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Analysis of Selected Earth-Space Rain Attenuation Models for a Tropical Station

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Abstract

The restrained use of millimeter bands is due to severe rain attenuation. Attenuation is caused when rain cells intersects radio wave's propagation path; resulting in deep fades. The effect of rainfall is more severe in tropical regions characterized by heavy rainfall intensity and large raindrops; hence, rain attenuation analyses are essential to study rain fade characteristics for use in earth-space link budget analysis, for outage prediction resulting from rain attenuation. Tropical regions are particularly challenged with signal outage, necessitating the formulation and development of suitable prediction model(s) for the region. Therefore, extensive knowledge of the propagation phenomena mitigating system availability and signal quality in these bands are required. Daily rainfall data were collected from the Nigerian Meteorological Services for Lagos for spanning January to December 2010. Results showed that although, the ITU-R model out-performed the other prediction models under consideration, none of prediction models matched the measurement data.

Keywords: *rain rate, attenuation, slant path, prediction models, tropics*

1. Introduction

At higher frequencies, rainfall and noise induced by atmospheric gases becomes a serious source of attenuation for microwave communications [1]. The result of these is evidenced in earth-space microwave signals' amplitude fading, scintillations, depolarization, and receiver antenna noise [2]. Attenuation is caused when rain cell(s) intersects the radio wave's propagation path; resulting in deep fades as the rain cell(s) occupies a large section of the Fresnel's ellipsoid between the transmitter and the receiver [3]. Attenuation experienced in tropical areas is caused by considerably higher rainfall rates and larger raindrop size as compared to other parts of the world [4]. It becomes particularly severe at frequencies higher than 10 GHz, especially for small aperture antennas. This phenomenon is particularly pronounced in areas with very high rainfalls, especially in tropical and equatorial regions [1].

Attenuation of electromagnetic waves by rain is a major impediment for telecommunications engineers and researchers, and signal attenuations in tropical regions are often due to degradations by hydrometeors such as rain, hail, cloud, and melting layer. These can cause several problems, such as signal fading, depolarization and co-channel polarization due to scattering along the slant path.

Rain attenuation modelling on satellite paths has been vigorously researched for over four decades. Slant path models are generally categorized into two:

1. Mathematical models, which attempt to define the physics of the process and model, the constituents of storm cells, etc., and
2. Empirical approaches, which are mainly based on real-time measurements with simplified assumptions.

As a result of inadequate global information on many of the physical inputs necessary to provide accurate results using mathematical and empirical models, the latter seem to be used most often and with consequent better results. Although theoretical and experimental studies of rain attenuation can be found in many literatures, the measured rain attenuation data is still insufficient in order to estimate the link within the individual spot beam. Most of the studies carried out in developed countries have employed the use of satellite beacon experiments, whereas tropical regions are being faced with signal outage which calls for the need to employ the most suitable model or rather, develop absolute prediction model for the tropical region.

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The effect of rainfall as an influential hydrometeor will be investigated on Ku band signals. Applicable rain attenuation models will be considered for this investigation and the most suitable for this region will be determined. The rain attenuation depends on the frequency, elevation angle, polarisation, temperature, size distribution of raindrops, and on their fall velocity. The frequency dependence of the specific rain attenuation can be obtained from ITU-R. P.838-3 [5]. Rain cell diameters are known to decrease with increasing rain rates and majority of the rain attenuation prediction models of are formulated with data from temperate regions where solid precipitation is common. Hence, there is need to supplement the meager available data in the tropical regions in view of the importance accorded it in the classical picture of global electrification [6]. The results of data analysis carried out and reported by [7] suggests that the average fade duration is inversely proportional to the fade depth, contrary to previous reported studies undertaken by Qing and Allnutt [8]. Rainfall type for tropical and sub-tropical regions had been classified as stratiform, convective, monsoon precipitation and tropical storm [9].

The problem with satellite communication is the inability to guarantee communication during rainfall or when the line of sight is obstructed [10]. The restrained use of millimeter bands for commercial operations is due to severe rain attenuation. Attenuation experienced in tropical areas is caused by considerably higher rainfall rates and bigger size of raindrops compared to other parts of the world [11]. Since the Ku frequency band (14/12 GHZ) has shown serious signs of depletion, research activity have since been directed towards the full utilization of the Ka band (30/20 GHz), while the V band (50/40 GHz) is being considered for applications in the near future [14]. Utilization of higher frequency bands such as the Ku band for satellite communication provides a number of important benefits. It relieves congestion in the lower frequencies which are shared with terrestrial links; it exploits the larger bandwidths available at higher frequencies and provides cheaper implementation of spectrum conservation techniques and a more efficient use of the geostationary arc. However, the severity of atmospheric impairments (especially due to rain) on radio wave propagation increases with the increase in frequency. Therefore, extensive knowledge of the propagation phenomena affecting system availability and signal quality in these bands are required.

Rain fading channel is a function of frequency, elevation angle, polarization angle, rain intensity, raindrop size distribution and rain temperature [10]. For temperate regions, rain attenuation increases inversely with elevation angle due to large rain cell size while for tropical regions, attenuation is directly proportional to elevation angle for the same rain rates; this necessitates the need for modeling the propagation factors for tropical regions [3]. Again, attenuation increases with rain rate and frequency in tropical regions; with vertical polarization producing less attenuation than horizontal polarization at millimeter wave bands [4]. According to ITU-R BO.791 [15], linear polarization is better suited for atmospheric propagation effects than circular polarization, because circular polarization is more susceptible to propagation impairments than linear polarization for high rainfall rates (greater than 12.5 mm/h) and low angles of arrival. Furthermore, vertically polarized signals present best performances when linear polarization is employed. However, this disadvantage of circular polarization may not be significant if compared with linear polarization transmission at or near 45° elevation [13].

1.1. An Overview of Selected Rain Attenuation Prediction Models

The ITU-R model is the model against which all emerging rain attenuation prediction models are tested for conformity and reliability. However, results from some recent researches have suggested that some ITU-R models may not necessarily be best suited or most reliable for all frequencies or in all geographical areas [14-17].

1.1.1. Simple Attenuation Proposed Model

The Simple Attenuation Model (SAM) [18] is one of the most widely used proposed slant path attenuation prediction models. It incorporates the individual characteristics of the stratiform and convective types of rainfall and utilizes the point rainfall rate at the ground for the calculation of the attenuation time series, as follows:

$$A = \gamma \, L_S; \; R_{\%p} \leq 10 \;\; (mm/hr) \tag{1}$$

$$L_S = \frac{H_R - H_S}{\sin\theta} \;\; (km) \tag{2}$$

In convective rainstorms, when $R > 10mm/hr$, the effective rain height, H_R depends on the rain rate. This is because strong storms push rain higher into the atmosphere, and thereby lengthening the slant path [9].

To determine the slant path attenuation, a modified value of effective path length must be used, as follows:

$$A = \gamma \frac{1 - \exp\left[-\gamma b \ln(\frac{R_{\%p}}{10})\right] L_S \cos\theta}{\gamma b \ln(\frac{R_{\%p}}{10}) \cos\theta}; \; R_{\%p} > 10\text{mm/hr} \quad (3)$$

Where the empirical constant $b = 1/22$;

Based on measurement data, the following empirical expressions for effective rain height H_R were derived:

$$H_R = \begin{cases} H_0 \; ; R \le 10 mm/hr \\ H_0 + \log\left(\frac{R}{10}\right); R > 10 \; mm/hr \end{cases} \quad (4)$$

H_R (km) is the rain height, L_S (km) is the slant path up to rain height, H_0 (km) is the $0^0 C$ isotherm height above mean sea level and its value can be obtained from the isotherm chats of ITU-R. P.839-3 [19].

1.1.2. ITU-R Recommendation P. 618-11 Model

ITU-R Recommendation P. 618-11 [20] rain attenuation prediction model is the most widely accepted international method for the prediction of rain effects on satellite communication systems. This model predicts the long-term statistics of the slant-path rain attenuation at a given location for frequencies up to 55 GHz. Rainfall rate at 0.01% of the time ($A_{0.01}$) is the major input to this model, and the subsequent resulting attenuation at 0.01% ($A_{0.01}$) was used as the basis for estimating the attenuation exceeded at other percentages ($A_{\%p}$). However, the ITU-R model assumes a constant rain height and a fixed reduction factor in calculating the slant path. This is not a good choice for the tropical and equatorial locations, because effective rain height, H_R is known to vary with rain intensity [21].

The step-by-step procedures for calculating rain attenuation cumulative distribution function over the satellite link are as follow can be found at the ITU website and several other researshers works. Tthe effective path length L_{eff} (km) through rain is obtained by multiplying the horizontally adjusted slant path by the vertical reduction factor, and is expressed as:

$$L_{eff} = L_{h0.01} r_{v0.01} \; (km) \quad (5)$$

The predicted slant path attenuation exceeded for 0.01% of an average year is:

$$A_{0.01} = \gamma_{0.01} L_{eff} \; (dB/km) \quad (6)$$

The predicted attenuation exceeded for other percentages $\%p$ of an average year may be obtained from the value of $A_{0.01}$ by using the following extrapolation according to ITU-R P. 618-11 [20]:

$$A_{\%p} = A_{0.01}\left(\frac{p}{0.01}\right)^{-\left[0.655 + 0.033\ln p - 0.045\ln A_{0.01} - z\sin\theta(1-p)\right]} (dB) \quad (7)$$

Where p is the percentage probability of interest and z is given by:

$$For\ \ p \geq 1.0\%, z = 0 \tag{8}$$

$$For\ p < 1.0\%,\ z = \begin{cases} 0;\ for\ /\phi/ \geq 36^0 \\ z = -0.005(/\phi/ - 36)\ \ for\ \theta \geq 25^0\ and /\phi/ < 36^0 \\ z = -0.005(/\phi - 36/) + 1.8 - 4.25\sin\theta,\ \ for\ \theta < 25^0\ and /\phi/ < 36^0 \end{cases} \tag{9}$$

1.1.3. Synthetic Storm Technique

The synthetic storm technique (SST) was first introduced by Drufuca [23] for terrestrial radio link based on the concept of the Hamilton-Marshall "synthetic storm", which he defined as a description of the rain pattern in terms of rainfall rate as a function of distance along a line in the direction of storm motion. The SST input data was obtained from a rain gauge record by converting the raw data of rainfall rate versus time into a function of distance by employing a storm translation velocity to transform time to distance.

The synthesized storms express rainfall rate, R as a function of distance, x by approximating the statistical properties of a large number of synthetic storms with the corresponding statistical properties of real storms using a statistical approach known as the “Taylor’s hypothesis”. The rainfall rate was the converted to specific attenuation, γ using Equation (7).

The attenuation over a distance L was then calculated by Integrating $\gamma(x)$ over an interval of length L using:

$$A(x_0, L) = \int_{x_0}^{x_0+L} \gamma(x)\, dx\ (dB) \tag{10}$$

Attenuation was calculated as a function of time for this storm from Equation (19) with L set at 5 miles and x_0 changing at a rate of 14 miles/hr; with values of k and α selected at 11.2 GHz.

SST is a model aimed at converting time into distance and rain rate time series into rain attenuation time series. The SST is a useful tool to obtain rain attenuation series from rain rate series for any satellite radio link with elevation angle above 10°, at any frequency and at polarization from any site, as long as the spatial-temporal field isotropy holds. The required input into the model includes advection velocity of rain cells, the slant path length and the rain rate time series of the location of interest.

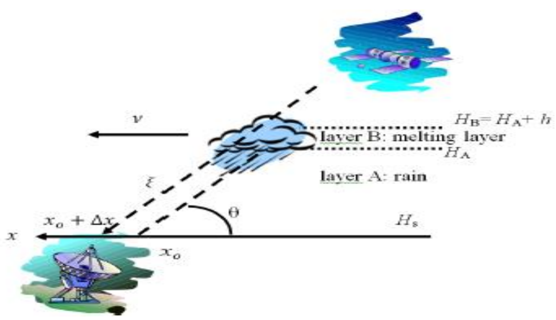

Figure 1. Schematic of Slant Path Rain Structure for SST [29]

Layer A is characterized by homogenous rain precipitation of rate R_A while layer B is representative of ice with apparent rain rate R_B. Their relationship is described as:

$$R_B = 3.134 R_A \; (mm/hr) \tag{11}$$

The slant path rain attenuation from the specific attenuation at a point is given as:

$$A = \int_0^{L_A} K_A R^{\alpha_A} (x_0 + \Delta x_0, \zeta) \delta\zeta + K_B (3.134)^{\alpha_B} \int_{L_A}^{L_B} R^{\alpha_B} (x_0, \zeta) \delta\zeta \; (dB) \tag{12}$$

Where ζ is the distance measured along the satellite slant path, k and α are correlation coefficients dependent on satellite signal frequency, polarization, elevation and rain drop size distribution; these can be obtained from ITU-R P.838-3 [5] for water at 20 ^oC and Parson's law drop size distribution for 0 ^oC from Magorri [30].

The radio path lengths L_A and L_B are defined as:

$$L_A = (H_A - H_S)/\sin\vartheta \tag{13a}$$

$$L_B = (H_B - H_S)/\sin\vartheta \tag{13b}$$

However, Matricciani [25] discovered the probability distribution function generated by SST can reliably be modeled by the relationship:

$$A = [C_0 K_A R^{\alpha_A} + (1 - C_0) K_B (3.134R)^{\alpha_B}] L^m \; (dB) \tag{14}$$

L (km) is the average long term slant path in the precipitation (and not an equivalent path length because it does not depend on radio electrical parameters) as given by ITU-R. P.839-3 [19]. It is defined by the relationship [24].

$$L = L_A + L_B \tag{15}$$

The value of the parameter *m* is computed from:

$$m = {}^{\Delta A / A} \big/ {}_{\Delta L / L} \tag{16}$$

The integration constant:

$$C_0 = L_A / L = \frac{0.4}{H_B - H_S} \tag{17}$$

Where H_B is the height of the top limit of the melting layer and 0.4 km is assumed melting layer thickness.

1.1.4. Bryant Proposed Model

The Bryant proposed model [31] employs the concept of effective rain cell and variable rain height to compute the distribution of rain attenuation at a location of interest. It uses measured rain rate exceedances with rain rate, the station height above mean sea level and earth station's elevation angle as the inputs to compute the attenuation exceeded for the station of interest. The following procedures are steps involved in such computation:

Step 1: Calculate the probability factor (PF) parameter:

$$PR = 1 + \frac{2}{\pi} \frac{L}{D} \tag{18}$$

Where D is the rain cell diameter defined as:

$$D = 340 R_p^{-1.2} \tag{19}$$

The horizontal projection, L is:

$$L = \frac{h_r}{\tan\theta} \tag{20}$$

Step 2: Calculate the rain height, h_r.

$$h_r = 4.5 + 0.0005 R_p^{1.65} (km) \tag{21}$$

Step 3: Compute the attenuation, A_s along the slant path:

$$A_s = 1.57 D_m k_n \gamma_p \frac{L_s}{\xi L + D} (km) \tag{22}$$

Where L_s (the slant path length) and γ_p (the specific attenuation) are as defined in Equation (5) and (7) respectively. k_n is the number of cells.

$$D_m = (\frac{2}{\pi}) D \, (km) \tag{23}$$

$$k_n = \exp(0.007 R_p) \, (km) \tag{24}$$

$$\xi = \begin{cases} \frac{1}{\sqrt{2}} \exp(\sin\theta) & \theta \le 55^0 \\ 1.1 \tan\theta & \theta > 55^0 \end{cases} \tag{25}$$

2. Research Method

2.1. Experimental Setup and Data Collection

Daily rainfall data were collected from the Nigerian Meteorological Services (NIMET) for Lagos, Nigeria for a period of one year (January to December 2010). Lagos is a coastal station in the rain forest area in the South-Western tropical Nigeria with an altitude of 380 m above mean sea level. It occupies the geographical latitude of 6.35^0N and longitude 3.2^0E. It is bordered on the south by the Atlantic Ocean, and with mean annual rainfall of 1425 mm. It experiences all the rainfall types as other tropical and sub-tropical regions as earlier described [32].

Measurement setup at the meteorological station consists of the buck-type rain gauge. The setup also comprises indoor and the outdoor units. The indoor unit consists of spectrum analyzer, field strength meter and a satellite tracker (digital receiver). The obtained parameters like signal strength during clear air and other precipitations can then be recorded and analyzed. Rain rate data is collected from the weather station in the same geographical location where beacon signal from Eutelsat W4 satellite at a downlink frequency of 12.437 GHz was monitored and recorded. The outdoor equipment is a dish antenna with low noise block converter (LNBC). The output of the LNBC was passed through a 3 dB splitter and fed into a digital receiver and a spectrum analyzer. The spectrum analyzer was set to 10.982 GHz and the video filter output of the spectrum analyzer was recorded and stored in a computer at a sampling rate of 1.0 Hz, using a data logger. A buck-type rain gauge rain gauge was installed at the measurement site to record the rain rate.

3. Results and Analysis

Presented in Figure 2 is the scatter plot from the measurement data and the four rain attenuation prediction models under investigation. From Figure 2, curves of best fit were plotted for each of the models of interest and the measured data as shown in Figure 3. These cumulative distributions plots of attenuation exceeded due to rainfall presents vivid evidential basis for the performance testing of the various prediction models.

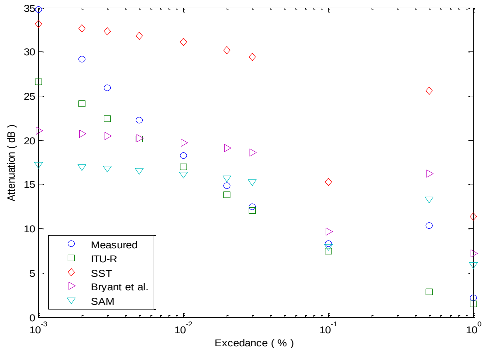

Figure 2. Scatter Plot for Attenuation

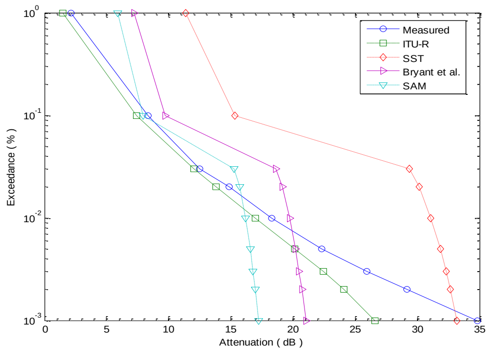

Figure 3. Comparison of Attenuation CDs

Table 1. Comparison of % Std. deviation, Mean square and RMS errors

$\%p$	μ_{ei}				σ_{ei}				D_{ei}			
	ITU-R	SST	Bry't	SAM	ITU-R	SST	Bry't	SAM	ITU-R	SST	Bry't	SAM
0.001	-0.0235	-0.0046	-0.0395	-0.0504	0.0142	1.5601	0.7944	0.6075	0.0188	1.5601	0.7934	0.6054
0.002	-0.0174	0.0119	-0.0290	-0.0418	0.0213	1.5601	0.7948	0.6081	0.0123	1.5600	0.7943	0.6067
0.003	-0.0135	0.0246	-0.0209	-0.0352	0.0239	1.5599	0.7951	0.6085	0.0198	1.5597	0.7948	0.6075
0.005	-0.0096	0.0428	-0.0094	-0.0257	0.0257	1.5595	0.7953	0.6090	0.0239	1.5589	0.7953	0.6085
0.01	-0.0074	0.0698	0.0077	-0.0117	0.0265	1.5585	0.7953	0.6094	0.0254	1.5570	0.7953	0.6093
0.02	-0.0072	0.1030	0.0288	0.0056	0.0265	1.5567	0.7949	0.6095	0.0256	1.5533	0.7943	0.6095
0.03	-0.0037	0.1350	0.0491	0.0222	0.0272	1.5543	0.7939	0.6091	0.0270	1.5484	0.7923	0.6087
0.1	-0.0721	0.1480	0.0573	0.0290	0.0666	1.5531	0.7933	0.6089	0.0982	1.5460	0.7912	0.6082
0.5	-0.0109	0.0834	0.0164	-0.0046	0.0252	1.5579	0.7952	0.6095	0.0228	1.5556	0.7950	0.6095
1.0	-0.0314	0.4222	0.2313	0.1716	0.0151	1.5019	0.7610	0.5849	0.0348	1.4414	0.7250	0.5592

Note: - Bry't = Bryant

Although none of the models matched the measurement, the ITU-R model despite underestimating the measurement all through, it however follows the trend with its best performance at 0.03% of the time; after which it began to further deviate from the measured, exhibiting the worst performance at 0.001%. The other (proposed) models on the other hand overestimated the measurement at all rain rates (see Figure 4), they however overestimated at various percentages of the time (except at $p = 0.001\%$ for SST; at $0.001\% \leq p \leq 0.005\%$ for Bryant; and at $0.001\% \leq p \leq 0.02\%$ for SAM). These are clearly shown in Table 1.

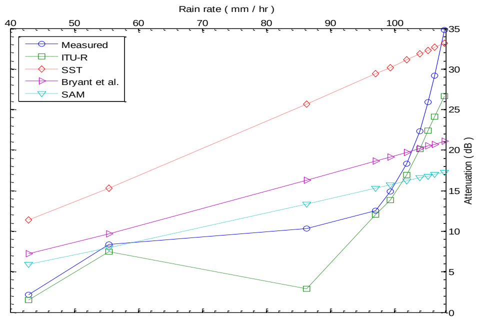

Figure 4. Comparison of Predicted vs. Measured Attenuation for Lagos

Generally, the ITU-R model out-performs the other prediction models under consideration, even though none of them matched the measurement data; this is in accordance to the evaluation procedures adopted for comparison of prediction methods as enunciated by the ITU-R P.311-13 [33], which recommended that prediction method that produces the smallest values of the statistical parameters is the best .

4. Conclusion

Presented in this paper is performance analysis and comparison of selected rain attenuation prediction models for Lagos, a tropical station. Overall, the ITU-R model out-performs the other prediction models under consideration, even though none of them matched the measurement data. However, specifically at 99.999% of availability, which translates to an outage of not more than 5.26 minutes/year, the SST exhibited the best performance. To sum up, all the rain attenuation prediction models considered in this paper will require further modifications to reliably predict attenuation exceedances for Lagos.

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