WRF Model Input for Improved Radar Rainfall Estimates Using Kalman Filter

Wardah, T.,[1] Sharifah Nurul Huda, S.Y.,[1] Suzana, R.,[1] Hamzah, A.,[2] and Maisarah,W.W.I[3]
[1] Faculty of Civil Engineering, Universiti Teknologi MARA.
[2]Faculty of Electrical Engineering, Universiti Malaya.
[3]Numerical Weather Prediction, Malaysian Meteorological Department

Abstract—**The indirect measurement of rain through radar reflectivity is associated with various sources of errors such as ground clutter, partial beam occultation, beam blockage and attenuation effects. Removing the systematic error (bias) and enhancing the precision and limitations of radar data sources are the main focus in enhancing radar rainfall accuracy. This research work was to reduce radar rainfall bias due to the process and measurement noises using Kalman Filter with a multivariate analysis technique. The implementation of this technique involved numerical weather prediction (NWP) namely the Weather Research Forecasting (WRF) model data output parameters such as temperature and relative humidity. The study found that filtering technique using Kalman Filter with multivariate analysis applying the WRF model output has satisfactorily improve radar rainfall estimates.**

Keywords- Bias; Radar Rainfall; Kalman Filter; Numerical Weather Prediction (NWP), Weather Research Forecasting (WRF)

I. INTRODUCTION

Weather radar has high potential in remotely sensing and detecting the development of flood causing thunderstorm. The main advantage of radar rainfall over point gauge rainfall is its ability to provide high spatial and temporal resolution rainfall information with a detailed view of the rainstorm over a large area. Nevertheless the indirect estimation of rain through reflectivity captured by radar is associated with various sources of error such as ground clutter, partial beam occultation, beam blockage and attenuation effects.

Originally meant for providing weather condition to assist the flight maneuvering system, the use of radar to provide quantitative precipitation forecast for flood forecasting system has recently become the subject of interest in Malaysia, a country with frequent flood occurrence. Studies on effectiveness of radar rainfall as alternative to gauged rainfall for flood forecasting have started about a decade ago in the country. Radar rainfall was used as validation to meteorological satellite based rainfall for flash flood forecasting by [1],[2], [3]. Studies on the improvement of Z-R relationship for Klang River Basin catchment based on categories of rainfall and monsoon were done by [4],[5] and [6]. Radar rainfall had been used as input to tank model [7] and to hydrodynamic flood forecasting using Infoworks [8] to forecast flow at Sg Gombak, Malaysia.

Research on reducing radar bias by using kriging and Kalman Filter had been done by [9] and [10]. Another study was done by [11] to calibrate radar-derived rainfall data for rainfall-runoff modeling in the Upper Bernam river basin in Perak and found that the watershed river flow can be better estimated by using radar-derived rainfall data.

The improvement of radar rainfall accuracy had long being studied by many researchers all over the world. Several studies over the last decades have sought to combine radar estimates with gauge measuring of quantitatively accurate and spatially continuous radar-derived precipitation fields. Researchers prefer to analyze the Radar to Gage (R/G) ratio [12],[13] while others have applied optimal interpolation methods [14],[15] and [16].

Comparison between radar rainfall estimates and rain gauge data was done for events of heavy rainfall intensity for Klang river basin and the results are shown in Figure 1[10]. The study found a satisfactory correlation of $r^2 = 0.66$ between rain gauge data and weather radar data for events (2-4 hours duration) of heavy rainfall rates.

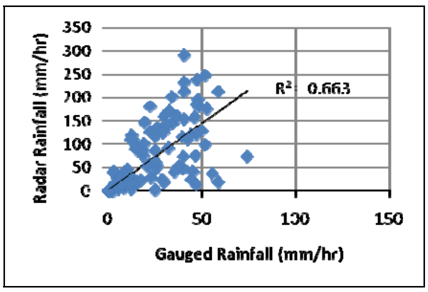


Figure 1. Correlation between radar rainfall estimates and gauged rain for Klang River Basin, from January 2009 until December 2009 for events of heavy rainfall [10].

The aim of this research is to enhance radar rainfall estimates by reducing noises using Kalman Filter. The

The authors would like to thank Research Management Institute, Universiti Teknologi Mara, RIF grants (600-RMI/DANA5/3/RIF(112/2012))

filtering technique works as a recursive predictor corrector algorithm to process the discrete measurement (inputs) with the help of a system model, into optimal state estimates (outputs). The approach by the Kalman Filter is to reduce the estimated error covariance due to the noise in a linear stochastic system. The noise may be divided into two categories, which are process noise and measurement noise that occurs due to the instrumentation used in monitoring and processing.

Kalman Filter has been extensively researched since the time of digital computing establishment and being commercially used [15]. Many researchers have found that Kalman Filter produced improved outcomes in the process of reducing radar rainfall bias. Among them were [10], [17], [18], [19], and [20]; who used the Kalman Filter method to forecast and update real-time mean field radar rainfall bias.. Weather radar works by giving the information on rainfall estimation by use of the Z-R relationship. Without further reception, processing, and support tools, these sources cannot easily be used to monitor weather conditions and flooding. Usually, Kalman Filter equations are used in updating model states from noisy observations of weather radar data.

Kalman Filter is suitable for stationary or non-stationary time series, and also works on time series with missing values [18]. The algorithm used to revise the moments of stochastic components of a linear time series model to reflect information about them, which is contained in time series data. It is normally used in deriving the moments of components at future points of time for forecasting purposes. It is useable in real-time applications, because revisions to the moment are made recursively as each successive member of a time series is observed. The design of the Kalman Filter equation for calculating the required means and variances were originally derived using projection theory in linear spaces. Kalman Filter equations could also be derived using a stochastic coefficient regression framework [18].

This study used the related meteorological factors including the temperature, humidity, gauged rainfall in the development of filtering algorithm which applied the multivariate technique as modelled in stationary variance. The approach of using the Kalman Filter combined with multivariate analysis is expected to improve radar rainfall estimates by prediction (time update) and correction (measurement update).

II. LOCATION OF STUDY AREA

Klang River Basin is located in the West part of Malaysia. The area of this basin is about 1290 km^2, including the 75 km length of its main river, known as the Klang River. The basin covers the Federal Territory of Kuala Lumpur, parts of Gombak, Hulu Langat, Kuala Langat, Sepang, Petaling and Klang, which are in districts of the State of Selangor.

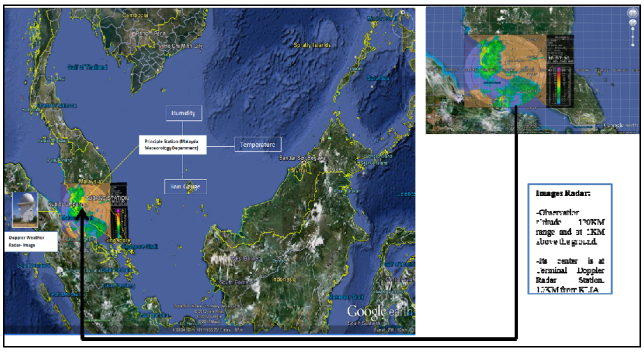


Figure 2. Location of case study with overlaid radar rainfall display from KLIA Doppler radar.

Figure 2 shows the location of Klang River Basin in Malaysia with an overlaid image produced by KLIA Doppler radar. The range of reflectivity measured was from the zero point at the radar center up to 120 km radius, covering a diameter of 240 km diameter including both land and ocean.

III. DATA COLLECTION

A. Gauged Rainfall Data

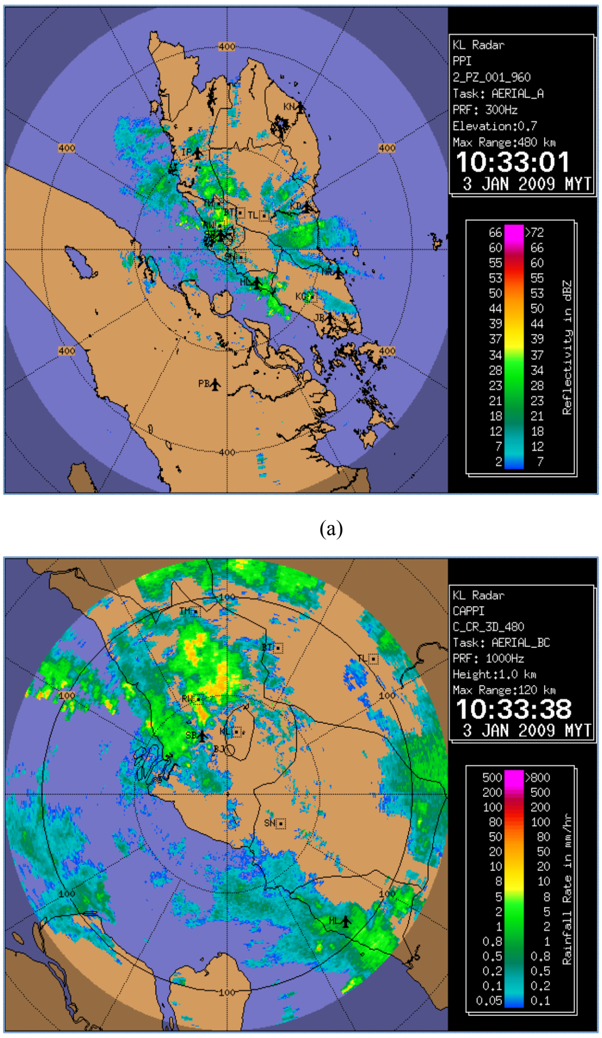
In this study rainfall data from 20 stations were collected during rainy seasons from July to December 2012. The latitude and longitude of the stations are provided in Table 1.

B. Numerical Weather Prediction Model Output Data

High-resolution numerical weather prediction (NWP) models such as the Weather Research and Forecasting (WRF) model with grid cell sizes between 2 and 14 km have great potential in contributing towards reasonably accurate meteorological parameters. The WRF model is a mesoscale numerical weather prediction model, suitable for research and operational forecasting [21]. The currently installed version in the MMD makes use of the ARW (Advanced Research WRF) solver, which is composed of several initialization programs for idealized and real-data simulations, and a numerical integration program. The model was designed to have three interactive nested domains with horizontal resolutions at 36, 12 and 4 km with the inner most domain covering the Peninsular Malaysia, Sabah and Sarawak [21]. This study used the model outputs from the highest spatial resolution of 4 km with initialization time 00 UTC. The WRF models output data are processed using the Grid Analysis and Display System (GrADS). GrADS is an interactive desktop tool that is used for easy access, manipulation, and visualization of earth science data. The data processed and retrieved from the system to be used in the study consist of temperature, relative humidity and wind speed.

Table 1. The location of the 20 rainfall stations included in this study.

	Station Name	Latitude	Longitude
1	Tanjung Malim	3.67691	101.52108
2	Kerling	3.58698	101.60368
3	Loji Air KKB	3.57199	101.66375
4	Ampang Pecah	3.54201	101.66375
5	Ulu Yam/Batang Kali	3.46707	101.63371
6	Kg Kalong Tengah	3.43709	101.66374
7	Rantau Panjang	3.40711	101.44602
8	Genting Sempah	3.36963	101.75382
9	Serendah	3.36215	101.60367
10	Teluk Penyamun	3.34712	101.26585
11	Air Terjun Sg Batu	3.33216	101.70126
12	Emp Batu	3.26472	101.68624
13	Emp Batu	3.26471	101.76131
14	Kuala Seleh	3.25721	101.76881
15	Empangan Genting Klang	3.23473	101.75379
16	TNB Ponsoon	3.20472	101.87388
17	Paya Jaras	3.19728	101.54362
18	Air Panas	3.18977	101.71625
19	Ldg Edinburgh	3.18229	101.63369
20	Bukit Antarabangsa	3.18227	101.7763



(a)

(b)

Figure 3. Doppler radar product (CAPPI) coverage over (a) Peninsular Malaysia (b) Klang River Basin

C. Doppler Radar Data

Radar rainfall data were collected from Terminal Doppler Radar at Kuala Lumpur International Airport (KLIA) which is situated in Bukit Tampoi, Dengkil, about 10 km to the north of KLIA. Figure 3 shows the images of Doppler Weather Radar product (CAPPI) produced by the Meteorological Station at KLIA . For the reflectivity data, 1 km CAPPI reflectivity data was used which may cover radius up to 120 km radius until 500 km radius. The observation area is around 50 km from the radar station and about 1 km above the ground.

IV. METHOD

In this research, the Kalman Filter technique was combined with a multivariate technique. It was developed by constructing a linear equation containing the entire data sample. All the data used was stated and applied into the least square method. The first hour of the weather parameter estimate was considered as the initial value. Figure 4 summarize the operation of Kalman Filter with time update and measurement update equation and noise covariance *Q* and *R*.

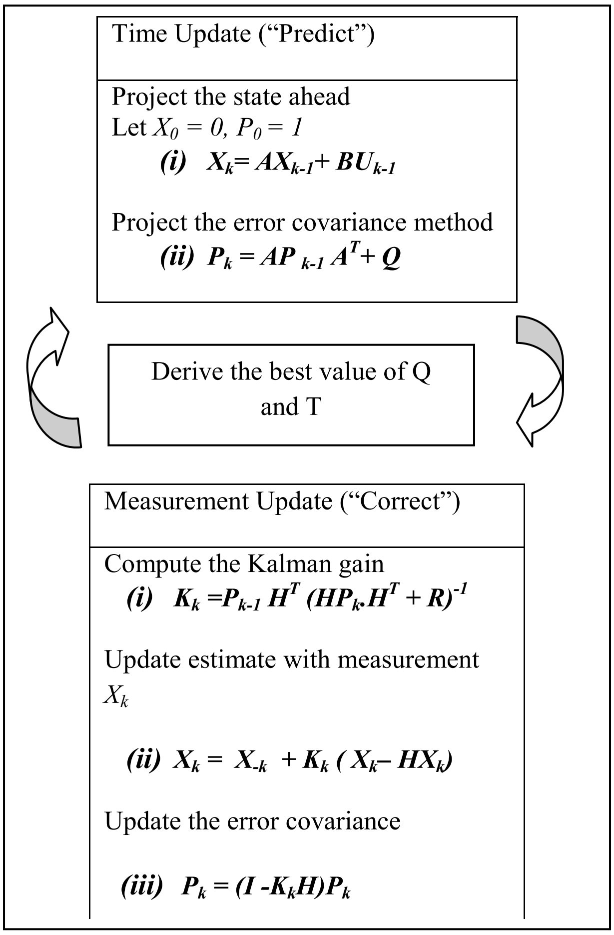


Figure 4. Operation of Kalman Filter

X_k is the state vector that needs to be estimated. A_k is the state transition model that is applied to the previous state X_{k-1}. B_k is the control-input model that is applied to the control vector U_{k-1}, which has been drawn by inserting the least square method,

$$U_k = a + x_1a_1 + x_2a_1 + x_3a_3 \quad (1)$$

where x_1 represented the hourly temperature reading while x_2 and x_3 represented hourly humidity and radar rainfall estimated. H represents the observational model that maps the true state space into the observed space. Q_k can be defined as the process noise covariance while R_k represents the measurement noise covariance. In this study Q_k and R_k were analyzed to minimize the error in radar rainfall reading. The measurement noise covariance R_k and the process noise covariance Q_k need to be defined and best value of need to be obtained to reduce error by tuning the filter parameters Q_k and R_k [10].

V. RESULTS

The gauged rainfall and radar data acquired were scrutinized and events were selected for Kalman Filter application with multivariate technique. The predicted radar rainfall values from the filtering process were plotted along the observed gauged rain values in a time series manner. Figure 5 until 10 illustrate the pattern of the time series predicted radar rain values versus observed gauged rain values. The selected events include light rain, moderate and heavy rain as categorized in Table 2.

Table 2. Rain category by the Drainage and Irrigation Department, Malaysia

Categorization of Rainfall Intensity: (depth in an hour)				
Category of Storm	Light	Moderate	Heavy	Very Heavy
Rainfall (mm)	1-10	11-30	31-60	>60

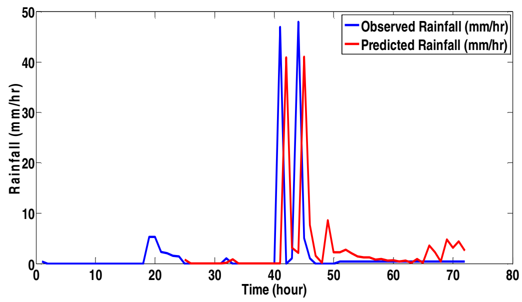


Figure 5. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 1-3 December, 2012 at Kerling Station – heavy rain

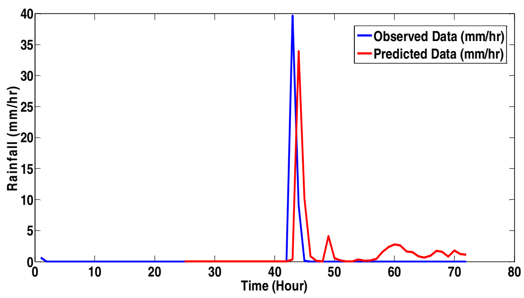


Figure 6. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 20-22 October, 2012 at Empangan Batu Station – heavy rain

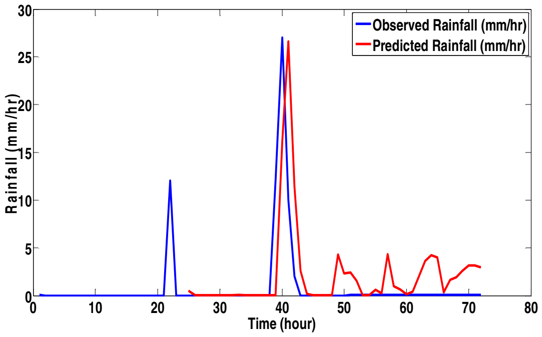


Figure 7. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 20-22 October, 2012 at TNB Ponsoon Station – moderate rain

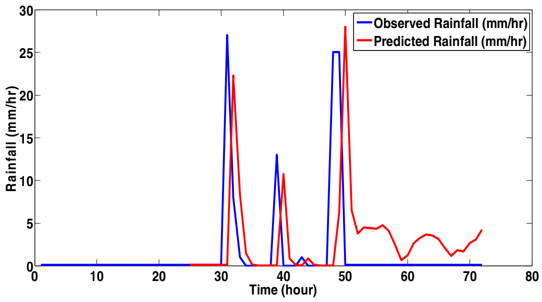


Figure 8. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 15-17 August, 2012 at Kg Sg Lui Station – moderate rain

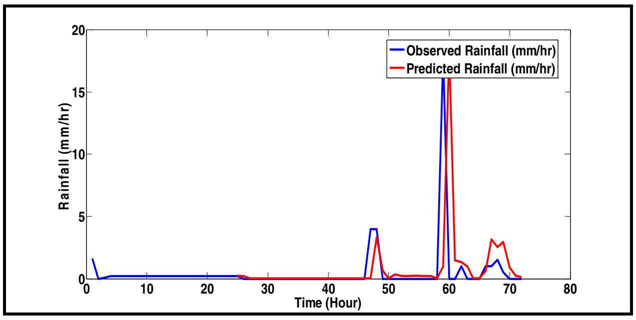


Figure 9. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 2-4 November, 2012 at Teluk Penyamun Station - light to moderate rain

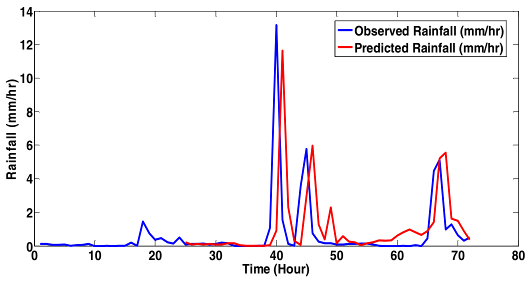


Figure 10. Time series of predicted radar rainfall with Kalman Filter versus observed gauged rainfall for events dated 1-3 December, 2012 at Serendah Station – light rain

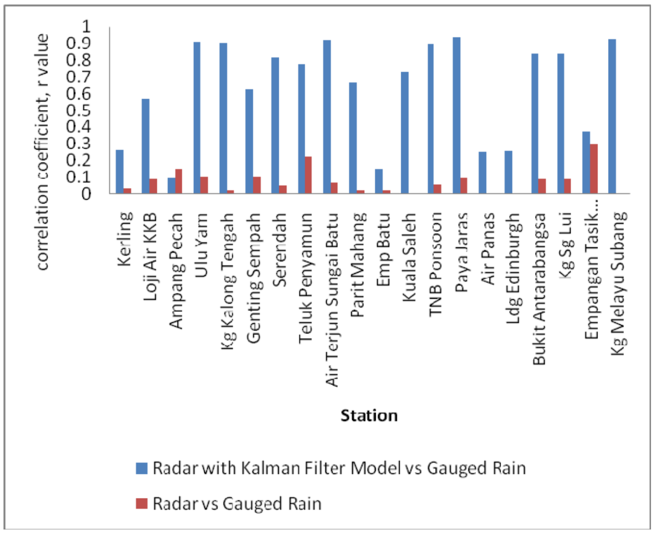


Figure 11. Correlation coefficient improvement after noise filtering of radar data for 3-days time series data

Filtering was done for various rainfall events for all the 20 stations. In general, the time series radar rainfall values are getting closer to the 'ground truth' or the observed gauged rainfall after the filtering process. Figure 11 summarized the improvement by showing the increase in correlation coefficient, r values after the application of Kalman Filter to the radar rainfall. The low value of r for the unfiltered data for continuous hourly 3-days time series data is due to the sensitivity to the hourly rainfall pattern within the 3 days duration. These unfiltered r correlation values are much less satisfactory than the event based radar-gauge correlation as in Figure 1. However the application of Kalman Filter has significantly improved the time-series prediction. For example, at Teluk Penyamun station, the r value improved to 0.77 after Kalman Filter process as compared to 0.23 without the filtering process.

VI. CONCLUSIONS AND RECOMMENDATION

The research work is an effort to improve radar rainfall estimates by technique of noise filtering and incorporate the the weather parameter factors affecting the rainfall development such as relative humidity and temperature. The weather parameter involved were retrieved from the NWP model products namely WRF. The forecasted weather parameter data from the WRF model become alternative to actual meteorological data that may not be easily available or measured at rainfall stations. Results indicated that the accuracy of radar rainfall estimates can be improved by using the Kalman Filter method with the multivariate technique involving the NWP model output.

The work of combining NWP data and radar rainfall will be enhanced further to attain quantitative rainfall forecast with reasonable accuracy for flood forecasting input.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of RIF grants (600-RMI/DANA5/3/RIF(112/2012)) from the Research Management Institute of Universiti Teknologi MARA. Special thanks to the Malaysian Meteorological Department (MMD), and the Department of Irrigation and Drainage (DID) for providing the data that has been used in this study. Appreciation also goes to the Flood Control Research Center, Faculty of Civil Engineering Universiti Teknologi MARA and the Faculty of Electrical Engineering, University of Malaya for their contributions.

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