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A Analysis of Raindrop Diameters for Rainfall Attenuation in Southern Africa

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ABSTRACT

The influence of critical raindrop diameters on the specific rainfall attenuation in Durban (29°52'S, 30°58'E), South Africa using various rainfall regimes is analyzed in this paper. Different rain rate values representing drizzle, widespread, shower and thunderstorm are selected for the purpose of analysis over the measured raindrop size distribution. The three-parameter lognormal and gamma DSD models with shape parameter of 2 are used to estimate the parameters required to investigate the drop sizes which produce a major contribution to the total specific rainfall attenuation for the selected rain rate values. The computed total specific attenuation increases with increasing frequencies and rain rates. The highest and prevailing contribution to the specific attenuation occurs at $D \sim 2$ mm for the stratiform (drizzle or widespread) and convective (shower or thunderstorm) rain types for the models considered. The total percentage fraction formed by drops in the diameter range 0.5 mm $\leq D \leq$ 2.5 mm and 1.0 mm $\leq D \leq$ 3.0mmare found to be most critical for the specific rain attenuation for the stratiform (drizzle and widespread) and convective (shower and thunderstorm) rainfall types especially at higher frequencies.

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1. INTRODUCTION

Rain has been identified as one of the major and important parameters affecting the propagation of signals in the microwave (3-30 GHz) and millimeter (30-300 GHz) wave bands. Other rain factors such as the canting angle, drop size and raindrop shapes also have profound effects on waves propagating in these bands at extremely high frequencies [1]. The specific rainfall attenuation is often predicted from three parameters, which are; the frequency, rain rate and polarization, where the population of the raindrops is represented by the single parameter, rainfall rate [2]. Although the rainfall rate remains very useful and has been broadly used for rain attenuation prediction [3], [4] and [5], a good knowledge of the drop size distribution (DSD) is very essential in the estimation of the rainfall attenuation at these radio frequency bands because it governs all the microwave and rainfall integral relations. The modeling of the DSD varies from one climate to another. Drop size distribution modeling in temperate region; characterized by moderate rainfall is well suitable with models such as proposed by Marshall and Palmer [6], Laws and Parsons [7] and the negative exponential model of gamma [8].

The modeling of DSD in the tropical region is most suitable with the globally accepted Ajayi and Olsen [9] lognormal model. In Durban, South Africa, a reasonable number of works have been carried out on rainfall attenuation and DSD [10], [11], [12], [13], [14] and [15] establishing the suitability of the lognormal and gamma models for DSD modeling in the region. Similarly, various approaches and models have been adopted by some researchers across the globe to investigate the particular contributions of certain raindrop diameters to the specific rain attenuation [16], [17], [18], [19] and [20]. The influence of critical raindrop diameters on the specific rainfall attenuation in Durban, South Africa using various rainfall regimes is analyzed in this work. Different rain rate values representing drizzle (below 5mm/h), widespread (5-20 mm/h) shower (20-50 mm/h) and thunderstorm (above 50 mm/h) as classified according to [9] and [21] are selected for the purpose of analysis over the measured raindrop size distribution. The three-parameter lognormal and gamma DSD models with shape parameter of 2 as determined in [15] for Durban, South Africa are used to represent the measured DSD, N(D).

2. DISDROMETER DATA ANALYSIS

The Joss-Waldvogel (J-W) RD-80 [22] disdrometer installed in 2008 at the rooftop of the School of Electrical, Electronic and Computer Engineering, University of KwaZulu-Natal was used to obtain over 80, 000 data samples for this work. The disdrometer converts the momentum of each falling drop impacting on the sensor's surface into an electric pulse of commensurate voltage. The detectable diameter range is divided into 20 intervals. The sampling time, T of the disdrometer is 60s with the sampling area, S of 50cm^2 (0.005 m^2). The data was gathered over a period of three (3) years. The data was sorted and classified into different types of rain based on rainfall rates R (*mm/h*) as classified in [6] and [18] namely: drizzle, widespread, shower and thunderstorm. The minimum and maximum rainfall rates were 0.003*mm/h* and 117.15 *mm/h* respectively. Rainfall events with overall sum of drops less than 10 were ignored from the disdrometer data to compensate for the dead-time errors. The instrument is located at an altitude of 140 meters above sea level. The location site is free of noise and protected from very strong winds. Equipment outage was observed but very minimal. From the disdrometer measurement, $N(D_i)$ is calculated as [22]:

$$N(D_i) = \frac{n_i}{v(D_i) * S * T * dD_i} \tag{1}$$

where$N(D_i)$ is the number of drops measured in the dropsize class, n_i is the number of drops per channel, $v(D)$ is the Gun-Kinzer [23] terminal velocity of water droplets and dD_i is the change in diameter of the (channel) in mm.

3. DROP SSIZE DISTRIBUTION MODELS

Raindrop size distributions were used to estimate the specific rainfall attenuation. Two DSD models are considered in this work; the lognormal and the gamma DSD models.

3.1. Lognormal DSD Model

The lognormal distribution model is expressed by [9] and [21]:

$$N(D) = \frac{N_T}{\sqrt{2\pi} \times \sigma \times D} exp\left[-\frac{1}{2}\left(\frac{\ln(D) - \mu}{\sigma}\right)^2\right] \tag{2}$$

whereN_T (concentration of rainfall drops) is a function of climate, geographical location of measurements and rainfall type, μ is the mean of $\ln(D)$ and σ is the standard deviation which determines the width of the distribution. The three parameters in (2) above are related to the rainfall rate R by [9]:

$$N_T = \quad a_0 R^{b_0} \tag{3}$$

$$\mu = A_\mu + B_\mu \ln R \tag{4}$$

$$\sigma^2 = A_\sigma + B_\sigma \ln R \tag{5}$$

where a_0,b_0,A_μ, B_μ, A_σ and B_σ are coefficients of moment regression determined using the least squares method of regression technique. The three-parameter lognormal DSD model as determined in [15] is given as:

$$\mu = -0.3104 + 0.1331 \ \ln R \tag{6}$$

$$\sigma^2 = 0.0738 + 0.0099 \ln R \tag{7}$$

$$N_T = 268.07R^{0.4068} \tag{8}$$

3.2. Gamma DSD Model

The three-parameter gamma distribution model in Durban as expressed by *Tokay* and *Short* [24] in the form of (2) was studied by *Adetan* and *Afullo* [15] with N_o $(m^{-3}\ mm^{-1-\mu})$ indicating the scaling parameter, μ (unitless) is the shape parameter, and Λ is the slope parameter in mm^{-1}. While the shape parameter does influence the slope of the distribution at larger diameter bound, it contributes largely on the curvature of the distribution at small diameters. The gamma distribution is particularly useful in tropical regions where the exponential distribution was found to be inadequate [9] and [24].

$$N(D) = N_o * D_i^{\mu} \exp(-\Lambda D_i) \tag{9}$$

where $N_o = 78259R^{-0.156}$, $\Lambda = 6.3209R^{-0.168}$ and $\mu = 2$

4. THE SPECIFIC RAINFALL ATTENUATION AND THE EXTINCTION CROSS SECTION

Generally, the specific rainfall attenuation γ (*dB/km*) is given by the relation [25]:

$$\gamma = 4.343 \times 10^{-3} \int_0^{D_{max}} Q_t . N(D) dD \quad [dB/km] \tag{10}$$

where Q_t is the total extinction cross-section, which is a function of the drop diameter, *D*, the wavelength, λ and the complex refractivity index of water drop, *m* (which depends on the frequency, *f* and the temperature, *T*). The extinction cross section, Q_t is evaluated using (11) as provided by *Odedina* and *Afullo* [13] in a power law relation, where κ and α are the coefficients that depend on rain rate, temperature, polarization and canting angle of droplets.

$$Q_t = \kappa \left(\frac{D}{2}\right)^{\alpha} \tag{11}$$

The classical scattering theory of Mie [26], [27] is used to compute the values of κ and α while assuming that each spherical raindrop illuminated by a plane wave is uniformly distributed in a rain field medium. The distance between each drop is assumed large enough to avoid collision. Table 1 shows the values of κ and α at *f* = 5-100 *GHz*. The total rainfall attenuation therefore, is evaluated by integrating over all the raindrop sizes.

$$\gamma = 4.343 \times 10^{-3} \int_{d_1}^{d_{max}} N(D) * \kappa \left(\frac{D_i}{2}\right)^{\alpha} \tag{12}$$

Table 1. Values of κ and α at *f* = 5-100 *GHz* at $T = 20^oC$

Frequencies(*GHz*)	k	α
5	0.0048	3.3911
10	0.3857	4.5272
19.5	1.6169	4.2104
25	2.4567	4.0186
40	4.3106	3.5077
60	6.0493	3.0094
80	7.0623	2.6621
100	7.6874	2.4156

5. RESULTS AND DISCUSSION

5.1. Specific Attenuation, Rainfall Rate and Frequencies

Although various methods have been adopted by a number of researchers to investigate the particular contributions of certain drop diameters to the specific rain attenuation, our approach is to estimate the specific rain attenuation by integrating the raindrop size distribution *N(D)* and the estinction cross section *Q(t)* over the raindrop diameters as indicated in equation (10). For instance, *Lee et al*. [16] and [17], in Singapore, *Fiser* [18], in the Czech Republic, *Lam et al*. [19] in Malaysia, and *Marzuki et al.* [20] in the Equatorial Indonesia concluded that small and medium-size drops contributed more to the rainfall attenuation as frequency increases. They also noted that the prevailing contribution to the specificattenuation is formed by raindrops of diameter not exceeding 2 *mm* especially at higher frequencies.The attenuation created by drops in the diameter intervals $0.1 \geq D \geq 7.0$ *mm* at various frequencies of transmission is shown in Tables 2. The total specific attenuation increases with increasing frequencies for all the rainfall regimes. The specific rain attenuation increases with increased rain rates with the thunderstorm having the highest attenuation. The highest and prevailing contribution to the specific attenuation occurs at $D \sim 2$ mm for the stratiform (drizzle or widespread) and convective (shower or thunderstorm) rain types shown in Figures 1 and 2 for the gamma and lognormal models, respectively (see Tables 4 and 5). The highest and prevailing contribution to the specific attenuation for the drizzle and widespread rainfall types occurs in the diameter range 0.5*mm* $\leq D \leq$ 2.5 *mm* while that of shower and thunderstorm rain types occurs in the range 1.0 *mm* $\leq D \leq$ 3.0 *mm* and 1.5*mm* $\leq D \leq$ 3.5 *mm* respectively.

5.2. Influence of Raindrop Diameters on Specific Rain Attenuation

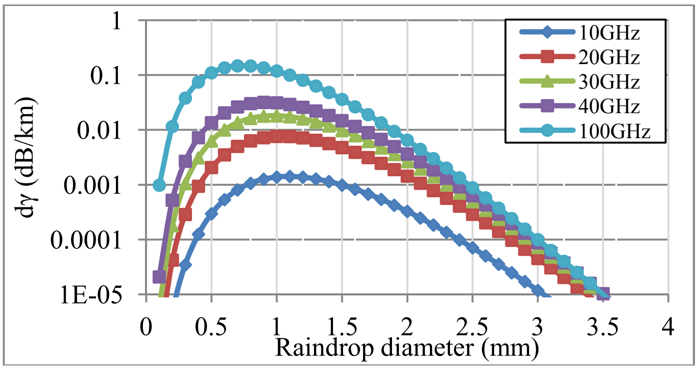
The percentage contribution formed by raindrop diameter intervals to the overall rain attenuation for different rain types is illustrated in Table 3. The contribution of larger diameters as observed is insignificant to the total attenuation. For instance, the highest contribution in the diameter range 4.0 *mm* $\leq D \leq 7.0$ *mm* is 1.46 % and 0.0005 % at f =100 *GHz* respectively for the thunderstorm and drizzle rain types. The largest contributions to the specific attenuation are due to drop diameters not exceeding 2 *mm* for all rainfall regimes at all frequencies and this confirms the results obtained in Singapore, Indonesia and Czech Republic. Hence, the diameter ranges 0.5 *mm* $\leq D \leq$ 2.5 *mm* are critical to attenuation in Durban being a coastal region characterized by drizzle rainfall type.

Table 2. Total Specific Rain Attenuation Formed by Raindrops in the Diameter Interval 0.1 *mm* $\geq D \geq 7.0$ *mm* forVarious Rainfall regimes at f = 5-100 *GHz*

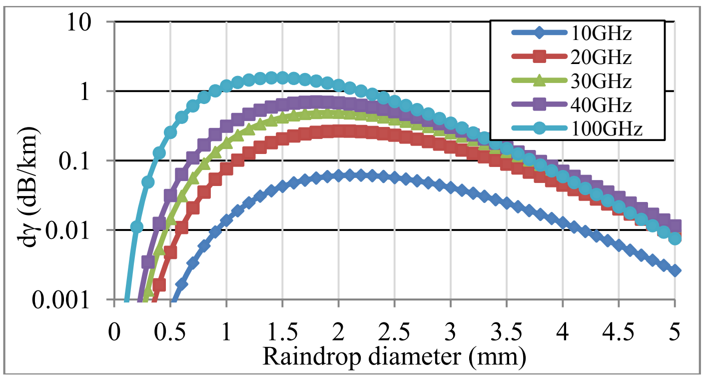
Rain Types	f (*GHz*)	γ(*dB/km*)
	5	0.005721
Drizzle	10	0.043265
(1.41 *mm/h*)	19.5	0.209261
	40	0.790270
	60	1.456975
	80	2.083624
	100	2.630704
	5	0.023946
Widespread	10	0.201346
(14.21 *mm/h*)	19.5	0.901362
	40	2.881511
	60	4.739811
	80	6.273028
	100	7.519103
	5	0.075375
Shower	10	0.689945
(44.52 *mm/h*)	19.5	2.903166
	40	8.121619
	60	12.19299
	80	15.1661
	100	17.4093
	5	0.204919
Thunderstorm	10	2.019329
(77.70 *mm/h*)	19.5	8.051879
	40	20.05557
	60	27.80548
	80	32.76383
	100	36.21787

Table 3. Percentage (%) Contribution of the Specific Attenuation formed by Drop Diameters (*mm*)

Rain Types	f(*GHz*)	$0.1 \le D \le 2$	$0.5 \le D \le 2.5$	$1.0 \le D \le 3.0$	$1.5 \le D \le 3.5$	$4.0 \le D \le 7.0$
Drizzle	5	95.55	99.25	81.93	29.99	0.004
	10	94.21	98.95	85.05	34.59	0.007
	19.5	95.21	99.18	82.82	31.21	0.005
	40	96.95	99.51	77.09	24.29	0.002
	60	97.83	99.64	72.43	19.94	0.001
	80	98.31	99.69	68.90	17.20	0.0007
	100	98.59	99.71	66.29	15.41	0.0005
Widespread	5	79.42	93.44	92.77	60.22	0.192
	10	75.26	91.49	93.37	65.17	0.296
	19.5	78.33	92.95	92.98	61.60	0.216
	40	84.29	95.49	91.14	53.18	0.105
	60	87.78	96.79	88.99	46.99	0.061
	80	75.16	97.50	87.09	42.69	0.041
	100	91.19	97.92	85.53	39.67	0.031
Shower	5	58.01	80.41	90.08	76.64	1.505
	10	52.26	76.14	88.19	79.28	2.150
	19.5	56.45	79.29	89.63	77.44	1.662
	40	65.44	85.34	91.61	71.89	0.906
	60	71.35	88.83	92.00	66.90	0.571
	80	75.16	90.88	91.79	63.01	0.408
	100	77.70	92.15	91.38	60.09	0.319
Thunderstorm	5	38.86	63.28	79.76	80.28	5.46
	10	32.99	57.46	75.54	79.81	7.37
	19.5	37.06	61.72	78.67	80.25	5.93
	40	46.58	70.61	84.43	79.31	3.57
	60	53.48	76.28	87.42	77.08	2.41
	80	58.25	79.84	88.95	74.80	1.80
	100	61.56	82.17	89.74	72.84	1.46

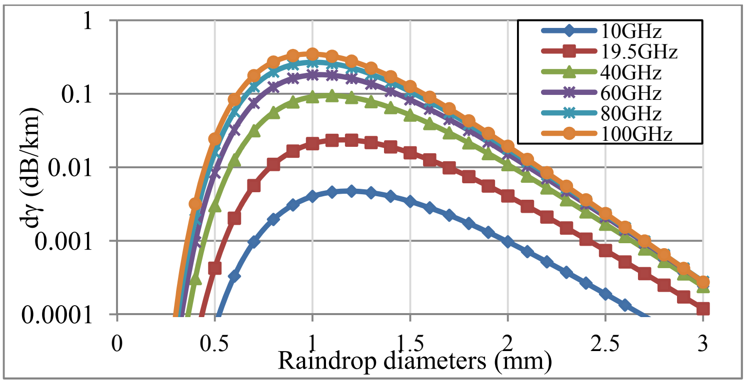


(a)

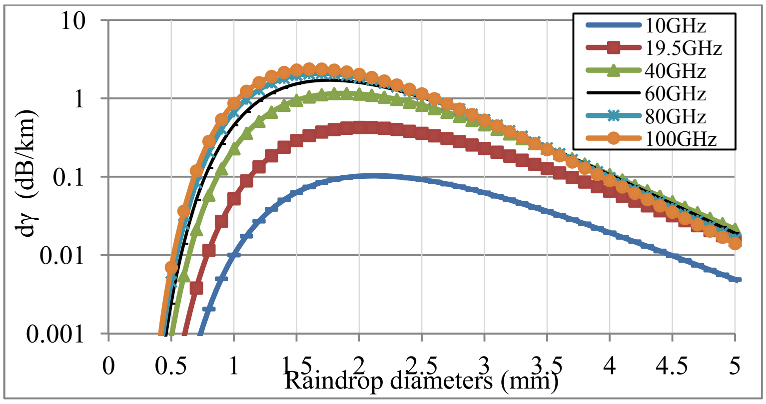


(b)

Figure 1. Rainfall attenuation and raindrop diameters for rainfall regimes at various frequencies for (a) R= 1.41 and (b) R= 77.70 *mm/h* using gamma DSD model



(a)



(b)

Figure 2. Rainfall attenuation and raindrop diameters for rainfall regimes at various frequencies for (a) R=1.41 *mm/h* and (b) R= 120 *mm/h* using lognormal DSD model.

Table 4. Rain attenuation created by drops in the diameter range 0.1 mm $\geq D \geq$ 7.0 *mm* at various frequencies for the gamma model

Frequency (GHz)	Drizzle	Widespread	Shower	Thunderstorm
10	0.015	0.199	0.707	1.311
20	0.081	0.925	3.079	5.533
30	0.186	1.844	5.723	9.943
40	0.318	2.781	8.111	13.670
100	1.336	7.624	18.032	27.440

Table 5. Rain attenuation created by drops in the diameter range 0.1 mm $\geq D \geq$ 7.0 *mm* at various frequencies for the lognormal model

Frequency (GHz)	Drizzle	Widespread	Shower	Thunderstorm
10	0.043	0.201	0.689	2.019
19.5	0.209	0.901	2.903	8.051
40	0.790	2.881	8.121	20.055
60	1.457	4.739	12.192	27.805
80	2.083	6.273	15.166	32.763
100	2.630	7.519	17.409	36.217

6. CONCLUSION

This paper considered the critical range of raindrop diameters at which the specific rainfall attenuation is most influenced. For the DSD models considered, the total percentage fraction formed by raindrops in the diameter range 0.5 mm $\leq D \leq$ 2.5 *mm* and 1.0 *mm* $\leq D \leq$ 3.0 *mm* are respectively found to be most critical for the specific rain attenuation for the stratiform (drizzle and widespread) and convective (shower and thunderstorm) in Durban, South Africa.

The contribution of larger diameters to the total attenuation is very low and insignificant when compared to medium and smaller diameters. The critical diameters are the range of diameters that contribute significantly to the rain attenuation. The highest contribution of raindrops diameters to the specific rain attenuation was created by drop diameters not exceeding 2 *mm*, especially at higher frequencies. This confirms the results obtained by [16], [17] in Singapore; [18] in Czech Republic; [19] in Malaysia and [20] in Equatorial Indonesia. At frequency above 40 *GHz*, the drop size diameter that gives the largest contribution to the total attenuation for all the rain rates considered does not exceed 3 *mm* (90%). This is similar to the results obtained by [20]. A good understanding of this rainfall attenuation characteristic will be helpful to properly design adequate fade margin levels, achieve the expected quality of service in a radio communication system operating in this region and for the purpose of link budget design by the engineers and service providers in this particular region.

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