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Estimation of rainfall rate and rain attenuation for satellite communication in Imo, Osun and Niger State of Nigeria

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Abstract
Nigeria has a tropical and equatorial region, which is characterized by dominant rainfall. Rain is the major attenuation factor of various communication signal of $f > 10$ GHz. Therefore, for efficient utilization of the microwave bandwidth during rainfall, it is necessary to determine the relationship between this attenuation effect and the bandwidth at various rainfall rate and frequencies at a particular location of interest. Thus, using propagation modelling, we investigated simultaneously the point rainfall and effects of rain for frequencies between 11 and 40 GHz (i.e. Ku, and Ka) for fixed satellite communication service on earth-space path at three (3) stations (Imo, Osun and Niger) in Nigeria by using rainfall data for the period of six (6) years (January 2011 to December 2016).

Keywords: Rain Attenuation, Rain Rate, Bandwidth, Microwave Propagation

Introduction
There is an increasing demand for broadband satellite services with the rapid growth of the information technology, which will provide reliable transmission of information. Satellite communication is an important segment for global telecommunications. The satellites to relay radio transmissions between earth terminals and number of applications includes services which had traditionally been available via terrestrial networks and radio broadcastings (Mandeep *et al*., 2006) [5].

A major factor to be considered in the design of satellite-to-earth links operating at frequencies above 10 GHz is Atmospheric effects. Raindrops absorb and scatter radio waves, leading to signal attenuation and reduction of the system availability and reliability. (Ojo *et al*., 2008) [8]

Rain causes the most significant loss of signal strength of frequency operating above 10 GHz amongst all atmospheric conditions. The amount of signal loss due to rain depends on the rate of rainfall, often measured in terms of millimetres per hour (mm/hr). Rain induced attenuation at higher frequencies is generally considered to be solely a function of frequency and rain fall intensity, with observed variability attributable to measurement errors, differences in rain drop size distribution, temperature differences and non-spherical shape of the rain drops. It was found that, assuming errorless measurements, the most important factor contributing to the observed variability in attenuation at a specific rainfall rate is due to variability in rain drop size distribution (DSD) (Ojo *et al*., 2008) [8].

Demands for larger bandwidth, consumer diversity and service convergence have led to a tremendous growth in communication systems which have resulted in congestion at lower frequency bands and consequently increased the need for higher frequency band usage. At these frequencies however, the presence of rain causes degradation of signals especially above 10 GHz.

Some of the advantages of telecommunications systems operating at higher frequencies include: large bandwidth, increased frequency reuse, small device size and wide range of spectrum availability. The major demerit to these frequency ranges is rain.

In recent years, the roll-out of fibre optic networks has not diminished the importance of satellite communication systems, especially for rural, remote and inland cities across the globe. The earlier satellite networks operate at L, S, C, and X bands, while the recent ones start operating at Ku, K, Ka, Q and V bands (Malinga *et al.*, 2013).

The method for the prediction of rain attenuation on microwave paths has been grouped into two classes: the empirical method which is based on measurement databases from stations in different climatic zones within a given region and the physical method which make an attempt to reproduce the physical behaviour involved in the attenuation process. However, when a physical approach is used not all the input parameters needed for the analysis is available. Empirical method is therefore the most used methodologies (Crane 1997).

For the empirical methodology, an appropriate distribution of rainfall rate at 1-minute integration time is needed for the site under study in order to predict accurate rain attenuation for the location. This input is sometime provided by meteorological and environmental agencies, universities, and independent researchers. Study has revealed that daily rainfall accumulations are universally recorded and hourly data are fairly available by national weather bureaus/environmental agencies (Salonen 1997) [11].

There is still dearth of rainfall rate of 1-minute integration time necessary for the study of rain induced impairment to telecommunication especially in the tropical region of Nigeria. This is because global national weather services are established to satisfy more traditional requirements such as those for agriculture, hydrology and forest management. A method for converting the available rain rate data to the equivalent 1-minute rain rate cumulative distribution is therefore necessary (Ajayi 1983) [1].

Study Area

The study areas to be considered in this research work are Owerri (Imo State), Osogbo (Osun State) and Minna (Niger State).

Owerri

Owerri is the capital of Imo State in Nigeria, set in the heart of Igboland. It is also the state's largest city, followed by Orlu and Okigwe as second and third respectively. Owerri consists of three Local Government Areas including Owerri Municipal, Owerri North and Owerri West. Owerri lies on coordinates 5.485° North and 7.035° East. It has an estimated population of about 1,001,873 as of 2016 and is approximately 100 square kilometres (40 sq mi) in area. Owerri is bordered by the Otamiri River to the east and the Nworie River to the south. Owerri has a tropical wet climate according to the Köppen-Geiger system. Rain falls for most months of the year with a brief dry season. The Harmattan affects the city in the early periods of the dry season and it is noticeably less pronounced than in other cities in Nigeria. The average temperature is 26.4°C. *(*Imo-*Archived*, 2010) [15]

Osogbo

Osogbo is the state capital city of Osun, lies on coordinate’s 7°46ˈ North 4°34ˈEast. Osogbo city seats the Headquarters of both Osogbo Local Government Area (situated at Oke Baale Area of the city) and Olorunda Local Government Area (situated at Igbonna Area of the city). It is some 88 kilometers by road Northeast of Ibadan. It is also 100 kilometers by road South of Ilorin and 115 kilometers Northwest of Akure. Osogbo shares boundary with Ikirun, Ilesa, Ede, Egbedore and Iragbiji and is easily accessible from any part of the state because of its central nature. It is about 48 km from Ife, 32 km from Ilesa, 46 km from Iwo, 48 km from Ikire and 46 km from Ila-Orangun; The City boasted of a population of about 156,694 people, based on the 2006 Census. (Osogbocity web, 2013) [13]

Minna

Minna city is the administrative headquarters of Niger State, estimated with population of 304,113 (2007 census) people and a land area of about 6,789 square kilometres. Minna lies at latitudes 9°37ˈN- 9°79ˈN and longitude 6°16ˈE - 6°65ˈE on a geological base of undifferentiated basement complex of mainly gneiss and magnetite. The climate of Minna lies within a region described as tropical climate. It has a tropical dry and wet climate. The region is characterized by double rainfall maxima. The town has a mean annual precipitation of 1300mm. The rainy season commences most of the time in April and lasts till October, with fluctuations in amount of rainfall received per year. The highest mean monthly rainfall is August with almost 208mm.Temperature is uniformly high throughout the year reaching the peaks of 40 ^{0}C (February/March) and 30^{0}C (November/December). These climatic characteristics favour the availability of domestic water to the people during wet season (National Oceanic, 2016) [14]

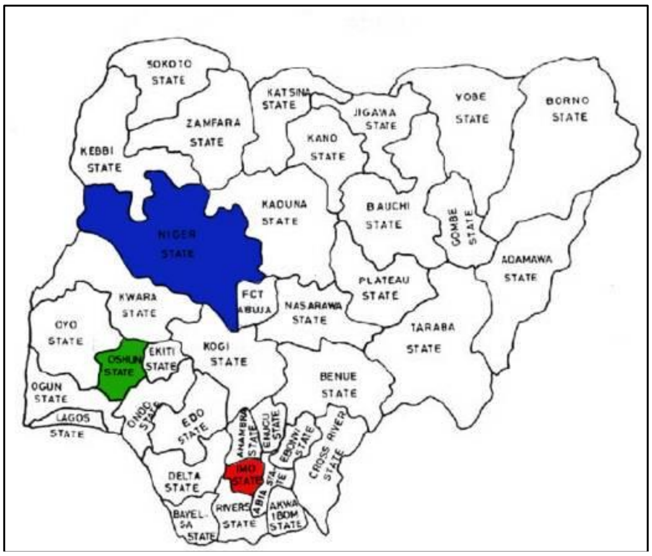

Fig 1: Map of Nigeria showing the states for the study area

Attenuation by Rain

Rain is associated with the propagation characteristics of the atmosphere that most strongly influence the satellite system. Rain attenuation also called Rain fade is caused by rain on a satellite radio path. The severity of rain attenuation depends on how hard it is raining which is described by the rain rate in millimetres of accumulation per hour and not on the total rain accumulation. Rain affects the transmission of an electromagnetic signal in three ways; (Ulbrich, 1983) [12]

1. It attenuates the signal
2. Its increases the system noise temperature
3. It changes the polarization

Attenuation of a signal is as a result of the effect of rain. The scattering and absorption of electromagnetic waves by drops of liquid water is caused by attenuation. The scattering diffuses the signal, while absorption involves the resonance of the waves with individual molecules of water. Attenuation is excluded for snow or ice crystals in which the molecules are highly bound and do not interact with the waves. As the wave’s length approaches the size of a typical raindrop, the attenuation increases which is about 1.5 millimetres. The frequency and wavelength are related by the equation; C = λf, where λ is the wavelength, f is the frequency and C ≈ $3x10^8$ m/s is the speed of light. The rain attenuation is represented by the standard method through an equation of the form:

$$L_r = \alpha R^{\beta} L = \Upsilon L \quad (1)$$

Where L_r is the rain attenuation in decibels (dB), R is the rain rate in millimetre per hour, L is an equivalent path length (km), and α and β are empirical coefficients that depend on frequency and to some extent on the polarization. ϒ is the specific rain attenuation in dB/km. The equivalent path length rely on the angle of elevation to the satellite, the height of the rain layer, and the latitude of the earth station. The rain rate comes into this equation because it is a measure of the average size of the raindrops.

Rain fade is usually estimated experimentally and also can be calculated theoretically using scattering theory of rain drop size distribution (DSD). Various mathematical forms such as Gamma function, lognormal or exponential forms are usually used to model the DSD. Mie or Rayleigh scattering theory with point matching or t-matrix approach is used to calculate the scattering cross section, and specific rain attenuation. Since rain is a non-homogeneous process in both time and space, specific attenuation varies with location, time and rain type.

Rain-Rate Prediction Models

Rainfall rate is a measure of the intensity of rainfall. It is measured by calculating the amount of rain that falls to the earth surface per unit area per unit of time (mm/hr). The differential rain rate is equal to the volume of the differential droplet number density multiplied with the terminal falling velocity V (D). From this product the rain rate is obtained by integrating over the drop size using the formula:

$$RR = \frac{\pi}{6}\int_0^{\infty} N(D)\, D^3 V(D) dD \quad (2)$$

Where N (D) is the drop size distribution and D is rain drop diameter. Their application includes evaporation and runoff modelling, water cycle, energy cycle, weather forecast and climate prediction model (gsfc archived-data file, 2016).

To assess the amount of precipitations fallen over large basins for hydrological purpose is one of the main uses of weather radar. River flood control, sewer management and dam construction are all areas where rainfall accumulation data are been used by planner. Calibration can be used which is derived by radar for rainfall estimates compliment surface station data. Rain rates over a point are estimated to produce radar accumulations by using the value of reflectivity data at individual grid points. A radar equation is used.

$$ZAR^b \quad (3)$$

Where Z is the radar reflectivity, R represents the rainfall rate, and A and b are constants, (Ojo *et* al., 1999).

Rainfall of high intensity is difficult to record and measure experimentally, as well as being highly variable from year to year. However, in system design it is the highest rainfall rates which are frequently of great interest. Short integration-time rainfall rate is the most essential input parameter in the prediction models for rain attenuation. Several models exist for the prediction of point rainfall-rate cumulative distribution; this include the work of Crane (1997) which has considerably influenced the zonal models of the ITU-R and have been used extensively in the United States, although to a lesser extent in other parts of the world, the limit of the model being the number of station-years of measurements available and not all stations fulfilled the one minute integration time requirement. The results reported by *Segal* also influenced the ITU-R zonal models, and provided a systematic approach for obtaining a specified number of rain zones in country such as Canada. Watson *et al.* later mapped rain rates exceeded for 0.1% and 0.01% of an average year based on data for 400 locations within Europe. This approach has been excellent in providing high quality estimates of rain intensity and was used to update the ITU-R rain zones in Europe. The drawback of this approach is that it requires a relatively high density of short integration-time point precipitation measurements or measurements from which these can be derived. The topography is also not explicitly taken into account, therefore requiring a high spatial resolution for the measurement data

This approach cannot be easily used on global data due to the low spatial resolution of point measurements on a global scale and the errors that would arise from the spatial interpolation of precipitation rates for fixed annual probability levels. Rice and Holmberg (1973) [9] also developed a model for obtaining rain rate values for use in fading calculations known as Rice and Holmberg's (1973) [9] model. The model requires certain parameters like; highest monthly rainfall accumulation observed in a set of 30-year period, number of thunderstorm days expected in an average year and the average annual accumulation. The thunderstorm ratio is not always readily available from local weather agencies. The model was later modified by *Dutton and Dougherty* to make it depend on four parameters, two of which are used to estimate the fraction of thunderstorm rain. However, it has been acknowledged that the Rice and Holmberg (1973) [9] method overestimates rain rates in the high-availability range (0.01%), and underestimates in the range between 0.1% and 1%. Recent analysis suggests that the rain rate distribution is better described by a model which approximates a log-normal distribution at the low rates, and a gamma distribution at high rain rate. This kind of model was developed by Moupfouma and Martins (1995) [6]. The model is good for both tropical and temperate climate and can be expressed as:

$$P(R \geq r) = 10 - 4rR + 10.01be^{(u[R_{0.01}-r])} \quad (4)$$

Where r (mm/h) represents the rain rate exceeded for a fraction of the time, $R_{0.01}$ is the rain intensity exceeded during 0.01% of time in an average year (mm/h) and b is approximated by the following expression:

$$b = r - R_0 R_{0.01} ln(1 + R_0 r_{0.01}) \quad (5)$$

The parameter u in Equation (4) governs the slope of rain rate cumulative distribution and depends on the local climatic conditions and geographical features. For tropical and sub-tropical localities

$$u = 4\ln 10 R_{0.01}\, e^{-\lambda R_0 r_{0.01} \gamma} \quad (6)$$

Where λ = 1.066 and γ = 0.214.
Thus, the Moupfouma (2009) [7] model requires three parameters; λ, γ and $R_{0.01}$. The first two parameters have been provided. To estimate $R_{0.01}$, the use of J. Chebil and Rahman's (1999) [2] model appears suitable, it allow the usage of long-time mean annual accumulation, M, at the location of interest. The power law relationship of the model is given by

$$R_{0.01} = \alpha M^{\beta} \quad (7)$$

where α and β are regression coefficients. Chebil and Rahman (1999) [2] has made a comparison between some models based on measured values of $R_{0.01}$ and M in Malaysia, Indonesia, Brazil, Singapore and Vietnam. He showed that his model is the best estimate of the measured data. The regression coefficient α and β are defined as
$\alpha = 12.2903$ and $\beta = 0.2973$
Thus, using the refined Moupfouma (2009) [7] model and Chebil and Rahman (1999) [2] model, the 1 minute rain-rate cumulative distribution is fully determined from the long term mean annual rainfall data.

Rain Attenuation Model
A number of rain attenuation prediction models have been published which claim global applicability. Attenuation predictions require first the estimation of a surface rain rate distribution and second the prediction of the radiowave attenuation value distribution, given by the rain rate distribution. Several workers have proposed different models for calculation of attenuation along a path. Way back in 1946, Ryde (1946) [10] presented a rain attenuation model. After three decades, Crane (1997) looked afresh at the model predictions and compared them with the measured values taking the data available and new data published after that. He found an average matching between model predictions and measurements. He later proposed another model called, two-component model, followed by the revised version. Several other models also include: simple attenuation model by Stutzman and Dishman, Dutton et al. model, Excell model, Misme Waldteufel, Garcia model, ITU-R model, Bryant model, Flavin model, DHA model, Moupfouma (2009) [7] Model among others. Details of these models can be obtained from *COST 255*. To develop the map for rain attenuation over Nigeria, ITU rain attenuation model was used. It has been reported that the ITU rain attenuation prediction model result was close to the average prediction of a set of results obtained from the application of eight different methodologies. [Fashuyi, et al., 2006] [4]

ITU-R Attenuation Model
The input parameters needed for this model are; height above sea level of the Earth station (km), point rainfall rate for the location for 0.01% of an average year (mm/h), elevation angle, frequency (GHz) and effective radius of the Earth (8500 km), latitude of the Earth station (degree).

Materials and methods
The data used for this study were collected from the Nigerian Meteorological Agency (NIMET) Abuja. The rainfall data measured for a period of four years. The Casella rain gauge was used for the measurement. This instrument is chosen because of its reasonably high degree of sensitivity to provide measurements and capability of indefinite operation, ensuring a long working life.

Casella Rain Gauge
The Casella rain gauge or Tipping Bucket Rain Gauge is an extremely robust and reliable transducer designed as a stand-alone sensor for operation within an existing data logging system such as the ISODAQ range. It incorporates a built-in spirit level to ease correct positioning and the bucket tips are monitored by a sealed reed switch, capable of indefinite operation ensuring a long working life. The body and funnel are made from aluminium alloy with an accurately machined septum ring at the top giving an aperture of 400 cm^2. The rain gauge comprises of a divided bucket assembly pivoted at the centre of 18-inch height. Rain is collected in one side of the bucket which then tips when a predetermined volume of water has been collected. The tipping action discharges the collected water and repositions the opposite side of the bucket under the discharge nozzle ready for filling.

Data Analysis
The rainfall data of 6 years (January, 2011 to December, 2016) collected from the Nigerian Meteorological Agency (NIMET) for Imo, Osun and Niger stations was analysed using the Chebil and Rahman (1999) [2] rain rate models to calculate the rain rate and ITU-R P.618-9 rain attenuation model to calculate the rain attenuation. The ITU-R model was executed using Microsoft Excel.

Chebil and Rahman (1999) [2] Rainfall Rate Model
The power law relationship of the model is given by
$R_{0.01} = \alpha M^{\beta}$

The regression coefficient α and β are defined as
α = 12.2903 and β = 0.2973

ITU-R Rain Attenuation Model
The step by step procedure for calculating the attenuation distribution is given below:

Step 1: Determine the rain height, h_R,
$hR = h0 + 0.36$ km

Step 2: For θ ≥ 5° compute the slant-path length, L_s, below the rain height from:

$$L_s = \frac{(h_R - h_s)}{\sin\theta} \text{ km} \quad (8)$$

For θ < 5°, the following formula is used:

$$L_s = \frac{2(h_R - h_s)}{\left(\sin^2\theta + \frac{2(h_R - h_s)}{R_e}\right)^{1/2} + \sin\theta} \text{ km} \quad (9)$$

If $h_R - h_s$ is less than or equal to zero, the predicted rain attenuation for any time percentage is zero and the following steps are not required.

Step 3: Calculate the horizontal projection, L_G, of the slant-path length from:

$$L_G = L_s \cos\theta \text{ km} \quad (10)$$

Step 4: Obtain the rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year (with an integration time of 1 min). If $R_{0.01}$ is equal to zero, the predicted rain attenuation is zero for any time percentage and the following steps are not required.

Step 5: Obtain the specific attenuation, γ_R, using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$, determined from Step 4, by using:

$$\gamma_R = k\,(R_{0.01})^{\alpha}\ \text{dB/km} \qquad (11)$$

Step 6: Calculate the horizontal reduction factor, $r_{0.01}$, for 0.01% of the time:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G\,\gamma_R}{f}} - 0.38\left(1 - e^{-2L_G}\right)} \qquad (12)$$

Step 7: Calculate the vertical adjustment factor, $v_{0.01}$, for 0.01% of the time:

$$\zeta = \tan^{-1}\left(\frac{h_R - h_s}{L_G\, r_{0.01}}\right) \text{ degrees}$$

$$\text{For } \zeta > \theta, \quad L_R = \frac{L_G\, r_{0.01}}{\cos\theta} \text{ km}$$

$$\text{Else, } L_R = \frac{(h_R - h_s)}{\sin\theta} \text{ km}$$

If $|\varphi| < 36°$, $\chi = 36 - |\varphi|$ degrees
Else, $\chi = 0$ degrees

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\,\gamma_R}}{f^2} - 0.45\right)}$$

Step 8: The effective path length is:

$$L_E = L_R\, v_{0.01} \text{ km} \qquad (13)$$

Step 9: The predicted attenuation exceeded for 0.01% of an average year is obtained from:

$$A_{0.01} = \gamma_R\, L_E \text{ dB} \qquad (14)$$

Step 10: The estimated attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 5%, is determined from the attenuation to be exceeded for 0.01% for an average year:

If $p \geq 1\%$ or $|\varphi| \geq 36°$: $\beta = 0$
If $p < 1\%$ and $|\varphi| < 36°$ and $\theta \geq 25°$: $\beta = -0.005(|\varphi| - 36)$
Otherwise: $\beta = -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta$

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - \beta(1-p)\sin\theta)} \qquad (15)$$

This method provides an estimate of the long-term statistics of attenuation due to rain

Basic Assumption of the Model Case

The ITU–R (formerly CCIR, International Radio Consultative Committee) rain attenuation model is the most widely accepted method for the estimation of rain attenuation on satellite communication system. The following procedure gives estimation of the long–term statistics of the slant–path rain attenuation at a given location for frequencies up to 55 GHz. The parameters required are $R_{0.01}$ point rainfall rate for the location for 0.01% of an average year (mm/h), h_s,:height above mean sea level of the earth station (km), θ: elevation angle (degrees), ϕ: latitude of the earth station (degrees), f : frequency (GHz), R_e: effective radius of the Earth (8500 km).
The ITU rain attenuation prediction model presents good results which have close proximity to the average prediction of a set of results obtained from the application of eight different methodologies, Hence, this research work makes use of this model for rain attenuation prediction.

Results and Discussion

The total rainfall obtained from the analysis of the rainfall data for Minna (Niger), Osogbo (Osun) and Owerri (Imo) has been analyzed. The rainfall event is for the period of 6 years (January 2011 to December 2016). The detailed analysis of the three stations are presented in this section.

Six (6) Years Total Rainfall for the Study Area

Table 1: Detailed data for the 6 years total rainfall for the study area

Location	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minna	0	0	176.8	338	830.8	1008.8	1285.9	1458.6	1278.9	2605.3	77.2	0
Osogbo	6.8	260.3	495.8	568.3	1072.2	999.1	990.8	748.9	1191.1	1494.8	495	2.1
Owerri	105.3	391.9	428.5	865.9	1683.7	1529.6	1568.3	2480.1	2179.2	1692.5	402.9	12

Figure 2 shows the 6 years total rainfall for the study area (2011-2016)

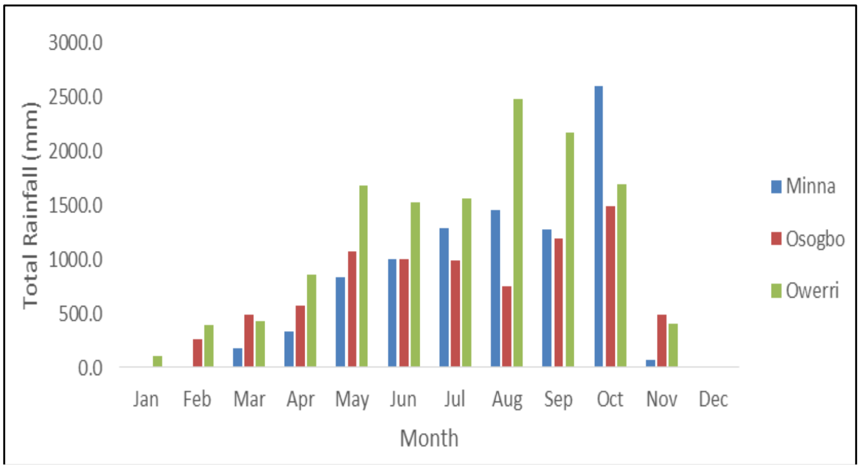

Fig 2: 6 Years Total Rainfall (mm)

It has been noted that Minna records no rainfall in January, February and December for the whole 6 years of study. The least rainfall is recorded in January and December in Osogbo while December recorded the least rainfall events in Owerri. October recorded the highest rainfall events in Osogbo while Owerri experienced the most rainfall in August

First 3 Years Average Rainfall for the Study Area

Table 2: Average rainfall value of the study areas within the first 3 years.

Location	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minna	0	0	165.9	153.5	399.4	399	661	541.5	637.4	405.5	77.2	0
Osogbo	3.7	184.3	139.3	323.3	514.2	468.1	470.2	468.3	671.8	786	324.4	0
Owerri	46.4	258.8	136.9	451.7	888.5	751.7	866.4	1274.7	1202.8	872.9	193.2	0

Figure 3 Presents the First 3 Years Average Rainfall for the Study Area (2011-2013)

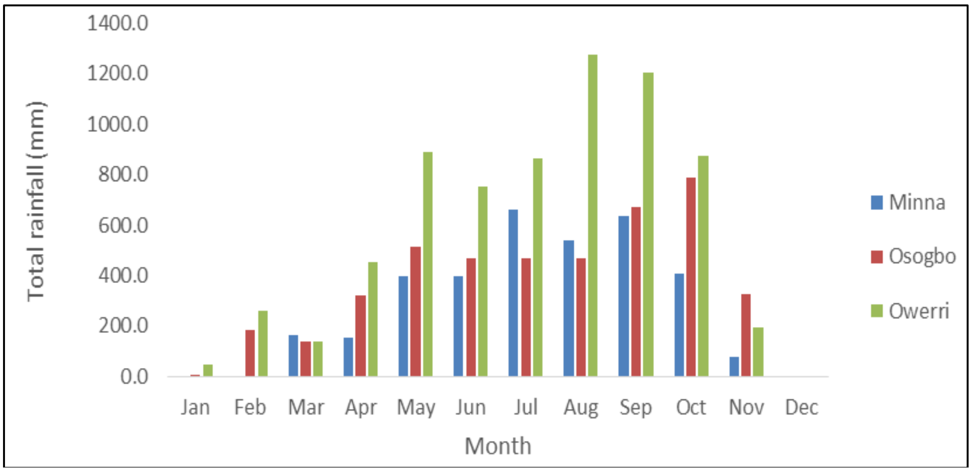

Fig 3: First 3 Years Total Rainfall (mm) for the study area

From the Table 2, it is observed that Minna records no rainfall in January, February and December for the first 3 years of study. Osogbo recorded no rainfall in December and only 3.7 mm in January while December recorded no rainfall in Owerri. Minna recorded the highest rainfall events in September, Osogbo recorded the highest in October while Owerri experienced the most rainfall in August.

Second 3 Years Average Rainfall for the Study Area

Table 3: Average second 3 years for the study areas.

Location	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minna	0	0	10.9	184.5	431.4	609.8	624.9	917.1	641.5	255.9	0	0
Osogbo	3.1	76	356.5	245	558	531	520.6	280.6	519.3	708.8	170.6	2.1
Owerri	58.9	133.1	291.6	414.2	795.2	777.9	701.9	1205.4	976.4	819.6	209.7	12

Figure 4; gives second 3 Years Average Rainfall for study area (2014-2016)

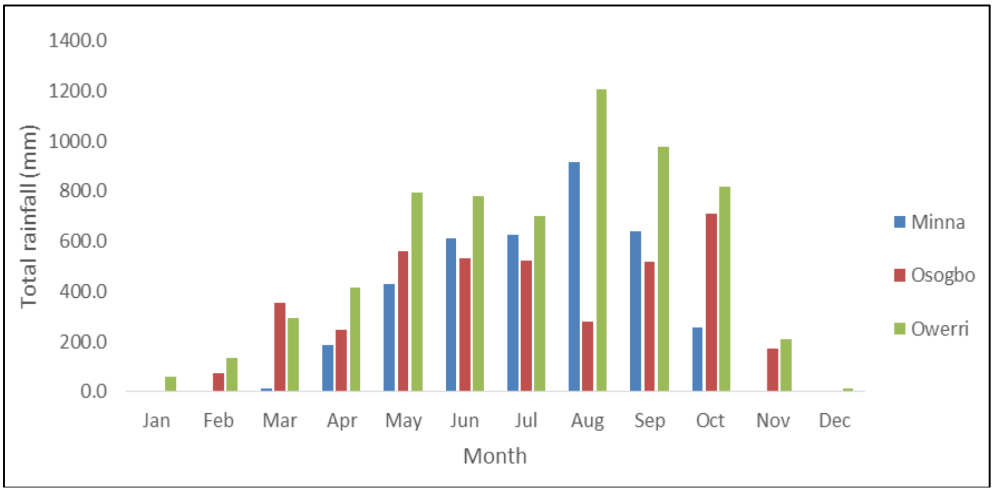

Fig 4: Second 3 Years Total Rainfall (mm) for the study area

January, February, November and December has no value for the period of the second 3 years of study in Minna. Least average rainfall is recorded in January and December in Osogbo while Owerri experienced the least rainfall in December. Highest average rainfall is recorded in August in Minna and Osogbo experienced its peak rainfall values in October while the highest rainfall in Owerri was experienced in August.

Rain Attenuation Calculation for the Locations Using ITU-R P.618-9 Model.

This model uses rain rate at 0.01% probability level for the estimation of attenuation and then applies an adjustment factor for the predicted rain attenuation depth for other probabilities. Table 4 shows the geographical and experimental parameters for the location under investigation.

Table 4: Geographical and Experimental parameters of Minna, Osogbo and Owerri.

Locations	Owerri	Minna	Osogbo
Latitude	5.5ˈN	9.5ˈN	7.8ˈN
Longitude	7.0ˈE	6.5ˈE	4.5ˈN
Height above sea level	118m	172m	302m
Elevation angle	42.5°	42.5°	42.5°
Polarization angle	45° Circular	45° Circular	45° Circular
Operating frequency	Downlink (11 GHz) And Uplink (14 GHz) For Ku-Band And Downlink (20GHz) and uplink (40GHz) for ka-band	Downlink (11 GHz) and uplink (14 GHz) For Ku-Band And Downlink (20GHz) and uplink (40GHz) for ka-band	Downlink (11 GHz) and uplink (14 GHz) For Ku-Band And Downlink (20GHz) and uplink (40GHz) for ka-band

The rain attenuation for Minna is thus calculated in the following manner.

Step 1: Determination of the rain height, H_R as given by the ITU R P.618-9 model where h_o is the 0^o C isotherm height above mean sea level of the location and is given as 4.426 km. Hence

H_R =4.786 km

Step 2: Determining the slant-path length Ls. θ is the Elevation angle which is 42.5° and H_S is the height of the location above sea level given as 0.172 km.

Ls= 6.829 km

Step 3: The horizontal projection, L_G, of the slant-path length is calculated below. Where θ = 42.5°

L_G = 5.035 km

Step 4: The point rainfall rate $R_{0.01}$ (mm/h) as in eqn (2.7) for Minna, exceeded for 0.01% of an average year is obtained from one minute integration rain rate data for the location as

$R_{0.01}$ = 100.667 mm/hr

Where α = 12.2903, β = 0.2973 and mean average rainfall (M) = 1180.5 mm

Step 5: Obtain the specific attenuation, γ_R, using the frequency-dependent coefficients and the rainfall rate, $R_{0.01}$.

For 11 GHz, $\gamma_{R0.01}$= 4.1991 dB/km

For 14 GHz, $\gamma_{R0.01}$= 6.2848 dB/km

For 20 GHz, $\gamma_{R0.01}$= 10.3581 dB/km

For 40 GHz, $\gamma_{R0.01}$= 22.4420 dB/km

Step 6: The horizontal reduction factor, $r_{0.01}$, for 0.01% of the time is calculated as:

For 11 GHz, $r_{h0.01}$ = 0.587745

For 14 GHz, $r_{h0.01}$ = 0.557812

For 20 GHz, $r_{h0.01}$ = 0.532025

For 40 GHz, $r_{h0.01}$ = 0.517858

Step 7: The vertical adjustment factor, $v_{0.01}$, for 0.01% of the time is:

For 11 GHz, $v_{0.01}$ =0.762923

For 14 GHz, $v_{0.01}$ = 0.884241
For 20 GHz, $v_{0.01}$ = 1.066346
For 40 GHz, $v_{0.01}$ = 1.348033

Step 8: The effective path length L_E:

For 11 GHz, L_E= 3.062411
For 14 GHz, L_E= 3.368622
For 20 GHz, L_E= 3.874573
For 40 GHz, L_E= 4.767658

Step 9: Predicted attenuation exceeded for 0.01% of an average year for varying frequencies are

For 11 GHz, $A_{0.01}$ = 12.85928
For 14 GHz, $A_{0.01}$ = 21.17106
For 20 GHz, $A_{0.01}$ = 40.13307
For 40 GHz, $A_{0.01}$ = 106.9959

The above steps are repeated using both the downlink and uplink frequency of Ku-band (11 GHz and 14 GHz) and Ka-band (20 GHz and 40 GHz) for the other two study area (Owerri and Osogbo) and Table 5 gives the variation of the rain attenuation with respect to percentage of time exceeded of an average year. From Table 5 it is evident that an increase in frequency leads to a significant increase in the attenuation.
Also, attenuation by rain varies from location to location due to different rainfall rate experienced in the various locations. Owerri in Imo state has highest rainfall rate compared to Osogbo in Osun state which also has higher rainfall rate than Minna in Niger state hence there is most signal attenuation occurrence in Owerri compare to Osogbo and more in Osogbo compare to Minna.

Step 10: Estimated attenuation to be exceeded for other%, in the range 0.001% to 10%, is determined from the attenuation to be exceeded for 0.01% for an average year:

Table 5(a) – (d): Variation of rain attenuation with respect to% time exceeded for the study areas.

	(a) Rain attenuation at 11 GHz for the study areas				
% time Exceeded	**0.001**	**0.01**	**0.1**	**1**	**10**
Owerri	23.873	14.983	6.473	1.286	0.223
Minna	21.480	12.859	5.316	1.069	0.182
Osogbo	21.631	13.171	5.525	1.101	0.188

	(b) Rain attenuation at 14 GHz for the study areas					
% time Exceeded		**0.001**	**0.01**	**0.1**	**1**	**10**
	Owerri	37.018	24.441	11.109	2.322	0.423
	Minna	33.584	21.171	9.216	1.952	0.351
	Osogbo	33.738	21.603	9.539	2.000	0.360

	(c) Rain attenuation at 20 GHz for the study areas				
% time Exceeded	0.001	0.01	0.1	1	10
Owerri	65.162	45.930	22.286	4.972	0.968
Minna	59.581	40.133	18.667	4.225	0.811
Osogbo	59.611	40.766	19.225	4.305	0.828

		(d) **Rain attenuation at 40 GHz for the study areas**				
% time Exceeded		0.001	0.01	0.1	1	10
	Owerri	154.229	120.093	64.372	15.866	3.412
	Minna	143.498	106.996	55.090	13.801	2.932
	Osogbo	142.469	107.753	56.201	13.919	2.960

Table 6: Point rainfall for the Study Areas

Location	**Owerri**	**Minna**	**Osogbo**
Point Rainfall ($R_{0.01}$)	123.0988mm/hr	100.6671mm/hr	105.3712mm/hr

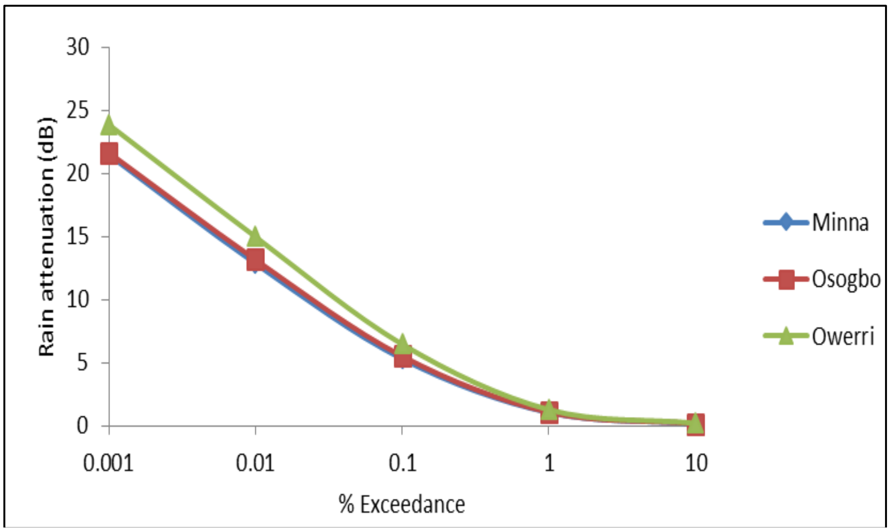

Fig 5: Rain attenuation at 11 GHz for the study area

Rain does not occur all the time in a year and its rate does not remain same either all the time, when it occurs, thus, the amount of rain fade margin needed to compensate rain effects varies with time. Figure 5 gives a graphical representation of the rain attenuation at 11 GHz Ku downlink frequency. At 0.01%-time exceedence, the rain Attenuation level for Owerri, Minna and Osogbo are 14.98 dB, 12.86 dB and 13.17 dB respectively. These indicate that attenuation is more pronounced Owerri than Osogbo and least in Minna.
Figure 6 presents the Rain attenuation at 14 GHz (Ku-uplink frequency) for the study area.

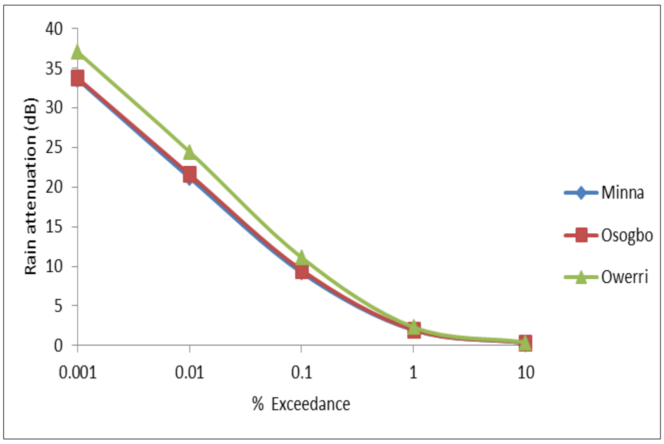

Fig 6: Rain attenuation at 14 GHz for the study area

Similarly, Figure 6 also presents rain attenuation at Ku-band uplink frequency 14 GHz for Owerri, Minna and Osogbo at 0.01% of time exceedence are respectively 24.44 dB, 21.17 dB and 21.60 dB.

Figure 7 presents the Rain attenuation at 20 GHz (ka-downlink frequency) for the study area.

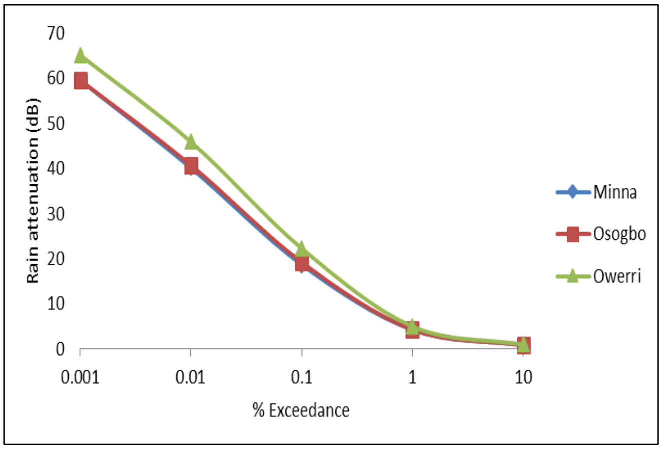

Fig 7: Rain attenuation at 20 GHz for the study area

Figure 7 gives the graphical representation at Ka-band downlink frequency 20 GHz, showing that at 0.01%-time exceedence, the rain attenuation for Owerri, Minna and Osogbo are 45.93 dB, 40.13 dB and 40.76 dB. Hence Owerri experiences more attenuation than Osogbo and Minna at this frequency.

Figure 8 shows the Rain attenuation at 40 GHz (Ka- uplink frequency) for the study area

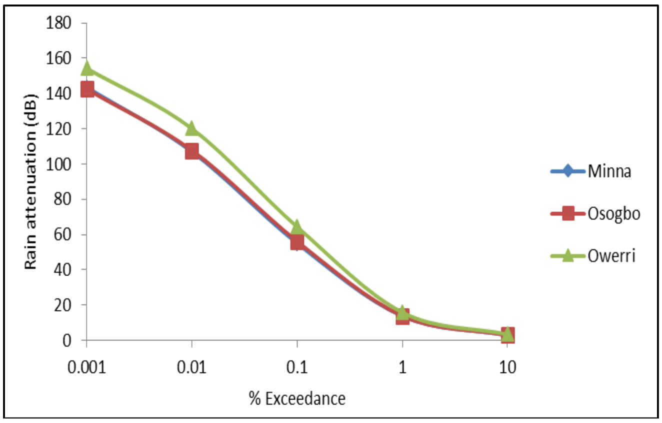

Fig 8: Rain attenuation at 40 GHz for the study area

Lastly, Figure 8 gives the rain attenuation at Ka-band uplink frequency 40 GHz, which also shows that the rain attenuation for Owerri, Minna and Osogbo are 120.09 dB, 106.99 dB and 107.75 dB respectively.

As it is observed, increase in frequency leads to a correspond increase in attenuation.

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Conclusion

The effects of rainfall on satellite communication link at Ku-band and ka-band have been investigated for links to Nigerian communication satellite-1 Replacement (NIGCOMSAT-1R) based on local input data. Rain rate and rain attenuation graphs were developed for 0.001-10% of time using the Chebil and Rahman's (1999) [2] rain rate model for the rain rate graph and ITU-R P.618-9 rain attenuation model for the rain attenuation graphs over Owerri, Minna and Osogbo. Rainfall rate which is one of the inputs in the calculation of rain attenuation was evaluated and the result shows that a higher rainfall rate, $R_{0.01}$ (123.09 mm/hr) was experienced in Owerri, than Osogbo with a value of $_{R0.01}$ (105.37 mm/hr) and the least is Minna with a value of $R_{0.01}$ (100.67 mm/hr) and this is due to the difference in meteorological condition of the study areas. Hence pronounced rain attenuation is experienced in Owerri than Osogbo and Minna at both the downlink and uplink frequencies of ku-band and ka-band.

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