Supported by tetfund
TERTIARY EDUCATION TRUST FUND

CHARACTERIZATION AND EFFECTS OF RADAR-MEASURED RAINFALL PARAMETERS IN TROPICAL CONVECTIVE AND STRATIFORM RAINS

A. C. Tomiwa
Department of Physics & Electronics, Adekunle Ajasin University, Akungba Akoko, Ondo State, Nigeria
tomiwaakinyemiclem@gmail.com; akinyemi.tomiwa@aaua.edu.ng

Received: December 14, 2017 **Accepted:** March 18, 2018

Abstract: Measurements of rainfall parameters such as the liquid water content (M), radar reflectivity factor (Z), rain rates (R) and the falling velocities (w) were carried out in this study using a vertically looking Micro Rain Radar (MRR) located at the Department of Physics of The Federal University of Technology Akure (7°15´N, 5°15´E). The parameters were measured from the ground level to a height of 4.8 km above sea level with a vertical resolution of 0.16 km and over a total of 30 range gates with 1 min integration time. The measurements covered a period of four years (2008, 2009, 2010 and 2014).The study established relationships between all the parameters measured and in particular between radar reflectivity (Z) and rain rates (R) and liquid water content (M) and rain rates (R). The results show that the values of the correlation coefficients obtained for the relationships were more than 0.64 showing good Z-R and M- R relationships and the values of coefficients, *a* and exponents, *b*are in good agreement with what was obtained in other locations around the world. The results of rain attenuation computed show a consistent increase in the specific attenuation from drizzle rain type to thunderstorm rain type until the values reach a critical stage at frequencies ranging from 31-100 GHz.

Keywords: Stratiform, Convective, radar reflectivity, micro rain radar

Introduction

In a tropical region like Nigeria, rainfall is the major source of fresh water which if in excess causes flood and deficiency causes draught, this is apart from the effect of rainfall on communication along the Earth Satellite path. Signals received in these regions are often hampered by very intensive rainstorms that are characterized by large size raindrops. In developing appropriate propagation models for a region, a lot of rain fall parameters are needed to optimize the empirical model. These parameters include: rain rates (R), Liquid water content (LWC or M), Radar reflectivity and falling velocity (W). Some of these parameters had been estimated at the surface level at both tropical and temperate regions using Disdrometer and Rain gauge. However, data measured at different height profiles are scarce especially in the tropical region due to insufficiency of the needed instruments. The tropical rainfall comprises more than two thirds of global rainfall and it is the primary distributor of heat through circulation in the atmosphere. Thus, the study of rainfall and its variability is crucial to understanding and predicting global climate change. In-situ measurements of the rainfall parameters are few and have so many limitations, especially in the tropics (Harikumar, 2009).

There is therefore the need for profile data for modelling as it has been observed that at times rain continue to fall at high altitude up to the troposphere without reaching the ground surface. This sometimes account for sudden signal loss during the daily usage of satellite services that transmit through the atmosphere to home Ku services such as DSTV, telephone services, data transmission, banking services and so on, (Adrian, 2011). Thus, understanding the vertical profile microstructure of rain is one of the key tools to the physical process of rain attenuation.

This study characterized rainfall parameters measured using a 24.1 GHz vertically looking Micro Rain Radar (MRR). It also used the data obtained to investigate attenuation caused by rain and the effects of the raindrop size distribution (DSD) for better understanding of the impact of using SHF/EHF in order to improve the effectiveness of propagation models.

Rainfall plays a very important role in hydrological cycle, which is a key unit in driving energy circulation in the atmosphere and hence, is the most dominant impairment for the propagation of radio waves (Das*et al.*, 2010). Rain water may seriously affect the performance of microwave links operating at frequencies greater than 10 GHz (Kamakar *et al.*, 2011; Ojo *et al.*, 2009, 2013). Thus, Rain Drop-Size Distribution (RDSD) is one of the most widely used parameters for better understanding and complete description of rain phenomenon. Various RDSD models such as: Lognormal, Gamma, Weibull, Marshall and Palmer have been earlier employed to parameterize the RDSD at different locations in the temperate region (Mahen *et al.*, 2006).

It is important to note that rain which can cause several decibels of attenuation has been identified to be a major cause of visual impairment at millimetre wave frequencies (above 10 GHz) and is the limiting factor in satellite/terrestrial link design, especially for tropical and equitorial regions which experience heavy rainfall (Ajewole *et al.*, 1999; Narayana *et al.*, 2007).

Instrumentation

The major equipment used for this work is the Micro Rain Radar which is an FM-CW Doppler radar that operates at the frequency of 24.1GHz. It provides DSD information by converting measured Doppler spectra into drop diameters by a known relationship. Other parameters such as Rain rates(R), Liquid water content (LWC), falling velocity (W) and radar reflectivity (Z) were calculated from the Drop size distribution as measured directly by the Micro rain radar.

According to Das *et al.* (2010), the spectral volume reflectivity $\eta(f)$ received by the radar with depth ∂r is given by:

$$\eta(r,f)df = p(r,f)df.c\frac{r^2}{\partial r}t^{-1}(r) \quad (1)$$

Where: *p(r,f)* is the spectral power, f is the Doppler frequency in Hz. C is the radar constant. The DSD is calculated from the volume reflectivity $\eta(D)$ related;

Thus: $N(D) = \frac{\eta(D)}{\sigma D}$ (2)

N(D) is the number of drops with size D to D + ΔD in m/s.

The mean fall velocity (V_m) is given by:

$$V_m = \frac{\lambda}{2}\frac{\int_0^\infty f.P(f)df}{\int_0^\infty P(f)df} \qquad (3)$$

P(f) is the spectral power related to Doppler frequency λ is the wavelength.

A typical MRR used for this measurement is made up of the following parts: Parabolic Dish, Transducer, Radar control and processing device (RCPD), Junction box, Cable Junction box – PC, AC power cable, Cable RCPD – Junction box, Antenna arm, Pivot, Tube socket and Control and valuation Computer with an operating system of Windows 2000 or XP.

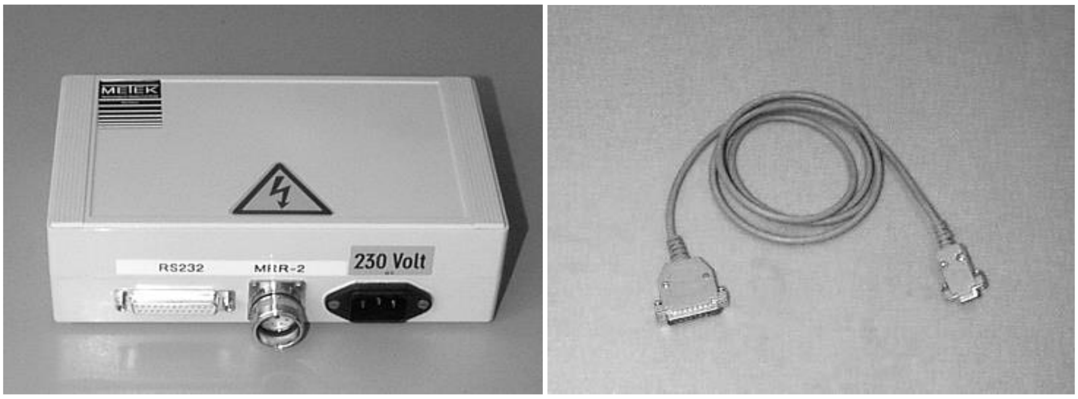
The radiation is transmitted vertically into the atmosphere where a small portion is backscattered to the antenna from the raindrops or other forms of precipitation. As a result of the falling velocity of rain drops on the antenna, there is a frequency deviation (Doppler frequency) between the transmitted and received signal. The backscattered signal is sent to the RCPD where the power spectrum is analysed and later values of Z, R, LWC W and other rainfall parameters are analysed in the control and evaluation computer.

Project Site

The parameters used for this work are measured with a vertically pointing Micro rain radar located at the Federal University of Technology Akure, Ondo State, Nigeria (7º15`N, 5º15`E). The measurements were taken for a period of four (4) years of 2008, 2009, 2010 and 2014 (Fig. 4).

(a) **(b)**

Fig. 1 (a and b): Outdoor unit and RADAR electronics unit of the micro rain radar installed in Physics Department, FUTA



(a) **(b)**

Fig. 2 (a and b): Connection box and connecting cable to the personal computer

(c) **(d)**

Fig. 3: (c and d): Connection cable of the RADAR electronics unit and in-door unit

Fig. 4: Map of measuring site

Theoretical Concepts

The Z-R relationship

The relationship between the radar reflectivity and rain rate depends on the structure of the drop size distribution, (Gerhad *et al*., 2005) and is expressed as:

$$Z = aR^b \qquad (4)$$

Where: *a* and *b* are constant parameters,
Equation(2.3) is applicable under Rayleigh scattering condition whereby the radar wavelength is more than the drop diameter (Serafin, 1990).
Linearizing equation (4) gives:

$$\ln Z = \ln a + b \ln R \qquad (5)$$

Existing Models of Drop-Size Distribution (DSD)

Various models of the effects of rain on radio wave propagation through it are always required to numerically relate the two physical quantities. Examples of such are relations of attenuation to rain rates, to radar reflectivity, to differential attenuation or to absolute attenuation in one, and so on. These quantities are obtained as integrals over the drop size distribution function N(D) which is the number of drops per unit volume with drop diameter D and *D* + *dD* (Adimula, 1997).
Models of raindrop size distributions that already existed in literature include: Laws and Parson, Marshall and Palmer, Fujiwara, Lognormal distribution and so on. The most common of all these are the Marshall and Palmer and the lognormal distribution, and they will be discussed as follows.

(a) Marshall and Palmer Distribution

The DSD is well represented by an expression developed by Marshall and Palmer (1948) and found out that it follows a function of the form:

$$N(D) = N_O \exp(-\Lambda D) \qquad (6)$$

where N(D) is the concentration of raindrops per diameter in the diameter interval dD in mm, D is the rain drop diameter, N_o is the intercept parameter with fixed value of 8 x 10^3 $mm^{-1}m^{-3}$, ∧(mm^{-1}) is the slope parameter and is defined as,

$$\wedge = 4.1R^{-0.21}\ mm^{-1} \qquad (7)$$

Where: R is the rainfall rate (mm/h).

Marshall-Palmer discovered that rain DSDs' for several rain rates, the exponential function does not fit the observation. Hence, it is sometimes necessary to consider the Marshall – Palmer curves applicable at diameters greater than 1-1.5 mm (Battan, 1973).

(b) Lognormal distribution

Log-normal distributions are usually characterized in terms of the log-transformed variable using as parameters, the expected values, or means, of its distribution and the standard deviation. The log-normal distributions are symmetrical also at the log level (Eckhard *et al*., 2001).
Log-normal representation is suitable for a broad range of applications and can facilitate interpretation of the physical processes that control the shape of the distribution.
Mahen *et al*. (2006) expresses Lognormal distribution as:

$$N(D) = \frac{N_t}{(2\pi)^{0.5}\ln D}\exp[-\frac{\ln^2(D/D_g)}{2\ln^2\delta}] \qquad (8)$$

Where: N_t is the total number of drops per unit volume, D_g is the geometric mean of the drop diameter in mm, δ is the standard deviation of D.
Expression for the lognormal from equation (2.7) is reproduced as:

$$N(D) = (\exp A/D)\exp\{-0.5[(\ln D - B)/C]^2\} \qquad (9)$$

where,

$$A = \ln\left[\frac{N_T}{\sqrt{(2\pi)}\ln\sigma}\right] \qquad (10)$$

$$B = \ln D_g \qquad (11)$$

$$C = \ln\sigma \qquad (12)$$

A, B and C in equations (10) to (12) are fit parameters of the lognormal distribution.
$\ln D_g$ and $\ln\sigma$ are values of geometric mean of drop diameters and standard deviation of drop diameters respectively. They are both calculated by:

$$\ln D_g = \left(\frac{1}{N_T}\right)\sum_{i=1}^{20} N_i \ln D_i \qquad (13)$$

$$\ln^2\sigma = \left(\frac{1}{N_T}\right)\sum_{i=1}^{20} N_i\left(\ln D_i - \ln D_g\right)^2 \qquad (14)$$

N_T is the drop number concentration (m^{-3}) in the observed spectrum and N_i is the number of drops in size category D_i (Jassal *et al*., 2011).

Results and Discussions

Z-R relationship for all rain types

Values of R and the corresponding values of Z for the rainy periods in years 2008, 2009 and 2010 were plotted across all heights and for all the rain types as shown in Figs. 5 to 12.

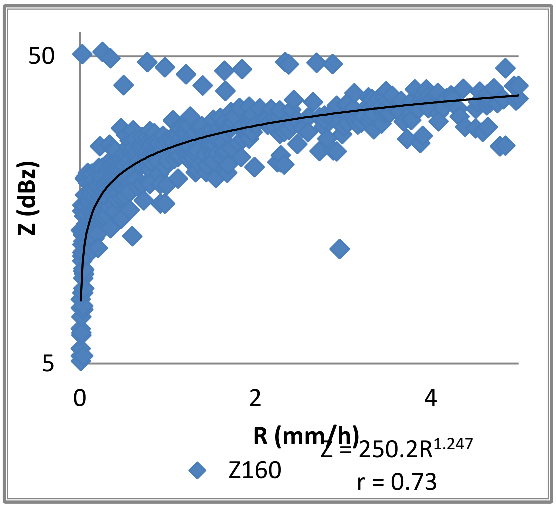


Fig. 5 (a): Z-R relation at height 160 m for rizzle rain type during the year 2008

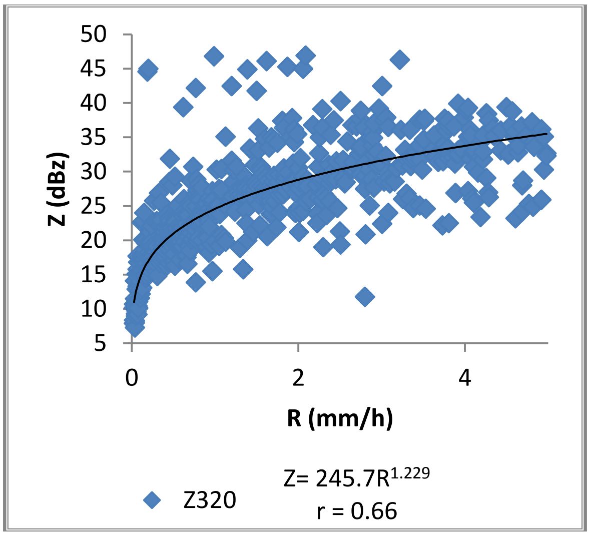


Fig. 5 (b): Z-R relation at height 320 m for drizzle rain type during the year 2008

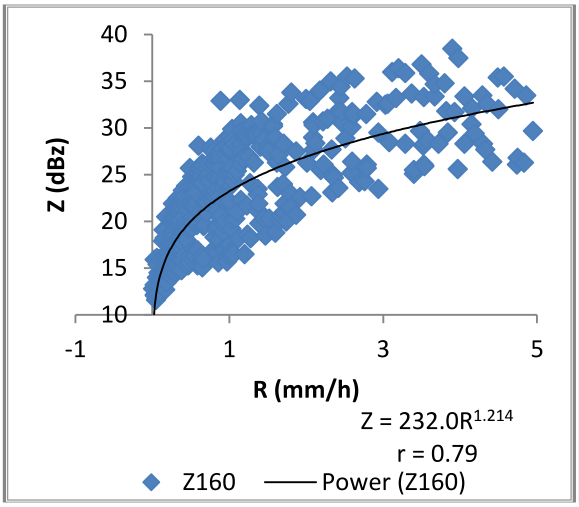


Fig. 5 (c): Z-R relation at height 160 m for drizzle rain type during the year 2009

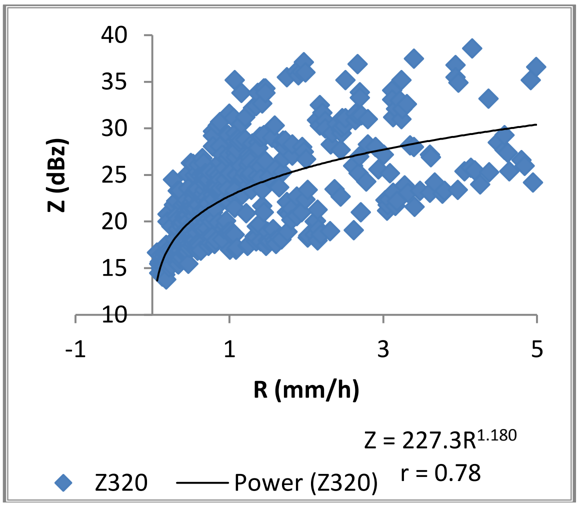


Fig. 5 (d): Z-R relation at height 320 m for drizzle rain type during the year 2009

LWC-R or M-R relationship for all rain types

Values of R and the corresponding values of LWC for the rainy periods in years 2008, 2009 and 2010 were plotted across all heights and for all the rain types as shown in Figs. 6a to 13.

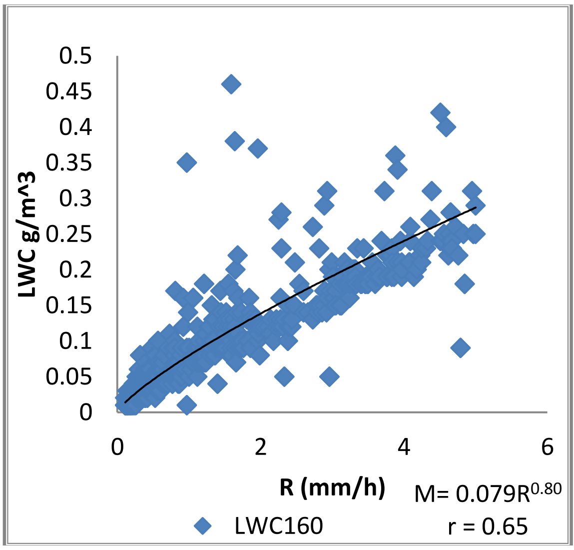


Fig. 6 (a): M-R relation at height 160 m for

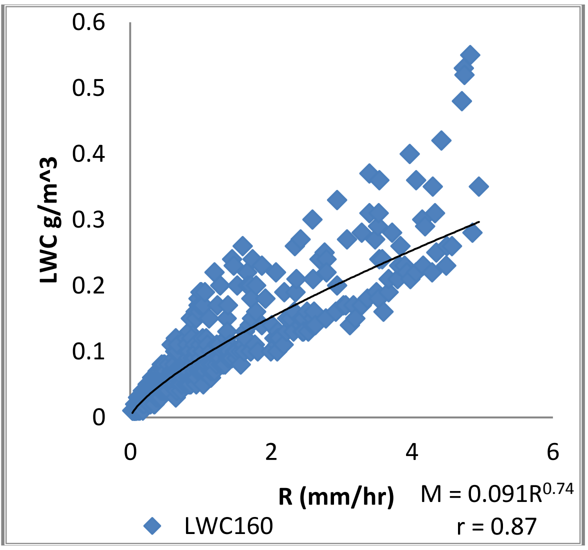


Fig. 6 (b): M-R relation at height 160 m for drizzle rain

drizzle rain type during the year 2008 **type during the year 2009**

Temporal variation of rain drop size distribution and rain microstructures

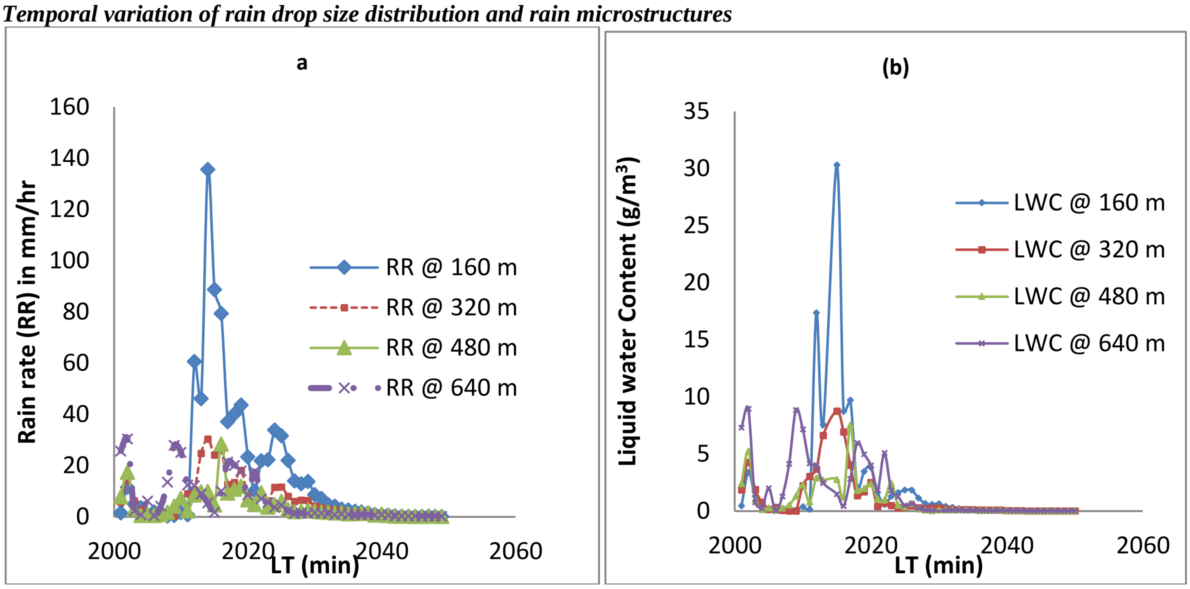


Fig. 7: Time series event of (a) Rain rate and (b) LWC at different heights on the 7th of March, 2008

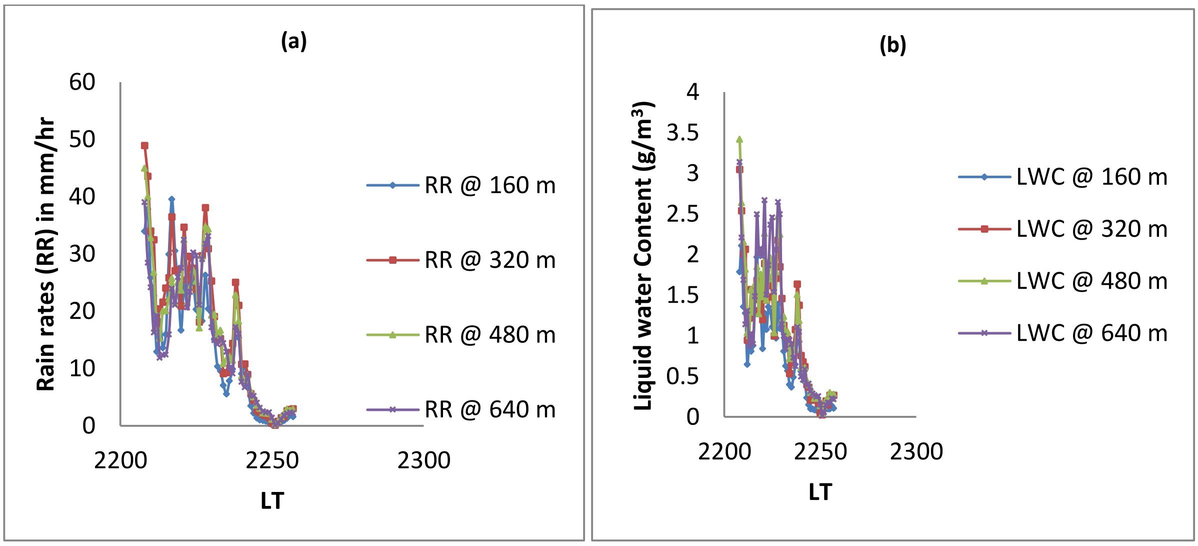


Fig. 8: Time series event of (a) Rain rate and (b) LWC at different heights on the 10th of July, 2009

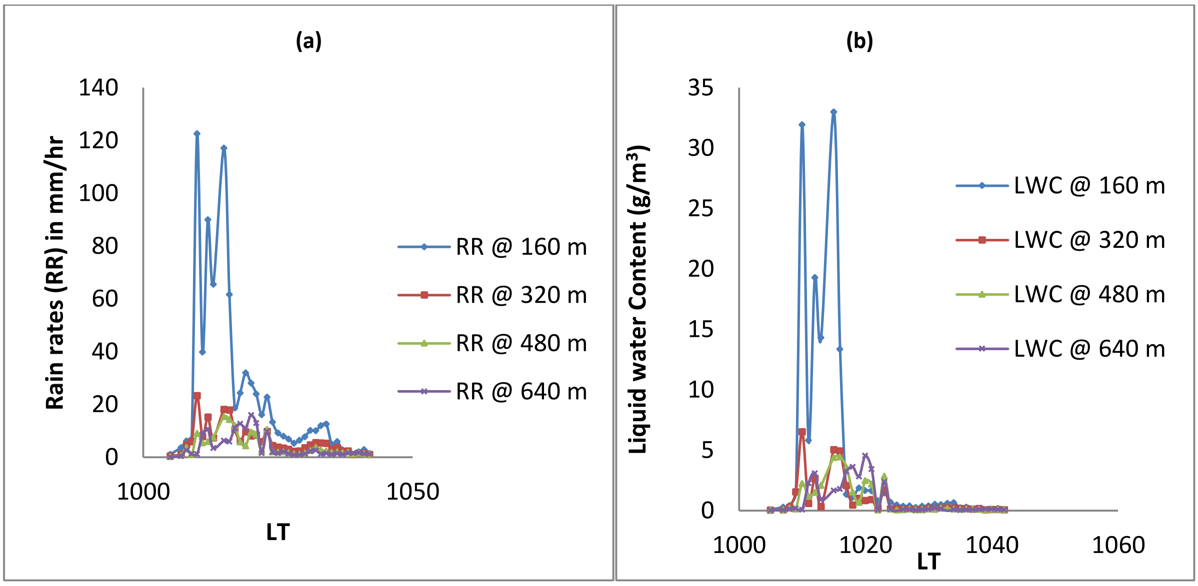


Fig. 9: Time series event of (a) Rain rate and (b) LWC at different heights on the 31st of October, 2010

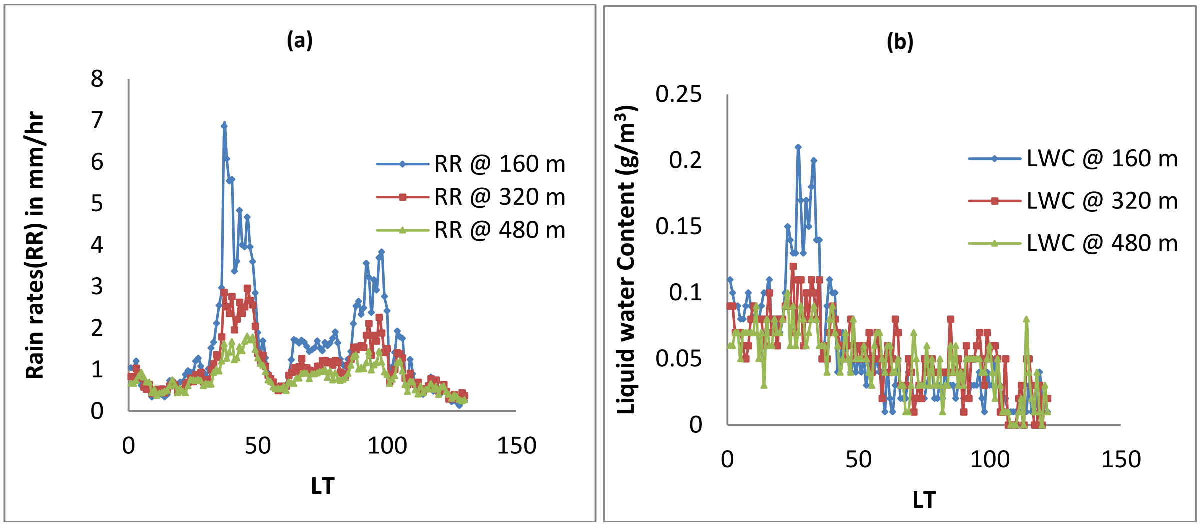


Fig. 10: Time series event of (a) Rain rate and (b) LWC at different heights on the 10th of April, 2014

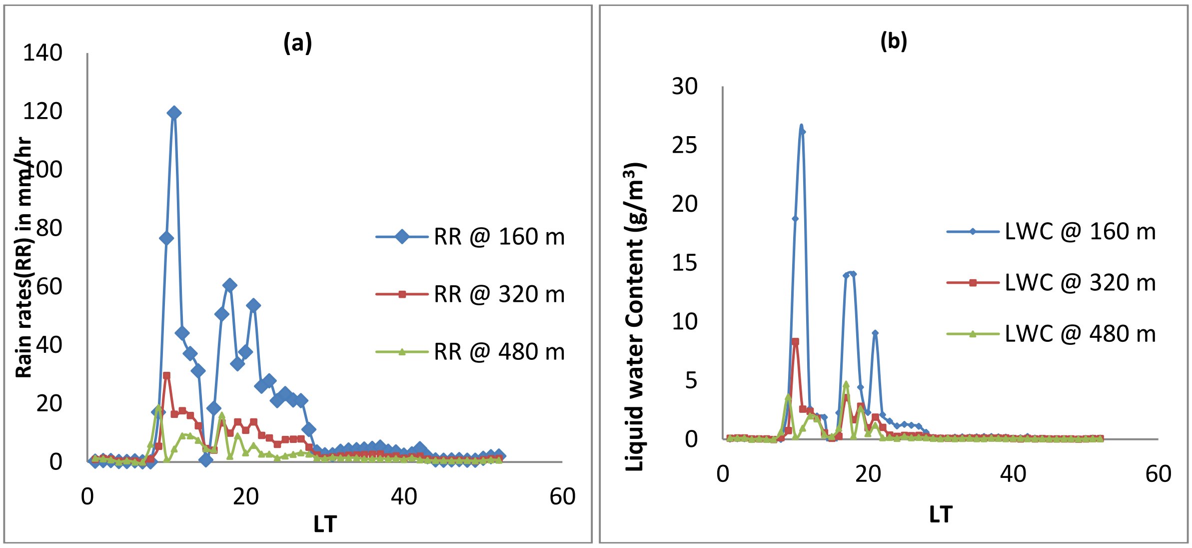


Fig. 11: Time series event of (a) Rain rate and (b) LWC at different heights on the 27th of May, 2014

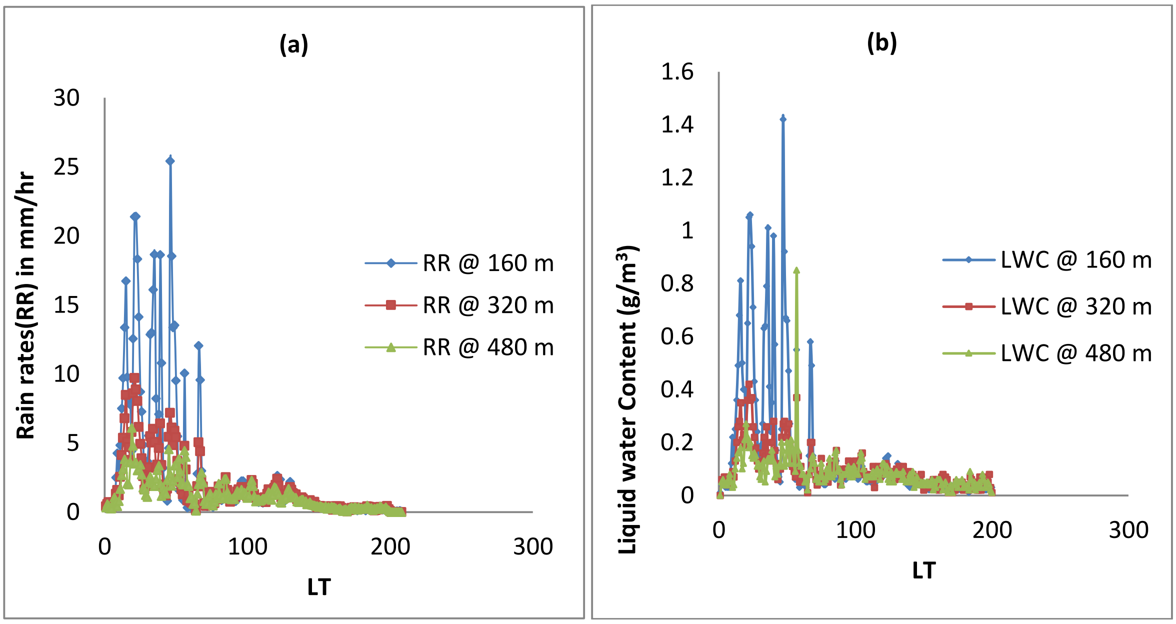


Fig. 12: Time series event of (a) Rain rate and (b) LWC at different heights on the 23rd of June, 2014

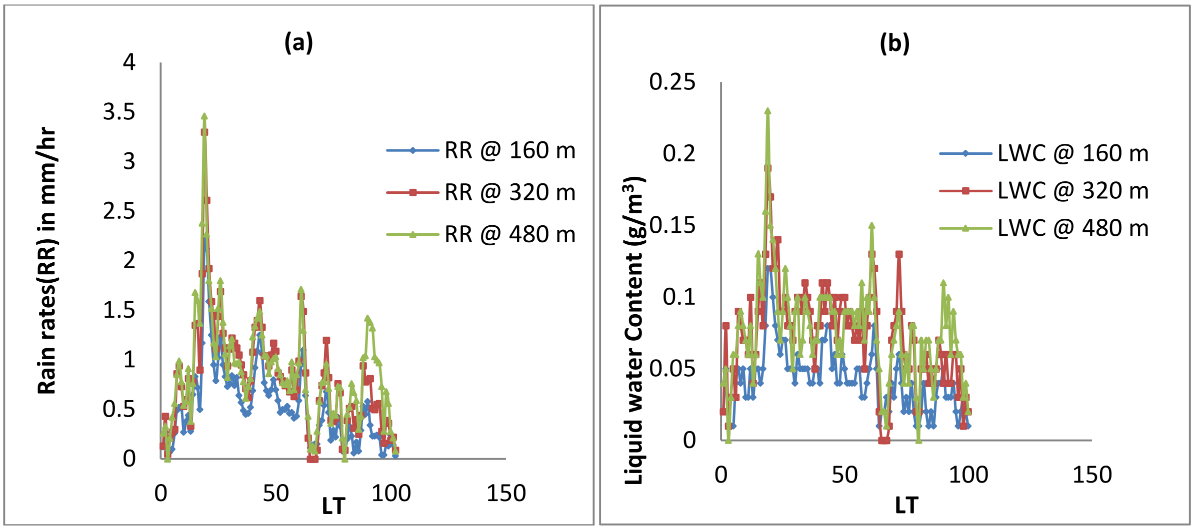


Fig. 13: Time series event of (a) Rain rate and (b) LWC at different heights on the 6th of September, 2014

Z-R and M-R relationship

Values of Z and R were considered for each year across all heights from 0 – 4800 m above sea level in establishing the general equation for the periods of measurements (2008, 2009, 2010 and 2014). The heights were divided into 30 levels of width 160 m each.

The data obtained were classified into drizzle, widespread, shower and thunderstorm rain types depending on the values of rain rates *R* and plots of Z-R relations for some selected periods in the years 2008, 2009 and 2010 are presented in Figs. 5 to 6. Also the time series plots of some rainy periods in the year 2014 were also presented in Fig. 6 to 12.

The empirical relationship between the radar reflectivity (Z) and the rain rates (R) at different heights were deduced from the data obtained from the MRR over three years duration. The relationship for the different rain regimes namely: drizzle, widespread, shower and thunderstorm have been obtained for heights ranging from 160 m to 4,800 m.

For example, Fig. 5 shows the Z-R relation for drizzle rain type at the height of 160 m for the year 2008. A good correlation was observed as shown from the power law fit from the scatter plot. The power law coefficient and exponents are given as 250.2 and 1.25, respectively, while the correlation coefficient was 0.73.

Figure 6 also shows the relation for drizzle for the height of 160 m and 320 m for the year 2009. A good correlation was also obtained as seen in the power law fit from the scatter plot. The power law coefficient *a* and exponent *b* are given as 232.0 and 1.21 and 227.3 and 1.18, respectively; while the correlation coefficients are 0.79 and 0.78, respectively and so on.

The observation and values derived for other heights (up to about 3200 m) and rain types are presented in Tables 1. It is important to note that MRR data above 3200 m are not considered in this study since they may not be useful due to the pollution in the back-scattered data obtained from the MRR due to the effect of melting layer. The values of coefficient *a* and exponent *b* for all the experimental heights are as summarised in the Tables. For example in Table 1 the average value of the coefficient, *a*, and exponent, *b*, are 206.0 and 1.22, respectively with a correlation coefficient of approximately 0.60 which indicate good correlation for widespread rain for the year 2009 across the heights 160 to 1760 m.

Other Tables follow the same trend although with different values of coefficient *a* and exponent *b*.

Figures 6 (a) and (b) are the plots of the M-R relationship from the power law relation from the data obtained for years 2008 and 2009. The data were also classified into drizzle, widespread, shower and thunderstorm depending on the values of rain rates R. Figure 6(a) shows the M-R relation for drizzle rain type at the height of 160 m for the year 2008. A good correlation was observed as shown from the power law fit from the scatter plot. The power law coefficient *a* and exponent *b* are given as 0.079 and 0.080 respectively, while the correlation coefficient is 0.65.

Figure 5(b) also shows the M-R relation for drizzle rain type at height 160 m for year 2009. The power law fit of the scatter plot shows a good correlation. The values of coefficient *a* and exponent *b* are 0.09 and 0.74, respectively, while 0.87 is the correlation coefficient.

Observation and values derived for other experimental heights and rain types are presented in Tables 1 to 5. The values of coefficient *a* and exponent *b* are as shown in the Tables. For example, Table 2 is the M-R relation for the drizzle rain type over varying experimental heights of 160 m and 2880 m for the year 2008. Other heights could not be presented because data are not available at these heights during rain. Other Tables follow the same trend although with different values of coefficient *a* and exponent *b*.

Results of coefficients *a* and exponents *b* obtained from this study are compared with those obtained at some other tropical locations as shown in Tables 4 and 5. Values of correlation coefficient *r* are well over 0.5 in all cases indicating a relatively high degree of correlation between Z and R and also for M and R.

Table 1: Z-R relationship for widespread rain type at different heights for the year 2009

Height (m)	a	b	Z	r
160	204.3	1.26	$204.3R^{1.26}$	0.65
320	202.8	1.23	$202.8R^{1.23}$	0.57
640	204.9	1.20	$204.9R^{1.20}$	0.60
800	258.0	1.08	$258R^{1.08}$	0.51
960	220.7	1.15	$220.7R^{1.15}$	0.52
1440	176.6	1.27	$176.6R^{1.22}$	0.72
1600	164.1	1.29	$164.1R^{1.29}$	0.62
1760	220.7	1.17	$220.7R^{1.17}$	0.60
Average	206.0	1.22	$206.02R^{1.22}$	0.60
160 – 1760	195.26	0.9215	$195.26R^{0.9215}$	0.75

Table 2: M-R relationship for drizzle rain type at different heights for the year 2008

Height (m)	a	b	M	r
160	0.089	0.80	$0.079R^{0.79}$	0.65
960	0.094	0.84	$0.094R^{0.84}$	0.66
1280	0.101	0.90	$0.101R^{0.90}$	0.73
1600	0.102	0.98	$0.102R^{0.98}$	0.77
1920	0.106	0.99	$0.106R^{0.99}$	0.74
2240	0.125	0.86	$0.125R^{0.86}$	0.78
2560	0.110	1.07	$0.11R^{1.07}$	0.80
2720	0.106	1.02	$0.106R^{1.02}$	0.79
2880	0.106	1.00	$0.106R^{1.00}$	0.72
Average	0.103	0.94	$0.103R^{0.94}$	0.74
160 – 2880			0.1163R + 0.255	0.67

Table 3: M-R relationship for thunderstorm rain type at different heights for the year 2010

Height (m)	a	b	M	r
160	0.005	1.64	$0.005R^{1.64}$	0.65

Table 4: Z-R Relationships for some locations

Rain types	Source	Location	Z-R
Stratiform	Joss *et al.* (1970)	Locarno-mouti	$250R^{1.5}$
	Marshall & Palmer (1984)	Switzerland	$220R^{1.6}$
	Fujiwara (1965)	Miami, U.S.A	$250R^{1.48}$
	Ajayi & Owolabi (1986)	Ile-Ife, Nigeria	$312R^{1.35}$
	Present study		
	2008	Akure, Nigeria	$239.75R^{1.165}$
	2009		$216.53R^{1.184}$
	2010		$235.77R^{1.13}$
Convective	Joss *et al.* (1970)	Locarno-mouti	$500R^{1.5}$
	Jones (1956)	Illinois, USA	$486R^{1.37}$
	Fujiwara (1965)	Miami, U.S.A	$450R^{1.37}$
	Ajayi & Owolabi (1986)	Ile-Ife, Nigeria	$524R^{1.27}$
	Present study		
	2008	Akure, Nigeria	$351.75R^{1.06}$
	2009		$306.39R^{1.1}$
	2010		$237.77R^{1.08}$

Table 5: M-R Relationships of some locations

Rain types	Source	Location	M-R
Stratiform	Marshall & Palmer (1984)	Switzerland	$0.072R^{0.88}$
	Ajayi & Owolabi (1986)	Ile-Ife, Nigeria	$0.0059R^{0.88}$
	Present study		
	2008	Akure, Nigeria	$0.091R^{1.067}$
	2009		$0.137R^{0.84}$
	2010		$0.136R^{0.99}$
Convective	Ajayi & Owolabi (1986)	Ile-Ife, Nigeria	$0.063R^{0.89}$
	Sekhon & Srivastava (1971)	Cambridge, USA	$0.052R^{0.94}$
	Jones (1956)	Illinois, USA	$0.052R^{0.95}$
	Mueller (1965)	Miami, USA	$0.053R^{0.95}$
	Present study	Akure, Nigeria	
	2008		$0.132R^{1.17}$
	2009		$0.112R^{0.815}$
	2010		$0.115R^{1.23}$

Time series events of rain rate and liquid water content

Precipitation in liquid rain reflects the nature of the microphysical processes of hydrometeor formation, growth and transformation and it is important to distinguish different types of rainfall occurring in the tropical regions. We can therefore analyse the similarities and differences between raindrop size distributions in various precipitation tyes and their impact on Z-R relationship (Ochou *et al.*, 2011).

Figures 6 to 12 show two typical cases of stormy rainfall in Akure south-western Nigeria for years 2008, 2009, 2010 and 2014. Their time signature at the surface up to four height steps of 160 m are all characterized by two distinctive regions: a leading part called convective of relatively short duration (20 to 30 min) and characterized by high rain up to 120 to 140 mm/hr and another part called stratiform rain region which can last 1 to 4 h (as the case may be) and at low intensities below 10 mm/hr. The curves of rain rates, liquid water content versus local time follow the same pattern.

The event for 31st October 2010 (Fig. 8) has duration of about 45 min. It is obvious that convective cell produce rain rate above 10 mm/h but for short duration not more than 15 min between the peak of 10:10 and 10:25 LT. Example of stratiform rain here is between 10:25 and 10:45 and 10:05 to 10:09 LT. The plots of rainfall rate and the duration (LT) shows that most of the rainfall rates were mixed classes with rain coming from the drizzle, widespread, shower and Thunderstorm clouds with the latter not well developed.

Conclusion

Rain events for years 2008, 2009, 2010 and 2014 collected using a Micro Rain Radar were used for this research. They were classified into high and low intensity rains according to the values of rain rates. The high intensity rains were further classified into shower and thunderstorm, while the low intensity rain was classified into drizzle and widespread. It was observed that most of the rain events in this part of the world is the low intensity rain (stratiform) i.e. rain rates below 10 mm/hr. This is evident in the various plots of rain rate versus local time and the absolute distribution of the statistical plots of rain rates using the METEK graphics.

From the Z-R relations, the values of coefficient a and exponent b so obtained ranges from 204.3 to 279.7 and 1.13 to 1.26 respectively for low intensity rain, and 277.8 to 466.4 and 1.01 to 1.13 for high intensity rain. These values are in agreement with what was obtained by previous researchers in other parts of the world. The correlation coefficients are mostly high and from 0.5 to 0.85 on the average.

Similarly from the M-R relations, values of **a** and **b** obtained from the study are similar to that obtained by researchers in other tropical regions and they all have good correlation coefficients.

The study has demonstrated that the cumulative distribution of rain rate recommended by ITU and that are applicable in other regions of the world are inadequate for this location. The results of this study will assist in improved design and planning of terrestrial and satellite radio communication systems in this location.

References

Adimula IA 1997. Radio Parameters in Iliorin, and their applications to Microwave Radio Propagation'', *PhD Thesis*, University of Ilorin, Nigeria.

Adrian Justin Townsend 2011. A study of the raindrop size Distribution and its effect on Microwave Attenuation. *PhD Thesis*, Electronics and Electrical Engineering, University of Bath.

Ajayi GO & Barbaliscia F 1990. Prediction of attenuation due to rain: Characteristics of the 0° isotherm in temperate and tropical climates. *Int. J. Satellite Communication*, 8: 187-196.

Ajayi GO & Owolabi IE 1987. Rainfall parameter dropsize measurements at a tropical station. *Annales des Telecommunication*, 42(1-2): 3-12.

Battan Louis J (1973), ''Radar observation of the Atmosphere'', *University of Chicago press*. 324 pages.

Das S, Ashish K & Maitra A 2010. Investigation of vertical profile of rain microstructure at Ahmedabad in Indian tropical region. *Advances in Space Res*., 45: 1235-1243.

Eckhard Limpert, Werner A S & Markus A 2001. Lognormal distributions across the science, Keys and clues'', *Journal of Bioscience*. Vol. 51, No. 5. pp. 341-352.

Fujiwara M 1965. Rain dropsize distribution from individual storms. *J. Atmospheric Sci.,* 22: 585-591.

Gerhard Peters, B Fischer, H Munster, M Clemens and A Wanger 2005. Profile of raindrop size distributions as retrieved by Micro rain radars. *J. Appl. Meteorol*., 44: 1930-1949.

Harikumar 2009. Study of tropical rain drop size distribution and integral rain parameters using ground based and satellite measurements. *PhD Thesis*.

International Telecommunication Union Recommendation 2007. *Rain height model for the prediction methods,* (ITUR, Geneva, Switzerland), pp. 839-843.

Jassal BS, Anurag Vidyarthi, Gowri R & Ashish K Shukla 2011. Modeling of rain drop size distribution for a tropical hot semi-arid site in India'', *Indian Journal of Radio and Space Physics*, vol. 40, pp. 330-339.

Jones D 1956. Rainfall dropsize distribution and radar reflectivity. *Illinois State Water Sarvey Meteor Lab. Res.*, p. 20.

Joss J, Schram K, Thams JC & Waldvogel A 1970. On the quantitative determination of precipitation by radar. *Eidgenossische Kommission Zum Stadium der Hagelbildung under Hagelabwehr, Zurich Wissenschaftliche Mitteilubg*, 73: 38.

Karmakar PK, Maiti M, Bhattacharyya K, Angelis CF & Machado LAT 2011. Rain attenuation studies in the microwave band over southern latitude. *The Pacific J. Sci. Tech. (Hawaii),* 12: 196-205.

Mahen Konwar, DigantaKumar Sarma, Jyotirmoy Das & Sanjay Shama 2006. Shape of the rain drop size distributions and classification of rain type at Gadanki. *Indian J. Radio & Space Physics* 35: 360-367.

Marshall JS & McK Palmer W 1948. Shorter contribution: The distribution of raindrops with size. *National Res. Council of Canada*, 5: 165-166.

METEK Meteorologische Messtechnik, Gmb H 2005, Micro Rain Radar Physical Basics, Version 1.8.3.

Ochou DAbe, Zahiri Eric-Pascal, Bakary B & Manlandon K 2011. Understanding the Variability of Z-R Relationships Caused by Natural Variations in Raindrop Size Distributions (DSD): Implication of Drop Size and Number. *J. Atmospheric & Climate Sci.*, 1: 147-164.

Ojo JS, Ajewole MO & Emiliani LD 2009. Development of 1-minute rain rate contour maps for radio communication over Nigeria. *IEEE Antenna. & Propagation Magazine,* 51(5): 82-89.

Ojo JS, Ajewole MO & Olurotimi EO 2013. Characterization of rainfall structure and attenuation over two tropical stations in Southwestern, Nigeria for the Evaluation of Microwave and Millimeter-wave Communication", *J. Meteorology & Climate Sci.,* 11(1): 40-48.

Oluwadare EJ, Tomiwa AC & Ajewole MO 2010. Investigation of Radiowave propagation impairment at Super High Frequency due to rain in Akure. *Am. Int. J. Contemporary Res.*, 2(10): 122-137.

Serafin RJ 1990. Meteorological Radar. In: Skolnik M; *Radar Handbook,* 2nd edition, New York, McGraw-Hill.