Application of Attenuation Correction to Quantitative Precipitation Estimation on C-Band Weather Radar in Bengkulu

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Abstract. A weather radar is an active system remote sensing tool that observes precipitation indirectly. Weather radar has an advantage in estimating precipitation because it has a high spatial resolution (up to 0.5 km). Reflectivity generated by weather radar still has signal interference caused by attenuation factors. Attenuation causes the Quantitative Precipitation Estimation (QPE) by the C-band weather radar to underestimate. Therefore attenuation correction on C-band weather radar is needed to eliminate precipitation estimation errors. This study aims to apply attenuation correction to determine Quantitative Precipitation Estimation (QPE) on the c-band weather radar in Bengkulu in December 2018. Gate-by-gate method attenuation correction with Kraemer approach has applied to c-band weather radar data from the Indonesian Agency for Meteorology and Geophysics (BMKG) weather radar network Bengkulu. This method uses reflectivity as the only input. Quantitative Precipitation Estimation (QPE) has obtained by comparing weather radar-based rain estimates to 10 observation rain gauges over a month with the Z-R relation equation. Root Mean Square Error (RMSE) is used to calculate the estimation error. Weather radar data are processed using Python-based libraries Wradlib and ArcGIS 10.5. As a result, the calculation between the weather radar estimate precipitation and the observed rainfall obtained equation $Z = 2.65R^{1.3}$. The attenuation correction process with Kraemer's approach on the c-band weather radar has reduced error in the Qualitative Precipitation Estimation (QPE). Corrected precipitation has a smaller error value ($r = 0.88$; RMSE = 8.38) than the uncorrected precipitation ($r = 0.83$; RMSE = 11.70).

1. Introduction
A weather radar is an active system remote sensing tool that observes precipitation indirectly. Weather radar observing hydrometeors and other atmospheric scatterers by emitting and receiving radio frequency signals. Weather radar has an advantage in estimating precipitation because it has a high spatial resolution (up to 0.5 km) \cite{1}. Weather radar can determine precipitation in areas without rain gauges \cite{2}. Reflectivity ($Z$) generated by weather radar still has signal interference caused by attenuation factors. Attenuation is the gradual loss of power as the radar energy travels through precipitation. Attenuation causes quantitative precipitation estimation to underestimate. Many measurements have been an attempt to correct this \cite{3}. The weakening strength of the electromagnetic waves on the C band weather radar even occurs in light rain intensity. The decrease in reflectivity on the weather radar generated by attenuation disturbances will cause an error when estimating
precipitation. Therefore, Attenuation correction on C-band weather radar is needed to eliminate precipitation estimation errors.

This study aims to evaluate the gate-by-gate attenuation correction by Kreamer's approach using reflectivity as the only input. This method adds a Path-Integrated Attenuation (PIA) to the reflectivity at each gate [4]. The Gate-by-gate attenuation algorithm will apply to the Bengkulu c-band radar during December 2018. Quantitative Precipitation Estimation (QPE) determine base on the comparison between radar-based estimates to 10 observation rain gauges over December 2018 with the Z-R relation equation. Root Mean Square Error (RMSE) is used to quantify the overall estimation error. Weather radar data processing using wradlib (open-source library for weather radar data processing) and ArcGIS 10.5.

This study expected that Quantitative Precipitation Estimation (QPE) of corrected weather radar has better accuracy than uncorrected weather radar.

2. Data and Methods
Bengkulu weather radar location is at 3° 51' 30.9" S and 102° 20' 28.0" E. Bengkulu weather radar manufactured by Gematronik German. Specifications of Bengkulu weather radar showed in Table 1.

| Parameter                | Specification                        |
|--------------------------|--------------------------------------|
| Type                     | Gematronik Meteor-635CLP10            |
| Altitude                 | 15 meter                             |
| Installation year        | 2012                                 |
| Operating Frequency      | 5.64 GHz                              |
| Peak Power               | 457, 449, 470 kW                     |
| Long Pulse Width         | 2.00 μs                              |
| Medium Pulse Width       | 0.80 μs                              |
| Short Pulse Width        | 0.48 μs                              |
| PRF                      | 250 - 1200 Hz                        |
| Receiver Type            | Digital                              |
| Frequency Range          | C-band                               |
| Noise Figure             | 1.84 dB                              |
| MDS LP Mode              | -118.0 dBm                           |
| SP mode                  | -109.0 dBm                           |
| Azimuth Travel Range     | 0° - 360°                            |
| Elevation Travel Range   | -2° - 180°                           |
| Azimuth Velocity         | 1 - 36°/s                            |
| Elevation Velocity       | 1 - 36°/s                            |
| Diameter                 | 4.3 meter                            |
| Polarization             | Horizontal                           |
| Beam Width               | 0.9°                                 |
| Gain                     | 45.2 dBi                             |
| Diameter                 | 6.5 meter                            |
| Transmission Losses      | 0.2 dB                               |

Bengkulu weather radar records data to produce information products every 6 minutes. It requires a standby time of 4 minutes so that the temporal resolution on the weather radar of the Fatmawati Soekarno Bengkulu Meteorological Station is 10 minutes, while the data generated by the weather radar has a spatial resolution of 0.5 km x 0.5 km.

Bengkulu weather radar implements a series of data scanning strategies by radar antennas, with 360° rotation and multiple elevations angles 0°, 1.2°, 2.1°, 3.2°, 4.4°, 6.0°, 7.8°, 10.0°, 12.6°, 15.7°, 19.5°. Weather radar scanning strategies covered the area up to 250 km from the radar site and an altitude up to 10 km. The scanning strategies of Bengkulu weather radar showed in Figure 1.

The radar data used is from 1 December 2018 at 00.00 UTC to 31 December 2018 at 00.00 UTC with 10-minute intervals. For comparison with rainfall station data of 9 manual rain gauges and an
automatic rain gauge on the Automatic Weather Station (AWS) are chosen in this study. Rain gauges are located in Batu Bandung (04°21'36.1"S; 102°57'23.4"E), Bunga Mas (04°30'10.7"S; 102°58'31.2"E), Sulau (04°32'58.1"S; 103°09'10.4"E), Kanpel Linau (04°50'19.1"S; 103°24'49.4"E), Tanjung Harapan (04°37'50.3"S; 103°14'29.1"E), Masmambang (04°10'06.7"S; 102°42'14.4"E), Rimbo Kedui (04°05'39.6"S; 102°33'00.5"E), Sukaraja (03°58'08.5"S; 102°25'05.7"E), Talang Dantuk (04°03'41.0"S; 102°32'56.0"E), and AWS Manna (04°26'45.6"S; 102°54'15.4"E). The radar site and the distribution of the rain gauges showed in Figure 2.

Figure 1. Bengkulu weather radar scan strategy

Figure 2. Weather radar and rain-gauge distribution

Weather radar data processed by wradlib, a python-based open-source software. Wradlib uses widely for weather radar data processing and its applications. Wradlib functions to process weather radar data, especially in producing Quantitative Precipitation Estimation (QPE) products [7].

This study uses Kreamer's approach to attenuation correction of c-band weather radar in Bengkulu. This method has shown promising results determining Quantitative Precipitation Estimation (QPE) on c-band weather radar in Feldberg, Germany. Attenuation correction uses Kreamer's approach with the following explanation. Radar reflectivity Z (mm^6 M^{-3}), rainfall intensity R (mm h^{-1}), and specific attenuation A (dB km^{-1}). The relationship between R and A [7], Z and A [8] as equations (1) and (2).
\[ A = aR^b \]  
\[ A = cZ^d \]  
\[ (1) \]
\[ (2) \]

Where \( a, b, c, \) and \( d \) are empirical parameters. By using equation (2) and the length of \( \Delta r \), we get equation (3).

\[ PIA_i = c \sum_{j=0}^{i-1} cZ_i^d \Delta r \]  
\[ (3) \]

Kreamer recommends a value of \( c = 1.67 \times 10^{-4} \) and \( d = 0.7 \). The \( Z_i \) of radar data will correct by adding the equation (3) Path Integrated Attenuation (PIAi) in dB so that corrected radar data obtained as in equation (4).

\[ Z_{cor,i} = Z_i + PIA_i \]  
\[ (4) \]

Determination of rainfall uses a commonly used method that relates the reflectivity of radar data \( Z \) (mm6 M\(^{-3}\)) with rainfall intensity \( R \) (mm h\(^{-1}\)). The approach used is to make a relationship between radar reflectivity and rain gauge. The general equation known as the \( Z\)-\( R \) relationship showed in equation 5, where \( a \) and \( b \) are constants. The constants \( a \) and \( b \) have different values in each place depending on the distribution of rain and conditions [8].

\[ Z = aR^b \]  
\[ (5) \]

Estimation of precipitation using equation 5 tested statistically to measure the accuracy of the observed rain data. The statistical test parameters used are the correlation coefficient \( (r) \) and the Root Mean Square Error (RMSE) in equations 6 and 7.

\[ r(x, y) = \frac{\sum(x, y) - \bar{x} \bar{y}}{\sqrt{\sum(x, y^2) - \bar{x}^2 \bar{y}}^2} \]  
\[ (6) \]

\( r \) = correlation coefficient  
\( x \) = independent variable  
\( y \) = dependent variable

\[ RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \bar{Y}_i)^2}{n}} \]  
\[ (7) \]

RMSE = Root Mean Square Error  
\( Y_i \) = Precipitation estimation on observation \( i \)  
\( \bar{Y}_i \) = Gauge observation \( i \)  
\( n \) = Amount of data

3. Results and discussion

3.1 Attenuation Correction

As an example, an overview of the attenuation correction process described in Figure 3 uses Bengkulu weather radar images on 22 December 2018 from 16.30 UTC to 17.00 UTC. The blue line marks indicate the direction of the weather radar beam at the Automatic Weather Station. The Automatic Weather Station location is on azimuth 134°. The reflectivity along the radar beam of each azimuth is plotted to the farthest radius of coverage (see Figure 4). The Plotting aims to analyze the reflectivity distribution along the beams. The radar beam plotting method at an azimuth has been used for attenuation correction by Jacobi and Heistermann (2016) [3].

Figure 4 shows an overview of the reflectivity along the radar beam at azimuth 134° (green line). Beam at azimuth 133° (blue line) and 135° (red line) show a comparison of the reflectivity around azimuth 134°. Figure 3 and Figure 4 are still reflectivities before attenuation correction. Equation 4 is described correction attenuation by adding Path Integrated Attenuation (PIA) to each reflectivity.
value in the weather radar grid data. The corrected weather radar reflectivity will be obtaining after attenuation correction.

![Figure 3](image)

**Figure 3.** Reflectivity on 22 December 2018 at 16.30 UTC until 17.00 UTC, blue line marks the beam at an azimuth of 134°.

Figure 5 presents the comparison between the radar reflectivity before and after corrected attenuation along azimuth 134°. It shows that there is a change in the reflectivity after attenuation correction. The differences between corrected and uncorrected radar reflectivity increase with increasing distance. Attenuation increases as distance increases. Echoes from the rain near the radar is thus not attenuated as much as that from farther away [9].

![Figure 4](image)

**Figure 4.** Reflectivity along beams on 22 December 2018 at 16.30 UTC until 17.00 UTC at an azimuth of 133°, 134°, 135°.
3.2 Relationship between radar reflectivity and precipitation observation

The relationship between weather radar reflectivity (Z) and rainfall (R) forms Equation 5. The coefficients a and b are obtained using linear regression of the logarithms. The constants a and b have different values in each place depending on the distribution of precipitation and topographical conditions [10]. Equation 5 is known as the Marshall-Palmer equation with the value of the relationship Z=200R^{1.6} [11]. This equation is a reference for developing methods of calculating rainfall in subsequent studies.

Coefficients a and b determine by Weather radar reflectivity data from BMKG Bengkulu and precipitation observations from 9 rain gauges and an Automatic Weather Station (AWS) in December 2018. The result is the coefficient a = 2.65 and b = 1.3. So that the general equation Z-R relation for Bengkulu radar as equation 8.

\[ Z = 2.65 \times R^{1.3} \]  

(8)

Precipitation estimation calculates by using equation 8. In this example, we are still using the data on 22 December 2018 from 16.30 UTC until 17.00 UTC. The rain gauge used from the Automatic Weather Station (AWS) is at azimuth 134°. Figure 6 shows the comparison between the corrected and uncorrected radar with the AWS observation rain gauge. Figure 6 shows the corrected radar (blue line) is closer to the AWS observation precipitation (yellow dot) than the uncorrected radar (dashed green line). These results indicate that corrected radar can improve the quality of rainfall estimates.

![Figure 5. Reflectivity before and after attenuation correction](image_url)

![Figure 6. Comparison between corrected and uncorrected precipitation.](image_url)
Figure 7. Spatial comparison between corrected and uncorrected precipitation on 22 December 2018 at 13.00 UTC until 14.00 UTC.

Figure 7 shows the spatial comparison between the corrected (a) and uncorrected (b) accumulated precipitation. In this example, we are using a weather radar image for 22 December 2018, from 13.00 UTC to 14.00 UTC. The attenuation correction process causes differences in the spatial distribution between corrected and uncorrected precipitation. There is increasing accumulated precipitation after correction.

3.3 Verification

This study aims to investigate the effect of attenuation correction at Qualitative Precipitation Estimation (QPE). QPE verification using RMSE and the correlation coefficient of 9 rain gauges and 1 Automatic Weather Station (AWS). The verification results show corrected precipitation has a coefficient correlation of 0.88 and RMSE 8.38 mm (Figure 8.a), while uncorrected precipitation has a coefficient correlation of 0.83 and RMSE 11.70 mm (Figure 8.b). It shows that corrected radar has an error smaller than uncorrected radar.
4. Conclusion
The results of calculation between the weather radar estimate precipitation and the observed rainfall obtained equation $Z=2.65R^{1.3}$. Qualitative Precipitation Estimation (QPE) error reduced by the attenuation correction process with Kreamer's approach on the c-band weather radar. The results shows corrected precipitation has an error ($r = 0.88$, RMSE = 8.38) smaller than the uncorrected precipitation ($r = 0.83$, RMSE = 11.70).

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