Ku-band specific attenuation coefficients for high-throughput satellites in equatorial region

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ABSTRACT

Ku-band have a larger attenuation during heavy rain in the equatorial region. Despite that, Ku-band has been identified as a frequency band in high-throughput satellite systems (HTS) for broadband satellite communication. The available rain fade prediction models are still not able to accurately predict rain attenuation in the equatorial region. The models depend on the specific attenuation parameters produced based on the international telecommunication union radiocommunication sector (ITU-R) instead of the measured value. Direct measurement of specific attenuation is more accurate but difficult to obtain because the correlation of rainfall rate and satellite signal loss due to rain must be obtained simultaneously. This paper aims to derive new specific attenuation frequency-dependent coefficients for Ku-band using the semi-empirical method. The Malaysia East Asia Satellite 3 (MEASAT-3) satellite data was collected using a 13 m antenna located at Cyberjaya, Selangor while the rainfall data was collected by the nearby hydrological station. The specific attenuation was obtained from correlations of the direct measurement of rain attenuation and rainfall rate. The new frequency-dependent coefficients for Ku-band specific attenuation values are $k = 4.6690$ and $\alpha = 0.1941$. The newly acquired specific attenuation coefficients have improved the rain attenuation model prediction for the equatorial region.

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1. INTRODUCTION

Satellite communication uses wireless technology to provide worldwide communication coverage and long distance connections without the need for terrestrial infrastructure. Satellite communication link has evolved to support and complement broadband services through a new hightroughput satellite system (HTS) [1], [2]. HTS communication satellites provides more throughput (> 100 Gb/s) than the conventional fixed satellite services (FSS) which has 36 MHz bandwidth. This is more than 2000 times increased in capacity. The major issue in satellite communications in the equatorial region is rain fade. Numerous studies were made to produce an accurate rain fade prediction model in the equatorial region. However, the past studies are based on conventional FSS satellites. Thus, new assessments of rain fade and rain fade mitigation were required for the HTS system before it is fully implemented [3]–[5]. Moreover, these initial studies on rain fade and rain fade mitigation were conducted in the northern latitude countries which has lower rainfall rate than the equatorial region. Even though western studies are more focused on higher bands than Ku, the Ku-band rain fade issues have not been able to be successfully overcome in the equatorial region [6]–[8]. Ku-band has been implemented in Malaysia as in the Ku-band and Ka-band pair for the HTS system in the Malaysia East Asia Satellite (MEASAT) series satellite. Apart from using Ku-band in geostationary satellites for HTS application, updated Ku-band application is also found in new space based low earth satellite internet services, for example, SpaceX's Starlink broadband internet services [9] and CubeSats constellation application [10]–[13]. Before a satellite signal reaches the earth's surface, there are common impairments encountered by the satellite communication system such as transmitter and transponder impairments, mismatch losses in polarization, antenna pointing losses and atmospheric signal impairment [14]. However, the rain attenuation or atmospheric impairment is an arduous impairment to characterized as it is weather dependent, which means it is difficult to replicate and investigate in a lab test during a satellite development. Atmospheric impairment happens in the propagation channel between the satellite and the ground station, as the transmitted signal may be absorbed and scattered [15] by other elements that exist in the sky such as rain, oxygen and water vapour [16]. The most significant atmospheric impairment is rain attenuation. Rain attenuation is obtained from the knowledge of specific attenuation integrated over an effective path length from the ground terminal to the rain height [17]. Therefore, a rain prediction model consists of two parts which are the specific attenuation and the path length of the rain. However, most predictions are dependent on the specific attenuation produced based on conventional FSS satellite systems and international telecommunication union radiocommunication sector (ITU-R) specific attenuation parameters which are based on rainfall drop size distribution. Direct measurement of specific attenuation is more accurate but difficult to obtain because the correlation of rainfall rate and satellite signal loss due to rain fade has to be obtained simultaneously. Thus, investigating specific attenuation for Ku-band atmospheric attenuation using direct measurement is critical and may improve the prediction of rain attenuation in the equatorial region since a new high throughput satellite system requires a small margin of error. This research anticipates that more accurate specific attenuation coefficients would be able to improve the rain attenuation predicting model in satellite communication for the equatorial region using direct measurement. Thus, this article aims to produce and evaluate specific attenuation for a Ku-band frequency in the equatorial region based on direct measurement of Ku-band beacon and rainfall rate and then obtain specific attenuation coefficients by correlations using a semi-empirical method.

Research on specific attenuation is very minimal in the tropical-equatorial region, nevertheless, these studies have shown that the ITU-R specific attenuation is less accurate [18]–[20]. The procedure used by [18]–[20] was to measure the rain attenuation for a period, analyze the data statistically and produce the specific attenuation parameters. The data is exploited to obtain the average distribution over the time exceedance percentage. In [18], the specific attenuation is obtained by integrating the rain attenuation over the effective path length model extracted from the simple attenuation model (SAM). SAM provides a path length that accommodates changes in rainfall rate according to its time exceedance. However, the experiment set up is using a satellite at a very low elevation whereas most satellites operating in Malaysia have a higher elevation angle. The experiment was conducted on a small terminal that may not have enough dynamic range to compensate for the heavy rain attenuation in the equatorial region. In [19], a similar method is used to obtain the specific attenuation, the instruments used were a commercial 13 m diameter ground station antenna. The large size antenna provides a very good gain for rain attenuation data collection. However, in [19], instead of using the path length extracted from SAM, the effective path length extracted ITU-R P.618 was used. The disadvantage of using ITU-R effective path length is it only accommodates for path length from rainfall rate at 0.01% exceedance. Recent studies in South Korea using semi-empirical method, a country in non-equatorial region had also shown that the specific attenuation of the ITU-R is still inaccurate [21], thus there is a need to review the specific attenuation.

This paper will propose a solution to overcome the ambiguity or uncertainty in determining the specific attenuation using semi empirically method by deriving specific attenuation using measured rain attenuation data, measured rainfall rate data and evaluating it with different path length models to obtain the most accurate specific attenuation coefficients. The evaluation will be using the SAM effective path, ITU-R slant path and ITU-R effective path. The differences in the derived specific attenuation coefficients based on the correlation of rainfall rate and different effective path lengths model will be implemented in the rain prediction model and compared with actual rain attenuation measurement. This article will provide a new and more accurate specific attenuation for Ku-band for predicting rain fade in the equatorial regions.

2. RESEARCH METHOD

The rain attenuation is difficult to be predicted accurately due to the rainfall non-uniformity, it can only be measured by collecting the statistical data of rain rate measurements for the particular region [21]. Hence, the rainfall data can be used to assist the prediction of specific attenuation. A series of rain attenuation data and rainfall data will be measured and collected to predict the specific attenuation. Then, the regression analysis will be conducted, and the obtained result will be compared to other commonly used models to determine which model is the best to predict rain attenuation for equatorial regions. For this experiment, the rainfall rate and rain attenuation data were measured and collected in a year which is from January 2017 until December 2017. In order to ensure accurate data collection, the data is obtained through a collaboration between Measat Broadcast Network Systems Sdn Bhd (ASTRO), a satellite broadcast company that owns, operates, and maintains a 13 m commercial Ku-band earth station. The well maintained and well calibrated 13 m earth station provides accurate and reliable data collection. The data are then statistically analyzed to obtain the cumulative distribution function (CDF) for rain attenuation. The raw satellite data is retrieved from the ASTRO ground station which is located in Cyberjaya with an elevation angle of 77.5° with latitute and longiude of 2.9356°N, 101.6584°E. The satellite used is MEASAT-3 at 91.5°E using the frequency of 12.201 GHz with vertical polarization. The measured data is in terms of rainfall attenuation with one-minute integration time for a one-year period which is in 2017. While the rainfall data was measured by the rain gauge from the national rain gauge network managed and operated by the Department of Irrigation and Drainage (DID) Malaysia which is installed at Paya Indah rainfall station, nearby to the ASTRO's ground station at Cyberjaya, Malaysia.

An attenuation prediction model is used to estimate the attenuation values at a corresponding exceedance percentage. The attenuation values can be predicted by calculating the specific attenuation at different rainfall rates. There are many rain attenuation prediction models that were proposed by researchers with various used parameters and procedures. In this paper, the commonly used rain fade prediction models which are ITU-R and SAM prediction models will be reviewed by integrating the local measured values into the procedures. Then, the predicted values are compared with measured attenuation data.

The ITU-R rain attenuation model requires specific attenuation, slant path lengh, and effective path length to be calculated. The coefficients of k and α are derived to calculate the specific attenuation. To obtain k and α coefficients using ITU-R 838-3 recommendation [22], the vertical and horizontal polarization coefficient values need to be determined first. The calculated value of k and α at 12.201 GHz are 0.0257 and 1.1441 respectively.

ITU-R P.618-13 [23] model provided two different methods of calculating rainfall path length which are the slant path length, L_s and the effective path length, L_E. Slant path length is the simplest path that is used to determine specific attenuation. Figure 1 shows the schematic of an earth-space path link that visually descibed slant path length. The slant path length, L_s can be determined by considering the elevation angle, θ. Slant path length, L_s can be calculated by (1) yields 4.9309 km.

$$L_S = \frac{(h_R - h_S)}{\sin\theta}\ km \tag{1}$$

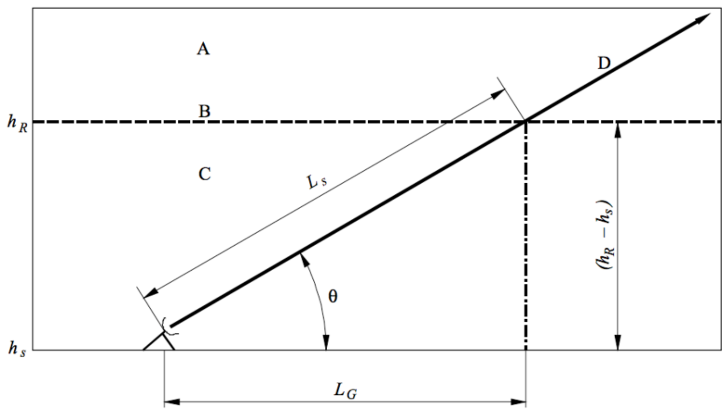


Figure 1. Schematic presentation of an earth-space path giving the parameters to be input into the attenuation prediction process [23]

The ITU-R effective path length, L_E is the extended version of slant path length which considers other parameters such as horizontal reduction factor and the vertical reduction factor. To obtain the horizontal reduction factor, the horizontal projection of slant path can be determined by (2).

$$L_G = L_S \cos\theta\ km \tag{2}$$

Based on (2) L_G = 0.0261 km, then, the horizontal reduction factor can be calculated using (3) yielding a horizontal reduction factior of 0.8088.

$$r_{0.01} = \frac{1}{1+0.78\sqrt{\frac{L_G\gamma_R}{f}}-0.38(1-e^{-2L_G}} \quad (3)$$

The vertical adjustment factor, $v_{0.01}$, is obtained as 0.6809 for 0.01% of the time is then calculated by:

$$\zeta = \tan^{-1}\left(\frac{h_R-h_S}{L_G r_{0.01}}\right) \text{ degrees} \quad (4)$$

For ζ > θ,

$$L_R = \frac{L_G r_{0.01}}{\cos\theta}\ km \quad (5)$$

For Malaysia, | φ | < 36°, hence χ = 36 – | φ_e | degrees.

$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left(31\left(1-e^{-\left(\frac{\theta}{1+\chi}\right)}\right)\frac{\sqrt{L_R\gamma_R}}{f^2}-0.45\right)} \quad (6)$$

Therefore, ITU-R effective path length, L_E can be calculated from (7).

$$L_E = L_R v_{0.01}\ km \quad (7)$$

The calculated values are ξ = 79.4533°, L_R (km) = 3.9880, χ = 33.0644°, $v_{0.01}$ = 0.6809 hence L_E = 2.7153 km. The SAM also has its own derivation method to obtain the effective path length. The advantage of deriving effective path length using SAM procedures is the model requires the changes of rainfall rate, as higher rainfall leads to shorter rain path length. By inputting the measured rainfall rate, R, initial frequency-dependent coefficient, α from ITU-R 838-3, rate of decay, β which is 1/22 , and the elevation angle, θ, the SAM effective path length, L_{eff} can be derived by using (8).

$$L_{eff} = \frac{1-\exp(-\alpha\beta\ln(R/10)L_S cos\theta)}{\alpha\beta\ln(R/10)cos\theta} \quad (8)$$

3. RESULTS AND ANALYSIS

The calculated coefficients and parameters that were calculated by different models with integration of local measured values. The data are listed in Table 1. Thus, the specific attenuation can be calculated by integrating the obtained path length (from ITU-R slant path or ITU-R effective path length or SAM effective path) to (9).

$$\gamma_R = \frac{A}{L_{(S\ or\ E\ or\ eff)}}\ (\text{dB/km}) \quad (9)$$

Table 1. Calculated parameters and coefficients

Parameters	Values
L_{eff} (km): SAM	3.86
$A_{0.01}$ (dB)	39.27
γ_R (dB/km)	10.15
β	0.1653

3.1. Modelling the attenuation prediction

The three models of specific attenuation were derived by dividing the measured rain attenuation to the three different path length models described in section 2, which were SAM effective path, L_{eff}, ITU-R slant path, L_S and ITU-R effective path, L_E which were named as model 1, model 2, and model 3 respectively. Then, power law analysis was conducted based on the correlation of specific attenuation data against the measured rainfall rate to obtain a new set of specific attenuation frequency-dependent coefficients for each model. After deriving the frequency-dependent coefficients, the new rain attenuation can be predicted for different percentage exceedance.

As for model 1, SAM has also provided the method to predict rain attenuation from rainfall rate as in (10) by applying the rate of decay, β = 1/22, elevation angle, θ, slant path length, L_s and the derived frequency-dependent coefficients, k and α:

$$A = kR^{\alpha} \frac{1-\exp(-\alpha\beta \ln(R/_{10}) L_S cos\theta)}{\alpha\beta \ln(R/_{10}) cos\theta} \tag{10}$$

For model 2, the rain attenuation can be predicted by integrating the obtained slant path length, L_S and the derived specific attenuation into (9) which is modified in terms of attenuation, A as in (11).

$$A = \gamma R\, L_S\, dB \tag{11}$$

While for model 3, the predicted attenuation exceeded for 0.01% of an average year is based on ITU-R P.618-13 [23] as in (12).

$$A_{0.01} = \gamma R\, L_E\, dB \tag{12}$$

Based on the (14) the ITU-R model defines the predicted attenuation is dependent on the two main factors, which are the specific attenuation and the effective path length. For a probabilistic value, $p < 1\%$ and $|\varphi| < 36°$ and $\theta \geq 25°$ where β:

$$\beta = -0.005(|\varphi| - 36) \tag{13}$$

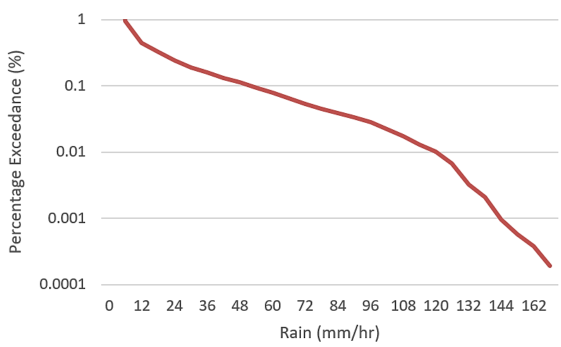
The predicted attenuation is, therefore:

$$A_p = A_{0.01} \left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\, ln(p) - 0.045\, ln(A_{0.01}) - \beta(1-p) sin\ \theta)} \tag{14}$$

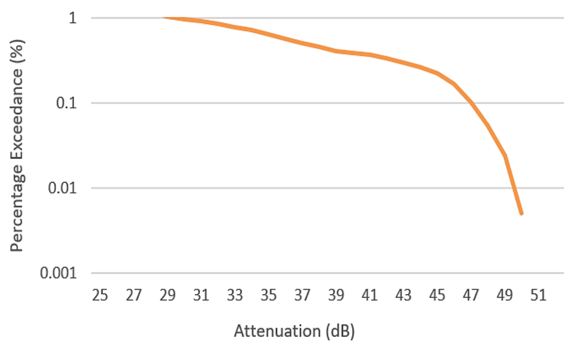
Thus, the obtained results will be plotted against percentage exceedance to compare with the measured data. These three models will also be compared with past researches using semi-empirical method from Universiti Sains Malaysia (USM) [18] and International Islamic University Malaysia (IIUM) [19]. In Mandeep *et al*. [18], the effective path length correlation coefficients were adapted to calculate the specific attenuation using local measured values. While the prediction values for [19] are gained by inserting the frequency-dependent coefficients obtained from the research to (11) directly.

3.2. Measured rain attenuation in cumulative distribution

The annual rainfall rate and attenuation data that were measured were statistically analysed into CDF. Figure 2(a) shows the annual CDF plot of rainfall rate and attenuation that is used to determine the particular data for each percentage of the time. From Figure 2(a), it can be observed that the average rainfall rate at 99.99% service quality is about 120 mm/hr in 2017. From the pivoted satellite data in 2017, the average attenuation at 99.99% service quality is about 50 dB as graphed in Figure 2(b). The time exceedance for rainfall rate at exceedance percentage of 0.01%, 0.1%, and 1% are 5 mm/hr, 50 mm/hr, and 120 mm/hr respectively. The time exceedance for Ku-band attenuation at exceedance percentage of 0.01%, 0.1%, and 1% are 29 dB, 47 dB, and 50 dB respectively.



(a)



(b)

Figure 2. CDF characteristics of (a) rainfall rate and (b) Ku-band rain attenuation

3.3. Determination of a new specific attenuation coefficients

The specific attenuation and frequency-dependent coefficients, k and α were derived for model 1, model 2, and model 3 using (9) where rain attenuation, A is obtained from the result presented in Figure 2(b). The plotted graph of specific attenuation versus rainfall rate for different models are depicted in Figure 3(a). From Figure 3(a), the major difference was shown between the specific attenuation that was derived from model 1 and model 3. This is due to a great difference in path length calculated by using SAM and ITU-R effective paths. While the specific attenuation derived from model 2 did not have so much difference with model 1, the difference becomes greater as the rainfall rate increases. As SAM effective path length derivation (model 1) took rainfall rate changes into account, it is expected the result is more reliable compared to the slant path model (model 2). The derived frequency-dependent coefficients for each plot are then tabulated in Table 2.

Now, the three new specific attenuation coefficients are used in the rain attenuation prediction model described in section 3.1 were plotted in Figure 3(b). The ITU-R P.618-13 rain attenuation prediction model together with specific attenuation coefficients obtained from ITU-R P.838-8 parameters were also plotted in Figure 3(b) for benchmarking purposes. The comparison between the series of predicted attenuation using the newly derived specific attenuation coefficients and measured rain attenuation values are graphically plotted in Figure 3(b). Overall, it is clearly shown in Figure 3(b) that the attenuation values predicted by model 1 is almost accurate to the measured values and followed up by model 2 but the contradiction is due to different path length derivation methods. While the values predicted model 3 are very far from the measured values' trendline. This shows the obtained result of the new specific attenuation coefficient increases the relevancy of the ITU-R prediction model as the model 3 prediction values are more correlated towards the measured values compared to ITU-R theoretical values.

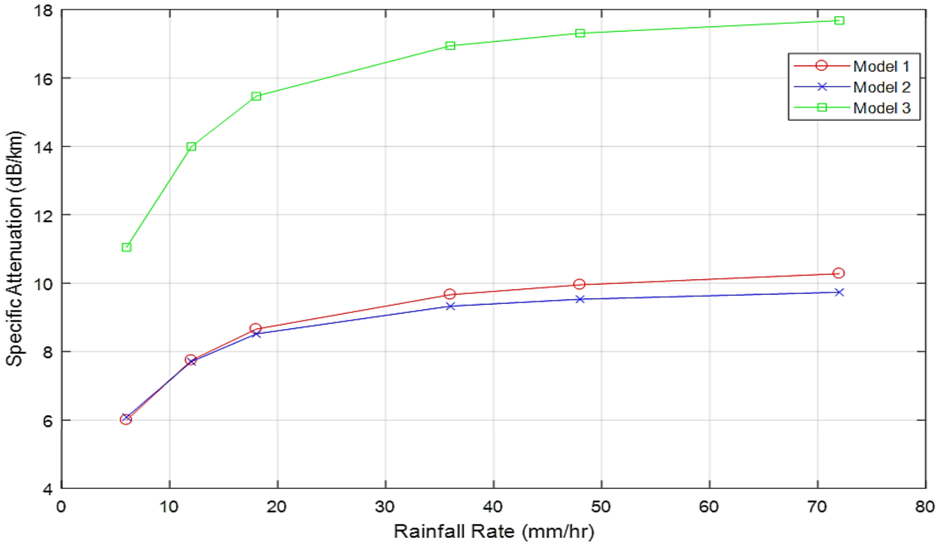
Table 2. Derived specific attenuation frequency-dependent coefficients

Model	k	α
1	4.6690	0.1941
2	4.9390	0.1687
3	8.9690	0.1687
ITU-R P.838-8	0.0257	1.1441

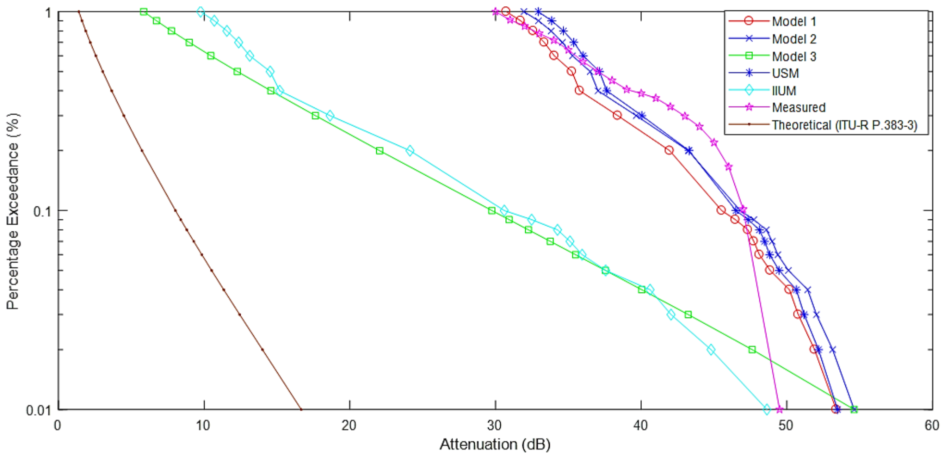
In addition, the prediction models from [18], [19] were compared to the measured values. As for the prediction by IIUM [19], the contradiction is quite high due to differences in frequency-dependent coefficients. The specific attenuation frequency dependent coefficient derived in [19] were based on semi-empirical method where it depends on the ITU-R slant path. Hence, the result are quite similar with model 3 result. This has improved the prediction but still less accurate compared to measured value because the path length used is ITU-R slant path which is inflexible towards rainfall rate changes. While the prediction made by USM [18] is almost accurate to the measured results, but there is an overestimation occurred at 0.01% exceedance. The predicted values were almost complying with model 1 because both implement the SAM method in calculating the effective path length. Therefore, the resulting values are almost the same, but the differences may be due to the parameters were derived using a lower elevation antenna.

The root mean squared analysis was conducted between the values resulted by prediction models describe in Figure 3(b) and measured. In the analysis, the root-mean-squared error (RMSE) is calculated to determine the most accurate prediction compared to the measured attenuation values. The calculated RMSE is from ITU-R P.311-13 [24] by getting the information of the predicted and measured attenuation for each point. The results for RMSE are model 1 = 4.0709, model 2 = 5.1259, model 3 = 16.1632, USM [18] = 4.8440, and IIUM [19] = 14.2062.

It can be concluded that the least RMS error is gained by the values predicted by model 1 which makes the prediction model most accurate and relevant towards the measured values. The result from this experiment shows that new specific attenuation coefficients for Ku-band from model 1 are the most accurate in predicting the rain attenuation. The new coefficient k = 4.6690 and α = 0.1941 should be used for predicting rain attenuation for HTS satellite operating Ku-band in the equatorial region particularly in Malaysia or the Southeast Asian region. The local rainfall rate should be used with the newly derived specific attenuation frequency-dependent coefficients to obtain a more accurate rain attenuation prediction. This finding also validates that the specific attenuation can be accurately obtained based on the effective path length describe in (8) which is the best effective path in length in the semi-empirical method because it considers variation in rainfall rate and equatorial region rainfall rate is higher and bigger variation compared to another climate. In fact, using the revised specific attenuation frequency-dependent coefficients, a local variation of rainfall rate and SAM effective path length is much simpler to be implemented as it requires fewer parameters needed to be calculated [25].



(a)



(b)

Figure 3. Results: (a) specific attenuation derived by model 1, 2, 3 and (b) comparison of prediction models with measured values

4. CONCLUSION

It is observed that each of the prediction models has its advantages and disadvantages. From the results, the worst prediction is made by using ITU-R effective path model to produce specific attenuation and rain attenuation. This is because the ITU-R rain attenuation model disregard changes in rainfall rate and only rely on a baseline of 0.01% exceedance for extrapolation at other rainfall rates. This method is impractical for equatorial regions as the rainfall rate varied widely and higher compared to the temperate region. Therefore, changes in rainfall rate as a parameter is necessary to predict result accurately for specific attenuation and subsequently rain attenuation. The most accurate prediction is provided by model 1 by having the least RMSE. The new coefficient $k = 4.6690$ and $\alpha = 0.1941$ produced based on model 1 should be adopted in rain attenuation prediction in the equatorial region for the Ku-band link. The findings from this research also proved that using the revised specific attenuation frequency-dependent coefficients in Ku-band together with SAM effective path length model are more reliable compared to the ITU-R rain attenuation model. This also resolves the ambiguity in terms of methods in determining specific attenuation using the semi-empirical method. This is because the presented method takes into account the changes in rainfall rate which makes the prediction more accurate and relevant especially in equatorial regions with its fluctuating rainfall rate. The revised and new specific attenuation frequency-dependent coefficients obtained from the results will serve as a good tool for satellite system operators to operate HTS Ku-band frequency in the equatorial region.

Therefore, the propagation impairment prediction for future HTS satellites operating in Ku band links due to rain attenuation can be made more reliable with these new coefficients. The new derived specific attenuation frequency-dependent coefficients value can help in designing a better rain attenuation model for satellite links operating in the equatorial and tropical climate regions or countries. As mentioned earlier, obtaining specific attenuation using direct measurement and semi-empirical method are accurate but more complex where more frequencies and rainfall rate correlations have to be obtained to have a range of specific attenuation coefficients that covers a wider range of frequencies band. This experimental result serves as a good fundamental to further evaluate and produce new specific attenuations at higher frequency bands such as Ka to have a better prediction for frequencies above 12 GHz.

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