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A NEW RAIN ATTENUATION CONVERSION TECHNIQUE FOR TROPICAL REGIONS

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Abstract—Rain attenuation is one of the most crucial factors to be considered in the link budget estimation for microwave satellite communication systems, operating at frequencies above 10 GHz. This paper presents a mathematical model for converting terrestrial rain attenuation data to be used for satellite applications at Ku-band. In the proposed technique, the ITU-R P 618-9, together with a combination of ITU-R P 530-12 and the revised Moupfouma model have been adopted for satellite and terrestrial rain attenuation predictions, respectively. The model has been used for transforming the measured rain attenuation data of some DIGI MINI-LINKS operating at 15 GHz in Malaysia, to be used for MEASAT 2 applications. It was found that the model predictions are fairly reasonable when compared with direct beacon measurements in Malaysia and similar tropical locations. The model will provide a relatively accurate method for transforming the measured terrestrial rain attenuation to be used for satellite applications; and therefore substantially reduce the cost of implementing Earth-satellite links in some tropical regions that have sufficient rain attenuation data for the terrestrial links.

1. INTRODUCTION

In the design of Earth-space links for communication systems, several factors must be put into consideration. These factors include absorption in atmospheric gases; absorption, scattering and

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depolarization by hydrometeors such as clouds and precipitation [1]. All these effects must be considered as they are the causes of signal impairment for both terrestrial and Earth-satellite systems; with rainfall being the most crucial especially at frequencies above 10 GHz. The effect of rainfall is more severe in tropical regions which are characterized by heavy rainfall intensity and presence of large raindrops [2, 3]. Raindrop size distribution changes with geographical location and it can strongly influence rain specific attenuation and, consequently, total rain attenuation.

The rain-attenuation analyses are important for the study of the rain fade characteristics, which is a useful piece of information in the link budget estimation for predicting the expected outage as a result of rain attenuation on a microwave link [4, 5]. Long-term rain attenuation data are usually available for the terrestrial links in most tropical regions and so there is the need to convert them for use in satellite applications. This has become imperative because of the fact that these regions do not have sufficient earth-satellite data, which is useful in the preliminary design of earth-satellite microwave links.

There are two broad classes of rain attenuation predictions on any microwave link: The analytical models which are based on physical laws governing electromagnetic wave propagation and which attempt to reproduce the actual physical behavior in the attenuation process; and the empirical models which are based on measurement databases from stations in different climatic zones within a given region [6, 7]. The aim of this paper is to present a mathematical model for converting the rain-induced attenuation data on the terrestrial links to be used for satellite applications at Ku-band, based on the ITU-R recommendations ITU-R 618 -9 [8], ITU-R 530-12 [9] and the revised Moupfouma model [10]. The results may also be extrapolated to be used in other tropical regions that have similar situation.

2. A HANDFUL OF SOME EXISTING CONVERSION TECHNIQUES AND MODELS FOR RAIN ATTENUATION

Various conversion methods have earlier been developed for different applications in rain attenuation predictions for both terrestrial and satellite communication systems. These include the conversion of rain rate integration time from higher time to a shorter one; and the frequency scaling techniques for converting the measured rain attenuation at one frequency to the equivalent value at other frequencies for the same site.

However, no comprehensive research works have previously been done on converting terrestrial rain attenuation data to be used for satellite applications. The only published research works in the literature are those of Singlair et al. [11, 19], who proposed a transformation method for converting terrestrial rain attenuation time-series into satellite attenuation time-series, based on terrestrial rain attenuation measurement. The model is given by:

$$A_s(t) = \frac{k_s L_s}{1 + L_s/d_0} \left[\frac{A_T(t)(1 + L_T/d_0)}{k_T L_T} \right]^{\frac{\alpha_s}{\alpha_T}} \tag{1}$$

where k_s, k_T, α_s and α_T are ITU-R recommended parameters whose values depend on frequency band, polarization, temperature and elevation, $A_s(t)$ is the transformed rain attenuation time series of the satellite link, $A_T(t)$ is the measured rain attenuation time series of the terrestrial link, L_s and L_T are the slant path and the physical length of the satellite and terrestrial links, respectively; and d_0 is the ITU-R reduction factor given by:

$$d_0 = 35e^{(-0.015 R_{0.01})} \tag{2}$$

The major limit of the model being that the terrestrial rain attenuation data were measured in Hungary, a temperate region with rain rates less than 40 mm/h. This implies that the model is unarguably unsuitable for tropical climates like Malaysia which experiences heavy rain rates, as high as 120–130 mm/h. Rain rate is the most crucial factor in any rain attenuation predictions. Therefore, it has been considered as the principal input in the new proposed conversion technique, as indicated in Equation (22). Also, the proposed technique has been validated using the terrestrial rain attenuation data measured in Malaysian tropical climate.

3. DEVELOPMENT OF THE PROPOSED RAIN ATTENUATION CONVERSION TECHNIQUE

The development consists of three stages; first is the calculation of rain attenuation over the satellite link using the ITU-R P. 618-9 and second is the prediction of terrestrial rain attenuation, using a combination of ITU-R P. 530-12 and the revised Moupfouma model. The third stage involves derivation of the proposed transformation method, by finding the ratio of the two attenuation values at the same rain rate, since both links are sited in the same location.

3.1. Calculation of Rain Attenuation for the Satellite Link

The step-by-step procedure for calculating rain attenuation cumulative distribution function (CDF) over the satellite link is given below:

Step 1: Freezing height during rain, H_R (km) is calculated from the absolute values of station's latitude and longitude, both in degrees, as follows [12]:

$$H_R = 0.36 + h_0 \tag{3}$$

where h_0 is the 0°C isotherm height above mean sea level (km) and its value can be obtained from the isotherm chats of the Recommendation ITU-R P.839-3.

Step 2: The slant-path length, L_S (km), below the rain height is calculated as:

$$L_S = \frac{H_R - H_S}{\sin\theta} \tag{4}$$

where H_S is the station altitude, above the sea-level, in km and θ (degrees) is the elevation angle.

Step 3: The horizontal projection of the slant path length, L_G is evaluated from:

$$L_G = L_S \cos\theta \tag{5}$$

Step 4: The point rain rate, $R_{0.01}$ (mm/h), exceeded for 0.01% of an average year may be obtained from one- minute integration rain rate data, if it is available. An alternative method is by applying the Chebil model, which makes use of long-term mean annual accumulation, M, at the location under study; and is given by [13]:

$$R_{0.01} = \alpha M^{\beta} \tag{6}$$

where α and β are regression coefficients. This model was shown to provide good approximation of the measured data. The regression coefficients are defined as:

$$\alpha = 12.2903 \quad \text{and} \quad \beta = 0.2973 \tag{7}$$

We have found that the recommendation ITU-R P.837-5 is not suitable for estimating $R_{0.01}$ in tropical Malaysian climate, because it substantially underestimates the measured rain rate values [14, 21]. For instance, the ITU-R P.837-5 has predicted a value of **105 mm/h** for $R_{0.01}$ at UTM; whereas both direct measurement and Chebil's approximation of Equation (6) have given a value of approximately **125 mm/h** for the same location.

Step 5: The specific attenuation, $\gamma_{s\,0.01}$ (dB/km), for 0.01% of time is calculated from:

$$\gamma_{s0.01} = k_s R_{0.01}^{\alpha_s} \tag{8}$$

The parameters k_s and α_s depend on frequency, rain temperature, raindrop size distribution, and polarization. Their values can be obtained from ITU-R P.838-3 [15].

Step 6: The horizontal path adjustment reduction factor, $r_{h0.01}$, for 0.01% of the time is also calculated as:

$$r_{h0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \gamma_{0.01}}{f}} - 0.38[1 - \exp -2L_G]} \tag{9}$$

Therefore, the horizontally adjusted rainy slant path length is calculated from:

$$L_{h0.01} = \begin{cases} L_G r_{h0.01} / \cos\theta, & \text{for } \rho > \theta \\ (H_R - H_S) / \sin\theta, & \text{for } \rho \leq \theta \end{cases} \tag{10}$$

where

$$\rho = \tan^{-1}\left(\frac{H_R - H_S}{L_G r_{h0.01}}\right) \tag{11}$$

Step 7: The vertical reduction factor, $r_{v0.01}$, for 0.01% of the time is also given by:

$$r_{v0.01} = \frac{1}{1+\sqrt{\sin\theta}\left[31\,(1-\exp(-\theta/[1+\sigma]))\,\frac{\sqrt{L_G \gamma_{0.01}}}{f^2} - 0.45\right]} \tag{12}$$

where

$$\sigma = \begin{cases} 36 - |\varphi|, & \text{for } |\varphi| < 36^\circ \\ 0, & \text{for } |\varphi| \geq 36^\circ \end{cases} \tag{13}$$

Step 8: The effective path length through rain, L_{eff} (km) is finally obtained by multiplying the horizontally adjusted slant path by the vertical reduction factor of Equation (10); that is,

$$L_{eff} = L_{h0.01} r_{v0.01} \tag{14}$$

Step 9: The predicted attenuation exceeded for 0.01% of an average year is obtained from:

$$A_{s0.01} = \gamma_{s0.01} L_{eff} \tag{15}$$

Step 10: The predicted attenuation to be exceeded for other percentages, p of an average year may be calculated from the value of $A_{s0.01}$ by using the following:

$$A_{s\%p} = 0.12 * A_{s0.01} * p^{(-(0.546+0.043*\log 10(p)))} \tag{16}$$

3.2. Calculation of Rain Attenuation for the Terrestrial Link

Step 1: The specific attenuation for the terrestrial link is given by:

$$\gamma_{T0.01} = k_T R_{0.01}^{\alpha_T} \tag{17}$$

Again, parameters k_T and α_T depend on frequency, rain temperature, raindrop size distribution, and polarization. Their values can be obtained from ITU-R P.838-3, as earlier mentioned in step 5 of section 3.1.

Step 2: For the terrestrial link, path reduction factor is calculated using the revised Moupfouma's model given by [10]:

$$\delta(R_{0.01}, L_T) = \exp\left(\frac{-R_{0.01}}{1 + \zeta(L_T) * R_{0.01}}\right) \tag{18}$$

where $\delta(R_{0.01}, L_T)$ is the reduction factor for 0.01% of the time observed on any terrestrial microwave radio path of length, L_T (km), such that the equivalent propagation path, L_{eq} is:

$$L_{eq}(R_{0.01}, L_T) = L_T * \exp\left(\frac{-R_{0.01}}{1+\zeta(L_T) * R_{0.01}}\right) \quad \text{with } \zeta(L_T) = -100 \text{ for any } L_T \leq 7\,\text{km} \tag{19a}$$

and

$$L_{eq}(R_{0.01}, L_T) = L_T * \exp\left(\frac{-R_{0.01}}{1+\zeta(L_T) * R_{0.01}}\right) \quad \text{with } \zeta(L_T) = \left(\frac{44.2}{L_T}\right)^{0.78} \text{ for any } L_T > 7\,\text{km} \tag{19b}$$

Step 3: The predicted attenuation exceeded for an average year is then obtained from the following:

$$A_{T0.01} = \gamma_{T0.01} L_T \delta(R_{0.01}, L_T) \tag{20}$$

The predicted attenuation to be exceeded for other percentages, $p \neq 0.01\%$, of an average year may be calculated from the value of $A_{T0.01}$ by using the Equation (16). In this paper we have deliberately chosen not to use the ITU-R path reduction factor of Equation (2) for the terrestrial link. This is due to its unsuitability for the tropical regions.

3.3. Data Collection for Terrestrial Links

The received relative intermediate frequency (IF) rain attenuation data, sampled every second, were collected from seven 15 GHz operational microwave links of DIGI Telecommunications. Meteorological stations were installed at the particular locations of the investigated links, in order to be able to determine the relationship between the rain attenuation and rain intensity.

Four year precipitation data were collected at Universti Teknologi Malaysia, (UTM), Malaysia, Skudai campus and the data have been used to investigate the DIGI link located at Johor Bahru. The rain rate data were collected from January 2003 to December 2006, using Casella rain gauge and thirty months using OSK rain gauge. Both gauges are tipping bucket type and having 0.5 mm sensitivity. Casella records the total rainfall occurring in each minute without recording non-rainy events; therefore the rain rate is recorded as an integral multiple of 0.5 mm/min, or 30 mm/h. In contrast, OSK records the actual tipping time up to decimal of seconds.

The campus is located at Johor, southern part of Malaysia peninsula close to Singapore. Malaysia is located in the South-Eastern part of Asia, and falls in the zone P of the ITU-R rainfall rate climatic zone with annual average accumulation as high as 4184.3 mm. The Malaysian climate is tropical, and is characterized by uniform temperature, high humidity and heavy rainfall which arises mainly from the maritime exposure of the country. The heaviest amounts of rainfall are noted to occur in the last two months of the year; that is November and December. The uniform periodic changes in the wind flow patterns result in seasons' classifications as: The south-west monsoon, the north-east monsoon and the two shorter inter-monsoon seasons.

The specifications for the MINI-LINK are given in Table 1, while the measured rain attenuation data at UTM, Johor Bahru are shown in Table 2.

4. MATHEMATICAL DERIVATION OF THE CONVERSION FACTOR

First it is logical to assume that the terrestrial rain attenuation is greater than that of the satellite, under the same conditions of rainfall intensity. This fact is justified as follows [15, 16]: Satellites in geostationary orbit are 35,800 km above the earth, and since rain only forms in the troposphere, which extends seven miles above the earth, a signal traveling through a rain cell will experience attenuation during only a small portion of its transmission path. Therefore, terrestrial microwave transmissions are more susceptible to the effects of rain attenuation because their signal paths are entirely in the troposphere, and the signal may pass through an entire rain cell.

Table 1. Specifications of the 15 GHz DIGI MINI-LINKS.

Links Location	Hop Length (km)	Frequency Band (GHz)	Maximum Transmit Power (dBm)	10^{-6} BER (2x2 Mbs) Receive Threshold (dBm)	Antennas for both Transmit & Receive Side	
					Size (m)	Gain (dBi)
Johor Bahru	5.83	14.8	+18.0	−84.0	0.6	37.0
Kuala Lumpur-I	3.96	14.8	+18.0	−84.0	0.6	37.0
Taiping	3.48	14.8	+18.0	−84.0	0.6	37.0
Butterworh	11.33	14.8	+18.0	−84.0	0.6	37.0
Alor Star	4.85	15.3	+18.0	−84.0	0.6	37.0
Temerloh	5.36	14.8	+18.0	−84.0	0.6	37.0
Kuantan	1.45	14.8	+18.0	−84.0	0.6	37.0

Table 2. Measured rain attenuation of Johor Bahru MINI-LINK.

Percentage of time (%)	0.001	0.003	0.01	0.03	0.1	0.3	1.0
Rain attenuation (dB)	111.22	79.25	51.90	33.65	19.87	11.72	6.24

Therefore, the conversion factor $C_{\%p}$ is more conveniently expressed as the ratio of terrestrial rain attenuation to that of the satellite's. Thus dividing Equation (20) by Equation (15) would yield the following expression:

$$C_{\%p} = \frac{A_{T\%p}}{A_{S\%p}} \tag{21}$$

which gives

$$C_{\%0.01} = \frac{k_T L_T r_{d0.01}}{k_s L_{eff}} [R_{0.01}]^{(\alpha_T - \alpha_S)} \tag{22}$$

According to Equation (22), the conversion factor $C_{\%p}$ is proportional to $R_{0.01}$ since all other parameters are constant; and its variation over different rain rates, at 0.01% of the time, is presented in Figure 1.

It can be clearly seen from Figure 1 that the conversion factor increases with an increasing rain rate. Also since the latter is a function of $p\%$ of the time, further analyses have therefore revealed that the former also is functionally related to $p\%$, as presented in Figure 2.

It is glaring that the conversion factor is approximately 2.0159, at 0.01%, which corresponds to a rain rate of 125 mm/h, as already indicated in Figures 1 and 2. It is therefore evidently implied that either the rain rate $R_{0.01}$ or the probability level p could be used as the input in the proposed rain attenuation conversion factor $C_{\%P}$.

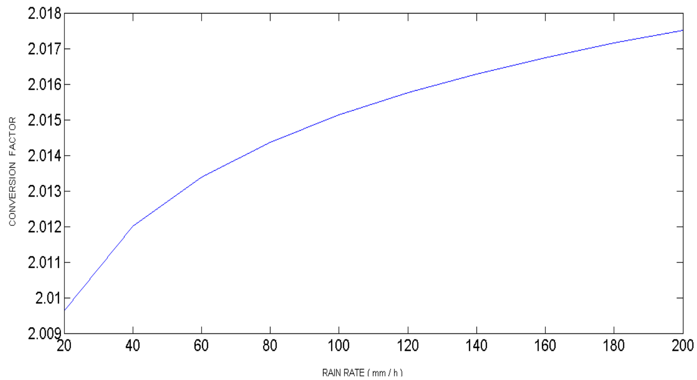

Figure 1. Variation of conversion factor with respect to rain rate.

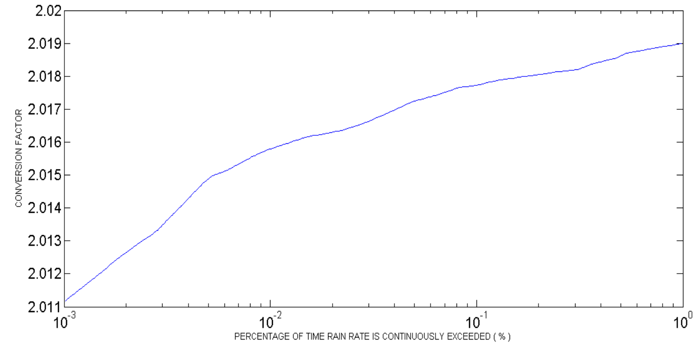

Figure 2. Variation of conversion factor with $p\%$ of the time in an average year.

4.1. Applications of the Proposed Conversion Method

Equations (21) and (22) have been used for converting the predicted and measured yearly rain attenuation for the 15 GHz DIGI MINI-LINKS in Malaysia, to be used for MEASAT 2 applications. The predictions are expected to provide a rough estimate of rain attenuation to be expected on earth-satellite links in the Malaysian tropical region. Figure 3 shows the comparison between predicted satellite attenuation for both measured and predicted terrestrial rain attenuation.

As clearly indicated in Figure 3, the corresponding satellite attenuation values could be obtained from the measured terrestrial rain attenuation, by direct application of the Equations (21) and (22). For instance, the measured attenuations for the 15 GHz DIGI MINI-LINK, at 0.01% and 0.1%, are nearly 52 dB and 20 dB, respectively; whereas the corresponding satellite attenuation values are 25.8 dB and 9.9 dB, respectively.

However, if there are no terrestrial rain attenuation data, then the predictions of Equation (20) may be used as the input in Equation (21) for deriving the equivalent satellite values, as shown in Figure 3. Although the weakness being that the inherent errors associated with such predictions would naturally be inherited by the transformed satellite values. According to Figure 3, the predicted values of terrestrial rain attenuation, at 0.01% and 0.1%, are nearly 54.7 dB and 21 dB, respectively; while the corresponding satellite attenuation values are 27.1 dB and 10.4 dB, respectively.

Even though it is noted in both cases that the transformed values for the satellite link are about 50% of the terrestrial rain attenuation for all percentages, $\%p$ of the time, the terrestrial rain attenuation predictions are a bit over estimated, compared to the actual measured

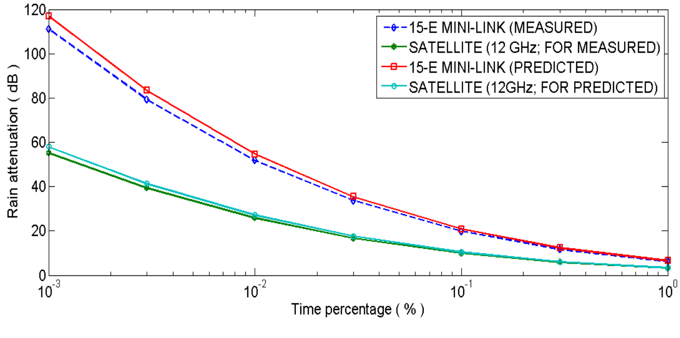

Figure 3. Comparison of terrestrial and satellite rain attenuation.

value. These prediction errors would naturally corrupt the transformed satellite values. In this paper, the errors are generally insignificant (less than 5%); and so they are overlooked. For instance, at 0.01% and 0.1% of the time, the prediction errors in the terrestrial rain attenuation are 2.7 dB and 1.0 dB, respectively; while the corresponding errors inherited by the satellite attenuation values are 1.3 dB and 0.5 dB, respectively.

Table 3 shows the site locations, propagation parameters and the measured rain attenuation values, at 0.01% and 0.1% of the time, for the earth-satellite links that were compared with the proposed model predictions.

The comparison between the model's estimates of Equations (21) and (22) and measured Earth-satellite attenuation data (MEASAT 2 & SUPERBIRD-C [17]) are provided in terms of Complementary Cumulative Distribution Functions (CCDFs) of attenuation as shown in Figures 4 and 5.

The proposed model predictions appear to be in good agreement with MEASAT 2 and SUPERBIRD-C at lower rain rates from 1.0% to 0.1%, when the rain attenuation of the terrestrial link is in the range of 6.0 dB to 21 dB. Also, the model predictions appear to be reasonable at medium rain rates from 0.1% to 0.01%, which correspond to a range of 21 dB to 54.7 dB of terrestrial attenuation. However, the predictions generally overestimate the measured Earth-satellite attenuation data at higher rain rates, from 0.01% to 0.001%.

4.2. Validation of the Model

According to Recommendations ITU-R P.311-13 [20], the rain attenuation prediction models for Earth-satellite links are determined for exceeding time percentages in the range 0.001% to 0.1%. Therefore percentage errors between measured Earth-satellite attenuation data A_m (dB) and the model's predictions A_p (dB) are calculated for each

Table 3. Characteristics of the Earth-satellite measurement sites.

Earth-Station Locations	Altitude (m)	Frequency (GHz)	Elevation (degrees)	Polarization	$R_{0.01}$ (mm/h)	Rain attenuation (dB)	
						0.1 %	0.01 %
MEASAT 2 UTM-Johor, Malaysia 1.45 ^{0}N, 103.75 ^{0}E	1.0	12.594	70.0	V	125	9.8	25.0
SUPERBIRD-C USM, Malaysia 51.7 ^{0}N, 100.4 ^{0}E	57.0	12.255	40.1	V	130	8.98	23.5

exceeding time percentage of interest on the microwave radio link, as follows:

$$E_i = \frac{A_{p_i} - A_{m_i}}{A_{m_i}} * 100\% \ (i = 1 \text{ to } N) \tag{23a}$$

$$\text{if: } |A_{p_i} - A_{m_i}| < 1 \text{ then } E_i = 0 \tag{23b}$$

The standard deviation, σ_{e_i} of the error distribution can be defined from:

$$\sigma_{e_i} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2 - (\mu_{e_i})^2} \tag{24}$$

where μ_{e_i} is the mean square error for each exceedance time percentage; and is given by:

$$\mu_{e_i} = \frac{1}{N}\sum_{i=1}^{N} e_i \tag{25}$$

The mean square error and standard deviation are then used to calculate the Root Mean Square, D_{e_i} (RMS); which is defined as follows:

$$D_{e_i} = \left[(\mu_{e_i})^2 - (\sigma_{e_i})^2\right]^{1/2} \tag{26}$$

Table 4 compares parameters μ_{e_i}, σ_{e_i} and D_{e_i} for the proposed prediction model with measured Earth-satellite attenuation data (MEASAT 2 and SUPERBIRD-C).

According to the evaluation procedures adopted by the Recommendations ITU-R P.311-13, a lower standard deviation σ_{e_i} and a lower

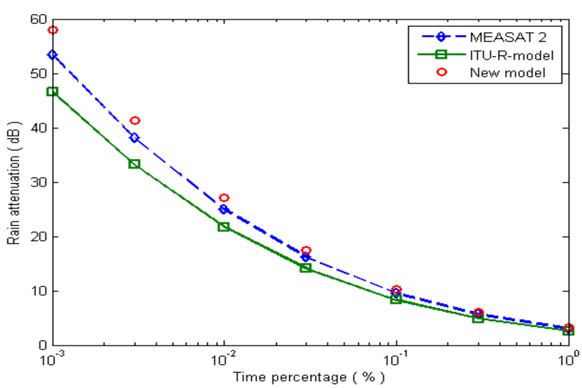

Figure 4. Comparison between measured and predicted attenuation for MEASAT 2-UTM.

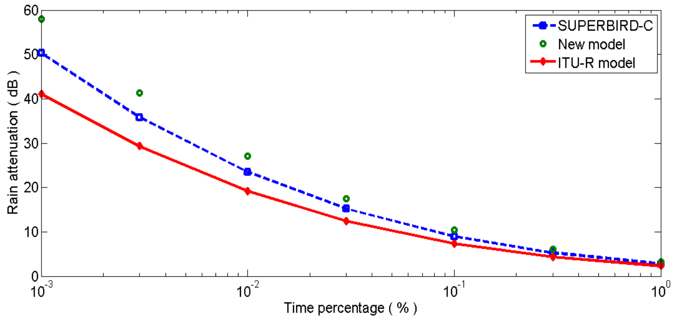

Figure 5. Comparison between measured and predicted attenuation for SUPERBIRD-C, USM.

Table 4. Percentage errors and RMS comparison.

Parameters	Earth-satellite	Time Percentages (p %)						
	links	0.001	0.003	0.01	0.03	0.1	0.3	1.0
μ_{ei}	Proposed model	18.46	13.16	8.62	5.59	3.30	1.95	1.04
	ITU-R model	−26.99	−19.23	−12.59	−8.16	−4.82	−2.84	−1.51
σ_{ei}	Proposed model	1.62	1.15	0.76	0.49	0.29	0.17	0.09
	ITU-R model	3.42	2.44	1.60	1.04	0.61	0.36	0.19
D_{ei}	Proposed model	18.53	13.20	8.65	5.61	3.31	1.95	1.04
	ITU-R model	27.21	19.38	12.69	8.23	4.86	2.86	1.52

RMS value D_{e_i} for the whole range or for the majority of time percentages of interest suggest a high accuracy of the proposed model.

5. CONCLUSIONS

The conversion technique has been developed based on the ITU-R P 618-9, together with a combination of ITU-R P 530-12 and the revised Moupfouma model, for the satellite and terrestrial rain attenuation predictions, respectively.

The proposed method has been used for converting the measured and predicted rain attenuation data exceeded for an average year for 15 GHz DIGI MINI-LINKS in Malaysia; and the results have been found to be comparable with direct measurements taken in Malaysia and similar tropical climates like Singapore and Nigeria [2, 18]. The model is therefore recommended for converting terrestrial rain attenuation data to be used for earth-satellite applications at Ku-band in the Tropical Malaysian Peninsula and other climates that have similar situations.

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