The Reliability of X-Band Multiparameter Radar Rainfall Estimates

Q R Fajriani¹, R Jayadi², D Legono², J Sujono²

¹ Department of Civil Engineering, Yogyakarta State University - Indonesia
² Department of Civil and Environmental Engineering, Universitas Gadjah Mada - Indonesia
Corresponding author: rizqifajriani@uny.ac.id

Abstract. Rainfall monitoring is an important activity for the development of a water-related disaster mitigation system. The rain gauge measurement is still regarded as the "ground truth". To obtain the rainfall that represents an area, a high density of rain gauges network is needed. Besides, the installation of a large numbers of rain gauges is considered inefficient. The utilization of advanced technology is deemed necessary to complement the rainfall monitoring system, one of which is by using radar. Although the radar rainfall estimates have a better spatial resolution, but the reliability needs to be evaluated. This study was carried out to evaluate the reliability of rainfall data from an X-Band Multiparameter radar by classifying the intensity of heavy rain and moderate rain. Then radar rainfall data was corrected using the Adjustment Factor (AF) method. The results show that the radar rainfall has better accuracy in predicting the moderate rain rather than the heavy rain. Furthermore, the X-Band MP radar has better accuracy when predicting rain in an area that has the elevation below the radar than the higher elevation area. Correction of the radar rainfall data using the AF factor produces a rainfall estimates which is closer to the ARR rain.

1. Introduction
The development of a water-related disaster mitigation system is very important for areas of high rainfall intensity such as Indonesia. One part of the flood disaster mitigation system is the flood early warning system. A flood early warning system requires a sophisticated rain monitoring system. As of today, rain measurements have been carried out by installing a manual rain gauge or Automatic Rainfall Recorder (ARR) and producing point rainfall data. The measurement results from the surface rain gauge still considered as 'ground truth' as it has good accuracy and represents the actual surface rainfall. However, to obtain the rainfall that represents an area (area rainfall), a rain gauge network is needed with a large numbers of station density following the spatial and temporal characteristics of the rain in the watershed. Rain gauges maintenance is an expensive and arduous process, therefore, the installation of rain gauges in large quantities is considered inefficient. The utilization of advanced technology is deemed necessary to complement the rainfall monitoring system.

One of the technologies for rainfall estimation is Radio Detecting and Ranging (Radar). The advantage of radar compared to traditional rain gauges is that they can present rainfall data spatially and in real-time. However, the reliability of the radar in estimating rain depth needs to be evaluated. There are many types of radar used for weather estimation, one of which is the X-Band radar. X-Band radar is a radar with a short wavelength. The advantage of short wavelength radar is that they can detect smaller particles than S- or C-band radars, therefore they can estimate the small intensity rainfalls.
However, the estimation of rain intensity by X-Band radar is highly sensitive to the attenuation effects [5]. Attenuation is the weakening of the signal during the wave propagation process.

Weather radar works by emitting electromagnetic waves into the atmosphere. When these waves hit hydrometeorological objects in the atmosphere (water droplets, ice, etc.), the waves will be reflected and captured by the radar receiver in the form of radar output parameters. The non-dimensional parameter generated by the radar is called DRO (dimensionless radar output). The type of DRO produced depends on the radar’s type. Marshall and Palmer [7] derived an equation for estimating the radar rain intensity from the DRO. According to the derived equation from several DROs, the parameter which is closely related to rain intensity is radar reflectivity (Z), so that the radar reflectivity-intensity equation is derived as power function shown in Equation 1.

\[ Z = aR^b \]  

(1)

where \( Z \) is the reflectivity (mm^6/mm^3), \( R \) is the rain intensity (mm/hour), \( a \) is the prefactor, and \( b \) is the exponent. The \( a \) and \( b \) values are empirical coefficients that depend on the type of rain, location, topography, and duration of rain [9]. Many researchers have derived the \( Z-R \) equation with different radar types and locations. Although the reflectivity value is closely related to the rainfall intensity, does not mean that only the reflectivity value affects the amount of rain [9]. In the polar X-band radar, the best radar equation is to combine the \( K_{dp} \), \( Z_{dr} \), and \( Z_t \) parameters [8]. The use of \( K_{dp} \) parameters in predicting rain intensity aims to prevent errors due to radar attenuation because the attenuation effect on X-Band radars cannot be ignored. Attenuation in the \( Z_t \) and \( Z_{dr} \) values needs to be corrected so that there is no underestimation in the rainfall estimation [5].

Many errors may occur in the process of radar rainfall estimation. Several factors that influence the radar rainfall estimation are radar range [1,3,11], elevation [9], rainfall duration [2,9], and rainfall intensity [10]. Internal radar calibration is required to reduce the errors of the rainfall estimation. DRO radar is needed, including \( K_{dp} \), \( Z_{dr} \), and \( Z_t \) to perform internal calibration. These data are difficult to obtain, so the calibration process with DRO is relatively hard. Therefore, in this study, the evaluation of radar data was carried out using the radar rainfall intensity data then compared with the surface rainfall data.

2. Methodology

An X-Band Multiparameter (X-Band MP) radar rainfall data reliability was evaluated by comparing 1 pixel of rain data located above the ARR station with the surface rainfall data obtained from the recording of 20 ARR stations which are spread over the radar coverage for a 10 minute time interval as shown in Table 1. The analysis was carried out based on rain events from November 2016 to December 2018, by classifying the rain into two categories: rainfall higher than 20 mm/hour and rainfall lower than 20 mm/hour. All pairs of radar-ARR rainfall data with zero value or one with zero value are not used in the calculation because it will complicate the correlation analysis of the two objects under study [14].

| ID  | ARR Station   | Altitude (m) | ID  | ARR Station   | Altitude (m) |
|-----|---------------|--------------|-----|---------------|--------------|
| BS01| Pucanganom    | 465          | LH01| BE-D4        | 683          |
| BS02| Randugunting | 135          | LH02| BO (Turgo)   | 1021         |
| BS03| Sopalan      | 155          | LH03| PA (Ketep)   | 1053         |
| BS04| Sopalan      | 300          | LH04| PU-D2       | 700          |
| BS05| Jrakah       | 1200         | LH05| GE (Kaliadem) | 1072         |
| BS06| Ketep        | 1154         | LH06| KU-(Ngipiksari) | 759         |
| BS07| Ngandong     | 840          | LH07| WO (Sukorini) | 547          |
| BS08| Plosokerep  | 530          | LH08| BO/CO (Sipil) | 166          |
| BS09| Stabelan     | 1402         | LH09| BO/CO (Lembah) | 166         |
| BS10| Talun        | 590          | LH10| BO (Donoharjo) | 304         |

The evaluation of the correlation between radar rainfall data and ARR rainfall data performed using three statistical parameters [6]: Root Mean Square Error (RMSE), Pearson correlation coefficient (\( r \),
and ratio of ground and radar rainfall depth (G/R). The statistical parameters have been calculated by Equation 2 to Equation 4.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{N} (i_r - i_g)^2}{N}}
\]

(2)

\[
\left(\frac{G}{R}\right)_j = \frac{\sum_{i=1}^{n} G_i}{\sum_{i=1}^{n} R_i} \quad j = 1,2,3,4, ..., 20
\]

(3)

\[
r^2 = \frac{n \sum_{i=1}^{n} G_i^2 \sum_{i=1}^{n} R_i - \sum_{i=1}^{n} G_i \sum_{i=1}^{n} R_i}{\left[ n \sum_{i=1}^{n} G_i^2 - \left( \sum_{i=1}^{n} G_i \right)^2 \right] \left[ n \sum_{i=1}^{n} R_i^2 - \left( \sum_{i=1}^{n} R_i \right)^2 \right]}
\]

(4)

with \(i_r\) is radar rainfall intensity (mm/hour), \(i_g\) is the ARR rainfall intensity (mm/hour), \(N\) is the amount of data, \(G_i\) is the ARR rainfall depth (mm), and \(R_i\) is the radar rainfall depth (mm). If the RMSE value is close to zero it means the small difference in radar rainfall data and ARR. The G/R parameter shows the ratio of ground rainfall depth and radar rainfall depth.

The results of the correlation analysis between the X-Band MP and ARR radars were evaluated against the elevation difference between the X-Band MP radar and the ARR (\(\Delta EL\)). Then, the X-Band MP radar rainfall data was corrected to be closer to ground rainfall data. The correction of the X-Band MP radar rain data was performed by using Adjustment Factor (AF) [11]. AF value was obtained by the regression equation that is closest to the relationship between the G/R value and the \(\Delta EL\) factor using Equation 5. After the regression equation is obtained, radar data corrected by Equation 6 [4,11].

\[
AF_{(\Delta EL)} = \frac{10}{b} \log_{10}(e^x)
\]

(5)

where AF is the spatial correction factor, \(b\) is the radar reflectivity equation constant, and \(x\) is the regression analysis's constant.

\[
R_{AF} = R + AF
\]

(6)

with \(R_{AF}\) is the depth of the radar rain after corrected with AF.

3. Results and Discussions

Sosrodarsono and Takeda [12] categorized the rainfall intensity into five groups as shown in Table 2. Based on Table 2, heavy rain is identified as a rainfall that is more than 20 mm/hour. Sujono et al. [13] identified the heavy rain as rain with rainfall depth of more than 50 mm on one rainfall event. So, this study separates the rainfall into heavy rainfall with a rainfall intensity higher than 20 mm/hour and moderate rainfall with an intensity of lower than 20 mm/hour. Then the G/R analysis was carried out with the results shown in Figure 1.

| Rainfall classification | Rainfall intensity (mm/hour) |
|------------------------|-----------------------------|
| Very light rain        | <1                          |
| Light rain             | 1-5                         |
| Moderate rain          | 5-10                        |
| Heavy rain             | 10-20                       |
| Very heavy rain        | >20                         |
Based on Figure 1 it can be seen that in the event of heavy rainfall has a higher G/R value than moderate rainfall in almost every ARR station. These results indicate that the accuracy of the X-Band MP radar affected by the amount of rainfall intensity. The X-Band MP radar has better accuracy when reading moderate intensity of rainfall than heavy rainfall. The highest G/R value of moderate rainfall is 2.3 which is owned by BS05. It means in the average that the radar rainfall estimation has about half of the ground rainfall data. But for the heavy rainfall, the highest G/R value is about 4.5 that means the ground rainfall data can be 4 times higher than radar rainfall estimation. For the use of flood mitigation, the accuracy of heavy rainfall estimation is crucial. Inaccuracy in estimating high rainfall will have fatal consequences for the safety of flood-prone areas, especially in relation to evacuation time estimates.

Furthermore, an analysis of the relationship of log(G/R) of each ARR station with ∆EL is performed. Figure 2 and Figure 3 show the graph of the log (G/R) relationship with ∆EL for moderate rainfall and heavy rainfall.
There is an increase in log(G/R) value at higher ∆EL in the event of heavy rainfall. The increasing (G/R) value indicates that there is a high influence of ∆EL on the ratio of radar rainfall and ground rainfall. The greater the ∆EL, the greater the ratio of the depth of ground rainfall and radar rainfall. However, in the event of moderate rainfall, the regression line tends to be close to horizontal, indicating that the effect of ∆EL on the ratio of radar rainfall and ARR is not significant. The regression analysis results in Figure 2 and Figure 3 are used to calculate the AF value and used to correct the radar rain data. A comparison of the G/R values before and after corrections is presented in Figure 4 and Figure 5.
Figure 4 and Figure 5 show that in heavy rainfall, the G/R value after correction tends to be close to one. In the event of moderate rainfall, not all ARR stations get G/R values that are close to one. So, AF correction method is more suitable for correcting heavy rainfall. After being corrected by AF, the RMSE value tends to decrease, in other words, the radar rainfall estimation is closer to the ground rainfall (ARR).

![Figure 6. RMSE value of corrected radar rainfall](image)

**4. Conclusions and Suggestions**

X-Band MP radar has better accuracy in predicting rainfall in areas below the radar than above the radar elevation. This factor should be considered when using the X-Band MP radar in mountainous areas. There is an indication that the accuracy of the X-Band MP radar affected by the amount of rainfall intensity. In case of the heavy rainfall, Radar X-Band MP tend to give smaller estimation than the ground rainfall data (ARR). The accuracy of heavy rainfall estimation is crucial especially for mitigation system. The error of estimating heavy rainfall will have fatal consequences for the safety of vulnerable areas, especially in predicting the flood evacuation time. Correction of the X-Band MP radar rainfall data using the AF factor for heavy rainfall produces radar rainfall estimation that is closer to the ARR.

**5. References**

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