Validation of Composite Polarimetric Parameters and Rainfall Amounts from an X-band Polarimetric Radar Network in the Tokyo Metropolitan Area

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1. Introduction

Dual-polarized weather radar provides valuable data for hydrological and meteorological studies, including quantitative rainfall amounts, raindrop size distributions (DSD), hydrometeor types, and information regarding the microphysical processes that take place within precipitation systems (Zrnić and Ryzhkov 1999; Bringi and Chandrasekar 2001; Gorgucci et al., 2002). Estimates of rainfall amounts having a high temporal and spatial resolution are especially important if we are to improve the accuracy and efficacy of nowcasting, water resource management, and warning systems for urban disasters.

Quantitative precipitation estimation (QPE) using X-band (wavelength: 3 cm) dual-polarized radars has received recent attention because it has several advantages over alternative approaches. These include a finer resolution (despite the smaller antennae), easier mobility for the same beam widths, and lower costs compared with longer wavelength radar (C- and S-band). Moreover, the specific differential phase \( K_{dp} \) is much larger in the X-band than at longer wavelengths for a given rainfall rate (Matrosov et al., 1999; Chandrasekar et al., 2002; Maki et al., 2005b); this is advantageous when attempting to accurately measure rainfall rates during low-intensity events.

However, a significant disadvantage at X-band wavelengths is the signal extinction area, which is defined as the area where rainfall attenuation causes the backscattered signal to fall below the receiver noise level. In a signal extinction area the radar cannot detect precipitation, and because such signal extinction is common in the X-band, adequate countermeasures are required in meteorological and hydrological applications of X-band polarimetric radar.

An alternative countermeasure involves the radar network itself. An X-band polarimetric radar network was developed by the engineering center for Collaborative Adaptive Sensing of the Atmosphere (CASA) in Oklahoma to study severe storms (Junyent and Chandrasekar, 2009, 2010). The National Research Institute for Earth Science and Disaster Prevention (NIED) implemented this X-band polarimetric radar network (X-NET) in the Tokyo metropolitan area to study severe storms, and to develop a prediction system for meteorological disasters in urban areas (Maki et al., 2008). NIED successfully used X-NET to monitor, in real time, a heavy rainfall event that occurred in Zoshigaya, Tokyo in 2008 (Kato and Maki, 2009; Hirano and Maki, 2010). Composite rainfall maps derived from X-NET were validated by rain gauge data and used for QPE (e.g., Park et al., 2005a, 2005b; Maki et al., 2005a, 2005b). However, detailed validation analyses have not been completed on the polarimetric radar variables that are essential for microphysical studies of precipitation. The present study aims to answer two questions.

1. How accurate is a composite map of polarimetric radar parameters?
2. Can such maps be used for the retrieval of precipitation parameters?

In the following sections, composite maps of the polarimetric variables horizontal polarization \( Z_0h \), differential reflectivity \( Z_{DR} \), specific differential phase shift \( K_{DP} \), and rainfall intensity \( R \) using the X-NET data deployed by NIED and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) in the Tokyo Metropolitan Area are evaluated by comparison with scattering simulations derived from ground-based disdrometer data, and rain gauge data. In addition, the composite DSD parameters, median volume diameter \( D_0 \), and normalized number concentration \( (\log_{10} N_w) \) were retrieved from the X-band polarimetric radar network and preliminary results are presented.

2. Data Acquisition and Processing

2.1 Observations

A localized heavy rainfall event over the suburbs of Tokyo on 28 September, 2010, associated with a fast-moving cold front that passed through the Kanto region, was observed by four X-band polarimetric radars located in Ebina (EBN), Kisarazu (KSR), Saitama (SAT), and Yokohama (SYK). Ground truth data was provided by an impact type Joss–Waldvogel disdrometer (JWD) located between the SAT and SYK radars, and 10 rain gauges operated by the Tokyo Metropolitan Government. Figure 1 shows the locations of the radar stations, JWD, and rain gauges. Specifications and descriptions of radars SAT and SYK, operated by MLIT, are given in Maesaka et al. (2011), and those for the EBN and KSR radars, operated by NIED, are given in Maki et al. (2008).

Figure 1. Locations of the four radar stations: EBN, KSR, SAT, and SYK, JW disdrometer (☆), and 10 rain gauges (×). Circles indicate the observation range of each radar (r = 80 km).
2.2 Processing of disdrometer measurements

The number of drops counted by the JWD was initially processed using the quality-control procedures described by Park et al. (2005a). Drop spectra were also corrected for the dead-time (Sheppard and Joe, 1994; Sauvageot and Lacaux, 1995). To derive the polarimetric variables, T-matrix scattering simulations were performed using these quality-controlled drop spectra under the following conditions: 1) a temperature of 15 °C; 2) an elevation angle of 0°; 3) the mean axis ratios (Thurai et al., 2007); and 4) a Gaussian canting angle distribution with a mean of 0° and standard deviation of 7°.

2.3 Processing of radar data

Prior to data analysis, noise, ground clutter, and non-meteorological echoes were removed (Maesaka et al., 2011). Then, the system bias of $Z_H$ and $Z_{DR}$ were estimated (Kim et al., 2010), and the derived $Z_H$ biases from the four radars were $-5.1$ dBZ (EBN), $-7.6$ dBZ (KSR), $-3.7$ dBZ (SAT), and $-3.2$ dBZ (SYK), and the $Z_{DR}$ biases were $+2.78$ dB (EBN), $-0.5$ dB (KSR), $-0.2$ dB (SAT), and $-0.9$ dB (SYK). $Z_H$ and $Z_{DR}$ measured at X-band wavelengths are subject to rainfall attenuation, and it is important that this is corrected for. We used the shifted self-consistent method (SSCM; Kim et al., 2010), which considers variability in the optimum coefficient $\alpha (A_\beta = aK_{DP})$ along the radar slant-range. X-band weather radar sometimes misses precipitation echoes behind heavy rainfall due to severe rainfall attenuation in the signal extinction area. We identified the signal extinction area using the method proposed by Iwanami et al. (2007). Rainfall intensity was derived from the composite estimator of the relationships $R-K_{DP}$ and $R-Z_H$:

$$R(Z_H; K_{DP}) = \begin{cases} 5.72 \times 10^{-2} Z_H^{0.621} & \text{for } K_{DP} \leq 0.3 \text{ deg km}^{-1} \text{ or } Z_H \leq 35 \text{ dBZ} \\ 19.84 Z_H^{0.703} & \text{otherwise} \end{cases}$$

(1)

where $R$, $Z_H$, and $K_{DP}$ are in mm h$^{-1}$, mm$^6$ m$^{-3}$, and °km$^{-1}$, respectively. The coefficients and exponents in Eq. 1 were derived from scattering simulations under the conditions described in Section 2b using quality-controlled drop spectra collected during the analyzed storm that passed over the JWD site. The threshold value of 0.3 °km$^{-1}$ for $K_{DP}$ is the standard error of $K_{DP}$ calculated by Park et al. (2005b), and confirmed by Kim et al. (2010).

The estimated rainfall rates and the polarimetric variables from each radar were composited into a Cartesian coordinate system with a horizontal grid interval of 0.5 km, and we adopted a modified Cressman-type weighting function which considered an altitudinal weighting, with lower-altitude observations being more strongly weighted (Maesaka et al., 2011).

3. Results

A convective precipitation line associated with a cold front passed over the observation area between 1100 and 1400 LST on 28 September, 2010. The core region of the convective system passed over the disdrometer site. Figure 2 shows PPI images of attenuation corrected $Z_H$ (a, b, c, and d) and $Z_{DR}$ (e, f, g, and h), measured $K_{DP}$ (i, j, k, and l), and radar-rainfall intensity $R$ (m, n, o, and p) from the four radars at 1140 LST when severe attenuation occurred. The curved high reflectivity region (dotted line) ≥ 40 dBZ, which moved northwards, is located over the disdrometer. In general, the reflectivity patterns from each radar image were similar. However, due to the strong rainfall attenuation, signal extinction (gray area) occurred on the north side of the rainband for EBN, KSR, and SYK, but on the south side of the rainband for SAT. The signal extinction area was calculated as 13.8%, 22.5%, and 32.6% for EBN, KSR, and SYK, respectively. The $Z_{DR}$ from the four radars followed a similar pattern.

The boundary patterns of high $K_{DP}$ near the signal extinction area of each radar are quite different, especially from EBN (Figure 2). An abrupt decrease in $K_{DP}$ values, behind a large $K_{DP}$ area, with increasing distance from the radar in Figure 2i is the result of a decreasing signal to noise ratio (SNR) ($K_{DP}$ filtered in low SNR area) caused by severe attenuation. Also
notable is the $K_{DP}$ noise in the weak rainfall region of KSR. The speckled $K_{DP}$ south of the strong rainband (close to the radar station) was observed by KSR, but not by the other radars. This speckled $K_{DP}$ could lead to an over attenuation correction of $Z_H$, and consequent over-estimation of the rainfall rate. Rainfall intensity (Figure 2m–p) was estimated using attenuation corrected $Z_H$ and $K_{DP}$. The spatial variation in $R$ is similar to that in $K_{DP}$ in the strong rainband region, and similar to $Z_H$ in the weak rainfall region (<10 mm h$^{-1}$). The higher rainfall rates ($\geq$80 mm h$^{-1}$) were located around the disdrometer site for all radars.

The areal composite of the attenuation corrected $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ are shown in Figure 3. The extinction area was successfully compensated for (signal extinction 0%) by the other radars in the overlapping observation area, and the precipitation echo was completely identified. A curved region of high $Z_H$ was observed, and regions with $Z_H > 40$ dBZ largely coincide with areas where $Z_{DR}$ is 1.0 dB. In the core of the precipitation echo over the disdrometer, $Z_H$ and $Z_{DR}$ were >55 dBZ and 2 dB, respectively. A high $K_{DP}$ of 2.5–7.0 km$^{-1}$ was observed in the core of the echo, and the pattern of $K_{DP}$ was consistent with that of the rainfall rate (Figure 3d). The value of $R$ in the core of the precipitation echo was estimated to be 60–80 mm h$^{-1}$.

Comparisons of composite map data and $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ from the four radars, with data calculated from the JWD are shown in Figure 4. The radar data were averaged within a 1 km radius of the JWD site. In addition, a five minute moving average was calculated for the simulated values using the JWD data, and for radars SAT and SYK, because the PPI scan at EBN and KSR was repeated every five minutes. The four variables from each radar, and the composite values, show reasonably good agreement with the values derived from the disdrometer. The corresponding slopes (correlation coefficients) of composite data for the four variables $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ are 1.03 (0.92), 1.08 (0.88), 1.07 (0.94), and 1.04 (0.90), respectively.

![Figure 3](image)

Figure 3. Composite maps from the four radars at 1140 LST on 28 September, 2010: (a) $Z_H$, (b) $Z_{DR}$, (c) $K_{DP}$, and (d) $R$. Also shown are radar sites (□) and disdrometers (☆).

![Figure 4](image)

Figure 4. Scatter plots of polarimetric variables and rainfall rate obtained from radar observations versus the simulated values (JWD) over the disdrometer site from 1100 to 1300 LST on 28 September, 2010: (a) $Z_H$, (b) $Z_{DR}$, (c) $K_{DP}$, and (d) $R$. Gray dots are data from the composite map of the four radars. COM = composite data.
Table 1. The normalized error (NE) and normalized bias (NB) percentages associated with values of $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ from the four radar stations and in the composite data (COM).

<table>
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<tr>
<th></th>
<th>$Z_H$</th>
<th>$Z_{DR}$</th>
<th>$K_{DP}$</th>
<th>$R$</th>
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<td>EBN</td>
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<td>26.25</td>
<td>19.15</td>
</tr>
<tr>
<td></td>
<td>NB</td>
<td>1.15</td>
<td>–12.43</td>
<td>–18.49</td>
</tr>
<tr>
<td>KSR</td>
<td>10.90</td>
<td>33.86</td>
<td>28.70</td>
<td>30.27</td>
</tr>
<tr>
<td>SAT</td>
<td>2.38</td>
<td>33.74</td>
<td>4.74</td>
<td>–1.21</td>
</tr>
<tr>
<td>NE</td>
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<td>16.20</td>
<td>19.80</td>
<td>22.88</td>
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<tr>
<td>SYK</td>
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<td>21.82</td>
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</table>

The accuracy of the polarimetric parameters and rainfall rate measured and composited by the four radars, compared with those calculated from disdrometer DSD data, was quantified by calculating the normalized error (NE) and normalized bias (NB) (Table 1). Radar SYK showed the best agreement with the disdrometer data, and a corresponding NE (NB) of $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ are 3.5% (2.0%), 16.8% (3.3%), 16.2% (–2.4%), and 12.8% (–1.4%), respectively. In contrast, radar KSR had poor NE and NB for all variables. In particular, $Z_{DR}$ was over-estimated, with a corresponding NE and NB of 33.9% and 33.7%, respectively; while the $Z_{DR}$ of EBN was under-estimated, with a corresponding NE and NB of 26.3% and –12.4%, respectively. This over-estimation (under-estimation) of the $Z_H$ and $Z_{DR}$ at KSR (EBN) was caused by noise (excessive filtering) in $K_{DP}$ as explained previously (Figure 2). The composite $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ produced NE (NB) values of 6.0% (3.8%), 19.9% (14.0%), 23.9% (–2.2%), and 21.8% (1.4%), respectively. These results are within the ranges quoted in previous studies (e.g., Kim et al. 2010) report an NE of 5.3% and 17.2% for $Z_H$ and $Z_{DR}$, respectively, Park. et al. (2005b) report an NE of 21.1% for $R$, and Seliga et al. (1981) an NE of 14%–26% for $R$), despite the relatively poor results from KSR.

The composite map of polarimetric radar parameters can be used to retrieve rain DSD, and this provides useful information for the microphysical study of the storm. Figure 5 shows the retrieved rain DSD parameters, $D_0$ and log$_{10} N_w$, that were calculated using the algorithm proposed by Kim et al. (2010). The value of $D_0$ in the core of the precipitation echo near that JWD site was estimated to be 2.0–3.0 mm, and $N_w$ was 3.0–3.8 mm$^{-1}$ m$^{-3}$. The validation of $D_0$ and log$_{10} N_w$ were accomplished by comparison with simulated DSD parameters from the JWD data (Figure 5c, d). The comparison shows good agreement; for $D_0$ the corresponding NE and NB are 13% and 7%, respectively, and for log$_{10} N_w$ are 9.2% and –3.3%, respectively. Successive rain DSD parameters, without the occurrence of signal extinction areas, can provide invaluable information for many meteorological applications, such as the analysis of microphysical properties, quantitative estimates of precipitation, and the initialization and verification of cloud models.

4. Summary and Conclusion

This paper presents the results of the validation of a composite map of four X-band polarimetric radar parameters and rainfall amounts using data from a surface disdrometer and a rain gauge network. We analyzed a locally heavy rainfall event that occurred over the suburbs of Tokyo on 28 September, 2010. Due to severe rainfall attenuation, all four X-band radars suffered a loss of received signal power (signal extinction). The extinction area was compensated for by the multiple radar observations and validation with a disdrometer. Temporal variations in the value of the composite $Z_H$, $Z_{DR}$, $K_{DP}$, and rainfall rate $R$, and in those same variables simulated from the disdrometer data, were in reasonably good agreement. The normalized error (NE) associated with the composite $Z_H$, $Z_{DR}$, $K_{DP}$, and $R$ values was 6.0%, 19.9%, 23.9%, and 21.8%, respectively, and the normalized bias (NB) was 3.8%, 14%, –2.2%, and 1.4%, respectively.

We conclude that a network of radars is essential when X-band polarimetric radar is used to observe heavy rainfall events. Composite polarimetric radar parameters can provide useful information, not only for hydrological applications, but also for microphysical studies.

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Figure 5. (a) Median volume diameter ($D_0$), and (b) normalized number concentration (log$_{10} N_w$) from the composite radar data at 1140 LST on 28 September, 2010. Comparisons of these variables over the disdrometer site are shown in (c) and (d). respectively. The correlation coefficients of these parameters were 0.92, 0.82, 0.94, and 0.90, respectively. From the inter-comparisons of the four radars, $Z_H$ and $Z_{DR}$ showed better results when compared with the disdrometer, but $K_{DP}$ and $R$ showed similarly good results from all stations. The results of comparison with a rain gauge network will be discussed in conference.

We conclude that a network of radars is essential when X-band polarimetric radar is used to observe heavy rainfall events. Composite polarimetric radar parameters can provide useful information, not only for hydrological applications, but also for microphysical studies.
References


