Evaluation of Satellite Based Rainfall Estimation

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Abstract. Rainfall is one major source of water supply needed for most human activities encompassing agricultural activities to heavy industries. Therefore, a reliable and up to date approach shall always be required to accurately quantify rainfall precipitation. In Malaysia, there are three basic systems for providing rainfall measurements; which are conventional ground-based rain gauges, weather radar precipitation, and satellite-based precipitation. This study focused on data from Multi-Functional Transport Satellite (MTSAT-1R) and Terminal Doppler Weather Radar product for rainfall estimation in Malaysia. Both data were verified with the ground rain gauge data. Comparative analysis towards the data was taken based on daily and hourly approaches. Daily rainfall data were taken at Bukit Rajah, Batang Kali, Connaught Bridge, Petaling Jaya and Subang Jaya while hourly rainfall datasets were taken at Petaling Jaya and Subang Jaya. The satellite and radar data is processed using MTSAT HRIT and IRIS software respectively with the aid from Malaysian Meteorological Department (MMD). The correlation coefficient is used in this study to investigate the relationship between the satellite and radar with ground rain gauge data.

1. Introduction

Water is very important and vital for all people around the world. It is an important thing that is most needed for human life and activities. Therefore, we need to accurately quantify the rainfall estimation in order to preserve this natural resource. Nowadays, there are three basic systems for providing rainfall measurements which are conventional ground based rain gauges, weather radar precipitation, and satellite based precipitation. Weather Radar and Geostationary Meteorological Satellite can complement well with the traditional methods of meteorological data collection.

They also can effectively provide large scale and multi-temporal information for weather forecasting. This study is to investigate which method provides the best results for rainfall estimating between Terminal Doppler Weather Radar and Geostationary Meteorological Satellite data. Then both of the results will be verified together with rain gauge measurement.

The common method of rainfall for estimation purposes on the ground is using a rain gauge. Rain gauges, as the only direct measuring device of surface precipitation, are still counted as the most reliable source of precipitation information in hydrology. Rain gauges might be poor in capturing the instantaneous precipitation intensity, but the measurement error diminishes rapidly as the integration time increases [1].
Moreover due to the factor where the physical locations of gauge are nearby to the actual rainfall occurrences, thus it is able to provide higher accuracy estimation. The only drawback is that in order to attain high accuracy precipitation from rainfall gauges, it needs to be densely located within the area of interest. A gauge is often insufficient because of the high spatial and temporal variability of rainfall, especially in low-density gauge networks [2].

The conventional weather radar tends to underestimate rainfall compared to rain gauges [3]. However, due to their large coverage, high spatial resolution and temporal frequency, weather radars produce observations that adequately represent precipitation structure and evolution [1]. The drawbacks of the radar system include the multiplicative bias increases with rainfall intensity [4], radar beam blockage by obstacles, overshooting and partial beam filling, clutter and the attenuation of the radar signals [2].

However, the developments in radar technology including the switch from single to dual polarization has led to significant progress in terms of clutter suppression, hydrometeor classification and attenuation correction, greatly improving the accuracy of radar rainfall estimates [4]. Thus weather radar are ideal tools for monitoring and studying weather and climate processes, evaluating numerical simulations of precipitating cloud systems, and monitoring and forecasting hazardous precipitation events. They work at high spatial (~1 km) and high temporal resolution (10 min), providing four-dimensional information on the distribution of hydrometeors, precipitation intensity, and convective cloud dynamics [5].

The aim of this project is to investigate which is the best method of rainfall estimation between Terminal Doppler Weather Radar (TDR) and Satellite based precipitation. Rain gauge is a method that is used to provide rainfall measurement. It is available at most location covering the Peninsular Malaysia. Although the results provided are nearly accurate, they also face several problems such as no coverage for certain remote areas, variety in gauge design, experienced wind effect and the point measurement not representing the whole areas. Besides that, the costing for operating and maintaining large number of rain gauge to show spatial rainfall variability is quite expensive. Even though, rain gauge support temporal resolution but it causes a weakness in the quality of spatial resolution because the point measurement of the rain gauge did not representing the whole areas. Hence, weather radar and geostationary satellite that covers much larger areas has become the most attractive instruments for monitoring rainfall especially in an operational context.

Radar reflectivity is used to calculate the total rainfall. It can be used to estimate the distributions of precipitation amounts and could detect rain events, which would not have been detected by the rain gauges. Meanwhile, satellite measurement has two methods of observation, one is cloud top temperature and another one is cloud top brightness.

The analysis of precipitation data can be used to estimates average of rainfall of an area, to know the patterns and movements of individual storms, to study the occurrences of rainfall of different magnitude and to produce the estimation of the probable maximum precipitation [6]. Hence, using remote sensing tools, it offers an exact in spatial resolution and rainfall data by using both remote sensing and ground rain gauge data together. The usage of remote sensing technology nowadays could help to reduce the costing for providing spatial rainfall variability.

2. Data and Method

The study area for this project is based on the location of the selected rain gauge stations used for the study. The selected stations are Petaling Jaya, Subang Jaya, Bukit Rajah, Connaught Bridge, and Batang Kali.

The data was selected according to the area of interest which focuses on low and high coverage of rain gauge distribution. Types of data used in this study consisting of:

- Meteorological Satellite data obtained from MTSAT-1R satellite
- Radar data from RAIN1 and RAINN product using IRIS Software
- Rainfall data from the selected rain gauge station
Table 1 below shows the datasets includes daily and hourly data using three methods which are ground rain gauge data, satellite data and radar data from the selected location and selected date.

**Table 1. The Dataset of Rainfall Estimation Data**

| Daily Datasets | Rain Gauge Station | Date                          |
|----------------|--------------------|-------------------------------|
| Petaling Jaya  | 2,3,4,10 & 12 November 2013 |
| Subang Jaya    | 1,2,3,4, & 10 November 2013 |
| Bukit Rajah    | 2,4,10,12 & 13 November 2013 |
| Batang Kali    | 3,4,10,11 & 13 November 2013 |
| Connaugh Bridge| 1,2,4,12 & 13 November 2013 |

| Hourly Datasets | Rain Gauge Station | Date                  |
|-----------------|--------------------|-----------------------|
| Petaling Jaya   | 17 November 2013   |
| Subang Jaya     | 17 November 2013   |

The first step to obtain the rainfall estimation is selection of an appropriate region. Next is the selection of rain gauge stations in the study area. Then the data collection of the MTSAT-1R, radar, and rain gauge data is obtained from Malaysian Meteorological Department (HQ) at Petaling Jaya, Malaysia. The overall methodology flow chart can be seen in Figure 1.

The radar images were derived from the Terminal Doppler Weather Radar (TDR) located at Subang Jaya, Malaysia. For this study the CAPPI product from the IRIS software is used to estimate the rainfall predicted volume [7]. The CAPPI product is selected based on the selected date and time for this project studies. In this process, selecting product CAPPI is very important because the IRIS server need to load the data from database and generate the data for display or manipulation. From the CAPPI product only two products were used; the Hourly Rain Accumulation (RAIN1) and 24 Hours Rain Accumulation (RAINN). Figure 2 shows the flow of radar data processing.
The Multi-functional Transport Satellite (MTSAT-R) images were used for this study. The MTSAT-1R satellite located at longitude 140 degree. It has five spectral channels which four infrared channel and the last one is visible channels [6]. The MTSAT High Information Transmission (HRIT) Ingest Software is required to receive the MTSAT-1R images in HRIT raw data format. Then, the Satellite Ingest System will be configured automatically the project system on the ingested HRIT data by integrating the MTSAT HRIT Project execution software. The data of the rainfall then generated in RFF File (*.rff) and it after that it will be used in Lakseng MTSAT Browser Software to generate rainfall estimation product [8].

3. Results and Discussions
The final products for the MTSAT-1R satellite rainfall estimation are the daily and hourly rainfall value with their corresponding images. Figure 3 illustrates the example of MTSAT-1R satellite image product. The satellite rainfall data is determined based on the rainfall intensity estimation in (.rff) format. It has three components in the image to show the condition of a place whether it has a rainfall amount or not which are land, water and rainfall amount. Each of them is denoted by values 1, 2, and the amount of the rainfall rate itself respectively. The color of the cloud in the satellite image indicates the magnitude of the rainfall rate starting with the lowest rate with bluish color until the highest rate in reddish color.

Figure 2. Radar data processing.

Figure 3. The example of MTSAT-1R image.
Meanwhile, the final product for the radar rainfall estimation is the daily and hourly rainfall value with their corresponding images. Figure 3 illustrates the example of radar image product. The image shows the rainfall rate at height of 3 km above mean sea level as observed by Subang Weather Radar. The MYT in the radar image stands for Malaysian Time. The color scale on the right side of the radar image indicates the magnitude of the rainfall rate starting with the lowest rate with bluish color until highest rate in reddish color. The time of the radar image represents the time when the radar completes its scan. It will take about half an hour to generate the radar image. The radar rainfall estimation product for this study is RAIN1 (hourly data) and RAINN (daily data) product respectively.

![Radar Image Example](image)

**Figure 4.** The example of radar image.

To verify the MTSAT-1R and radar rainfall estimation amount, the verification process is done by comparing both methods with the actual hourly and daily data on the selected date and location that have been identified earlier in this study.

Figures 5 to 9 show the daily rainfall average over Bukit Rajah, Connaught Bridge, Batang Kali, Petaling Jaya & Subang Jaya respectively.

![Daily Rainfall Comparison](image)

**Figure 5.** Daily rainfall comparison in Bukit Rajah
Figure 6. Daily rainfall comparison in Connaught Bridge

Figure 7. Daily rainfall comparison in Batang kali
A cloud classification is carried out to classify whether the cloud shall cause a rain or not using split window techniques by MTSAT HRIT Sat Browser Software. Meanwhile RAIN1 and RAINN product from IRIS radar system is used to know the predicted volume of the precipitation in the cloud. This project investigates the relationship of brightness temperature and predicted volume of precipitation respectively together with rain gauge measurements. The correlation coefficient, r is used as indicators to test the accuracy of rainfall estimation [4]. Table 2 and 3 shows the correlation coefficient value for each daily and hourly datasets respectively.

From Table 2 and 3, it is clear that all the values of Pearson product-moment correlation coefficient (r) are positive. This shows that all of the data at each selected station on the selected date have relation to each other and the strength of linear dependence between the MTSAT-1R and radar accumulated estimation rainfall and actual accumulated rainfall from stations are strong as all the correlation coefficient (r) are in positive value and near to 1[9].
Table 2. The Dataset of Rainfall Estimation Data

| STATION       | MTSAT-1R | Radar |
|---------------|----------|-------|
|               | r        | r²    | r    | r²    |
| Petaling Jaya | 0.448    | 0.200 | 0.995| 0.991 |
| Subang Jaya   | 0.522    | 0.272 | 0.369| 0.136 |
| Bukit Rajah   | 0.945    | 0.892 | 0.160| 0.026 |
| Batang Kali   | 0.965    | 0.931 | 0.884| 0.782 |
| Connaught Bridge | 0.873  | 0.761 | 0.547| 0.299 |

Table 3. The Dataset of Rainfall Estimation Data

| STATION     | MTSAT-1R | Radar |
|-------------|----------|-------|
|             | r        | r²    | r    | r²    |
| Petaling Jaya | 0.955    | 0.912 | 0.998| 0.995 |
| Subang Jaya | 0.854    | 0.730 | 0.997| 0.994 |

It is also evident that both hourly and daily results of the analysed dataset produces the similar trends by observing the correlation regression values where both are near to positive values that indicates positive relationship between both variables. The highest positive correlations are at evident in the Petaling Jaya radar datasets for both hourly and daily rainfall precipitations.

The analysis of the relationship of MTSAT-1R and rain gauge, radar and rain gauge is simply done by creating a scatter plot graph. The estimated and observed data are plotted together in the same unit of measurement. The scatter graph on Figure 10 until Figure 19 shows the correlation coefficient of daily MTSAT-1R and Radar versus ground rain gauge data. The results are based on the selected date and location that have been identified earlier in this study.
Figure 10. The correlation coefficient of daily MTSAT-1R versus actual daily rainfall data in Bukit Rajah

Figure 11. The correlation coefficient of daily radar versus actual daily rainfall data in Bukit Rajah
Figure 12. The correlation coefficient of daily MTSAT-1R versus actual daily rainfall data in Connaught Bridge

![Graph showing correlation between daily MTSAT-1R and daily rain gauge rainfall estimation in Connaught Bridge. The equation is $y = 1.1168x + 4.4309$ with $R^2 = 0.7615$.](image1)

Figure 13. The correlation coefficient of daily radar versus actual daily rainfall data in Connaught Bridge

![Graph showing correlation between daily radar and daily rain gauge rainfall estimation in Connaught Bridge. The equation is $y = 3.2113x + 38.055$ with $R^2 = 0.2993$.](image2)
Figure 14. The correlation coefficient of daily MTSAT-1R versus actual daily rainfall data in Batang Kali

Figure 15. The correlation coefficient of daily radar versus actual daily rainfall data in Batang Kali
Figure 16. The correlation coefficient of daily MTSAT-1R versus actual daily rainfall data in Petaling Jaya.

Figure 17. The correlation coefficient of daily radar versus actual daily rainfall data in Petaling Jaya.
Figure 18. The correlation coefficient of daily MTSAT-1R versus actual daily rainfall data in Subang Jaya

The scatter graph on Figure 20 until Figure 23 gives the correlation coefficient of hourly MTSAT-1R and Radar versus ground rain gauge data. The results are based on the data on 17 March 2014 in Petaling Jaya and Subang jaya.
Figure 20. The correlation coefficient of hourly MTSAT-1R versus actual hourly rainfall data in Petaling Jaya

Figure 21. The correlation coefficient of hourly radar versus actual hourly rainfall data in Petaling Jaya
Figure 22. The correlation coefficient of hourly MTSAT-1R versus actual hourly rainfall data in Subang Jaya

The coefficient of determination ($r^2$) is useful because it gives the proportion of the variance of one variable that is predictable from the other variable. The coefficient of determination is such that $0 < r^2 < 1$, and denotes the strength of the linear association between $x$ and $y$ [9]. The coefficient of determination
represents the percentage of the data that is the closest to the line of best fit. For example, by referring to Figure 23 above, the correlation determination, $r^2 = 0.9908$, which means that 99% of the sample data in y satisfy the linear relationship between x and y in the whole sample. The coefficient of determination is a measure of how well the regression line represents the data. If the regression line passes exactly through every point on the scatter plot, it would be able to explain all of the variation. The further the line is away from the points, the less it is able to explain [4].

For the daily data, the result shows inconsistent result in the closeness between radar and satellite versus the rain gauge data. Then, for the hourly data, the event that happens on 17 March 2014 in both Subang Jaya and Petaling Jaya stations showed quite precise values between hourly rainfall estimation from Terminal Doppler Radar, MTSAT-1R Satellite and ground rain gauge. However, radar rainfall is much closer within the radar and rain gauge data value compared to MTSAT-1R data. This is because radar technology has the ability to detect cloud and precipitation structures in real time regional information [10]. Meanwhile, satellite product gives the result from the top of cloud brightness.

Based on all the results, it was found that the differences of the rainfall value between MTSAT-1R satellite data, radar data and rain gauge data happens because meteorological satellites data are capturing the cloud images from the cloud top. Sometimes satellite data have an inability to distinguish a cloud that contains rain and other cloud. The brightness temperature and rain rate does not occur at the exact time as the temporal resolution on the satellites data is not the same. Also, not all rainfall content falls to the ground, some of them get evaporated before they reach the ground and the clouds that cause rain may be moving to other places due to the wind flow factor. Moreover, radar data sometimes are missing due to the inability of the server system to support the previous data and that makes this study face several difficulties especially during the processing of the daily data because the data is not complete.

4. Conclusions

From this study, it can be concluded that a remote sensing application using satellite and radar in accessing rainfall could be fully used for weather forecasting and towards issuance of severe weather warning. The correlation coefficient is used in this study to investigate the relationship between the satellite and radar with ground rain gauge data. For the daily data, it could be concluded that, there was uncertainties in the closeness between radar and satellite versus the rain gauge data. Meanwhile for the hourly data, the results show that the Terminal Doppler Weather Radar was more reliable in estimating rainfall compares to MTSAT-1R. The relationship radar with ground based data on 17 March 2014 at Petaling Jaya show best correlation ($r$) value with $r$ equal to 0.998 and $r^2$ equal to 0.995. From the above conclusion, it is confirmed that all the study objectives are achieved.

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