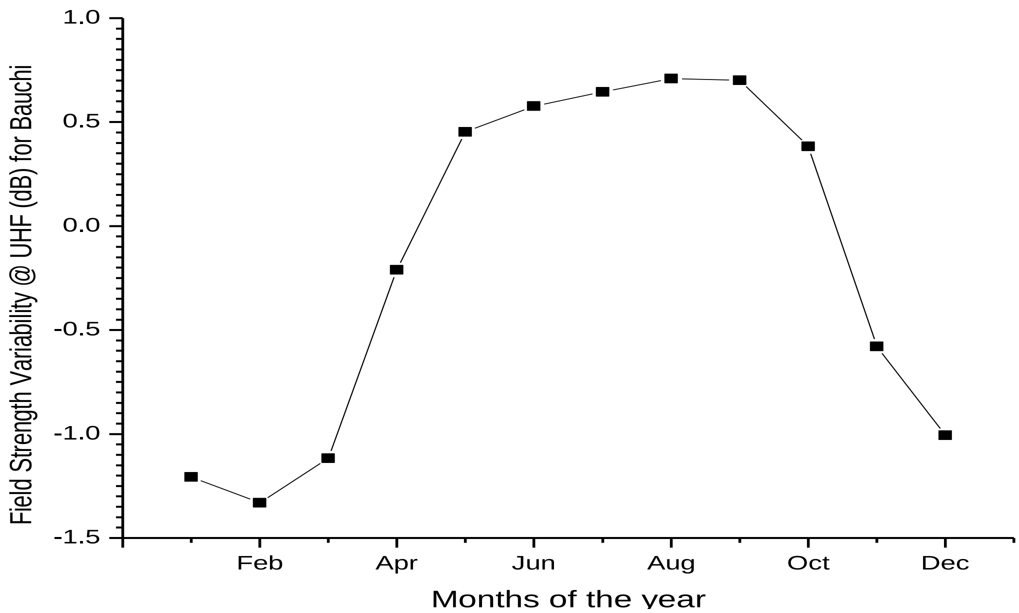

Figure 5: Seasonal Field Strength Variability at UHF Variation for Bauchi

Figure 5 depicts the seasonal variation of field strength variability at UHF for Bauchi during the study period. The FSV at UHF gradually decreases from January to February where it attained its least value of -1.3304 dB in the dry season, it then increases from its lowest value until it gets to the peak value of 0.7092 dB in the month of August during the rainy season. The FSV at UHF also maintained almost a close value from the maximum value up to September with 0.7005 dB in the rainy season and then decreases gradually to December. Furthermore, the maximum average value of field strength variability at UHF for Bauchi was found to be 0.4654 dB in the rainy season signifying a good transmission quality as it has positive value, while the minimum average value of -1.0479 dB was obtained in the dry season signifying a weak signal or indicating poor transmission quality as it shows negative value.

3.2.2 Maximum Angle of incidence for Bauchi

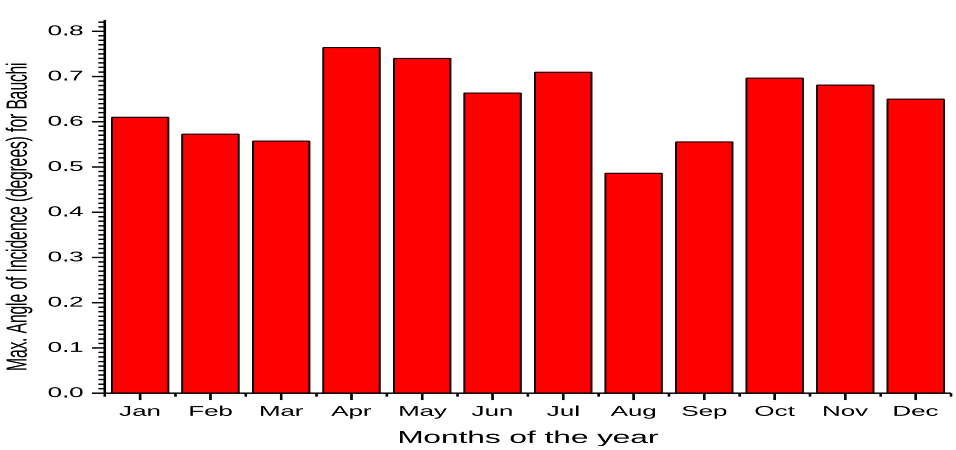

Figure 6: Monthly Variation of Maximum Angle of incidence for Bauchi

The monthly change of angle of incidence for Bauchi over the investigation period (1981-2022) was demonstrated in the figure 6. The outcome of the result indicated that the highest value of angle of incidence was recorded in the month of April with 0.7640º during the rainy season, while the lowest value of angle of incidence was observed in the month of August still in the rainy season with 0.4860º, which is approximately within the value (0.5º - 1º) as reported by Dairo and Kolawole (2017). Furthermore, May, July, October and November had values of 0.7400º, 0.7093º, 0.6965º and 0.6811º, which are importantly closed to the peak value. The maximum average value of angle of incidence observed was in rainy season with 0.6592º while the minimum average value of 0.6141º was obtained in the dry season as revealed in figure 6. The average maximum angle of incidence for Bauchi during the studied period is 0.6404º which falls within the range of values reported by Dairo and Kolawole (2017).

3.2.3 Regression Analysis between FSV@UHF with Meteorological Parameters for Bauchi

The multivariate regression equation is for Bauchi is given by

FSV@UHF = - 94.6 + 0.107 T + 0.0945 P + 0.0324 RH (R^2 = 98.9%) (12)

Equation (12) shows the regression equation between the Field Strength Variability at Ultra High Frequency (FSV@UHF) with the meteorological parameters of Temperature (T) in ℃, pressure (P) in hPa and relative humidity (RH) in %. The result shows strong correlation with coefficient of determination of 98.9%.

3.2.4 Field Strength Variability at UHF for Jos

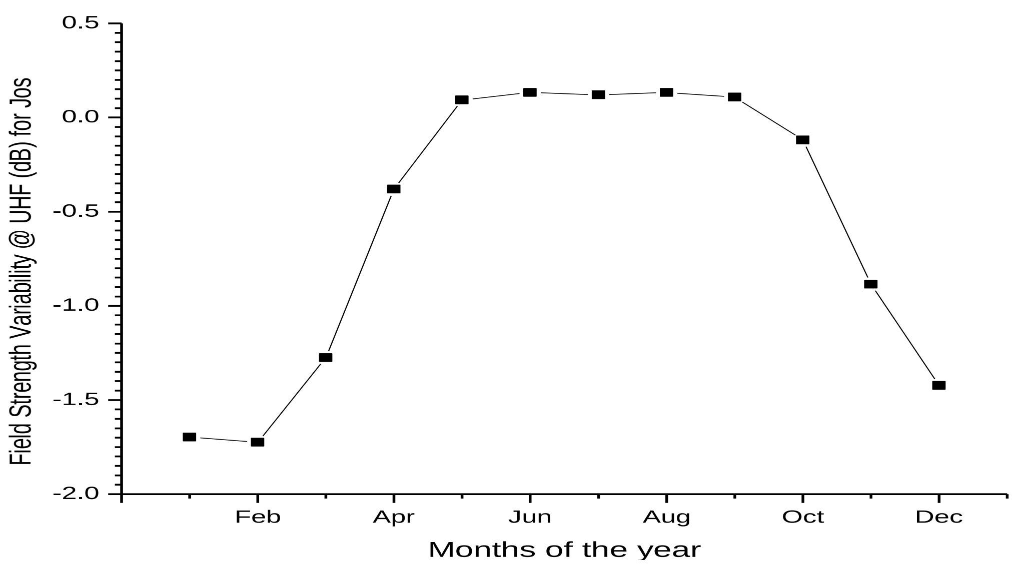

Figure 7: Seasonal Field Strength Variability at UHF Variation for Jos

Figure 7, depicts the seasonal variation of field strength variability at UHF for Jos during the investigation period. The figue indicates that FSV at ultra high frequency decreases slightly from January to its lowest value of -1.7249 dB in February and then increases until it reaches May. However, the FSV at UHF maintained almost closed value from May until it get to the highest value of 0.1334 dB in the month of August, then gradually decreases to December. Furthermore, the peak and the minimum values were obtained during the rainy and dry season respectively. The result also revealed that the maximum average value of FSV at UHF for Jos was found in the rainy season with 0.0126 dB while the minimum average value of -1.4011 dB was recorded during the dry season. The negative value indicates that the signal strength is low or experiences interference at the frequency band within the dry season; while the positive value recorded during the rainy season indicates strong signal strength.

3.2.5 Maximum Angle of incidence for Jos

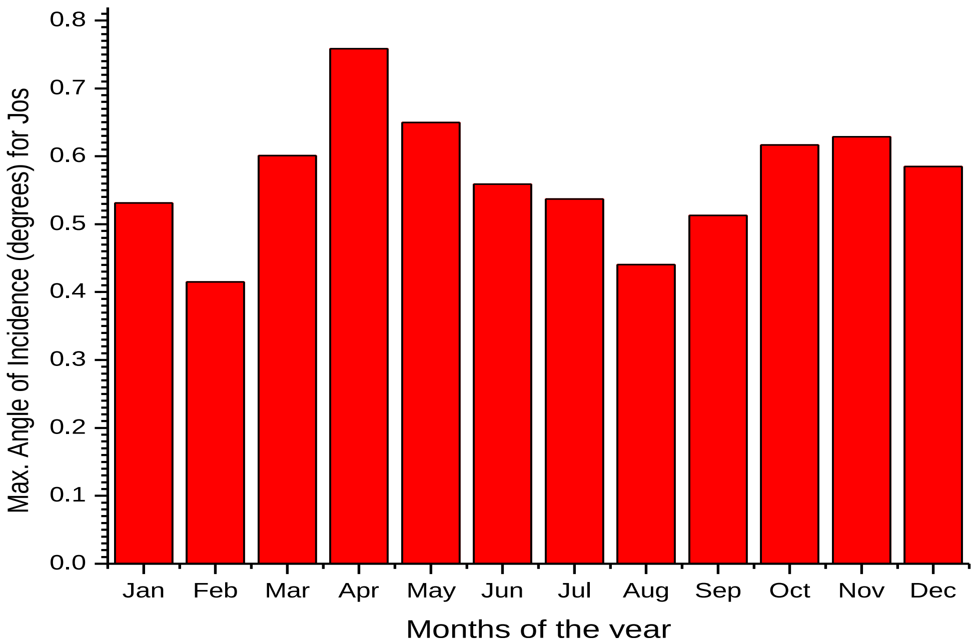

Figure 8: Monthly Variation of Maximum Angle of incidence for Jos

Figure 8 demonstrate the monthly change of angle of incidence for Jos over the study period (1981- 2022). The result shows that the value of angle of incidence occurred at its peak in the month of April within the rainy season with 0.7585^{o}, while the least value during the dry season with the value of 0.4148^{o} in the month of February, which is slightly less than the reported value (0.5^{o} - 1^{o}) by Dairo and Kolawole (2017), this could be as a result of the low value of change in radio refractivity in the month of February obtained to be 26.2262 N-units. The maximum average value of angle of incidence obtained in Jos was 0.5820^{o} found in the rainy season and the minimum average value obtained was 0.5521^{o} within the dry season. The average maximum angle of incidence for Jos during the studied period is 0.5696^{o} which falls within the range of values reported by Dairo and Kolawole (2017).

3.2.6 Regression Analysis between FSV@UHF with Meteorological Parameters for Jos

The multivariate regression equation is for Jos is given by

$$FSV@UHF = 35.4 + 0.0550\, T - 0.0432\, P + 0.0312\, RH \quad (R^2 = 99.3\%) \qquad (13)$$

Equation (13) shows the regression equation between the Field Strength Variability at Ultra High Frequency (FSV@UHF) with the meteorological parameters of Temperature (T) in ℃, pressure (P) in hPa and relative humidity (RH) in %. The result shows strong correlation with coefficient of determination of 99.3%.

Table 2: FSV at UHF Average Values for the Selected Locations

Climatic zones	Selected Locations	Average values
Sahel Savannah	Sokoto Maiduguri	-0.0885 dB -0.0885 dB
Midland Zone	Bauchi Jos	-0.1651 dB -0.5764 dB

Table 2 shows the field strength variability (FSV) at UHF average values for the selected locations. Based on the chosen sites, Sokoto, Maiduguri, Bauchi, and Jos depicts negative average values, this indicates that the signal in the locations signify a weak signal.

Table 3: FSV at UHF during the dry and rainy seasons for the Selected Locations

Climatic zones	Selected Locations	Dry Season	Rainy Season
Sahel Savannah	Sokoto Maiduguri	- 0.9940 dB - 0.9940 dB	0.5583 dB 0.5583 dB
Midland Zone	Bauchi Jos	- 1.0479 dB - 1.4011 dB	0.4654 dB 0.0126 dB

Table 3 shows field strength variability at UHF during the dry and rainy seasons across the climatic zones. It shows that in dry season the four locations experiences negative average values which signify that the signal strength is low in the locations or experiencing interference at the frequency band. However, in rainy season, the entire locations depict positive values showing that the signal is strong with good transmission quality. The high values of FSV at UHF during the rainy season are influenced by a combination of atmospheric conditions, the physical effect of rain on radio wave propagation and environmental changes.

Table 4: Maximum Angle of incidence Average Values for the Selected Locations

Climatic zones	Selected Locations	Average values (degrees)
Sahel Savannah	Sokoto Maiduguri	0.5749º 0.5749º
Midland Zone	Bauchi Jos	0.6404º 0.5696º

Table 4 depicts maximum angle of incidence average values across the studied locations. Based on the chosen sites, Bauchi has the highest averaged value of angle of incidence with 0.6404º situated in the Midland zone, and this is followed by Sokoto and Maiduguri with same value of 0.5749º located in Sahelian region.

Table 5: Maximum Angle of incidence Average values during the dry and rainy seasons for the Selected Locations

Climatic zones	Selected Locations	Dry Season	Rainy Season
Sahel Savannah	Sokoto Maiduguri	0.5113º 0.5113º	0.6204º 0.6204º
Midland Zone	Bauchi Jos	0.6141º 0.5521º	0.6592º 0.5820º

Table 5 depict maximum angle of incidence average values during the dry and rainy seasons across the selected climatic zones. The table shows that in both dry and rainy seasons, Bauchi has the highest average value with 0.6141º and 0.6592º respectively which is situated in the Midland zone.

4. CONCLUSION

In this study, the field strength variability (FSV) at UHF and maximum angle of incidence for four selected locations situated across the Sahelian and Midland climatic zones of Nigeria was investigated using the measured monthly climatic data obtained from the National Aeronautics and Space Administration during the period of forty-two (42) years (from 1981 to 2022). The maximum and minimum average values of FSV at ultra high frequency were observed to be (0.5583 dB and -0.9940 dB); (0.5583 dB and -0.9940 dB); (0.4654 dB and -1.0479 dB) and (0.0126 dB and -1.4011dB) for Sokoto, Maiduguri, Bauchi, and Jos respectively. The result indicated that the signal strength was found to be stronger during the rainy season than in the dry season. The physical impact of rain on radio wave propagation, atmospheric conditions, and environmental changes all contribute to the high FSV values at UHF during the rainy season. The maximum and minimum average values of angle of incidence obtained were (0.6204º and 0.5113º); (0.6204º and 0.5113º); (0.6592º and 0.6141º) and (0.5820º and 0.5521º). The average maximum angle of incidence for Sokoto, Maiduguri, Bauchi, and Jos during the studied period are respectively 0.5749º, 0.5749º, 0.6404º and 0.5696º which falls within the range of values (0.5º - 1º) as reported in the literature. This study's findings are crucial for optimizing communication system performance, understanding environmental interactions, improving network design, ensuring regulatory compliance, and enhancing telecommunications technology in the evolving wireless communication landscape.

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