Assessment of Radar Reflectivity-Rainfall Rate, Z-R Relationships for a Convective Event in Malaysia

Nuurul Hudaa Mohd Sobli, Ahmad Fadzil Ismail, Farah Nadia Md. Isa, and Hasmah Mansor
Department of Electrical and Computer Engineering, Kulliyyah of Engineering,
International Islamic University Malaysia (IIUM), Jln. Gombak, Selangor, Malaysia
Email: {hudaa, af_ismail, farahn, hasmahm}@iium.edu.my

***Abstract*—Various relationships between radar reflectivity Z and rainfall rate R commonly identified as Z-R relationships have been derived in order to provide better accuracy for rainfall rate estimation using weather radar. It is critical for the air traffic management at the airport to accurately detect existence of potential microburst and wind shear. There are numerous factors that can certainly affect the accuracy of Z-R relationships including poor hardware calibration. However, the inaccuracy of Z-R relationships also might be due to the differences between the precipitation at the ground level and the precipitation aloft because radar does not scan all the way down except at close range. Several Z-R relationships had also been proposed in the attempt to achieve better accuracy for rainfall estimates by radar system in the tropical region. Nonetheless, the most accurate Z-R relationship for Malaysia weather radar is yet to be investigated and to be identified within the study period. This paper presents the preliminary analyses of previously proposed Z-R relationships for Malaysia weather using new radar data and ground rainfall rate. Comparisons were made between values obtained from the previously proposed relationships for radar and the ground truth measurements. It was identified that the previously proposed relationships estimations are significantly lower than the rain gauge data.**

***Index Terms*—radar reflectivity, rainfall rate, Z-R relationship, convective, tropics, Malaysia**

I. Introduction

Weather radar was originally used to forecast very short-term weather conditions and issue warnings for hazardous and severe weather phenomena. Weather radars measure the electromagnetic radiation backscattered by cloud raindrops and thus providing reflectivity, Z values for this volume of raindrops. Furthermore, they have the potential to estimate rainfall rates by exploiting the reflectivity, Z values. In addition, weather maps are particularly important in aviation field especially for flight planning and avoidance of dangerous weather conditions. Malaysian weather radars are expected to scan enough angles to generate a 3D set of data over certain areas of coverage. With the use of reliable radars, it is somewhat easy to ascertain the maximum altitude of rain within the volume as well as the rain intensity. Accurate rainfall rate estimation by weather radar has been the goal of radar designers for decades. It has always been a great fear where unsuitable Z-R relationship was used to estimate rainfall rate and evidently inflict considerable error in quantitative precipitation measurements; even though radar calibration was performed [1].

II. Radar Reflectivity-Rainfall Rate Relationship

The empirical power-law *Z-R* relationship is used to estimate rainfall intensity reflectivity measurements as follows [2]:

$$Z = A R^{b} \tag{1}$$

where the reflectivity, Z is expressed in mm^6/m^3 and the rainfall rate, R in mm/hr. The coefficients A and b are the radar parameters of interest to be estimated that vary according to meteorological, climatic and physiographic conditions of a specific region.

Marshall and Palmer derived the *Z-R* relationship that is also known as MP equation in 1948. It is commonly used for radar rainfall estimate by weather radar as given:

$$Z = 200 R^{1.6} \tag{2}$$

Subsequently, Rosenfeld [3] had carried out further investigation involving heavy precipitation event. He formulated a revised *Z-R* relationship exclusively for convective rain as follows:

$$Z = 250 R^{1.2} \tag{3}$$

However, large discrepancies had been discovered when (2) and (3) were applied to tropical region especially during heavy rain [4]-[18].

III. Previously Proposed Z-R Relationships in Equatorial and Tropical Regions

Suzana and Wardah had proposed several Z-R relationships in 2011 for seven identified rain types in Malaysia [19]. Afterwards in 2012, Kamaruzzaman and Subramaniam suggested three Z-R relationships based on

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data acquired from three radar stations located at Butterworth, Kluang, and Alor Star [20]. The Malaysian researchers had shown that their suggested Z-R relationships managed to offer better rainfall rate estimation compared to that of Marshall-Palmer's and Rosenfeld's. Nonetheless, it was also highlighted that the findings should be treated with caution because of the limitations of the rainfall data used in the study. Another concern is because they did not provide comprehensive coverage to take into account of all possible environmental and physical conditions.

IV. System Set-Up

The investigation of Z-R relationships made use of the single polarization S-band Terminal Doppler Weather Radar (TDWR). The radar located at Bukit Tampoi with 2° 50.8'N, 101° 40.3'E and approximately 11km from Kuala Lumpur International Airport (KLIA). This TDWR has an operating frequency of 2.8745 GHz with transmit power of 750kW. The radar is operated by Malaysia Meteorological Department (MMD).

TABLE I. Specifications of TDWR

Item	Specifications
Location (Lat, Lon)	Bukit Tampoi (2 °50.8'N, 101 °40.3'E)
Radome	12 m diameter
Round parabolic reflector	8.5 m diameter
Beam width	Maximum 1.0 °
Wavelength	10.43 cm
Frequency	2.8745 GHz
Peak power	750 kW
Pulse width	1.0 micro sec. and 3.0 micro sec.
Pulse repetition frequency (PRF)	1000 Hz (at 1.0 micro sec. pulse width) 300 Hz (at 3.0 micro sec. pulse width)
Azimuth resolution	1 °
Range resolution (bin spacing)	125 m

The radar system is programmed to operate in two scanning modes; Aerial mode and Airport mode. The Aerial Mode is a mode used when the weather around the airport is calm and the Airport Mode is the mode used when the weather condition around the airport have the potential to affect the safety of aircrafts. The radar will automatically shift from Aerial mode to Airport mode when the vertical integrated liquid (VIL) value inside a protected area is above the threshold level of 0.1mm/hr with an area exceeding 20km^2. The protected area is any region within 30km x 40km centered at the airport. Each mode consists of three different volume scans called TASKs with different predetermined range and elevation angles. Each elevation angle contains 360 rays of data that is corresponding to 360 azimuth angles with no interlaced beams. Total of 10 beams associated with the elevation angles are used. The radar antenna rotates at the speed of 2 revolutions per minute (RPM) with pulse repetition frequency (PRF) of 300 Hz for scanning elevation angles less than 1° and maximum range of 499km. The radar will be rotating at faster speed of 4 RPM with PRF of 1000 Hz for elevation angle between 5° to 40° and maximum range of 120km. There are 961 bins for 120km and the bin spacing is 125m. Table I summarized the specifications of this TDWR.

The ground truth measurement data were collected from the rain gauge located at MMD station KLIA with 2° 44' N and 101° 42' E, about 5km from the airport and 16.3m above mean sea level. The rain gauge used by MMD consists of standard tipping bucket in order to collect the measured rainfall values. The tipping bucket rain gauge follows the standard by World Meteorological Organization (WMO).

The tipping bucket comprises of two components; funnel-shaped at the top supported by a cylindrical-shaped at the bottom. This funnel has a water filter at the end of the funnel opening. As rain falls it lands in the funnel of the tipping bucket rain gauge. Water flowing into the funnel will be screened and will be collected by two metal water collectors (tipping buckets). The raindrops is poured into the cylinder when one of the collectors receives the raindrops of amount 0.2mm and the next rain will then fall to the other metal collectors. This process is repeated and this repetition process is connected to a computing system (counter) that will count the number of times the rain that falls into the water collector metal. The amount of rainfall rate is calculated based on multiplication of the number of times the precipitation that falls on the metal rain collector with 0.2mm of rain droplets. Maximum rainfall amount that can be obtained is 200mm/hr. Table II summarized the specifications of the tipping bucket rain gauge operated by MMD. Fig. 1 shows the overall system setup for the study.

TABLE II. Specifications of Tipping Bucket Rain Gauge

Item	Specifications
Location (Lat, Lon)	KLIA, Sepang (2° 44' N and 101° 42' E)
Distance from KLIA	±5km
Receiving collector	203mm ±0.2mm
Accuracy	±1% to 200mm/hr
Bucket capacity	0.2mm
Dimensions	300mm height 230mm body diameter 280mm base diameter
Physical	5.5kg net weight

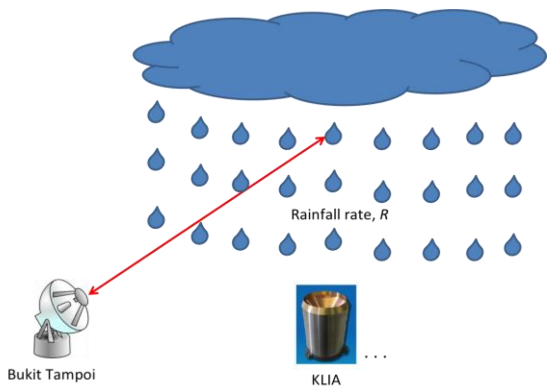

Figure 1. Overall system setup.

V. Results and Discussions

The preliminary findings are obtained from processing of two types one-year data. The data are radar data from TDWR and rain gauge measurements data from KLIA rain gauge station from January to December 2009. These data comprise only the days and times where precipitation more than 0.1mm/hr occur. The data from TDWR are acquired by MMD at KLIA in .RAW format. This format of data is the format generated by the weather radar software with its associated TASKs i.e. modes and volume scans. This type of data needs to be processed by utilizing weather radar software, Vaisala Interactive Radar Information System (IRIS) version 8.12.4. The rain gauge measurement data consists of the rain gauge tipping bucket reading every one-hour in mm/hr which shows the ground truth measurements of the rainfall rate within one-hour duration.

In order to generate the desired product output, the .RAW data format need to be converted to a meaningful and readable format. The first step is that the .RAW data will be input to the IRIS and reingest to get usable product file. Then, Constant Altitude Plan Position Indicator (CAPPI) product is configured in product configuration menu to obtain the desired CAPPI product. In the product configuration menu, the mode selected is the Airport mode with two volume scans; volume scan B and volume scan C. This Airport mode is selected because this mode will only be triggered when the weather condition around the airport affects the safety of the aircrafts. Furthermore, two volume scans; volume scan B and volume scan C are selected for the maximum range of each scan is 120km and PRF of 1000Hz with elevation angles from 1° to 1.5° and from 1° to 40° respectively. This selection is made because of the distance between TDWR and KLIA terminal is approximately only 11km.

Fig. 2 shows the constant altitude plan position indicator (CAPPI) scan for the event recorded on 24th March 2009 at 10:31:00 which is classified as convective event. This figure shows the location of TDWR, KLIA, and the KLIA rain gauge. Fig. 3 shows its corresponding reflectivity cross section in mm/hr.

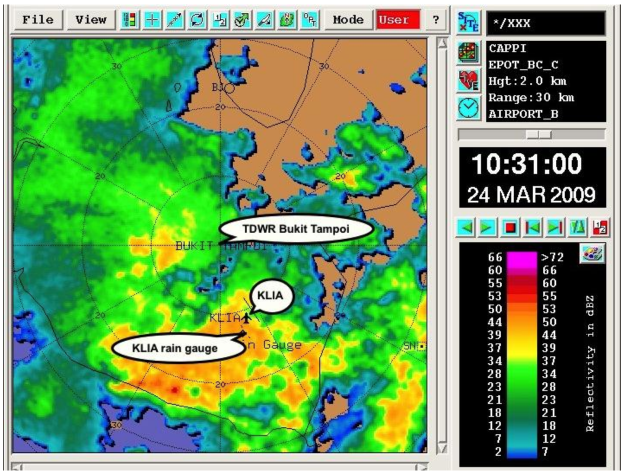

Figure 2. CAPPI scan with $Z = 200\ R^{1.6}$

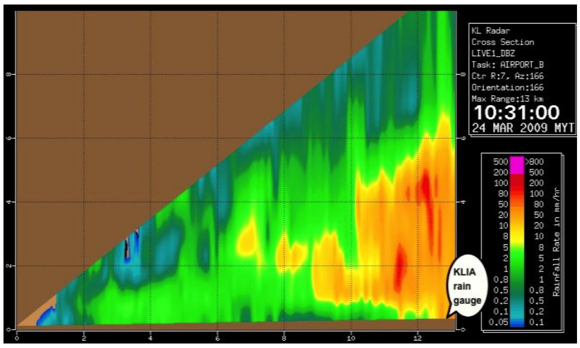

Figure 3. Cross section in mm/hr with $Z = 200\ R^{1.6}$

Fig. 4 shows the rainfall rate in mm/hr by using Z-R relationships proposed by Suzana and Wardah for heavy rainfall rate in Kuala Lumpur. Meanwhile, Fig. 5 and Fig. 6 show the rainfall rate by using Z-R relationships suggested by Adam-Moten for Kluang and Rosenfeld's respectively. Their recommended equations were applied to radar data obtained from KLIA TDWR. Fig. 8.4 and Fig. 5 show that the rainfall rate value is 26.55mm/hr and 65.80mm/hr respectively for 13.3km distance. Furthermore, Fig. 6 shows the rainfall rate value of 183.37mm/hr at 13.3km. This distance is the location of the rain gauge for measuring ground truth rainfall rate from the radar location. However, according to MMD data, the ground truth measurements using rain gauge during that particular event is 71.8 mm/hr. The preliminary results show that the MP, Suzana-Wardah, and Adam-Moten equations under estimate measured rainfall rate values for this convective event. Meanwhile, Rosenfeld equation over estimate measured rainfall rate for the same event.

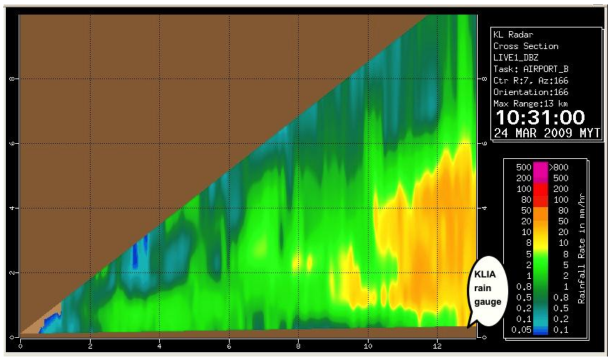

Figure 4. Cross section in mm/hr with $Z = 262\ R^{1.9}$

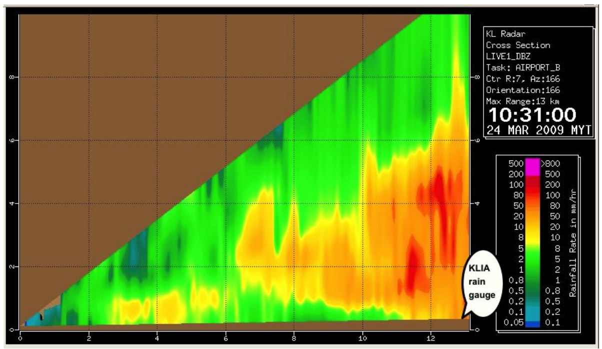

Figure 5. Cross section in mm/hr with $Z = 13\ R^{2.2}$

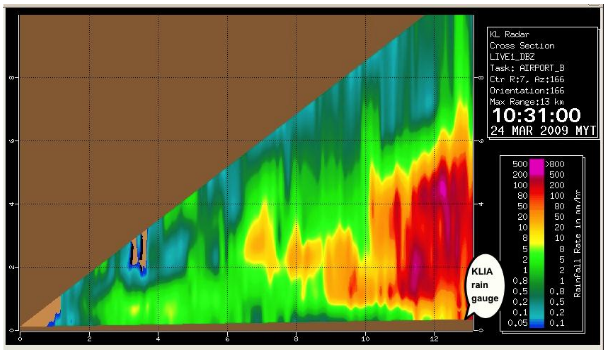

Figure 6. Cross section in mm/hr with $Z = 250\ R^{1.2}$

Table III summarized the comparison between MP, Suzana-Wardah, Rosenfeld, and Adam-Moten Z-R relationships with the ground truth measurement from the KLIA rain gauge. The table shows that the values of *R* having large differences when compared with the ground truth measurement for these three Z-R relationships. The difference might be due to unfitting relationship. It is made aware that previous researchers employed radar data that were obtained at every 10 minutes while the rain gauge measurement were taken hourly. This temporal mismatch and inappropriate used of Z-R relationships might be the cause of inaccurate radar rainfall estimates.

TABLE III. COMPARISON OF RAINFALL RATE FOR THREE DIFFERENT Z-R RELATIONSHIPS DERIVED FOR MALAYSIA WEATHER

Z-R Relationship	**Recommended Use**	***R* (mm/hr) from rain gauge**	***R* (mm/hr)**
Marshall-Palmer $Z = 200\ R^{1.6}$	General Stratiform Precipitation	71.8	56.32
Suzana R. and Wardah T. $Z = 262\ R^{1.9}$	Heavy Rainfall Rate	71.8	26.55
Rosenfeld Tropical $Z = 250\ R^{1.2}$	Tropical Convective System	71.8	183.37
M.K.M.Adam and S.Moten $Z = 13\ R^{2.2}$	Kluang radar station	71.8	65.80

However, the analysis of measurement data from one rain gauge station is not enough to study the overall variation of different precipitation types around the airport. Thus, more measurement data from other rain gauge stations located within 30km to 40km in radius centered at KLIA will be processed. Additional radar data corresponds to these rain gauge stations also need to be evaluated and studied. The study of the precipitation types, its characteristics and behavior by using more data from other rain gauge stations and also radar data within the perimeter radius from KLIA could improve the results and hence a better Z-R relationship can be obtained for Malaysia weather. Furthermore, regression method will be used in order to find the best Z-R relationship and it is expected that the new and improved relationship will differ from its conventional composition format.

VI. Conclusion and Future Works

This paper attempts to evaluate the four previously proposed relationships using new measurement data in Malaysia. The previous models had been evaluated in how well they fit to the new acquired Malaysia weather data. From the preliminary results obtained, it appears that MP, Suzana-Wardah, Rosenfeld, and Adam-Moten Z-R relationships were not able to precisely estimate the rainfall rate. Nevertheless, these preliminary findings are not yet conclusive. More events need to be processed and validated with other proposed Z-R relationships for tropical region, with different precipitation types. Hence, more data from other rain gauge stations located within 30km to 40km radius centered at KLIA also need to be processed. Additional radar data according to these rain gauge stations also need to be evaluated. Larger variation might occur for heavier precipitation or a more severe convective event. However, stratiform precipitation type needs to be processed accordingly because it is critical for the air traffic management at the airport to detect potential microburst and wind shear problems. Evidently, the best Z-R relationship is hoped to be identified in the very near future.

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Nuurul Hudaa Mohd Sobli obtained her BEng and MSc from International Islamic University Malaysia (IIUM) in 2006 and 2010 respectively. She is currently one of the faculty members of Faculty of Engineering, IIUM and recently commenced her PhD studies in Radar and Radiometry research, quantifying propagation effects on microwave and millimeter links. Nuurul Hudaa is a member of IEEE and has published and co-authored papers in International Journals as well as Conferences on subjects relating to antenna design and rainfall estimation in the tropical regions.

Ahmad Fadzil Ismail is currently serving as a lecturer at the Department of Electrical and Computer Engineering, Faculty of Engineering, International Islamic University Malaysia. He completed his bachelor degree studies in Electrical Engineering at Gannon University, Pennsylvania, USA with Cum Laude Latin honors. He holds MSc from University of Essex, UK and PhD from University of Bath, UK. His research interests include millimeter and microwave propagation studies, development of active and passive target tracking algorithms and Cognitive Radio applications. He is a registered Professional Engineer with Board of Engineering Malaysia and also a Senior Member of the IEEE.

Farah Nadia Md. Isa is an Assistant Professor at International Islamic University Malaysia. She obtained her first-degree B.Eng (Hons) Electronics Engineering majoring in Microwave Communication from Multimedia University Malaysia. In 2005 and 2012 she obtained her MSc in Technologies for Broadband Communication and PhD in Electrical & Electronic Engineering from University College London (UCL). Her main researches interests are focused on ground penetrating radar, design of sparse array antennas and cognitive radio.

Hasmah Mansor is currently an Assistant Professor at International Islamic University Malaysia a member of IEEE and Instrumentation & Measurement Society (Malaysian Chapter) since 2011 and a member of Board of Engineers Malaysia since 2012. She obtained her B.Eng in Electronic & Electrical Engineering from University of Salford, United Kingdom in 1999. She holds MSc and PhD in Control and Automation Engineering from Universiti Putra Malaysia. She was one of the pioneers who directly involved in design and development of first Malaysian Programmable Logic Controller (PLC) named DA2000. Her research interests are control systems, modeling, robust control, adaptive control and intelligent control.