

## Article

# A Novel Electromagnetic Wave Rain Gauge and Its Average Rainfall Estimation Method

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**Abstract:** It is essential to accurately estimate rainfall to predict and prevent hydrological disasters such as floods. In this paper, an electromagnetic wave rain gauge system and a method to estimate average rainfall using the system's multiple elevation observation data are presented. The compact electromagnetic wave rain gauge is a small-sized radar that performs very short-range observations using K-band dual-polarization technology. The method to estimate average rainfall is based on the concept of an average observation derived from multiple elevation scans with very short range and dual-polarization information. The proposed method was evaluated by comparing it with ground instruments, including a pit-gauge, tipping-bucket rain gauges, and a Parsivel disdrometer. The evaluation results demonstrated that the new methodology worked fairly well for various rainfall events.

**Keywords:** electromagnetic wave rain gauge; average rainfall estimation; K-band; dual-polarization; multiple elevation angle

## 1. Introduction

A reliable hydrological disaster forecast-warning system requires a more effective method to observe the spatial distribution of rainfall than can be achieved using conventional point-based rain gauges. Ground-based rain gauges have the advantage of providing continuous and direct measurements of rainfall. However, in areas where such gauges are absent, it is not possible to provide accurate information about the spatial distribution of rainfall [1–4]. In addition, rain gauge rainfall measurements tend to be underestimated in strong winds [5]. Weather radars have been suggested as an alternative to conventional ground-based rain gauges to estimate rainfall. They can cover a relatively large area and provide a high spatial and temporal sampling. In particular, the introduction of dual-polarization technology has facilitated rainfall estimations that are highly accurate [6–12]. A weather radar is the most commonly available, wide-area precipitation observation equipment, and is used to estimate rainfall intensity in conjunction with ground rain gauges. However, it is difficult to directly reflect rainfall at the ground level, as radar observations are conducted at elevations of several hundred meters to several kilometers above the ground. To address these issues, an electromagnetic wave rain gauge (EWRG) was developed. This is a new area rain gauge system that uses electromagnetic waves. To achieve the accuracy and spatial resolution of ground-level rainfall, the EWRG system operates at a low altitude, at a close range, and estimates the average rainfall with dual-polarization variables averaged over the observed area [13,14]. Note that micro-rain radar (MRR) can be another alternative for rainfall estimation using electromagnetic waves [15]. MRR is a vertical pointing FMCW system, while EWRG is a scanning dual-polarization system.

Typically, dual-polarization radar parameters, including reflectivity ( $Z_h$ ), differential reflectivity ( $Z_{dr}$ ), and the specific differential phase ( $K_{dp}$ ) are used either alone or in combination to estimate rainfall intensity. Representative quantitative precipitation estimation (QPE) algorithms for dual-polarization radar include those of the Joint Polarization Experiment (JPOLE) [7] and Colorado State University

(CSU) [9,12]. The radar-based rainfall estimation method calculates the rainfall intensity for each gate from the radar data. The rainfall estimation method, which calculates rainfall intensity values per gate, may be suitable for radar systems with relatively long distances. However, it may not be appropriate to apply this method to area average rainfall estimation using EWRG data with very short distances (for example, 1–2 km or less). Therefore, it is necessary to develop a method that can more accurately calculate the rainfall intensity value through the concept of average rainfall in a very close-range observation area. In this study, we developed a method for estimating the average rainfall intensity using multiple elevation observation data obtained from the dual-polarization EWRG. The average rainfall intensity of the observed area can be estimated using mean values per elevation angle of reflectivity and the specific differential phase of multiple elevations. The average rainfall of the EWRG is the amount of rainfall estimated using the mean values of the radar parameters for the area, and this varies depending on the observation range. In this study, average rainfall was based on an area of 3.14 km<sup>2</sup> and an EWRG observation projected radius of 1.0 km was assumed.

The remainder of this paper is organized as follows. In Section 2, the system specifications of the developed EWRG prototype and scan strategy are briefly described. Section 3 describes the proposed method used to estimate the average rainfall. In Section 4, the proposed areal average rainfall estimation method is applied to various rainfall events. Comparisons are made with the results of conventional ground-based equipment, and the results are discussed. Section 5 presents a summary and conclusions.

## 2. Description of the EWRG

### 2.1. EWRG Specifications

The EWRG developed in this study is an average rainfall estimation system that complements the conventional tipping bucket rain gauge. It is a compact, integrated system that combines a transmitter, receiver, and a data collection system into two assemblies (Figure 1). The system uses dual-polarization technology and operates at the K band frequency. The transmitter/receiver generates a linear frequency modulation (LFM) signal with a peak power of 4 W per channel (H/V). The parabolic dish antenna had a diameter of 50 cm and a beamwidth of 1.6°.

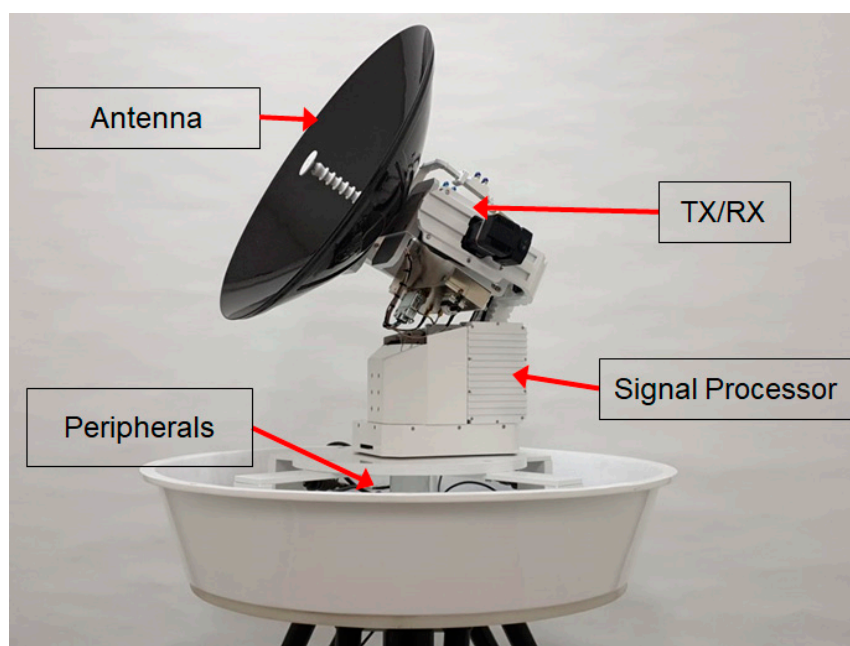


Figure 1. A prototype electromagnetic wave rain gauge (EWRG).

The system block diagram is shown in Figure 2. The intermediate frequency (IF) signals of the horizontal and vertical channels received from the transmitter/receiver of the EWRG were sampled by an analog-to-digital converter (ADC) and then converted to digital signals. They then undergo a digital down converter (DDC) and pulse compression process and are converted into I/Q data. The various observation variables are calculated from the I/Q data, and the final output is transferred to the operation control device via Ethernet. The observation variables are reflectivity ( $Z$ ), radial velocity ( $V$ ), spectral width ( $W$ ) for each polarization, differential reflectivity ( $Z_{dr}$ ), correlation coefficient ( $\rho_{hv}$ ), and differential propagation phase ( $\Phi_{dp}$ ). Table 1 presents the specifications of the EWRG in detail.

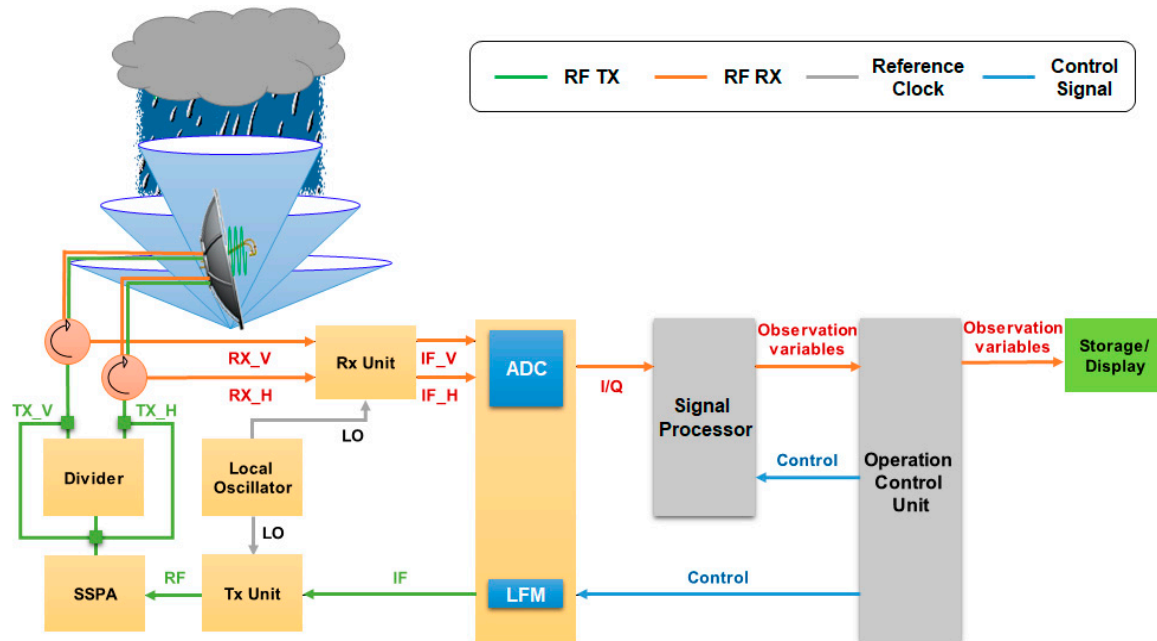


Figure 2. EWRG prototype block diagram.

Table 1. Specifications of EWRG prototype.

| Item                        | Specification                        |
|-----------------------------|--------------------------------------|
| Operating frequency         | 24.15 GHz                            |
| Polarization                | Simultaneous (H/V)                   |
| Transmit peak power         | 4 W/channel (H/V)                    |
| Antenna shape               | Parabolic reflector (Carbon)         |
| Antenna diameter            | 50 cm                                |
| Beamwidth                   | 1.6 degree                           |
| Gain                        | 40 dBi                               |
| Voltage standing wave ratio | <1.5:1                               |
| Driving range (deg)         | 0–360 (Azimuth), –2– +92 (Elevation) |
| Effective observation range | 1.5 km                               |
| Waveform                    | 5 MHz (LFM pulse)                    |
| Pulse width                 | 1 $\mu$ s                            |
| Pulse repetition frequency  | 10,000 Hz                            |
| Range resolution            | 7.5 m                                |

## 2.2. EWRG Scan Strategy

Given the complexity of rainfall and the vertical variability of the radar parameters, it is important to obtain low-altitude observations to reduce uncertainties in rainfall estimation [8]. However, if systems are installed close to the ground, data can be affected by topographic features, such as mountains or buildings. Generally, EWRG is installed close to the ground. Therefore, a specific scan strategy is required to minimize ground clutter effects and to enable rainfall observations to be conducted at a low altitude depending on the installation surroundings. Figure 3 shows the current scan strategy of the EWRG. Projections of each scan are shown in the XY plane. The system conducts scans at elevations of  $30^\circ$  (blue),  $45^\circ$  (red), and  $60^\circ$  (cyan) to estimate average rainfall. The lowest altitude,  $30^\circ$ , was chosen to keep the rainfall estimates consistent across multiple test sites, and  $45^\circ$  and  $60^\circ$  were chosen arbitrarily. Note that the scan strategy can be changed according to the installation location and surrounding environment.

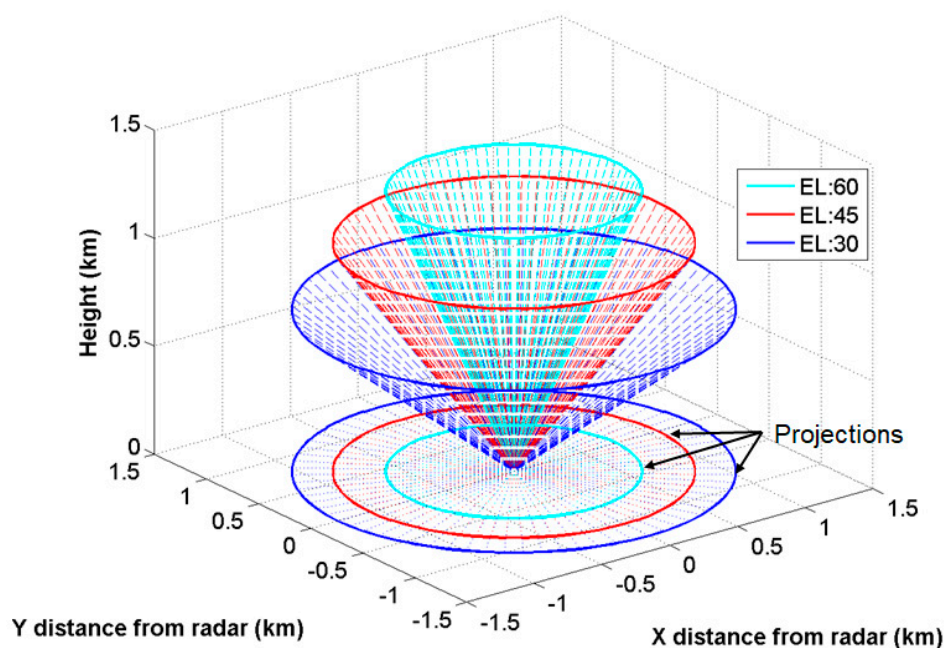


Figure 3. EWRG scan strategy. Blue, red, and cyan contours represent  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$  scans, respectively.

## 3. EWRG Average Rainfall Estimation Method

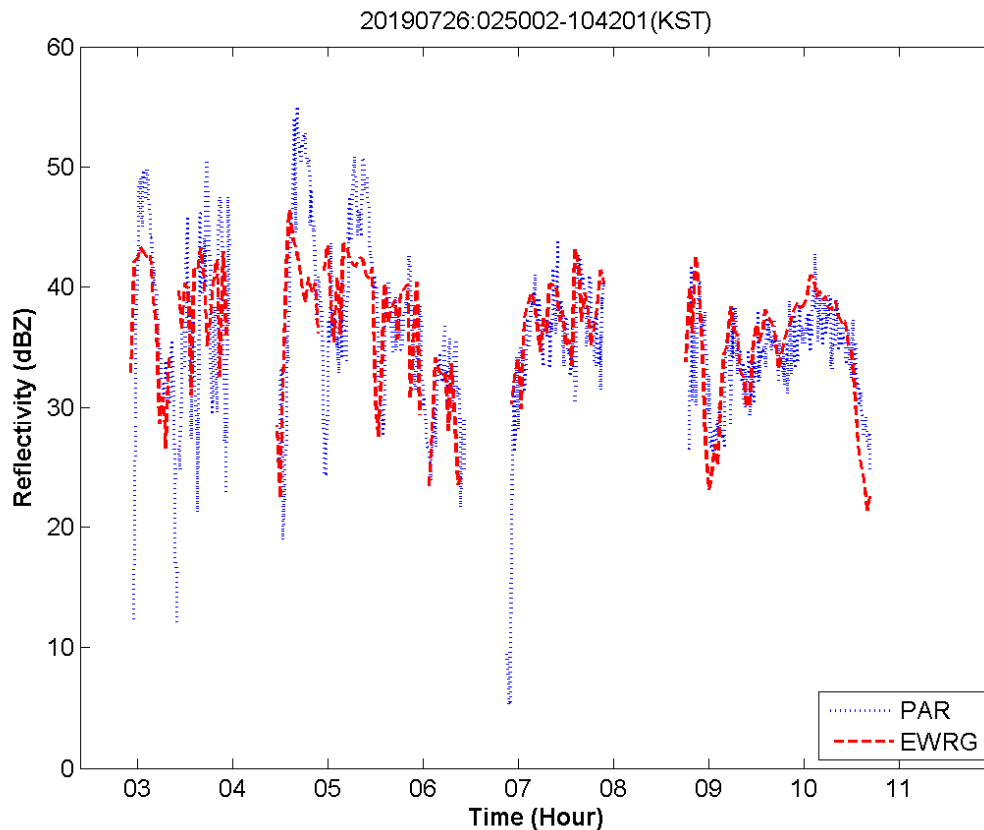
The EWRG rainfall estimation method is based on the assumption that the spatial variability of rainfall distribution can be small at very close distances. The proposed method uses the average values of multiple elevation scan data in a very short range. At higher frequencies, such as the K band,  $K_{dp}$  can be an important parameter for rainfall estimation because it is not affected by propagation attenuation and the absolute calibration error of the radar system [16,17]. However, if the echo is weak,  $K_{dp}$  is very small and can fluctuate. In this case,  $Z_h$  can be better than  $K_{dp}$ . Therefore, the proposed method uses  $Z_h$  or  $K_{dp}$ , depending on the decision criteria described in Section 3.2.

### 3.1. Reflectivity Calibration

$K_{dp}$  is immune to system bias, but  $Z_h$  is strongly affected by system errors. Therefore,  $Z_h$  calibration is necessary for the estimation of rainfall. In this study, we used a conventional method to monitor absolute calibration using a direct comparison of EWRG data and disdrometer measurements [18,19]. Observed  $Z_h$  values were compared with  $Z_h$  values retrieved from Parsivel data during a weak rain period (averaged observed  $Z_h < 35$  dBZ). EWRG bias was then obtained at the best-matched bias value. Figure 4 shows an example of the comparison results of EWRG and Parsivel reflectivity after



$Z_h$  calibration. As can be seen in the figure, the EWRG  $Z_h$  peak is much smaller than Parsivel (by approximately 4–6 h) may be due to the attenuation of the radome and path. Note that the reason for selecting data during a period of weak rainfall is to minimize the impact of radome and path attenuation. The locations of Parsivel and EWRG were co-located at the Geoje field test site, and the Parsivel at the Yeoncheon site was located about 700 m away from the EWRG (see Chapter 4 for detailed layout of test sites).



**Figure 4.** An example of  $Z_h$  comparison results of EWRG and Parsivel after  $Z_h$  calibration.

### 3.2. EWRG Average Rainfall Estimation Procedure

The detailed process used to estimate the average rainfall is shown in Figure 5. The method consists of five main steps. (i) For inputs,  $Z_h$  and  $\Phi_{dp}$ , as the multiple elevation scan data of the dual-polarization radar observing a very short distance, were used. The input scan observation data are observation variables obtained at elevation angles of 30°, 45°, and 60°:  $Z_h(30)$ ,  $Z_h(45)$ ,  $Z_h(60)$ ,  $\Phi_{dp}(30)$ ,  $\Phi_{dp}(45)$ , and  $\Phi_{dp}(60)$ , respectively. (ii) Next, the mean  $K_{dp}$  ( $\langle K_{dp} \rangle$ ) for each elevation was retrieved from  $\Phi_{dp}$ . The  $\langle K_{dp} \rangle$  retrieval process is illustrated in Figure 6.  $\Phi_{dp}$  were averaged, and then  $\langle K_{dp} \rangle$  was calculated from a slope of averaged  $\langle \Phi_{dp} \rangle$  as  $\langle K_{dp} \rangle = \frac{\Delta \langle \Phi_{dp}(r) \rangle}{2 \cdot \Delta r}$ . (iii) Mean  $Z_h$  ( $\langle Z_h \rangle$ ) for each elevation was obtained using  $Z_h$  scan data; (iv) the multiple elevation means of  $Z_h$  and  $K_{dp}$  ( $\mu(Z_h)$  and  $\mu(K_{dp})$ ) were calculated using  $\langle Z_h \rangle$  and  $\langle K_{dp} \rangle$  for each elevation; (v) finally, according to conditions, the average rainfall intensity was estimated. In this study,  $\mu(Z_h)$  of 35 dBZ and  $\mu(K_{dp})$  of 0.2°/km were used as threshold values. Note that in this study, attenuation correction was not applied for  $Z_h$ .

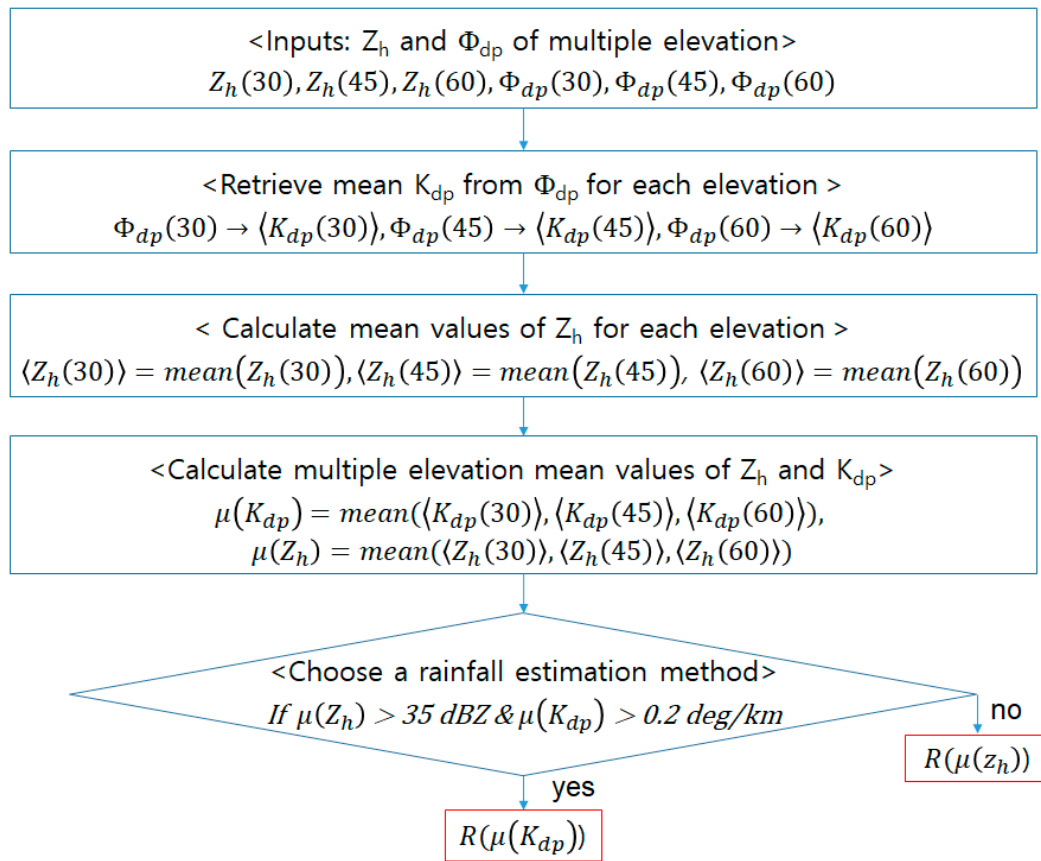


Figure 5. Flowchart showing the process for estimating average rainfall of the EWRC.

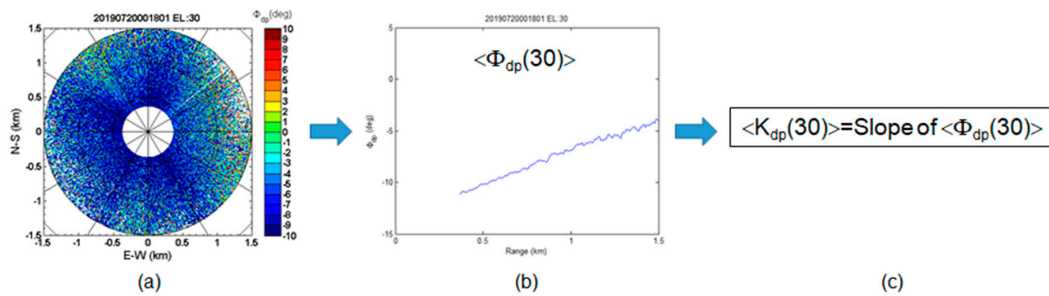


Figure 6. An example of mean  $K_{dp}$  ( $\langle K_{dp} \rangle$ ) retrieval from  $\Phi_{dp}$  scan. (a)  $\Phi_{dp}$  scan, (b) averaged  $\Phi_{dp}$  ( $\langle \Phi_{dp} \rangle$ ), (c) mean  $K_{dp}$  ( $\langle K_{dp} \rangle$ ).

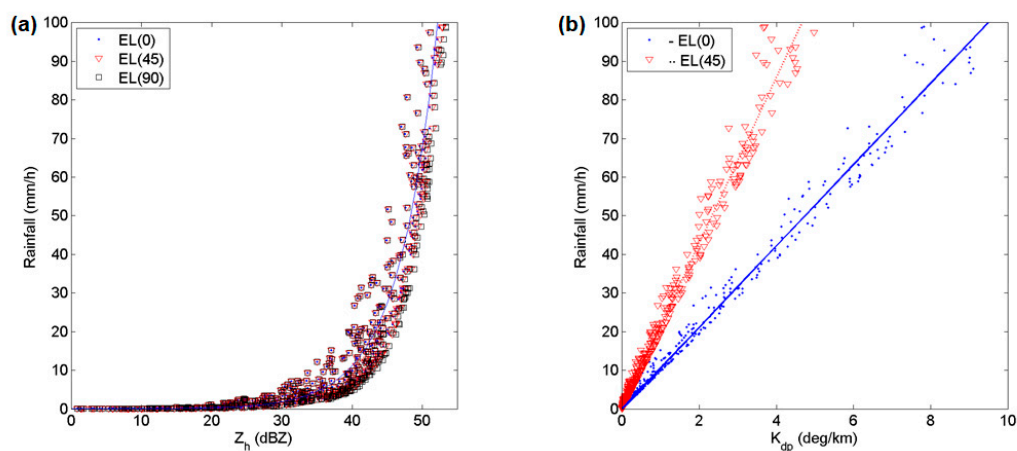
The rainfall estimation equations using reflectivity and specific differential phase are as follows:

$$R(\mu(Z_h)) = a(\mu(Z_h))^b \quad (1)$$

$$R(\mu(K_{dp})) = c(\mu(K_{dp})) \quad (2)$$

where  $Z_h$  ( $\text{mm}^6 \text{m}^{-3}$ ) is the reflectivity factor at horizontal polarization. Parameters  $a$ ,  $b$ , and  $c$  were obtained by scattering simulation using the shape model proposed by Bringi et al. [20], which is a combination of the Andsager et al. [21] and the Beard and Chuang [22] model at a temperature of 15 °C. The scatter plots of  $Z_h$  versus rainfall and  $K_{dp}$  versus rainfall for different elevations are shown in Figure 7. From the figures, it can be seen that  $Z_h$  does not change significantly with elevation at which  $K_{dp}$  varies significantly. In this study,  $a = 0.001$ ,  $b = 0.78$ , and  $c = 21.4$  were used for a frequency of 24 GHz and at an observation elevation of 45°. By assuming symmetry of scan elevations, parameters

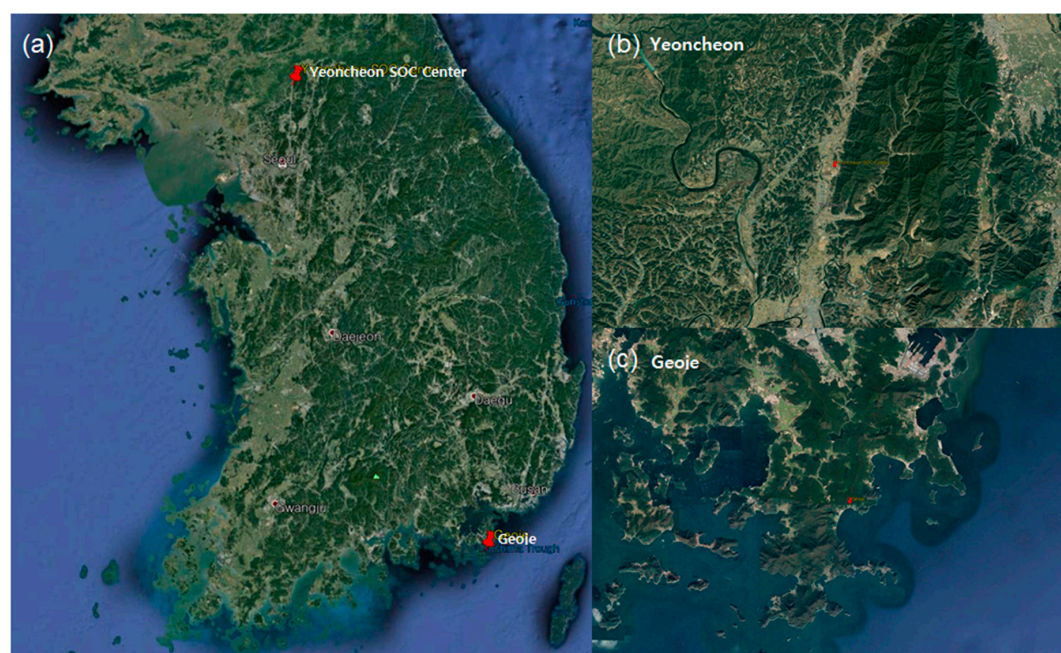
of only middle elevation are used. Note that if the scan strategy is changed, especially parameter  $c$ , must be adjusted.



**Figure 7.** Scatter plots of (a)  $Z_h$  versus rainfall, and (b)  $K_{dp}$  versus rainfall according to elevation.

#### 4. Evaluation of EWRG Average Rainfall Estimation and Discussion

To test the EWRG, field tests for several rainfall events were conducted at multiple locations. In this paper, two main rainfall events (occurring on 17–20 July 2019 at Geoje, and on 26 July 2019 at Yeoncheon) were analyzed. A variety of ground instruments (conventional tipping bucket rain gauges, Parsivel disdrometers, and a pit-gauge) were used to evaluate the average rainfall estimation. A well-known problem associated with Parsivel is the underestimation of rainfall, especially during heavy rains. For this reason, Parsivel rainfall data were used only for qualitative evaluation in this study. Figure 8 shows the locations of the two main sites. The Geoje test site (approximately 30 m above sea level) is surrounded by the sea to the south and mountains to the north, and the Yeoncheon site (about 77 m above sea level) is located in a valley.



**Figure 8.** Configuration of the location of the two main test sites. (a) Sites location on South Korea map and detailed location of (b) Yeoncheon and (c) Geoje.



#### 4.1. EWRG Field Test (Geoje)

Due to the influence of Typhoon Danas, heavy rain occurred in the southern part of the Korean Peninsula, from 17 to 20 July 2019. To evaluate the estimation of EWRG average rainfall, two tipping bucket rain gauges and one Parsivel disdrometer were installed near the EWRG. The layout of the EWRG test site is shown in Figure 9.

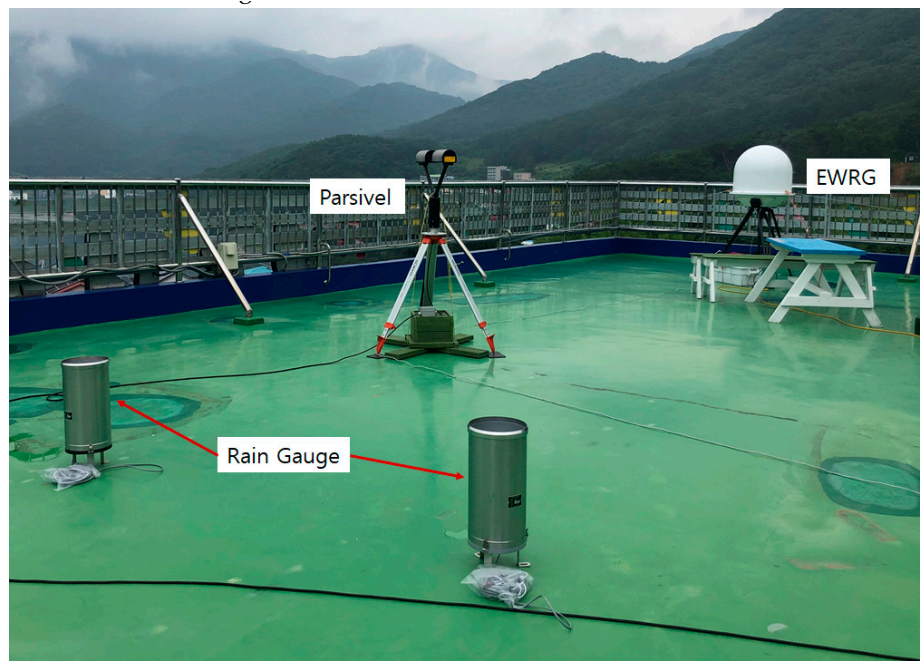


Figure 9. Layout of the EWRG comparative test site at Geoje.

An example of the EWRG data obtained at 23:33:49 on 17 July 2019, is depicted in Figure 10 (where reflectivity, the correlation coefficient, and the differential phase shift are represented from left to right). The significant reduction of  $Z_h$  and  $\rho_{hv}$  presented in the figure with the height-range is due to heavy rain attenuation.

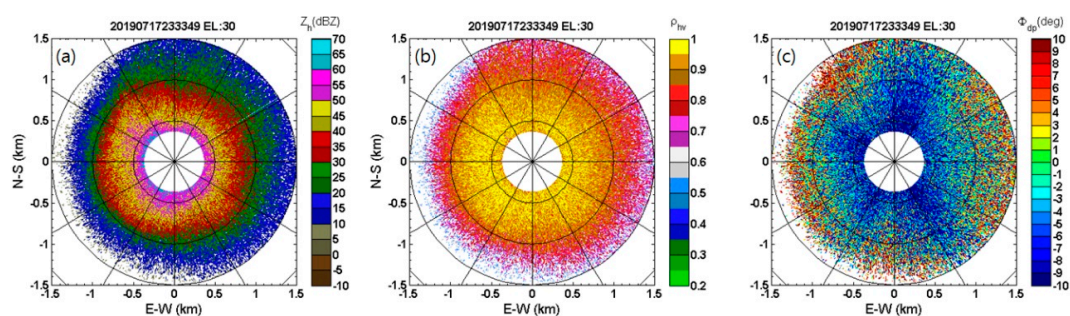
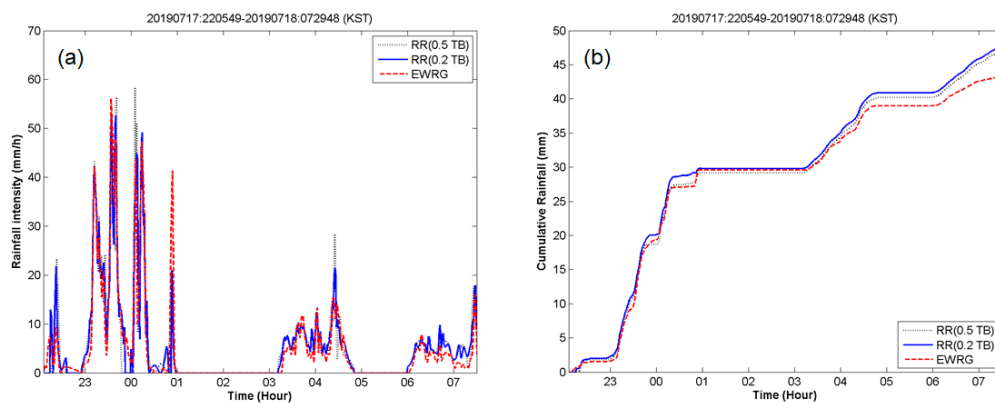


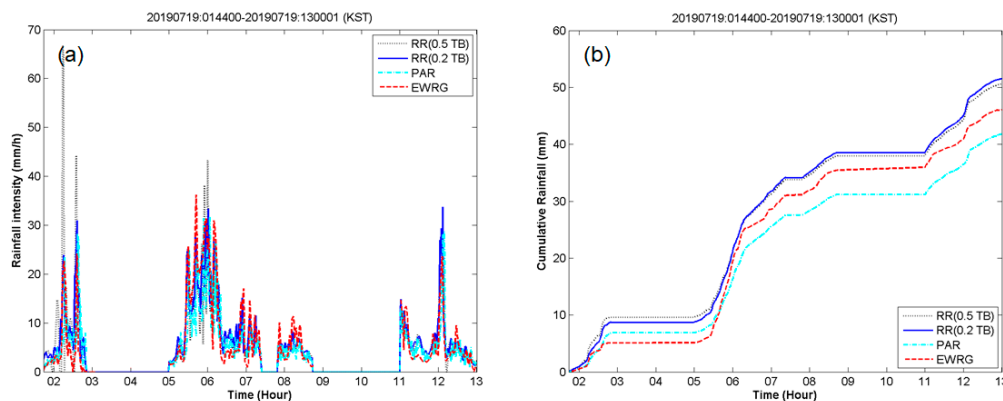
Figure 10. Rainfall observation image obtained using the EWRG (2019/07/17 23:33:49, Geoje), (a) Reflectivity ( $Z_h$ ); (b) Correlation Coefficient ( $\rho_{hv}$ ); and (c) Differential Phase Shift ( $\Phi_{dp}$ ).

For a detailed analysis of the rainfall event that occurred on 17–20 July 2019, the event was further classified into three separate events, according to the time of occurrence. The first was a very heavy rainfall event that occurred from 22:05 LST on 17 July 2019, to 07:29 LST on 18 July. The second event occurred from 01:44 to 13:00 on 19 July 2019, and the third occurred from 23:10 on 2019/07/19 to 06:10 on 2019/07/20. Figure 11 shows the results of a comparative analysis of the first event. The instantaneous average rainfall intensity (mm/h) estimated by EWRG and rainfall from the rain gauge are shown in Figure 11a, and Figure 11b shows a comparison of cumulative rainfall (mm). The comparative

analysis of events 2 and 3 are shown in Figures 12 and 13, respectively. Figures 12a and 13a show the instantaneous average rainfall intensity (mm/h) estimated by the EWRG and rain gauge, and Figures 12b and 13b show a comparison of cumulative rainfall (mm). It is of note here that the EWRG rainfall is the areal-averaged rainfall, whereas that of the rain gauges is point rainfall. Figures 11 and 12 show that there is little difference between EWRG-derived rainfall and rain gauge rainfall. However, for the event occurring on 20 July (Figure 13), there is an error of about 20% between EWRG and rain gauge rainfalls. These errors are considered to be due to the systemic limitation of EWRG and the spatiotemporal variability of rainfall. This system limitation is caused by the high-minimum detectable signal (MDS) due to the low transmit power and errors in the reflectivity calibration. During heavy rain,  $K_{dp}$  is not significantly affected by these factors, but during weak rainfall,  $Z_h$  can be greatly affected. For these reasons, the current EWRG prototype tends to underestimate weak rainfall.



**Figure 11.** Comparison between rainfall obtained by the EWRG and rain gauges for event 1. (a) EWRG average rainfall (mm/h) and rain gauge rainfall (mm/h); (b) cumulative EWRG average rainfall (mm) and cumulative rain gauge rainfall (mm). The red dotted line is the average rainfall of the EWRG, and the solid blue line and the black dotted line are rainfall measured by the tipping bucket rain gauges (0.2, 0.5), respectively.



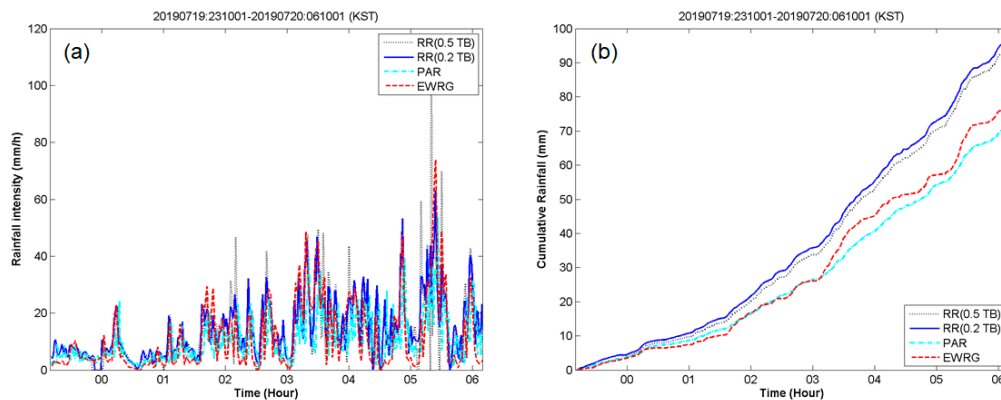
**Figure 12.** Comparison between rainfall obtained by the EWRG and rain gauges for event 2. (a) EWRG average rainfall (mm/h) and rain gauge rainfall (mm/h); (b) cumulative EWRG average rainfall (mm) and cumulative rain gauge rainfall (mm). The red dotted line represents the average rainfall of the EWRG prototype; the solid blue line and the black dotted line represent rainfall observed by the tipping bucket rain gauges (0.2, 0.5), and the light blue dashed line represents rainfall from the Parsivel disdrometer.

#### 4.2. EWRG Field Test (Yeoncheon)

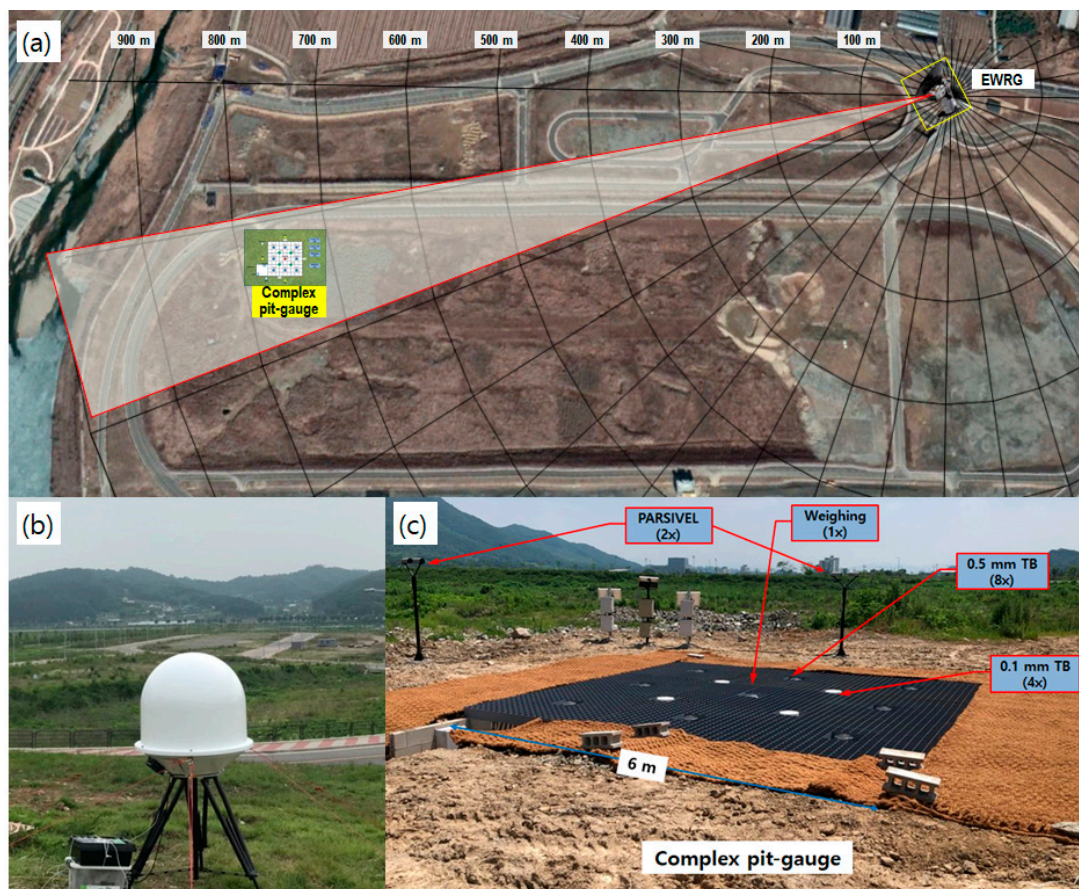
To evaluate the EWRG's performance, a testbed was established at the Yeoncheon SOC Demonstration Research Center of the Korea Institute of Civil Engineering and Building Technology. In addition to using a typical tipping bucket rain gauge and Parsivel disdrometer, a pit-gauge was



installed to obtain more accurate ground rainfall observations at the site. The layout of the comparison testbed (complex pit-gauge and EWRG) established in the Yeoncheon SOC Demonstration Research Center is depicted in Figure 14.

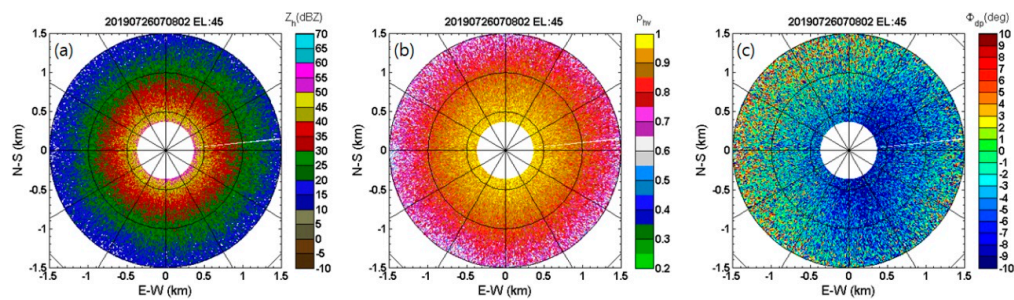


**Figure 13.** Comparison between rainfall obtained by the EWRG and rain gauges for event 3. (a) EWRG average rainfall (mm/h) and rain gauge rainfall (mm/h); (b) cumulative EWRG average rainfall (mm) and cumulative rain gauge rainfall (mm). The red dotted line represents the average rainfall of the EWRG prototype; the solid blue line and the black dotted line represent rainfall observed by the tipping bucket rain gauges (0.2, 0.5), and the light blue dashed line represents rainfall from the Parsivel disdrometer.

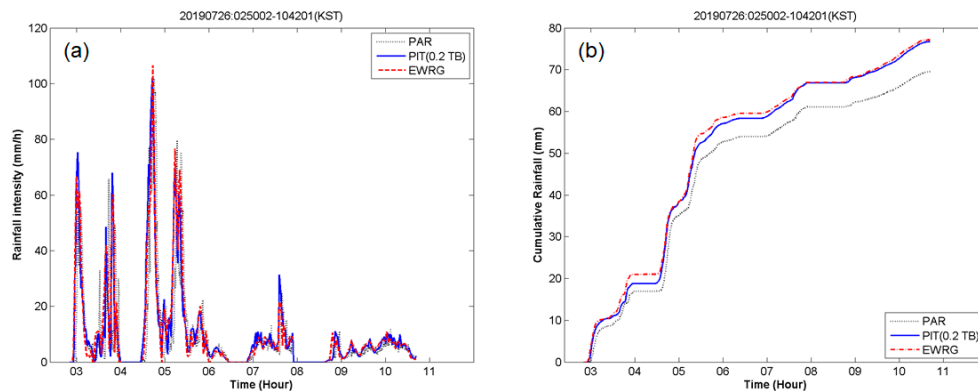


**Figure 14.** EWRG testbed at Yeoncheon SOC center. (a) Layout of the EWRG and complex pit-gauge; (b) EWRG installation; (c) Pit-Gauge and Parcivel installation.

On 26 July 2019, heavy rain (event 4), caused by a strong seasonal rain front, hit the central and northern parts of the Korean Peninsula, causing a downpour exceeding 100 mm/h. EWRG observation images taken at 07:08 on 26 July 2019, are shown in Figure 15 (from left to right: reflectivity, correlation coefficient, and differential phase shift). Figure 16a shows the instantaneous average rainfall intensity (mm/h) estimated by the EWRG and the rainfall intensity obtained by the ground instruments, and Figure 16b compares the cumulative rainfall (mm). In this figure, a comparison of the results of the pit-gauge (installed approximately 600 m from EWRG) and the EWRG show that, for this event, the average rainfall estimates of the EWRG were almost identical to the rainfall measured at the pit-gauge. However, as with the Geoje event, the observation results for this event demonstrated that the rainfall intensity estimation of the Parsivel disdrometer tends to be slightly underestimated.



**Figure 15.** Rainfall observation image of EWRG (2019/07/26 07:08:02, Yeoncheon). (a) Reflectivity ( $Z_h$ ); (b) Correlation Coefficient ( $\rho_{hv}$ ); (c) Differential Phase Shift ( $\Phi_{dp}$ ).



**Figure 16.** Comparison between results obtained for event 4: (a) EWRG average rainfall (mm/h) and rain gauge rainfall (mm/h); (b) cumulative EWRG average rainfall (mm) and cumulative rain gauge rainfall (mm). The red dotted line shows the average rainfall obtained by the EWRG, and the solid blue line and the black dotted line indicate rainfall measured by the pit-gauge and Parsivel disdrometer, respectively.

#### 4.3. Comprehensive Analysis

We conducted a comparative analysis between the EWRG average rainfall estimates and the data obtained from several ground instruments. Both rainfall events analyzed in this study were heavy, with instantaneous rainfall intensities of 30–100 mm/h, which are suitable for analyzing the performance of the EWRG and for determining whether it could be used to assist in the prevention of hydrological disasters. The errors between the total cumulative average rainfalls obtained by the EWRG and the ground rain gauge are summarized in Table 2.

The error used in the analysis was calculated as follows:

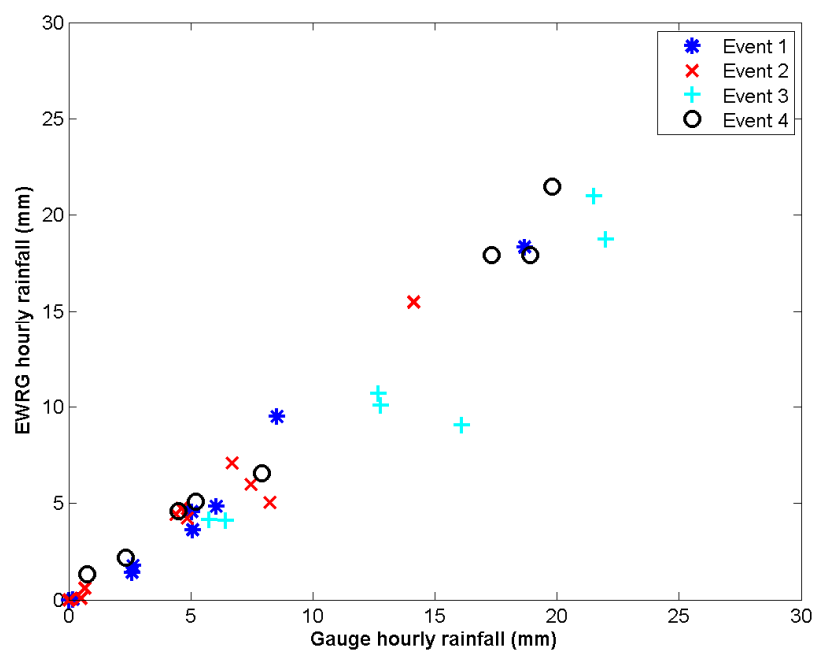
$$\text{Error}(\%) = \frac{(\text{ER} - \text{GR})}{\text{GR}} \times 100 \quad (3)$$

where ER represents the EWRG total cumulative rainfall and GR is rain gauge total cumulative rainfall.

For further evaluation, hourly rainfall between the rain gauge and EWRG was compared. The comparison results are shown in Figure 17 and Table 3. Figure 17 shows a scatterplot of gauge hourly rainfall versus EWRG hourly rainfall for all events.

**Table 2.** Error comparison of total cumulative rainfall between the EWRG and ground-based equipment (Pit-Gauge, Tipping gauge).

| Event | Pit-Gauge (mm) | Tipping Gauge (0.2) (mm) | EWRG (mm) | Error (%) |
|-------|----------------|--------------------------|-----------|-----------|
| 1     | -              | 48.9                     | 44.2      | −9.6      |
| 2     | -              | 51.9                     | 46.1      | −11.2     |
| 3     | -              | 96.4                     | 76.2      | −21.0     |
| 4     | 76.7           | -                        | 77.2      | 0.7       |



**Figure 17.** Scatterplot of hourly rainfall of EWRG and rain gauge for all events.

**Table 3.** Comparison results of hourly rainfall between the EWRG and ground-based equipment (Pit-Gauge, Tipping gauge).

| Event | NAME   | CORR   | RMSE |
|-------|--------|--------|------|
| 1     | −13.48 | 99.20  | 0.93 |
| 2     | −15.04 | 95.72  | 1.30 |
| 3     | −19.94 | 95.01  | 3.37 |
| 4     | 7.17   | 99.35  | 0.88 |
| All   | 14.30  | −96.90 | 1.83 |

For quantitative analysis, normalized mean absolute error (NMAE), Pearson correlation coefficient (CORR), and root-mean-square error (RMSE) of the rain gauge hourly measurements and EWRG average rainfall for four events were calculated as

$$\text{NMAE} = \frac{\langle |ER - GR| \rangle}{\langle GR \rangle} \times 100 \quad (4)$$

$$\text{CORR} = \frac{\sum[(\text{ER} - \langle \text{ER} \rangle)(\text{GR} - \langle \text{GR} \rangle)]}{\sqrt{\sum(\text{ER} - \langle \text{ER} \rangle)^2} \sqrt{\sum(\text{GR} - \langle \text{GR} \rangle)^2}} \times 100 \quad (5)$$

$$\text{RMSE} = \sqrt{\langle (\text{ER} - \text{GR})^2 \rangle} \quad (6)$$

where the angle brackets mean sample average.

The NMAE, CORR, and RMSE results for each of the events as well as for all events are shown in Table 3. The analysis shows that NMAE, CORR, and RMSE for the hourly rainfall of the four events are −14.3%, 96.9, and 1.83, respectively. From Figure 17 and Tables 2 and 3, it is evident that the proposed method produces reasonable results compared to the ground rain gauges.

## 5. Summary and Conclusions

EWRG is a new concept of an electromagnetic-based rain gauge system that measures average rainfall over a very short distance, aiming to complement the conventional tipping bucket rain gauge in terms of area coverage. In this study, we developed a method for estimating average rainfall using multiple elevation observation data obtained from the EWRG. The EWRG measures rainfall at a low altitude close to the ground and provides an average spatial cover with a projected radius of 1.0 km (3.14 km<sup>2</sup>), which represents an enhanced areal average. The proposed method was developed based on the assumption that the spatiotemporal variation of rainfall distribution is low, owing to the very short observation range and scan time of the EWRG.

In addition, the performance of the novel EWRG was compared with the results obtained from a conventional rain gauge and Parsivel disdrometer at several locations in Korea. In this study, four rainfall events from two main test sites (Geoje and Yeoncheon) were analyzed. The total cumulative average rainfall estimation results from the EWRG were within 10% (on average) of those obtained from conventional ground rain gauge equipment, which verified its ability to measure rainfall. In addition, the comparison of the hourly rainfall of the EWRG and ground rain gauge shows that the rainfall estimation of EWRG is relatively accurate in terms of NAME, CORR, and RMSE.

By applying the EWRG and rainfall estimation method developed in this study, it is possible to obtain accurate measurements of rainfall over a small area. Therefore, we conclude that the proposed method is suitable for use as a new method for measuring rainfall, providing an equivalent performance (in terms of accuracy) to that of a conventional rain gauge and disdrometer. Rain gauges and EWRG have their pros and cons. It cannot be said that EWRG can completely replace a rain gauge, especially in the case of weak rainfall. However, this EWRG system can be used more effectively in mountainous or urban areas with high rainfall spatial variability for hydrological purposes.

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