Evaluation of Small-scale Spatial Distribution of Rain Cells in Equatorial Malaysia for Rain Attenuation Modeling

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***Abstract*—This work evaluates the spatial features of the synthetic rain cell profile based on two years of real rain cells database extracted from weather radar observation located in Kluang, Johor, Malaysia. Single rain cells modeled by an analytical exponential and Gaussian profile are evaluated and investigated based on certain features of real rain cells such as maximum rain rate and root mean square rain rate inside a single rain cell. Preliminary results indicate the Gaussian profile with a shape factor *k* of 1 best represents real single-peaked rain structures in this particularly heavy rain area. However, the validity of results rely highly on the resolution limitation of the database used in this work, where the commercial operating meteorological radar consists of coarse quantization resolution of rain-rate, which might misinterpret the real rain cell profile at a lower rain rate. Nevertheless, this work still provides radio engineers with useful information for the design of wireless communication systems in this particular area (heavy rain region).**

***Index Terms*—Rain cells, equatorial region, weather radar, shape factor.**

I. INTRODUCTION

MODERN satellite communication systems which operate at high frequencies will suffer from deep signal fades due to rain particularly in equatorial regions. Specifically, the spatial distribution of precipitation is of key importance for the design of radio communication systems at frequencies above 10 GHz [1],[2]. In fact, such physical characteristics of rainfall are predominantly significant in equatorial areas, which exhibit extremely high rain rates and localized features when compared to precipitation in temperate regions [3],[4].

To cope with severe attenuation phenomena caused by rain, the implementation of Propagation Impairment Mitigation Techniques (PIMTs) are required. Recent development of the advanced rain field model such as MultiEXCELL [5], whose resemble the spatial and temporal properties of actual rain fields, will allow evaluating the effectiveness of PIMT. However, it is worth noting that the spatial features produced by these rainfall models are built on a fundamental aspect of a single rain cell profile, which is commonly defined as the continuous area in which the rain rate is higher than a given threshold value[5].

Prior to the development of the MultiEXCELL model, several works focused on the investigation and modeling of rain cell spatial features that were carried out across the US and Europe [1], [7], which finally fostered the development of well- established cellular models, EXCELL [7] and HYCELL [8], specifically oriented to a propagation application. In this respect, the EXCELL model proposes an exponential decay of the rain rate around a peak rain rate, whilst HYCELL suggests a hybrid profile which describes the horizontal rain intensity profile in a single rain cell using a mixed Gaussian-exponential function. However, it should be noted that such advanced models rely on the simple rain cell profile that was developed based on the observation of weather radar in a temperate region, whilst the modeling work devoted to the rain cell profile in a heavy rain region has yet to be fully investigated due to the lack of meteorological data from these regions. Therefore, it is worthwhile to further evaluate the small-scale spatial distribution profile of rain cell in these areas based on local weather radar observation.

This work aims to evaluate the spatial characteristics of single rain cells in equatorial Malaysia by means of a rain cell database derived from weather radar data collected in Kluang, Johor (103.3º E, 2.02º N), Malaysia from January 2007 to December 2008. Details on the rain cell database are briefly provided in Section II. Section III describes the fundamentals of the optimum rain cell from the EXCELL model. The core of the paper lies in Section IV, in which evaluation of the small-scale spatial distribution of rain rate within a single rain cell profile with respect to the shape factor of exponential, Gaussian or Hyper-exponential are presented. Finally, conclusions are drawn in Section V.

II. RAIN CELLS DERIVED FROM WEATHER RADAR DATABASE

In this work, the database consists of 253,767 un-corrupted rain cells extracted from 69,351 rainfall maps through observation of S-band weather radar managed by the Malaysia Meteorological Department located in Kluang [4]. Details of the rain-rate extraction from radar data are available in [4]. Initially, two different thresholds, 1 mm/h and 5 mm/h are identified according to the same automatic contouring algorithm employed in [5] as shown in Fig.1, and total number of rain cells identified at the threshold of 1 and 5 mm/h are reported in Table I. These cells are carefully identified and those affected or touched by a single pixel of the problematic pixels (contaminated by clutter or blockage) will be classified as corrupted cells, hence, will not be considered in this work. For the sake of brevity, please refer to [4], [5] for a more detailed explanation of the rain cell identification procedure.

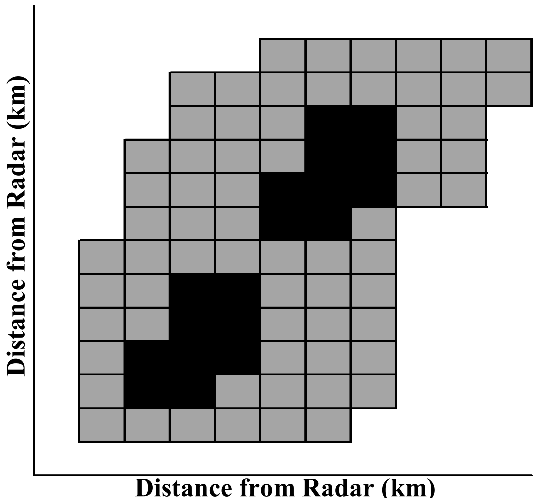

Fig. 1. Example of identified rain cells at threshold of 1 mm/h (gray pixels) and 5 mm/h (black pixels).

TABLE I
EXTRACTED RAIN CELLS FROM THE WEATHER RADAR DATABASE

Threshold	Uncorrupted	Corrupted	Total	Corrupted %
1 mm/h	34,0657	18,1043	521,700	34.7
5 mm/h	154,566	99,201	253,767	39.1

III. OPTIMUM SINGLE RAIN CELL PROFILE

The morphology features of rain cells extracted from weather radar data reflects peculiarities of local rain cells. Unfortunately, radar data are not easily available, and radar information usually requires complex and time consuming processes. For this reason, an optimum single rain cell model with the ability to preserve, at best, the main characteristics of real rain cells, is necessary. This goal is achieved by considering a simple synthetic rain cell profile suggested by [4], which can be represented in the following analytical form:

$$R(\rho) = R_{\max} e^{-\left(\frac{\rho^2}{\rho_o^2}\right)^{\frac{1}{k}}} \tag{1}$$

where $R\ (mm/h)$ is the rain rate, $\rho\ (km)$ is the distance from the cell center where the peak rain rate $R_{max}\ (mm/h)$ is located. $\rho_o(km)$ is the equivalent radius for $R = R_{max}/e$. The coefficient k represents the shape factor of rain cell profiles (i.e. $k = 1, k = 2$ and $k = 3$ respectively, and are classified as Gaussian, exponential and hyper-exponential as illustrated in Fig.2 [5].

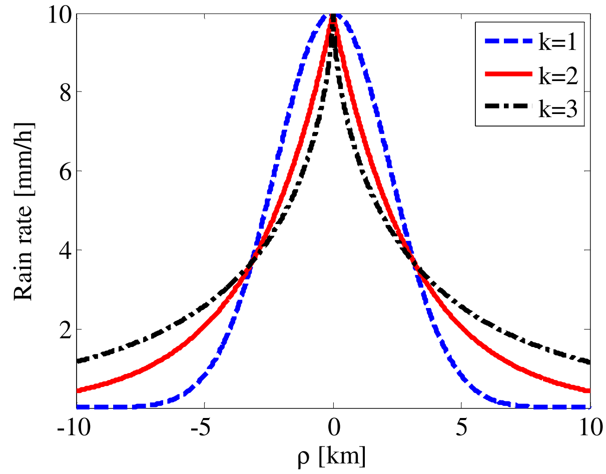

Fig. 2. Rain cell profile dependent on shape factor *k* [5]

IV. RESULTS AND DISCUSSION

To quantitatively assess the best rain cell profile with respect to the measured cell from weather radar, cell descriptors such as the peak rain rate R_{max}, and the root mean square of rain intensity R_{rms}, have been chosen as reference indicators for the evaluation of the most optimum profile with respect to real rain cells. The following error figure ε is considered:

$$\varepsilon = 100 \times \frac{V_p - V_m}{V_m} \tag{2}$$

where V_p and V_m indicate the value of the descriptor under test, respectively calculated from the synthetic and measured rain cells.

Fig.3 illustrates an example of the error figure ε with respect to the R_{max} for three rain cell profiles (Gaussian, exponential and hyper-exponential) at a threshold of 5 mm/h. From this initial observation, the Gaussian rain cell profile seems to provide lower ε values with respect to the exponential and hyper-exponential profile. This is confirmed by the numerical results shown in Tables II and III.

As can be noticed from the results, for cells at 5 mm/h, the Gaussian profile clearly provides a better estimation of a measured rain cell profile from weather radar in terms of the root mean square of the rain rate and cell dynamic compared to the other two profiles. This result was in agreement with the radar observation in South-Western France, which underlines the Gaussian character of the convective rain cell [8]. However, studies published by Capsoni *et al.* [7] in temperate regions (mainly characterized by stratiform rain), suggested the

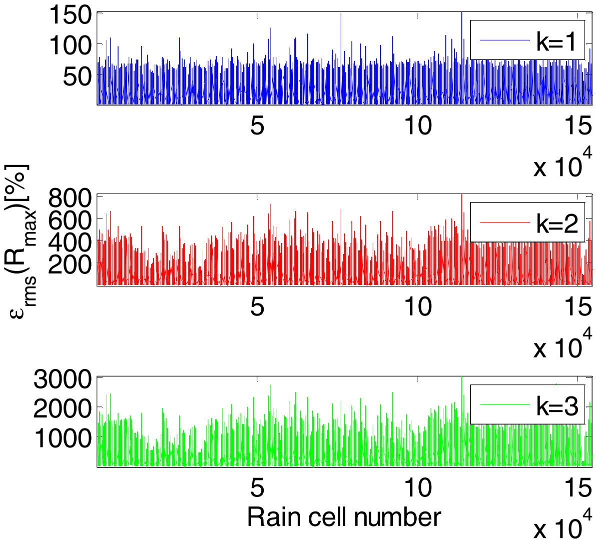

Fig. 3. Trend of $\varepsilon_{R_{max}}$ for the uncorrupted rain cells at threshold 5 mm/h.

TABLE II

TEST RESULTS OF PEAK RAIN INTENSITY R_{max} (5) RELATIVE TO THE THREE RAIN CELL PROFILES WITH THE VALUES OF MEAN ERROR (ε_{mean}), STANDARD DEVIATION ERROR (ε_{std}) AND ROOT MEAN SQUARE ERROR (ε_{rms}) IN %

Shape factor k	ε_{mean}	ε_{std}	ε_{rms}
1	-10.48	19.82	22.42
2	73.56	67.88	100.09
3	254.47	242.98	351.85

TABLE III

TEST RESULTS OF ROOT MEAN SQUARE RAIN INTENSITY R_{rms} (5) RELATIVE TO THE THREE RAIN CELL PROFILES WITH THE VALUES OF MEAN ERROR (ε_{MEAN}), STANDARD DEVIATION ERROR (ε_{STD}) AND ROOT MEAN SQUARE ERROR (ε_{RMS}) IN %

Shape factor k	ε_{mean}	ε_{std}	ε_{rms}
1	-1.53	4.49	4.74
2	6.60	9.24	11.35
3	14.42	17.20	22.44

exponential profile is the best representation of real rain structures.

Moreover, the latest study in [5] suggested that the best shape factor k might lie between 1 and 2, i.e. a mixed Gaussian-exponential synthetic cell, which allows more accurate modeling of a rain cell profile. To further confirmed this statement and what've been obtained thus far, R_{max} and R_{rms} have been calculated for the associated synthetic cells by considering shape factor k ranging from 0.5 to 3. Figs. 4 and 5 shows the rms values of error figure ε for R_{max} and R_{rms}

Obviously, as can be observed from the above results, the best shape factor shows a minimum error percentage in estimating peak rain rate and root mean square of rainfall are not from the integer value of k (i.e. k=1, 2, 3). It should be underlined that although these shape factors could provide better accurate modeling of rain cells, unfortunately, the non-integer ((i.e. k=1.2~1.3) choice would strongly increase the mathematical complexity of the model [5].

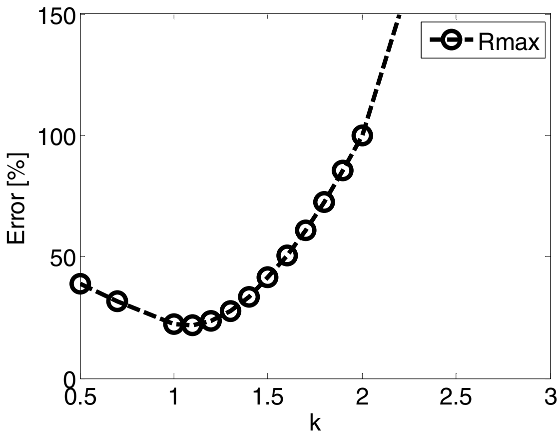

Fig. 4 Root mean square value of error figure ε for R_{max} as a function of shape factor k.

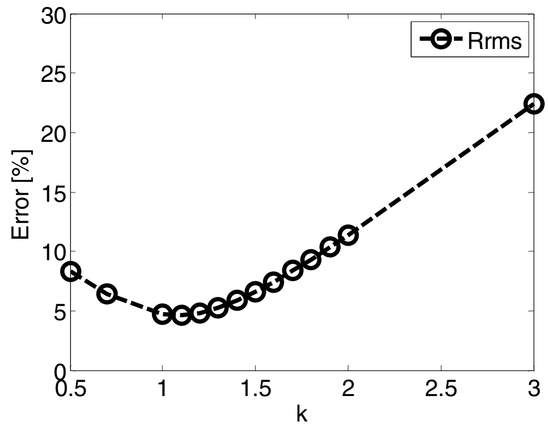

Fig. 5 Root mean square value of error figure ε for R_{rms} as a function of shape factor k.

In general, although preliminary results seem to indicate the Gaussian profile is best to represent real rain cells in this region, one should bear in mind that these results are highly dependent on the real rain cells observed from the weather radar data. Unfortunately, coarse rain intensity quantization and/or low spatial resolution (which decreases with the increase in the distance from the radar) characterizing the radar database used in this work, might affect the findings on the most suitable rain cell profile in this area (e.g. the peak rain rate values in the cells might be underestimated due to the limited quality of the radar data). In fact, several studies published in the past have suggested the choice of a purely exponential profile [5],[7],[9], are based on the observations made by higher resolution experimental weather radar instead of operating meteorological data. Hence, the preliminary results should be interpreted carefully and further research is required to confirm the findings from this work.

Finally, Fig.6a and 6b show an example of a single rain cell profile deduced from weather radar observation as well as the profile of the EXCELL model with the Gaussian shape factor (k=1).

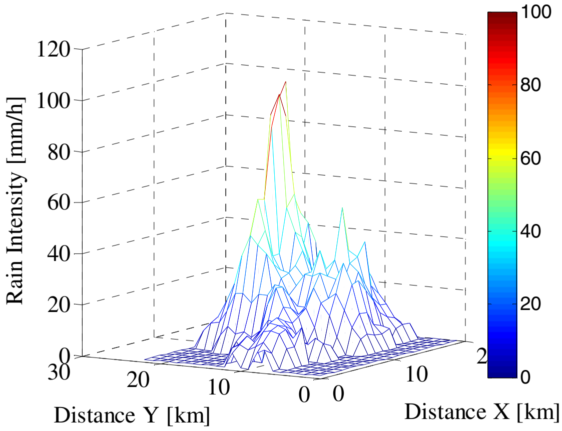

Fig. 6a. Example of radar observation rain cell with the peak rain rate R_{max}=100.2 mm/h.

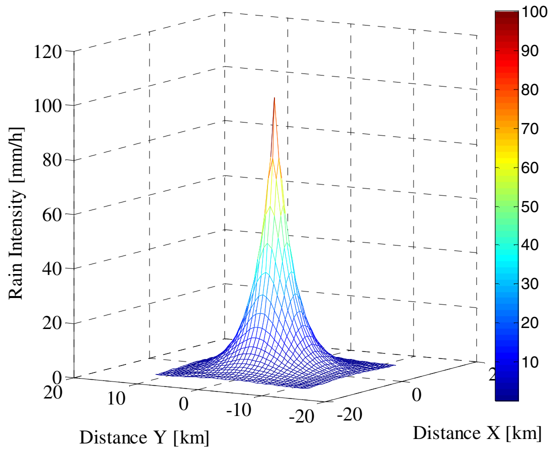

Fig. 6b. Example of EXCELL model rain cell observed by the radar as in Fig. 6a with Gaussian shape factor k=1.

V. CONCLUSION

This work evaluates small-scale spatial distribution of a real rain cell profile observed from the weather radar database in equatorial at Kluang, Johor, Malaysia with respect to the synthetic isolated rain cell from the EXCELL model for exponential and Gaussian shape profiles. Preliminary tests on the synthetic rain cell profile, which focused on the comparison of two rain cell descriptors, R_{max} and R_{rms}, have shown that a synthetic rain cell with the Gaussian profile are capable to reproduce the local features of a single rain cell profile as observed from the weather radar with respect to the one in the purely exponential profile. However, one should pay attention to the resolution limitation of the radar database used in this work as the low resolution of the operating commercial meteorological radar at a lower rain rate might misinterpret the real structure of the rain cell in this particularly heavy rain region. Furthermore, the results presented could at least provide substantial information on the rain cell in heavy rain region for the implementation of PIMTs for communication system operating at high frequencies [10]. Future work will focus on cross-validation of the rain cell profile with the meteorological rain-gauge network as well as the observation of spaceborne radar/ satellite from the Global Precipitation Measurement (GPM) mission or the Tropical Rainfall Measuring Mission (TRMM) to improve the accuracy of the synthetic rain cell profile model in this heavy rain region.

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