Development and Testing of Conversion Models from 60-minute to 1-minute Rainfall Distribution over Gqeberha, South Africa for Millimeter Wave Applications

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Abstract. Rainfall is the main cause of signal degradation along the communication signal links above 10 GHz frequency. A crucial parameter for accurately determining rain attenuation is the 1-minute rainfall integration time which is very scarce. This paper presents a conversion model for Gqeberha in South Africa on a 5-year (2016–2020) rainfall rate from a 60-minute integration time to 1 minute using three recognized empirical models (Segal, Burgueno, and ITU-R). The root mean square error (RMSE) metric measure has been used to test the performance of the model. The results show that the annual 60-minute rainfall rate integration time varies with no significant pattern over the 5-year observation, while compared to other models; the Segal model in this study predicts Gqeberha with greater accuracy based on the lowest RMSE of 10.

Keywords: Empirical Rain Rate Conversion Models; Integration Time; Higher Frequency Bands; Millimeter Wave Applications.

1 Introduction

Higher frequency bands such as Ku, Ka, and C-bands are essential in satellite communications [1] due to various advantages such as repetitive frequency usage, smaller antenna size, and broad spectrum. The effect of signal degradation is greatly affected by rainfall along these bands, a complex and multifaceted issue [2]. Rainfall rate affects satellite signal strength indirectly by increasing system noise and scattering and absorption of electromagnetic signals. Also, rainfall causes propagation path loss, which is a critical challenge in free space or wireless communication systems by reducing the signal strength as it propagates [3, 4]. Rainfall usually varies according to climate, frequency, and time [5]. To reduce the effect of degradation on signal strength, there is a need for a 1-minute rainfall rate integration time to predict the attenuation along the earth-space links accurately. Accurate attenuation prediction is crucial to maintaining reliable satellite communications [6]. The work of [7] also stated that lower time integration of rainfall is crucial as it significantly affects a certain percentage time exceedance, which is 0.01%. The International Telecommunication Union-Radiocommunication (ITU-R) recommends a rainfall rate exceedance of 0.01% ($R_{0.01}$) of 1-minute inte-

I. Adimula et al. (eds.), *Proceedings of the 8th URSI-NG Annual Conference (URSI-NG 2024)*, Advances in Physics Research 12,
https://doi.org/10.2991/978-94-6463-644-4_24

gration as the threshold for accurate attenuation prediction. However, 1-minute integration is scarce nationwide, and only higher integrations, such as 5, 10, 15, 30, and 60-minute integrations, are available across several nations' local meteorological departments. This includes the South African Weather Service (SAWS), the local meteorological department of the Republic [8], where 60-minute integration time is available. Researchers have developed several methods to convert higher integration times to 1-minute integration. These methods are categorized as physical, analytical, and empirical methods. However, the issue of methods of integration conversion to one minute in South Africa has yet to be dealt with. South Africa has several climates, and several researchers have worked on several aspects of rainfall, but there is limited information on using a 1-minute integration time measurement. Therefore, our work investigates the conversion of some existing empirical methods using a 60-minute integration time of 5-year (2016-2020) rainfall data obtained from the SAWS database over Gqeberha, one of the coastal locations in the Republic. Gqeberha (33° 57' S, 25° 36') is known as the most populous and significant coastal city in the Eastern Cape province of the Republic, with several attributes such as an economic, cultural, and financial hub that attract several investors, tourists, and researchers that require the use of undistracted communication signals via the use of satellite and terrestrial networks for their operations. Hence the need for this research.

2 Empirical Methods of Rainfall Time Integration Conversion

The empirical method is a rain rate conversion method that converts higher integration times to lower times. The method relies on database measurements of rainfall data from multiple locations within a specific region. Its uniqueness, simplicity, and ability to provide better predictions make it suitable for converting rainfall with higher integration times in any location. The following section describes the models considered in this work.

2.1 Burgueno's Method

This method designated as Burgueno model [9]; the model uses a longer rainfall measurement (about 49 years) of several sampling rain gauge intervals to estimate the rain rate distribution in Barcelona, Spain. Therefore, developed a universal expression for different integration times [9], as:

$$R_1(P) = aR_T^b(P) \quad \text{mm/h} \tag{1}$$

where a, b, $R_1(P)$ and $R_T(P)$ are regression coefficients,1- and T-min rainfall rates integration times with $T = 60$ of the probability of occurrence (P) exceeded, respectively.

2.2 Segal's Model

Segal developed this model based on a 10-year rainfall data analysis of about 45 locations in Canada. Also, Segal estimated the correlation of rainfall rate cumulative distributions for different time integrations [10, 11]. The method proposed is:

$$R_1(P) = \rho_\tau(P)R_\tau(P) \quad \text{mm/h} \tag{2}$$

with

$$\rho_\tau(P) = aP^b \tag{3}$$

where $\rho_\tau(P)$ is the conversion factor, $R_1(P)$ is the rainfall rate for 1-minute integration time, and $R_\tau(P)$ is the corresponding τ-min integration time rainfall rate exceeded with a probability of occurrence *(P)*, $\tau = 60$, a and b are the regression coefficients obtained from the measured rainfall data.

2.3 ITU-R Model

The ITU-R in 837-7 report recommended as one of the empirical models which can be adopted in 1-minute integration conversion [12]. The model is based on the measured equiprobable rain rate relationship with T and 1 minute integration time and expressed as:

$$R_1(P) = a(T)R_T(P)^{b(T)} \tag{4}$$

where $R_1(P)$and $R_T(P)$, while P is the common probability level, with global coefficients $a(T)$ and $b(T)$ are the integration time dependent at $T = 60$, developed from power law regression over a multiple database measurements from different regional climatic countries and further information are reiterated in [13].

3 Result and Discussion

The results of the rain rate distribution are presented in this section. The section consists of statistics of rainfall distribution, annual variation and yearly conversion of 60 to 1-minute integration rain rate results from conversion.

3.1 Annual Rain Rate Distribution

Fig. 1 shows the annual variation of the 60-minute integration rainfall rate. The 5-year total rainfall accumulated was about 2345.60 mm. The rainfall observed over Gqeberha varies yearly with no significant pattern which indicated that rainfall varies per time and location. The recorded values range from the lowest amount of about 402.4 mm in 2019 to 406.2 mm in 2018, then 443.4 mm in 2016, 495 mm in 2017, and the highest was about 598.6 mm in 2020. Also, the observation shows that the recording hours and maximum rainfall varies over the years. Table 1 presents the 5-year statistical analysis of 60-minute integration rainfall rate over the location of study.

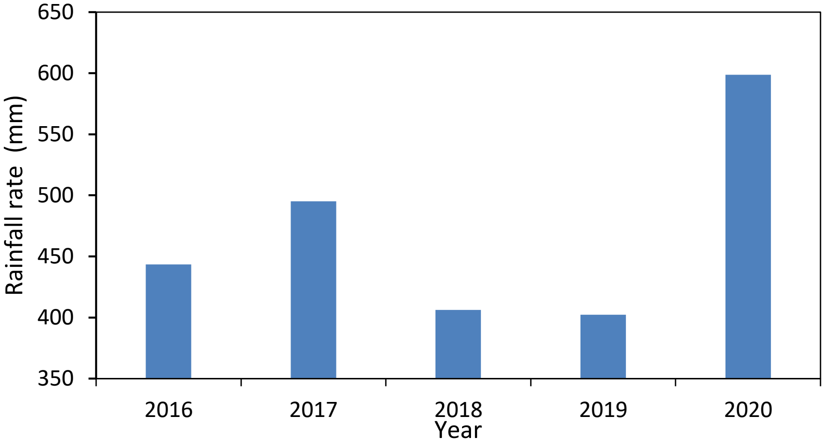

Fig. 1. Annual variation of 60-minute integration time rainfall rate (mm).

Table 1. The 5-year statistical analysis of 60-minute integration time rainfall rate for Gqeberha.

	2016	2017	2018	2019	2020	5-year overall
Mean per annum (mm)	1.05	1.19	1.04	1.00	1.03	1.06
Standard deviation	1.54	1.86	1.41	1.36	1.37	0.21
Number of rainy hours	424	417	389	401	579	2210
Maximum rainfall recorded (mm)	14.20	19.00	10.80	12.40	18.00	19.00

3.2 Cumulative Distribution of Rainfall Rate

The annual rain rate distribution between the 1- and 60-minute integration times was examined using three empirical models (ITU-R, Segal and Burgueno) over the studied location, as depicted in Fig. 2. Over the 5-year of observation, it is generally observed that yearly rainfall rate recorded was low over Gqeberha. The ITU-R model predicted the lowest, followed by the Segal model, and the Burgueno model gives the highest prediction across different percentages of times (0.1 and 0.01). Fig. 2(a) shows that the ITU-R model gives its value of about 12.6 mm/h (low), the Segal model gives 16.4 mm/h, and the Burgueno model gives the highest of about 26.4 mm/h (highest). A similar prediction was observed over the remaining years, although the patterns differed. Table 2 summarizes the root mean square error (RMSE) to determine the model with better prediction and the $R_{0.01}$ exceedance over the models. We observed that the RMSE Segal model gives better prediction across all years, and the five years studied.

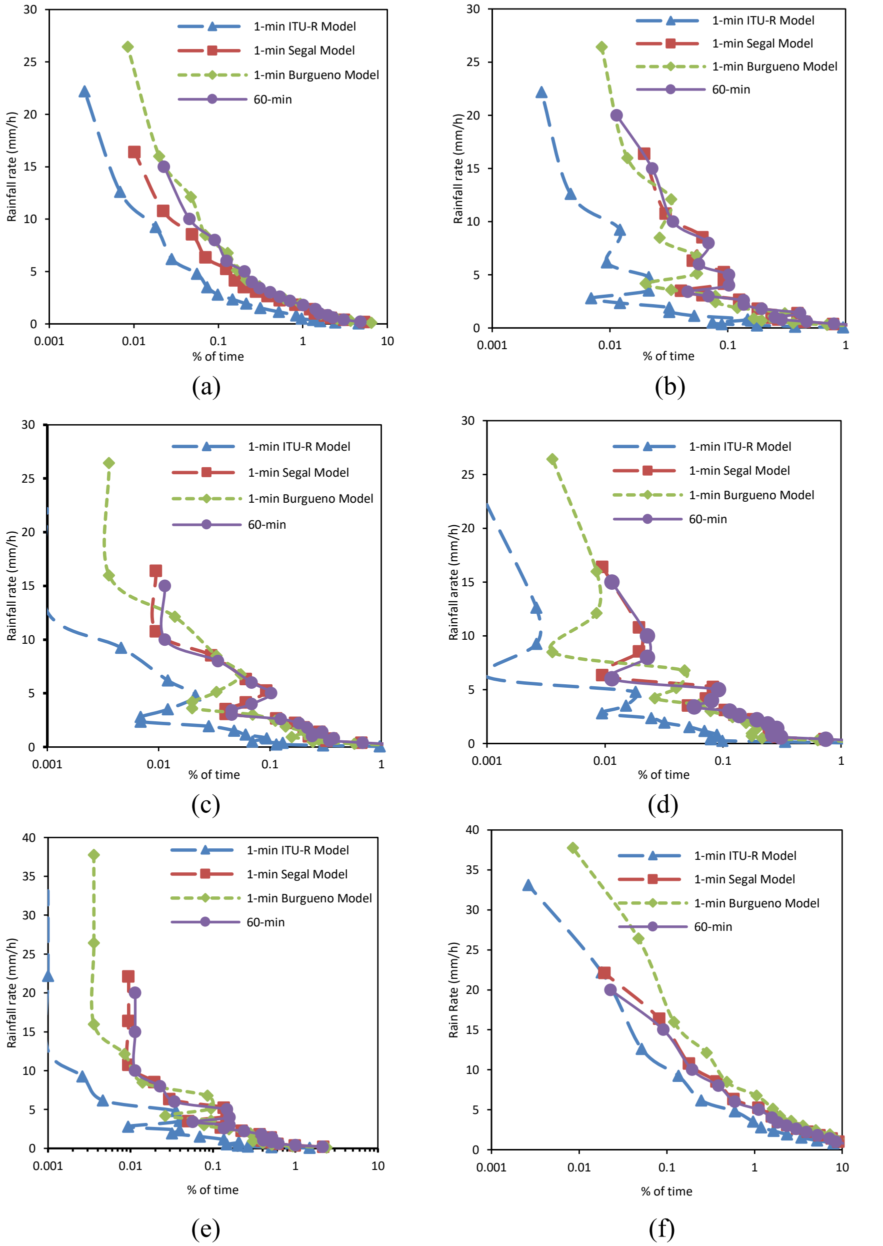

Fig. 2. Annual cumulative distributions (a) 2016, (b) 2017, (c) 2018, (d) 2019, (e) 2020, and (f) 5-year overall of 60-minute and 1-minute integration time.

Table 2. RMSE and $R_{0.01\%}$ of the prediction over the study location.

	Model	2016	2017	2018	2019	2020	5-year overall
RMSE	ITU-R	7.09	6.99	7.00	7.00	10.66	13.56
	Segal	5.92	5.82	5.83	5.83	7.92	10.00
	Burgueno	8.86	8.72	8.73	8.73	12.65	16.13
$R_{0.01}$ (mm/h)	ITU-R	12.60	10.05	6.20	6.00	6.20	23.00
	Segal	16.40	20.00	10.80	6.30	10.80	-
	Burgueno	26.40	20.05	13.50	8.50	12.10	34

4 Conclusion

This paper tested three empirical rain rate conversion models using local meteorological data from SAWS over Gqeberha, one of the coastal locations in South Africa. We observed and presented the yearly predictions of 1-minute integration time. The observation shows the annual variations in 60-minute integration time and the converted 1-minute integration times. The observed rainfall data show variations over the years of study. The ITU-R model exhibits lower prediction values, whereas the Burgueno model displays the highest value at $R_{0.01}$. We evaluated the better prediction based on RMSE, and the Segal model gives the lowest value of 1-minute integration time over the study location. These results have practical implications for the proper planning and dimensioning of operating systems in wireless and satellite communications at higher frequencies over the coastal locations of South Africa, providing valuable insights for professionals in the field.

Acknowledgements. The authors would like to that SAWS for providing the data used in this study. The authors also acknowledge the support and express gratitude to the University of Johannesburg's University Research Committee (URC) grant for Prof. KA Ogudo and the Department of Electrical and Electronic Engineering Technology. This work was partly supported by a grant from the University of Johannesburg Library Research Funds (UJ).

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