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A RADIOMETEOROLOGICAL STUDY BASED ON DATA FROM MALAYSIA AND AMAZON REGION

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Abstract

Based on rain gauge and radar measurements carried out in Malaysia and Amazon region (Brazil), this paper deals with the description of meteorological factors affecting the radio wave propagation in low latitude areas. As it will be shown along the paper, in spite of the large geographical separation between these two countries similar results have been observed. In this context, the following topics are discussed: a) Climatic classification; b) Rainfall rate features, including the prediction of annual and worst month cumulative distributions; c) Horizontal and vertical spatial distribution of precipitation; d) Path length factor and effective rain height associated, respectively, to terrestrial and Earth-space radio links. The concepts and experimental data presented here are of fundamental relevance for rain attenuation studies at frequencies above 10 GHz in the equatorial region of the world.

Keywords— *Equatorial climate, low latitude, path length facor, radiometeorology, rainfall rate*

I. INTRODUCTION

The problem of rain attenuation prediction has been studied along the years. In spite of the effort developed in different parts of the world, there are yet some points to be clarified. This question is quite difficult to be solved, mainly due to the complexity of rain structure. Rain varies randomly both in time and space, and the accuracy of a prediction model depends on its capacity to describe these variations. Usual prediction models are based on meteorological parameters like cumulative distribution of precipitation rate and rain cell shape and dimension. This problem is particularly critical in regions characterized by severe precipitations, such as low latitude areas. Based on rainfall rate and rain attenuation data measurements from Malaysia and Amazon region (Brazil) a radiometeorological study is carried out. The meteorological data used in this paper were taken from a Report [1] of the Malaysian Meteorological Service (MMS) and from the doctoral dissertation published recently by Cerqueira [2]. Regarding applications for evaluating the performance of communication systems, in Malaysia the most important source was the research work developed by UTM (Universiti Teknologi Malaysia) [3-7], while in Brazil the origin of the material described here was mainly from a series of papers by Assis and others [8-15]. Of course, information arising from other authors was also considered and will be referred to along the text.

The first step in this investigation is the comparison between climates taking into account the Köppen classification [16] and the annual rainfall rate statistical distribution measured in Referring to rain attenuation prediction, it is recommended to use different models based on the climate of the region where the radio link is located. different sites in the areas under study. Once demonstrated the

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climatic similarity, the following items are discussed: a) Worst month characteristics; b) Horizontal distribution of rain; c) Vertical distribution of rain; d) Terrestrial paths; e) Slant paths.

Considering the rain forest as the basic feature of the equatorial climate [16], it is hoped that the concepts and experimental data presented here could be also used by other tropical/equatorial countries in the planning and performance analysis of communication systems operating at frequencies above 10 GHz. It should be pointed out that, although the data referred to here were published elsewhere in the technical literature, the novelty of this paper is that they were, for the first time, employed together to generalize the behaviour of meteorological parameters and their influence on rain attenuation in low latitude rainy areas.

II. CLIMATE CLASSIFICATION

A climate classification is an attempt to define regions with the same climatic conditions. This is an important issue when defining the rainfall rate distribution to be used as reference in a given area. The success of this procedure depends obviously on the homogeneity of several factors, as temperature, precipitation, vegetation and relief. Köppen climate classification [16] was adopted in this study because its structure depends on these factors. According to this classification, the climate of Amazon region is a tropical rainy type (A) where 3 subtypes can be identified:

a) Rainy equatorial (Af) – with a large annual rainfall (over 2000 mm) and practically no dry season;

b) Monsoon tropical (Am) – the annual rainfall is equal to or larger than Af, but there is a short dry season (one to three months);

c) Wet-and-dry tropical (Aw) – with an annual rainfall around 1000 to 2000 mm and well defined wet and dry seasons.

The geographical limits of these climatic subtypes are also shown in Fig.1a [2].

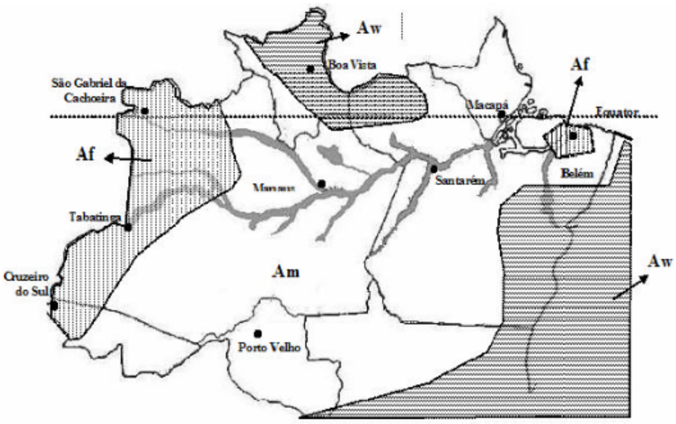

Fig. 1(a): Tropical Rainy Climate – Brazilian Amazon Region [2]

Similarly to the climate of the Amazon region, the Malaysian climate is also a tropical rainy, see Fig. 1b [5]. Accordingly to the Malaysian Meteorological Services [1] there are four main distinguishable seasons, all of them characterized by a monsoon tropical type (Am): The South-West monsoon, the North-East monsoon and two shorter inter-monsoon seasons. The seasonal wind flow patterns and the local topographical features determine the rainfall distribution over Malaysia. Mountains and highlands receive more rainfall than nearby low lands. Peninsula Malaysia is divided into five rainfall regions: north-west, west, south-west, east and Port Dickson-Muar coast.

For the north-west region, the highest amounts of rainfall are usually recorded in year during the months of April, May and October; while the lowest amounts of rainfall are recorded in the months of February and June. The rainfall distribution of the western region is almost similar to that of the north-west Peninsula. Maximum amounts of rainfall occur in the months of April and October or

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November; while February and July are the driest months of the year. Port Dicson-Muar coast record the heaviest rainfall in October and the lowest rainfall in January or February. For the south-west Peninsula, the rainfall is fairly even distributed along the year; heaviest rainfall occurs in October and November; while February is the driest. Finally, in the east coast the maximum is in November, December and January; while June and July are the driest months.

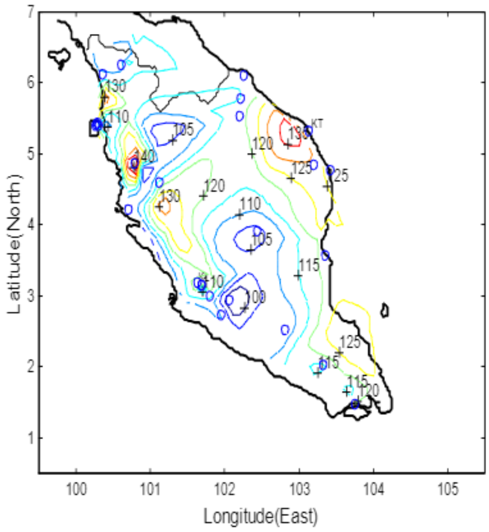

Fig. 1(b): Rain Rate Contour Map at 0.01% of the time in Peninsular Malaysia [5]

III. Rainfall Characteristics

For practical purposes, two types of rain can be classified: stratiform rain and convective rain. Stratiform rain covers a relative extensive region (several kilometers) with low precipitation intensity. The precipitation rate upper limit to that type of rain is around 20 ~ 30 mm/h. The convective rain is localized, presenting a high precipitation rate, greater than 30 ~ 40 mm/h and its occurrence, depending on the climatic conditions, is normally lesser than 0.1% of time in an average year. In reality, as shown in Fig. 2 [2], radar measurements indicate a transition region between stratiform rain and convective rain. It should be noted that in this figure, the conversion from radar reflectivity Z(mm6/m3) to rainfall rate R(mm/h) was based on the classical relation Z = aRb.

Rain in the tropics is predominantly convective in origin. Convective clouds may occur individually or in groups forming a cluster of cells. In the worst case, cloud structure consists of a heavy layer of nimbostratus with cumulonimbus towers superimposed on it. The average separation between towers is around 20 – 25 km. This cloud structure is illustrated in Fig. 3 [9].

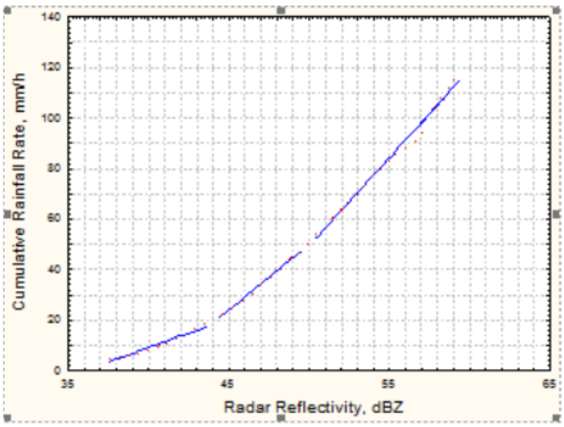

Figure 2: Three-segmented relationship $Z = aR^b$ [2]

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High rainfall rates have small probability of occurrence and tend to be concentrated in short periods of time (on the order of minutes). Reliable data require a long observation period and the utilization of rain gauges with an adequate time constant and compatible with the duration of each significant event. According to the Radiocommunication Sector of the International Telecommunication Union (ITU-R) [17] the basis for statistical studies is one year referenced to a rain gauge with one-minute integration time.

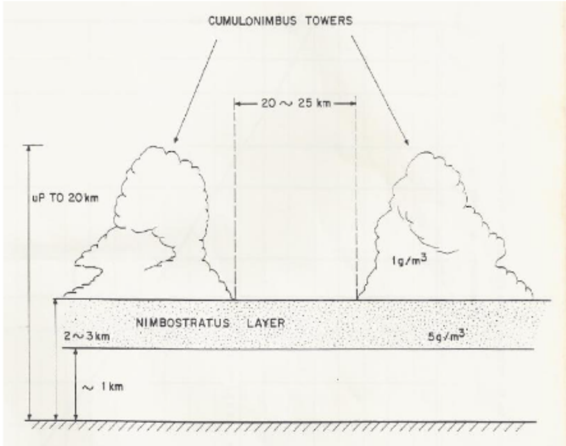

Figure 3: Cloud structure in the tropics – worst case [9]

IV. Rainfall Rate Prediction

In the Amazon region, precipitation measurements were carried out for a period of one year in the sites shown in Table 1 [2], where it is displayed the geographical coordinates, the up-time in percentage and the rainfall rate exceeded for 0.01% of both annual and monthly cumulative distributions (R0.01%). The complete annual distribution for each site is depicted in Fig.4 [2]. As it is pointed out in Table 1, the site of Boa Vista is the only one located in the climate Aw (wet and dry tropical) and the least rainy in Fig.4. On the other hand, Table 2 [3] shows the average annual rainfall rates cumulative distribution for 7 sites in Malaysia. The localization of these 7 sites in accordance with their latitude and longitude is depicted in Fig. 5 [3]. An excellent agreement between these data is observed.

Table 1: Site characteristics [2]

Site	Köppen Class.	Lat.	Long.	Avail.	$R_{0.01\%}$ annual	$R_{0.01\%}$ worst month
Belém	Af	01^0 23' S	48^0 12'W	97.40 %	136.3 mm/h	173.3 mm/h
Boa Vista	Aw	02^0 47' N	60^0 41'W	100 %	80.7 mm/h	138.1 mm/h
Cruzeiro do	Af	07^0 36'	62^0 40'W	100 %	120.1 mm/h	162.5 mm

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Sul		S				/h
Mac apá	A m	00^0 02' S	51^0 05'W	10 0 %	100.3 mm/h	126. 6 mm /h
Man aus	A m	03^0 05' S	60^0 04'W	96 .2 0 %	93.4 mm/h	118. 4 mm /h
Sant arém	A m	02^0 30' S	54^0 43'W	92 .7 0 %	114.4 mm/h	177. 4 mm /h
São Gabr iel da Cac hoei ra	A f	00^0 07' S	67^0 04'W	82 .0 0 %	113.9 mm/h	153. 5 mm /h
Taba tinga	A f	04^0 14' S	69^0 56'W	96 .7 0 %	113.6 mm/h	137. 1 mm /h

Table 2: Annual rainfall distributions – Malaysia [3]

Links	Rain rate (mm/h)								
	0.001	0.002	0.003	0.005	0.01	0.02	0.03	0.5	0.1
Penang	184	167	157	143	125	105	94	79	59
Temerloh	176	157	146	132	114	95	84	70	52
Alor Star	166	148	137	124	107	90	79	66	49
Kuala Lumpur 1	201	180	168	153	133	113	101	86	65
Taiping	198	183	174	163	147	130	120	107	88
Terengganu	196	179	171	160	145	128	116	103	79
Kuantan	210	185	171	158	135	94	88	73	52

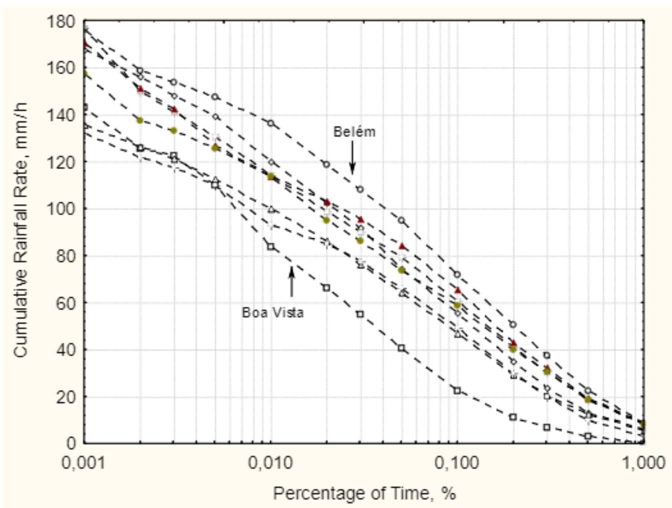

Figure 4: Annual rainfall distributions – Amazon region [2]

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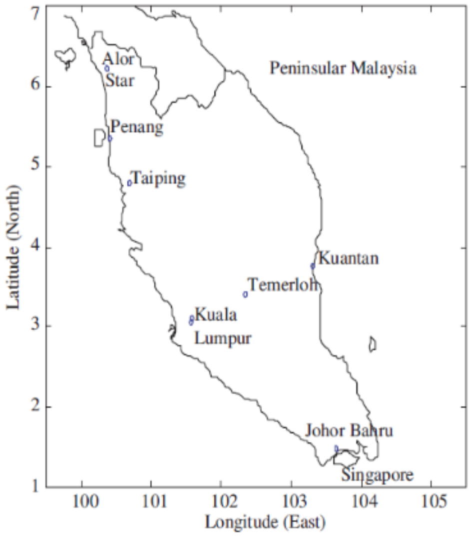

Figure 5: Sites referred to in Table 2 [3]

Regarding rainfall rate prediction, following Cerqueira [2] three mathematical functions, which are the basis of the Paraboni and others [18], Moupfouma-Martin [19] and Salonen-Baptista [20] models, were compared and tested against the experimental data shown in Fig. 4. All these functions present a very good performance. The correlation between measured and predicted data was higher than 99%, with a rms error below 10% in most cases [2]. Salonen-Baptista model was taken as reference for rainfall rate prediction in the Amazon region. The reason for choosing this model was its global coverage and its dependence on meteorological parameters available in the region under study allowing to be continuously extended over a large area. In Malaysia, Chebil and Rahman [5] use successfully the Moupfouma-Martin model for the same application. However, this model depends on the value of R0.01% which, if not known, requires an empirical power law expression function of the long-term mean annual precipitation for its estimation.

V. Worst Month

In Malaysia and Brazil, where excessive precipitation is a common phenomenon throughout the year, the knowledge of the worth month rainfall rate statistics is an important tool for the design of terrestrial and Earth-space links. Fig. 6 shows the worst month distributions measured at UTM in Johor Bahru, Malaysia [6] and Fig. 7 [2] depicts the worst month distribution for each site shown in Table 1. It is observed that, up to 0.1%, the worst month distribution in December at Johor Bahru is quite similar to other sites in Brazil, except in Belém. For smaller percentages of time, Brazilian sites show higher rainfall rates.

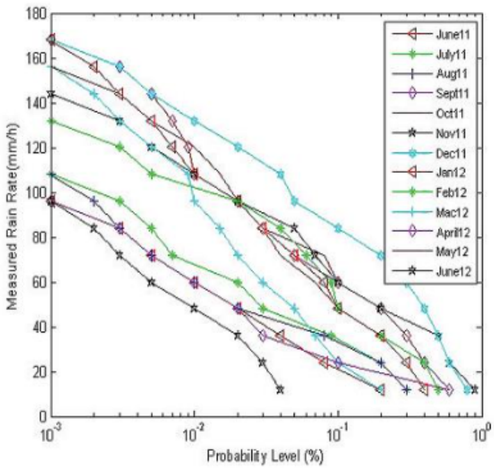

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Figure.6 – Monthly rainfall rate distribution at Johor Bahru [6]

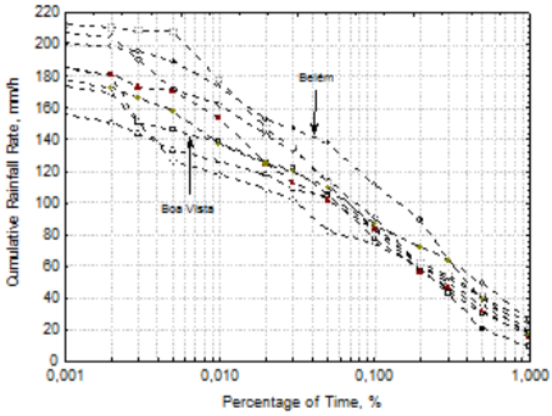

Figure 7: Worst-month rainfall rate distributions – Amazon region [2]

VI. Horizontal Distribution Of Rain

In the Amazon region, the analysis of the horizontal extent of rain was based on meteorological radar data. More than 20,000 CAPPI (Constant Amplitude Plan Position Indicator) scans in each radar station were taken into account. An example of CAPPI scan is given in Fig. 8 [2]. Following Pawlina [21], in order to avoid ground clutter contamination, the investigation of the horizontal distribution of rain in each CAPPI was carried out in a reference level located 1.5 km above the earth. As the variation of rainfall rate up to about 4 ~ 5 km is, in general, quite small, this level was proved to be adequate. On the other hand, only data within the range of 80 km were considered. In using this range restriction, it was not necessary to introduce any correction to the measured values of radar reflectivity [2].

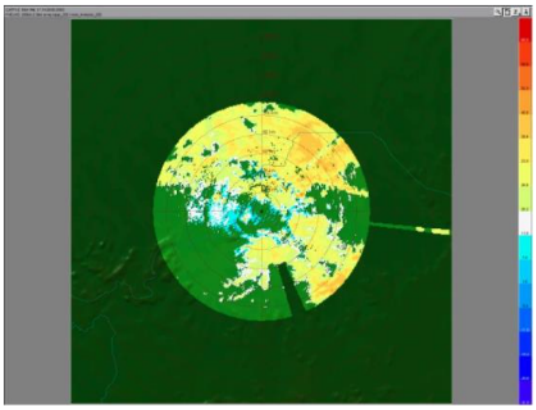

Figure 8 – An example of CAPPI [2]

Each CAPPI consists of a set of small squares (bins), with an area of 1 km2, associated to a given value of reflectivity. The rain cell is defined as a set of side by side bins where the reflectivity exceeds a settled threshold. It should be pointed that bins connected by the vertex do not belong to the same cell. All the bins where the reflectivity is below this threshold are not taken into account. Fig. 9 [2] shows, in detail, two examples of rain cell (thick border) where it was fixed a threshold of 45.0 dBZ.

Once most rain attenuation prediction methods are based on geometrical models with a circular section, it is possible to by-pass this problem supposing the rain cell with a circular horizontal projection where the equivalent diameter is given by being the area A equal to the number of bins inside the irregular cell.

$$D(km) = 2\sqrt{\frac{A(km^2)}{\pi}}$$

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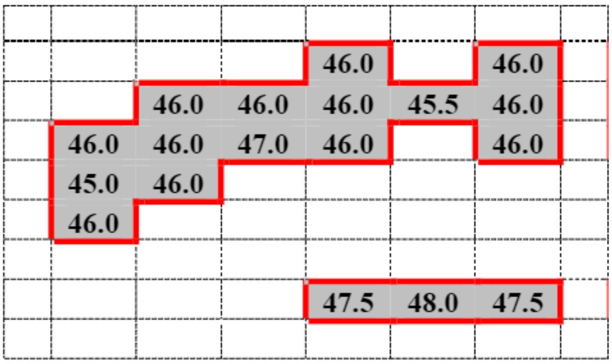

Figure.9– Examples of rain cell [2]

A general result relative to the horizontal extent of rain cells is given in Fig. 10 [2]. This figure shows, for Cruzeiro do Sul, the cell diameter, as a function of the percentage exceeded, for different values of the precipitation rate, i.e, p(D>D0/R > Ro), the conditional probability of a diameter D larger than a reference value D0, once the precipitation rate R is larger than R0. These curves are compatible with results reported by others authors [21, 22].

A possible application of the previous result is the evaluation of the probability of a rainfall rate R0 to be exceeded, simultaneously, in two points separated by a distance L, as shown in Fig.11[2]. This information can be used in the analysis of site diversity configuration for satellite communication systems [23]. It is observed in this figure that, for all values R0, saturation occurs for distances between 10 and 15 km. Site diversity gain curves empirically derived from rain attenuation measurements [24, 25] have a similar behaviour.

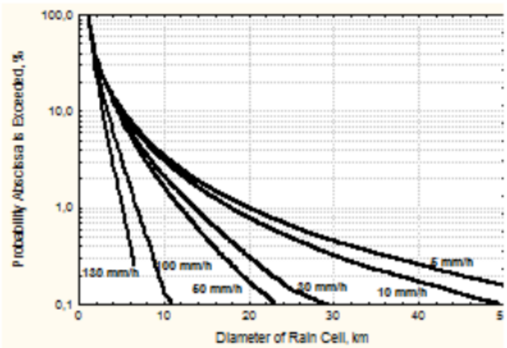

Figure 10: Distribution of rain cell size for different values of rain rate exceeded over the cell [2]

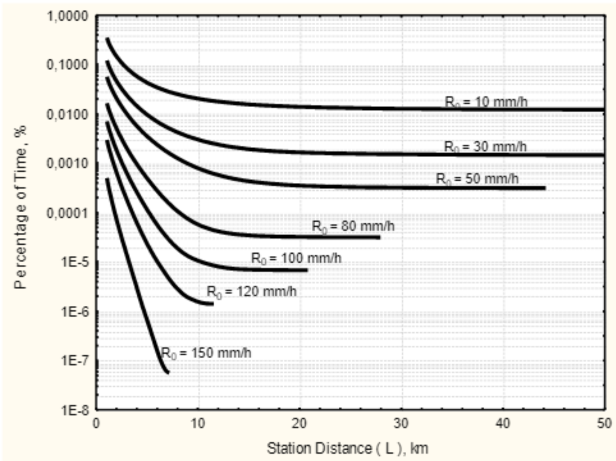

Figure 11: Percentage of time that a precipitation rate R_0 is simultaneously exceeded in two points separated by a distance L [2]

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VII. Vertical Distribution Of Rain

Weather radar observations [26] show that, on average, the rain intensity does not vary from the surface of the Earth up to the 0°C isotherm (h0). Radar measurements carried out in Manaus (03°08'S; 60°01'W) for stratiform rain and convective rain are exemplified in Figs. 12 and 13 [2]. In the case of stratiform rain the reflectivity is roughly constant from the ground up to the melting layer (bright band) which is located around the 0°C isotherm. The convective rain has a similar behaviour where the 0°C level is an acceptable reference. Based on these results, along the years h0 has been used as reference for modelling the rain height.

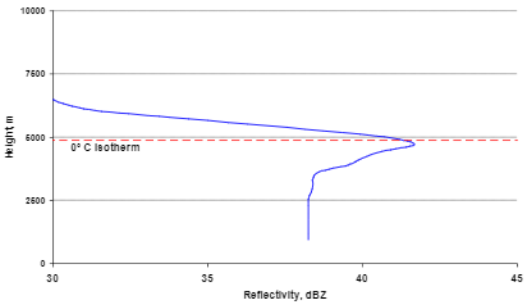

Figure 12: Stratiform rain [2]

It should be pointed out that radar data eventually indicate the existence of heavy rain well above the 0°C isotherm. An example is given in Fig. 14 [14] with data from radar station of Tefé, Brazil (03.22° S; 64.42°W) recorded in the event of 18 October 2005. This Figure shows profiles of radar reflectivity measured at 8 points separated by 250m in a range of 2km. considering that the average value of h0 is around 4.5km, the rain rate in this example is constant up to km.

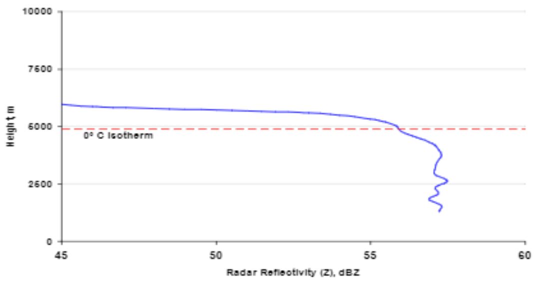

Figure 13: Convective rain [2]

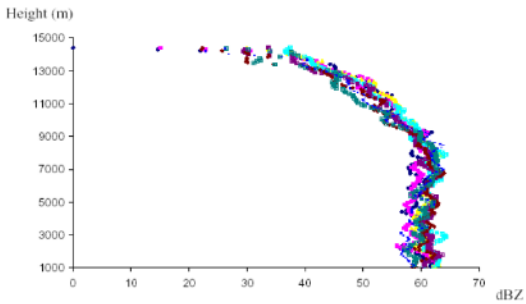

Figure 14: Vertical distribution of an exceptional rainfall event – Tefé, Brazil [14]

In Malaysia this problem was studied based on radiosonde observations during 5 years (2001 – 2006) [27]. The observations were taken from the Malaysian Meteorological Department over four stations located in Ipoh (4.34 N; 101.4 E), Kuala Lumpur (3.1 N; 101.42 E), Melaka (2.28 N; 102.5 E) and Terengganu (4.13 N; 4.13 E) twice a daily, one at 00:00 GMT and the other at 12:00 GMT corresponding to morning and late evening time Based on these observations the following comments can be done: Rain height varies from 4.7 to 5.1 in a year over Ipoh, 4.9 to 5.3 over Kuala Lumpur, 4.6

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to 5.0 over Melaka and 4.8 to 5.1 to Terengganu. The cumulative distribution was also evaluated in those stations. Taking into account the measurements carried out in all stations over the probability range from 99.99 to 0.01% a total variation of 2.7 to 8.5km was observed. As reference, the ITU-R rain height is given as 4.5 km [28].

Table 3 [12] compares values of h0 taken from ITU-R digital maps [28] with radiosonde measurements (yearly average) carried out in several Brazilian sites. It should be noted that this table includes data from a small island (Trindade island), located far from the continent, which is representative of the 0°C isotherm behaviour over the sea. In all locations a reasonable agreement between experimental data and predicted values is observed with a maximum error around 10%. However, as it is shown in Table 4 [12], monthly variations can be quite large. This behaviour, despite being important for low availability satellite systems (worth month) cannot be predicted by the ITU-R digital maps.

Table 3: Yearly average of 0°C isotherm height in Brazil [12]

Location	LATITUDE	LONGITUDE	h_0(m) (measured)	h_0(m) (Rec. 839-1)
Belém	01°23' S	48°29' W	4868	4538.6
Manaus	03°08' S	60°01' W	4807	4466.6
Fernando de Noronha	03°51' S	32°25' W	4872	4577.3
Natal	05°55' S	35°12' W	4916	4574.4
Cachimbo	09°20' S	54°57' W	4933	4484.3
Vilhena	12°42' S	60°06' W	4780	4513.5
Brasília	15°52' S	47°56' W	4707	4468.6
Trindade Island	20°30' S	29°18' W	4449	4284.7
Campo Grande	20°28' S	54°40' W	4675	4489.5
Rio de Janeiro	22°54' S	43°10' W	4375	4243.1
São Paulo	23°37' S	46°39' W	4443	4174.1
Curitiba	25°31' S	49°16' W	4335	4196.6
Porto Alegre	30°00' S	51°11' W	4011	4236.8

Table 4: Monthly variation 0°C isotherm height [12]

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LOCATION	Height (m)											
	Jan	Fev	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Belém	4944	4950	4935	5007	5027	4917	4816	4700	4752	4758	4844	4843
Trindade Is.	4741	4608	4497	4412	4456	4635	4806	4226	4158	4173	-	-
Campo Grande	4800	4808	4827	4813	4620	4599	4463	4414	4503	4588	4656	4826
Rio de Janeiro	4603	4615	4589	4207	4267	4172	4093	4126	4416	4312	4499	4508
Curitiba	4781	4797	4638	4207	4307	4017	4074	3904	4316	4194	4388	4384

VIII. TERRESTRIAL PATHS

An illustration of the horizontal variability of rain measured at the radar station of Cruzeiro do Sul, Brazil (7.36°S; 71.56°W) is shown in Fig. 15 [13]. Considering the non-uniform aspect of the rain cell shown in this figure, it is clear the difficulty to model it by a simple geometrical shape. Most prediction models use the concept of path length factor (or path reduction factor) for solving the problem of non-uniformity of rain along the propagation path. This factor is evaluated by dividing the rain attenuation (measured or predicted) exceeded for a given percentage of time by the specific attenuation ($\gamma = kR\alpha$) for the same percentage of time, k and being primarily functions of frequency and polarization. However, considering that is not feasible to derive a rigorous mathematical expression for this factor, an alternative is the use of experimental data for fitting an empirical solution based on a given rain cell model.

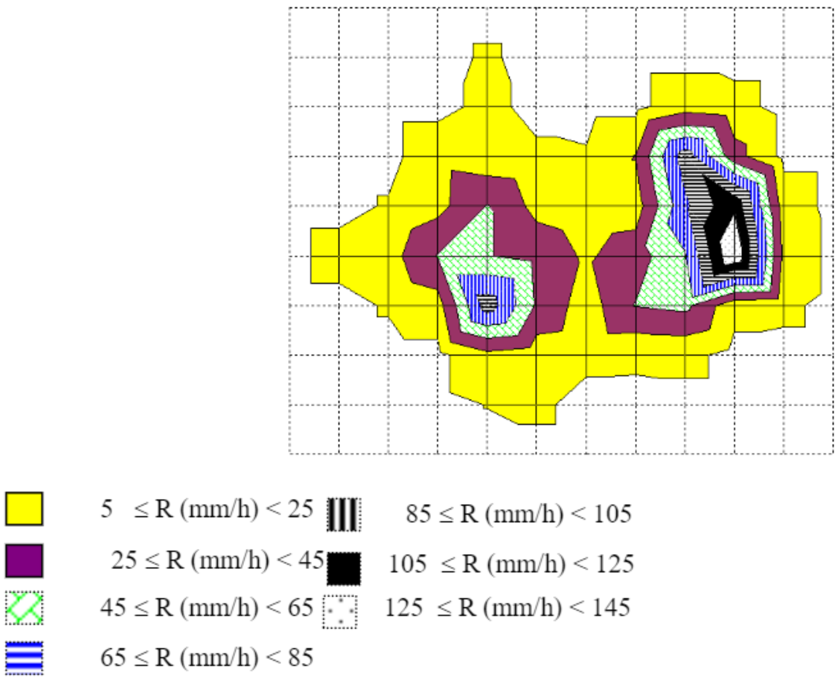

Figure 15: An example of the horizontal variability of rain – Cruzeiro do Sul, Brazil [13]

There are different procedures proposed for achieving the path length factor. In this paper, it is proposed a revision to a model previously developed by Timóteo da Costa and Assis [11]. This new model has as reference a truncated exponential rain cell and some preliminary calculations has shown promising results. An important reason for choosing this model was because through a combination of cylindrical and exponential shapes, it was avoided the restriction associated to a measured path length factor greater than one, common to other predicting methods. According to this model the rain cell has a rotational symmetry, being defined by,

$$R(x) = R_0 \quad \text{for} \quad 0 \leq x \leq \rho_0$$

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$$R(x) = R_o e^{-\frac{x-\rho_0}{\rho_m-\rho_0}\beta} \quad \text{for} \quad \rho_0 \leq x \leq \rho_m$$

$$R(x) = 0 \quad \text{for} \quad x > \rho_m$$

where

$\rho_0(km) = 7{,}675 R_0^{-0,44235}$ is the radius of the rain cell core;

$\rho_m(km)$ is the maximum value of the rain cell;

$$\beta = \ln \frac{R_o}{R_m}$$

R0 is the point rainfall exceeded in the same percentage of time as the rain attenuation considered in the numerical analysis, x is the distance along the path and Rm is the precipitation rate corresponding to ρm.

The radius of the rain cell core ρ0 was achieved by fitting a power function to radar data and is given by

$$\rho_0(km) = 7{,}675 R_0^{-0,44235}$$

Finally, based on experimental data the most adequate values for β and are β = 3, R0/Rm = 20 and ρm = 10 km.

Introducing the concept of equivalent precipitation [29],

$$R_e = \left[\frac{1}{d} \int_{-d/2}^{+d/2} R(x)^{\alpha} dx \right]^{1/\alpha}$$

the path length factor (r) for the truncated exp2onential cell is given by,

$$r = \frac{2}{d} \left\{ \rho_0 + \frac{1}{Y} \left[1 + e^{-\frac{Y}{2}(d-2\rho_0)} \right] \right\}$$

where $Y = \dfrac{\alpha\beta}{\rho_m - \rho_0}$, d is the path distance in km and α the exponent in the rain specific attenuation given by $\gamma(dB/km) = kR^{\alpha}$.

The main results derived from this study can be summarized as follows:

a) The effective path length factor is, in general, larger than one when the core of the rain cell is larger than the path distance;

b) The prediction error increases for distances larger than about 20 km. This condition occurs when attenuation is due to the existence of more than one rain cell along the propagation path;

c) Although experimental data from terrestrial paths located in tropical and equatorial regions are scarce, there is some evidence that the effective path length factor depends on the climate of the area under study.

Although the results commented here were derived from the precipitation rate exceeded for 0.01% of time of an average year, there is some evidence that this path length fact factor enables the evaluation of rain attenuation in a point-to-point basis. This question is being investigated, as well as a possible improvement in the prediction of rain attenuation in tropical and equatorial areas.

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In this context, in Malaysia, an important contribution from UTM was recently published by Abdulrahman, Rahman and Rahim [3]. This paper describes the technique for deriving the path length factor from experimental rain rate and rain attenuation data over seven 15 GHz terrestrial links. The relationship between path reduction factors with different link lengths has been studied using multiple non-linear curve-fitting techniques. The localization of these links is depicted in the map of figure 5 and the corresponding measured average yearly rain attenuation cumulative distributions are shown in Table 5. As an example of the mathematical analysis carried out, the relationship between path length and the corresponding path reduction factor at 0.01% of time is illustrated in Fig. 16 [3]. This figure compares the experimental data with the proposed model and ITU-R predictions. It can be observed that the ITU-R considerably underestimate the experimental path reduction for five links (Penang, Alor Star, Kuala Lumpur, Taiping and Kuantan). While for Temerloh and Terenganu links the experimental and ITU-R predicted values are nearly the same. On the other hand, the prediction by the model proposed by Abdulrahman and others are in good agreement with experimental values. The only exception refers to the Alor Star link which shows a noticeable deviation. It should be pointed out that, the path length factor predicted by this method has a reasonable agreement with the model based on a truncated exponential rain cell described previously.

Table 5: Average yearly rain attenuation in seven radio links in Malaysia [3]

Site	Measured rain attenuation (dB)								
Locations	0.001	0.002	0.003	0.005	0,01	0.02	0.03	0.05	0.1
Penang (11.33km, 14.8 GHz)	53.42	48.00	46.17	44.86	42.44	39.06	36.02	31.46	24.68
Terengannu (5.98 km, 14.8 GHz)	45.64	41.17	39.22	37.98	36.33	34.08	32.00	28.64	20.06
Temerloh (5.36 km, 14.8 GHz)	40.78	37.59	36.25	33.14	29.91	25.77	23.58	20.35	14.36
Alor Star (4.85 km, 15.3 GHz)	37.94	37.40	35.56	32.22	28.53	23.81	20.35	16.43	11.82
Kuala Lumpur (3.96 km, 14.8 GHz)	38.24	34.90	33.98	33.21	30.14	26.57	23.58	20.00	14.71
Taiping (3.48 km, 14.8 km)	33.50	31.94	31.11	30.78	29.21	27.03	23.92	21.02	17.18
Kuantan (1.45 km, 14.8 GHz)	28.00	26.30	23.88	20.04	15.98	13.00	10.08	8.20	5.80

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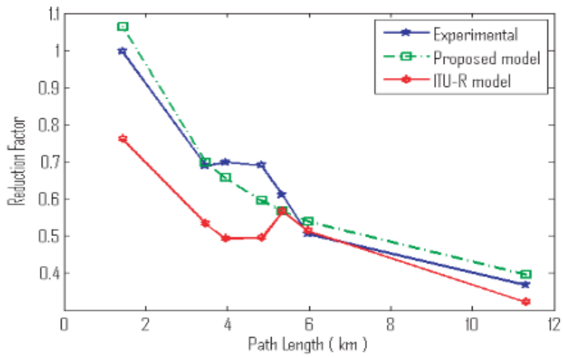

Figure 16: Comparison of path reduction factors [3]

Table 6 [3] shows the mean error and the standard deviation, as a function of time percentage, for the radio links referred to above. It is observed that for time percentages between 0.1 and 0.005 % the proposed model has high accuracy. However, the proposed model overestimates the measured rain attenuation at higher rainfall rates in the range 0.003 to 0,001%.

Table 6: Mean error and standard deviation [3]

Parameter	Percentage of time (%)						
	0.001	0.003	0.005	0.01	0.03	0.05	0.1
Mean error	6.481	3.232	1.807	0.420	-0.266	-0.237	-0.248
Standard deviation	8.139	5.810	4.415	1.358	0.502	0.472	0.484

As a final remark to the question of terrestrial rain attenuation, it seems to be advisable that a joint effort must be carried out to find a model really adequate for equatorial/tropical regions. As pointed out by Assis [8,9] and Assis and Dias [10], the rain attenuation in temperate and tropical/equatorial climates show remarkable differences. On the other hand, in general, a totally empirical model has a critical dependence on the parameters used to adjust it with rain attenuation experimental data. According to these considerations, the model to be proposed should be semi-empirical, or in other words, the model must have an accurate physical basis derived from measurements of the rain cell shape and then fitted to the experimental data available in the tropics.

IX. Slant Paths

It has been discussed throughout this paper that the accuracy of a rain attenuation prediction model depends critically on the knowledge of the spatial structure of precipitation. Particularly important for slant paths is the vertical variability of rain. Based on radiosonde and radar measurements, this problem was considered in Section 6 emphasizing the importance of the 0° C isotherm (h0). However, for developing a rain attenuation model for Earth-satellite path, the concept of effective rain height seems to be more appropriate. This approach supposes the radio path entirely within a rain cell, a hypothesis rigorously valid when the elevation angle is 90° (zenith attenuation). However, without damaging the final results, slant paths with a minimum elevation angle of 70° can be taken into account in the analysis. The effective rain height is then given by,

$$h_R = \frac{A_R \sin\theta}{\gamma}$$

where

AR – measured rain attenuation (dB);

γ = kRα – specific attenuation (dB/km);

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θ – elevation angle;

R – rain rate (mm/h);

and the parameters k and α where defined previously.

Fig. 17 [13] shows an example based on measurements carried out in the 12 GHz band in the Amazon region, which also include reference to the 0°C isotherm level. The concept of effective rain height was adopted by Assis [8] in the analysis of data from six locations in Brazil, India and Papua-New Guinea, all of them located in the tropics, and with a minimum elevation angle of 70°. The result of this analysis is shown in Fig. 18 [8], where the effective rain height is given as a function of precipitation rate. From the observation of this figure the following remarks can be pointed out:

a) For rainfall rates above 30 mm/h (convective rain), the effective rain height is practically constant. In this case, the rain produced by the coalescence mechanism [15] and the constant height is, possibly, a consequence of the physical limitation of the maximum raindrop in the process;

b) For rainfall rates below 30 mm/h (stratiform rain) the effective rain height increases approximately in a linear way as the precipitation rate decreases. This behavior may be attributed to the contributions of bright band and cloud attenuation which were not considered in the evaluation of the effective rain height.

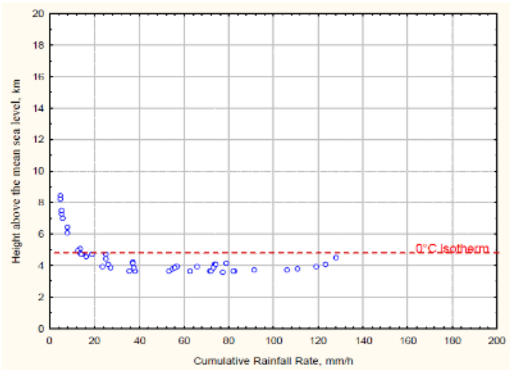

Figure 17: Manaus [03°09'S; 60°11'W] – Elevation angle = 83.05°

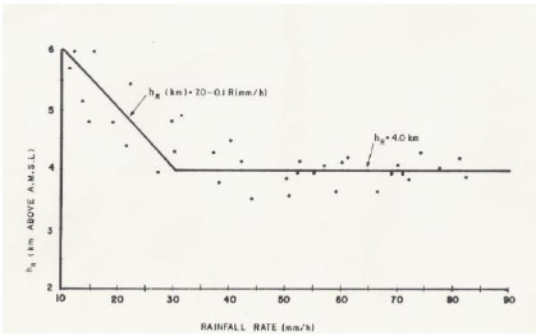

Figure 18: Effective rain height [8]

As a preliminary conclusion, for convective rain, the effective rain height evaluated from attenuation measurements in high elevation angle paths (greater than 70°) seems to be always below h0. However, the limited amount of experimental data used in the study described here do not allow to take a final decision about the value of rain height to be used in a rain attenuation prediction model for slant paths in low latitude areas. Anyway, the analysis based on zenithal or quasi-zenithal paths seems to be an adequate approach for facing the problem. Nevertheless, considering the empirical basis of this approach, as it was pointed out by Assis [8], this solution should be considered only after solving the problem of the horizontal distribution of rain.

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As a complement to the material presented in this Section, it should be mentioned that an investigation dealing with the problem of precipitation event duration were also carried out in the Amazon region [15]. In this study, the following questions were analyzed: a) The statistical behaviour of the rain event duration ; b) The use of the two variables Weibull function as mathematical model to characterize such events; c) The mathematical representation, by a power function, of the rain event duration in terms of the precipitation rate and the time percentage that this precipitation is exceeded; d) The average event duration of interest for designing fade countermeasures (e.g., adaptive FEC and/or modulation techniques, up link power control, etc.) for satellite systems; e) The evidence of a correlation between the durations of rain and fade events. Under the practical point of view, it must be emphasized that the results of this study are quite relevant for planning low availability satellite systems in Ku and Ka bands in equatorial regions [30].

X. Concluding Remarks

Based on radio meteorological data from Malaysia and Amazon region (Brazil) available in the technical literature, this paper carried out an analysis aiming two objectives. First it was shown that the annual and monthly rainfall rate distributions, as well as the rain height variations are quite similar in these two regions. This result has allowed to inferring that the same agreement could be observed in other equatorial/tropical countries. The second objective was the rain attenuation prediction. Regarding terrestrial paths, different approaches were considered in Malaysia and Brazil. In Malaysia, a model totally based on experimental data was developed, while in Brazil emphasis was given to a theoretical model derived from a truncated exponential rain cell. As pointed out, the best solution would be a semi-empirical model based on the knowledge of the rain cell shape and adjusted with experimental data Of course, the solution for slant paths should follow the same guidance.

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