RAIN-INDUCED PROPAGATION PARAMETERS FOR EARTH-SPACE COMMUNICATION IN NIGERIA

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Abstract: This paper reports the calculation of rain-induced attenuation along the earth-space path at two elevation angles and some rain rates representing high and low availability requirements in Nigeria. The paper first calculates the slant path scattering parameters at various frequencies and rain rates, and then uses the new ITU-R recommendation P.618-8 to predict the slant path attenuation at the elevation angles of 23^0 and 55^0, which are used frequently for satellite communication in Nigeria. The results obtained show that the old ITU Report 564-4 recommendation could underestimate the total path attenuation by as much 36 dB at a rain rate of 150 mm/h. Some results are also presented for the scattering amplitude functions and propagation constant at the two elevation angles. The parameters of a power-law relationship to calculate the differential propagation constant in terms of the rain rate at the elevation angles are also presented. These parameters when used to calculate the slant path differential propagation constant have a maximum error margin of 1.2% from the actual.

Keywords: rain-induced attenuation, earth-space path, rain rates, differential propagation constant

1. INTRODUCTION

The success of any communication depends in part on the role played by the medium through which the communication is done. The design of earth-space communication systems must consider the effects of the ionized and non-ionized atmosphere- the ionosphere and the troposphere respectively, on the quality of the link. The non-ionized atmospheric effects include absorption and scattering by hydrometeors, the most important of which is rain, depolarization by hydrometeors, absorption by atmospheric gases, short-term variations of the ratio of attenuations at the up- and down-link frequencies, the effect of varying elevation angle to the satellite for non-geostationary satellites etc. In the tropical regions, rain-induced propagation losses are enormous on satellite communication links particularly at frequencies higher than 10 GHz, at which the signal wavelength becomes comparable to raindrops size, thereby leading to strong rain induced losses along the path. Thus, on tropical propagation paths, the rain-induced losses could lead easily to complete system outage even in the absence of other loss inducing effects.

In most calculations of earth-space propagation characteristics such as the recent report by Norbury et al. [1], the specific attenuation is usually calculated in terms of the power-law relation between attenuation and rain rate. This is because, the approximate scaling parameters for the calculation is readily available, and so the rigorous procedure of calculating the slant path scattering parameters is cleverly avoided. However, the result of the specific attenuation obtained usually has an error margin of about $\pm$ 10% [2]. This error comes largely from the multiple approximations used in the derivation of the relation on one hand, and the approximate frequency dependent coefficients k and α of the relationship itself.

This study investigates the scattering of electromagnetic radiation by rain and its effect on the propagation characteristics of downlink signal of communication satellites in Nigeria. The study is applicable to frequencies up to 40 GHz, which is presently the most active band for providing telecommunication services. The study first calculates the Forward Scattering Amplitude (FSA) functions of thirteen oblate spheroidal raindrops with radii in the size range 0.25-3.25 mm and wave incidence at satellite look angles of 23^0 and 55^0, respectively, in Nigeria. The results obtained are used to calculate the propagation constant in the rain medium on the slant path at the required elevation angle. These latter results are then used to calculate the attenuation of the signal along the earth-space propagation path.

Previous calculations of FSA functions and the propagation constants for spherical and oblate spheroidal raindrops using data from Nigeria at elevation angles of 0°, 55°, and 70 °, respectively have been reported by Ajewole et al., [3, 4]. The elevation angle of 0° is used for terrestrial (horizontal) propagation while the latter two angles, which are not presently being used in Nigeria, are suitable for earth-space communication. Recently, Nigeria launched a satellite into space for remote sensing activity. The

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successful launching of the satellite makes it the more important to investigate forward scattering characteristics of rain on satellite communication in Nigeria particularly when the ground satellite antenna is at the elevation angle of 23° or 55°.

In this study, linear polarizations (horizontal –H and vertical –V) are assumed, and the calculations are made for these polarizations at the frequencies 10, 16, 18, 19.3 22, 26, 30, 34.8, 36, and 40 GHz for rain rates varying from 0.25-150mm/h. We present results for the FSA functions, the propagation constant, the parameters of an empirical power law scaling relationship between the differential propagation constant and the rain rate, the specific attenuation, total slant path attenuation and the frequency characteristics of the effective path length to the rain region in Nigeria.

2. COMPUTATION

The calculation procedure of the forward scattering amplitude function is always very rigorous and time consuming. Uzunoglu et al., [5] proposed a scaling relation to calculate the forward scattering amplitude function for arbitrary angles of incidence α in terms of those for nose-on i.e. for vertical propagation path ($\alpha = 0^0$) and broadside i.e. for horizontal propagation path ($\alpha = 90^0$). This scaling relation which has also been employed in this study, has an error margin of 0.4% for raindrops with equivolumic radii in the size range 0.25 mm to 3.25 mm and rain rates not exceeding 150 mm/h [6]. It is expressed as

$$f_{v,h}(\alpha_0,0,\tilde{a}) = f(0,0,\tilde{a})\cos^2\alpha_0 + f_{v,h}\left(\frac{\pi}{2},0,\tilde{a}\right)\sin^2\alpha_0 \qquad (1)$$

where $f_{v,h}(\alpha,0,\tilde{a})$ is the forward scattering amplitude for vertically and horizontally polarized waves incident at an angle α to the raindrops axes. $f(0,0,\tilde{a})$ and $f_{v,h}(\frac{\pi}{2},0,\tilde{a})$ are the forward scattering amplitude functions corresponding to nose-on and broadside wave incidences, and $\tilde{a}$ is the radius (mm) of the equivolumic raindrop. The corresponding values of $f(0,0,\tilde{a})$ and $f_{v,h}(\frac{\pi}{2},0,\tilde{a})$ used in this study are taken from [7]. The validity of eqn. (1) on earth-space propagation paths at frequencies lower than 50 GHz has been confirmed by [6].

To calculate the propagation constant in the rain medium along the earth-space path, eqn. (1) is required along side information about the incident wave frequency and the raindrop size distributions. Thus, assuming that plane waves with electric fields polarized in the horizontal (H) and vertical (V) directions are incident on the rain medium, Oguchi [8] proposed a relationship between the propagation constant, the scattering amplitude function and the raindrops number density which is expressed as

$$k_{v,h} = \frac{2\pi}{k_0}\int_0^{\infty} f_{v,h}(k_1,k_1)n(\tilde{a})d\tilde{a} \qquad (2)$$

where $f_{v,h}(k_1,k_1)$ represents the scattering amplitude functions of a raindrop with equivolumic radius $\tilde{a}$ in the forward direction and for vertical and horizontal polarizations. It is also a function of the rain rate. $n(\tilde{a})$ is the raindrop size distribution, while $d\tilde{a}$ is the raindrop size interval, which is 0.25 mm in this study. This expression is summed over the raindrop sizes in a rain slab. The raindrops number density $n(\tilde{a})$ has been calculated using the tropical lognormal raindrops size distribution of [9], which is expressed as

$$n(\tilde{a}) = \frac{n_t}{\sigma\tilde{a}\sqrt{2\pi}} exp\left[\frac{-[ln(\tilde{a})-\mu]^2}{2\sigma^2}\right] \qquad (3)$$

The parameter μ represents the mean of $\ln(\tilde{a})$, σ represents the standard deviation and n_t represents the total number of raindrops of all sizes. These parameters; μ, σ and n_t are climate and location dependent. In addition, they depend on rain rate R and the rainfall type. For Nigeria, these parameters are expressed [9] as

$$n_t = 108R^{0.363}$$
$$\mu = -0.195 + 0.199 ln R \qquad (4)$$
$$\sigma^2 = 0.137 - 0.013 ln R$$

Using eqns. (1-4), the specific attenuation can be calculated for a 1 km propagation distance for the polarization types (H- and V) and at the different frequencies, using the expression [6],

$$A_{v,h} = 8.686 \times \mathrm{Im}(k_{v,h}) \times 10^5 \qquad (5)$$

The total slant path attenuation at the two elevation angles can now be calculated for some percentages of time representing typical availabilities. In this study, we shall look at the high and low availability margins and typical worst month result. To do this, the ITU-R Rec. P. 618-8 [10] with the rain height given by ITU-R Rec. P. 839-3 [11] will be used first to calculate the equivalent slant path length from the satellite earth station antenna to the rain region and then the slant path attenuation. Thus, the predicted slant path attenuation exceeded for 0.01% of an average year is calculated in terms of the frequency dependent effective path length (L_E) to the rain region in Nigeria. The new approach by the ITU-R Rec. P. 618-8 [10] now incorporates a vertical reduction factor in addition to making the horizontal reduction factor frequency dependent. The new horizontal reduction factor is expressed in terms of the specific attenuation γ_R and the signal frequency f as

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \gamma_R}{f}} - 0.38(1 - e^{-2L_G})} \tag{6}$$

L_G is the horizontal projection of the slant path on the ground. The vertical reduction factor on the other hand is expressed as

$$v_{0.01} = \frac{1}{1 + \sqrt{sin\theta}\left[31\left(1 - e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\frac{\sqrt{\gamma_R L_R}}{f^2} - 0.45\right]} \tag{7}$$

$L_R = \frac{L_G r_{0.01}}{cos\theta}$ and θ is the path elevation angle. For latitudes φ lower than 36^0, such as for Nigeria, the parameter χ is defined as $\chi = 36 - |\varphi|$. The effective path length is then expressed as

$$L_E = L_R v_{0.01} \tag{8}$$

The attenuation exceeded for 0.01% of the time is calculated at the elevation angles of 23^0 and 55^0 using the relation

$$A_{0.01} = A_{v,h} L_E \text{ (dB)} \tag{9}$$

Next the differential attenuation of the waves on the earth-space path is calculated using the expression [6]

$$\Delta A = 8.686 \times \mathrm{Im}(k_h - k_v) L_E \text{ (dB)} \tag{10}$$

For practical applications, the use of empirical scaling relationship can be employed to estimate the differential propagation constant. The power-law relationship between differential propagation constant and rain rate takes the form

$$\Delta k = k_h - k_v = cR^d \tag{11}$$

where c and d are constants, which are derived from linear regression analysis. The parameters c and d are estimated for earth-space propagation in Nigeria at two angles of incidence (elevation angles).

3. RESULTS AND DISCUSSION

The forward scattering amplitude functions are calculated at ten frequencies in the range 10-40 GHz and at elevation angles of 23^0 and 55^0 for horizontally and vertically polarized signals. Some results are shown in Table 1. The results show that the real and the imaginary parts of the forward scattering amplitude at both polarizations have small values for small size raindrops at lower frequencies. In the frequency range 36-40 GHz and raindrop size range 3.00-3.25 mm, the real part of the horizontal polarization is smaller than the real part of the vertical polarization, $f_v > f_h$. The implication is that the differential scattering amplitude function $\mathrm{Re}(f_h - f_v)$ will decrease to negative values for large raindrops and in this frequency range. This explains why the differential phase shift always decreases to negative values in this frequency range.

Some results are also presented for the effective propagation constant at some frequencies as shown in Table 2. The real and imaginary parts of the effective propagation constant for both polarization increases with increasing rain rate and frequency. The imaginary part of the propagation constant for horizontal polarization is bigger than the imaginary part for vertical polarization at all rain rates and frequencies. The real part of the propagation constant for vertical polarization on the other hand is bigger than the real part of the horizontal polarization at rain rates higher about 50 mm/h and frequencies higher than about 30 GHz. For this reason, the differential phase shift will decrease to negative values at frequencies higher than about 30 GHz. Table 3 also shows the frequency dependent regression parameters of the power-law relationship for differential propagation constant in terms of the rain rate. A comparison of the differential propagation constant calculated using these parameters with those calculated directly from the table 2 shows a maximum difference of 1.2%.

Figure 1 presents the specific attenuation at some rain rates for the elevation angles investigated. Figure 1a shows that the specific attenuation is nearly equal in magnitude in the two polarizations.

Table 1: Forward scattering amplitudes at frequencies of 10 and 40 GHz and elevation angle of 23^0 and 55^0

	Elevation angle = 23^0	
	Frequency = 10 GHz	
Radius (mm)	Horizontal Polarization	Vertical Polarization
0.25	0.6658480450E-06 +j -0.1689521582E-07	0.6655758763E-06 +j -0.1688242405E-07
0.50	0.5474288557E-05 +j -0.2008512997E-06	0.5459138392E-05 +j -0.1999726665E-06
0.75	0.1937182349E-04 +j -0.1155016977E-05	0.1923415162E-04 +j -0.1143493693E-05
1.00	0.4888458600E-04 +j -0.5001234136E-05	0.4832075563E-04 +j -0.4922271630E-05
1.25	0.1028948546E-03 +j -0.1866566574E-04	0.1010211341E-03 +j -0.1816144383E-04
1.50	0.1846222954E-03 +j -0.6048163784E-04	0.1805275531E-03 +j -0.5819470329E-04
1.75	0.2663509343E-03 +j -0.1423794572E-03	0.2609913631E-03 +j -0.1381258099E-03
2.00	0.3424311393E-03 +j -0.2153967213E-03	0.3313163373E-03 +j -0.2118919577E-03
2.25	0.4790282734E-03 +j -0.2841854600E-03	0.4556519888E-03 +j -0.2762783715E-03
2.50	0.6840363141E-03 +j -0.4055174689E-03	0.6466379223E-03 +j -0.3866198326E-03
2.75	0.9343298149E-03 +j -0.6075302815E-03	0.8814378037E-03 +j -0.5715286052E-03
3.00	0.1212952580E-02 +j -0.9147968412E-03	0.1143803717E-02 +j -0.8520591310E-03
3.25	0.1483986920E-02 +j -0.1330880670E-02	0.1402473691E-02 +j -0.1230744568E-02
	Frequency = 40 GHz	
Radius (mm)	Horizontal Polarization	Vertical Polarization
0.25	0.1086498393E-04+j -0.1475470302E-05	0.1086054192E-04+j -0.1474458256E-05
0.50	0.9144358645E-04+j -0.3102825976E-04	0.9118031704E-04+j -0.3090283013E-04
0.75	0.2720286583E-03+j -0.1889184085E-03	0.2699740365E-03+j -0.1868013543E-03
1.00	0.4331532895E-03+j -0.5909526759E-03	0.4312343704E-03+j -0.5800205917E-03
1.25	0.4003293898E-03+j -0.1089126318E-02	0.4076086433E-03+j -0.1066135314E-02
1.50	0.3243084239E-03+j -0.1531015003E-02	0.3421737120E-03+j -0.1498217376E-02
1.75	0.3308381297E-03+j -0.2023760691E-02	0.3584173829E-03+j -0.1973417877E-02
2.00	0.3550504759E-03+j -0.2682994617E-02	0.4044616890E-03+j -0.2607020929E-02
2.25	0.2899720734E-03+j -0.3461538953E-02	0.3711937480E-03+j -0.3369819779E-02
2.50	0.1701409546E-03+j -0.4264755997E-02	0.2741237483E-03+j -0.4161547121E-02
2.75	0.7263965878E-04+j -0.5103305416E-02	0.1983287843E-03+j -0.4976089825E-02
3.00	-0.3401510864E-06+j -0.6061665121E-02	0.1643654191E-03+j -0.5903523350E-02
3.25	-0.8979248369E-04+j -0.7122931278E-02	0.1184173381E-03+j -0.6946166635E-02
	Elevation angle = 55^0	
	Frequency = 10 GHz	
Radius (mm)	Horizontal Polarization	Vertical Polarization
0.25	0.6658748443E-06+j -0.1689843422D-07	0.6646784394D-06+j -0.1684220386D-07
0.50	0.5475428568E-05+j -0.2015304392D-06	0.5408831155D-05+j -0.1976681247D-06
0.75	0.1939275021E-04+j -0.1172053132D-05	0.1878756929D-04+j -0.1121398837D-05
1.00	0.4903366923E-04+j -0.5169662310D-05	0.4655517186D-04+j -0.4822557265D-05
1.25	0.1035105324E-03+j -0.1999023123D-04	0.9527399247D-04+j -0.1777376197D-04
1.50	0.1840018851E-03+j -0.6704669165D-04	0.1660021309D-03+j -0.5699373668D-04
1.75	0.2531263928E-03+j -0.1535465573D-03	0.2295666772D-03+j -0.1348482852D-03
2.00	0.3194423414E-03+j -0.2186873097D-03	0.2705836610D-03+j -0.2032809963D-03
2.25	0.4508408751E-03+j -0.2890676650D-03	0.3480829122D-03+j -0.2543095190D-03
2.50	0.6347173738E-03+j -0.4157895101D-03	0.4703207374D-03+j -0.3327188832D-03
2.75	0.8535137735E-03+j -0.6099975856D-03	0.6210099591D-03+j -0.4517406602D-03
3.00	0.1099214925E-02+j -0.8996401618D-03	0.7952488996D-03+j -0.6238564165D-03
3.25	0.1334751169E-02+j -0.1296714518D-02	0.9764336023D-03+j -0.8565341365D-03
	Frequency = 40 GHz	
Radius (mm)	Horizontal Polarization	Vertical Polarization
0.25	0.1086550907E-04+j -0.1476095873D-05	0.1084598278D-04+j -0.1471647098D-05
0.50	0.9138941918E-04+j -0.3116579822D-04	0.9023213396D-04+j -0.3061443204D-04
0.75	0.2700572785E-03+j -0.1897557587D-03	0.2610255286D-03+j -0.1804495670D-03
1.00	0.4232109446E-03+j -0.5886479582D-03	0.4147757196D-03+j -0.5405924729D-03
1.25	0.3802023261E-03+j -0.1067677557D-02	0.4122006216D-03+j -0.9666132146D-03
1.50	0.3069649320E-03+j -0.1479065716D-02	0.3854975407D-03+j -0.1334893221D-02
1.75	0.3266460444E-03+j -0.1951223557D-02	0.4478795052D-03+j -0.1729925554D-02
2.00	0.3351717188E-03+j -0.2600584513D-02	0.5523745680D-03+j -0.2266617779D-02
2.25	0.2298164748E-03+j -0.3323297402D-02	0.5868524189D-03+j -0.2920116329D-02
2.50	0.1098620576E-03+j -0.4040779940D-02	0.5669518077D-03+j -0.3587092193D-02
2.75	0.3101822436E-04+j -0.4833778932D-02	0.5835251243D-03+j -0.4274561965D-02
3.00	-0.8638709092E-04+j -0.5752413413D-02	0.6376291163D-03+j -0.5057250493D-02
3.25	-0.2453020353E-03+j -0.6716264937D-02	0.6699510756D-03+j -0.5939239202D-02

Table 2: Effective propagation constant at frequencies of 10 and 40 GHz and elevation angle of 23^0 and 55^0

Rain Rate (mm/h)	k_h (Horizontal Polarization)	k_v (Vertical Polarization)
	Elevation angle = 23^0	
	Frequency = 10 GHz	
0.25	0.5278505462E-05+j-0.2475950760E-06	0.5257348370E-05 +j-0.2452314138E-0
0.50	0.9902972704E-05 +j-0.5395596371E-06	0.9853218175E-05 +j-0. 5332283501E-06
1.25	0.2318153753E-04 +j-0.1569021543E-05	0.2302952529E-04 +j-0.1545623312E-05
2.50	0.4425115198E-04 +j-0.3596474509E-05	0.4390087441E-04 +j-0.3533512386E-05
5.00	0.8426710609E-04 +j-0.8375678973E-05	0.8346665558E-04 +j-0.8206679581E-05
12.5	0.1970588862E-03 +j-0.2612222474E-04	0.1947046844E-03 +j-0.2550614068E-04
25.0	0.3747729618E-03 +j-0.6230858602E-04	0.3695150724E-03 +j-0.6069656949E-04
50.0	0.7112408928E-03 +j-0.1485853667E-03	0.6996520617E-03 +j-0.1444608796E-03
100.0	0.1341179979E-02 +j-0.3511923885E-03	0.1316017482E-02 +j-0.3409591733E-03
150.0	0.1934518839E-02 +j-0.5762161692E-03	0.1895197378E-02 +j-0.5591091470E-03
	Frequency = 40 GHz	
Rain Rate (mm/h)	k_h (Horizontal Polarization)	k_v (Vertical Polarization)
0.25	0.2024439549E-04+j -0.8217620276E-05	0.2018119437E-04+j -0.8149503215E-05
0.50	0.3659137850E-04+j -0.1752324936E-04	0.3645914938E-04+j -0.1735518232E-04
1.25	0.7964557225E-04+j -0.4704455079E-04	0.7932144727E-04+j -0.4650693527E-04
2.50	0.1405408365E-03+j -0.9765069069E-04	0.1399543549E-03+j -0.9639009269E-04
5.00	0.2408381178E-03+j -0.1991384799E-03	0.2398923780E-03+j -0.1962630510E-03
12.5	0.4654289367E-03+j -0.4950307374E-03	0.4642069347E-03+j -0.4868904682E-03
25.0	0.7323400041E-03+j -0.9580646843E-03	0.7320803799E-03+j -0.9409294544E-03
50.0	0.1099137608E-02+j -0.1800209951E-02	0.1103274898E-02+j -0.1765578900E-02
100.0	0.1558242737E-02+j -0.3274031421E-02	0.1575152994E-02+j -0.3206917423E-02
150.0	0.1857031157E-02+j -0.4574804168E-02	0.1888767591E-02+j -0.4477805462E-02
	Elevation angle = 55^0	
	Frequency = 10 GHz	
Rain Rate (mm/h)	k_h (Horizontal Polarization)	k_v (Vertical Polarization)
0.25	0.5281245333E-05+j -0.2519997791E-06	0.5188242542E-05+j -0.2416095433E-06
0.50	0.9909507760E-05+j -0.5522286807E-06	0.9690795753E-05+j -0.5243974759E-06
1.25	0.2320056545E-04+j -0.1619712953E-05	0.2253234684E-04+j -0.1516858515E-05
2.50	0.4428925231E-04+j -0.3739588098E-05	0.4274949479E-04+j -0.3462817869E-05
5.00	0.8432786019E-04+j -0.8774259663E-05	0.8080922302E-04+j -0.8031368582E-05
12.5	0.1970445283E-03+j -0.2762091010E-04	0.1866958781E-03+j -0.2491271482E-04
25.0	0.3741949062E-03+j -0.6626462355E-04	0.3510821655E-03+j -0.5917848741E-04
50.0	0.7082002656E-03+j -0.1586450341E-03	0.6572578381E-03+j -0.1405145272E-03
100.0	0.1329260031E-02+j -0.3755111086E-03	0.1218650197E-02+j -0.3305277263E-03
150.0	0.1909890310E-02+j -0.6157458814E-03	0.1737040207E-02+j -0.5405464738E-03
	Frequency = 40 GHz	
Rain Rate (mm/h)	k_h (Horizontal Polarization)	k_v (Vertical Polarization)
0.25	0.2019046629E-04+j -0.8236307293E-05	0.1991264460E-04+j -0.7936876883E-05
0.50	0.3645367381E-04+j -0.1755228607E-04	0.3587241496E-04+j -0.1681349344E-04
1.25	0.7919158603E-04+j -0.4705850847E-04	0.7776677131E-04+j -0.4469524682E-04
2.50	0.1394647763E-03+j -0.9753182786E-04	0.1368866342E-03+j -0.9199046458E-04
5.00	0.2383856106E-03+j -0.1984966585E-03	0.2342280250E-03+j -0.1858567877E-03
12.5	0.4586362729E-03+j -0.4916927262E-03	0.4532628973E-03+j -0.4559095594E-03
25.0	0.7185480329E-03+j -0.9483534447E-03	0.7174003209E-03+j -0.8730300401E-03
50.0	0.1072855434E-02+j -0.1774667504E-02	0.1091017260E-02+j -0.1622435599E-02
100.0	0.1511733175E-02+j -0.3212351264E-02	0.1585970609E-02+j -0.2917330136E-02
150.0	0.1794550598E-02+j -0.4475268212E-02	0.1933843028E-02+j -0.4048879258E-02

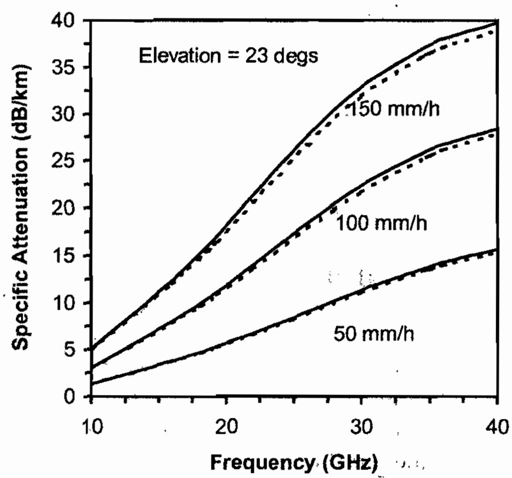
Table 3: Regression coefficients c and d for estimating the differential propagation constant using the expression $\Delta k = cR^d$ for elevation angles of 23^0 and 55^0

Frequency (GHz)	Elevation angle = 23^0		Elevation angle = 55^0	
	c	d	c	d
10	1.7245E-08	1.38733	7.5808E-08	1.38733
16	5.3860E-08	1.33449	2.3676E-07	1.33449
18	7.0670E-08	1.33658	3.1065E-07	1.33658
19.3	8.3293E-08	1.33579	3.6614E-07	1.33579
22	1.1426E-07	1.32581	5.0227E-07	1.32581
26	1.7131E-07	1.29310	7.5303E-07	1.29310
30	2.3752E-07	1.24710	1.0441E-06	1.24710
34.8	3.2064E-07	1.18503	1.4095E-06	1.18503
36	3.4090E-07	1.16944	1.4985E-06	1.16944
40	4.0353E-07	1.11963	5.6697E-08	1.06109

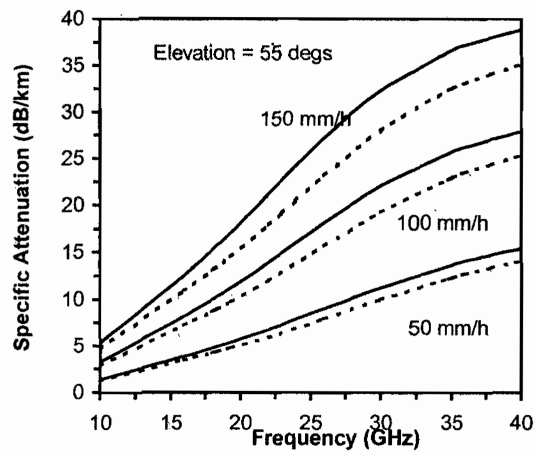
In Figure 1b however, the horizontal polarization is higher by about 2 dB at high rain rates and frequencies higher than about 25 GHz. Figure 2 shows the frequency characteristics of the effective path length to the rain region at the two elevation angles. The curves labeled "a" are for the elevation angle of 23^0 while those labeled "b" are for the elevation angle of 55^0. The results for the 23^0 elevation show a gradual decrease of effective path length with increasing frequency, while there is a small rise in the effective path length with increasing frequency at 55^0 elevation angle. The effective path length for vertical polarization at the elevation angle of 55^0 is longer than the effective path length for horizontal polarization by about 1 km at all rain rates and frequencies. This is because the vertical reduction factor for vertical polarization at this elevation angle is larger than the horizontal component. This is evident from the terms defining L_R in eqn. (7) in addition to the lower specific attenuation of vertical polarization, which is required in evaluating equations (6-7).

Figures 3 and 4 also present the results of the total attenuation along the earth-space path in Nigeria using the computed forward scattering amplitude functions and the results of Ajayi et al., [12] which are based on the power-law relation between specific attenuation and rain rate. The present results are at three-rain rates 50, 100 and 150 mm/h, and are compared with Ajayi et al., at rain rates of 50 and 100 mm/h only, since their work did not present any results for the rain rate of 150 mm/h. The results show that the difference between the horizontal and vertical attenuation on the earth-space path in Nigeria increases with increasing elevation angle, rain rate and frequency. The comparison of the results also show that the Ajayi et al., results are lower than the results obtained using the calculated forward scattering amplitude functions and the new recommendation ITU-R Rec. P. 618-8 [10]. For an elevation angle of 23^0 on the slant path, the difference between the slant path attenuations increases from about 4 dB at a frequency of 10 GHz to about 20 dB at a frequency of 40 GHz for a rain rate of 50 mm/h. The difference increases from about 8 dB to 28 dB at the rain rate of 100 mm/h for the same path elevation angle. At the elevation angle of 55^0, the difference varies from about 2 dB to 36 dB as the frequency increases from 10 to 40 GHz. One reason for this large difference might be the introduction of the vertical reduction factor in addition to the modified horizontal reduction factor in the new ITU-R Rec. P. 618-8 [10]. Secondly, the reduction factors are now frequency dependent in contrast to the old ITU-R Rept. 564-4 [13] used by Ajayi et al,. It is also possible that this large difference may be due to the calculation of the attenuation in terms the scattering parameters that were obtained with high accuracy (0.4% error). The power-law approach on the other hand is based on multiple approximations or scaling of the major parameters. Thus, the cumulative error arising from that approach might have been responsible for the large difference in path attenuation.

Figure 5 shows the frequency characteristics of the differential path attenuation. The differential attenuation increases as frequency increases and attains a maximum around the frequency of 30 GHz. This maximum increases with frequency. Further increase in frequency results in a gradual decrease of the differential attenuation. This is because at frequencies higher than about 30 GHz, the parameter $\text{Im}(f_h - f_v)$ for large raindrops decreases as frequency increases. It is important to note that, while differential attenuation below 30GHz increases with frequency for a given rain event, it decreases for a given fade depth. This is because less deformed smaller raindrops make a



(a)



(b)

Figure 1: Specific attenuation at elevation angles of 23 and 55 degrees and some rainfall rates in Nigeria. - - - Vertical polarization ___ Horizontal polarization).

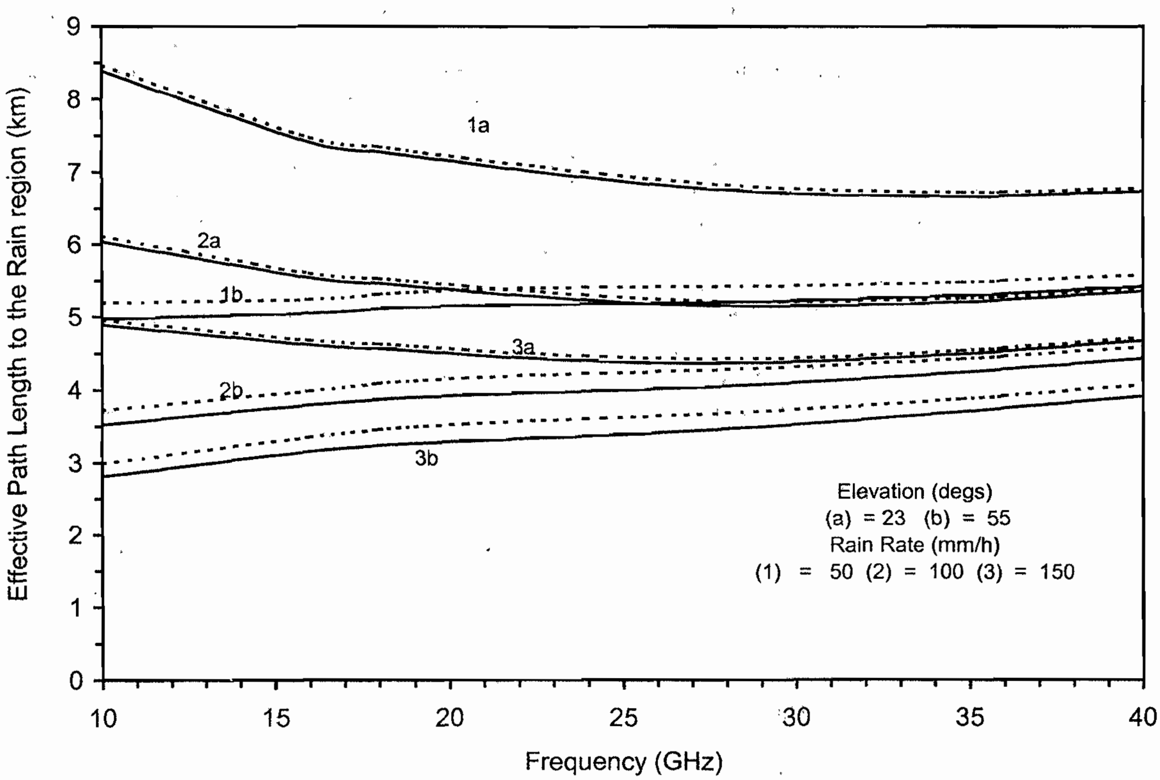


Figure 2: Frequency characteristics of the effective path length to the rain region at some rain rates and elevation angles of (a) 23^0 and (b) 55^0. - - - Vertical Polarization ___ Horizontal Polarization

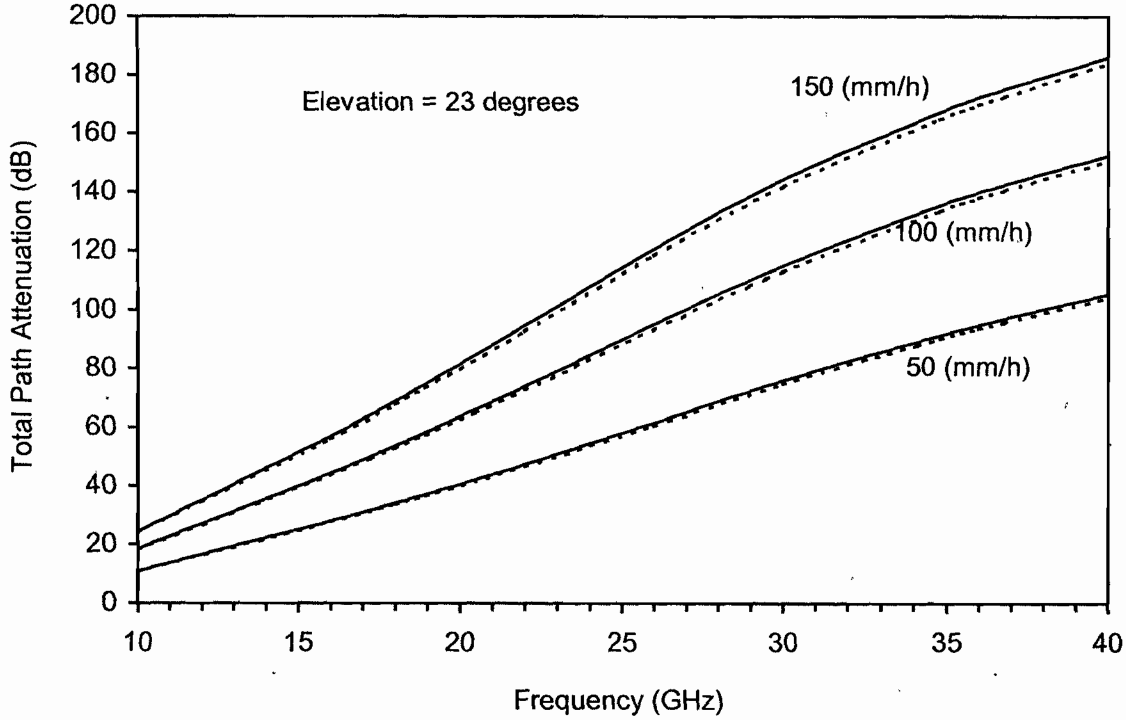


Figure 3: Frequency characteristics of the slant path (total) attenuation at some rainfall rates and elevation angle of 23^0. - - - Vertical Polarization ___ Horizontal Polarization

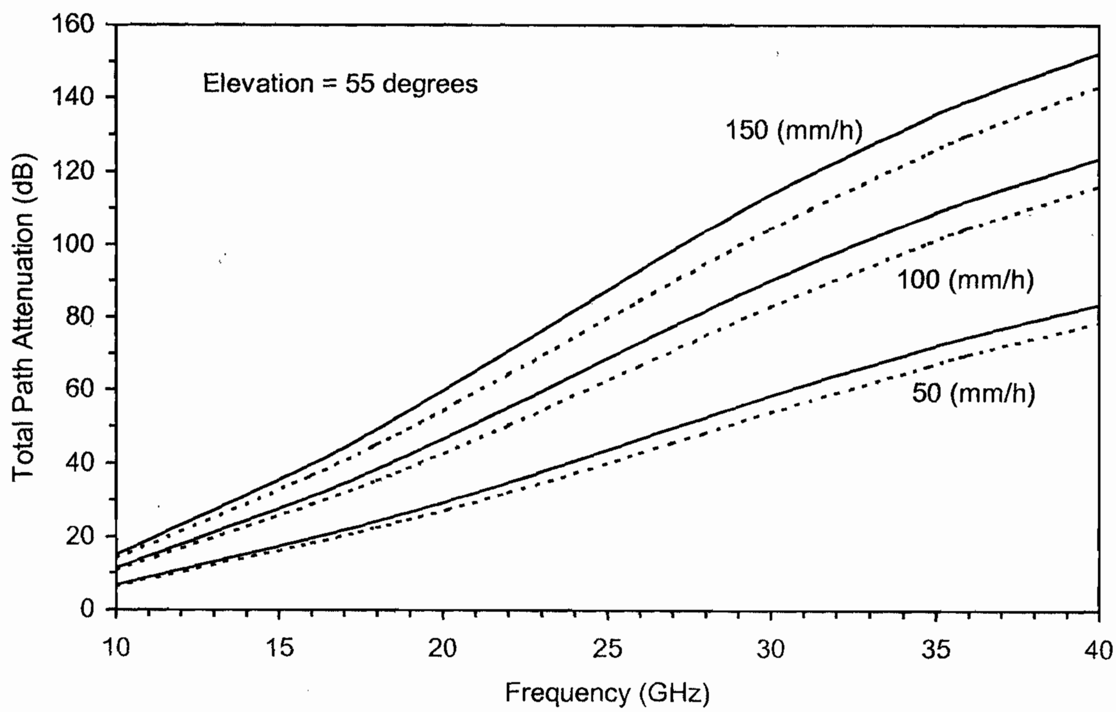


Figure 4: Frequency characteristics of the slant path (total) attenuation at some rainfall rates and elevation angle of 55^0. - - - Vertical Polarization ___ Horizontal Polarization

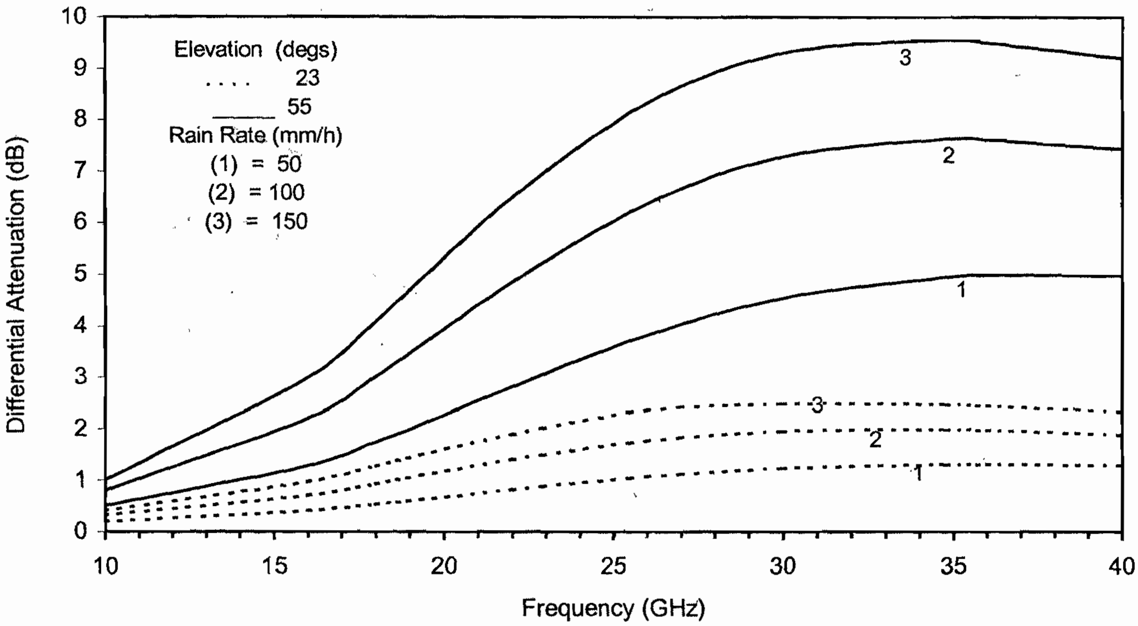


Figure 5: Frequency characteristics of the differential attenuation at some rainfall rates and elevation angles of 23^0 and 55^0 respectively.

greater relative contribution to the total attenuation as frequency is raised and at high altitudes where raindrop canting is less.

4. CONCLUSIONS

This work has examined the effect of the direct calculation of the scattering parameters and the use of the new ITU-R Rec. P. 618-8 [10] on the calculation of attenuation exceeded on earth-space propagation paths at two elevation angles in Nigeria. The results obtained using these approaches show that the attenuation on the earth-space link in Nigeria could be underestimated by as much as 36 dB at a rain rate of 150 mm/h depending on the path elevation angle when the attenuation-rain rate power law and the ITU-R Rept. 564-4 [13] are used. Some results are presented for the scattering amplitude functions and the propagation constant at elevation angles of 23^0 and 55^0, two angles used frequently for satellite communication in Nigeria. The parameters of a power-law relationship between differential propagation constant and rain rate, which could be used in the calculation of cross-polarization discrimination, are also presented.

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