Effect of Rainfall on Millimeter Wavelength Radio in Gough and Marion Islands

P. A. Owolawi, T. J. Afullo, and S. B. Malinga
University of KwaZulu-Natal Durban, P.O. Box 4000, South Africa

Abstract—With the increasing in spectrum occupancy and demand for high bandwidth for evolution of complex radio access network, the need to explore the advantages of millimetric wave band has become imperative. The advantages of the band are: large spectrum availability, high frequency re-used potential, small antenna and equipment size. In this paper, a new-hybrid approach is used to convert rainfall from five-minute integration time to one-minute integration time for the calculation of rain attenuation. The paper also provides information on cumulative distributions, seasonal variability, and worst month of rainfall rate for the islands. Consequently, relationship between average year (AY) and average worst month (AWM) are obtained.

1. INTRODUCTION
Marion Island (46°38’S & 37°59’E) and Gough Island (40°21’S & 09°53’W) are located approximately 1500 Km and 2500 Km south-east and south-west of Cape Town, South Africa respectively. Due to the biological diversity and environmental uniqueness of both islands which make them a main attraction for both tourists as well as scientific researchers, need for data transfer, video and voice communication has become inevitable. The microwave and millimeter wave spectrum at 30–300 GHz are of great interest to service providers and systems designers today because of the wide bandwidths available for communications at these frequencies. Such wide bandwidths are valuable in supporting applications such as high speed data transmission and video distribution [1]. However, radio signals at millimeter wavelengths suffer greatly from attenuation [2]. The principal limitation of the millimeter-wave link availability is precipitation. While the hardware designer cannot account for rain, the link or network planner can and must, by incorporating a sufficient margin into the link design [3].

To successfully estimate rain attenuation along the link path, the point rainfall rate characteristics statistics must be available in the location of interest [4]. Information such as rainfall rate characteristics, i.e., rainfall rate integration time, average rainfall rate cumulative distributions, worst-month rainfall rate distributions are required by a radio link planner in order to estimate path loss.

Previous works done by the author [5–10] were based on five years rainfall data, while the recent ones are based on more than ten years rainfall data. In addition, a location-based conversion factor is developed in order to convert rainfall rate from higher integration rate (five-minute) to one-minute equivalent recommended by International Telecommunication Union Recommendation (ITU-R).

2. RAINFALL RATE CUMULATIVE DISTRIBUTION
Daily rainfall accumulations are universally recorded and hourly data are also fairly widely available at national weather bureaus [11]. As a result of unavailability of one-minute rainfall rate data, thus a conversion method needs to be employed. Methods commonly used to estimate one minute rainfall rate distribution from different integration times include Rice-Holmberg’s model [12], Segal [13], Ajayi-Ofoche [14], Singh et al. [15], Burgueno et al. [16], Chebil-Rahman [17], Joo et al. [18], Karasawa-Matsudo [19], Ito-Hosoya [20], Moupfouma [21], and Moupfouma-Martin [22].

In this paper, a hybrid approach is employed. The approach combines Ito et al. and Moupfouma et al. at defined percentage of exceedence and interpolates by using Lagrange interpolation method. The Lagrange interpolation method is chosen because of its simplicity and precision. A linear least-square fit is plotted as shown in Figures 1–3 and return relationship given below:

\[ R_{1\text{ min}} = \varphi R_\tau + \psi \] (1)

where is the integration time at which rainfall rate data is collected, coefficients \( \varphi \) and \( \psi \) at 5-minute integration time is shown in Table 1. Equation (1) coefficients give positive slopes and
positive intercepts for Durban, Pretoria Cape Town while the two Islands return negative intercept. The table shows that fitted models for Gough Island, Marion Island, Durban and Pretoria overestimate the distribution except in Cape Town, by 32%, 23%, 165% and 99% respectively. The rainfall rate at one-minute integration time estimate is used to plot cumulative distributions for four different climatic regions namely: Midlatitude (Gough and Marion Island), coastal (Durban), temperate (Pretoria) and Mediterranean (Cape Town) in Figure 4. Figure 4 shows cumulative distributions of rainfall rate for five locations. It plays an important role in the assessment of attenuation due to rainfall in the location of interest especially at $R_{0.01}$. Table 2 shows details of the site from which data was collected; longitude, latitude and percentage of time rainfall rate exceed 0.01%. At 0.01%, the maximum rainfall rate is recorded for Durban while the least is observed in Cape Town.

### Table 1: Coefficient of Equation (1).

<table>
<thead>
<tr>
<th>Site</th>
<th>$\varphi$</th>
<th>$\psi$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gough Island</td>
<td>1.3231</td>
<td>-0.4394</td>
<td>0.9335</td>
</tr>
<tr>
<td>Marion Island</td>
<td>1.2333</td>
<td>-1.4414</td>
<td>0.9673</td>
</tr>
<tr>
<td>Durban</td>
<td>2.6474</td>
<td>1.7811</td>
<td>0.9756</td>
</tr>
<tr>
<td>Cape Town</td>
<td>0.9796</td>
<td>5.3765</td>
<td>0.9666</td>
</tr>
<tr>
<td>Pretoria</td>
<td>1.9793</td>
<td>5.4599</td>
<td>0.9806</td>
</tr>
</tbody>
</table>

3. CHARACTERISTICS OF RAINFALL REGIME

Figure 5 shows the mean yearly rainfall accumulation over 30 years for Gough Island, Marion Island, Durban, Cape Town and Pretoria. The two islands experience regular rainfalls all year long from...
about 17 mm to 241 mm. Durban and Pretoria have their maximum rainfall accumulation during summer (January) while Cape Town records it maximum in winter (June).

Table 2: Characteristics of five selected sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude</th>
<th>$R_{0.01}(1 \text{ min})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gough Island</td>
<td>40°21'S</td>
<td>9°53'MW</td>
<td>54 m</td>
<td>47.2</td>
</tr>
<tr>
<td>Marion Island</td>
<td>46°53'S</td>
<td>37°52'E</td>
<td>22 m</td>
<td>37.04</td>
</tr>
<tr>
<td>Durban</td>
<td>29°58'S</td>
<td>30°57'E</td>
<td>68 m</td>
<td>135.22</td>
</tr>
<tr>
<td>Cape Town</td>
<td>33°58'S</td>
<td>18°36'E</td>
<td>44 m</td>
<td>28.86</td>
</tr>
<tr>
<td>Pretoria</td>
<td>25°44'S</td>
<td>28°11'E</td>
<td>1330 m</td>
<td>100.47</td>
</tr>
</tbody>
</table>

The maximum average rainfall accumulation for Gough Island, Marion Island, Durban, Cape Town and Pretoria are 310 mm, 232 mm, 134 mm, 93 mm and 136 mm respectively. The minimum average rainfall accumulation for Gough Island, Marion Island, Durban, Cape Town and Pretoria are 26 mm, 17 mm, 9 mm, 1 mm and 3 mm respectively. The maximum range difference is recorded in Gough Island while minimum is experienced in Cape Town.

4. RAINFALL RATE VARIABILITY

Rainfall occurrences are dynamic and distributed in time and space [23]. These results in month to month, year to year and season to season variability in rainfall rate distribution. ITU-R P.837-1 to P.837-4 and the revised edition [24] recommendation which define the characteristics of precipitation modeling reflects discrepancy from their recommendation P.837-1 to the revised P.837-4. The ITU-R recommendation P.837 is the standard the link budget planner and system designer use to estimate the fade margin as a result of rainfall.

In this section, seasonal variability is investigated and classified into four different seasons namely: summer, autumn, winter, and spring. In the case of the two islands, the lower rainfall rate variability indicates the consistency from one season to another. The other stations show higher variability in rainfall rate which indicate distinction in seasonal variability. The seasonal variability is important to link planner in the sense that the fade margin provided by the rainfall rate at a defined percentage of exceedence need to be compensated. The rainfall rate at 0.01% of exceedence for winter in Gough Island, Marion Island, Durban, Cape Town and Pretoria are 50.37 mm/hr, 34.07 mm/hr, 19.49 mm/hr, and 119.47 mm/hr respectively. At 0.01% percentage of exceedence, the maximum rainfall rate is experienced in summer in some areas such as Marion...
Island, Durban and Pretoria while in Gough Island records maximum rainfall during Autumn season. The Cape normally records its maximum rainfall rate during the winter season. The minimum rainfall rate distribution is observed in spring in locations such as Gough Island, Marion Island, and Durban. Cape Town records its minimum during summer and Pretoria records its minimum during winter at 0.01% percentage of exceedence.

5. WORST MONTH AND ITS STATISTICS

The reliability of a communication link is specified in terms of the desired percentage of time that the basic transmission loss, catered for, would not be exceeded over a specified period of time, generally taken as one year. The concept of worst-month is also used to meet the percentage of ‘any month’ performance criteria since annual cumulative statistics is related to annual worst-month
statistics [25].

The ITU-R [26] has defined the concept of worst-month statistics. This concept can be applied to terms such as rainfall rate, rain attenuation and cross polarization discrimination (XPD) for a period of 12 consecutive calendar months. The annual worst month for a pre-selected threshold is defined as the month (30 days period) with the highest probability of exceeding that threshold level at each annual occurrence level. To describe worst month [27], we assume $X_{ij}$ to be the probability of exceeding a threshold level $j$ in the $i$th month. The worst month for level $j$ is the month with the highest $X_{ij}$ value, $X_{hj}$, among all 12 months [28]. The calendar month to which $X_{hj}$ belongs may vary from one threshold to another. For multiple years data, the averages of the individual annual worst-month probabilities for each level $j$ [28] is determined. In a more simplify

![Figure 7: (a) Comparison of measured data, estimated model and ITU-R model in Gough Island. (b) Comparison of measured data, estimated model and ITU-R model in Marion Island. (c) Comparison of measured data, estimated model and ITU-R model in Durban. (d) Comparison of measured data, estimated model and ITU-R model in Cape Town. (e) Comparison of measured data, estimated model and ITU-R model in Pretoria.](image-url)
form, the relationship between average worst-month statistic probability ($X$) and average annual statistics probability ($Y$) is given by the parameter $Q$, which is the ratio between the worst-month and annual probability and is given as:

$$Q = \frac{X}{Y} \quad (2)$$

ITU-R [29] suggests that $Q$ and $Y$ be approximated by power law relationship of the form:

$$Q = Q_1 Y^{-\beta} \quad \text{for} \quad (Q_1/12)^{1/\beta} \% < Y < 3\% \quad (3)$$

where $Q_1$ and $\beta$ are two parameters. To relate $X$ and $Y$, Equation (3) has been written as:

$$X = Q_1 Y (1 - \beta) \quad (4)$$

The ITU-R states that standard values of $Q_1 = 2.85$ and $\beta = 0.13$ can be used for global planning at define probability percentage as defined in Equation (3). The calculation of the average annual time percentage of excess from the given value of the average annual worst-month time percentage of excess is done through the inverse relationship [29] given below:

$$p = \frac{p_w}{Q} \quad (5)$$

In the case of global parameter given by ITU-R, Equation (5) can be re-written as shown below, where $\alpha = 0.30$ and $\beta = 1.15$.

$$p(\%) = \alpha p_w^\beta (\%) \quad (6)$$

The same approach is used to obtain the coefficient $\alpha$ and $\beta$ in Table 3. The coefficients are used to plot distributions in Figures 7(a) to 7(e). The figures show that the ITU-R model slightly under-estimates the distribution except in Marion Island where it over-estimates. The results are optimized using root mean square (rms) which is shown in Table 4. The root mean square table shows that in all the selected sites, the estimated model proves to be the best when compared with the ITU-R which is not too high in rms value.

<table>
<thead>
<tr>
<th>Site</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gough Island</td>
<td>0.89</td>
<td>1.35</td>
</tr>
<tr>
<td>Marion Island</td>
<td>0.82</td>
<td>2.202</td>
</tr>
<tr>
<td>Durban</td>
<td>0.81</td>
<td>1.294</td>
</tr>
<tr>
<td>Cape Town</td>
<td>0.70</td>
<td>1.27</td>
</tr>
<tr>
<td>Pretoria</td>
<td>0.547</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**Table 4: Root mean square for comparison (RMS).**

<table>
<thead>
<tr>
<th>Site</th>
<th>RMS ITU-R model</th>
<th>RMS estimated model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gough Island</td>
<td>0.34</td>
<td>0.075</td>
</tr>
<tr>
<td>Marion Island</td>
<td>0.35</td>
<td>0.17</td>
</tr>
<tr>
<td>Durban</td>
<td>0.16</td>
<td>0.012</td>
</tr>
<tr>
<td>Cape Town</td>
<td>0.087</td>
<td>0.045</td>
</tr>
<tr>
<td>Pretoria</td>
<td>0.091</td>
<td>0.038</td>
</tr>
</tbody>
</table>

6. CONCLUSION

Based on a 10-year rainfall data, a simple linear expression is developed to convert rainfall rate at 5-minute integration time to 1-minute integration time as recommended by ITU-R. By using a
linear regression, coefficients are determined for each selected location. This result can be used to convert a 5-minute data to 1-minute equivalent for any location within the selected region.

The cumulative distributions of rainfall rate are plotted from which the values of rainfall rate 0.01% of exceedence are determined for different sites. The value 0.01% is important because it a value generally used to determine link availability. At 0.01%, Gough Island, Marion Island, Durban, Cape Town and Pretoria record 47.2 mm/hr, 37.04 mm/hr, 135.22 mm/hr, 28.86 mm/hr and 100.47 mm/hr of rainfall rate respectively over an average year. This result can be used by link budget planners to estimate the specific rain attenuation that should be contributed to the link.

Due to dynamic characteristics of rainfall, the yearly, seasonal or monthly changes become question to be answered when planning a link budget. The rainfall regime is classified into four major seasons: summer, autumn, winter and spring. The result shows that Marion Island, Durban and Pretoria record their maximum rainfall rate during summer while Cape Town and Gough Island record their maximum during the winter and autumn respectively.

The worst-month statistics on rainfall rate are very useful in designing high quality communication link. The relationship between the average year and average worst-month are developed. The results are compared with the ITU-R model on worst-month. It is confirmed that in all selected sites, the ITU-R model under-estimates the distributions while Marion Island over-estimate the distribution. The rootmean- square results confirm that both ITU-R and estimated models can be employed to determine the average worst-month from average year data or vice-versa. The estimated models proposed will give a better estimate for the conversion.

REFERENCES


