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Earth to space link

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1. Introduction

The measurements were taken continuously from 1st January 2006 to 31st December 2008. The measured rainfall data was analyzed and presented in this chapter. Three years averaged measured rain rate and rain attenuation were compared with the cumulative probability distributions existing prediction models. Some rainfall data from selected tropical climates sites were used to make a comparison of rain rate and rain attenuation prediction.

2. The Variation of Rainfall Amount

Malaysia experiences heavy rain throughout the year and the rainfall distribution is patterned by monsoon activities. The Northeast monsoon is from October to March and the Southwest monsoon is from May to September. The Northeast Monsoon is the major rainy season in the country. The Northeast Monsoon blows from South China Sea during the months of October to March, this affects high brought rainfall to the East Coast of Peninsular Malaysia and a few other locations at Peninsular Malaysia. It was recorded by Malaysian Meteorological Department that the Northeast Monsoon has give the highest rainfall in all location in Malaysia because the wind of this monsoon blows from South China Sea without obstruction by island, peninsular and mountain. Monsoon weather systems that develop in the conjunction with cold air outbreaks from Siberia produce heavy rains, which often cause severe floods along the east coast of Malaysia. The Southwest monsoon is comparatively drier throughout the country except for the state of Sabah. During this season, most states experience monthly minimum rainfall. This is attributed to relatively stable atmospheric conditions in the equatorial region. In particular, the dry condition in Peninsular Malaysia is accentuated by the rain shadow effect of the Sumatran mountain range. During the inter-monsoon periods, winds are light and variable. Morning skies are often clear and this favours thunderstorm development in the afternoon. In the states of west coast of Peninsular Malaysia, thunderstorms contribute to a mean monthly rainfall maximum in each of the two transition period.
Figure 1 shows the monthly variation of rainfall amount at USM. A relationship between the monsoon activities and monthly rainfall amount can be studied. Based on the measurement, the total rainfall for the year 2006 was 1835 mm, for the year 2007 was 2065 mm and for the

year 2008 was 2111 mm. The total average annual rainfall at USM for three years was 2004 mm. The total average rain accumulation for the Northeast Monsoon (October – March) and Southwest Monsoon (May – September) was 1192 mm (59% of the annual averaged) and 640 mm (32% of the annual averaged), respectively. The maximum rainfall amount was in November for the year 2006 that is 274 mm, in September for the year 2007 that is 287 mm and in December for the year 2008 that is 280 mm. The minimum rainfall amount was in July for year 2006 that is 66mm, in August that is 58 mm and in May that is 5 mm. From this figure, it indicates that the rainfall amount for Northeast Monsoon is higher than Southwest Monsoon.

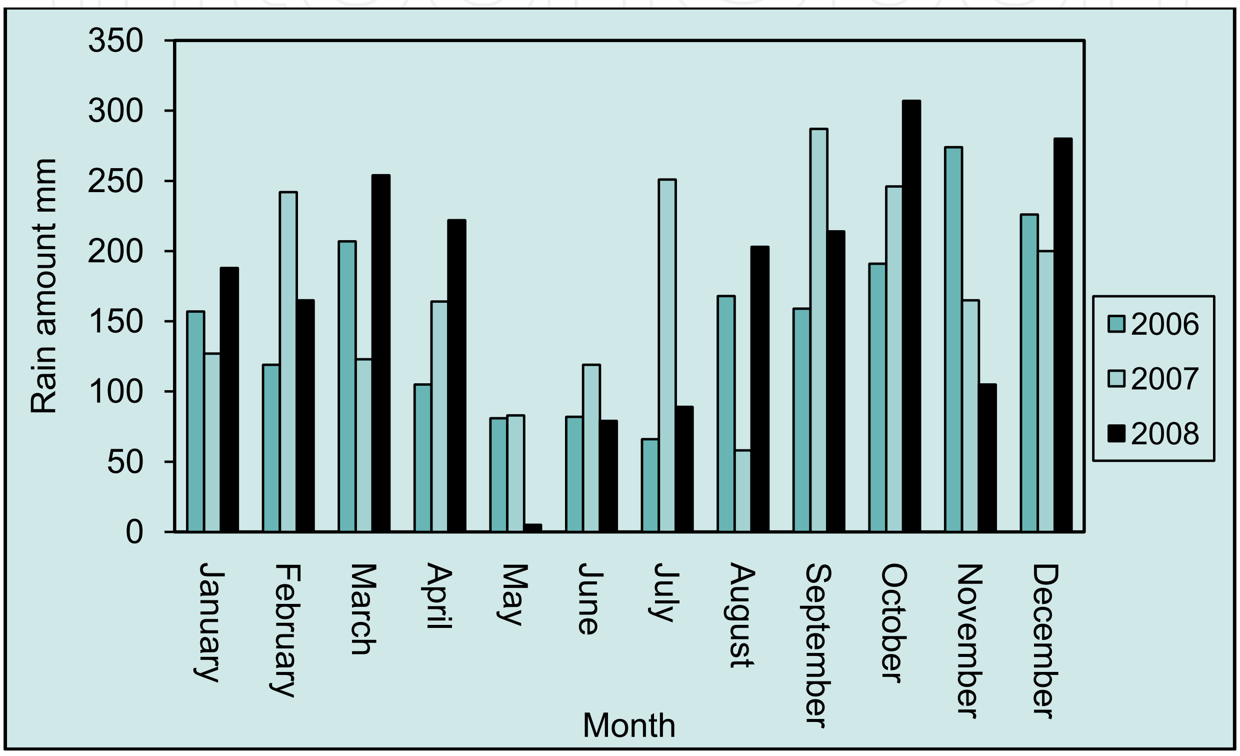

Fig. 1. Variation of monthly rainfall amount at USM for the year 2006, 2007 and 2008

3. Testing of Prediction Models

The achievement of high availability targets in advanced satellite link design requires a deep knowledge of the radio channel behavior. The effects due to different atmospheric causes, such as precipitation, clouds, atmospheric gases and tropospheric scintillation can be measured quite accurately by means of satellite beacon signals. Most prediction models of probability distribution function (pdf) of exceeding rain attenuation in slant path, based on rain rate pdf, when tested against concurrent satellite beacon measurements show large errors (Matricciani, *el at.*, 2008).

Two types of prediction tests used for this analysis:

1. The percentage error
2. The Real Mean Square (RMS) error

For certain percentage of time (from 0.001 to 1 percent of the year), for which data are available, percentage relative error, E_{rel} (percent) between the predicted value and the measured value are calculated

$$E_{rel} = \frac{A_{predicted} - A_{measured}}{A_{measured}} \times 100\% \tag{1}$$

The mean error, μ_e and standard deviation, σ_e are used to calculate the Root Mean Square, D_e (RMS). The parameter is defined as follows

$$D_e = [(\mu_e)^2 + (\sigma_e)^2]^{1/2} \tag{2}$$

According to evaluation procedures adopted by the CCIR the preferred prediction method is the one producing the smallest RMS values (CCIR, 1983)

4. Statistical analysis rainfall

4.1 The correlation of Rain Rate and Rain Attenuation

Fig. 2 shows a typical variation of rain rate and rain attenuation measured on a rainy day (2nd March 2008). The rapid small-scale fluctuations of the signal level are because of ionospheric and tropospheric scintillations and slower variation correspond to rain events - fade. At certain times, the decrease in the relative signal strength (attenuation) and the increase in the rain rate are coincidental, however at other times, the decrease in the signal strength was leading the increased rain rate. It is probably the result of raindrops held aloft by updrafts in the cloud, and then their time of arrival at the ground would be considerably delayed. This delay time is variable and is as long as 4–8min (Ramachandran, *et. al.*, 2004, Mandeep, 2008). In the data presented in Fig. 2, delay (corrections) time of 8 min was accounted for when investigating the correlation between rain rate and rain attenuation.

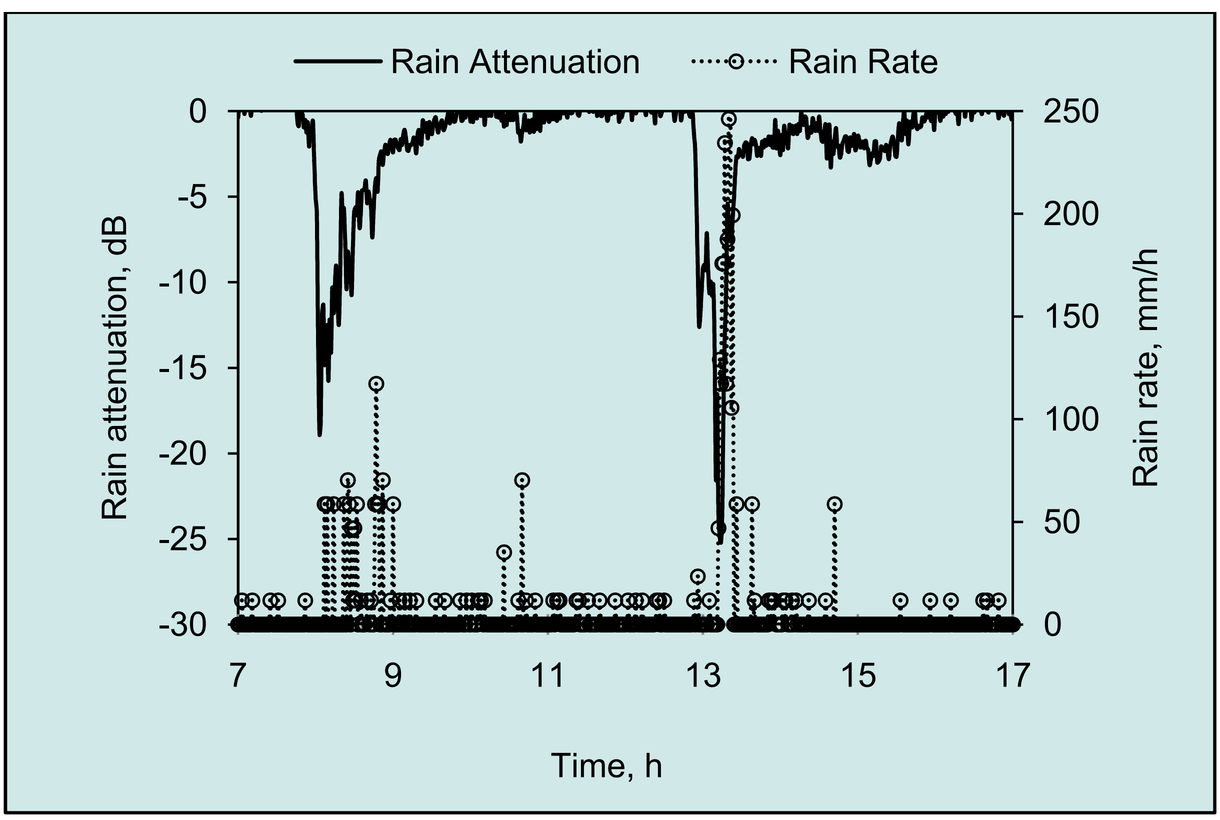

Fig. 2. Time series record of attenuation and rain rate

To determine the nature and strength of the relationship between rain rate and rain attenuation, correlation analysis has been done to indicate the strength of the relationship between rain rate and rain attenuation is high. Fig 3 shows the relation between rain rate and rain attenuation. Form that figure, the dots are obtained by straightforwardly plotting rain attenuation versus rain rate and the solid line is the best fit curve obtained by fitting rain attenuation versus rain rate. The R- square is 91.39%. It indicates that the correlation between rain rate and rain attenuation is high.

The attenuation for the site was a logarithmic function of rain rate and can be simplified as:

$$A\ (\mathrm{dB}) = 0.054R^{1.2315}$$

where A denotes as attenuation and R denotes as the site rain rate, mm/h. This empirical equation would be helpful to system designer to determine the link margin at the site. Calculating by using this empirical equation, a threshold of 19.6 dB is considered as the economical limits.

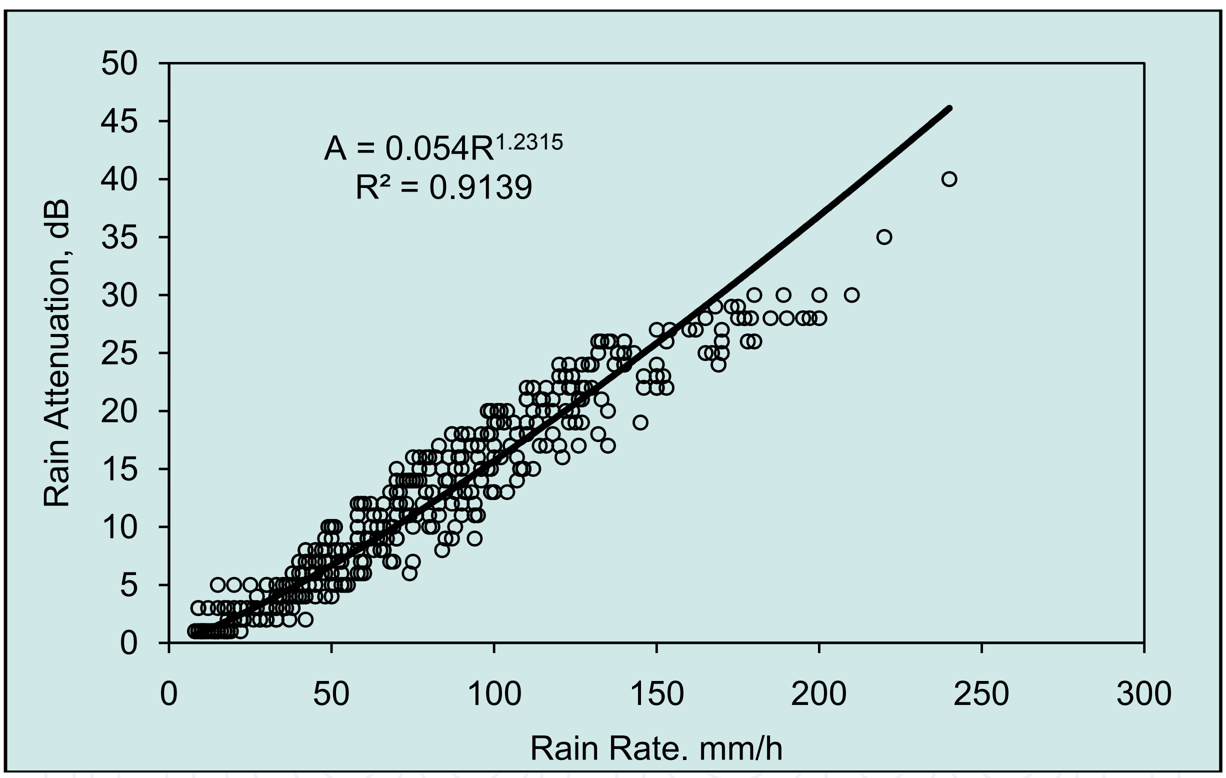

Fig. 3. The correlation between rain rate and rain attenuation

4.2 Statistical Confidence Level and Interval of the Measured Data

In statistics, a confidence interval (CI) is an interval estimate of a population parameter. Instead of estimating the parameter by a single value, an interval likely to include the parameter is given. Thus, confidence intervals are used to indicate the reliability of an estimate. How likely the interval is to contain the parameter is determined by the confidence level or confidence coefficient. The end points of the confidence interval are referred to as confidence limits. Increasing the desired confidence level will widen the confidence interval. For analysis purpose, a 95% confidence level was used because it is recommended by many statistical analysts. By using Minitab software, the confidence limits for 95%

confidence level were calculated. Fig 4, 5 and 6 show the confidence level of cumulative distribution of measured rain rate data in the year 2006, 2007 and 2008, respectively. In any statistical investigation, the variations of values in a measured data are due to random and systematic errors. The measured rain rate data for the year 2006, 2007 and 2008 lie in between the 95% confidence limits. The R-square is 99.7%, 99.2%, 97.8%, respectively. Therefore, these rain rate data are suitable to be used for comparison with models.

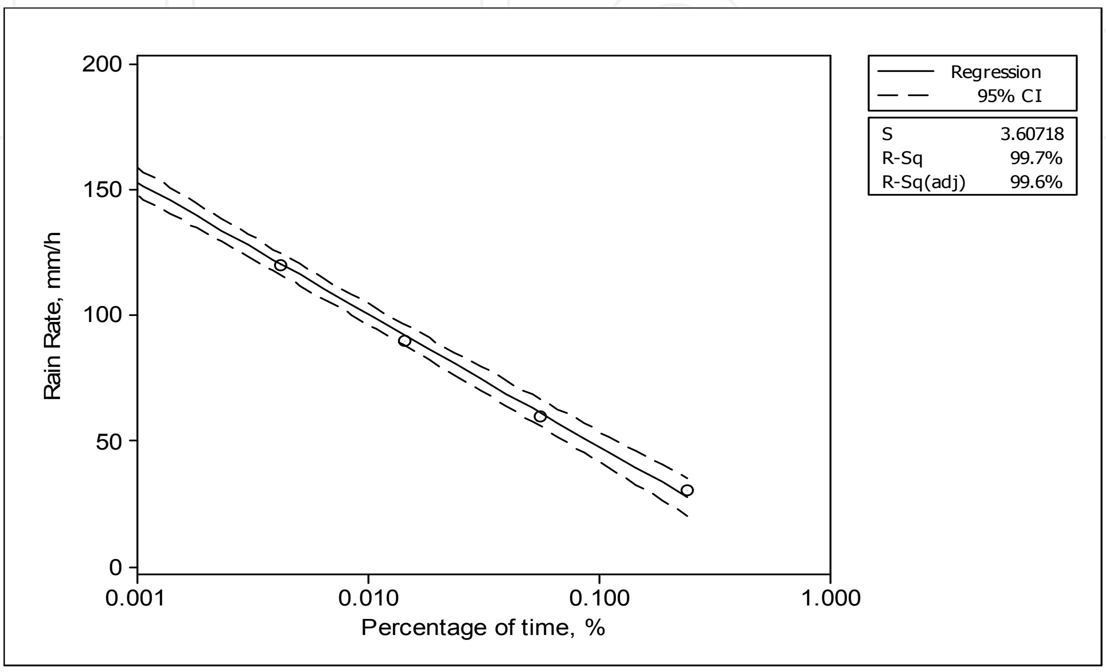

Fig. 4. The confidence level of cumulative distribution of measured rain rate data in year 2006

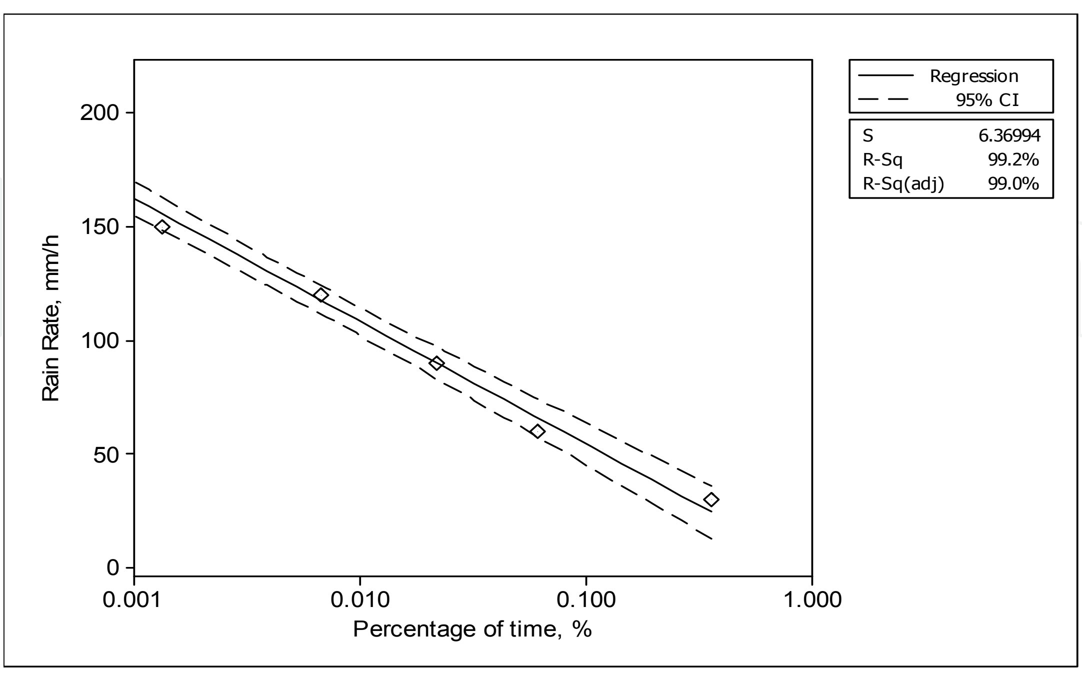

Fig. 5. The confidence level of cumulative distribution of measured rain rate data in year 2007

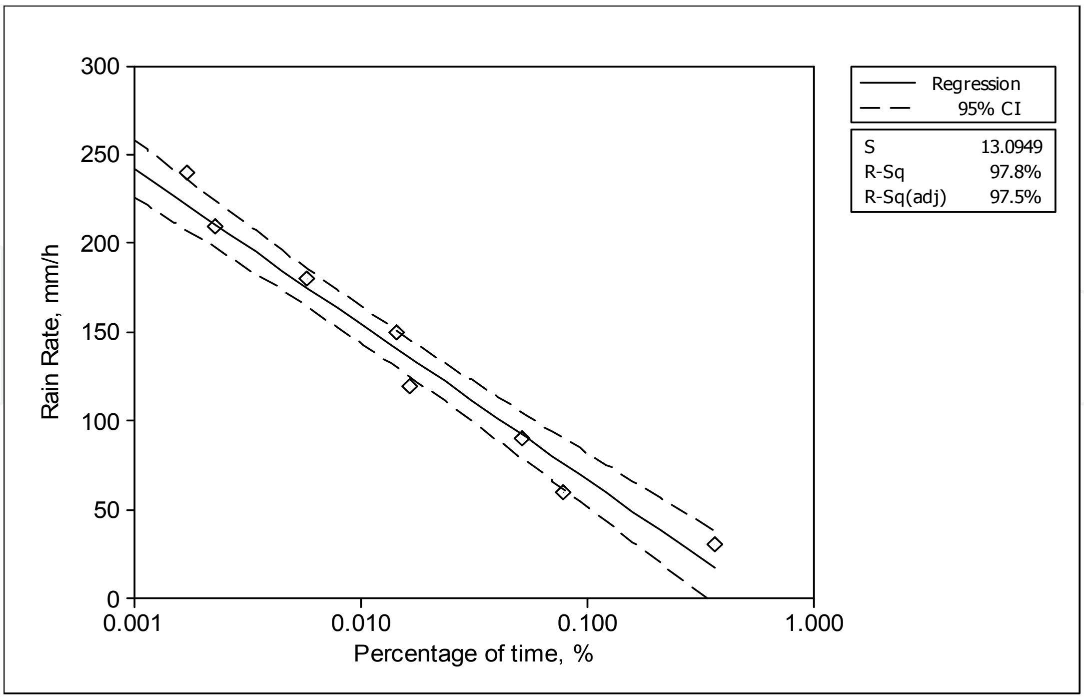

Fig. 6. The confidence level of cumulative distribution of measured rain rate data in year 2008

To calculate the confidence limit, having drawn a random sample and calculated the mean and standard deviation, the lower confidence limit (LL) is found by

$$LL = \bar{X} - z\left(\frac{\alpha}{2}\right)s_{\bar{x}} \tag{3}$$

In a similar way, the upper confidence limit (UL) is found by

$$UL = \bar{X} + z\left(\frac{\alpha}{2}\right)s_{\bar{x}} \tag{4}$$

where a is the significance level. At 95% confidence level, $z\left(\frac{\alpha}{2}\right)$ is equal to 1.96 and $s_{\bar{x}} = \frac{s}{\sqrt{N}}$, where s is the standard deviation and N is the sample size.
By using equation (3) and (4), the confidence limits were calculated for 95% confidence level. The confidence limits are calculated for the rain attenuation data in year 2006, 2007 and 2008 data are shown in Fig 7, 8 and 9. The measured rain attenuation data lies in between the 95% confidence limits for the entire measurement time. Hence, these rain attenuation data are suitable to be used for comparison with models.

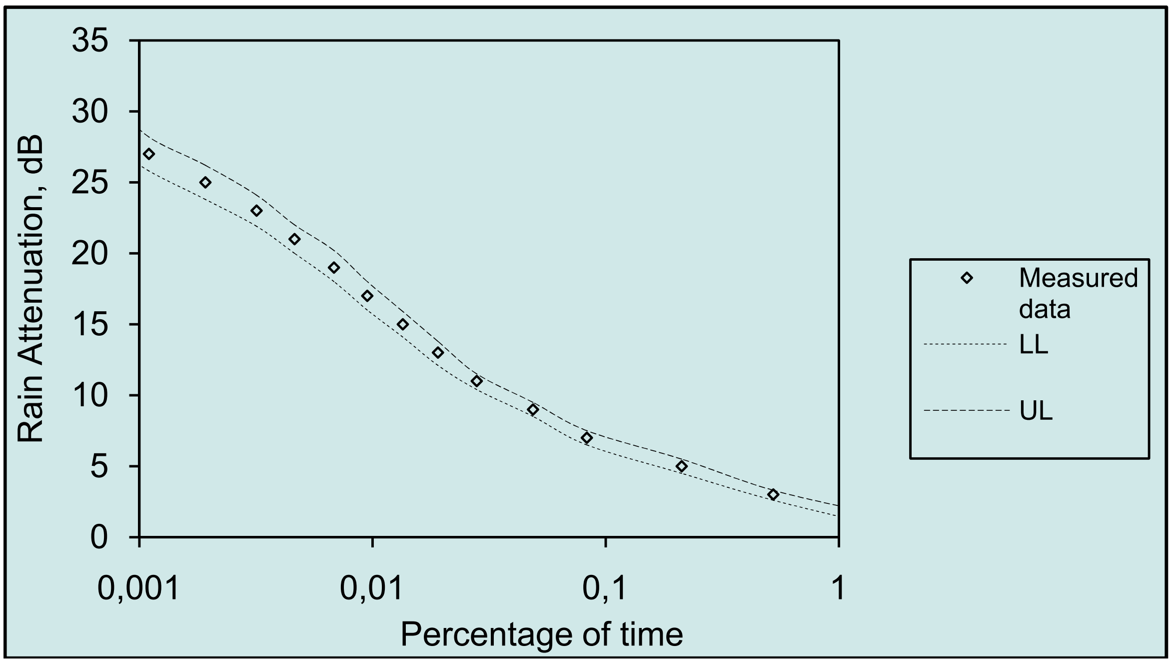

Fig. 7. The confidence level of cumulative distribution of measured rain attenuation data in year 2006

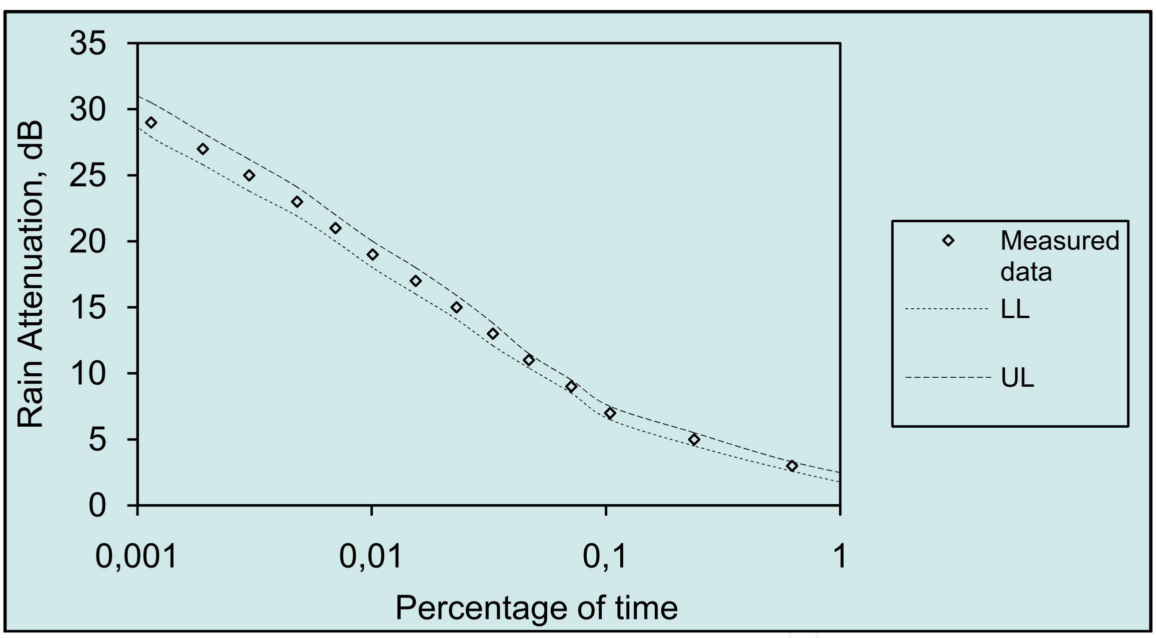

Fig. 8. The confidence level of cumulative distribution of measured rain attenuation data in year 2007

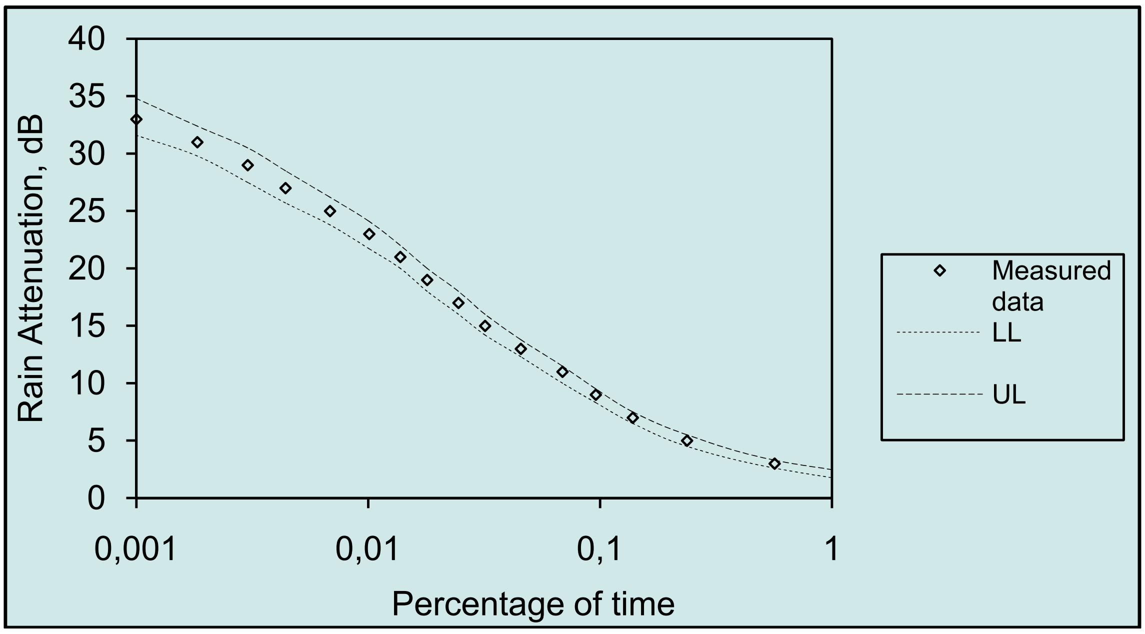

Fig. 9. The confidence level of cumulative distribution of measured rain attenuation data in year 2008

5. Rain Rate, Rain Attenuation Analysis

Communication systems operating at frequencies beyond 10 GHz in tropical and equatorial climates are subjected to many fade occurrences due to heavy rain. The information on rain rate and attenuation statistic is useful in link budget design. The considerable average worst month from year to year and within individual years is important in the planning of satellite earth-link design.

Rain rate is the volume of liquid water that falls through a unit area per unit time period. Rain attenuation is the depletion of electromagnetic energy during propagation through rain, caused by raindrop scattering and absorption. Worst month distribution of rain rate and attenuation is defined as the highest rain rate and attenuation, respectively within a set of individual monthly distributions of rain rate and attenuation for a year.

Best fit lines of the annual cumulative distribution of measured rain rate and rain attenuation for these three years have been used to make the comparison.

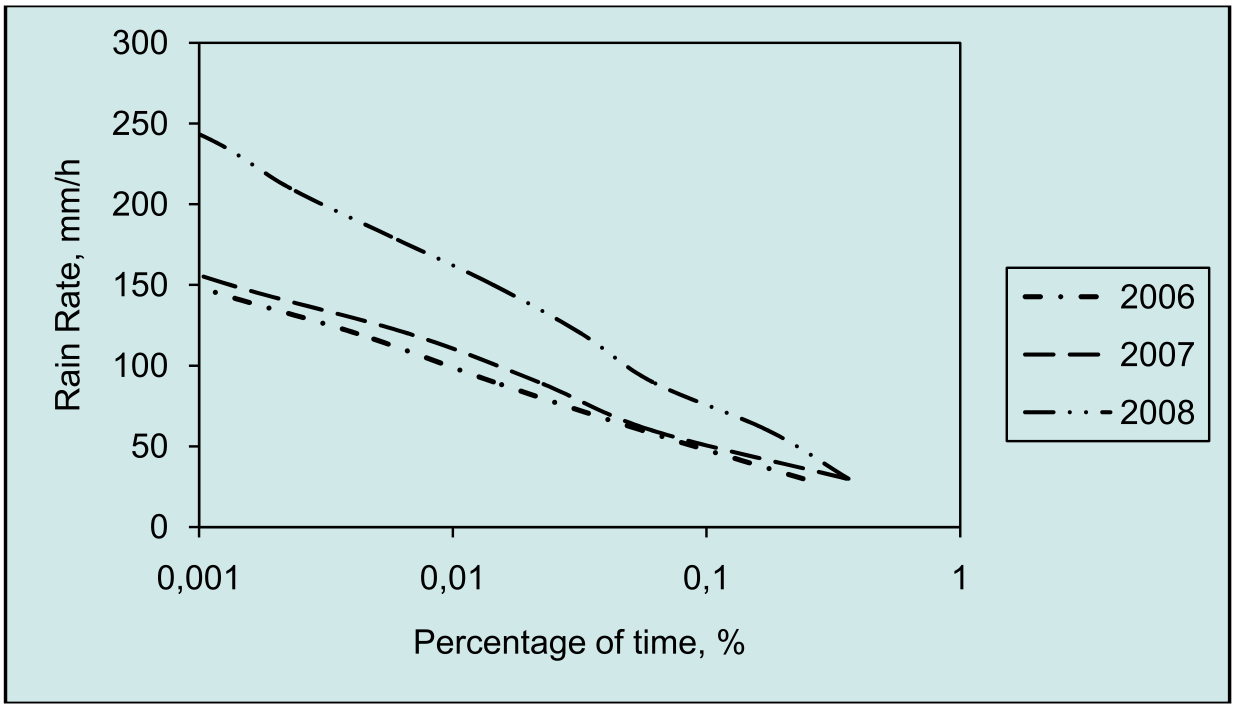

Fig. 10. Cumulative distribution of measured rain rate

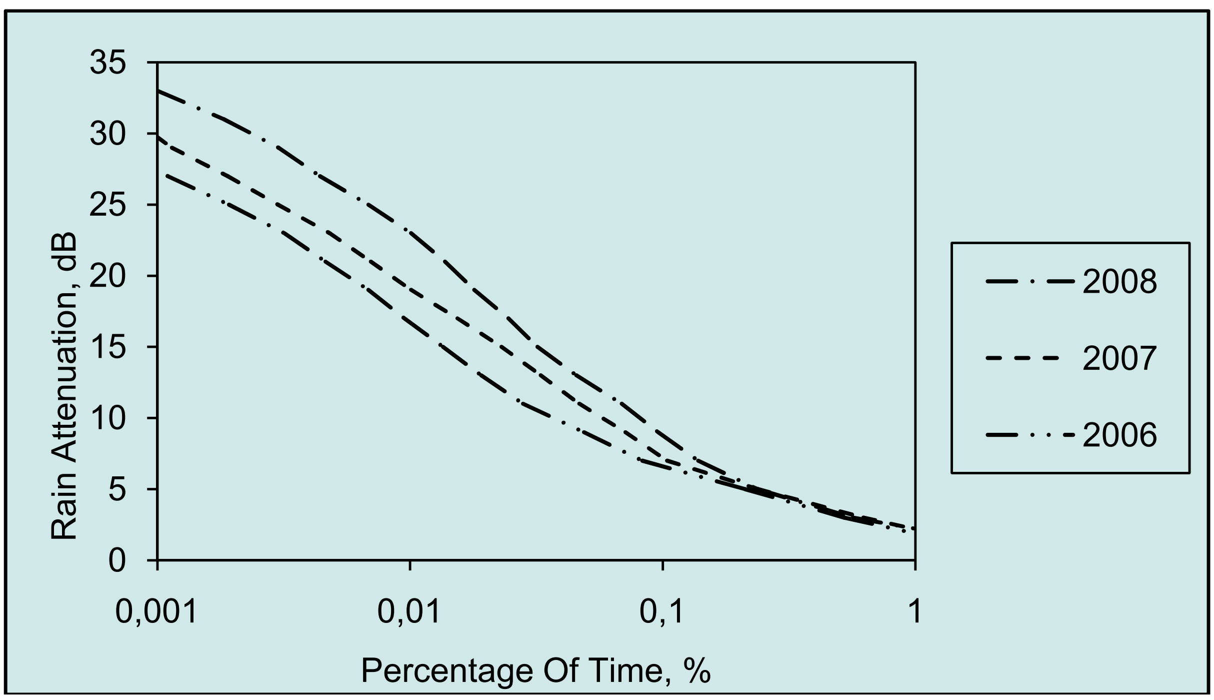

Fig. 11. Cumulative distribution of rain attenuation

Fig 10 and Fig 11 show the annual cumulative distribution of rain rate and rain attenuation for three years (2006-2008), respectively. Table 1 shows the record of rain rate and rain attenuation at point 0.01% of time and maximum point for the year 2006, 2007, 2008.

Year	Rain Rate. mm/h		Rain Attenuation, dB	
	At point 0.01%	Maximum	At point 0.01%	Maximum
2006	100	180	17	29
2007	110	210	18	31
2008	160	270	28	31

Table 1. The record of rain rate and rain attenuation at point 0.01% of time and maximum point for the year 2006, 2007, 2008

6. Worst Month Statistics

Worst month distribution of rain attenuation is defined as the highest rain attenuation within a set of individual monthly distributions of rain attenuation for one year. Rain attenuation data for year 2006, 2007 and 2008 at USM was analyzed.
In planning of the design of reliable communication systems, the required statistics of propagation effects is relevant to the worst month reference. On the other hand, the reference statistics for several propagation prediction methods are the long term average annual distribution. Therefore, the conversion of the yearly statistic to the worst month is important. The annual and worst-month rain attenuation exceedance curve is shown in Fig.12, Fig 14 and Fig 16 for year 2006, 2007 and 2008, respectively. The worst month for 2006, 2007 and 2008 were November, October and March, respectively. The Q factor as a function of annual percentage of exceedance for Ku-band rain attenuation is shown in Fig.13, Fig 15 and Fig 17 for year 2006, 2007 and 2008, respectively.

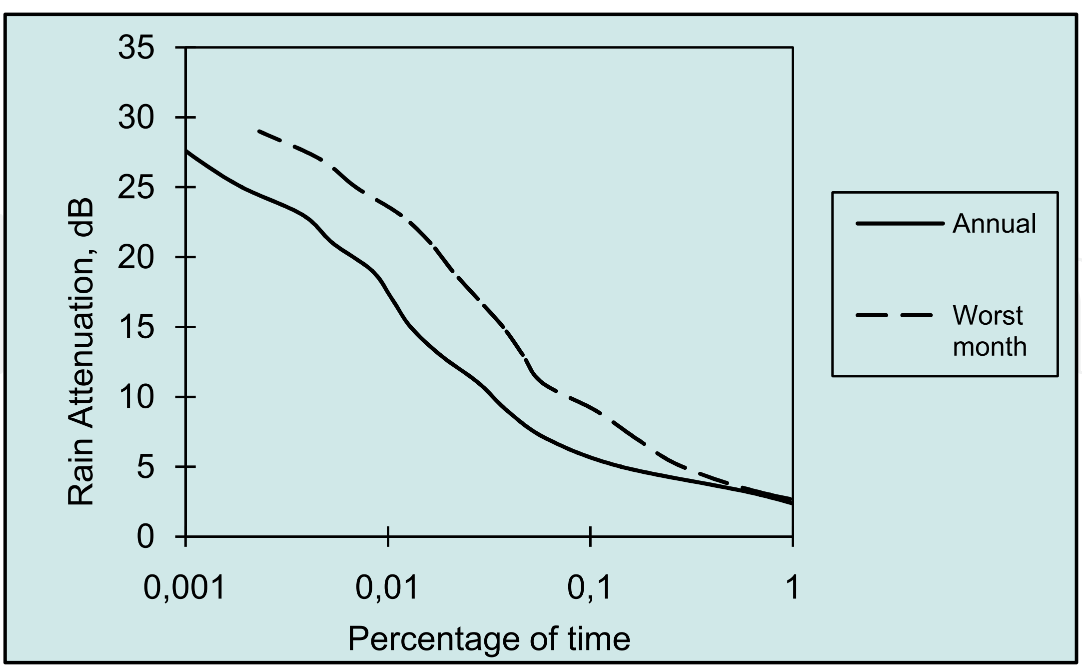

Fig. 12. The annual and worst-month rain attenuation exceedance curve at Ku-band for year 2006

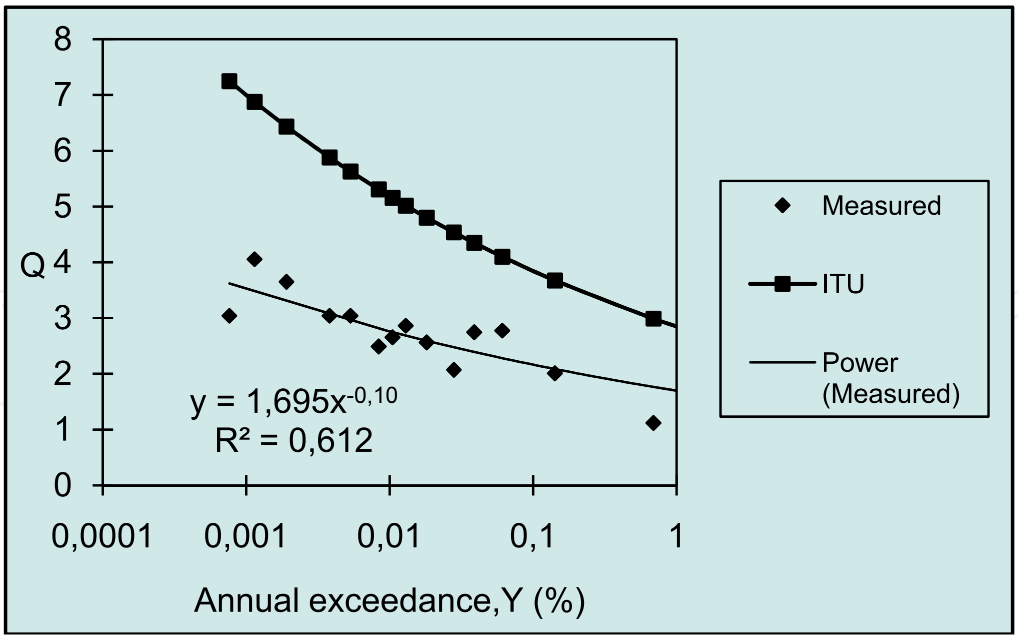

Fig. 13. The Q factor as a function of annual percentage of exceedance for rain attenuation at Ku-band for year 2006

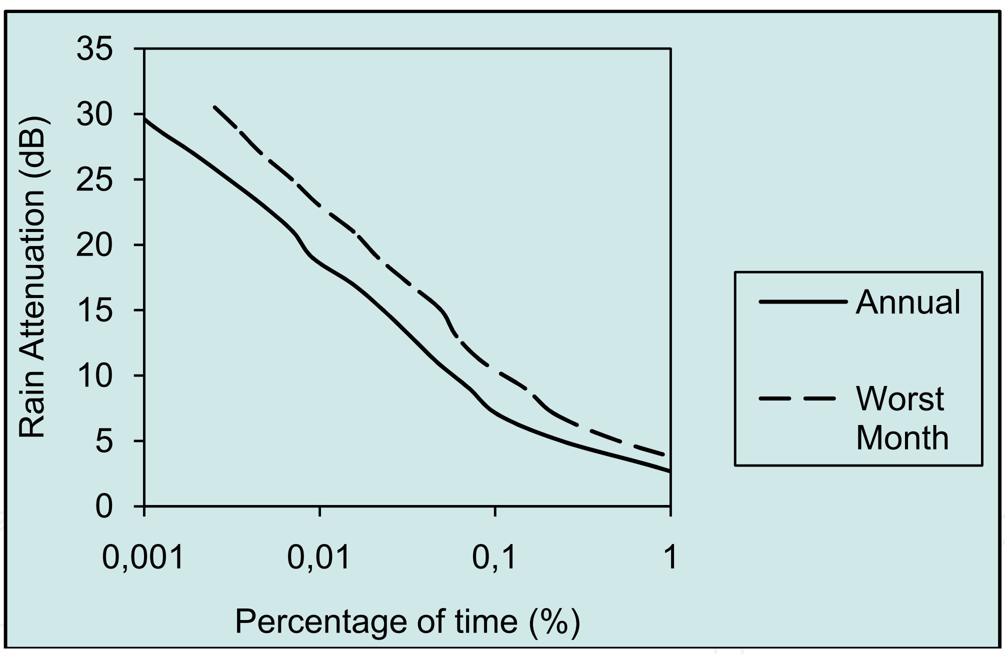

Fig. 14. The annual and worst-month rain attenuation exceedance curve at Ku-band for year 2007

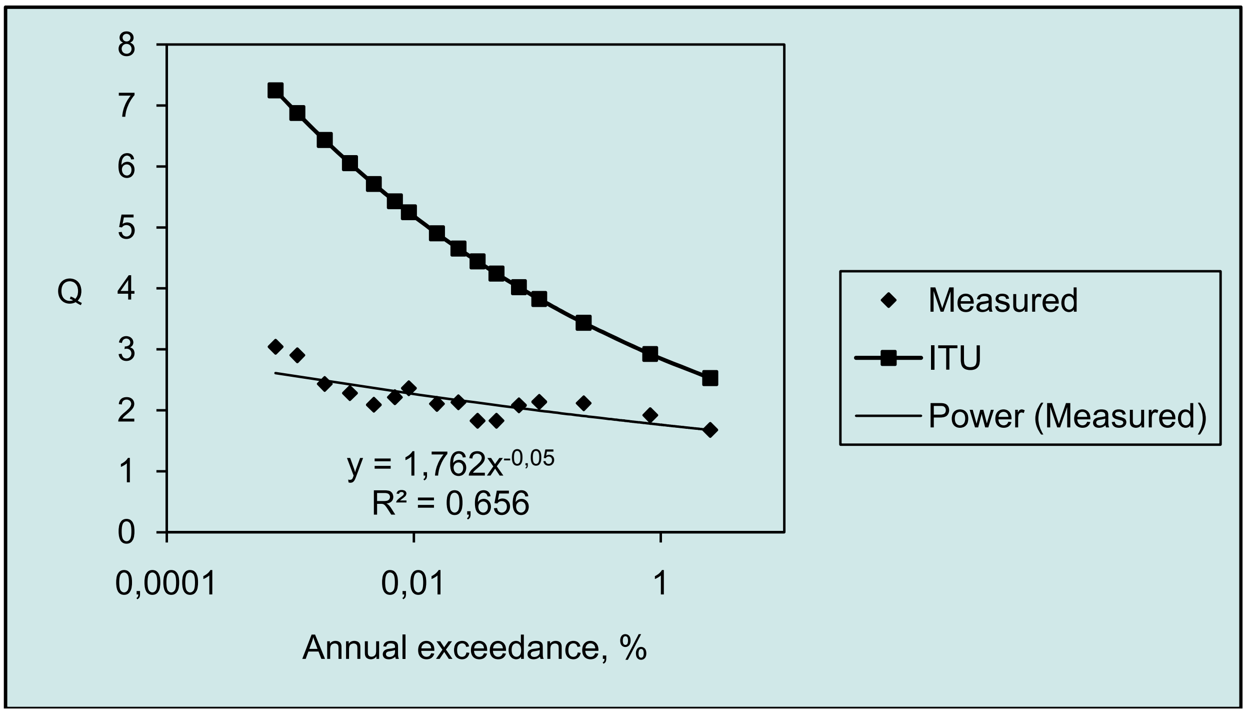

Fig. 15. The Q factor as a function of annual percentage of exceedance for rain attenuation at Ku-band for year 2007

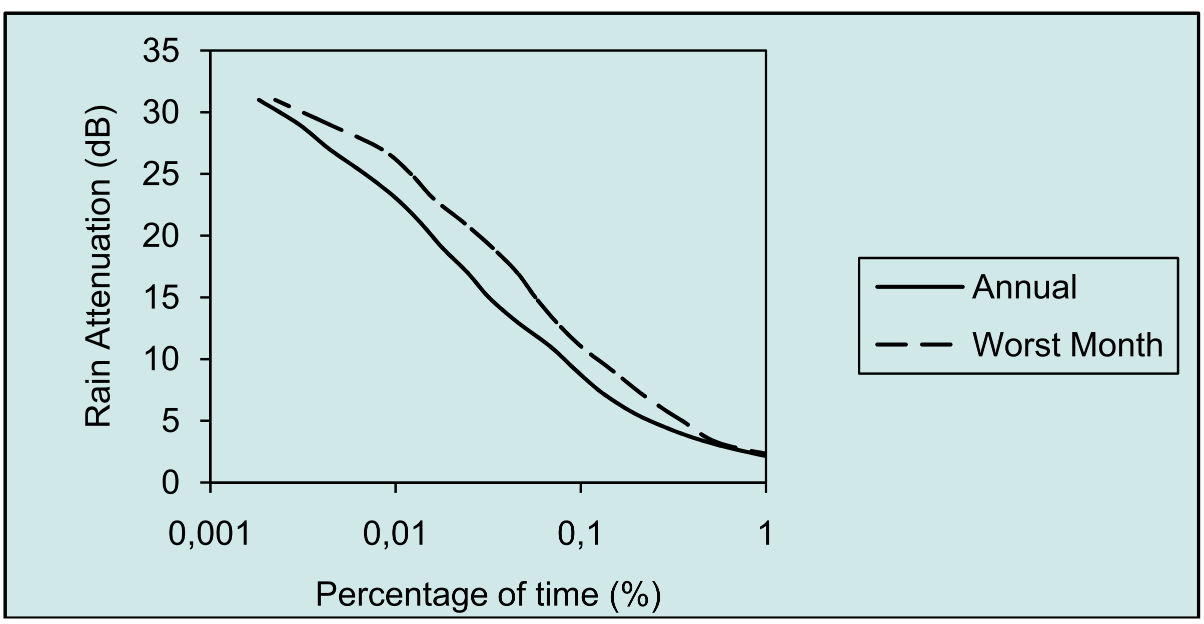

Fig. 16. The annual and worst-month rain attenuation exceedance curve at Ku-band for year 2008

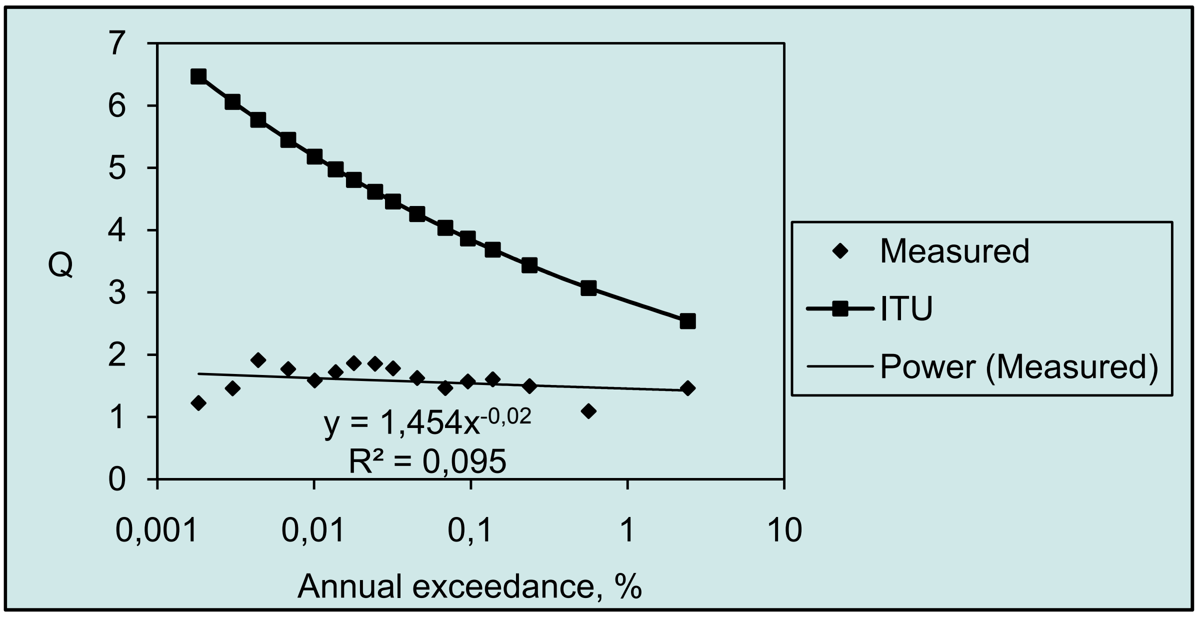

Fig. 17. The Q factor as a function of annual percentage of exceedance for rain attenuation at Ku-band for year 2008

The Q factor for rain attenuation was found to follow the power law of the form $Q=AY^{-\beta}$. Table 2 shows the parameter A and β for year 2006, 2007 and 2008.

Year	A (Proposed by ITU-R = 2.82)	B (Proposed by ITU-R = 0.15)
2006	1.6953	0.106
2007	1.7624	0.055
2008	1.4547	0.024

Table 2. The parameter A and β for year 2006, 2007 and 2008

For global rain rate applications, the ITU P.841-4 has recommended values of **A** = 2.82 and β = 0.15 for tropical, subtropical and temperate climate regions with frequent rain. The percentage of time for worst month distribution of rain attenuation is significantly higher than annual distribution of rain attenuation. There is a large difference between the A and β values obtained for tropical area with the ITU proposed. It shows that the ITU values are not suitable for use in worst-month analysis for tropical area. This indicates that the Q factors are climatic dependant. The worst month curve was strongly influenced by the Northeast Monsoon during which the highest levels of attenuation occurred. Worst month attenuation statistics are very important for the study of the performance of a communication system during periods of up to 31 days.

Ku-band TV services are affected by outages for time-critical transmission such as real-time news and sports broadcasting. Service providers need to consider the use of appropriate forward error correction codes, the choice of modulations, and the range of uplink power controls to use during severe rain fade periods in the overall design of their communications networks (Pan*, et al,* 2008). These techniques can be used to provide a significant improvement in both performance and availability for worst month attenuation.

7. Specific Attenuation Analysis

The measurement ran continuously from 1st January 2006 to 31st December 2008. Three years of cumulative distributions are obtained. The measurement ran continuously from 1st January 2006 to 31st December 2008. Three years of cumulative distributions are obtained. The relation between rain attenuation and rain rate in year 2006, 2007 and 2008 were shown in Fig. 18, 19 and 20. In these figures, the symbols × are obtained by directly plotting the rain attenuation against rain rate and the solid line is the best-fit curve obtained by fitting the rain attenuation against rain rate. The effective path length, L_{eff}, is a function of rain rate and has a direct correlation with the measured rain rate. The effective path length has been found by using equation 2.5 and 2.6 and shown in Fig. 21. The effective path length for the site is a power-fitting function of rain rate and can be simplified as

$$L_{eff}\,(\text{km}) = 13.367\, R^{-0.21} \tag{5}$$

The L_{eff} is obtained from the equation 5 is used to divide the total attenuation to obtain specific attenuation, γ at different rain rate. Fig. 22, 23 and 24 show the relation between specific attenuation, γ and rain rate in the year 2006, 2007 and 2008.

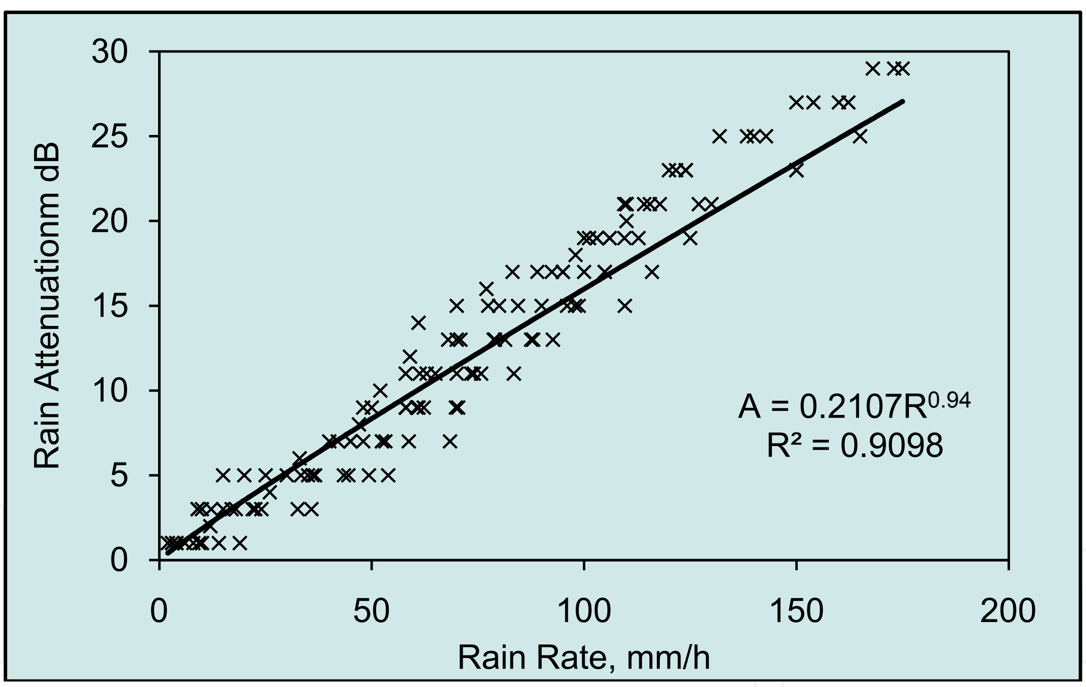

Fig. 18. The correlation between rain attenuation and rain rate in year 2006

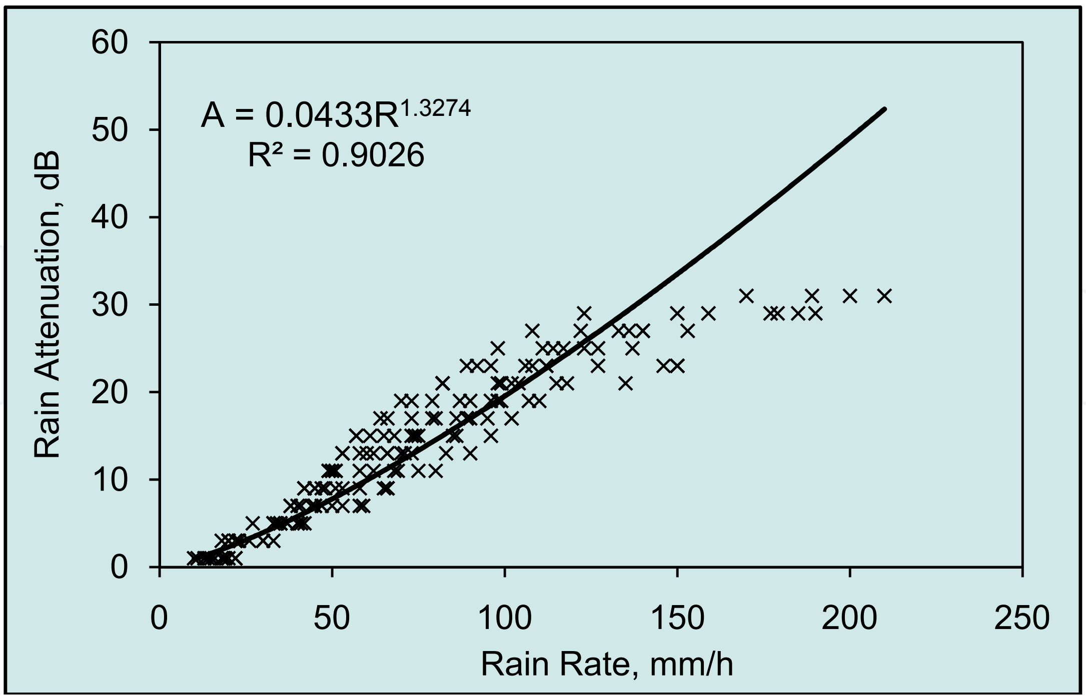

Fig. 19. The correlation between rain attenuation and rain rate in year 2007

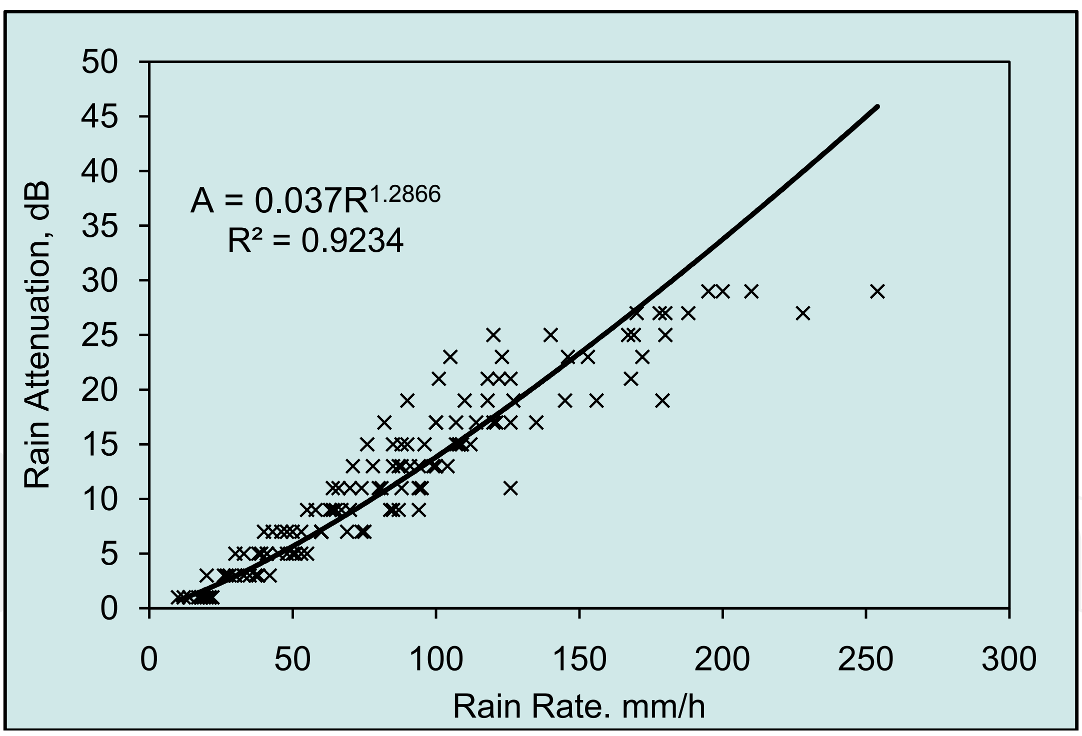

Fig. 20. The correlation between rain attenuation and rain rate in year 2008

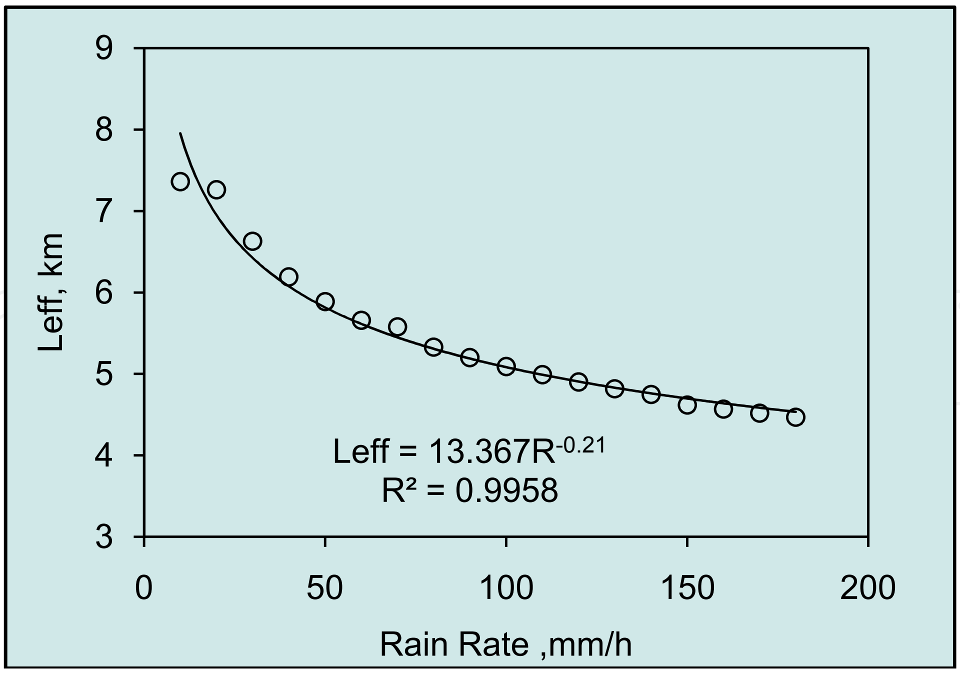

Fig. 21. The correlation between the effective path length and rain rate.

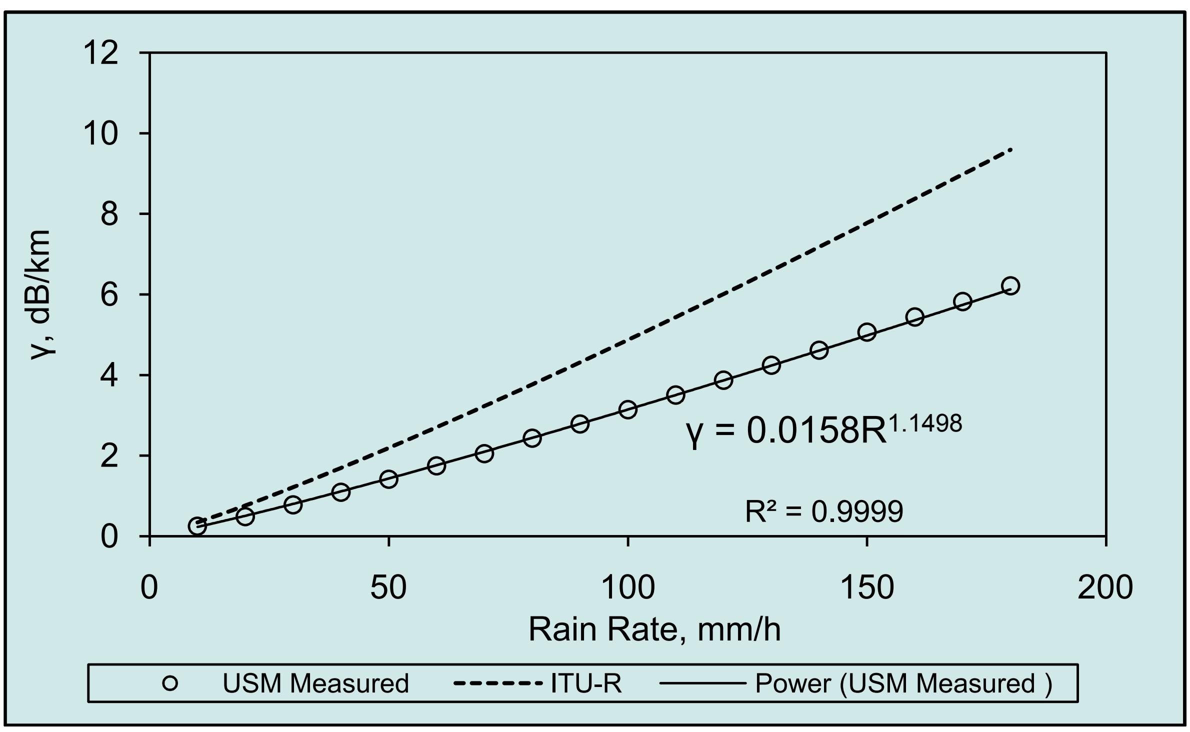

Fig. 22. Relationship between specific attenuation and rain rate compared with ITU-R in year 2006

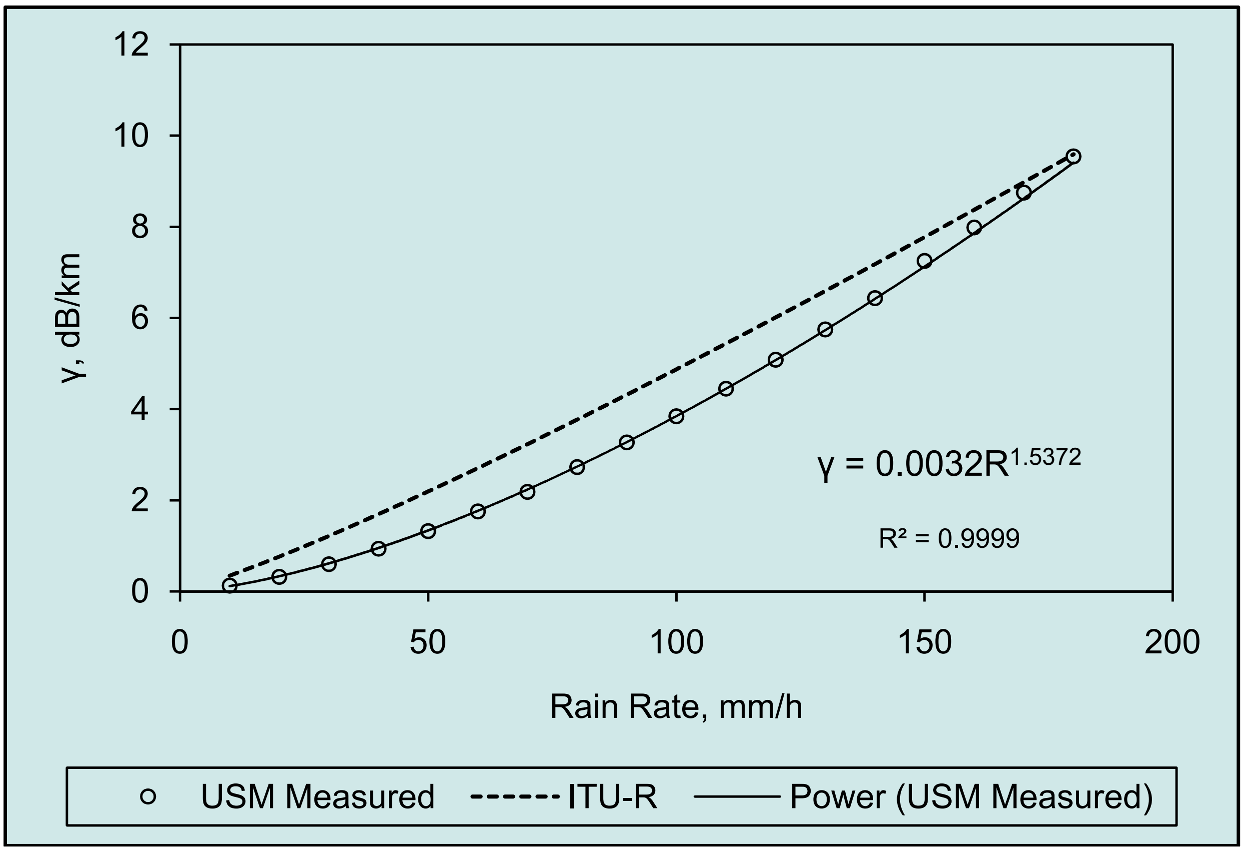

Fig. 23. Relationship between specific attenuation and rain rate compared with ITU-R in year 2007

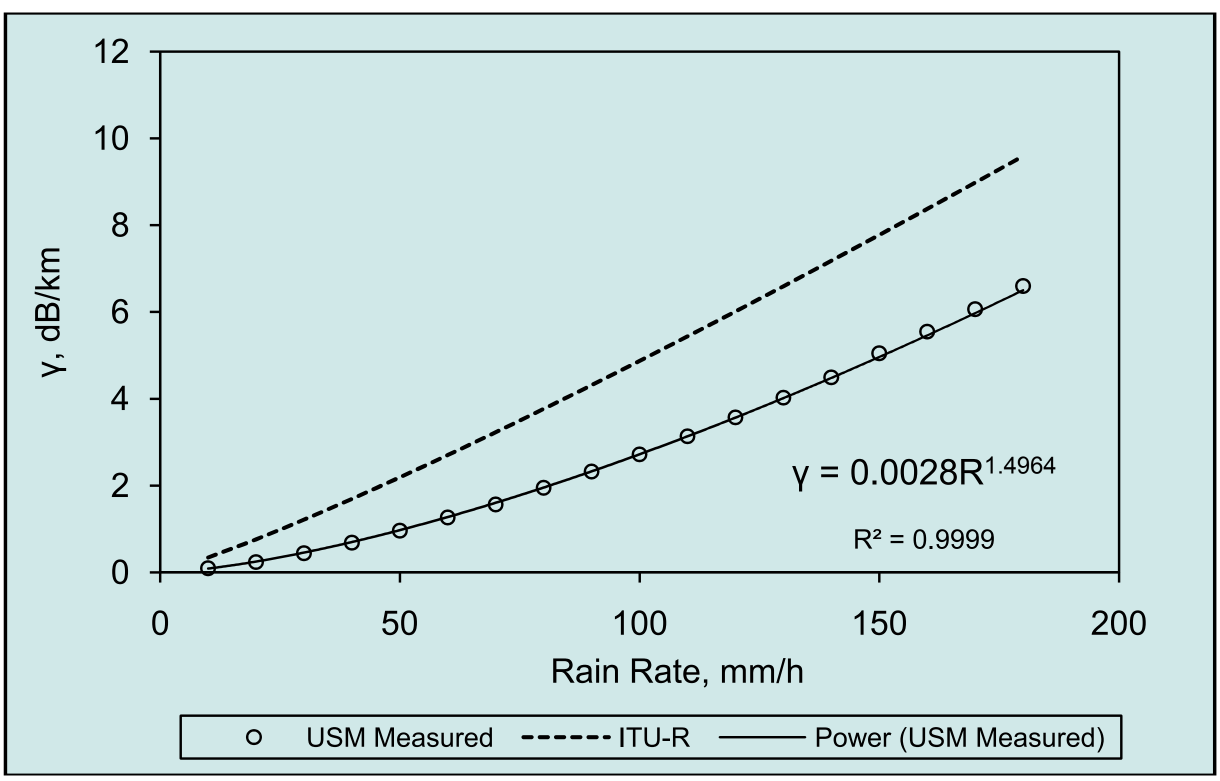

Fig. 24. Relationship between specific attenuation and rain rate compared with ITU-R in year 2008

Using equation 2.2 and 2.3, *k* and *a* that obtained are 0.0242 and 1.152 respectively. Table 3 shows the regression coefficients for k and α by using empirical procedure.

Year	*k*	α
2006	0.0158	1.1498
2007	0.0032	1.5372
2008	0.0028	1.4964

Table 3. Regression coefficients for k and α by using empirical procedure

Based on rain rate and rain attenuation measurements, the ITU-R has overestimated the specific rain attenuation due to tropical rainfall at least in the 3 years term view. The coefficients of k and α are found that can significantly vary and be considerably different from the ITU-R proposed for regression coefficients and it implies that the raindrop size distribution (DSD) in Malaysia's tropical region is quite different from that adopted by ITU-R, at least in our experiment period. There are many factors influencing the specific attenuation. This is considered due to the verity of the drop size from temperate regions to the tropical region. The availability and accuracy of measured data is the factor to influence the empirical value. Therefore, ITU-R recommendation for regression coefficients of rain specific attenuation is not suitable use in predicting rain attenuation for Malaysia.

8. Analysis of One-Minute Rain Rate Measured Data with Existing Models

The comparison of the measured one minute rain rate values with existing rain rate models is shown in this section. There are 5 tropical climates sites (e.g. USM, Bangkok, Bandung, Manila, Fiji) 2 years average (from the years 2002 to 2003) measured one-minute rain rate that used in comparison. The 2 years (from 1st January 2007 to 31st December 2008) average USM measured rain rate has been used in the comparison. The existing models that applied in the prediction one minute rain rate are Moupfouma model, ITU-R model, KIT simplified model, Rice & Holmberg model and Dutton & Dougherty model. The prediction rain rate depends on the annual rainfall values. The annual rainfall values for these tropical climates sites are shown below:

Sites	Annual rainfall (mm)
USM	2088.0
Bangkok	1565.0
Bandung	1956.0
Manila	2300.0
Fiji	3087.5

Table 4. The average annual rainfall

The comparison of one minute rain rate prediction models with measured data for the 6 tropical climates sites are shown in Fig 25, 26, 27, 28 and 29.

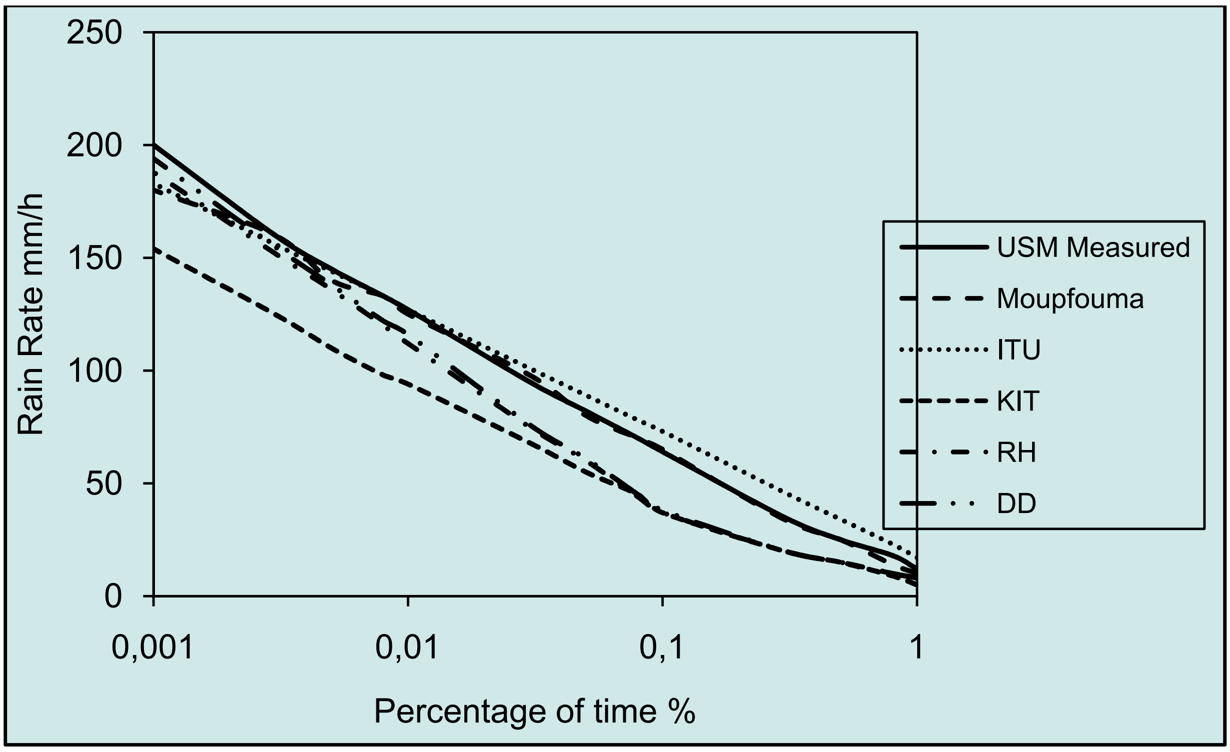

Fig. 25. Comparison of one minute rain rate prediction models with measured data for USM site.

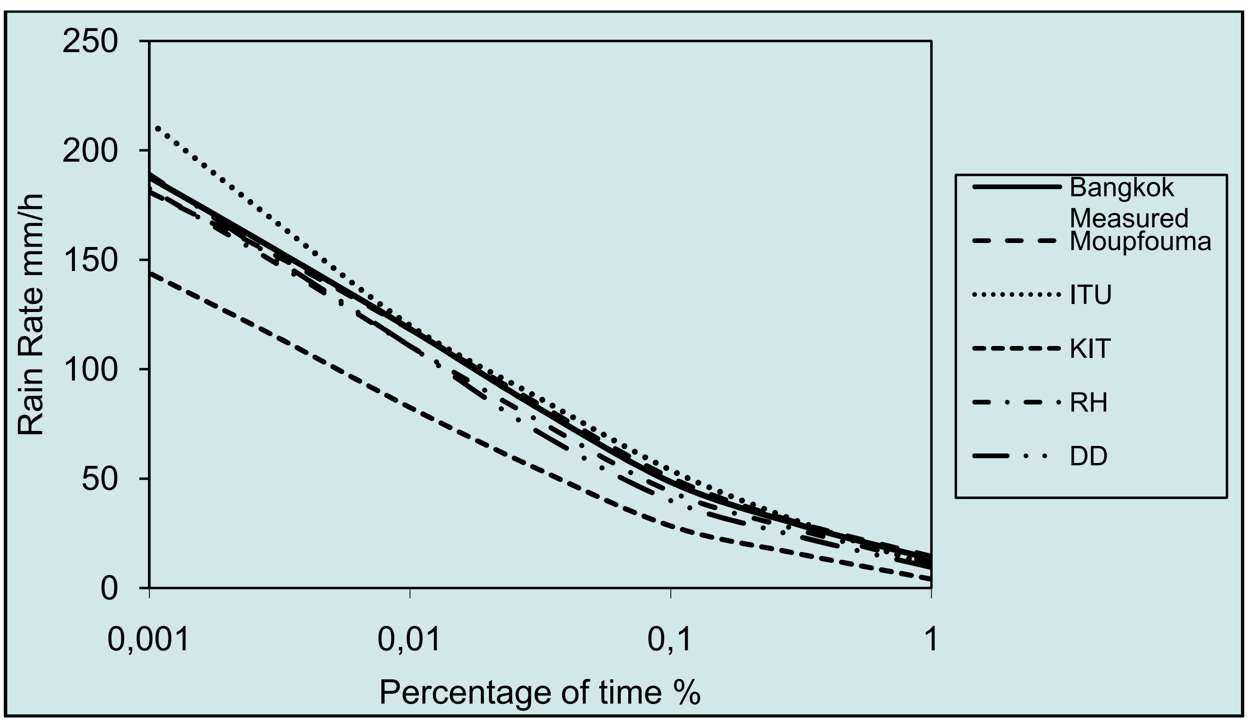

Fig. 26. Comparison of one minute rain rate prediction models with measured data for Bangkok site.

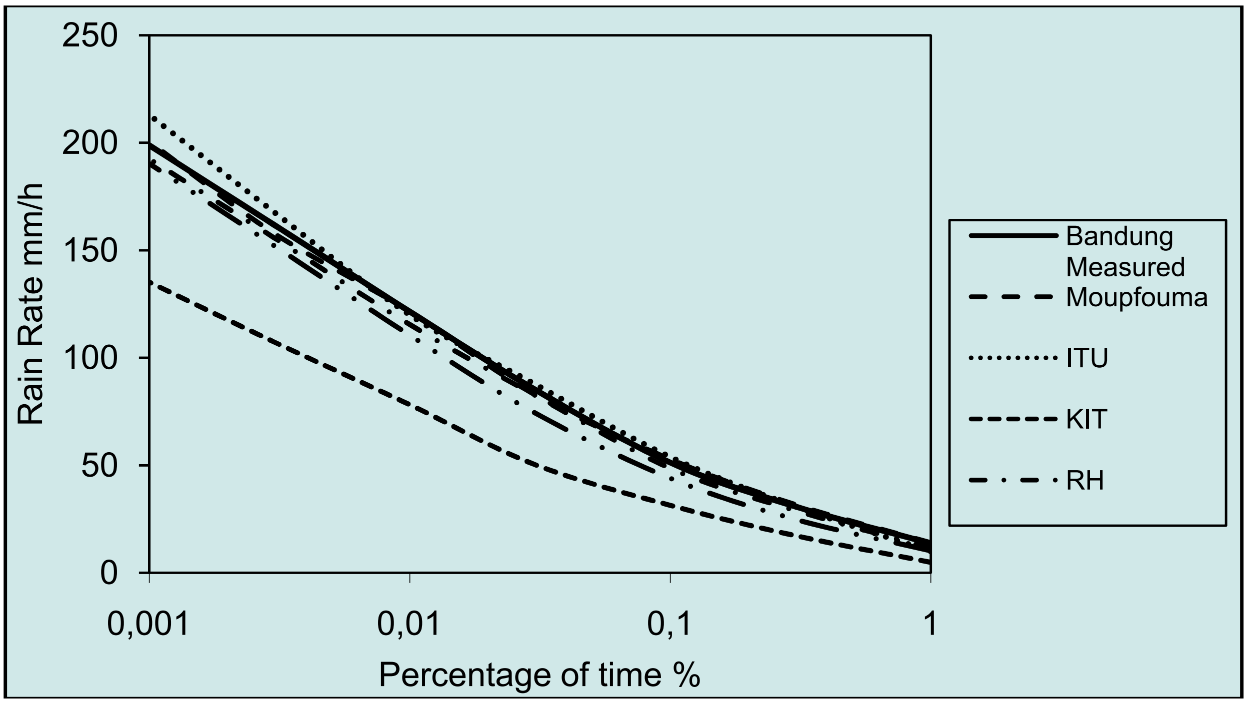

Fig. 27. Comparison of one minute rain rate prediction models with measured data for Bandung site.

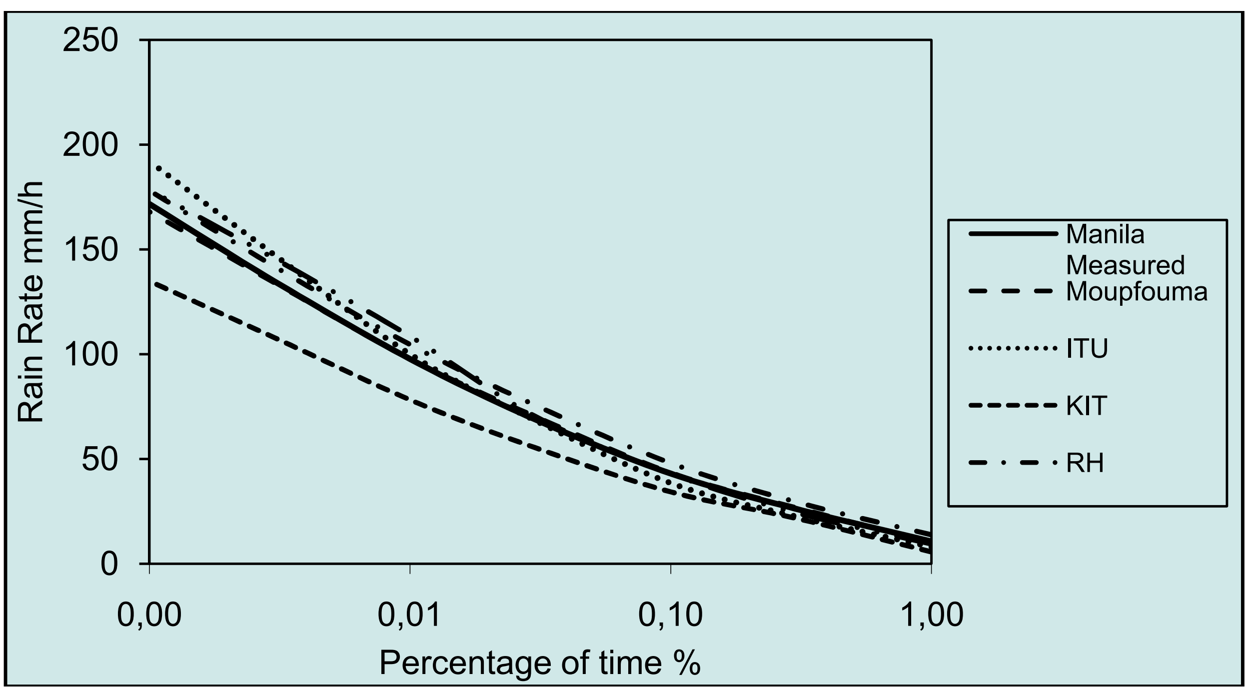

Fig. 28. Comparison of one minute rain rate prediction models with measured data for Manila site.

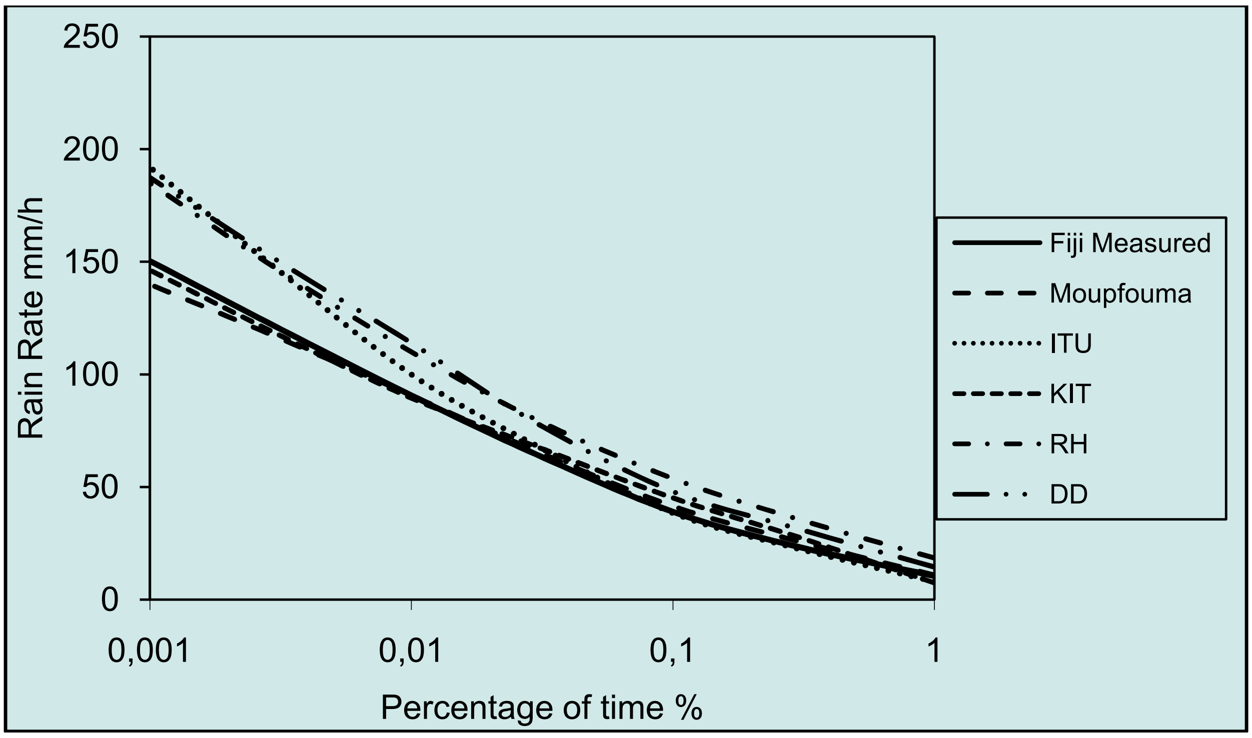

Fig. 29. Comparison of one minute rain rate prediction models with measured data for Fiji site.

The Moupfouma model overestimates the one minute rain rate from 0.01% to 1% of time and underestimates the rain rate from 0.001% to 0.01% at USM sites. The model gave a RMS value of 8.64% for USM. This is because the model has a probability law behavior that underlines the complexity of the rain rate distribution according to the climate of the zone of interest. For Bangkok, Bandung, Manila and Fiji sites, the model follows closely the measured rain rate values throughout the entire percentage of time that the rain rate is exceeded. The model gave a low RMS value for those tropical sites. The model's RMS values were 53% (Bangkok), 2.33% (Bandung), 1.69% (Manila) and 6.22% (Fiji). The coefficients of λ and Y values from the slope of rain rate curve in equation 2.18 depend strongly on the measured rain rate data. For tropical and sub-tropical localities, $\lambda = 1.066$ and $Y = 0.214$ are used in calculation of rain rate cumulative distribution slopes.

The ITU-R model overestimates the one minute rain rate from 0.01% to 1% of time and underestimates the rain rate from 0.001% to 0.01% at USM sites. The model gave a RMS value of 20.72% for USM. For Bangkok, Bandung, Manila and Fiji sites, the model follows closely the measured rain rate values up to 0.01% of time that rain rate is exceeded before the model overestimates the measured values. The model gave a RMS value of 13.18% for Bangkok site, 11.75% for Bandung, 13.65% for Manila and 17.90% for Fiji. The ITU-R has the climate zones used in the equatorial region are subdivided further that includes region with the similar rain rate characteristics and a large number of measured rain rate database that are available for equatorial region.
For USM, Bangkok, Bandung and Manila, the Kitami Institute of Technology (KIT simplified) model underestimates the measured rain rate throughout the entire percentage of time that the rain rate is exceeded. The model's RMS value was 36.56% (USM), 41.59% (Bangkok),

42.72% (Bandung) and 25.57% (Manila). The model gave a high RMS value for these sites because the annual rainfall amount at these sites were not more than 2300 mm. The KIT model prediction at Fiji, gave a low RMS value of 15.62%. The model follows closely the measured rain rate values at the entire percentage of time that the rain rate is exceeded. This is because the annual rainfall at Fiji was above 3000 mm. The KIT model states that the accuracy of the model depends largely on the annual rainfall values, where the higher the annual rainfall values better the prediction gets.

The RH model underestimates the measured rain rate at USM, Bangkok and Bandung throughout the entire percentage of time that the rain rate is exceeded. The model gave a RMS value of 29.65% at USM, 8.59% at Bangkok and 7.58% at Bandung. The RH model overestimates the measured rain rate at Manila and Fiji throughout the entire percentage of time that the rain rate is exceeded. The model gave a RMS value of 149% at Manila and 42.16% at Fiji. The RH considered the convective rain activity and stratiform rain activity was neglected. The thunderstorm ratio, β was based on thunderstorm rain but on the convective rain activity days to total rain days. The model gave a high RMS value at Fiji site because the β value given by RH is 0.3, however the β value calculated to be 0.75.

The Dutton and Dougherty (DD) model underestimates the measured rain rate at USM, Bangkok and Bandung and overestimates the measured rain rate at Manila and Fiji throughout the entire percentage of time that the rain rate is exceeded. The model gave a RMS value of 29.04% at USM, 16.03% at Bangkok, 186% at Bandung, 7.73% at Manila and 28.10% at Fiji. The M (average annual total rainfall depth, ,mm) values used to calculate the coefficient constant in Europe were below 1200mm per year, but the annual rainfall, M is above 1800mm per year in tropical climate.

A summary of the info is as show in Table 5 and a conclusion of the best and worst model is given. The comparison of rain rate was done between measured data and five pre-existing mathematical models. For the tropical region, it was found that Moupfouma model revealed a close fit to the measured data for low, medium and high rain rates. The Moupfouma model is judged suitable for use in predicting rates in tropical climates. The KIT simplified model exhibited poor performance in comparison.

Site	Annual rainfall, mm	RMS value, %					Conclusion	
		Moupfouma	ITU-R	KIT	RH	DD	Best Model	Worst Model
USM	2088.00	8.64	20.72	36.56	29.65	29.04	Moupfouma	KIT
Bangkok	1565.00	35	13.18	41.59	8.59	16.03	Moupfouma	KIT
Bandung	1956.00	2.33	11.75	42.72	7.58	186	Moupfouma	KIT
Manila	2300.00	1.69	13.65	25.59	149	7.73	Moupfouma	KIT
Fiji	3087.50	6.22	17.90	15.62	42.16	28.10	Moupfouma	RH

Table 5. The summary of the comparison of rain rate prediction model

9. Analysis of Rain Attenuation Measured Data with Existing Models

The rain attenuation prediction models exposed in literature calculate the attenuation related to a given rain rate or else to a given percentage of time. For terrestrial as well as satellite microwave links, one of the fundamental needs for the link designer is to have at his disposal an effective model that predicts attenuation caused by rain on the propagation path with a good accuracy. Most of the models available are empirical or semi empirical and their accuracy are based on the accuracy of the measured rain rate cumulative distribution (Moupfouma, 2009).

The comparison of the measured rain attenuation values with existing rain attenuation models is shown in this section. There are 5 tropical climates sites that are USM, Bangkok, Bandung, Manila, Fiji measured rain attenuation that is used for the comparison. The 2 years (from 1st January 2007 until 31st December 2008) average USM measured rain attenuation has been used in the comparison. The existing models that applied in the prediction rain attenuation are ITU-R model, Ong model, Ramachandran and Kumar model, CETUC model, Leitao and Watson model, Garcia-Lopez model, SAM model and Assis-Einloft model. The comparison measured rain attenuation with existing predicted models at these 8 tropical climates sites are shown in Fig 30, 31, 32, 33 and 34.

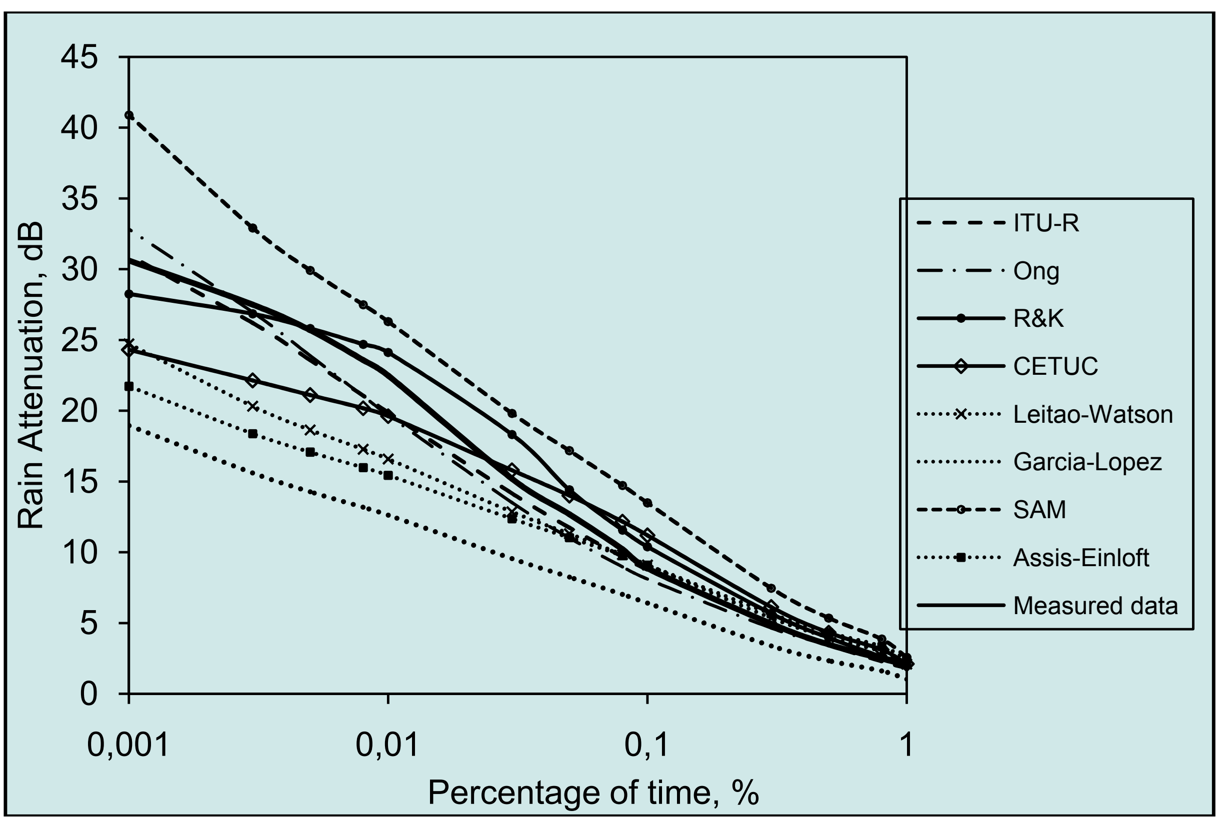

Fig. 30. The comparison measured rain attenuation with existing predicted models at USM

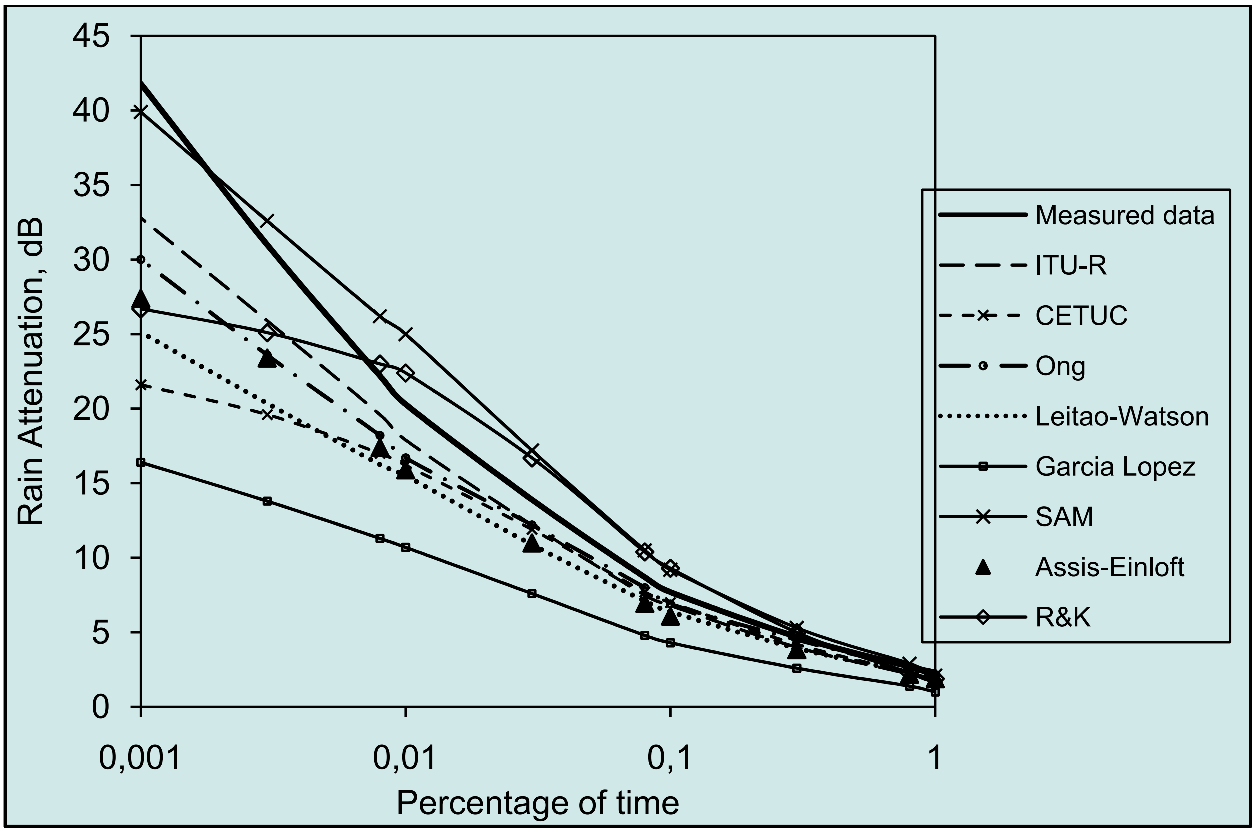

Fig. 31. The comparison measured rain attenuation with existing predicted models at Bangkok

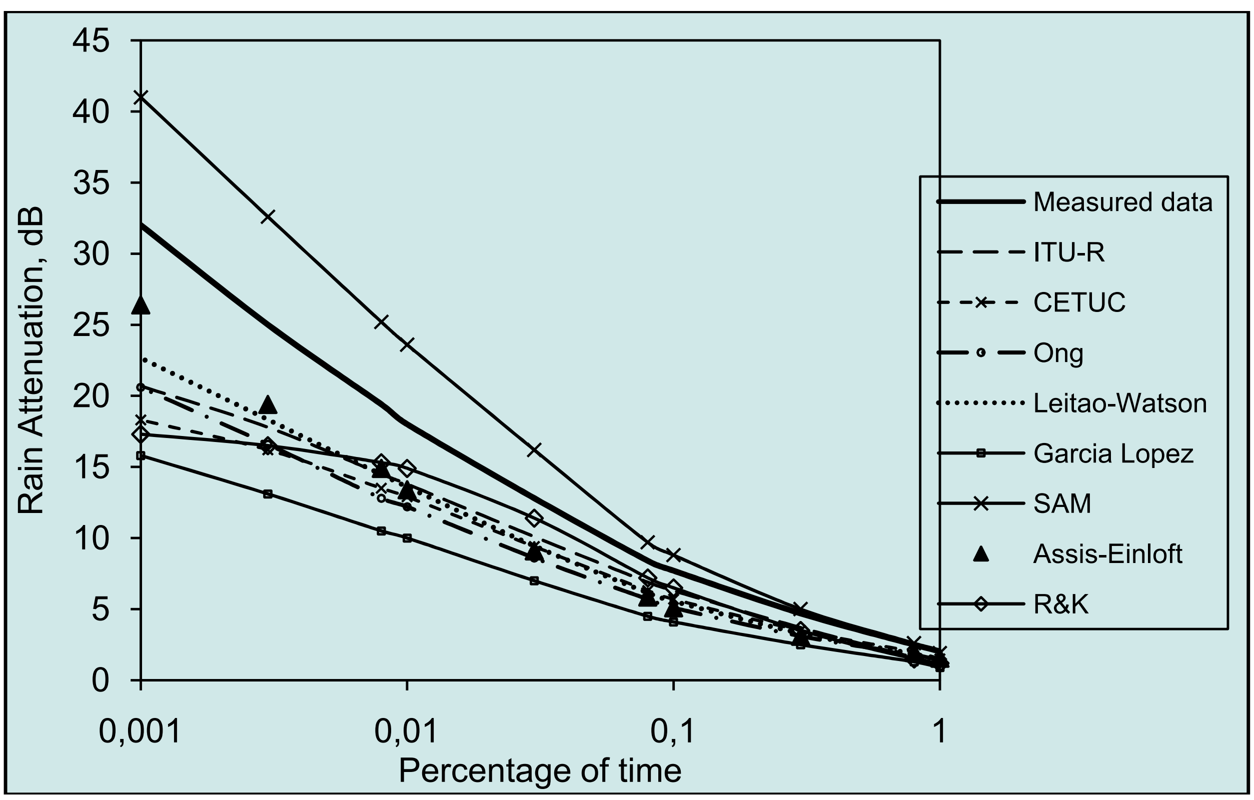

Fig. 32. The comparison measured rain attenuation with existing predicted models at Bandung

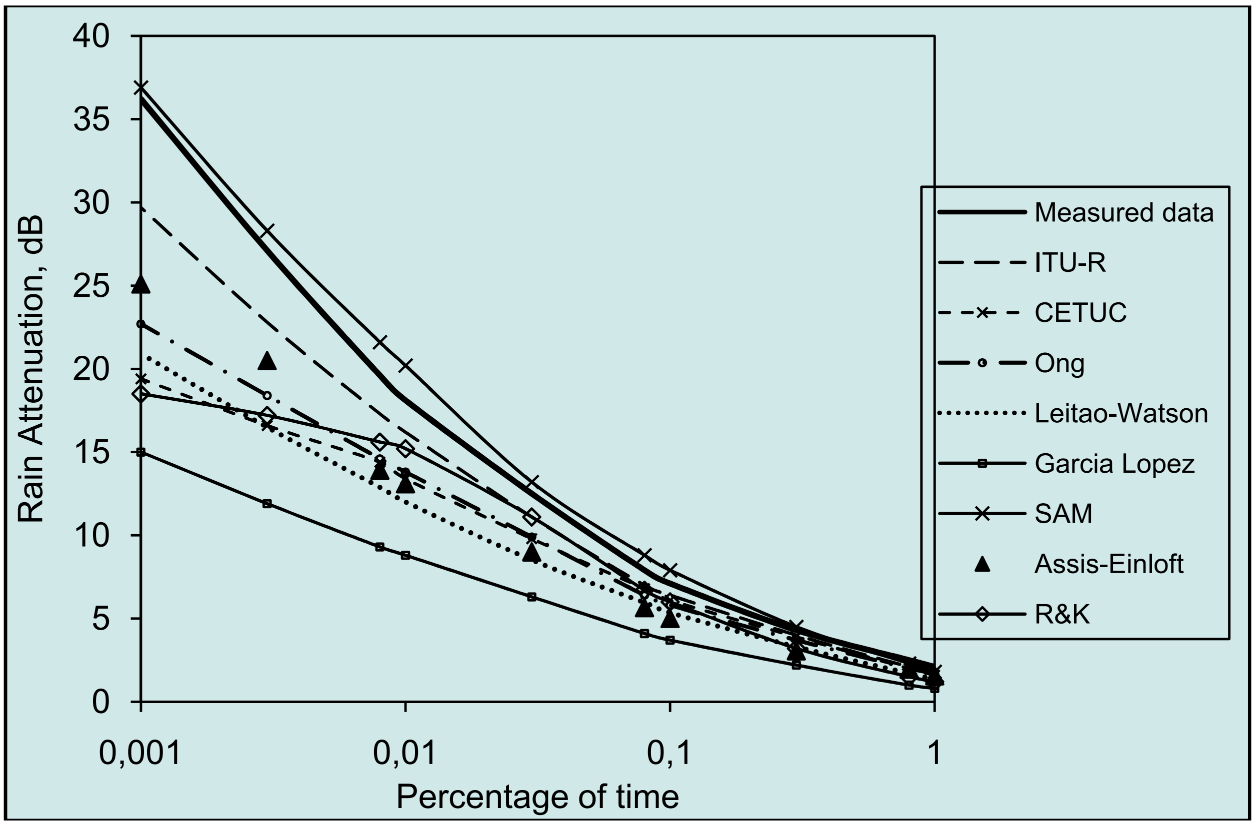

Fig. 33. The comparison measured rain attenuation with existing predicted models at Manila

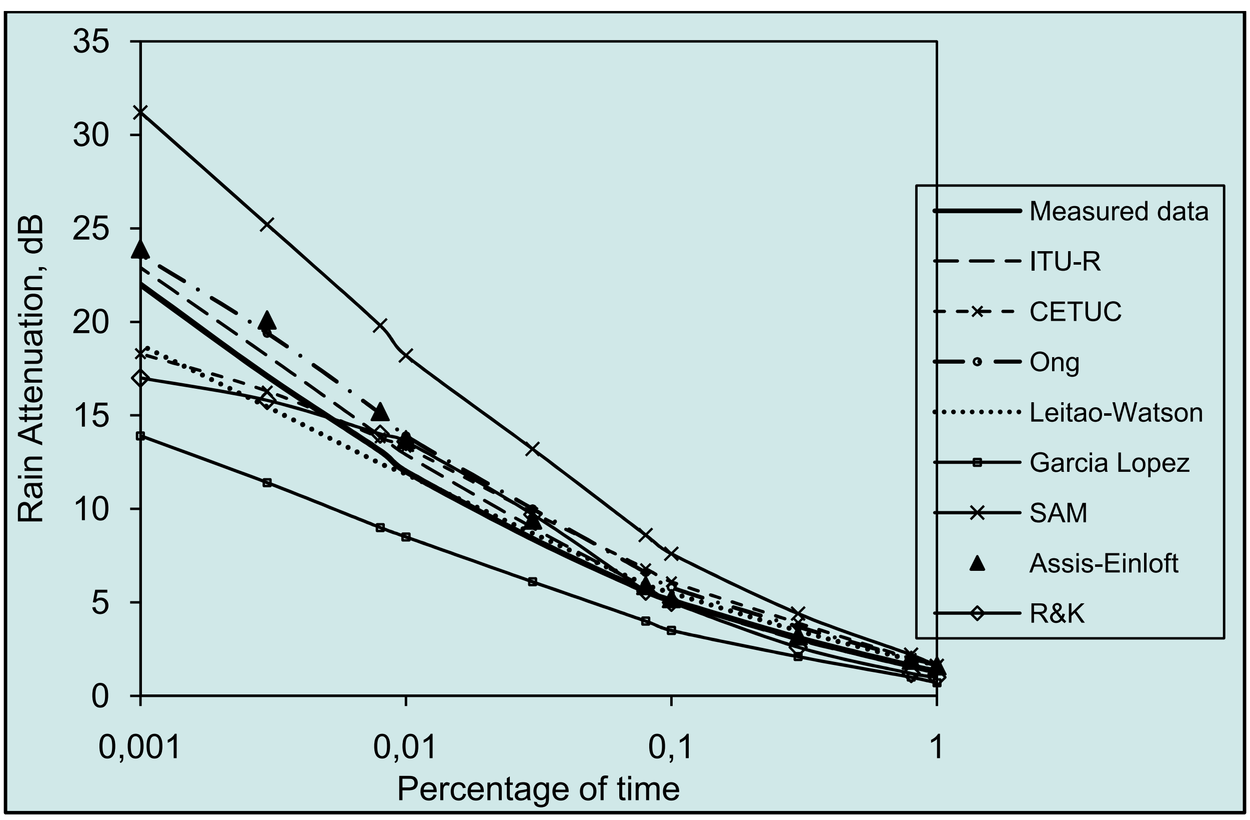

Fig. 34. The comparison measured rain attenuation with existing predicted models at Fiji

The ITU-R model underestimates all of these 5 tropical climates, except Fiji throughout the entire percentage of time. The model follows closely with the USM measured data from 0.05% - 1% of time. ITU-R underestimates the rain attenuation at the lower percentage of time because of the roll over effect, where as the rain rate increases, the attenuation reduce. This is because of the lack of high rain rate data from tropical climates. The rain column height is constant and maximum (10 km) when the rain reaches its saturation point, but the rain-cell diameter continues to decrease with increasing rain rate. Hence, the proportional increase of rain volume, which is a combination of rain-cell diameter, rain column height and rain rate would cause saturation (Ramachandran and Kumar, 2004). The vertical path reduction coefficient was used to minimize the prediction error. At Bangkok, Manila and Fiji, the ITU-R models gave a lower RMS value. At Fiji, the ITU-R model follows closely the measured rain attenuation throughout the entire percentage of time. The model gave a low RMS value because the rain rate of 90.7 mm/h was used for calculating the rain attenuation at 0.01% of time. This model was developed based on low rain rate of 85 mm/h at 0.01% of time from temperate climates. At Bangkok and Manila, the model gave a high RMS value because of the high rain rate vales at 0.01% of time have been used in calculating the rain attenuation. At Bandung, the model gave a high RMS values. At Bandung, the high elevation angle of above 60^0 was applied in experimental. The station height above sea level that used was 700m, whereas this model was developed by station heights above mean sea level from 20m to 400m.
The Ong model at USM underestimates rain attenuation at the entire measurement time. The model gave a percentage error of ±14% with a range RMS value of 9.62% at USM. This model was revised from ITU-R model. The model has a roll over effect at lower percentage of time, because it was developed for 4/6 GHz. At Fiji, the Ong model follows closely the measured rain attenuation for the entire measurement time. The station height above sea level at both of these sites is below 60m. The station height above sea level that was used to develop this model was below 60m. At Bangkok, the model agrees reasonably well with the measured rain attenuation down to an outage time of 0.03% and deviates considerably from the measured values from 0.03% to 0.001%. At lower percentage of time above 0.01%, the model relative error increases because of the model was developed for 4/6 GHz. When the higher operational frequency gets, the higher rain attenuation will be at lower percentage of time. The Ong model at Bandung and Manila give poor performance for the entire measurement time. The model gave a high RMS value at these sites. It is because the station heights above sea level are above 80m and the elevation angle of the measurement site was above 55°.
At USM, Bangkok and Fiji, Ramachandran and Kumar model (R&K) follows closely with the USM rain attenuation measured from 0.03% to 1% of time. However, the model underestimates the rain attenuation from 0.03% to 0.001% of time. For this model takes into account the effect of the breakpoint to predict the attenuation exceedance in the tropics. In the tropics when the rain rate increase and approach the breakpoint the rain structure gradually changes from stratiform to convective. If the breakpoint is reached at a lower rain rate, then the rain tends to saturate fast (Ramachandran and Kumar, 2004). Because of this reason, the model has a roll over effect at lower percentage of time. The model gave a RMS value of 19.91% at Bangkok and 16.41% at Fiji. For the $0.003 \le p \le 1$, the rain attenuation increase gradually with increasing rain rate. Beyond 0.003% of time, the rain attenuation tended to saturation finally leading to total outage. At Bandung and Manila, the model is rejected for prediction for the entire measurement time. The model gave high RMS values for these sites. This is because of the rain rate (R_{AB}) at the breakpoint is above 70mm/h at these measurement sites. The rain rate of 58mm/h at the breakpoint was used to determine the model coefficient.

The CETUC model is simple to apply and uses the full rain rate distribution to predict the attenuation distribution, avoiding extrapolations functions dependent on the percentage of time. The model keeps the concept of an equivalent rain cell. The attenuation dependence on frequency is completely described by the parameters k and α (ITU-R recommendation parameters that used in calculating specific attenuation). At Fiji, the CETUC model agrees reasonably well with the measured values from 0.008% -1% of time and deviates considerably from the measured values from 0.001% to 0.008% of outage time. It gave a percentage error of ±25% with a RMS value of 18.96%. The model gave a low RMS value because the elevation angle was 45.5^0 and the station height was 13m. The model was developed based on an average elevation angle 42^0 and the altitudes below 50m. At USM, the model gave a high RMS value of 19.34% at USM, because the parameters k and α that recommended are not suitable used in USM. The highest rain rate and rain attenuation values were 200 mm/h and 30 dB, respectively used to apply the model. At Bandung, Manila and Bangkok, the CETUC model deviated considerably the measured rain attenuation for the entire measurement time. At Bandung and Bangkok sites, the model gave a high percentage error with a RMS value because the rain height calculated by CETUC was 3.18 km. The height above sea level for Bandung station was 700m. However, the rain height used to develop the model was based on limited number of stations with height above sea level below 50m. At Manila, the model gave a high percentage error of ±38.7% with a RMS value of 26.6%. This is because the effective length of the rain cell was developed by the rain rate values from 12 mm/h at 1% to 150 mm/h at 0.001% of time and the rain height calculated by CETUC was 3.18 km.

At Fiji, the Leitao-Watson model appears to work well down to the entire measurement time. The model gave a lower RMS values. The model parameters *s, t, u, v* and *w* are suitable to be used at Fiji site. Besides Fiji, the Leitao-Watson model underestimates the rain attenuation for the entire measurement time at the other sites. The model gave high RMS value of 24% and above. The model developed according to radar observation of rainfall structure, proposed the same set of equations with different parameters for widespread and convective rain (discrimated by a rain rate threshold of 20 mm/h) (Capsoni, *et. al.,*2009). The model was developed by using Europe rainfall data. It will make the model cannot perform well and give a high RMS value in predicting rain attenuation in tropical countries.

The Garcia-Lopez gave a high RMS value of above 30% and above for all these measurement sites. The model is underestimates the rain attenuation values for the entire outage time of an average year at all these measurement sites. This is because the rain height of 4km was given by Garcia-Lopez. The rain heights in tropical countries are above 5km, which are given by the ITU-R map of rain height above mean sea level. The coefficient constant of the model was obtained based on low rain rate of 60 mm/h at 0.01% of time. The range of rain rate at 0.01% of time for tropical climates is from 100mm/h to 130mm/h of time depending on the geographical area. The station height used to determine coefficient constant was averaged to 200m above mean sea level.

The SAM model at USM and Fiji site overestimates and shows poor performance in predicting rain attenuation. The model gave a high RMS value. This is because the model of the parameter controlling the rate of decay of the horizontal profile (γ). The model would give a lower RMS value below 10% if γ parameter was optimized against the set of data obtained from the measurement sites (Stutzman & Yon, 1986). At Bangkok and Bandung, the model follows closely the measured rain attenuation from 0.08%-1% of time and overestimates the rain attenuation from 0.08% to 0.001%. At low percentage of times, the large errors are due to the fact that the predicted rain rates are less accurate in regions of high occurrence levels. The median values of the observations were estimated for each probability level in order to develop the model because long data sets were not available and the pooling of data from a number of locations was necessary to reduce the estimation error. The model appears to work well for the entire measurement time at Manila. The model gave a low RMS value of 9.8% because the parameter γ value given by SAM was optimized against the measured data sets.

At Fiji, Assis-Einloft model agrees reasonably well with the measured values for the entire measurement time. This is because the development of the reduction factor for this model was based on the measurement done at temperate and tropical climates, whereby at tropical climates 80 data sets at antenna elevation angles from 40^0 to 50^0 were used in order to reduce the prediction error at high rainfall intensity regions. Assis-Einloft model is not show the good agreement for the entire measurement time at Bangkok, Bandung and Manila. This is because the antenna elevation angles that used at these measurement sites were above 50^0. The path length that was considered by Assis was from 6km to 20.7km, but the path lengths at these measurement sites were below 6km. At USM, the model gave a high RMS value. A uniform rain rate was assumed for developing the model by introducing the concept of path length reduction factor. The path length at USM sites was below 6km.

The summary of the best model and worst model at the comparison sites was done and shown in Table 6. In this section, the comparison of rain attenuation was done for the measured data. For the tropical climate, it was found that no model revealed a close fit to the measured data for low, medium and high rain rates. The models do not predict rain attenuation at the lower percentage of time. The noticeable difference between the measured and the predicted variation is the existence of the breakpoint. The exceedance curves show that as the rain rate increases, the trend of the slope of the curve gradually decreases from large negative value, and then the trend that changes is referred to as the breakpoint in the exceedance curve (Ramachandran, *et. al.*, 2004, Mandeep, *et. al.*, 2008). The breakpoint exceedance curve usually occurs at high rain rate. When the rain structure is stratiform, the rainfall is widespread with low rain rates.

Site	RMS value, %								Conclusion	
	ITU-R	Ong	R&K	CETUC	Leitao	Garcia	SAM	Assis	Best Model	Worst Model
USM	7.11	9.62	11.50	19.34	18.75	38.58	37.96	25.80	ITU-R	Garcia
Bangkok	17.36	15.82	19.91	221	251	49.98	16.45	22.35	Ong	Garcia
Bandung	28.78	32.79	29.43	29.29	27.35	47.86	22.36	26.70	SAM	Garcia
Manila	13.02	202	30.45	26.60	32.73	53.75	9.57	27.63	SAM	Garcia
Fiji	5.57	18.91	16.41	18.96	137	33.85	46.49	100	ITU-R	SAM

Table 6. The summary of the comparison of rain attenuation prediction models

The ITU-R model is judged suitable for use in predicting rain attenuation in these measurement tropical climates sites. The Garcia-Lopez model exhibited poor performance in comparison. The results are particularly important for the tropical and equatorial region because not much of research that has been done in these regions.

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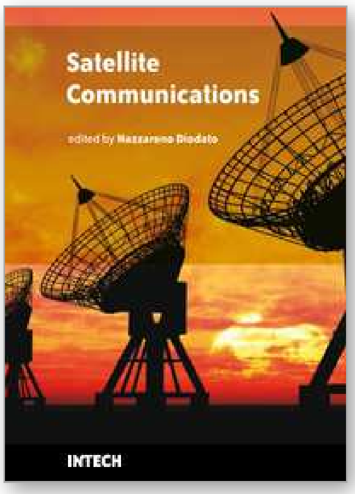

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This study is motivated by the need to give the reader a broad view of the developments, key concepts, and technologies related to information society evolution, with a focus on the wireless communications and geoinformation technologies and their role in the environment. Giving perspective, it aims at assisting people active in the industry, the public sector, and Earth science fields as well, by providing a base for their continued work and thinking.