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Advances in Space Research xxx (xxxx) xxx

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

www.elsevier.com/locate/asr

Performance evaluation of some rain rate conversion models for microwave propagation studies

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Received 6 July 2020; received in revised form 18 January 2021; accepted 30 January 2021

Abstract

An important characteristic of rainfall levels at a particular place is the statistical distribution of rainfall rate. In this paper, 5-min integration time rainfall data for the Northcentral region of Nigeria was obtained from the Tropospheric Data Acquisition Network (TRODAN), Anyigba, Nigeria. Also, 1-min integration time rainfall was measured at Minna, Nigeria. In order to obtain the optimal rain rate model suitable for this region, two globally recognised rain rate models were critically evaluated and compared with the 1-min measurements. These are the ITU-R P.837-7 and Lavergnat-Gole (L-G) models. The results obtained showed that the ITU-R P.837-7 and L-G models respectively underestimated the measured rain rate by 7.3 mm/h and 9 mm/h at time percentage exceedance of 0.1%, while they underestimated the measured rain rate by 23.4 mm/h and 13 mm/h respectively at 0.01%. At 0.001%, the measured rain rate was overestimated by the ITU-R P.837-7 and L-G models by 27.4 mm/h and 3 mm/h respectively. Further performance evaluation of the predefined models was carried out using different error metrics such as sum of absolute error (SAE), mean absolute error (MAE), root mean square error (RMSE), standard deviation (STDEV) and Spearman's rank correlation. The results obtained adjudged the Lavergnat-Gole model as the best rain rate prediction model for this region.

Keywords: Cumulative distribution; Integration time; Rain Rate

1. Introduction

The severity of rain-induced degradation in the centimetric and millimetric wave bands has been a major concern to terrestrial and satellite communication engineers especially in the tropics where the amount of liquid precipitation is higher than in other regions (Ojo & Omotosho, 2013; Obiyemi et al., 2014a; Yussuff et al., 2018). Therefore, this propagation effect has to be considered by engineers and scientists in the system design for the two types of communication systems in order to improve the quality of the networks (Igwe et al., 2019).

However, the in-homogeneity of rain complicates the determination of its attenuation effect on electromagnetic waves. This is because rain exhibits enormous variation in size, shape and density. Hence, for any given rainfall rate, there exists no unique distribution of drop sizes as this varies in time and space (Tamošiunaite et al., 2010). Even though quite a number of efforts at developing rain rate and rain attenuation models have been made, the accuracy of the prediction of rain attenuation by such efforts over a communication link is still dependent on the locally measured rainfall data (Obiyemi et al., 2014b).

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https://doi.org/10.1016/j.asr.2021.01.055
0273-1177/

Please cite this article as: K. C. Igwe, O. D. Oyedum, M. O. Ajewole et al., Performance evaluation of some rain rate conversion models for microwave propagation studies, Advances in Space Research, https://doi.org/10.1016/j.asr.2021.01.055

A very important parameter usually considered in the analysis of rain-induced attenuation is the rain rate (Rafiqul et al., 2018; Sujimol et al., 2015). For optimal prediction of rain attenuation, accurate evaluation of the corresponding rain rate has to be made. Two types of rain attenuation prediction models exist. These are the empirical and semi-empirical models and the accuracy of each model is very much dependent on the accuracy of the computed rain intensity, hence the need to ensure precise measurement of the corresponding rain rate. Rain rate conversion from any integration time to 1-min has been a significant and accepted approach for effective and good analysis of rain-induced attenuation, especially when local 1-min data are unavailable. Since the requirement for the prediction of rain attenuation in terrestrial and satellite systems design is based on 1-min rain rate distribution (Ito & Hosoya, 2004; Shrestha & Choi, 2018), different models have been employed in the conversion of rain rates from other integration times to 1-min when there is no direct 1-min rain rate data. However, there is need for comparison with the direct 1-min rain rate measurement so as to validate the accuracy of the models utilised.

Different instruments and techniques abound for measuring rainfall intensity albeit with their peculiar advantages and limitations; for instance, measurements by remote sensing cover wider areas but with limited spatial resolution and accuracy, whereas rain gauges and disdrometers give more accurate point measurements but limited in wide coverage (Giannetti et al., 2017; Giro et al., 2020). Rainfall rate varies significantly from one locality to another all over the world. For a particular location, the measurement and accuracy of the empirical data enhances the development of the rain attenuation model, which is also dependent on the knowledge and accuracy of the rainfall rate distribution (Shrestha & Choi, 2016; Hossain & Islam, 2017).

In Nigeria, several commendable efforts have been made on rainfall rate studies, especially in the Southwestern region. A few of such works are worthy of mention here. Ojo & Falodun (2012) carried out empirical distribution functions for 1-min average rain-rate values for two Southwestern stations (Akure and Lagos) and one North eastern station (Yola) in Nigeria, using data collected by tipping bucket rain gauge at the Nigerian environmental and climatic observatory program (NECOP) terminal sites. Comparison was made between empirically generated distribution functions and cumulative distribution functions generated from four different rain rate models. The models used are the ITU-R P.837-6 (ITU-R, 2012), Rice & Holmberg (1973), Kitami (Ito and Hosoya, 1999) and Moupfouma & Martin (1995). The results showed that Moupfouma and Martin model predicted closely to the measured data for low, medium and high rain rates. Two years after, Ojo & Olurotimi (2014) investigated the tropical rainfall structure and characteristics of two Southwestern stations (Akure and Lagos) in Nigeria using two years rainfall data of 1-min integration time, also obtained from NECOP. From their results, comparison of the measured data with ITU-R P.837-6 data revealed that rainfall rate at 0.01% time exceedance probability was overestimated by the ITU-R P 837-6 model by about 21% for Akure, while it was underestimated by about 31% for Lagos.

In the same manner, Obiyemi et al. (2015) investigated one-min rainfall rate statistics for microwave applications in another Southwestern station (Oshogbo, Osun State) of Nigeria using seventeen months data measured by the Davis vantage vue electronic weather station. The cumulative rain rate distribution from the measured rain rate was also compared with predictions by the ITU-R P.837-6, Rice-Holmberg, Kitami and Moupfouma-Martin models. Results from their work showed that predictions from the ITU-R P.837-6 model underestimated the measured cumulative rain rate statistics between 0.001% and 0.1% time exceedance probability. However, there was better agreement of the other models (especially the Kitami model) with the measured data.

The authors of this paper thus deemed it necessary to conduct this cognate research in the Northcentral region since no comprehensive study on rain rate have been carried out in this region.

This paper thus evaluates two rain rate models (the ITU-R P.837-7 and the Lavergnat & Golé) widely used globally for rain rate studies and also adjudged to be very suitable for the type of data employed in this work (Ito & Hosoya, 2004; Emiliani et al., 2009; Emiliani & Luini, 2010; Chun & Mandeep, 2013; Ojo, 2016; Shrestha et al., 2016; Ng et al., 2017; Shrestha & Choi, 2017; Oktaviani & Marzuki, 2019; Singh & Acharya, 2019). Although, the ITU-R P.837-6 model was used in the cited works, it should be noted that the new ITU-R P.837-7 model is the same as the ITU-R P.837-6 for the local conversion of between 5 and 60 min integration time to 1-min integration time (see Annex 2 of ITU-R P.837-7 and Annex 3 of ITU-R P.837-6). The ITU-R P.837-7 and the Lavergnat & Golé models were compared with the direct one-minute rain rate measurements in order to determine the most accurate rain rate model for the Northcentral region of Nigeria.

2. Background

2.1. Rain rate models

Cumulative distribution of rainfall rate is imperative in evaluating attenuation due to rain in any location for terrestrial and earth-space communications. There are several rain rate models that have been developed for predicting rain rate of 1-min integration time from other integration times. However, not all models are suitable for all rainfall data especially at lower integration time of 5-min. So, careful considerations were made before the choice of the two models used in this work as they have been tested with measured data from different regions of the world and found to be reliable.

Please cite this article as: K. C. Igwe, O. D. Oyedum, M. O. Ajewole et al., Performance evaluation of some rain rate conversion models for microwave propagation studies, Advances in Space Research, https://doi.org/10.1016/j.asr.2021.01.055

2.1.1. ITU-R P.837-7 rain rate model

The ITU-R P.837-7 model (ITU-R, 2017) was developed by the International Telecommunication Union-Radio (ITU-R) to enable users estimate the local rainfall rate, R (mm/h) at 1-min integration time statistical distribution, P(R) using:

1. Global digital maps of precipitation parameters derived from Numerical Weather Prediction data as input.
2. Conversion of local cumulative distribution of rainfall rate measured at integration times of between 5 and 60 min to cumulative distribution of rainfall rate at 1-min integration time. This method requires the cumulative distribution of the rainfall rate, the integration time of the rainfall statistics and the geographical coordinates of the station of interest as input.

The second method of the recommendation is incorporated in a computer program. The software was developed in Matlab and executed through a Graphical User Interface (GUI). The software package implementing this section is available on the ITU-R website. This part of the recommendation is based on the EXCELL rainfall statistics conversion model (ERSC). Details of this method is given in Annex 2 and Reference Manual of ITU-R P.837-7. This second method was employed for the rain rate conversion in this paper.

2.1.2. Lavergnat and Gole rain rate model

The Lavergnat and Golé (1998) model considered the time interval separating two consecutive rain drops. The general application of the model is the conversion of cumulative distributions from an integration time t_1, to a target integration time t_2, which is accomplished by means of a conversion factor, defined as the ratio of the integration times:

$$P_2(R_2) = CF^a P_1(R_1) \tag{1}$$

where

$$CF = \frac{t_2}{t_1} \tag{2}$$

and

$$R_2 = R_1/CF^a \tag{3}$$

where P_1 is the cumulative probability obtained with a rain gauge of t_1 (min) integration time,

R_1 (mm/h) is rain rate for P_1,

P_2 is the cumulative probability obtained with a rain gauge of t_2 (min) integration time,

R_2 (mm/h) is rain rate for P_2

$a = 0.115$ for temperate regions.

It was also suggested that parameter ‘a’ has a regional dependence, and if it could be estimated for each location, this method would cover every region of the world (Ito & Hosoya, 2004). Hence, for the tropical climatic region, a value of 0.143 was deduced by Emiliani et al. (2009).

3. Methodology

3.1. Measurement of 5-minute integration time rainfall

The rainfall data taken at 5-min intervals were measured at the Tropospheric Data Acquisition Network (TRODAN) situated at the Federal University of Technology, Bosso Campus, Minna (Fig. 1). This experimental measurement campaign sponsored by the Center for Atmospheric Research (formerly Centre for Basic Space Science), an outfit of the National Space Research and Development Agency (NASRDA) is also situated on the campuses of some Nigerian Universities nationwide. Additional data from four of such Universities in the Northcentral region were used in this work. These are the University of Abuja, Abuja, Kogi State University, Anyigba, Benue State University, Makurdi and University of Jos, Jos. The instrument used for this measurement is the Campbell CR-1000 data logger (Fig. 2). Four years data of in-situ measurement were made available in Minna and Anyigba, while two years data were obtained from the Abuja and Jos stations. Makurdi station had three years data.

The rainfall data measured at 5-min integration time were filtered after which the rainfall intensity was computed from the rainfall accumulation. The range of rainfall rate was then determined and the computed rain intensities for the years considered were arranged and summed up accordingly. The cumulative frequency was then computed. The computed cumulative frequency was used to compute the percentage exceedances. The computed rain intensity and percentage exceedances are relevant input parameters for the existing models (The ITU-R P.837-7 and Lavergnat-Gole). These models were used to convert the rainfall rate from 5-min integration time to 1-min integration time.

Fig. 1. TRODAN weather station in Bosso campus, FUTMinna.

Fig. 2. Campbell CR-1000 data logger.

3.2. Measurement of 1-minute integration time rainfall

The rainfall data of 1-min integration time was measured using a rain gauge with an accompanying data logger (Rain 101A), both manufactured by MadgeTech incorporation (Fig. 3). The Rain 101A data logger is capable of measuring and recording data at many user-specified intervals. Different Start options are available for this device. There is the Custom Start option which selects or modifies logging options, the Real Time Start option which allows the device to report readings back to the central PC instantly and the Batch Start option which allows devices of the same model to be programmed with the same Custom Start settings. The Custom Start option with a reading interval of 10 seconds was chosen and used during the data collection for this research. During recording, the data logger stores the readings in its internal memory which can be viewed as a graph, a data table or statistical report after downloading. After downloading, the data is saved by exporting to Microsoft Excel spreadsheet. Two years of 1-min integration time rainfall data was obtained and analysed.

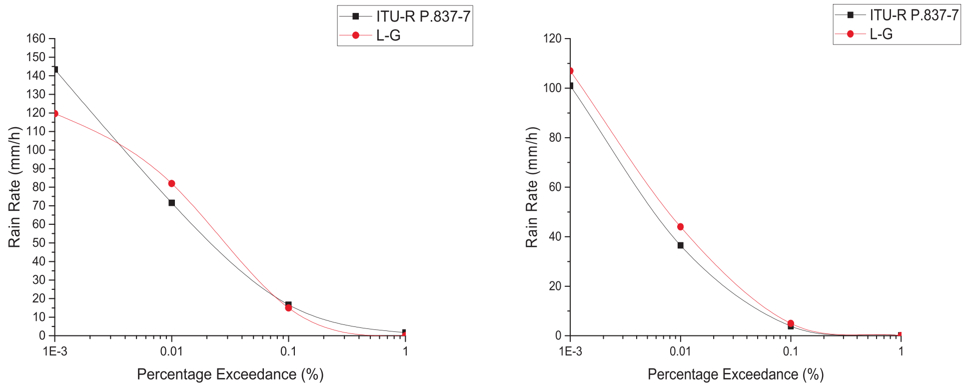
4. Results and discussion

4.1. Cumulative distribution of predicted 1-min rainfall rate

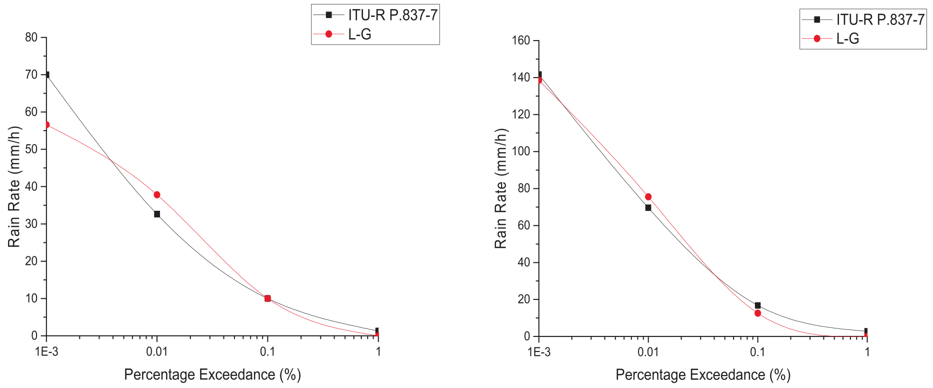
The cumulative distribution of the 5-min integration time rainfall data which were converted to 1-min rain rate using the two predefined rainfall rate models are presented in Fig. 4 (a-e).

From the results obtained in Fig. 4, it is observed that the ITU-R P.837-7 model reasonably agrees with the L-G model with only a little deviation at time percentage exceedances of 0.1% and 0.01% at all the stations. At 0.1%, differences in values is between 0 mm/h and 4 mm/h, while at 0.01% values ranged from 0 to 10 mm/h but there are significant differences at time percentage exceedance of 0.001%. At 0.001%, values ranged from 3 to 24 mm/h. The higher values were predicted by the ITU-R P.837-7

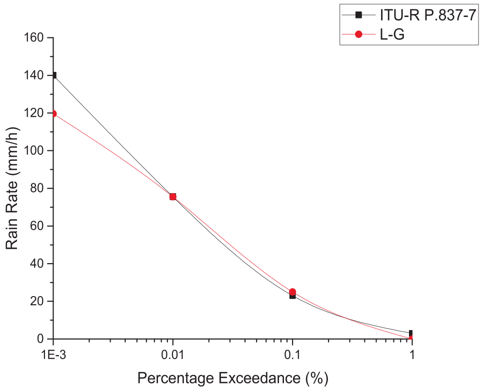
Fig. 3. Rain 101A data logger and rain gauge.



(a) Minna (b) Abuja



(b) Anyigba (d) Makurdi



(e) Jos

Fig. 4. Cumulative distribution of predicted 1-minute rain rate for the study area.

and this is conspicuous in Minna, Anyigba and Jos stations.

4.2. Comparison of measured and predicted 1-min rain rates

The cumulative distribution of direct 1-min rain rate measurement in Minna using rain 101A rain gauge and data logger was compared with the predicted 1-min rain rate using the predefined rain rate models. This is shown in Fig. 5. The comparison is necessary in order to find the margin of differences in the expected rain rate cumulative distribution and hence deduce the optimal model for the location. The Minna station is used as a standard reference to the other stations since the Northcentral States have the same rainfall pattern and 1-min rainfall data is not available in the other stations.

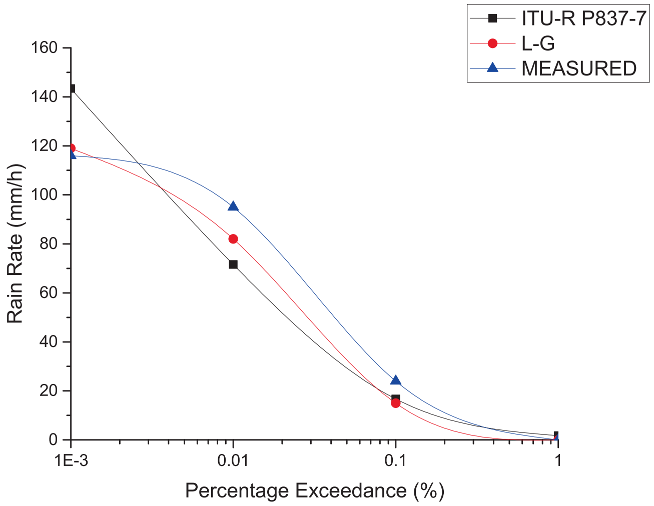


Fig. 5. Comparison of measured and predicted rain rate distribution in Minna.

As observed in Fig. 5, 1-min integration time rain rate of 24 mm/h was measured, while 16.7 mm/h and 15 mm/h were predicted by the ITU-R P.837-7 and L-G models respectively at time exceedance probability of 0.1%. At 0.01%, the measured rain rate was 95 mm/h, while the ITU-R P.837-7 and L-G models predicted 71.6 mm/h and 82 mm/h respectively. At 0.001%, the measured rain rate was 116 mm/h, while the ITU-R P.837-7 and L-G models predicted 143 mm/h and 119 mm/h respectively. From these results, it is observed that at time exceedance percentage of 0.1% the measured rain rate is higher than the predicted rain rate using ITU-R P.837-7 and L-G models by 7.3 mm/h and 9 mm/h respectively. Also, the measured rain rate is higher than the predicted rain rate using ITU-R P.837-7 and L-G models by 23.4 mm/h and 13 mm/h respectively at 0.01%. At 0.001%, the measured rain rate is lower than the predicted rain rate by 27.4 mm/h using ITU-R P.837-7 model, while it is lower than the L-G model by 3 mm/h.

Considering the differences between the measured and predicted rain rate at the various time exceedance probabilities, it can therefore be deduced that the Lavergnat and Gole model gave better prediction than the ITU-R P.837-7 model, especially for higher signal availability times. This deduction was further tested using different error metrics as given in subsection 4.3.

4.3. Performance evaluation of the predefined rain rate models

Using the direct 1-min rain rate measurement as the standard reference, the performance of the predefined rain rate models was evaluated using five error metrics. These are sum of absolute error (SAE), mean absolute error (MAE), root mean square error (RMSE), standard deviation (STDEV) and the Spearman's rank correlation which are defined as follows:

The sum of absolute errors (SAE) is the same as the sum of absolute deviations (SAD). It calculates the absolute errors between the predicted and measured values. It is defined mathematically as:

$$\sum_{i=1}^{N} |y_i - x_i| \tag{4}$$

The mean absolute error (MAE) averages the absolute difference between each pair of actual and forecast data points. It is expressed as:

$$\frac{1}{N}\sum_{i=1}^{N} |y_i - x_i| \tag{5}$$

The root mean square error (RMSE) is simply the square root of the mean square error. It is given as:

$$\sqrt{\frac{1}{N}\sum_{i=1}^{N} (y_i - x_i)^2} \tag{6}$$

The standard deviation is a measure of the spread of values within a set of data. It is given as:

$$\sqrt{\frac{1}{N}\sum_{i=1}^{N} (y_i - \bar{x})^2} \tag{7}$$

The Spearman's rank correlation coefficient shows the strength and direction of a linear relationship between two variables such as the predicted and measured values. It is expressed as:

$$\rho = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \tag{8}$$

where: y_i is the predicted value

x_i is the measured value

$\bar{x}$and $\bar{y}$are the mean of measured and predicted values respectively

N is the number of data points

The performance of the models based on their error estimates for $0.001\% < p < 0.1\%$ are graphically depicted in Figs. 6 and 7.

Appraising the performances of the rain rate models based on the SAE in Fig. 6, 58.10 mm/h was obtained for the ITU-R P.837-7 model, while 25 mm/h was obtained for the L-G model. For the MAE, 19.37 mm/h was computed for the ITU-R P.837-7 model, while the L-G model had 8.33 mm/h. The RMSE calculated for the ITU-R P.837-7 model was 21.23 mm/h, while 9.29 mm/h was computed for the L-G model. Considering the STDEV, the ITU-R P.837-7 model showed more variability with a value of 13.69 than the L-G model that recorded 5.89 mm/h.

Evaluating the last metric, the Spearman's rank correlation coefficient (Fig. 7), it is observed that both models actually exhibited high correlation between the predicted and measured rain rates. The values of 0.86 was obtained

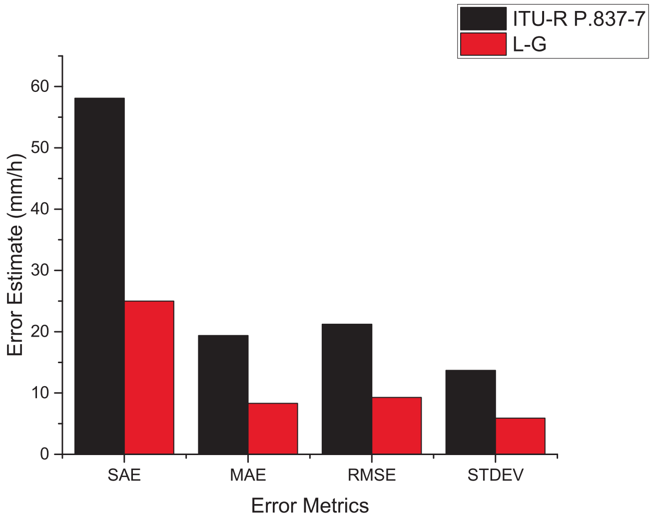


Fig. 6. Performance evaluation of 5-min to 1-min rain rate conversion models.

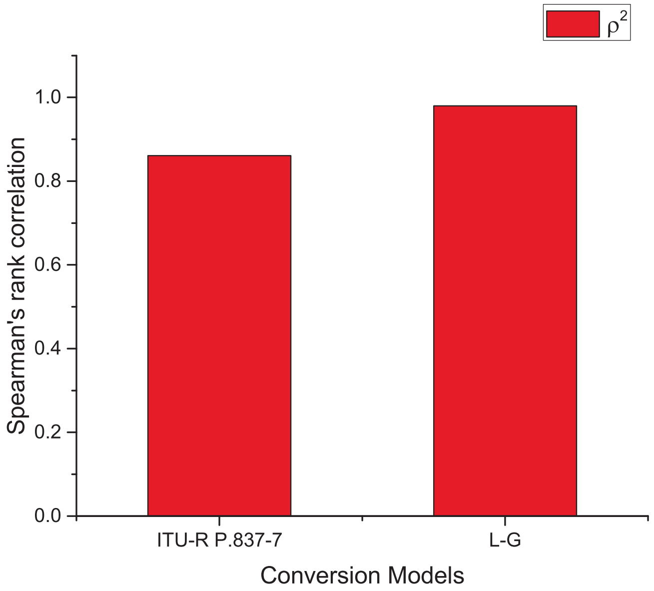


Fig. 7. Correlation of the rain rate models with measured data.

for the ITU-R P.837-7 model, while 0.98 was computed for the L-G model, which shows that the L-G model outperformed the ITU-R P.837-7 model.

Generally, the results obtained from the performance evaluation using the chosen error metrics showed that the L-G model performed very well from all indications, and hence can be used for 5-min to 1-min rain rate conversion in this region.

5. Conclusion

In order to obtain the optimal rain rate model suitable for converting rain rate of 5-min integration time to rain rate of 1-min integration time for the Northcentral region of Nigeria, the performance of two widely accepted rain rate models have been critically evaluated. These are the ITU-R P.837-7 and Lavergnat-Gole (L-G) models. This was achieved by comparing predicted rain rate values of 1-min integration time from the two predefined models with direct rain rate measurement of 1-min integration time, and carrying out performance evaluation of the predefined models using different error metrics. The results obtained have shown that the measured rain rate was underestimated by the ITU-R P.837-7 and L-G models by 7.3 mm/h and 9 mm/h respectively at time percentage exceedance of 0.1%. At 0.01%, the measured rain rate was underestimated by the ITU-R P.837-7 and L-G models by 23.4 mm/h and 13 mm/h respectively. However, the measured rain rate was overestimated by the ITU-R P.837-7 and L-G models by 27.4 mm/h and 3 mm/h respectively at time percentage exceedance of 0.001%. In addition, the performance evaluation carried out on the two predefined rain rate models revealed that the Lavergnat and Gole model performed better than the ITU-R P.837-7 model. Therefore, the Lavergnat and Gole model is recommended as the optimal model for converting rain rate of 5-min integration time to rain rate of 1-min integration time in the Northcentral region of Nigeria.

6. Data availability

Datasets related to this article can be found at Physics Department, Federal University of Technology, Minna, Nigeria and would be made available on request.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

Declaration of Competing Interest

None.

Acknowledgement

The authors appreciate the Center for Atmospheric Research (CAR), Anyigba, Nigeria (which is an activity center of the National Space Research and Development Agency) for providing the equipment used in measuring the 5-min integration time rainfall data.

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