An Improved Slant Path Attenuation Prediction Method in Tropical Climates

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Abstract. *An improved method for predicting slant path attenuation in tropical climates is presented in this paper. The proposed approach is based on rain intensity data* $R_{0.01}$ *(mm/h) from 37 tropical and equatorial stations; and is validated by using the measurement data from a few localities in tropical climates. The new method seems to accurately predict the slant path attenuation in tropical localities, and the comparative tests seem to show significant improvement in terms of the RMS of the relative error variable compared to the RMS obtained with the SAM, Crane, and ITU-R prediction models.*

Keywords

Convective rain, Crane model, link budgeting, rain height, SAM, ITU-R model, tropical climates.

1. Introduction

Rain-induced attenuation is the most serious technical issue faced by radio engineers at frequencies above 10 GHz. The attenuated signal translates to a reduction in the reliability, availability and performance of the communications link [1]. The signal attenuation due to rainfall is most severe in tropical and equatorial climates due to the prevalence of convective rainfalls. Tropical climates have heavy rainfall intensities and large raindrops. The rain cell diameters are also larger than the wavelengths of the transmitted signals, thereby resulting in scattering and absorption [2]. The major problem associated with the ITU-R model [3] is that, it assumes a constant rain height and a fixed reduction factor in calculating the slant path, which results in poor estimation [4]. Observations have shown that the effective rain height increases with increasing rain rate in convective rainfalls [1], [2].

2. A Brief Survey of Slant-Path Attenuation Prediction Models

Quite a large number of slant path attenuation prediction models can be found in the literature, based upon the use of geophysical data (surface point rain rate, the point-to-path variation in rain rate, rain height and specific attenuation provided the surface point rain rate is known). Most of the slant path attenuation prediction models are either empirical or semi-empirical and their accuracy is dependent on the accuracy of the measured rain rate cumulative distribution. Some of these models, as reported in [4], include the Crane Global model [2], ITU-R P.816-10 model [3], simple attenuation model (SAM) [5], Bodtmann and Ruthroff model [6], Garcia Lopez model [7], Asoka Dissanayake (DAH) model [8], and Bryant et. al model [9]. However, only Bryant et.al model provided avenue for the breakpoint analysis in attenuation exceedance [4]. It also accounts for multiple rain cells in the slant path, and requires the point rain-rate for its prediction.

Some valuable modifications were proposed in [4] to improve the ITU-R P.816-10 model for use in the tropical climates. These modifications are based on the properties that in the tropics (i) the accumulation time factor at the breakpoints is an invariant, (ii) for elevation angles < 60° and at high rain rates multiple rain cells intersect the slant path. The rain rate statistics were first used to estimate the breakpoint rain rate and its exceedance probability; which in turn is used for computing the corresponding breakpoint attenuation. However, it was found in this study that, the break-point attenuation so obtained seems to be too exaggerated. For example, the break-point attenuation value used for computing the attenuation exceedance in Malaysia was 34 dB, as reported in [4]. On the contrary, beacon observations made in Malaysian tropical climates have shown that experimental values of break-point attenuation range from 17.5 to 22 dB [10], [11].

The Synthetic Storm Technique (SST) [12] is a powerful prediction tool that can generate rain attenuation time series using rain rate time series, collected at a site with a rain gauge, as the input. The SST can generate attenuation time series at any frequency and polarization, and for any slant path above about 10°, as long as the hypothesis of isotropy of the rainfall spatial field holds, in the long term. However, the SST model has not been included in the comparative analysis presented in Section 4 because we do not have wind speed measurements.

The three most popular slant path attenuation prediction models (Crane model [2], ITU-R [3] and SAM [5]) have been compared with the performance of the proposed technique in this paper. However, the detailed descriptions of these models are not presented, since the materials can be found in the literature. The ITU-R model [3] predicts the long-term statistics of the slant-path rain attenuation at a given location for frequencies up to 55 GHz. Note that the rainfall rate at 0.01 % ($R_{0.01}$) is the principal input in this model, and also the calculated attenuation at 0.01 % ($A_{0.01}$) is used as the basis for estimating the attenuation exceeded at other percentages. Refer to reference [3] for details of the ITU-R prediction method. The major limitation of ITU-R model is the constant rain height and fixed reduction factor assumptions in calculating the slant path. In reality, effective rain height is not constant; rather it depends on rainfall intensity [11]. The ITU-R model is only applicable in temperate climates; while it is poorly representative of equatorial and tropical climates, as reported in [4] and [11].

SAM [5] is a popular model for predicting the attenuation exceedance along the slant-path. It incorporates the individual characteristics of stratiform and convective types of rainfall and utilizes the point rainfall rate at the ground to calculate the attenuation time series. SAM requires the point rain-rate to predict the path attenuation; and it assumes that at high rainfall rates, the rain height has linear logarithmic relationship with rainfall rate. Crane model [2] is an empirical model which uses the point rain-rate as the major input. It was developed using the geophysical observations of the: (i) point rain rate statistics, (ii) horizontal structure of rainfall, and (iii) vertical temperature structure of the atmosphere. The most important of these three parameters is the point rain rate statistics R. Therefore the model's inputs were supposedly more comprehensive, compared to the first two models.

Unlike in ITU-R model, where the rain height is assumed to be constant at 0.01 %, each of SAM and Crane model expresses the rain height as a function of complete rainfall distribution R. However, SAM and Crane models are both too computationally intensive, due to utilization of too many input parameters for their computations/simulations. Consequently, the errors arising from these two models are mainly due to computational complexity. Furthermore, it can also be concluded that Crane model is not suitable for predicting the slant path attenuation on vertically oriented radio waves (i.e. 90° elevation paths).

3. Proposed Method Description

According to the ITU-R [3], the slant path attenuation $A_{0.01}$ (dB) exceeded at 0.01 % is given by

$$A_{0.01} = k\,(R_{0.01})^{\alpha}\ \ (dB/km).\,L_{eff}\,(km)\ \ \text{dB} \qquad (1)$$

Parameters k and α can be obtained from the ITU-R 838-3 [13], depending on frequency and wave polarization as follows

$$k = \left[k_H + k_V + (k_H - k_V)\cos^2\theta\cos 2\tau\right]/2\ ,$$

$$\alpha = \left[k_H\,\alpha_H + k_V\,\alpha_V + (k_H\,\alpha_H - k_V\,\alpha_V)\cos^2\theta\cos 2\tau\right]/2k \qquad (2\text{ a, b})$$

where τ is the polarization tilt angle relative to the horizontal (τ = 45°for circular polarization).

The effective slant path L_{eff} is generally given by

$$L_{eff} = \frac{H_R - H_S}{\sin(\theta)}.r_H \qquad (3)$$

where H_R is effective rain height (km), H_S *is* station mean altitude above the sea level (km), θ is elevation angle (degrees), and r_H is reduction factor.

Equation (3) is only valid for elevation angles above 5° (because of the Earth curvature). It is possible to extract effective rain height from (3), for θ degrees elevation path and known altitude value H_S, as follows

$$H_R = \frac{L_{eff}\ .\sin(\theta)}{r_H} + H_S \quad [\text{ km}]. \qquad (4a)$$

For a special case of a 90° elevation path (when sin (θ) = 1.0), equation (4a) can further be simplified

$$H_R = \frac{L_{eff}}{r_H} + H_S \qquad [\text{km}]. \qquad (4b)$$

Note that r_H accounts for the non-uniformity of rain rate in the horizontal direction. The effective rain height takes into account the effects of the non-uniform vertical structure of rainfall. The effective slant path can be more conveniently estimated from the ratio of measured attenuation to rain rate, at equal probability level, as follows

$$L_{eff} = \frac{A_{0.01}}{k\,(R_{0.01})^{\alpha}}\ . \qquad (5)$$

The proposed prediction method was developed from large experimental databanks of rain intensity data $R_{0.01}$ and effective slant path L_{eff} from 37 tropical and equatorial stations. The scatter plots of effective slant path against rain rate are shown in Fig. 1. A curve fitting technique was then employed to obtain the empirical expression which relates the two variables. The expression obtained for effective slant path (see (6)) was in turn utilized in the general expression for calculating slant path attenuation exceeded at 0.01 % (see (1)).

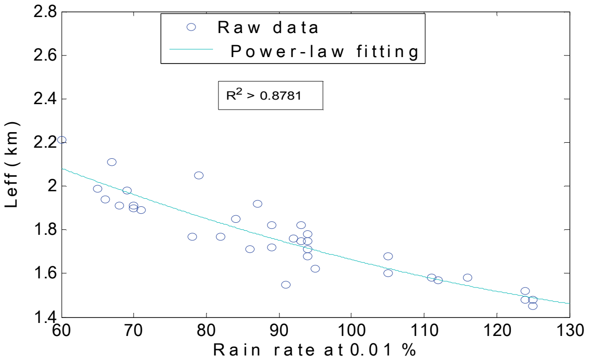

Fig. 1. Scatter plots of L_{eff} against $R_{0.01}$.

Regression analysis of the experimental data has shown that L_{eff} is related to $R_{0.01}$ by the following simple power law

$$L_{eff} = 18.1741\, R_{0.01}^{-0.36}\ ,\ \left(R^2 > 0.8781\right). \tag{6}$$

R^2 denotes the coefficient of determination. A rough rule of thumb is that if $R^2 > 0.8$, then the fit is good. The value of R^2 is 0.8781, which therefore imply good statistical reliability and high predictive accuracy.

An empirical expression for calculating $A_{0.01}$ is proposed by substituting (6) into (1) as follows

$$A_{0.01} = k\left(R_{0.01}\right)^{\alpha} .\ 18.1741\left(R_{0.01}\right)^{-0.36}$$
$$= 18.1741 k \left(R_{0.01}\right)^{\alpha - 0.36} . \tag{7}$$

For other percentages, p, of an average year, in the range 0.001% to 1.0 %, the attenuation can be estimated by the following extrapolation equation [14]:

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-\left[0.72 + 0.035 \ln p - 0.06 \ln A_{0.01} - \beta \sin\theta (1-p)\right]} \tag{8}$$

where $$\beta = -0.005\left(|\varphi| - 36\right). \tag{9}$$

As seen in (6), the procedure for computing the value of L_{eff} is more convenient and straightforward; unlike in the case of ITU-R model, in which lengthy and very complex procedures are required. The proposed technique also avoids the use of the 0°C isotherm height as an input, due to the effects of seasonal variability [4], [11]. Moreover, the proposed approach only requires $R_{0.01}$ as the major physical input parameter. This is greatly advantageous since the rain rate data exceeded for 0.01 % of the time are available in the ITU-R data bank for most of the hydro meteorological zones. The rain rate data $R_{0.01}$ (mm/h), observed for 0.01 % exceedance probability and measured with a 1 minute integration time, are less variable and likely more accurate than the rain rates related to either highest or lowest time percentages [15].

4. Validation of Proposed Model

The applicability of the proposed technique (6) – (9) was evaluated with the measured data from Islamic International University of Malaysia, (IIUM), Kuala Lumpur, Malaysia [10]. The measurement period was 2 years (i.e. January 2009 to December 2010). The experimental procedures for measuring rain rate and slant path attenuation at IIUM are briefly described in this section. The proposed model is further validated with the measurement data extracted from published results reported in [11], [16] and [17] for USM (Malaysia), Lagos (Nigeria), and Rio de Janeiro (Brazil), respectively.

(a) Slant path attenuation measurement at IIUM

The receiver site for monitoring ASTRO/MEASAT-3 beacon signal level was located on the roof top of the electrical and computer engineering building at IIUM in Kuala Lumpur. The receiver antenna, an off-set parabolic antenna dish having a diameter of 2.4 m, was pointed towards MEASAT-3, situated at 91.5° E (geostationary). The specifications of MEASAT-3 transponder are given in Tab. 1. The vertically polarized Ku-band beacon signal propagating at 10.982 GHz is down-converted to an IF signal (1.232 GHz) using a low noise block (LNB) converter having a noise figure of 0.3 dB. The output at LNB was fed to a spectrum analyzer via RG-11 coaxial cable, at a sampling rate of 1 sample every 10 seconds (i.e., 10-s intervals). The output of spectrum analyzer was sent to computer via General purpose interface bus (GPIB) cable and then stored using a data logger developed by labVIEW (sampling rate of 0.1 sample/s). The dynamic range of the maximum signal strength is about 40 dB for excess (i.e. rain) attenuation. This is adequately suitable for covering the entire dynamic range of rain attenuation for this study, because maximum rain attenuation measured is 36.0 dB.

EIRP (dB-W) maximum	57	
G/T (dB/K) maximum	+14	
TWTA power (W)	120	
Channel polarization	Linear	
Frequency band (GHz)	Uplink	Downlink
	13.75 - 14.5	10.95 -12.75

Tab. 1. Specifications of MEASAT-3 transponder.

The measured data is preprocessed to eliminate fast amplitude fluctuations (i.e. scintillation effects) by using a low-pass filter (LPF) with a suitable cutoff frequency. The unattenuated beacon signal level was used to provide a reference level (in dBm), which is the average signal power received under clear-sky conditions. During rain, the attenuation was estimated by measuring the excess attenuation over the clear weather attenuation values at respective rain rates. The raw data were converted from quantization levels to beacon RSL in dBm. The availabilities of the beacon receiver for 2009 and 2010 were 95 % and 90 %, respectively.

(b) Rain rate measurement at IIUM

A Casella rain gauge was installed at the measurement site for recording the rainfall rate alongside the beacon signal path. The gauge is of tipping bucket type, the bucket size is 0.5 mm of rain (i.e. calibration is 0.5 mm per tip) and it has a diameter of 20 cm. The rain gauges has a programmable data logger for recording the time of each tip to an accuracy of 0.1 s; and the clock of the data logger was perfectly synchronized with that of the computer. Note that about 0.5-mm bucket size is recommended for tropical countries. For instance in Malaysia, 0.01 % rain rate is higher than 120 mm/h, which occurs 4 tips per minute with very good resolution. The bucket size of 0.2 mm needs more than 10 tips per minute for higher rain rate and causes error due to mechanical inertia at higher than 100 mm/h rain rate. The availabilities of the rain gauge for the corresponding years, 2009 and 2010, were 95 % and 90 %.

5. Results and Discussions

The propagation characteristics of measurement sites used for validations are shown in Tab. 2. The rainfall rate and rain attenuation cumulative distributions CDs of these measurement sites are shown in Fig. 2 and 3 respectively; while the equal probability plots 0.001% ≤ *p* 1.0% of rain rate and rain attenuation are shown in Fig. 4. As shown in Fig. 4, there is a positive correlation between attenuation and rainfall rate for the four tropical stations. For instance, at 0.001 % exceedance probability, the rainfall rates are 201 mm/h and 180 mm/h in Kuala Lumpur and Rio de Janeiro, respectively; while the corresponding attenuation values are 35.9 and 29.8 dB. The measured attenuation CDs (exceedance probability range: 0.001 % to 1.0 %) are compared with those of predictions, as shown in Figs 5 - 8.

As shown in Figs 5 - 8, the measured attenuation, at 0.001 % and 0.01 % exceedance probability, for Kuala Lumpur, Malaysia, are 35.9 dB and 24.1 dB respectively; while the corresponding predicted values are 20 and 14 dB (ITU–R method); 22.4 and 12 dB (SAM); 20.3 and 7 dB (Crane model); 25.6 and 18.4 dB (proposed method). In Lagos, Nigeria, the measured attenuation, at 0.001 % and 0.01 % exceedance probability, are 34.8 and 18.3 dB respectively; while the corresponding predictions are 32 and 20.5 dB (ITU–R method); 9.1 and 5.0 dB (SAM); 20.1 and 7.5 dB (Crane model); 42 and 20.5 dB (proposed method).

Furthermore, in Rio de Janeiro, Brazil, the measured attenuation, at 0.001 % and 0.01 % exceedance probability, are 29.8 and 19.5 dB respectively; while the corresponding predictions are 25.6 and 14.2 dB (ITU–R method); 11 and

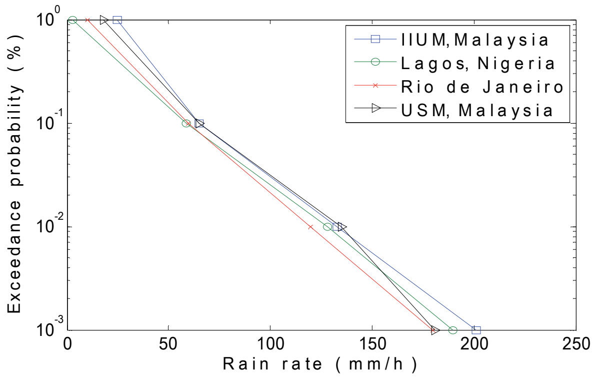

Fig. 2. Rain rate CDs.

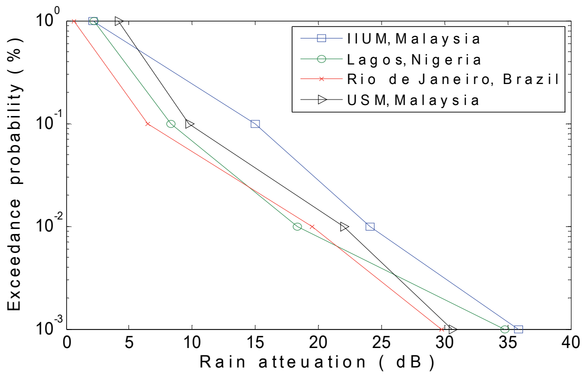

Fig. 3. Rain attenuation CDs.

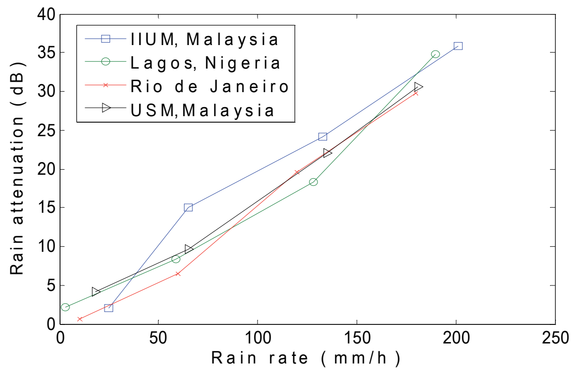

Fig. 4. Equal probability plots of rain rate and rain attenuation.

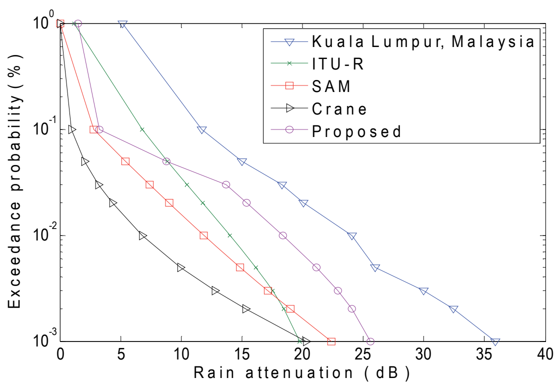

Fig. 5. Comparison of rain attenuation CDs for IIUM, Malaysia.

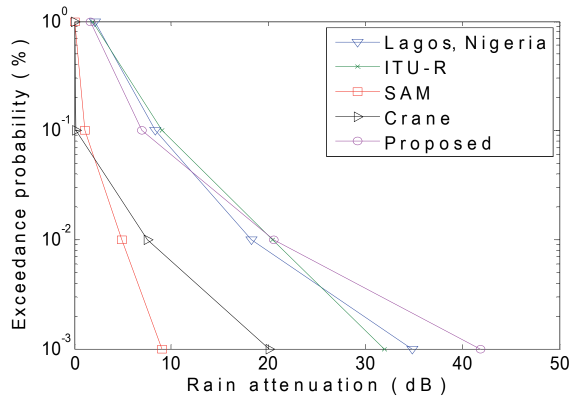

Fig. 6. Comparison of rain attenuation CDs for Lagos, Nigeria.

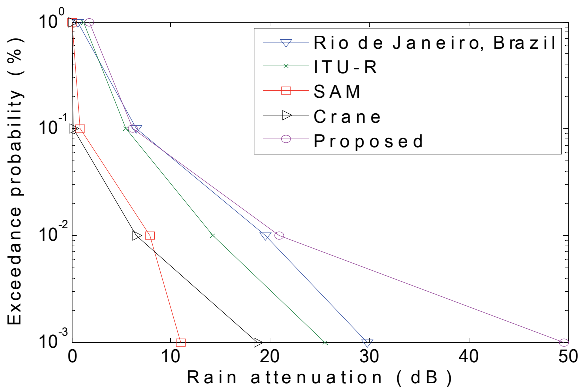

Fig. 7. Comparison of rain attenuation CDs for Rio, Brazil.

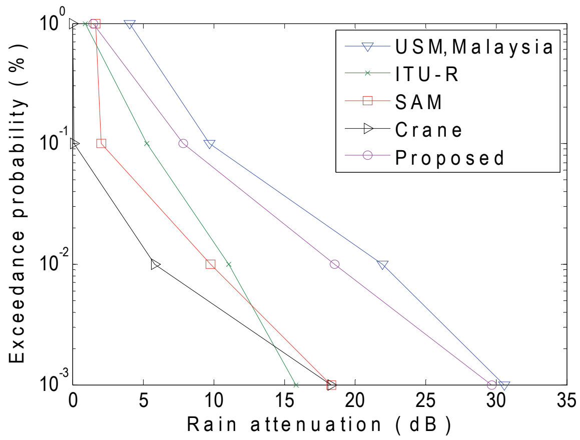

Fig. 8. Comparison of rain attenuation CDs for USM, Malaysia.

7.9 dB (SAM); 18.7 and 6.5 dB (Crane model); 49.6 and 21 dB (proposed method). In Universiti Sains Malaysia (USM), the measured attenuation, at 0.001 % and 0.01 % exceedance probability, are 30.6 and 22.0 dB respectively [10]; while the corresponding predictions are 15.8 and 11.1 dB (ITU–R method); 18.4 and 9.8 dB (SAM); 18.3 and 5.8 dB (Crane model); 29.7 and 18.6 dB (proposed method).

Based on the results presented in Figs. 5 - 8, one may generally conclude that both SAM and Crane model are not suitable for predicting slant path attenuation in the four tropical climates. SAM and Crane models largely underestimate all the measurements; with the errors ranging from 21 % to 51 %, and from 37 % to 73 % respectively. For IIUM, Malaysia (see Fig. 5), one can see that the proposed method predicted the measurements more accurately, compared to the other prediction models. For instance, at 0.001 % and 0.01 % exceedance probability, the proposed method has prediction errors of 28.7 % and 23.7 % respectively; while others have corresponding errors of 44.9 % and 42.0 % (ITU-R), 37.6 % and 88 % (SAM), and 79.7 % and 93 % (Crane). Both ITU-R and proposed models coincidentally predicted same value (20.5 dB) at 0.01 % exceedance probability for Lagos, Nigeria (see Fig. 6). However, the latter largely overestimated the measurement at 0.001 % exceedance probability with an error of 20 %; while the ITU-R model gave a more perfect prediction with only 8 % prediction error.

For Rio de Janeiro (see Fig. 7), the proposed method predicted the measured attenuation accurately at 0.01 % exceedance probability with an error of 7.7 %; while the ITU-R has an error of 27 %. But, the proposed model also largely overestimated the measurement at 0.001 % exceedance probability with a prediction error of 66 %; while the ITU-R model predicted the measurement more perfectly with an error of 14 %. And finally, the proposed method also performed excellently at USM, Malaysia (see Fig. 8). For instance, it predicted the measured attenuation with an error of 3.0 % at 0.001 % exceedance probability; compared to ITU-R model (48 % error), SAM (40 % error) and Crane model (approximately 40 % error). More so, at 0.01 % exceedance probability, the prediction error of the proposed model is 15.4 %; while those of ITU-R model, SAM and Crane model are 50 %, 55.5 % and 73.6%, respectively.

The comparison of measurement and predicted attenuation for all the four locations is summarized and presented in Fig. 9. The error, mean, standard deviation, and % RMS values for each percentage of time is shown in Tab. 3 according to Recommendation ITU-R P. 311 – 13 [18]. The RMS error is used as the metric to judge the overall fit of the prediction with the measurement. There is fairly a good agreement between the measurements and predictions of the proposed method, as shown in Tab. 3. For each percentage of time, the ratio of predicted attenuation, A_p (dB), to measured attenuation, A_m (dB), for each radio link is calculated as follows:

$$S_i = A_{pi} / A_{mi} \tag{10}$$

where S_i is the above ratio calculated for the i-th radio link, and the test variable is calculated as:

$$V_i = \ln S_i \left(A_{m,i}/10\right)^{0.2} \quad A_{m,i} < 10\,\text{dB}, \tag{11}$$

$$V_i = \ln S_i \quad\quad A_{m,i} \geq 10\,\text{dB} . \tag{12}$$

The procedure is repeated for each percentage of time, and then the mean μ_V, standard deviation σ_V, and RMS value ρ_V, of the V_i values are calculated for each percentage of time:

$$\rho_V = \left[(\mu_V)^2 - (\sigma_V)^2\right]^{\frac{1}{2}} . \tag{13}$$

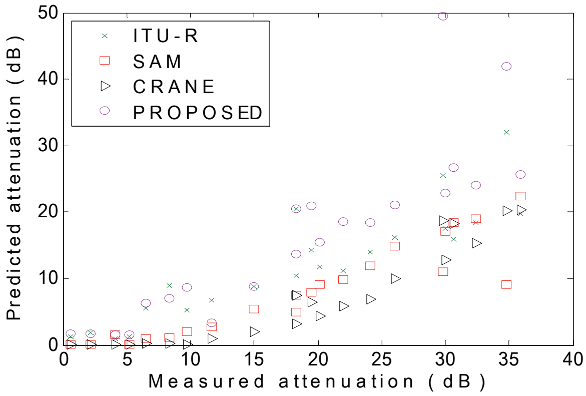

Fig. 9. Comparison of measured and predicted attenuation.

Station	Altitude (m)	Freq (GHz) / Polarization	Elevation (degs)	$R_{0.01}$ (mm/h)
IIUM, Kuala Lumpur, Malaysia, 3.3^0 N; 101.7^0 E	21.950	10.982 Vertical	77.400	133.000
Lagos, Nigeria; 7.17^0 N; 5.18^0 E	38.000	12.675 Vertical	42.500	128.140
Rio de Janeiro, Brazil; 22.92^0 S; 43.5^0 W	10.000	12.000 Vertical	53.900	128.000
USM, Malaysia 5.17^0 N;100.4^0 E	57.000	12.255 Vertical	40.100	135.000

Tab. 2. Propagation characteristics of Malaysia, Nigeria and Brazil.

6. Conclusions

An improved method for predicting slant path attenuation in tropical climates is presented in this paper; based on rain intensity data $R_{0.01}$ (mm/h) from 37 tropical and equatorial stations. When tested against measurement data, the proposed approach seems to predict the measured attenuation more accurately compared to SAM, ITU-R and Crane model. Equation 7, and the new set of coefficients given in (8) resulted in an improvement in terms of the RMS of the relative error variable compared to the RMS values obtained with the prediction models. The proposed approach also avoids the use of the 0°C isotherm height as an input, due to the effects of seasonal variability. It only uses rain intensity as the principal input parameter; which is greatly advantageous since the rain rate data exceeded for 0.01 % exceedance probability are available in the ITU-R data bank for most of the hydro meteorological zones. Hence the proposed model is justified, since the rain rate data observed for 0.01 % exceedance probability and measured with a 1 minute integration time, are less variable and likely more accurate than the rain rates related to either highest or lowest exceedance probability.

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Prediction models	Exceedance probability (%)								μ_V	σ_V	% ρ_V
	0.001	0.003	0.005	0.01	0.03	0.05	0.1	1.0			
ITU-R P. 618-10	-0.5974	-0.5373	-0.4770	-0.5415	-0.5581	-0.5272	-0.5478	-1.2960	-0.6177	0.2279	57.41
SAM	-0.4733	-0.5602	-0.5607	-0.7073	-0.9057	-1.0178	-1.4293	-5.7532	-1.2740	1.5180	82.54
Crane global model	-0.5697	-0.8517	-0.9576	-1.2614	-1.7462	-1.9961	-2.5333	-3.8736	-1.6066	0.9538	129.28
Proposed	-0.3381	-0.2703	-0.2080	-0.2716	-0.2905	-0.5369	-1.2754	-1.0963	-0.4848	0.3624	32.21

Tab 3. Error, mean, standard deviation, and % RMS values for each percentage of time.

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