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Hourly adjustment factor analysis using the Kalman Filter technique to reduce errors in Sattahip radar rainfall estimation

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Abstract

Weather radar can continuously measure rainfall immediately as it occurs, covering wide areas and providing high-resolution rainfall both spatially and temporally. However, in radar rainfall estimation, even when using Z-R relationships that vary according to rainfall clusters based on rainfall intensity measured from ground-based automatic rain gauges to reduce estimation errors, there remain discrepancies in adjusting radar rainfall measurements above ground to match actual ground rainfall. Additionally, each rainfall event has different raindrop distribution characteristics, resulting in varying physical characteristics across different rainfall events. This study collected data from 510 rainfall events between February 2, 2018, and August 31, 2020, comprising hourly rainfall from 110 automatic rain gauges and radar reflectivity within a 240 km radius of the Sattahip radar. The aim was to analyze rainfall estimation methods using Z-R relationships that vary by rainfall cluster according to rainfall intensity, combined with appropriate hourly adjustment factors for the Sattahip radar. The study found that the rainfall estimation method using Z-R relationships that vary by rainfall cluster according to rainfall intensity, combined with hourly adjustment factors analyzed using the Kalman Filter technique, most effectively reduced the errors in adjusting radar rainfall above ground to match ground rainfall. Considering the RMSE values, the method can reduce the rainfall estimation error by 21.53%, 4.10% (21.87%,5.19%). Based on the MSE values, it can reduce the estimation error by 47.71%, 8.37% (48.50%, 10.63%). Similarly, based on the MAE values, it can reduce the estimation error by 29.05%, 4.55% (31.32%, 6.28%) for the rainfall events used for calibration (Verification), compared to the rainfall estimation methods based on the current Z-R relationship, and the Z-R relationship that varies according to rainfall type and intensity without adjustment.

Keywords: Weather radar, Automatic rain gauge, Rainfall event, Hourly adjustment factor

1. Introduction

Rainfall data is an important and necessary data in meteorology-hydrology and water resource development. Although the detailed requirements of rainfall data vary from project to project, most of the similar purposes are to obtain data showing the amount and rainfall distribution both in terms of space and time rather than requiring only point rainfall at a particular point [1], which cannot measure the distribution of rainfall that changes in both space and time. In addition, the measurement of rainfall data with rain gauges, which are not densely located in the area, may not be a good representative of the actual rainfall in that area [2]. Currently, remote sensing techniques such as meteorological radars have gained more attention to survey the details and behavior of rain because weather radars can provide detailed information on rain covering the area under the radar radius and can continuously measure rain as soon as it covers a wide area. It provides high-resolution rainfall data in both spatial and temporal resolutions [3-5]. When used to assess rainfall together with rainfall data measured from automatic ground telemetry stations, it greatly improves the accuracy of the assessment of rainfall that falls on the ground [6-8]. However, there are still errors in the assessment of rainfall from radar, which consist of (1) errors in the radar reflectivity values. Which is affected by the problems of Ground Clutter, Beam Blockage and Beam Attenuation [9-10], etc. Before using the radar reflectivity data to analyze the Z-R relationship equation, (2) the error due to the use of the relationship equation between the radar reflectivity and the rain intensity measured from the automatic ground telemetry station Z-R ($Z=aR^b$) which is not appropriate [11-12] and (3) the error due to the correction of rain from the radar above the ground to be equivalent to the rain falling on the ground. The study [13-14] presented a method to calculate the correction value (G/R) with a single constant value for the entire study area, which is suitable for areas with a large number of rain measuring stations located in the area and spread throughout the area, [15-16] found that rain events that occurred at different times had different rain drop size distribution characteristics, resulting in different physical characteristics of the rain. Therefore, a method for calculating the correction value according to time (hourly correction value) has been presented, similar to [15-18]. The Kalman Filter has been applied to analyze the hourly correction value to help reduce the error in the assessment of radar rain to be more accurate. This study therefore aims to apply the Kalman Filter technique to analyze the hourly correction value to help reduce the error in the assessment of rain from the Sattahip radar.

2. Materials and methods

2.1 Data used in the study

The area under the 240 km measurement radius of the Sattahip Royal Rainmaking Radar Station, S-band Doppler radar type, is located in Sattahip District, Chonburi Province, Thailand at latitude 12° 38’ 56” N, longitude 100° 57’ 46” E, at an altitude of 174 meters above mean sea level, as shown in Figure 1. This study collected rainfall events that occurred. During February 2, 2018 to August 31, 2020, the radar reflectivity data that measured rain were stored in Volume files recorded in Coordinated Universal Time (UTC) with measurements every 6 minutes from the measured angle of 1.5°. The radar reflectivity data (Z) were stored in Volume files and the rain data from the automatic ground telemetry station of the Hydro-Informatics Institute (Public Organization) (HII). In each rain event used in the study, there must be rain measurement data from the radar and rain data from the automatic ground telemetry station that are consistent. Both of these data must pass the quality check and adjust the data error before being used in the study as follows:

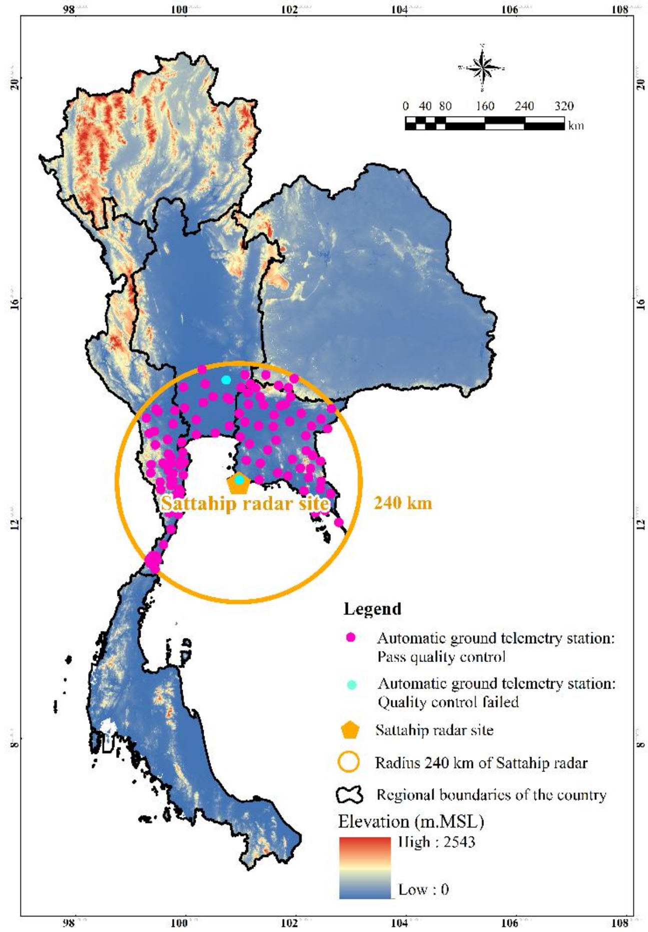
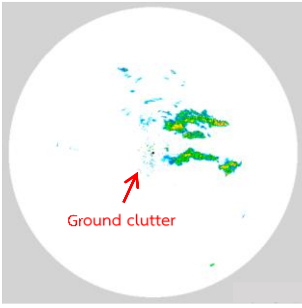


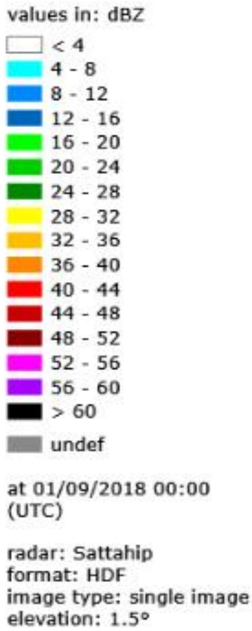
Figure 1 Area under the measurement radius of 240 km of the Sattahip radar station

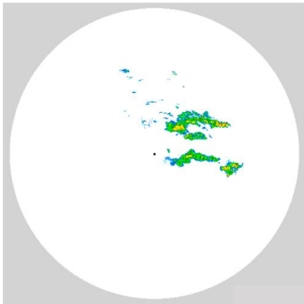
2.2 Data quality check and adjustment of the error of Sattahip radar reflectivity data

Data quality check and error correction of Sattahip radar reflectivity data from the measured elevation angle of 1.5°, which is the appropriate measurement angle of Sattahip radar (as studied in the article “Analysis of Z-R equations that change according to rain groups for evaluating Sattahip radar rain, 30th National Civil Engineering Conference”). However, the radar reflectivity data is still affected by the problem of radar beam hitting the permanent reflector (Ground Clutter). Therefore, a Ground Clutter Map with radar reflectivity (Reflectivity) was created to identify the location of Ground Clutter pixels and to adjust the error value due to the Ground Clutter problem of the pixels in the Ground Clutter position will be adjusted by calculating from the Reflectivity value of the neighboring pixels by the method Interpolation [19-20] The results of the correction of the radar reflectivity data due to the Ground clutter problem of the Sattahip radar are shown in Figure 2.



(a) Before correction of Ground clutter





(b) After correction of Ground clutter

Figure 2 The reflectivity data of the Sattahip radar before and after correction of Ground Clutter as of September 1, 2018 at 00:00 (UTC)

As for the impact due to the Beam Blockage problem, when the radar beam hits the permanent reflecting target, it results in the radar reflectivity value measured in the area behind the obstacle being lower than normal. Therefore, the correction was made by taking the Radar Reflectivity data from the monthly accumulated rainfall measurements into consideration to find the location of the Beam Blockage. The Radar Reflectivity value of the pixel in the Beam Blockage position was adjusted by calculating from the Radar Reflectivity value of the adjacent pixels by the method Interpolation [19-20]. The results of the correction of the radar wave reflectivity due to the Beam Blockage problem of the Sattahip radar are shown in Figure 3. While the effect of radar wave energy being absorbed (Attenuation) when traveling through atmospheric gases, water vapor, oxygen and rainfall [21], the radar wave energy is absorbed and reduced. The sensitivity of the radar signal to the reduction of energy depends on the radar wavelength that is transmitted. The reduction of energy is a problem for X-band and C-band radars, which have wavelengths of 2.5 and 5.5 cm, respectively, but not for S-band radars with wavelengths of 10.7 cm [22]. Therefore, for the Sattahip radar, which is an S-band radar, it is not affected by the Attenuation problem. In order to avoid the radar reflectivity value, the signal that is not caused by rain clouds is selected to use only the radar reflectivity value that is greater than 15 dBZ and to avoid the radar reflectivity value of the signal that is caused by hail. Therefore, in the case where the radar reflectivity is greater than 53 dBZ, it will be considered to be equal to 53 dBZ [23].

2.3 Quality control of hourly rainfall data from automatic ground telemetry stations

Quality control of hourly rainfall data from automatic ground telemetry stations that passed the inspection criteria and were used in the study must pass the quality control criteria using the Double mass curve method and have an R-squared statistic value greater than 0.90. The results of the quality control of hourly rainfall data from automatic ground telemetry stations that collected data between February 2, 2018 and August 31, 2020, a total of 110 stations, were checked for data quality. It was found that 108 automatic ground telemetry stations passed the data quality control and 2 stations did not. In order to make the rainfall assessment using weather radar data accurate, this study will use rainfall data from automatic ground telemetry stations that passed the data quality control criteria and are not located in the blind radar area of the Sattahip radar (area within a 10 km radius from the radar station) because in the blind radar area, the radar will measure less rain than the actual amount. The quality-verified and unverified ground telemetry stations are shown in Figure 1.

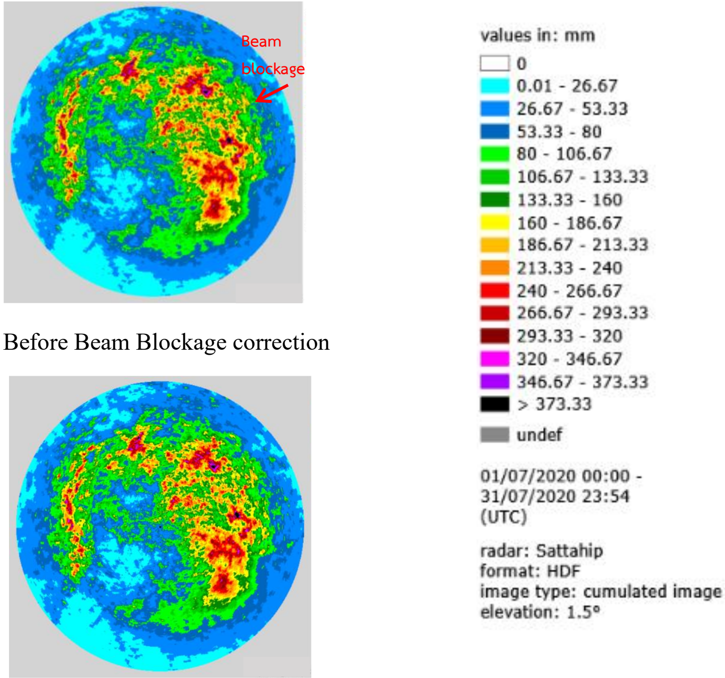
2.4 Z-R relationship equations used in the assessment of Sattahip radar rain

This study considered all 5 Z-R relationship equations studied in the article "Analysis of the Z-R equations that change according to the rain group for the assessment of Sattahip radar rain, which consisted of:

Case 1: Analysis of the average Z-R relationship equation, ($Z=175R^{1.6}$)

Case 2: Analysis of the average Z-R relationship equation in each rain group divided by the radar wave reflectivity value as follows:

Rain group 1	15 dBZ<=Reflection< 30 dBZ,	($Z=121R^{1.6}$)
Rain group 2	30 dBZ<=Reflection< 38 dBZ,	($Z=175R^{1.6}$)
Rain group 3	38 dBZ<=Reflection< 44 dBZ,	($Z=174R^{1.6}$)
Rain group 4	44 dBZ<=Reflection<=53 dBZ,	($Z=220R^{1.6}$)



(a) Before Beam Blockage correction

(b) After Beam Blockage correction

Figure 3 Monthly accumulated rainfall measured by the Sattahip radar for the July 2020 rain event before and after Beam Blockage correction

Case 3: Analyze the average Z-R relationship equation in each rain group divided by the rain intensity value measured from the automatic ground telemetry station by dividing the rain intensity range according to the study as follows:

Rain group 1	Rain intensity < 10 mm/hr,	($Z=465R^{1.6}$)
Rain group 2	10 mm/hr <=Rain intensity<= 30 mm/hr ,	($Z=94R^{1.6}$)
Rain group 3	Rain intensity > 30 mm/hr,	($Z=67R^{1.6}$)

Case 4: Use the Woodley and Herndon equation, ($Z=300R^{1.4}$)

Case 5: Use the Marshall and Palmer equation, ($Z=200R^{1.6}$)

2.5 Application of Kalman Filter to Analyze Hourly Correction Value in Radar Rainfall Assessment

The data of 510 rainfall events during February 2, 2018 to August 31, 2020 were applied using Kalman Filter technique to analyze hourly correction value in radar rainfall assessment. In this study, the data with radar reflectivity greater than 15 dBZ were selected and to avoid the impact of radar signal detection caused by hail, the case where the radar reflectivity was greater than 53 dBZ was considered to be equal to 53 dBZ [23]. The rainfall amount from the automatic ground telemeter station was considered to be greater than 0.2 mm/h and the method of randomly selecting automatic ground telemeter stations to obtain Z-R pairs in each rainfall event on each day was selected into 2 groups as follows: Group 1 data will randomly select 80% of the automatic ground telemeter stations from all automatic ground telemeter stations in each rainfall event on each day. The reflectivity (Z) results are converted to radar rain intensity values using the Z-R relationship equation in each of the five case studies, and the rain intensity values from the ground telemetry stations are applied using the Kalman Filter technique to analyze the hourly average correction value. The second group of data, the hourly average correction value analyzed from the first group of data, is tested for reliability by pairs of radar rain intensity data estimated using the Z-R relationship equation in each of the five case studies, and the rain intensity values from the ground telemetry stations remaining from the first group of data, which is 20% from all the ground telemetry stations in each rain event of each day.

The Kalman Filter was developed by [24], which has been widely used to estimate the state of the system or the correction value for the best radar rain assessment [15-18]. For the application of the Kalman Filter technique to analyze the hourly average correction value The steps are as follows:

Step 1: Calculate the hourly average correction value in Logarithm form from Equation 1.

$$\beta_t = \frac{1}{n}\sum_{i=1}^{n} \log_{10}\left(\frac{G_{t,i}}{R_{t,i}}\right) \tag{1}$$

where

β_t = the hourly average correction value in Logarithm form at time t

$R_{i,t}$ = the rainfall intensity calculated from the relationship equation (Z-R) at the automatic telemetry station i at time t (mm/h)

$G_{i,t}$ = the rainfall intensity from the ground automatic telemetry station i at time t (mm/h)

n = the number of corresponding data pairs of radar rainfall and rainfall at the automatic telemetry station i at time t

Step 2: Estimate the hourly average correction value $\hat{\beta}^{-}$ using the previous correction value from Equation 2 and calculate the variance of the error of $\hat{\beta}^{-}$ represented by the symbol P_t^{-} from Equation 3.

$$\hat{\beta}_t^{-} = \rho_\beta \times \hat{\beta}_{t-1} \quad (2)$$

$$P_t^{-} = \rho_\beta^2 P_{t-1} + (1-\rho_\beta^2) \times \delta_\beta^2 \quad (3)$$

where

ρ_β = the Lag-one correlation coefficient of the correction value

δ_β^2 = the variance of the correction value

P_{t-1} = the variance of the error at hour t-1

Step 3: Calculate the Kalman Gain from Equation 4 to use in adjusting the hourly average correction value and the variance of the error from the forecast.

$$K_t = P_t^{-}(P_t^{-} + \delta_{M_t}^2)^{-1} \quad (4)$$

where

K_t = the Kalman Gain at time t (h)

$\delta_{M_t}^2$ = the variance of the error from the measurement at time t (h)

Step 4: Use the Kalman Gain to adjust the hourly average correction value from the forecast. The hourly average correction value after the correction is represented by the symbol $\hat{\beta}^{-}$. In the same way, use the Kalman Gain to adjust the error variance. The error variance after the correction is represented by the symbol P_t^{-}.

• In the case of the hourly average correction value from the measurement at hour t, the hourly average correction value $\hat{\beta}^{-}$ after the correction can be calculated from Equation 5 and the error variance after the correction P_t^{-}, it can be calculated from Equation 6.

$$\hat{\beta}_t = \hat{\beta}_t^{-} + K_t(Y_t - \hat{\beta}_t^{-}) \quad (5)$$

$$P_t = (1-K_t)P_t^{-} \quad (6)$$

where

Y_t = the hourly average correction value obtained from the measurement

• In case there is no hourly average correction value from the measurement at hour t, the hourly average correction value after the correction $\hat{\beta}$ can be calculated from Equation 7 and the variance of the error after the correction P_t can be calculated from Equation 8.

$$\hat{\beta}_t = \rho_\beta \times \hat{\beta}_{t-1} \quad (7)$$

$$P_t = (1-\rho_\beta^2) \times \delta_\beta^2 \quad (8)$$

Step 5: The hourly average correction value after the correction at hour t is $\hat{\beta}_t$ and the variance of the error after the correction at hour t is P_t are entered into the calculation again in steps 2-4 until the number of hours used to calculate the hourly average correction value is complete.

Step 6: The hourly average correction value after the correction at hour t is $\hat{\beta}_t$ will be extracted from the Logarithm to find the hourly average correction value B_t using Equation 9 to apply the radar rain correction

$$B_t = 10^{(\hat{\beta}_t + 0.5P_t)} \quad (9)$$

Step 7: The hourly radar rain volume after correction can be calculated from Equation 10.

Radar rain volume after correction (mm/h) = B_t x Radar rain volume before correction (mm/h) (10)

2.6 Analyze the appropriate rain radar assessment method for Sattahip radar

The assessment method of Sattahip radar rain for this study will consider the radar rain intensity assessed from 10 radar rain assessment methods, namely:

• Method 1: Radar rain intensity assessed using the average Z-R equation ($Z=175R^{1.6}$)

• Method 2: Radar rain intensity assessed using the average Z-R relationship equation in each rain group divided by the radar wave reflectivity value as follows:

Rain group 1: 15 dBZ<=Reflection< 30 dBZ, ($Z=121R^{1.6}$)

Rain group 2: 30 dBZ<=Reflection< 38 dBZ, ($Z=175R^{1.6}$)
Rain group 3: 38 dBZ<=Reflection< 44 dBZ, ($Z=174R^{1.6}$)
Rain group 4: 44 dBZ<=Reflection<=53 dBZ, ($Z=220R^{1.6}$)

• Method 3: Radar rain intensity estimated using the average Z-R relationship equation in each rain group divided by the rain intensity values measured from the automatic ground telemetry station, divided into rain intensity ranges according to the study as follows:
Rain group 1: Rain intensity < 10 mm/hr, ($Z=465R^{1.6}$)
Rain group 2: 10 mm/hr <= Rain intensity <= 30 mm/hr, ($Z=94R^{1.6}$)
Rain group 3: Rain intensity > 30 mm/hr, ($Z=67R^{1.6}$)

• Method 4: Radar rain intensity estimated using the average Z-R equation Woodley and Herndon, ($Z=300R^{1.4}$).

• Method 5: Radar rain intensity estimated using the average Z-R equation Marshall and Palmer, ($Z=200R^{1.6}$).

• Method 6: Radar rain intensity estimated from the method 1 with the correction of the hourly average radar rain using the Kalman Filter technique.

• Method 7 The radar rain intensity estimated from Method 2 with the correction of the hourly average radar rain using the Kalman Filter technique.

• Method 8 The radar rain intensity estimated from Method 3 with the correction of the hourly average radar rain using the Kalman Filter technique.

• Method 9 The radar rain intensity estimated from Method 4 with the correction of the hourly average radar rain using the Kalman Filter technique.

• Method 10 The radar rain intensity estimated from Method 5 with the correction of the hourly average radar rain using the Kalman Filter technique.

We have examined to find the appropriate radar rain estimation method for the Sattahip radar by considering the RMSE (Root Mean Squared Error) , MSE (Mean Squared Error) , MAE (Mean Absolute Error) statistics as shown in Equation 11-13 between the Sattahip radar rain intensity estimated using the 10 proposed study methods compared to the rain intensity from the ground automatic telemetry station must have the lowest value. of both the rainfall event data used for calibration of group 1 data and the rainfall event data used for verification of group 2 data.

$$\mathrm{RMSE}=\sqrt{\frac{1}{\mathrm{N}\times\mathrm{N}_t}\sum_{\mathrm{t}=1}^{N_t}\sum_{\mathrm{i}=1}^{N}\left(R_{\mathrm{i,t}}-\mathrm{G}_{\mathrm{i,t}}\right)^2} \quad (11)$$

$$\mathrm{MSE}=\frac{1}{\mathrm{N}\times\mathrm{N}_t}\sum_{\mathrm{t}=1}^{N_t}\sum_{\mathrm{i}=1}^{N}\left(R_{\mathrm{i,t}}-\mathrm{G}_{\mathrm{i,t}}\right)^2 \quad (12)$$

$$\mathrm{MAE}=\frac{1}{\mathrm{N}\times\mathrm{N}_t}\sum_{\mathrm{t}=1}^{N_t}\sum_{\mathrm{i}=1}^{N}\left|R_{\mathrm{i,t}}-\mathrm{G}_{\mathrm{i,t}}\right| \quad (13)$$

where
$R_{i,t}$ = the rainfall intensity calculated from the relationship equation (Z-R) at the automatic telemetry station i at time t (mm/h)
$G_{i,t}$ = the rainfall intensity from the ground automatic telemetry station i at time t (mm/h)
N = the total number of automatic telemetry stations used
N_t = the rainfall period (h)

3. Results and discussion

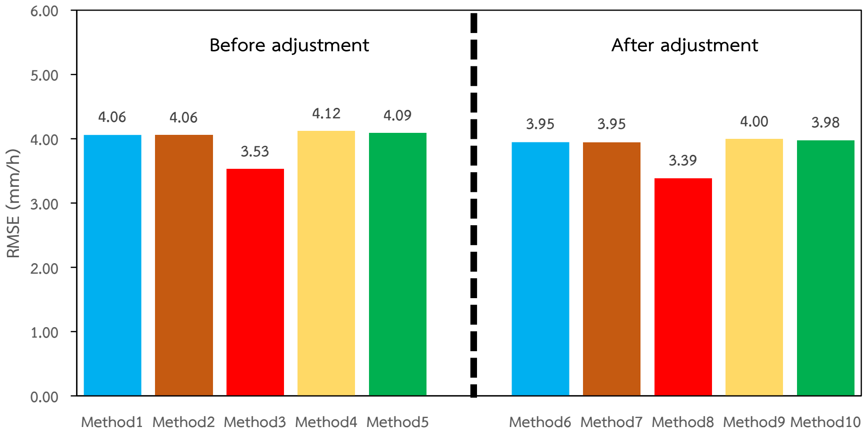
Results of the analysis of the appropriate rain radar assessment method for Sattahip radar. The results of the RMSE (Root Mean Squared Error), MSE (Mean Squared Error), and MAE (Mean Absolute Error) statistics between the Sattahip radar rain intensity assessed using the 10 proposed study methods compared to the rainfall amount from the ground-based automatic telemetry station must have the lowest value of both the rain event data used for calibration of group 1 data and the rain event data used for verification of group 2 data used for verification are shown in Table 1 and Figures 4-6, respectively.

RMSE results from Table 1 and Figure 4 (a) and (b) show that the radar rain intensity estimated by Method 8 (which is the method in which the radar rain intensity is estimated using the average Z-R relationship equation in each rain group divided by intensity value together with the hourly average radar rain correction using the Kalman Filter technique) has the lowest value of both the rain event data used for calibration of Group 1 data with a value of 3.39 mm/h and the rain event data used for reliability verification of Group 2 data with a value of 3.27 mm/h when compared to the rain intensity estimated by the other 9 methods.

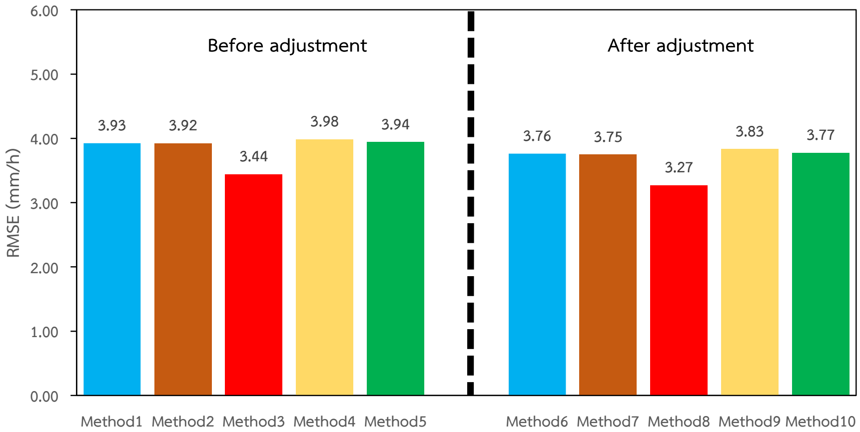
Table 1 Results of the analysis of the RMSE, MAE, and BIAS statistics of the 10 Sattahip radar assessment methods compared to the rainfall intensity measured from the ground-based automatic telemetry station

Methods for estimating radar rainfall	RMSE (mm/h)		MSE $(mm/h)^2$		MAE (mm/h)	
	Calibration	Verification	Calibration	Verification	Calibration	Verification
Method 1	4.06	3.93	16.50	15.43	2.08	2.09
Method 2	4.06	3.92	16.45	15.37	2.05	2.04
Method 3	3.53	3.44	12.45	11.83	1.75	1.74
Method 4	4.12	3.98	16.97	15.88	2.16	2.15
Method 5	4.09	3.94	16.71	15.55	2.14	2.13
Method 6	3.95	3.76	15.59	14.17	1.99	1.98
Method 7	3.95	3.75	15.59	14.05	1.96	1.93
Method 8	**3.39**	**3.27**	**11.49**	**10.69**	**1.67**	**1.64**
Method 9	4.00	3.83	15.96	14.69	2.07	2.05
Method 10	3.98	3.77	15.81	14.26	2.04	2.00

(Note: The details of each of the 10 study methods are shown in the section 2.6. Analysis of the appropriate radar rain assessment method for Sattahip radar)



(a) Rain event data used for calibration



(b) Rain event data used for verification

Figure 4 RMSE values between the Sattahip radar rainfall intensity estimated using the 10 proposed methods compared to the rainfall amount from the ground-based automatic telemetry station for the rainfall event data used in (a) calibration and (b) verification

The MSE results from Table 1 and Figure 5 (a) and (b) show that the radar rainfall intensity estimated by Method 8 has the lowest value of both the rainfall event data used for calibration of Group 1 data with a value of 11.49 $(mm/h)^2$ and the rainfall event data used for the reliability verification of Group 2 data with a value of 10.69 $(mm/h)^2$ compared to that of the radar rainfall intensity estimated by the other 9 methods.

The MAE results from Table 1 and Figure 6 (a) and (b) show that The estimated radar rainfall intensity from Method 8 has the lowest value of both the calibration rainfall data of Group 1 data with the value of 1.67 mm/h and the verification rainfall data of Group 2 data with the value of 1.64 mm/h when compared to that of the other 9 methods.

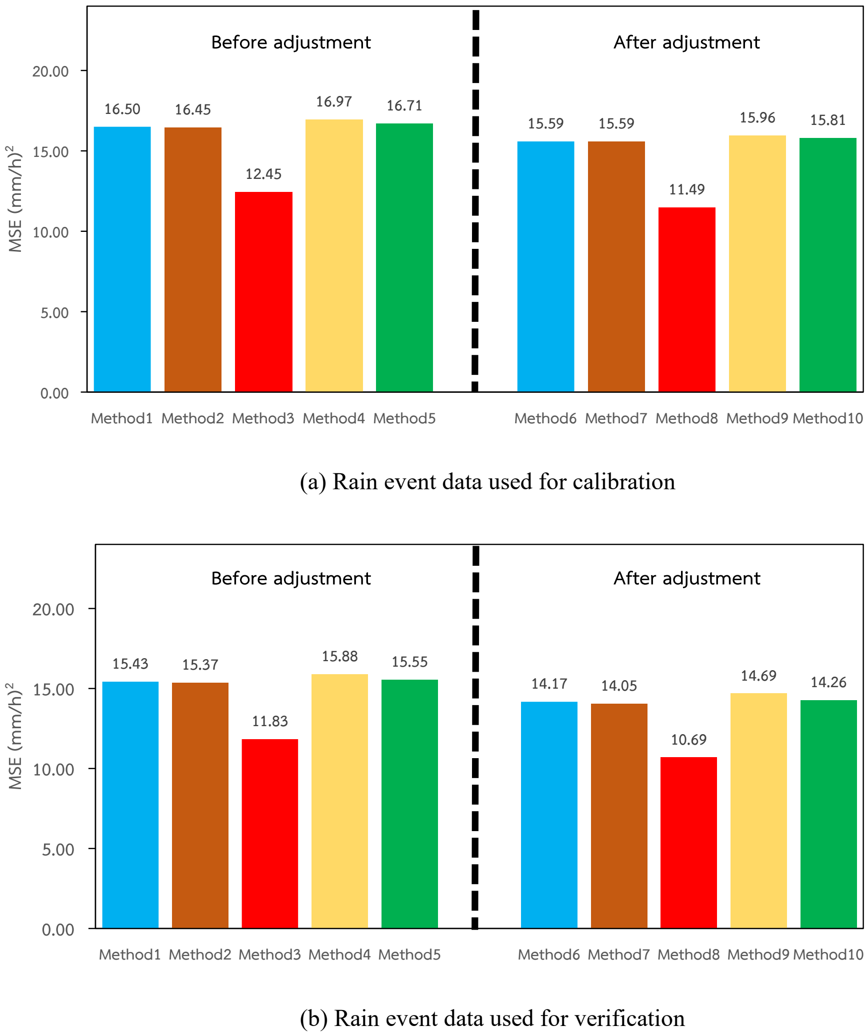
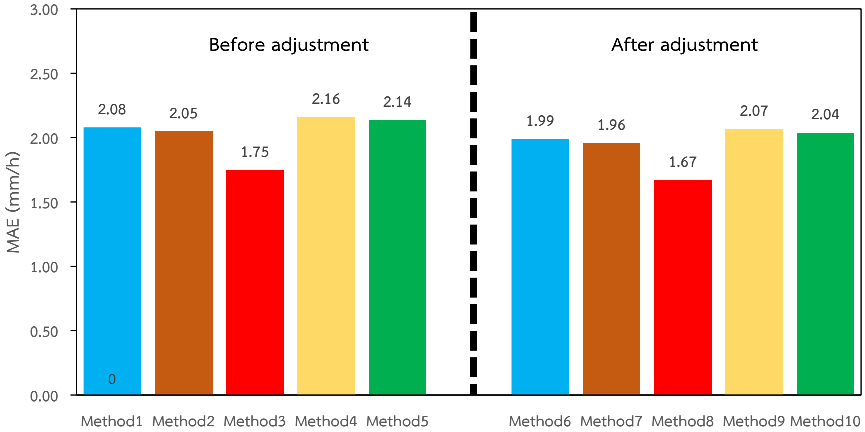
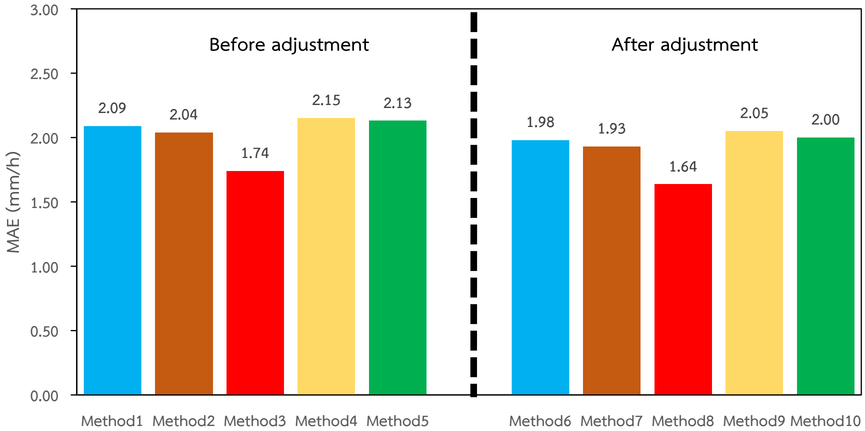


Figure 5 MSE values between the Sattahip radar rainfall intensity estimated by the 10 proposed methods compared to the rainfall amount from the ground automatic telemetry station for the rainfall data used for (a) Calibration and (b) Verification

The results of the study in Table 1 and Figures 4-6 show that the proposed radar rainfall assessment method 8 is the most appropriate rainfall assessment method for the Sattahip radar rainfall assessment, which is consistent with the study [15-16] that stated that rainfall events occurring at different times have different water droplet distribution characteristics, resulting in different physical characteristics of the rain. Therefore, the assessment of radar rainfall using only the Z-R relationship equation still has some error values, so the estimated radar rainfall should be adjusted with the hourly average correction value. The results of this study are also consistent with the study [15-18] when the Kalman Filter technique is applied to analyze the hourly average correction value and then used to adjust the radar rainfall assessment, which will greatly increase the accuracy of the radar rainfall assessment.



(a) Rain event data used for calibration



(b) Rain event data used for verification

Figure 6 MAE values between the Sattahip radar rainfall intensity estimated using the 10 proposed methods compared to the rainfall amount from the ground-based automatic telemetry station for the rainfall event data used in (a) calibration and (b) verification

4. Conclusions

1) Rainfall events in each period have different distribution characteristics of raindrops. The radar rain intensity estimated using the average Z-R relationship equation in each rain group divided by the rain intensity measured from the automatic ground telemetry station, together with the hourly average radar rain correction using the Kalman Filter technique in the proposed method 8, helps reduce the error due to the use of the current Woodley and Herndon Z-R relationship equation and helps reduce the error due to the correction of rain from the radar above the ground to be equal to the rain falling on the ground, which helps to increase the accuracy of the rain assessment.

2) The radar rain intensity estimated by Method 8 is the most suitable rain assessment method for use in assessing the Sattahip radar rain with the lowest RMSE, MSE and MAE values between the radar rain intensity estimated by Method 8 and the rain intensity from the automatic ground telemetry station. of both rainfall event data used for calibration and verification compared to the other 9 rainfall estimation methods used in the study

3) The radar rainfall intensity estimated from Method 8, when considering the RMSE value, can help increase the accuracy of rainfall estimation by 21.53%, 4.10%. When considering the MSE value, it can help increase the accuracy of rainfall estimation by 47.71%, 8.37%. When considering the MAE value, it can help increase the accuracy of rainfall estimation by 29.05%, 4.55% compared to rainfall estimation using the Woodley and Herndon equation and the rain estimation method 3, where the radar rainfall intensity is estimated using the average Z-R relationship equation in each rain group divided by the rainfall intensity value measured from the automatic ground telemetry station only without correction. For the rain events used in the calibration

4) The radar rain intensity estimated by Method 8, considering the RMSE value, can help increase the accuracy of rain assessment by 21.87%, 5.19%, considering the MSE value, can help increase the accuracy of rain assessment by 48.50%, 10.63%, considering the MAE value, can help increase the accuracy of rain assessment by 31.32%, 6.28% compared to the rain assessment using the Woodley and Herndon equation and the rain assessment method 3, where the radar rain intensity is estimated using the average Z-R relationship equation in each rain group divided by the rain intensity value measured from the ground-based automatic telemetry station only without adjustment for the rain event used in the reliability verification

5) In the future study, the researcher has the idea to apply the proposed radar rain assessment method 8 in the rain forecasting (Nowcasting) of the Sattahip radar station together with the Centroid Tracking Method of the rain group, which allows us to know the direction of rain group movement from the radar that is continuously measured. It helps to forecast rain 1-6 hours in the area. Such

information can be used to plan flood warnings in the area, together with rain forecasting methods from relevant agencies in the area, more effectively.

6) Future studies The researcher has an idea to study more from this study, which has a limitation: considering rain groups divided by intensity values on each day in the same intensity range to use the same Z-R equation every day to assess rain intensity, resulting in still remaining errors. However, since each rain group that occurs each day has different raindrop distribution characteristics, the Z-R relationship equation used to assess rain should have different values according to the rain groups divided by intensity values on each day. When combined with the adjustment for different radar rain in each area on an hourly grid basis using the Kalman Filter technique, it will help increase the accuracy of the Sattahip radar rain assessment.

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