Investigation of Radiowave Propagation Impairment at Super High Frequency due to Rain in Akure

Oluwadare E. J.
Department of physical sciences
Ajayi Crowther University
P.M.B. 1066, Oyo, Oyo State Nigeria.

Tomiwa, A. C.
Department of Physics and Electronics
AdekunleAjasin University
Akungba akoko, Ondo State, Nigeria.

Ajewole, M. O.
Department of physics
Federal University of Technology
Akure. P.M.B. 704, Akure, ondo State Nigeria.

Abstract

The measurement of the vertical profiles of rainfall parameters such as drop size distribution, rain rate, liquid water content, fall velocity and radar reflectivity were carried out by using Micro Rain Radar in 2006 and 2008 at Akure (Lat 5°15'E, long 7°15'N) in South-Western Nigeria. The vertical distributions of these parameters with heights are presented for 0 - 4800 m. The range gates for the measurement are 30 with a height step of 160 m. The variation of the drop size distribution, rain rate and liquid water content with height were evaluated. The highest rain rate and liquid water content were observed within the height range 0-160 m. For the all cases considered, the largest concentration of drop size with a diameter of 0.246 mm occurred in the height range 0-160 m. Empirical relations in the form $Y = aR^b$ *have been obtained for the rainfall rate, the radar reflectivity factor Z, and liquid water content using the least square power law regression. The results show that the relationship obtained for height range 0-160 m for the two years were in good agreement with the values available in the literatures. For all cases considered, there is a good correlation between the parameters. The measured rainfall rates were divided into classes using the criteria; for stratiform rain type, rain rate R < 50mm/h and convective rain type, rain rate R > 50 mm/h. These empirical relations were compared with results obtained at other locations. Though there is a good agreement between the relationships Z-R in Stratiform rain type with those in the literatures, however there is a slight difference with that of convective rain type. These parameters are then used to calculate specific attenuation due to rain at different rain types and rain rates. The specific attenuation was then evaluated for frequencies from 1 – 100 GHz. Results obtained show that specific attenuation increases with increasing frequency for both rain types at a critical frequency (around 31 GHz), the increasing specific attenuation starts to decrease.*

1.0 Introduction

Accurate measurement and prediction of the spatial and temporal distribution of rainfall are basic issues in communication. The measurement of various rainfall parameters have been carried out by many researchers using different instruments such as the rain gauge, used in the measurement of rain rate, and the disdrometer, used for drop size distribution measurement. With a known relationship, others parameters such as reflectivity and liquid water content are calculated from other measured parameters. As a result of the gradual development of radar technology over the last 50 years, ground-based weather radar is now finally becoming a tool for quantitative measurement of rainfall parameters instead of merely using it for qualitative rainfall estimation.

Potential areas of application of ground-based weather radar systems in operational hydrology include storm hazard assessment and flood forecasting, warning, and control (Collier, 1989).

The term propagation is used to describe the transfer of energy without necessarily transferring matter. The transfer of energy between two points in certain media is a result of changes with time in the spatial distribution of non-static field in that medium (this could be the electric or magnetic or both) but must change with time. The propagation medium has a great influence on the success of any telecommunication system. The International Telecommunication Union (ITU) has limited the term radio wave to electromagnetic waves with frequencies lower than 3000 GHz (Hall, 1991). The concept of frequency is the key to the understanding of radio frequency because almost everything in the radio frequency world is frequency dependent. A signal is distinguished on the basis of its frequency. The range of frequencies used is also the most common way to distinguish a wave from another. This is achieved by using the concept of frequency bands, i.e. the standard way to name specific range of frequencies. The list of radio frequency band of common use to radio wave propagation is shown in Table 1
This study deals with the analysis of rainfall parameters measured by the vertically looking micro rain radar. The parameters measured include the drop size distributions, rain rate, liquid water content, fall velocity and the radar reflectivity factor. Some of these parameters are then used to calculate the attenuation due to rain when radio signal passes through the measured rain types. The frequency range of interest is from 3 GHz to 100 GHz. For the calculation of attenuation due to different rain types, the power law relationship between attenuation and rain rate as recommended by International Telecommunication Union were used with the power law constant “a” and “b” for frequencies of 3 - 100 GHz calculated using regression analysis developed by Ajewole et al, (1999) for Nigeria.

2.0 Objectives of the Research

The specific objectives of the present work are to:

a. measure the vertical distribution of rainfall parameters (rain drop - size distributions, radar reflectivity, rain rate and liquid water content);
b. use the data obtained to validate the hitherto theoretically obtained power law constants of radar reflectivity, rain rate and liquid water content and rain rate and;
c. compute the specific attenuation due to rain at microwave frequencies.

3.0 Motivation for the Study

There have been extensive works done on the measurement of rain drop size distributions, radar reflectivity and rain rate for the investigation of rain-induced impairment to radio signals at super high frequencies. Most of these works were carried out in the temperate regions. However, some researchers have carried out similar studies in tropical locations. Such studies include the measurement of rain drop size distributions at Ile-Ife by Ajayi and Olsen (1985), Adimula and Ajayi (1996) at Ilorin, Zaria and Calabar using the disdrometer, while the measurement of rainfall intensity was done by a rain gauge.

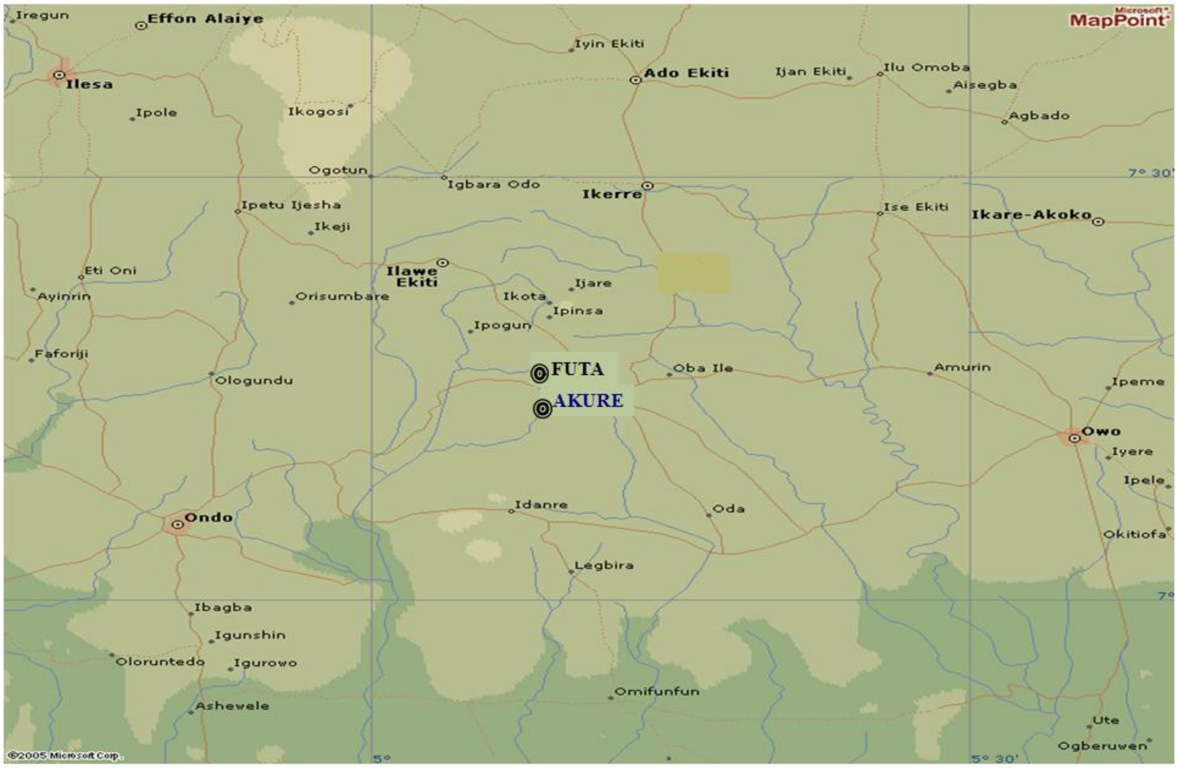
Until the present study, there has not been any measurement of the vertical profile of rainfall parameters in Nigeria. Previous measurements of the drop size distributions were done using the disdrometer usually placed at the ground level. Therefore, the uniqueness of this study is in using micro - rain radar, to measure the vertical profile of the drop size distributions, rain rate, liquid water content, fall velocity and the radar reflectivity factor simultaneously during a rain event.

Table 1: Radio frequencies and their applications.

Name	Designation	Frequency band	Wavelength	Applications
Extremely low frequency	ELF	3-30 Hz	10,000-100,000 km	Directly audible when converted to sound, communication with submarines
Super low frequency	SLF	30-300 Hz	1,000-10,000 km	Directly audible when converted to sound, AC power grids (50-60 Hz)
Ultra low frequency	ULF	300-3000 Hz	100-1,000 km	Directly audible when converted to sound, communication with mines
Very low frequency	VLF	3-30 kHz	10-100 km	Directly audible when converted to sound (ultrasound)
Low frequency	LF	30-300 kHz	1-10 km	AM broadcasting, navigation beacons
Medium frequency	MF	300-3000 kHz	100-1000 m	AM broadcasting, navigation beacons, maritime and aviation communication
High frequency	HF	3-30 MHz	10-100 m	Shortwave, amateur radio, citizens' band radio
Very high frequency	VHF	30-300 MHz	1-10 m	FM broadcasting, amateur radio, broadcast television, aviation, GPR
Ultra high frequency	UHF	300-3000 MHz	10-100 cm	Broadcast television, amateur radio, mobile telephones, cordless telephones, remote keyless entry for mobiles, GPR
Super high frequency	SHF	3-30 GHz	1-10 cm	Wireless networking, satellite links, satellite television, microwave links
Extremely high frequency	EHF	30-300 GHz	1-10 mm	Microwave data links, radio astronomy, remote sensing, advanced security scanning

4.0 Project Site

The measurement site chosen for the study is the Federal University of Technology Akure Ondo State Nigeria (7°15'N, 5°15'E) (fig 1). The measurement was taken for a period of two years 2006 and 2008. Ondo State is composed of lowlands and rugged hills with granitic outcrops in several places. In general, the land rises from the coastal part (less than fifteen metres above sea level) in the south, to the rugged hills of the north eastern area. The climate of Ondo State is of the Lowland Tropical Rain Forest type, with distinct wet and dry seasons. In the south, the mean monthly temperature is around 27°C, with a mean monthly range of 2°C, while mean relative humidity is over seventy five percent. However, in the northern part of the state, the mean monthly temperature and its range are about 30°C and 6°C respectively. The mean monthly relative humidity is less than seventy percent. In the south, rain falls throughout the year, but the three months of November, December and January may be relatively dry. The mean annual total rainfall exceeds 2000 millimetres. However, in the north, there is marked dry season from November to March when little or no rain falls. The total annual rainfall in the north, therefore, drops considerably to about 1800 millimetres.



(1)
Fig (1)**:** Map of Ondo state, Nigeria showing where data was collected

5.0 Instrumentation

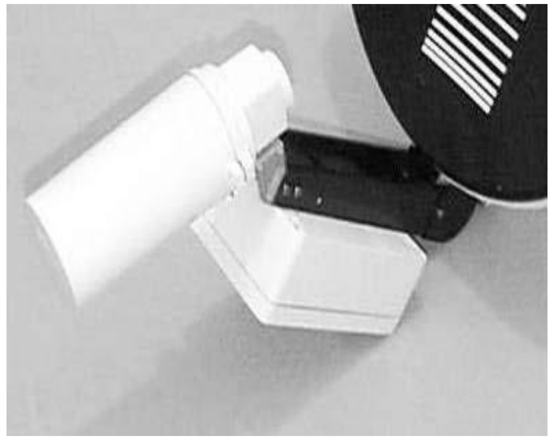
The instrument employed in taking the measurement is the Micro Rain Radar shown in Figure 2. The antenna is simultaneously used for the transmission of the RADAR signals and receiving of backscattered signals from the raindrops. It is designed as an offset parabolic dish. The angular aperture is approximately 2°. The parabolic dish is fastened together with the electronics unit and the RADAR module through the antenna mounting. The use of a parabolic dish allows a vertical alignment of the antenna beam without the need of a horizontal alignment. The antenna is positioned so as to allow rainwater drain off without retaining it.

The electronics unit shown in Figure 3 generates the RADAR transmitting signal and passes it to the RADAR module. It analyses the backscattered received signal and transfers the data to the connected control and evaluation computer, where the Doppler spectra are computed.

The electronics unit is located in a water protected IP65 housing, which is fixed to the antenna mounting. At the bottom side of the electronics unit there is a socket for the cable leading to the connection box/power supply.
The connection box shown in Figure 4 with the aid of a 25-pin D-sub-miniature socket female type (fig. 5) is used to pass the data through to the controlling computer. A flanged socket (fig. 6) is used for connecting RADAR electronics unit box (fig. 3) to the connection box, the power supply is also integrated in the connection box.
The vertical profile of the rain rate, liquid water content, fall velocity, radar reflectivity factor and drop size distribution up to 4800 m-height above sea level were then measured using the Micro Rain Radar at height levels 160 m steps above the radar.

The rain events were sampled with one minute time resolutions and stored subsequently as one minute averages for all the measured parameters.

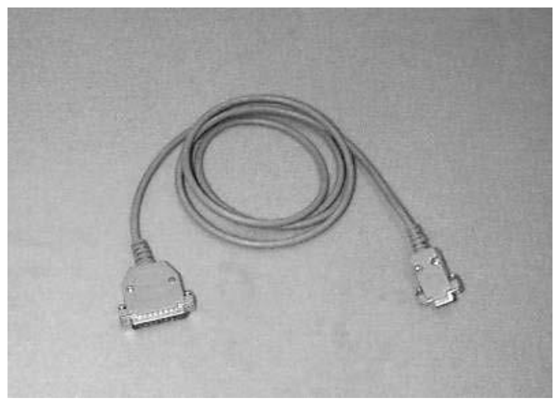
(2)



(3)

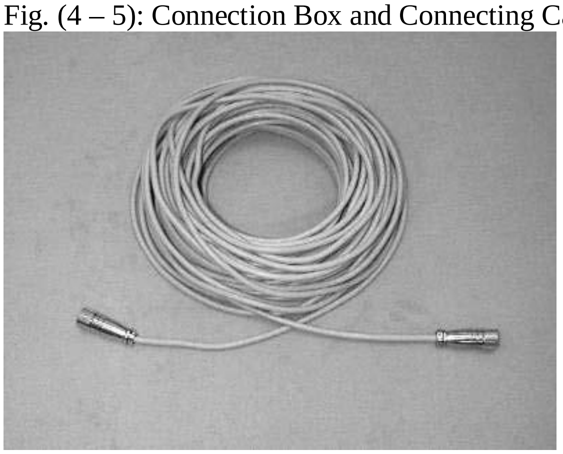
Fig (2 - 3): Outdoor unit and RADAR Electronics Unit of the Micro Rain Radar installed in Physics Department, FUTA.

(4)



(5)

Fig. (4 – 5): Connection Box and Connecting Cable to the Personal Computer



(6)

Fig (6): Connection Cable of the RADAR Electronics Unit.

6.0 Principle of Measurement of the Micro Rain Radar

The measuring principle of the Micro Rain Radar is based on electromagnetic waves of a frequency of 24 GHz. In contrast to normal rain-radar devices, the signals are emitted vertically into the atmosphere. A part of the emitted signal is scattered back to the parabolic antenna by the rain drops. The output signal is transmitted continuously (continuous wave, CW mode in contrast to pulsed radars). The Micro Rain Radar is a Doppler radar, that is, when falling to the ground the rain drops move relatively to the antenna on the ground, which act as both transmitter and receiver.

Due to the falling velocity of the rain drops relative to the stationary antenna there is a frequency deviation between the transmitted and the received signal known as Doppler frequency. This frequency is a measure of the falling velocity of the rain drops. Since rain drops of different diameter have different falling velocities (Atlas et al., 1973), the backscattered signal consists of a distribution of different Doppler frequencies. The spectral analysis of this signal yields a wide distribution of lines corresponding to the Doppler frequencies of the signal.
The Radar electronics determines this spectrum with a high time resolution of 10 seconds and sends it to the connected control and data acquisition system, where the drop spectrum is calculated from the Doppler spectrum considering the transfer function of the radar module. The integration over the entire drop spectrum, considering further correction terms, followed by an averaging for 30 seconds, results in the actual rain rate and the liquid water content.

The Micro Rain Radar measures the Doppler spectrum from 0 to 12 m/s. The standard real-time processing uses the relation given by Atlas et al., (1973) to attribute drop diameters to Doppler velocities.

Mie theory is then used to calculate the rain drop numbers from the spectral volume reflectivity. Corrections for oblate rain drops and lower air densities leading to higher falling velocities in high altitudes are applied. The Rain Drops Size Distribution (DSD) is then calculated for falling velocities from 0.78 to 8.97 m/s in 43 intervals, corresponding to drop diameters from 0.245 to 4.530 mm, which is the range where the signal to noise ratio is considered adequate. Appropriate attenuation correction for moderately high rain rates is done by calculating Mie extinction from the derived DSD. Rain rate, Liquid water content LWC, and Rayleigh reflectivity Z are calculated from the DSD, while the mean falling velocity (first Doppler moment) and integral reflectivity (zeroth Doppler moment) are calculated directly from the measured Doppler spectrum. The Micro Rain Radar range resolution can be set from 10 to 200 m in 30 height intervals. Attenuation at 24 GHz prevents the use of ranges higher than 6 km. The averaging time for one measurement can be set from 10 s up to several hours (3600 s).

6.1 Derivation of Rain Drops Size Distribution.

The drop size distribution was derived from the raw power received by the radar given as

$$p(f_D)\Delta f_D = C(r)\frac{1}{r^2}\frac{1}{\Delta h}\eta(f_D)\Delta f_D \quad (1)$$

where Δh is the range (height) resolution, r is the number of the range gate, $C(r)$ is a calibration function containing radar specific parameters, and $\eta(f_D)\Delta f_D$ is the spectral reflectivity density, that is, the backscatter cross section per volume and per frequency. Δf_D is the frequency resolution. The Doppler Spectra are resolved into 64 lines as

$$\eta_{nn} = 10^{F_{nn}/10} \quad (2)$$

where "*nn*" indicates the line number ($0 \le nn \le 63$). F_{nn} is called "logarithmic spectral volume reflectivity. The "spectral reflectivity" density is then defined as:

$$\eta(f_{D,nn}) = \frac{\eta_{nn}}{\Delta f_D} \quad (3)$$

where $\Delta f_D = 30.52 Hz$

using the generalized form, in which a height dependent density correction for the fall velocity d$v(h)$ Atlas (1973) is defined as:

$$v(D) m/s = (9.65 - 10.3\exp(-0.6D))\partial v(h) \quad \text{for } 0.109 \le \text{D} \le 6\text{mm} \quad (4)$$

Using the America Standard Atmosphere conditions for the height dependence of air density and making use of the relation of Foote and duToit (1969), $\partial v(h)$ under these assumptions is defined as:

$$\partial v(h) = \left[1 + 3.68\times10^{-5}h + 1.71\times10^{-9}h^2\right] \quad (5)$$

The spectral reflectivity can be calculated from the drop diameter using the expression:

$$\eta(D_{nn}) = \eta(f_{D,nn})\frac{\partial f_D}{\partial v}\frac{\partial v}{\partial D} \quad (6)$$

where

$$\frac{\partial f_D}{\partial v} = 160.1973m^{-1} \quad (7)$$

and

$$\frac{\partial v}{\partial D}\left(ms^{-1}mm^{-1}\right) = 6.18 \times \exp(-0.6D)\partial v(h) \quad (8)$$

Substituting equation (7) and (8) into (6) gives:

$$\eta(D_{nn})m^{-1}mm^{-1} = \eta(f_{D,nn}) \times 990.02 \times \exp(0.6mm^{-1}D) \quad (9)$$

Dividing equation (9) by $\sigma(D_{nn})$ gives:

$$N(D_{nn}) = \frac{\eta(D_{nn})}{\sigma(D_{nn})} \quad (10)$$

where $N(D_{nn})$, is the Drop size distribution and $\sigma(D_{nn})$ is the single particle backscattering cross section of rain drop of diameter D_{nn}.

6.2 Equivalent Radar Reflectivity Factor

The equivalent radar reflectivity factor is defined by

$$Z_e = \frac{\lambda^4}{\pi^5}\frac{1}{|K|^2}\int_0^\infty \eta(f_{D,m})\partial f_D \quad (11)$$

In the limit of small drops (Rayleigh approximation), *Ze* is equal to the 6th moment of the drop size distribution

$$Z = \int_0^\infty N(D)D^6 dD \quad (12)$$

Z is calculated on the basis of the drop size distribution measured by the Micro Rain Radar using equation 12.

6.4 Rain Rate

This is the rate at which water reaches the ground or the rate of accumulation of water per unit time (mm/h). The differential rain rate is equal to the volume of the differential droplet number density multiplied with the terminal falling velocity *v(D)*.

$$\left(\frac{\pi}{6}N(D)D^3\right) \quad (13)$$

From this product the rain rate is obtained by integrating over the drop size using the formula:

$$RR = \frac{\pi}{6}\int_0^\infty N(D)D^3V(D)dD \quad (14)$$

6.5 Liquid Water Content (LWC)

The liquid water content is the product of the total volume of all droplets with the density of water ρ_w, divided by the scattering volume. It is therefore proportional to the third moment of the drop size distribution. This is calculated by using the formula given below:

$$Lwc = \rho_w \frac{\pi}{6}\int_0^\pi N(D)D^3 dD \quad (15)$$

6.6 Calculation of Rain Attenuation

Attenuation is calculated using the power law relation:

$$A = aR^b \quad (16)$$

where " a " and " b " are the power law parameters which have been studied and calculated theoretically by many investigators. Ajewole et al., (1999), calculated these power law parameters for a tropical region, for the frequency range of 1–100 GHz. Using the rain rate measured by the MRR, the specific attenuation was calculated for the frequencies 1 – 100 GHz.

6.7 Z-R and M-R Relationships

Equation $Z = aR^b$ was used to determine the relationship between rainfall rate (*R*), radar reflectivity factor (*Z*) and Liquid water content (M) by making rainfall rate the independent variable. Natural logarithm is applied to both sides of the equation resulting in:

$$LnZ = Lna + bLnR \quad (17)$$

Comparing equation (3.17) with a straight-line function;

$$Y = \alpha + \beta X \quad (18)$$

where α and β are the y-axis intercept and the slope respectively. The coefficients a and b of equation 2.24 were estimated by linear regression for *Z* versus *R* and *M* versus *R*

Result and Discussion

7.0 Dropsize Distribution

The rain events observed for the years of 2006 and 2008 were analyzed for the 32 different range gates (0-4800 m, with a step of 160 m), Figs. 7 and 8 show that drop sizes measured varies from 0.25 mm in diameter to about 3.26 mm, with the larger concentration of the diameter around 0.250 - 0.559 mm (with an average diameter interval of 0.04 mm). As the rain drop diameter increases the drop size concentration decreases. Rain drops in the diameter bin of 0.25 mm which represent the drop spectrum N04 contributed most to the rain fall event throughout this period.

8.0 Vertical Distribution of Rain Rate and Liquid Water Content

The variation of the rain rate and liquid water content with height was evaluated and presented in figures (9) - (12) for the 2-years. The highest rain rate and liquid water content were observed along 0-160 m height for both cases considered. The implication of this is that along this height, we expect to have more attenuation of radio wave due to rainfall compared with the other height bins. This is because wind and hydrodynamic forces are lower at this height than higher height levels.

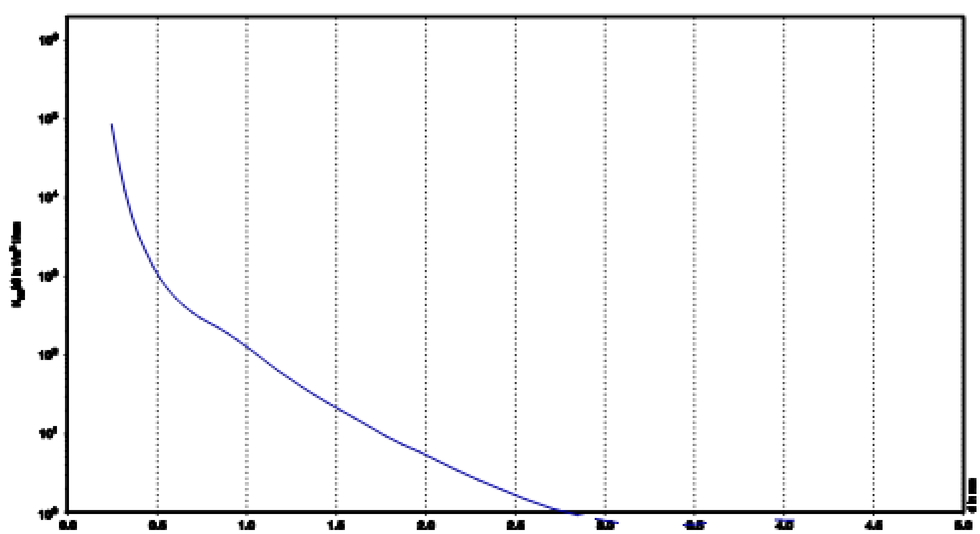


Fig (7): Drop size distribution at height 0-4800 m for the year 2006.

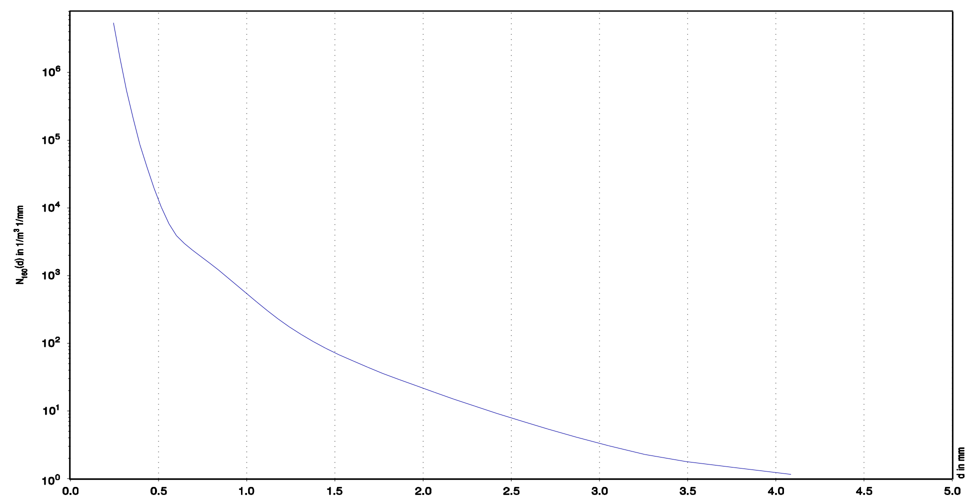
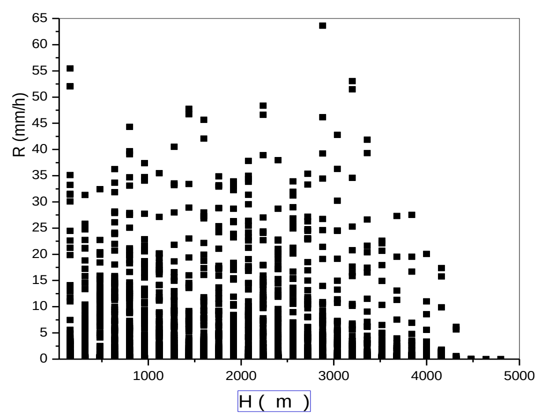
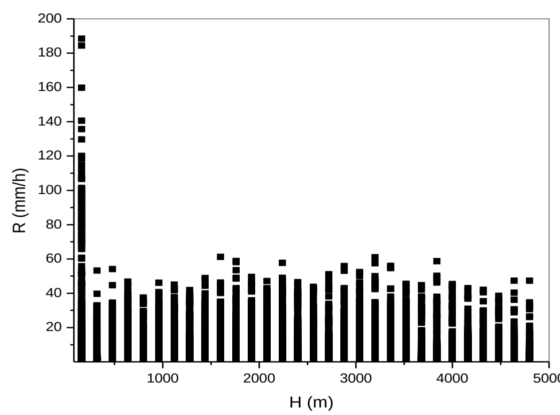


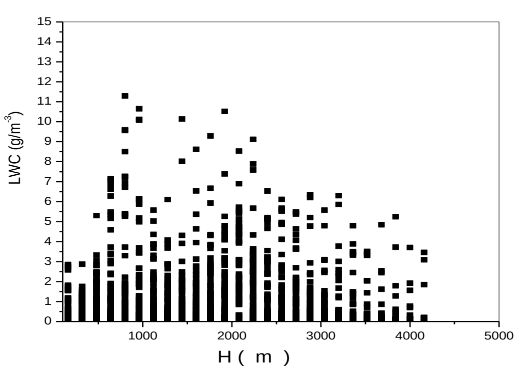
Fig (8): Drop size distribution at height 0-4800 m for the year 2008.

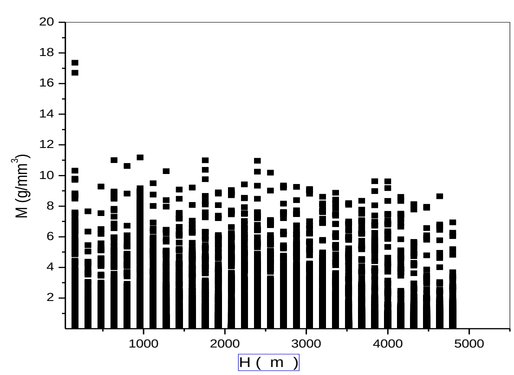




(9) (10)

Fig (9 and 10): Vertical distribution of rain rate for the year 2006 and 2008.





(11) (12)

Fig (11 and 12): Vertical distribution of liquid water content for the year 2006 and 2008.

9.0 Z – R Relationship

All values of R and Z were considered in establishing the general equation for both years of measurement considered (2006 and 2008). This gives two sets of equations, one for each year; the height considered is from 0 – 4800 m above sea level. The data were further divided into units and the heights from 0 – 160 m were also considered for comparison.

The results obtained are

$$Z = 111.66R^{1.17} \text{ (2006)} \tag{19}$$

$$Z = 208.5R^{1.21} \text{ (2008)} \tag{20}$$

The correlation coefficients are 0.71 and 0.76 respectively.

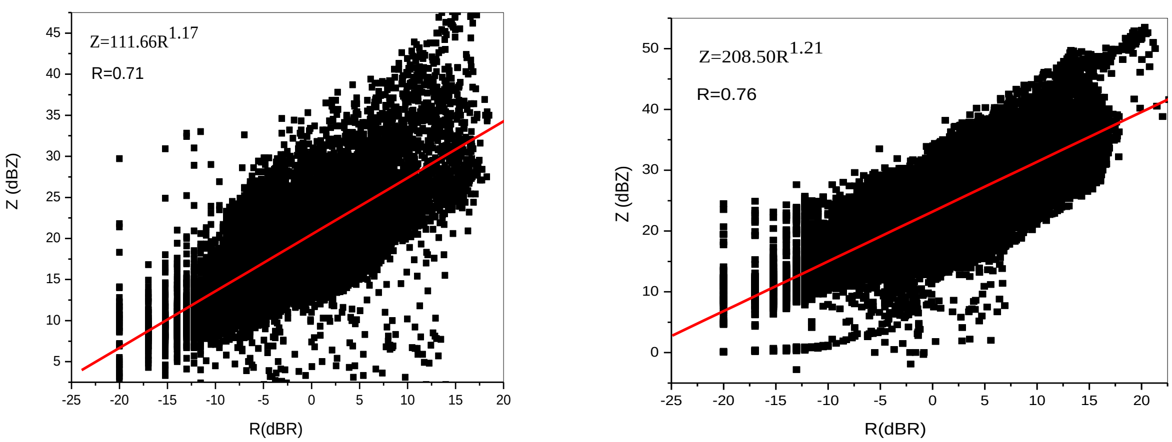
Figures (13) and (14) show the regression lines obtained for the two years considered, as for the height range 0-4800 m. The data was also compared in the height range 0 – 160 m for the two years. The results obtained are shown in figure (15) and (16) for the regression line. The relevant expressions are shown for the two years as

$$Z = 268.71R^{1.31} \text{ (2006)} \tag{21}$$

$$Z = 465.01R^{1.32} \text{ (2008)} \tag{22}$$

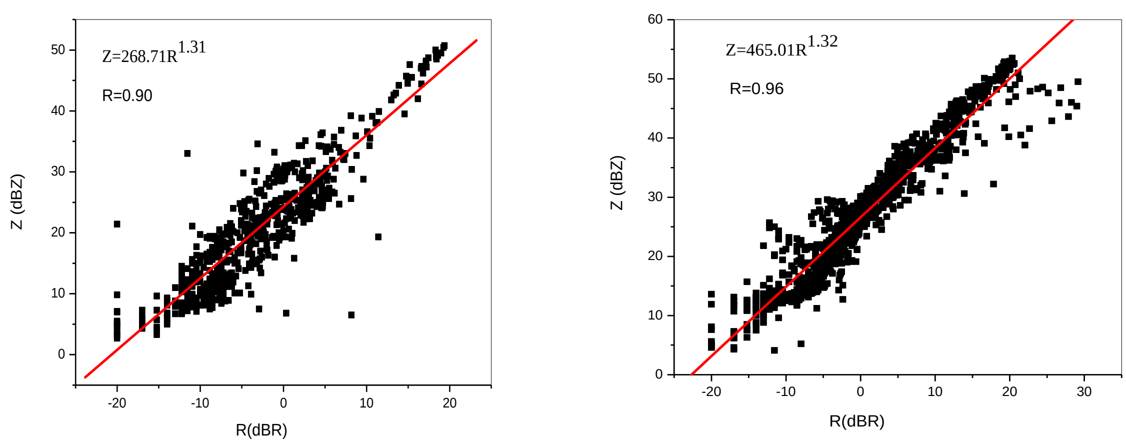
The correlation coefficients are 0.90 and 0.96 respectively.

From equations (21) and (22), we have good correlation coefficients as compared with those obtained in equations (19) and (20). This might be associated with the assumption made for the MRR that the measurement is taken in stagnant air, Metek (2005).



(13) (14)

Fig (13 and 14): Regression line *Z-R* for the whole data set (at 0-4800 m) for the year 2006 and 2008.



(15) (16)

Fig (15 and 16): Regression line *Z-R* for the whole data set (at 0-160 m) for the year 2006 and 2008.

10.0 Z–R Relationship for Stratiform and Convective Rainfall

The data were further divided into stratiform and convective rainfall, using the threshold rain rate $R < 50$ mmh^{-1} for stratiform rain and $R \geq 50$ mmh^{-1} for convective rain event as described in Joss et at., (1968).

Figures (17) and (18) show the regression line for stratiform rainfall while figures (19) and (20) show that for convective rainfall; the height level in view is from 0 - 4800 m.

The power law results are represented by the following equations

Stratiform rainfall

$Z = 111.25R^{1.17}$ r (0.70) (2006) (23)

$Z = 206.99R^{1.20}$ r (0.75) (2008) (24)

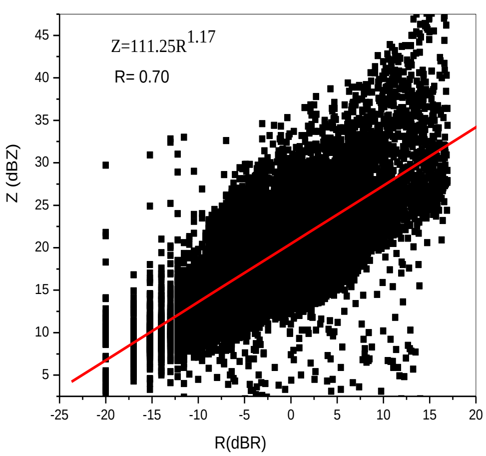
Convective rainfall

$Z = 64.28R^{1.17}$ r (0.45) (2006) (25)

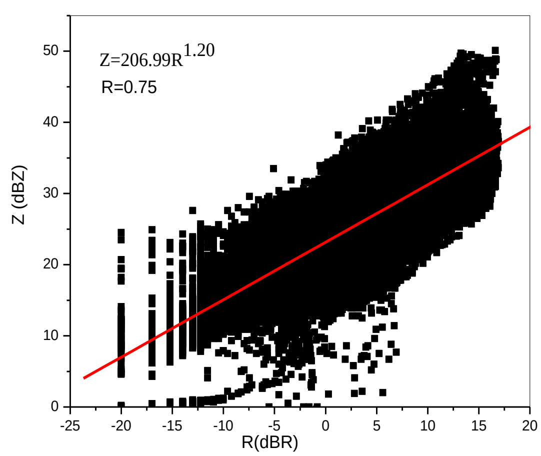
$Z = 90.35R^{1.39}$ r (0.40) (2008) (26)

Correlation coefficients of the convective rain type are very low for the height range (0-4800 m) for the year 2008 and 2006 respectively, while for the height range of 0 – 160 m, there is a good correlation above 0.90 for the year 2006 and 2008 respectively. This can be seen in figures (21 - 24). The values of a and b coefficients for the two years considered and for different rainfall types are given in Table 2.

Comparisons were made with other works done at the tropical locations, this is presented in Table 3, though these works looked at the vertical profile of the parameters measured and the relationships obtained were based on the vertical profile. This study represents the first of such measurements in Nigeria.

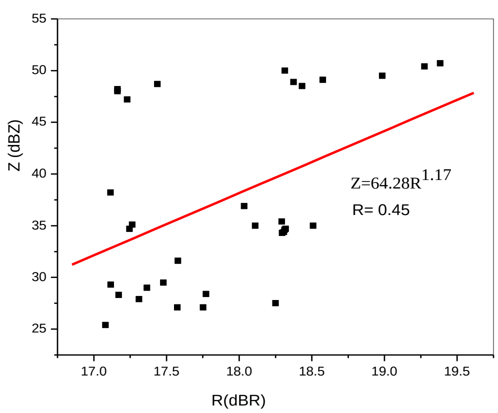


(17)

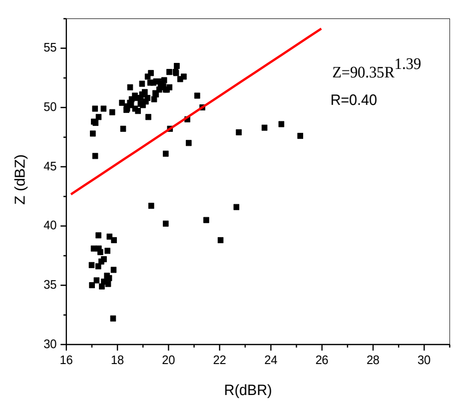


(18)

Fig (17 and 18): Regression line *Z-R* for Stratiform Rain (at 0-4800 m) for the year 2006 and 2008.

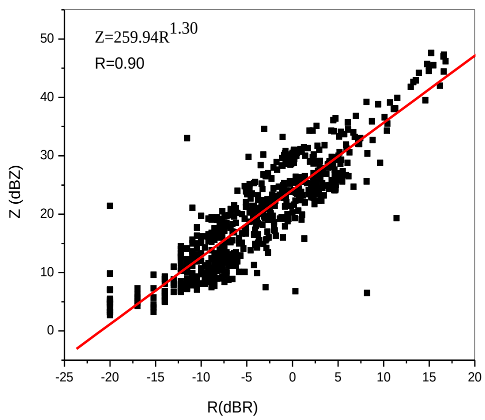


(19)

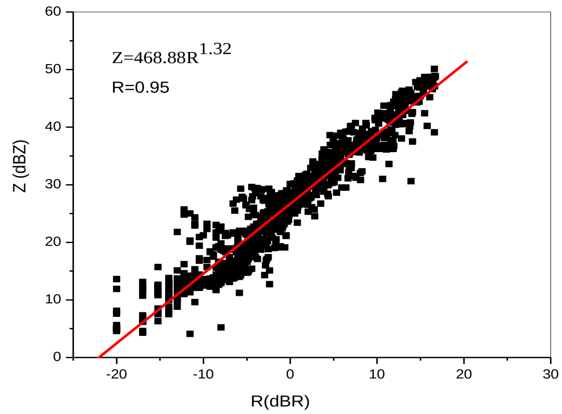


(20)

Fig (19 and 20): Regression line *Z-R* for Convective Rain (at 0-4800 m) in the year 2006 and 2008.

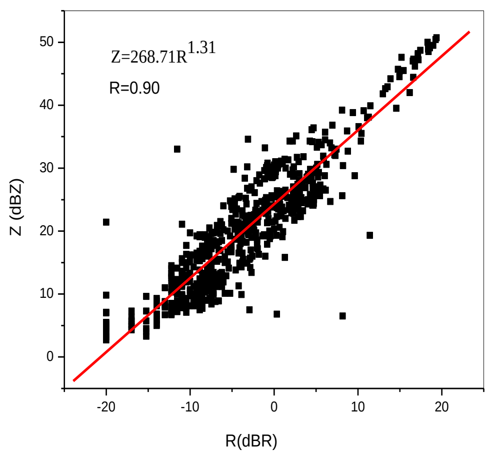


(21)

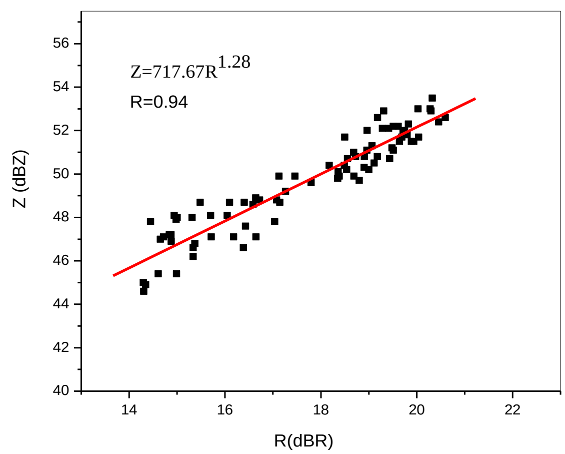


(22)

Fig (21 and 22): Regression line *Z-R* for Stratiform Rain (at 0-160 m) in the year 2006 and 2008.



(23)



(24)

Fig (23 and 24): Regression line *Z-R* for Convective Rain (at 0-160 m) in the year 2006 and 2008.

Table 2: Z-R Relationship and correlation coefficients for Convective and Stratiform Rain types in 2008 and 2006 at different heights

Year	Z-R Relation and correlation coefficients (r)		
	Stratiform	Convective	Height range (metres)
2008	$Z = 206.99R^{1.20}$ $r(0.75)$	$Z = 90.35R^{1.39}$ $r(0.40)$	0-4800
	$Z = 468.88R^{1.32}$ $r(0.95)$	$Z = 717.67R^{1.28}$ $r(0.94)$	0-160
2006	$Z = 111.25R^{1.70}$ $r(0.70)$	$Z = 64.28R^{1.17}$ $r(0.45)$	0-4800
	$Z = 259.94R^{1.30}$ $r(0.90)$	$Z = 268.71R^{1.31}$ $r(0.90)$	0-160

$Z\ is\ in\ mm^6\ m^{-3}\ and\ R\ in\ mm\ h^{-1};\ r\ is\ the\ coefficient\ of\ correlation$

Table 3: Comparison of Z-R Relationships with height at some locations

Rain type	Source	Location	Z-R	r
Stratiform Rain	Joss et al (1970)	Locarno-mouti	$Z = 250R^{1.5}$	
	Marshall and Palmer (1984)	Switzerland	$Z = 220R^{1.6}$	
	CCIR (1982)		$Z = 400R^{1.4}$	
	Fujiwara (1965)	Miami, USA	$Z = 250R^{1.48}$	
	Fundaçäo et al (2004)	Eastern coast, Brazil	$Z = 167.8R^{1.26}$	
	Ajayi and Owolabi (1986)	Ile-Ife, Nigeria	$Z = 312R^{1.35}$	
	Present Study (2008) (0-4800 m)	Akure, Nigeria	$Z = 206.99R^{1.20}$	0.75
	(0-160 m)		$Z = 468.88R^{1.32}$	0.93
	Present Study (2006) (0-4800 m)	Akure, Nigeria	$Z = 111.25R^{1.15}$	0.70
	(0-160 m)		$Z = 259.94R^{1.30}$	0.90
Convective Rain	Joss et al (1970)	Locarno - Monto, Austria	$Z = 500R^{1.5}$	
	Jones (1956)	Illinois, USA	$Z = 486R^{1.37}$	
	Fujiwara (1965)	Miami, USA	$Z = 450R^{1.37}$	
	Sekhon and Srivastava (1971)	Cambridge, USA	$Z = 300R^{1.35}$	
	Fundaçäo et al (2004)	Eastern coast, Brazil	$Z = 65.46R^{1.69}$	
	Diem (1966)	Entebbe, Uganda	$Z = 278R^{1.3}$	
		Lwiro, Congo	$Z = 240R^{1.3}$	
	Ajayi and Owolabi (1986)	Ile-Ife, Nigeria	$Z = 524R^{1.27}$	
	Present Study (2008) (0-4800 m)	Akure, Nigeria	$Z = 90.35R^{1.39}$	0.40
	(0-160 m)		$Z = 717.67R^{1.28}$	0.94
	Present Study (2006) (0-4800 m)	Akure, Nigeria	$Z = 64.28R^{1.17}$	0.45
	(0-160 m)		$Z = 268.71R^{1.31}$	0.90

Z is in $mm^6\,m^{-3}$ and R in $mm\,h^{-1}$; r is the coefficient of correlation

11.0 Liquid Water Content

The values of liquid water content (M) and Rain rate (R) for the two years under consideration were plotted and two sets of relationships were obtained,

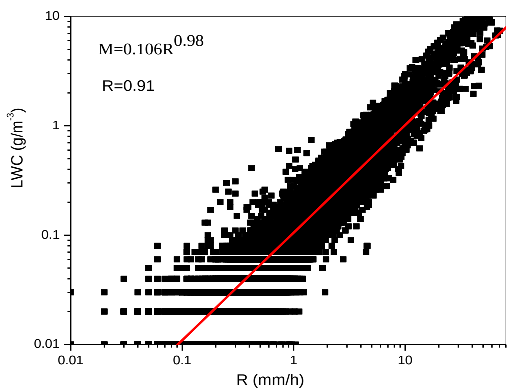
$M = 0.106R^{0.98}\ r(0.94)$ 2006 (27)

$M = 0.093R^{1.06}\ r(0.94)$ 2008 (28)

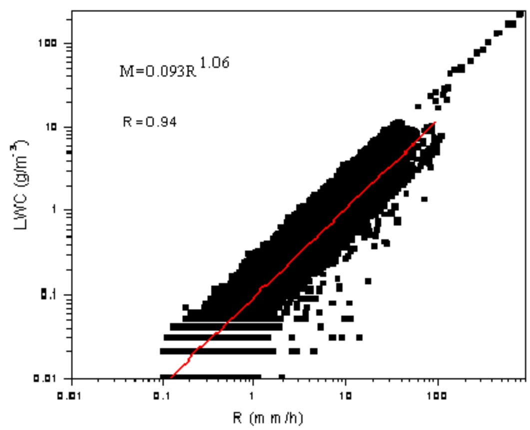
$r\ is\ the\ correlation\ coefficient$

Figure 25 shows the scattered diagrams and the regression line for M-R for the height 0-4800 m in the year 2006 while figure 26 shows that of 0-160 m for same year. Figure 27 shows the scattered plots for the height 0-4800 m in the year 2008 while figure 28 shows the scattered plots for the height 0-160 m for the same year.
There is a high degree of correlation in all cases considered, the coefficients of correlation are better than 0.91 for most of the rain types. The power relationships obtained were comparable for all the rain types.

Table 4 shows the comparison of the M-R relation obtained in Akure with other locations.

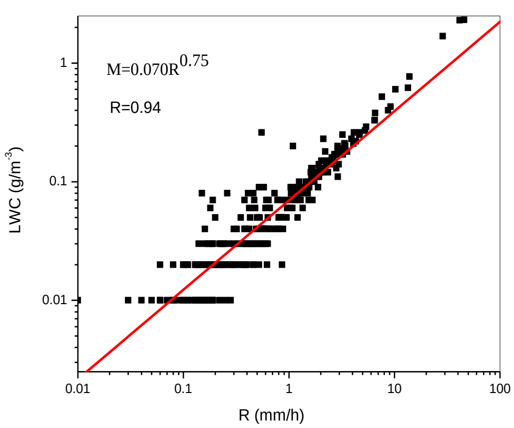


(25)

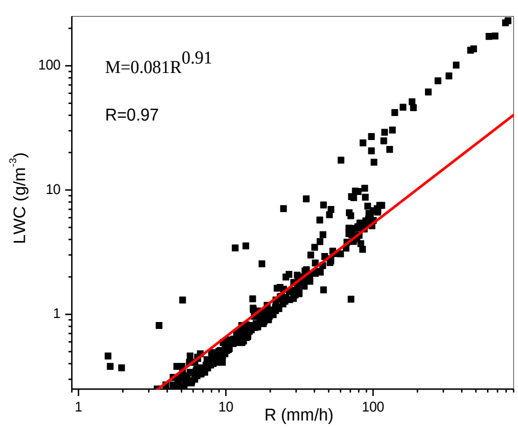


(26)

Fig (25 and 26): Regression line M-R for the whole data set (at 0-4800 m) for the year 2006 and 2008.



(27)



(28)

Fig (27 and 28): Regression line M-R for the whole data set (at 0-160 m) for the year 2006 and 2008.

Table 4: Comparison of M-R relations with height at some locations

Rain Type	Source	Location	M-R
Stratiform Rain	Marshall and Palmer (1984)	Switzerland	$M = 0.072R^{0.88}$
	Ajayi and Owolabi (1986)	Ile-Ife, Nigeria	$M = 0.059R^{0.88}$
	Present Study (2008)	Akure, Nigeria	
	(0-4800 m)		$M = 0.091R^{1.03}$
	(0-160 m)		$M = 0.072R^{0.75}$
	Present Study (2006)		
	(0-4800 m)		$M = 0.101R^{0.93}$
	(0-160 m)		$M = 0.068R^{0.73}$
Convective Rain	Ajayi and Owolabi (1986)	Ile-Ife, Nigeria	$M = 0.063R^{0.89}$
	Sekhon and Srivastava (1971)	Cambridge, USA	$M = 0.052R^{0.94}$
	Jones (1956)	Illinois, USA	$M = 0.052R^{0.97}$
	Mueller (1965)	Miami, USA	$M = 0.053R^{0.95}$
	Present Study (2008)	Akure, Nigeria	
	(0-4800 m)		$M = 0.132R^{0.97}$
	(0-160 m)		$M = 0.020R^{1.35}$
	Present Study (2006)		
	(0-4800 m)		$M = 0.103R^{1.13}$
	(0-160 m)		$M = 0.047R^{1.03}$

The units are M in $g\ m^{-3}$ and R in $mm\ h^{-1}$

12.0 Specific Attenuation

The frequency characteristics of specific attenuation for two rain types, stratiform and convective are presented in Figs 29 and 30 respectively. The specific attenuation was evaluated for frequencies of 1-100 GHz. In general, specific attenuation increases with increasing frequency for stratiform and convective rain types. At a critical frequency, which ranges from 31-100 GHz, the specific attenuation decreased slightly.

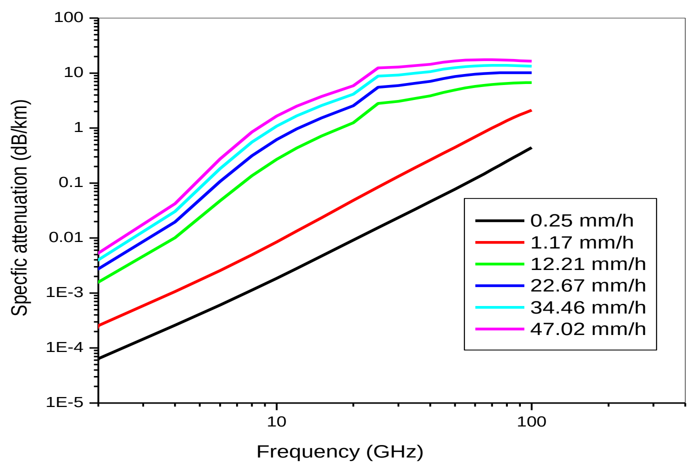


Fig (29): Frequency characteristics of specific attenuation for Stratiform rain type at different rain rates

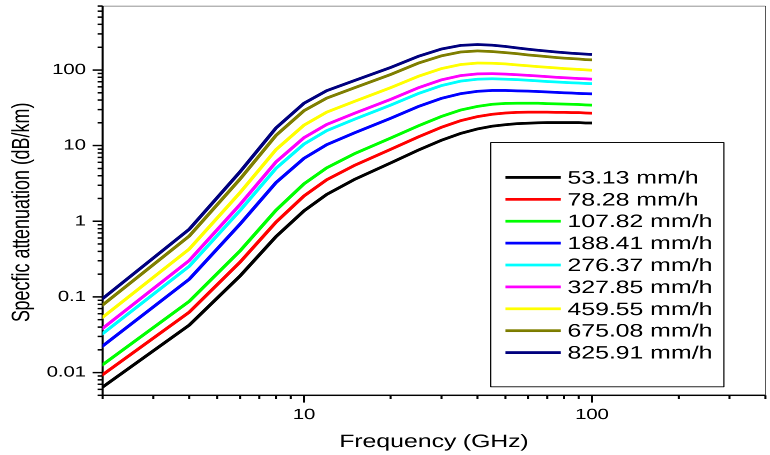


Fig (30): Frequency characteristics of specific attenuation for convective rain type at different rain rates

Conclusions

The rainfall parameters measured for the two years considered have been analyzed for a tropical station, Akure in Nigeria. It was observed that the drop diameters that contributed the most to the rain fall event were in the diameter bin of 0.246 to 0.559 mm (with a diameter interval of 0.04 mm). Rain drop of diameter bin of 0.246 mm contributed the highest rain drops to the rain event which is typical for drop size distribution in the tropical region. It was also observed that the rain rate below 5 mm/hr contributed the most to the rain event in the height range 0-4800 m while the height range of 0-160 m recorded the highest rain rate.

Empirical relations have been obtained among the rainfall rate, the radar reflectivity factor Z, and liquid water content for the rain types using the least square power law regression. The recorded rainfall rates were classified using the criteria described in Joss et at (1968), for Stratiform rain fall rate R < 50mm/h and convective rain R > 50 mm/h. These empirical relations have been compared with the results obtained at other locations by other workers. The empirical relations obtained in this analysis are intended to provide useful information about the rainfall parameters in Nigeria for communication purposes.

The correlation coefficients of Z-R relationship for stratiform rainfall for both years and height range considered are good; the values are above 0.70, while that of convective rainfall type is also very good for the height range of 0-160 m with values more than 0.89, but the correlation coefficient for the height range 0-4800 m is poor, with values below 0.50, this might be as a result of the large span of height considered (0-4800 m).

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