

## Comparison of measured rain attenuation in the 10.982-GHz band with predictions and sensitivity analysis

Yusuf Abdulrahman<sup>1,3,\*</sup>, Tharek A. Rahman<sup>1</sup>, Rafiqul M. Islam<sup>2</sup>, Benjamin J. Olufeagba<sup>3</sup> and Jalel Chebil<sup>2</sup>

<sup>1</sup>*Wireless Communications Centre, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia*

<sup>2</sup>*Electrical and Computer Engineering, Islamic International University Malaysia (IIUM), Kuala Lumpur, Selangor, Malaysia*

<sup>3</sup>*Electrical & Electronics Engineering Department, University of Ilorin, Ilorin, Nigeria*

### SUMMARY

The campaign to collect rain attenuation data on terrestrial links had commenced in Malaysian tropical climates for almost two decades. The terrestrial data so far collected have been greatly utilized to derive useful statistics for various microwave applications, such as frequency scaling, rain rate conversion factor, 1-min rain rate contour maps, wet antenna losses, and fade slope duration analysis. However, there is still severe scarcity of rain attenuation data on earth–space links in Malaysia. The results of the 2-year measurement (January 2009–December 2010) of rain rates and rain-induced attenuation in vertically polarized signals propagating at 10.982 GHz have been presented in this paper. The rain attenuation over the link path was measured at Islamic International University Malaysia and compared with ITU-R P.618-10 and Crane global models in this paper. The test results show that the two prediction models seem inadequate for predicting rain attenuation in the Ku-band in Malaysia. Sensitivity analysis performed on measured data also reveals that the sensitivity variables depend on rain rate. Copyright © 2014 John Wiley & Sons, Ltd.

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KEY WORDS: breakpoint attenuation; convective rain; system compensation; rain height; slant path; tropical and equatorial climates

### 1. INTRODUCTION

Absorption, depolarization, and scattering by hydrometeors such as rain, clouds, hail, ice crystals, or wet snow can cause impairment in the transmitted signal strength, thereby resulting in signal attenuation. Rain attenuation and fast amplitude fluctuations due to atmospheric turbulences and rain scattering become dominant signal impairment factors, as they reduce the reliability, availability, and performance of the communications link [1]. Rain is one of the biggest contributors to signal degradation at frequencies above 10 GHz [1]. The path attenuation caused by heavy rainfall can cause signals to become indistinguishable from the noise signal of the receiver. Attenuation is caused as a result of intersection between rain cell (s) and the radio waves' propagation path, thus absorbing and/or scattering the transmitted signal [2]. Geographical features, such as the presence of mountains, hills, and oceans or great lakes have considerable influence on the nearby climatology. Thunderstorms are more frequent in tropical and equatorial climates due to atmospheric instability caused by heat and moisture [3, 4].

Malaysia (Latitude: 1.45°N and Longitude: 103.75°E) is located in the southeastern part of Asia and surrounded by heavy water masses (oceans, seas, and lakes). It experiences heavy rainfall with annual average accumulation as high as 4184.3 mm and about 150–200 rainy days throughout the year. The

\*Correspondence to: Yusuf Abdulrahman, Wireless Communications Centre, Universiti Teknologi Malaysia, Skudai-Johor, Malaysia.

†E-mail: abdulrahman.yusuf@yahoo.com

Malaysian climate is tropical and is characterized by uniform temperature, high humidity, and heavy rainfall, which arise mainly from the maritime exposure of the country. According to the Malaysian Meteorological Services (MMS) Reports of 1987 [5], there are four main distinguishable seasons: the southwest monsoon, northeast monsoon, and two shorter intermonsoon seasons. Details of these descriptions could be found in [5, 6]. Adequate knowledge of the rain attenuation at a particular operating frequency and location is needed for design of reliable terrestrial or satellite links [7]. In view of this, the campaign to collect rain attenuation data for studying the effects of rainfall on microwave propagation had commenced since April 24, 1998. More than 4 years of rain rate and rain attenuation data had been collected at several geographically spread locations in Peninsula Malaysia. These include data collected from seven DiGi links operating at 15 GHz [6] and another DiGi link operating at 23 GHz [8], four experimental MINI-LINKs (15 E, 23 E, 26E, and 38 E) installed by Erisson at UTM, Skudai campus [9]. One year rain-induced attenuation data were also collected in 2006 from a terrestrial link located at Cyberjaya (2855'N 101839'E), operating at 32.6 GHz with a path of 1.4 km [10]. In addition, where 1-min rain rate data are not available, the long-term hourly precipitation data are obtainable from MMS and Drainage and Irrigation Department (DID). MMS and DID have 12 and 19 years of 1-h rain rate data from 36 to 99 stations, respectively, in Peninsula Malaysia [8, 9].

The rain rate and rain attenuation data have been utilized to investigate fade margin, frequency scaling (37.06/25; 37.06/21.95; 25/21.95; 37.06/14.6; 25/14.06; and 21.95/14.06 GHz) [11]; rain rate conversion factor [8]; wet antenna losses [12–14], path reduction [6] and fade slope, and duration analysis [15]. The rain rate conversion factor for converting rain rate of 1-h integration time to the equivalent 1-min integration time was based on 1-h rainfall data collected from over 70 locations in Malaysia, Indonesia, and Singapore. The method was found to be quite accurate and reliable, within reasonable limits of statistical accuracy, for the Malaysian tropical region and other tropical regions [7]. One minute rain rate contour maps had also been developed for microwave applications in Malaysia peninsula [16]. The results of antenna losses due to rain on experimental microwave links (as high as 5.5610 dB in UTM Skudai) were compared with those obtained from Advanced Communications Technology Satellite (ACTS) propagation experiments at the University of British Columbia, Colombia [12]. Other works include measurements and studies of rain drop size distribution in Malaysia [11]. However, there is still scarcity of satellite rain attenuation data in Malaysia, even though rain attenuation in the 12-GHz band measured for a 3-year period has been reported in reference [17]. Efforts were also made toward converting the sufficient Malaysian terrestrial data for use in satellite applications at Ku-band [18]. The results of measured rain rate and rain attenuation in the 10.982 GHz band have been commented and compared with ITU-R and Crane models in this paper. The results of sensitivity analysis performed on the measured data are also presented, which reveal the dependence of effective slant path, rain height, and overall path reduction factor on rain rate.

## 2. RAIN RATE AND RAIN ATTENUATION MEASUREMENTS

### 2.1. Rain attenuation

A measurement system was set up for monitoring ASTRO/MEASAT-3 beacon signal level. The receiver site was located on the roof top of the electrical and computer engineering building at Islamic International University Malaysia in Kuala Lumpur at 3.3°N and 101.7°E. The antenna elevation angle is approximately 77.4°, and the station height above mean sea level is 22.0 m. The receiver antenna, an offset parabolic antenna dish having a diameter of 2.4 m, was pointed toward MEASAT-3, situated at 91.5°E (geostationary). The specifications of MEASAT-3 transponder are given in Table I, whereas its footprint coverage is presented in Appendix F1, F2, and F3. The Ku-band satellite signal has a

Table I. Specifications of Ku-band MEASAT-3 transponders.

| Transmitted EIRP (dB-W) | G/T (dB/K)    | TWTA power (W) | Channel polarization | Bandwidth | Frequency band (GHz) |             |
|-------------------------|---------------|----------------|----------------------|-----------|----------------------|-------------|
|                         |               |                |                      |           | Uplink               | Downlink    |
| 57 (Maximum)            | +14 (Maximum) | 120            | Linear               | 24×36 MHz | 13.75–14.5           | 10.95–12.75 |

frequency of 10.982 GHz and is vertically polarized. The vertically polarized Ku-band beacon signal 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 (i.e., the down-converted signal) was fed to a spectrum analyzer via RG-11 coaxial cable at a sampling rate of one sample every 10 s (i.e., 10-s interval). The output of spectrum analyzer was sent to the computer via general purpose interface bus 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 the maximum rain attenuation measured is 36.0 dB at 0.001% of the time, which occurs at rain rate of 200 mm/h. The received beacon signal is consisted of two components (rain attenuation and tropospheric scintillation). Karasawa and Matsudo [19] proposed a periodogram method of power spectrum density technique to separate out two propagation effects by using a low-pass filter (LPF) with a suitable cutoff frequency. The scintillation effect was removed by using an LPF of 25 mHz cutoff frequency.

$$A(t) = \frac{1}{t_a} \sum_{t-t_a}^{t_a} A_r(t) \quad (1)$$

where  $A_r(t)$  is the raw (unfiltered) measured attenuation, and the moving average  $t_a$  is 10 s.

This separation technique is briefly illustrated in Figures 1(a,b). 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. For instance, attenuation is calculated by subtracting the clear sky signal power from the measured excess attenuation value at that instant.

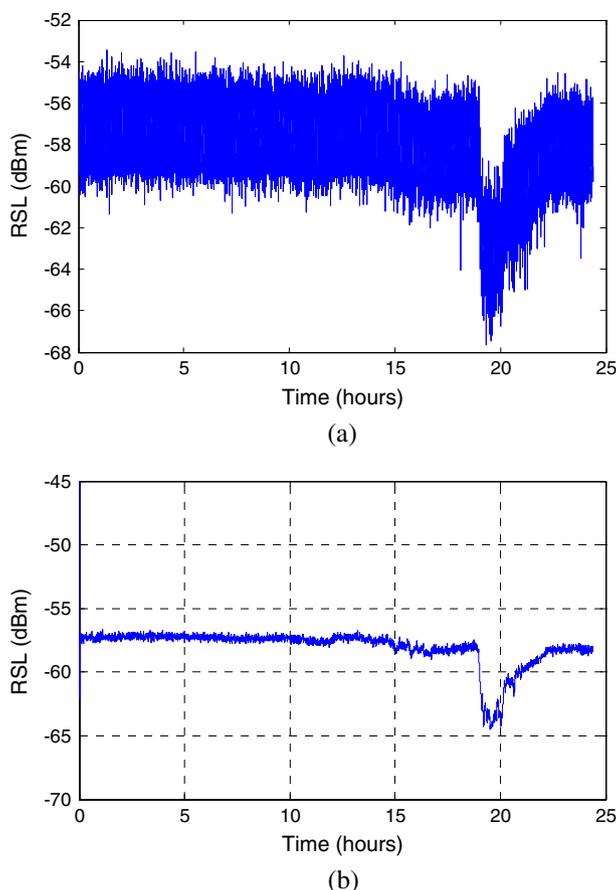


Figure 1. (a). Received signal level along the slant path for one rainy day (before filtering). (b). Received signal level along the slant path for one rainy day (after filtering).

## 2.2. Rain rate measurement and calibration

The point rainfall rate with 1-min integration time was measured using a tipping bucket arrangement of a diameter of 20 cm with 0.5 mm sensitivity. The rain gauge had its own programmable data logger, which records the time of each tip to an accuracy of 0.1 s. The clock of the logger was regularly synchronized with that of the computer every 10-s time interval in order to retrieve better data resolution. The gauge was calibrated in the laboratory by using a water measuring tube that can precisely measure 0.5 ml of water. Rain gauge resolution  $r$  (the amount of rainfall the rain gauge is set to detect) is usually expressed in millimeters and can be defined by [20]

$$r = \frac{4V}{\pi D^2} \quad (2)$$

where  $V$  is the bucket volume, and  $D$  is the rain gauge diameter (of the outer funnel).

The total volume of water was measured for six tips, where the diameter of the water collecting surface is also 22.5 cm. This experiment was repeated five times. The average water per tip (16.47 ml) recorded is 20.16 ml, which corresponds to 0.507 mm of bucket size (i.e., the gauge resolution), whereas the specified water per tip is 19.88 ml (i.e.,  $V = 0.25 \pi D^2 r$ ). Hence, the gauge underestimates measurement only by about 1.4%, which is within the equipment's specified  $\pm 5\%$  tolerance limit. The tipping buckets with sensitivities of 0.1 and 0.2 mm were found not suitable for measuring medium and high rainfall rates. For instance, in Malaysia, 0.01% rain rate is higher than 120 mm/h, which records four 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 higher than 100 mm/h rain rate. The cumulative distribution (CD) can be obtained by computing the probability  $P(R \geq r_t)$  that 1-min rainfall intensity  $R$  (mm/h) exceeds a threshold value  $r_t$  (mm/h) for a time  $T$ , expressed as [8, 9]

$$P(R \geq r_t) = N_t / N_T \quad (3)$$

where  $N_t$  is the number of rain rate data  $> r_t$ ; and  $N_T$  is the time in minutes in a time period  $T$ .

Rain rate data in 2 years may not be statistically stable for propagation studies due to seasonal variability (variation of rain rate CD from year to year, most especially at high rain rates). We have assumed that the 2-year CD will be fairly stable as the average annual value of the rainfall rate data will have a lower variance and thus smaller variation. More so, the use of single year, measured rain rate statistics as a model for the prediction of the statistics for subsequent years has been evaluated [21, 22]. No significant differences were found between year-to-year and location-to-location variability estimates relative to Crane and Consultative Committee International Radio (CCIR) rain rate prediction models. The collocated and synchronized rainfall rate and rain attenuation time series during 1 day are shown in Figures 2. Maximum rain attenuation (about 19 dB) occurs when the rain rate is maximum (about 100 mm/h), showing good correlation between the two measured variables.

## 3. OVERVIEW OF RAIN-INDUCED ATTENUATION PREDICTION MODELS

A large number of models have been proposed to predict Ku & Ka-band rain-induced attenuation. The prediction models are based on the use of geophysical data, such as surface point rain rate, point-to-path variation in rain rate, rain height or specific attenuation, provided the surface point rain rate is known. The ITU-R Rec. P.618-10 [23] is the newest version, which can predict the long-term statistics of the slant path rain attenuation at a given location for frequencies up to 55 GHz. The Bodtmann and Ruthroff model [24] predicts the specific attenuation as a function of rain rate. Simple attenuation model (SAM) [25] predicts the path attenuation as a function of rain rate based on an effective rain rate profile that is exponential in shape. The Kasarawa model [26] and Gracia Lopez model [27] predict the path attenuation as a function of rain rate and require the point rain rate. Dissanayake, Allnutt, Haidara (DAH) model [28] and Crane Global model [1] predict the attenuation exceedance for the slant path.

Others include Flavin model, Matricciani model, and Svjatogor model; and detailed descriptions of most of these prediction models could be found in the Actions COST 255 final reports [29]. The development of propagation impairment mitigation techniques (PIMT), channel modeling for Earth satellite and terrestrial paths above 20 GHz for application in PIMT development and system design, and PIMT

## COMPARISON OF MEASURED RAIN ATTENUATION

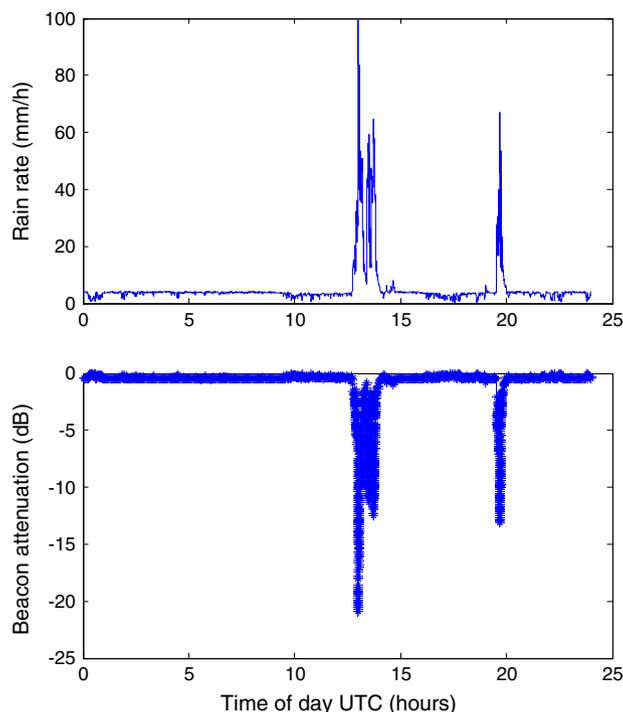


Figure 2. Collocated and synchronized rainfall rate and rain attenuation time series during 1 day.

performance assessment by simulation was reported in [30]. ACTS propagation experiment was designed to obtain slant path beacon attenuation statistics at Ka-band frequencies (20.2 and 27.5 GHz) [31]. Bryant model [32] described the breakpoints in rain rate and attenuation exceedances. The breakpoint may be described as the point at which the slope (attenuation or rain rate) changes, indicating tendency for saturation. A breakpoint exists in the rain exceedances, evident only for sites with convective rain events of sufficiently high rain rates, that is, probably greater than 150 mm/h [3, 33]. The breakpoint is more evident if the integration time is short, because the fine structure in the rain rate could be resolved [34]. In the tropical climates when the rain rate increases and approaches the breakpoint, the rain structure gradually changes from stratiform to convective in tropical climates when rain rate increases and approaches the breakpoint.

## 4. RESULTS AND DISCUSSIONS

### 4.1. Comparison of measurements with predictions

The results of slant path measurements at Islamic International University Malaysia, Malaysia, are compared with the two widely accepted models (ITU-R P.618-10 model and Crane global model) in this work. The main focus is rain-induced attenuation, so other atmospheric effects such as cloud attenuation, scintillation, and atmospheric gasses (described in the ITU-R P.618-10 and DAH models) were not considered. The rainfall rate exceedance of the 2-year measurements was compared with those predicted by ITU-R P.837-6 [35] and Crane global model, as shown in Figure 3, where both models have underestimated the measured rainfall rate, especially at high rates. For example, at 0.01% , if the time rain rate exceeded, the former predicts about 94.24 mm/h, whereas the latter predicts 90.2 mm/h; and the measured value was 133 mm/h. The measured rain attenuation exceedance is also compared with predictions, as shown in Figure 4 and then tested against the two prediction models using the ITU-R P.311-13 [36]. The ratio of predicted attenuation,  $A_p$  (dB), to measured attenuation,  $A_m$  (dB), is

$$S_i = A_p/A_m \quad (4)$$

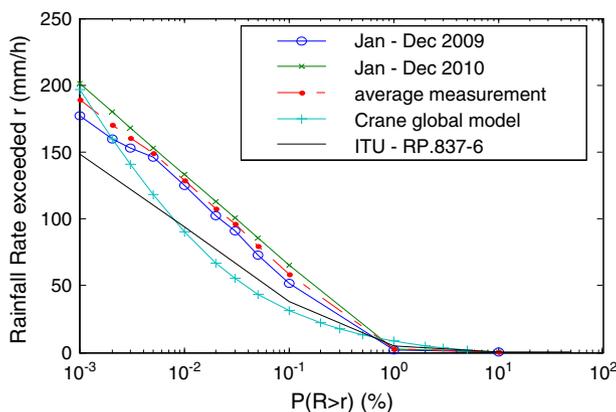


Figure 3. Comparison of rainfall rate exceedance.

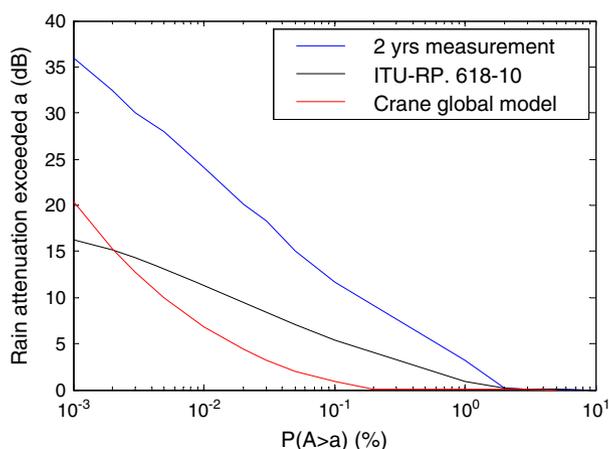


Figure 4. Comparison of rain attenuation exceedance.

And the test variable is

$$V_i = \begin{cases} \ln S_i (A_m/10)^{0.2} & \text{for } < 10 \text{ dB} \\ \ln S_i & \text{for } \geq 10 \text{ dB} \end{cases} \quad (5)$$

The mean  $\mu_V$ , standard deviation  $\sigma_V$ , and r.m.s. value  $\rho_V$  of the test variables ( $V_i$  values) for each percentage of time are presented in Table II. Note that

$$\rho_V = (\mu_V^2 + \sigma_V^2)^{1/2} \quad (6)$$

In the comparison of prediction methods, the best prediction method produces the smallest values of the statistical parameters. The two prediction models underestimate measured attenuation, with Crane global model even yielding higher errors as shown in the table. The applicability of the Rec. ITU-R P.618-10 in tropical and equatorial climates has extensively been researched and hotly disputed [3]. In the ITU-R P.839-3 rain height model [37], rain height depends on latitude, and it is assumed to be constant. This method is inadequate because rain height actually varies with rain intensity in tropical

Table II. Error, mean, standard deviation, and % RMS values for each percentage of time.

| Prediction models  | Exceedance probability (%) |       |       |       |       |       |       |       | $\mu_V$ | $\sigma_V$ | % $\rho_V$ |
|--------------------|----------------------------|-------|-------|-------|-------|-------|-------|-------|---------|------------|------------|
|                    | 0.001                      | 0.003 | 0.005 | 0.01  | 0.03  | 0.05  | 0.1   | 1.0   |         |            |            |
| ITU-R P.618-10     | -1.00                      | -0.76 | -0.74 | -0.76 | -0.76 | -0.79 | -0.76 | -0.76 | -0.788  | 0.075      | 78.52      |
| Crane global model | -5.58                      | -0.75 | -0.85 | -1.03 | -1.53 | -1.75 | -2.00 | -2.53 | -1.785  | 1.465      | 101.84     |

and equatorial climates [1, 25]. More so, rain attenuation increases with decreasing elevation angle in the temperate climates due to the large rain cell diameter, whereas for the same rain rate, the converse is the case in the tropical climates [38, 39]. Lastly, the complex parameter 0.01% recommended by the ITU-R model for determining attenuation is not a physical quantity and therefore not obviously related to the dynamics of rain structure [32]. The dynamics of the horizontal and vertical structure of rain are directly related to rain rate, rainfall volume, local geology, and climate. In view of the substantial differences between the precipitation characteristics of the tropical and temperate regions, the models used in predicting space–earth link in temperate regions should at least be modified, if not completely replaced, for adoption in the tropical regions [40]. However, the 2-year measured data are not sufficiently convincing to knockout the suitability of the two examined models in Malaysia, more especially the ITU-R P.618-10. The 2-year period of rainfall rate measurement used in the tests may be relatively short to characterize the behavior of rain precipitation in a location, especially in view of the yearly variability of rainfall and rainfall rate. The ITU-R.618-10 method considers that at least 5 years (or more) of measurements are necessary for the prediction model.

4.2. Sensitivity analysis

The concept of rain height is widely utilized in the prediction of attenuation due to rainfall on a satellite slant path [3]. As earlier mentioned, the ITU-R P.839-3 rain height is constantly equal to the sum of 0 ° C isotherm height and a factor ( $H_R = H_0 + 0.36$ ), thereby showing insensitivity to rain rate distribution. Generally, rain attenuation on a slant path is given by

$$A \text{ (dB)} = k R_p^\alpha \text{ (dB/km)} \cdot L_E \text{ (km)} \tag{7}$$

The effective slant path  $L_E$  is

$$L_E = L_S \times (r_H r_V) \tag{8}$$

The term ‘ $r_H r_V$ ’ represents the overall path reduction, whereas the slant path  $L_S$  is given by

$$L_S = \frac{H_R - H_S}{\sin(\theta)} \tag{9}$$

Let

$$H_R = 4.5 + 0.0005 R_p^{1.65} \tag{10}$$

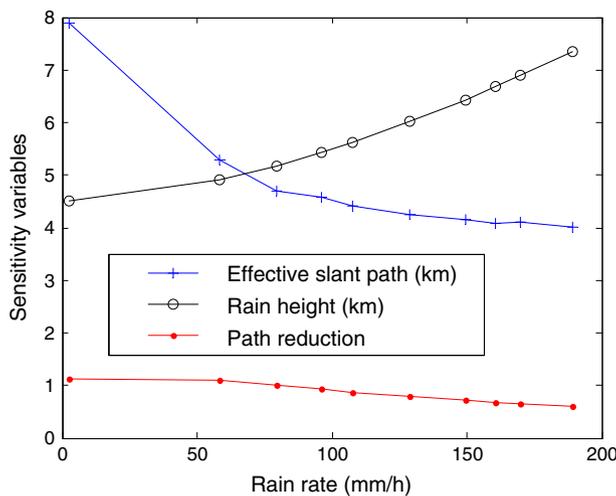


Figure 5. Relationship between sensitivity variables and rain rate.

Then, we can write

$$L_S = \frac{(4.5 + 0.0005 R_p^{1.65}) - H_S}{\sin(\theta)} \quad (11)$$

$L_E$  can be found from Equation (7) so that the term ' $r_H r_V$ ' may now be written as the ratio

$$r_H r_V = L_E / L_S \quad (12)$$

The sensitivity variables ( $H_R, L_E$ , and ' $r_H r_V$ ') were plotted against the rain rate (Figure 5), and the following set of power law equations are obtained from the results.

$$\left. \begin{aligned} L_E &= 9.025 R_p^{-0.16} \\ H_R &= 3.6693 R_p^{0.097} \\ (r_H r_V) &= 1.4477 R_p^{-0.13} \end{aligned} \right\} \quad (13)$$

The coefficient of determination for the effective slant path is  $R^2 = 0.985$  and the range of rainfall rates is 0 to 198 mm/h.

## 5. CONCLUSIONS

Rain attenuation data on earth–space links is still severely scarce in Malaysia. The results of the 2-year measurement of rainfall rates and rain-induced attenuation in vertically polarized signals propagating at 10.982 GHz have been reported in this paper and compared with the two widely accepted models (ITU-R P.618-10 model and Crane global model). The test results show that the two prediction models seem inadequate for predicting rain attenuation in the Ku-band in Malaysia. This fact is no more new as majority of researchers have reported the inadequacy of the ITU-R models in tropical and equatorial climates. However, the 2-year measured data used in this study are not sufficiently convincing to generally knockout the suitability of the ITU-R model for predicting rain attenuation in the Ku-band in Malaysia. The 2-year period of rainfall rate measurement used in the tests may be relatively short to characterize the behavior of rain precipitation in a location, especially in view of the yearly variability of rainfall and rainfall rate. The sensitivity analysis of measured data reveals that the sensitivity variables depend on rain rate, which is typical of tropical climates. The study supports the general consensus that the models used in predicting space–earth link in temperate regions should at least be modified, if not completely replaced, for adoption in the tropical regions. This will ensure design of appropriate compensation system for mitigating attenuation due to rainfall on a satellite slant path in tropical and equatorial climates.

## APPENDIX



F1. MEASAT 3 KU-BAND SOUTH ASIA BEAM



F2. MEASAT 3 KU-BAND INDONESIA BEAM



F3. MEASAT 3 KU-BAND MALAYSIA BEAM

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**Dr. Abdulrahman A. Yusuf** obtained his bachelor's (1999) and master's degrees (2005) in Electrical Engineering from the University of Ilorin, Nigeria, and a PhD degree in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Skudai, Malaysia, in 2012. His research interests include wireless mobile systems, radio propagation, and rain attenuation studies, especially in the tropics. Abdulrahman, a member of IEEE, has worked on development of a transformation model for inverting terrestrial rain attenuation data for satellite applications at Ku band in tropical regions. He has published few papers in International Journals related to antenna design and measurement and rain attenuation issues in tropical regions.



**Tharek Abdulrahman** is a Professor at the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM). He obtained his BSc in Electrical and Electronic Engineering from the University of Strathclyde, UK, in 1979; MSc in Communication Engineering from UMIST, Manchester, UK; and PhD in Mobile Radio Communication Engineering from the University of Bristol, UK, in 1988. He is the Director of Wireless Communication Centre UTM. His research interests include radio propagation, antenna and RF design, and indoors and outdoors wireless communication. He has also conducted various short courses related to mobile and satellite communication for the telecommunication industries and government bodies since 1990. He has wealth of teaching experience in the area of mobile radio, wireless communication system, and satellite communication. He has published more than 120 papers related to wireless communication in national/international journals and conferences.



**Md. Rafiqul Islam** received his BSc (Electrical and Electronic Engineering) from BUET, Dhaka, in 1987. He received his MSc and PhD both in Electrical Engineering from UTM in 1996 and 2000, respectively. He is a Fellow of IEB and Member of IEEE. He is currently Associate Professor in Electrical and Computer Engineering Department of the International Islamic University Malaysia. His areas of research interest are radio link design, RF propagation measurement and RF design, antennas design, free-space optics, and so on.

**B. J. Olufegaba** is a Professor at the Electrical & Electronics Engineering Department, University of Ilorin, PMB 1515, Nigeria. He obtained a PhD degree in Electrical Engineering from the University of Texas at Austin, Texas, in 1975.

**Dr. Jalel Chebil** obtained his PhD degree in Electrical Engineering from the Universiti Teknologi Malaysia in 1997. He is presently an Associate Professor at the Islamic International University of Malaysia.