Rainfall Estimation from an Operational S-Band Dual-Polarization Radar: Effect of Radar Calibration

Soohyun KWON

Dept. of Astronomy and Atmospheric Sciences, Research and Training Team for Future Creative Astrophysicists and Cosmologist, Kyungpook National University, Korea

GyuWon LEE

Dept. of Astronomy and Atmospheric Sciences, Research and Training Team for Future Creative Astrophysicists and Cosmologist, Kyungpook National University, Korea

Center for Atmospheric REmote Sensing, Kyungpook National University, Korea

and

Gwangseob KIM

Dept. of Civil Engineering, Kyungpook National University, Korea

(Manuscript received 26 September 2013, in final form 16 October 2014)

Abstract

The calibration biases of reflectivity ($Z_H$) and differential reflectivity ($Z_{DR}$) from an operational Mt. Bisl S-band dual polarization radar are derived to improve the accuracy of rainfall estimation. The effect of radar calibration in rain estimation is examined by using data from the dense rain gauge network.

The calibration biases of $Z_H$ are calculated by using the self-consistency constraint between $Z_H$ and specific differential phase shift ($K_{DP}$). This procedure is performed every 2.5 min. The biases are varied from −3.3 dB to 0.8 dB during the period between July 2010 to October 2011. The $Z_{DR}$ calibration biases are obtained by two methods: 1) vertically pointing measurements, and 2) comparison of observed data with the average $Z_H$–$Z_{DR}$ relationship derived from disdrometric data. The $Z_{DR}$ biases are varied from 0.25 dB to 0.7 dB and both methods show similar results. This $Z_H$–$Z_{DR}$ technique can be applied for a volume scan and does not require a special scan.

The rainfall relationships, $R(Z_H)$, $R(Z_H, Z_{DR})$ and $R(Z_H, \xi_{DR})$, where $\xi_{DR} = 10^{0.1Z_{DR}}$, are derived from measured disdrometer data and then adjusted with gauge data. The verification of rainfall estimation is performed by applying 1) average $Z_H$ and $Z_{DR}$ calibration biases for the entire period and 2) adaptive calibration biases that vary each rain event. The application of adaptive calibration biases is more effective for $R(Z_H, Z_{DR})$ and $R(Z_H, \xi_{DR})$ than that for $R(Z_H)$, thus indicating the necessity of frequent calibration of $Z_H$ and $Z_{DR}$.

Keywords dual-polarization radar; radar calibration; rainfall estimation

1. Introduction

Weather radars can observe the meteorological phenomena in high spatial and temporal resolution. In addition, the information of drop shape is presented by dual-polarimetric radar parameters such as differ-
potential reflectivity \( (Z_{\text{DR}}) \) and differential phase shift \( (\Phi_{\text{DP}}) \). However, the radar measurables contain errors such as calibration biases of radar reflectivity \( (Z_H) \) and differential reflectivity, ground echoes, beam broadening, bright band contamination, etc. These errors can lead to significant uncertainty in rainfall estimation. In particular, the error in rainfall estimation would be 18% with a \( Z_H \) \( (Z_{\text{DR}}) \) calibration bias of 1 dB \( (0.2 \text{ dB}) \) (Ryzhkov et al. 2005b). Thus, the accurate calibration of \( Z_H \) and \( Z_{\text{DR}} \) is essential to improve the quantitative precipitation estimation (QPE).

Many researchers have suggested various calibration methods to obtain the calibration bias of \( Z_H \) and \( Z_{\text{DR}} \). Reflectivity can be calibrated using a corner reflector or a known sphere target such as balloon (Atlas 2002). However, the sphere target cannot generally fill the radar sampling volume. The comparison between radar and disdrometer or rain gauge can be an alternative for reflectivity calibration (Brandes et al. 1999; Lee and Zawadzki 2006, Bringi et al. 2013). When the rain gauge is used to calibrate \( Z_H \), the variability of the \( R-Z_H \) relationship can be an error source. In addition, the different measuring volumes of radar and disdrometer or rain gauge observation can be significant. Hence, this method requires averaging over considerable spatial and temporal scales.

Rainfall rate can be independently estimated from the power (such as \( Z_H \) and \( Z_{\text{DR}} \)) and phase measurements (such as \( K_{\text{DP}} \) and \( \Phi_{\text{DP}} \)) in dual-polarimetric radar (Gorgucci et al. 1992). Hence, the phase measurement can be estimated from power measurement with a certain uncertainty and vice versa (Gorgucci et al. 1999a, b). Because \( K_{\text{DP}} \) is not affected by the absolute calibration of radar system, attenuation, and partial beam blockage (Zrnic and Ryzhkov 1996; Vivekanandan et al. 1999), the self-consistency constraint between power and phase measurements can be useful for deriving the absolute calibration of \( Z_H \).

The accurate \( Z_{\text{DR}} \) calibration is essential to improve radar QPE. The typical calibration method is to calculate the \( Z_{\text{DR}} \) bias with vertically pointing observations (Al-Khatib et al. 1979; Seliga et al. 1979; Gorgucci et al. 1999b). The symmetry of rain drop and the often near zero degree mean canting angle (with narrow distribution) are used to calculate calibration bias of \( Z_{\text{DR}} \) in vertically pointing observations.

The purpose of this study is to improve the accuracy of rainfall estimation from an operational Mt. Bisl dual-polarization radar by accurately calibrating the \( Z_H \) and \( Z_{\text{DR}} \) measurements. The stability of this S-band dual-polarimetric radar is also monitored with long term observations. Thereafter, the effect of the calibration bias in rainfall estimation is investigated by applying the derived calibration biases.

In this study, the characteristics of radar, gauge, and disdrometer data used are described in Section 2. The methodology of reflectivity calibration, differential reflectivity calibration, and rainfall estimator are shown in Section 3. Long term monitoring of calibration biases and its effect on rain estimation are shown in Section 4.

### 2. Data

#### 2.1 Radar data

Mountain Bisl S-band dual polarization radar data are used in this study. The general characteristics of Mt. Bisl S-band dual-polarization radar are shown in Table 1. A volume scan of six elevation angles \((-0.5^\circ, 0^\circ, 0.5^\circ, 0.8^\circ, 1.2^\circ, 1.6^\circ)\) is performed every 2.5 min to improve the temporal sampling rate during precipitation events. The \(1.6^\circ\) plan position indicator (PPI)
data were used for calculating the calibration bias of $Z_H$ to avoid the partial beam blocking and contamination by ground echoes. Thirty-five selected rain events from July 03, 2010 to August 08, 2011 (Table 2) are used in the calibration of $Z_H$.

To calculate the calibration bias of $Z_{DR}$, the vertically pointing measurements were performed thrice during the period (June 28, 2010, September 11, 2010, and May 11, 2011: see Fig. 1). For the first case, the data are collected with the gate spacing of 250 m and samples of 42, up to approximately 20 km height. This event is characterized by stratiform rain with the bright band height of 4.5 km. The second and third cases show the light rain with the bright band height of 4.5 km and 4 km, respectively. Unlike the first case, the data are collected with the gate spacing of 125 m with 128 samples. The data below the bright band are used to avoid possible bright band contamination (red box area in Fig. 1).

The PPI of the lowest elevation angle $-0.5^\circ$ is used to estimate the radar rainfall rate. The locations of rain gauges are not affected by ground clutter at $-0.5^\circ$. Data sampled every 2.5 min are used. The adjustment of rainfall estimators is performed by using the randomly selected rain events of five days (63 h of rain and total rainfall amount of about 324.5 mm) in 2011. The rest of rain events in 2011 are used for verification of radar rainfall rate. The total rain accumulation was about 740 mm, and the total duration of precipitation is approximately 140 h.

### 2.2 Rain gauge data

The rain gauge data are collected from eight tipping-bucket rain gauges deployed in the campus of Kyungpook National University (KNU). The location of rain gauges is shown in Fig. 2. The bucket size of all gauges is 0.2 mm, and the time resolution is 0.5 s. The rain gauges have been in operation since April 24, 2011. The cluster of gauges is located at the range of approximately 23 km and the azimuth angle of approximately 17° from the radar. The radar pixel that includes all gauges is about 1.6 km $\times$ 1.25 km that is composed of 40 pixels of $1^\circ \times 125$ m (Fig. 2).

### 2.3 Disdrometer data

The disdrometer data is used for the calculation of relationships between the rainfall rate and dual-polarimetric parameters. The data were collected from POSS (Precipitation Occurrence Sensor System: Sheppard 1990) from March to September 2001 in Busan. The theoretical radar parameters, $Z_H$, $Z_{DR}$, $K_{DP}$, and rain rate, are calculated from the measured drop size distribution using T-matrix scattering (Bringi et al. 1990; Vivekanandan et al. 1991). The dielectric constant for scattering simulation was calculated by using the method of Ray (1972). The condition assumed in the scattering calculation is shown in Table 3. Then, the various theoretical relationships

<table>
<thead>
<tr>
<th>Date (YYYY/MM/DD)</th>
<th>Accumulation [mm]</th>
<th>Rainfall duration [hour]</th>
<th>Date (YYYY/MM/DD)</th>
<th>Accumulation [mm]</th>
<th>Rainfall duration [hour]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010/07/11</td>
<td>81.0</td>
<td>22</td>
<td>2011/05/10</td>
<td>61.5</td>
<td>10</td>
</tr>
<tr>
<td>2010/07/16</td>
<td>69.5</td>
<td>12</td>
<td>2011/05/11</td>
<td>54.0</td>
<td>12</td>
</tr>
<tr>
<td>2010/07/17</td>
<td>42.5</td>
<td>12</td>
<td>2011/06/22</td>
<td>14.5</td>
<td>5</td>
</tr>
<tr>
<td>2010/08/07</td>
<td>44.5</td>
<td>2</td>
<td>2011/06/24</td>
<td>19.5</td>
<td>2</td>
</tr>
<tr>
<td>2010/08/10</td>
<td>21.5</td>
<td>9</td>
<td>2011/06/25</td>
<td>70.5</td>
<td>16</td>
</tr>
<tr>
<td>2010/08/11</td>
<td>61.5</td>
<td>13</td>
<td>2011/06/26</td>
<td>41.5</td>
<td>15</td>
</tr>
<tr>
<td>2010/08/13</td>
<td>20.0</td>
<td>9</td>
<td>2011/07/03</td>
<td>40.5</td>
<td>6</td>
</tr>
<tr>
<td>2010/08/15</td>
<td>104.5</td>
<td>5</td>
<td>2011/07/07</td>
<td>12.0</td>
<td>3</td>
</tr>
<tr>
<td>2010/08/16</td>
<td>74.5</td>
<td>6</td>
<td>2011/07/09</td>
<td>168.0</td>
<td>23</td>
</tr>
<tr>
<td>2010/08/17</td>
<td>28.0</td>
<td>8</td>
<td>2011/07/10</td>
<td>122.0</td>
<td>13</td>
</tr>
<tr>
<td>2010/08/25</td>
<td>30.5</td>
<td>3</td>
<td>2011/07/12</td>
<td>9.0</td>
<td>5</td>
</tr>
<tr>
<td>2010/09/02</td>
<td>18.0</td>
<td>5</td>
<td>2011/07/13</td>
<td>20.0</td>
<td>4</td>
</tr>
<tr>
<td>2010/09/06</td>
<td>38.0</td>
<td>8</td>
<td>2011/07/29</td>
<td>17.5</td>
<td>1</td>
</tr>
<tr>
<td>2010/09/07</td>
<td>49.5</td>
<td>9</td>
<td>2011/07/30</td>
<td>23.0</td>
<td>4</td>
</tr>
<tr>
<td>2010/09/11</td>
<td>15.0</td>
<td>9</td>
<td>2011/08/01</td>
<td>9.0</td>
<td>8</td>
</tr>
<tr>
<td>2010/09/12</td>
<td>25.0</td>
<td>5</td>
<td>2011/08/02</td>
<td>27.5</td>
<td>10</td>
</tr>
<tr>
<td>2010/09/22</td>
<td>11.0</td>
<td>9</td>
<td>2011/08/03</td>
<td>34.0</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2011/08/08</td>
<td>58.5</td>
<td>4</td>
</tr>
</tbody>
</table>
of radar estimation and $Z_H$ calibration are derived by using these calculated radar parameters. Because the disdrometer data are not from the same period as the radar data, we have adjusted the theoretical relationships with gauges to eliminate any existing biases in rain estimation. The details of adjustment are described in Section 3.3.

3. Methodology

The reflectivity factor is affected by the calibration error. However, the specific differential phase $K_{DP}$ is independent of the calibration error because this is related to the phase shift of the electromagnetic wave. Thus, comparison of observed $K_{DP}$ and derived $K_{DP}$ using the $Z_H$–$K_{DP}$ relationship indicates the calibration bias of $Z_H$ (Goddard et al. 1994). The $Z_{DR}$ bias is obtained from the specially performed vertically pointing observation. In addition, the $Z_{DR}$ calibration bias can be calculated by using the relationship between calibrated $Z_H$ and $Z_{DR}$ (Gorgucci et al.

Fig. 1. (a) Azimuth-height display of $Z_H$, (b) average vertical profile (black solid lines) of $Z_H$ and its standard deviation (horizontal bars), (c) azimuth-height display of $Z_{DR}$ and (d) azimuth-height display of $\rho_{HV}$ at 0344 KST, June 28, 2010 (top), 1057 KST, September 11, 2010 (middle), and May 11, 2011 (bottom).
The effect of calibration is verified in terms of estimation of rainfall rate between rain gauge and radar estimation.

3.1 Calibration of radar reflectivity

The calibration bias is calculated from the comparison of measured $\Phi_{DP,\text{obs}}$ with calculated $\Phi_{DP,\text{cal}}$ derived from $Z_H$ using the $Z_H$–$K_{DP}$ self-consistency relationship as following procedure (Lee and Zawadzki 2006).

1. Select the rain region to avoid the ground echoes and bright band contamination.
2. Calculate the $K_{DP}$ at the rain region from the observed $Z_H$ using the $Z_H$–$K_{DP}$ relationship.
3. Calculate $\Phi_{DP,\text{cal}}$ by integrating the calculated $K_{DP}$ along the ray.
4. Find $\Phi_{DP,\text{obs}}$ measured in the same ray.
5. Calculate the calibration bias ($\varepsilon$) by comparing $\Phi_{DP,\text{cal}}$ and $\Phi_{DP,\text{obs}}$ with the equation below:

$$\varepsilon[\text{dB}] = 10 \log_{10} \left( \frac{\Phi_{DP,\text{cal}}}{\Phi_{DP,\text{obs}}} \right),$$

$$\tan \theta = \sum \frac{\Phi_{DP,\text{cal}} \Phi_{DP,\text{obs}}}{\sum \Phi_{DP,\text{obs}}^2},$$

where the $b$ is the exponent $Z_H = a K_{DP}^b$. A more thorough procedure is shown in Lee and Zawadzki (2006). The rain region is selected by using the threshold of $\rho_{HV}$ and of the standard deviation of $Z_H$, $Z_{DR}$, $\Phi_{DP}$ and $\rho_{HV}$ at each PPI. The standard deviation (SD) is defined by the following equation:

$$\text{SD} = \sqrt{\frac{\sum_{i=1}^{i+N} (x_i - x_j)^2}{2N+1}},$$

where $i$ indicates the index number where the SD should be calculated. The term $2N + 1$ is a number of data centered at location $i$ and $N = 5$ is used. The probability density functions and cumulative proba-
bility density functions of each parameter are derived to determine the thresholds. The thresholds are selected at the values where the cumulative density reaches approximately 90%. The thresholds used in this study are SD (ZH) = 10 dB, SD (ZDR) = 3 dB, SD (ΦDP) = 20°, SD (ρHV) = 0.1, and ρHV = 0.95.

The ZH–KDP relationship (ZH = 7.3 × 10^4 KDP^{1.11}) is calculated from the ZH and KDP pairs derived from drop size distributions described in Section 2.3 (Fig. 3). Herein, only the ray path of rain region longer than 10 km is considered. The unfolded ΦDP value is obtained by comparing average ΦDP in a window range of 20 gates (2.5 km) with thresholds. The average of ΦDP is larger than the first threshold (119°) and the measured ΦDP at a considered gate is lower than threshold (79°), the measured ΦDP is then unfolded by adding 180°. After unfolding, an FIR (finite impulse response) filter is applied to remove the measurement noise (Hubbert and Bringi 1995) with the window size of 2.5 km. FIR filtering is performed for 10 times as recommended by Hubbert and Bringi (1995). The calibration biases are derived every 2.5 min of PPI data and then averaged for daily calibration biases.

3.2 Calibration of differential reflectivity

a. Calibration with vertically pointing measurements

In general, ZDR value of vertically pointing observation should be zero for the rain measurement. Measurement because of the existence of tumbling ice and the alignment of ice particles (Gorgucci et al. 1999b; Vivekanandan et al. 2003). To avoid the mixed phase precipitation and bright band, we have identified the bright band and determined the rain region from the vertical profiles of ZH, ZDR, and ρHV (Fig. 1). The data near the radar is removed to avoid contamination from ground clutters. The bias of ZDR is derived from the mean value of ZDR measurements within this rain region for every vertically pointing PPI. The vertically pointing PPI means a PPI scan with a 90° elevation angle. The temporal variation of derived ZDR biases is shown later in the next section and the dependency of calibration bias on ZH values is also investigated. We compute the average of ZH, ZDR, and ρHV as functions of azimuthal angles to investigate any possible azimuthal dependency.

b. Calibration with ZH–ZDR relationship from DSDs

The average relationship between ZH and ZDR can be estimated by using the measured drop size distribution from disdrometer. Thereafter, the radar measured ZH and ZDR can be compared with this average (climatological) relationship to derive the calibration bias of ZDR.

The relationship (ZDR = 4.23 × 10^3 ZH + 6.15 × 10^{-4} ZH^2) is established by using the least squared fit to the calculated ZH and ZDR from disdrometric data described in Section 2.3. Figure 4 shows the derived ZH and ZDR with the functional fit and average ZDR for 2 dB interval of ZH. The functional fit is compared with radar measured ZH and ZDR.

The biases are derived from data selected at the rain field to avoid the non-meteorological echo. The dependency of ZDR on elevation angle from −0.5° to 1.6° is within 0.1 dB (Ryzhkov et al. 2005b). Thus, this calibration is performed at the highest elevation (1.6°). The method for calculating the calibration bias of ZDR through the ZH–ZDR relationship as follows:

1. The measured ZDR is averaged to the 2 dB interval of ZH (ZDR_avg).
2. Calculate the ZDR bias by calculate the average of difference between ZDR_avg and ZDR_theo at each channel within a ZH range of 10–20 dBZ when the standard deviation at each channel is smaller than 0.3 dB. ZDR_theo is calculated from the average ZH–ZDR relationship.
ZZ ZDR bias DR _avg DR _theo = −ii,
where the is the channel number and means average.

3. If averaged mean absolute error (MAE) is larger than threshold (0.3 dB) that ZDR bias is neglected to remove events that are apart from the climatological ZH–ZDR relationship. The average value of the MAE of each event (day) was 0.3 dB.

This feedback loop with MAE can improve the stability of ZDR bias by eliminating the dependency of ZH–ZDR relationship for particular microphysical processes.

4. Thereafter, ZDR_bias is further adjusted by applying the average difference between ZDR biases from vertically pointing method and from ZH–ZDR relationship (detailed description is in appendix).

This method could be affected by DSD variation. However, the DSD variation after above method was less than 0.1 dB (Fig. A1).

3.3 Comparison of rainfall rates from radar and gauge

The radar rainfall rate is verified by applying the calculated ZH and ZDR calibration bias. The rain gauge used for verification is corrected by the laboratory test and long-term inter-comparison in fields for eight month from October 2009 to June 2010 (except for the month of April 2010) in KNU.

The radar data used herein are first processed to avoid clutter contamination, bright band, and biological targets by applying the threshold of ρHV and the standard deviation of ZH, ZDR, ρHV and ΦDR. The same thresholds as in Section 3.1 are used. The radar rainfall rate is averaged over the gauge network (4° by 1.25 km).

The comparison between the radar and rain gauge rainfall rates is performed by using the two different rain gauge sampling areas: 1) each gauge (0.018 km²), and 2) average of eight gauges (2 km²) area in Fig. 2. The calibration biases are applied in two different ways in order to examine their effect on radar QPE: 1) averaged ZH and ZDR calibration bias for all events, and 2) daily ZH and ZDR calibration biases (adaptive biases).

The rainfall retrieval relationships are calculated by using the simulated polarimetric parameters and rainfall intensity from measured disdrometer data (Table 3). The relationships, R(ZH), R(ZH, ZDR), and R(ZH, ξDR), are used. Here, ξDR is the linear scale of ZDR (10^0.1 ZDR). The rainfall algorithms, R(ZH, ZDR) and R(ZH, ξDR) derived from disdrometer data are adjusted by using ZH and ZDR measured from radar and R from rain gauges. The ZH and ZDR are smoothed for 10 gates (1.25 km) along the range direction and for 4° (about 1.50 km at the range of the gauge network) in azimuthal direction for adjustment. The adjustment is performed to the coefficient (a) and exponent (c) of ZDR (see Table 4) because the bias appears when the ZDR is added in the relationship.

To verify different polarimetric rain algorithms, we used the standard deviation (SD), normalized standard deviation (NSD) and the mean bias.

\[
SD = \left( \frac{1}{n} \sum_{i=1}^{n} (R_{r,i} - R_{G,i})^2 \right)^{\frac{1}{2}},
\]

\[
NSD = \left( \frac{1}{n} \sum_{i=1}^{n} (R_{r,i} - R_{G,i})^2 \right)^{\frac{1}{2}},
\]

\[
Bias = \frac{\sum_{i=1}^{n} R_{r,i}}{\sum_{i=1}^{n} R_{G,i}}.
\]
Here, \( n \) is the number of the \( R_r \) and \( RG \) pairs at given time integration \( \Delta t \), and \( r \) and \( G \) indicate radar and gauge; \( < RG > \) is the average rainfall rate of rain gauge for given time scale.

4. Analysis results

4.1 Calibration of radar reflectivity

The measured and calculated \( \Phi_{DP} \) at a given PPI are compared in Fig. 5. The pairs of \( \Phi_{DP, obs} \) and \( \Phi_{DP, cal} \) are mostly below the 45° slope line (thin solid line). This indicates that \( Z_H \) was underestimated and has \( Z_H \) bias of \(-2.6 \) dB (using Eqs. 1, 2).

Similar calculation is performed for each PPI every 2.5 min throughout this rain event (15 August 2010) and the derived calibration bias is shown in the upper panel of Fig. 6. The variation of \( Z_H \) is relatively small. The calibration biases suddenly decrease at 1102 LST. The averaged reflectivity over entire PPI (dots in bottom panel of Fig. 6) slightly decreases as well compared with its general trend. The average reflectivity near the radar is high over 45 dBZ at this period (plus sign in bottom panel of Fig. 6). This indicates the existence of the wet-radome attenuation in S-band radar caused by heavy rain above the radar site. The attenuation of rain at S-band radar can be negligible for light to moderate rain fall rate, but somewhat significant (particularly for \( Z_{DR} \)) in intense rainfall rate (Smyth and Illingworth 1998). The mean calibration bias is calculated by removing the individual biases to deal with wet-radome attenuation when the average reflectivity reaches over 35 dBZ near the radar site. The mean bias is about \(-2.7 \) dB for this rain event.

Similar analysis is applied for all rain events shown in Table 2. The calibration biases and their standard deviation are shown in Fig 7. The biases vary from \(-3.9 \) dB to \( 0.5 \) dB. The biases suddenly jump over \( 1 \) dB on June 24, 2011 and July 29, 2011 which is linked with hardware maintenance. In general, the variation of these derived calibration biases is significant and may affect the accuracy of rainfall rate estimation. Thus, the monitoring of the \( Z_H \) calibration bias is important.

4.2 Calibration of differential reflectivity

a. Calibration with vertically pointing measurements

The biases of \( Z_{DR} \) have constant values of \( 0.7 \) dB on June 28, 2010 and September 11, 2010 and \( 0.45 \) dB on May 11, 2011 regardless of the \( Z_H \) values. Figure 8 shows the scatter plot of average \( Z_H \) and average \( Z_{DR} \) for each vertically pointing PPI. The
horizontal and vertical lines are the standard deviation of $Z_H$ and $Z_{DR}$. The standard deviation of $Z_{DR}$ was for June 28 larger than those for the other two cases. The larger standard deviations are due to the lower number of pulses. The averaged $Z_{DR}$ for each vertically pointing PPI on 28 June 2010 is constant around 0.70 dB during about 2 hour. The temporal variation is within 0.1 dB. The calibration bias of $Z_{DR}$ on September 11, 2010 is the same value (= 0.70 dB). Thus, the $Z_{DR}$ bias does not likely change between June 28 and September 11, 2010. However the calibration bias on May 11, 2011 is 0.45 dB for about 6 h. This may indicate some change in system performance during this period. In general, the calibration of $Z_{DR}$ using the vertically pointing radar is performed in light rain such as on September 11, 2010. However, the $Z_H$ values are broadly distributed from 28 dB to 38 dB on June 28, 2010 and May 11, 2011, indicating the application of vertically pointing calibration up to 9 mm h$^{-1}$.

We investigate the variation of $Z_H$, $Z_{DR}$, and along the azimuthal direction (Fig. 9). The $Z_H$ and $\rho_{HV}$ values are constant over different azimuthal angles for the first and third cases when mean $Z_H$ is over 30 dBZ. However, the $Z_{DR}$ values exhibit bimodality with two peaks (two minimum) at 150° and 330° (60° and 240°).

The following could be the five reasons for the wavy shape: 1) terrain or radome effect, 2) bias in antenna positioning, 3) wind effects, 4) structure of radome, 5) noise related bias. The second reason is not relevant because the variation of 0.3 dB at differential reflectivity was found with the antenna tilting of more than 80° (Ryzhkov et al. 2005a). During the three events, the wind direction was not constant. This eliminates the wind effect. Gourley et al. (2006) shows the azimuthal variation of $Z_{DR}$ at orange peel type radome. However, the Mt. Bisl radar has a random panel radome which shows no preferred scattering direction. In the simultaneous dual polarization radar, $Z_{DR}$ and $\rho_{HV}$ were affected by difference of mean noise powers at horizontally and vertically polarized (Bringi and Chandrasekar 2001). In this case, measured $Z_{DR}$ and $\rho_{HV}$ should be systemically related with each other. However, there is no significant systemic relation between $Z_{DR}$ and $\rho_{HV}$ in our vertically pointing observation. Thus, the wave shape may originate from nearby terrain. In addition, the issue of radar hardware, in particular a permanent feature in pedestal may exist with this radar system.
b. Calibration with mean $Z_H$–$Z_{DR}$ relationship from DSDs

The calibration bias of $Z_{DR}$ is also calculated by comparing with the $Z_H$–$Z_{DR}$ relationship from drop size distributions. The averaged $Z_{DR}$ values for $Z_H$ in the range 10–20 dBZ are used for calculating the bias. The measured $Z_{DR}$ is larger than the average relationship, leading to the positive $Z_{DR}$ bias. The time variation of $Z_{DR}$ biases obtained from the two methods (vertically pointing and $Z_H$–$Z_{DR}$ relationship) is represented in Fig. 10, and vertical bar is the mean absolute error over entire ranges of $Z_H$.

The $Z_{DR}$ biases vary from 0.25 dB to 0.64 dB with time and the mean absolute error distributed from 0.14 to 0.28. The physical reason for this temporal variation is uncertain. However, this may be because of the system instability or partially because of...
residual DSD variability inherent in the used method. The difference of $Z_{DR}$ bias between two methods was similar to the difference of $Z_{DR}$ derived from Appendix.

4.3 Verification of rainfall estimation

The rainfall rate from Mt. Bisl S-band radar is retrieved with three different relationships, $R(Z_H)$, $R(Z_H, Z_{DR})$, and $R(Z_H, \xi_{DR})$. The comparison between radar and rain gauge rainfall rate is conducted by applying the average calibration bias (average bias for the entire analysis period) and adaptive calibration bias (daily bias) as functions of accumulation time such as 10 min, 1 h, and 2 h. In addition, the verification is performed for the original and adjusted relationships.

The radar rainfall rate at the scale of 2 km$^2$ is compared with the rainfall rate obtained from each rain gauge for different calibration options and accumulation time (Table 5). The average biases of $Z_H$ and $Z_{DR}$ are $-1.3$ dB and $0.51$ dB, respectively. The bias is reduced from $0.67$ to $0.86$ for 10 min and from $0.56$ to $0.90$ for 2 h with $R(Z_H)$. However, $R(Z_H, Z_{DR})$, and $R(Z_H, \xi_{DR})$ are overestimated by approximately 17 %–23 % and the NSD increases from 93 % to 117 % at 10 min. After applying adaptive calibration bias, the NSD decrease to 79 % with $R(Z_H)$. In general, the adaptive bias is more effective than the averaged bias in terms of reduction of random error in rainfall estimation. Applying the average bias of $Z_H$ and $Z_{DR}$, there was less overestimation than adaptive bias.

A similar comparison is represented in Table 6 and Fig. 11 for radar rainfall $R_r$ at the scale of 2 km$^2$ and areal average $R_G$ of 8 rain gauge within the same area. The SD of rainfall error is slightly reduced by using areal average $R_G$. The adaptive calibration performs the best with bias and NSD. However, as shown in Fig. 11, the overall underestimation (gray dots) is noticed without calibration of $Z_H$ and $Z_{DR}$. This underestimation disappears and slight overestimation is noticed in particular with $R(Z_H, Z_{DR})$, and $R(Z_H, \xi_{DR})$ (see black dots in the first row). After applying the adjusted relationship (black dots in the second row), nearly no bias is present (the bias is within 7 %). Similar results are shown for different accumulation times (Table 6). The bias is removed and the NSD reaches 41 % and 30 % for an accumulation time of 1 h and 2 h, respectively. In general, the results suggest the necessity of adaptive calibration of $Z_H$ and $Z_{DR}$ to further improve radar QPE. This calibration is more important in dual-polarimetric radar QPE.

5. Conclusion

In this study, the calibration bias of $Z_H$ and $Z_{DR}$ from the Mt. Bisl S-band dual-polarization radar is calculated to improve the accuracy of rainfall estimation. The error of rainfall estimation was reduced by using the daily $Z_H$, $Z_{DR}$ biases, thus indicating the necessity of frequent calibration of $Z_H$ and $Z_{DR}$. The stability of calibration bias is also monitored by long term data.

The calibration biases of $Z_H$ are calculated by using
Table 5. Statistical errors of radar rainfall rate estimation for the spatial scale of 2 km$^2$ (radar) and 0.018 km$^2$ (gauge) and temporal scales of 10 min, 60 min, and 120 min. Results are shown for applying different calibration bias. The SD and NSD stand for the standard deviation and normalized standard deviation.

<table>
<thead>
<tr>
<th></th>
<th>Before calibration</th>
<th>Apply averaged bias</th>
<th>Apply adaptive (daily) bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>5.66</td>
<td>0.67</td>
<td>5.59</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>6.23</td>
<td>0.51</td>
<td>7.35</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>6.19</td>
<td>0.52</td>
<td>7.56</td>
</tr>
<tr>
<td></td>
<td>60 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>2.72</td>
<td>0.69</td>
<td>2.58</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>3.07</td>
<td>0.52</td>
<td>3.10</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>3.02</td>
<td>0.54</td>
<td>3.23</td>
</tr>
<tr>
<td></td>
<td>120 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>2.12</td>
<td>0.69</td>
<td>1.95</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>2.41</td>
<td>0.52</td>
<td>2.35</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>2.35</td>
<td>0.53</td>
<td>2.44</td>
</tr>
</tbody>
</table>

Table 6. Same as in Table 5 except for the spatial scale of 2 km$^2$ (radar) and 2 km$^2$ (gauge). The statistical error within the parenthesis is for results from adjusted relationships shown in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Before calibration</th>
<th>Apply averaged bias</th>
<th>Apply adaptive (daily) bias</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>4.49</td>
<td>0.73</td>
<td>5.05</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>3.99 (5.32)</td>
<td>0.56 (0.36)</td>
<td>5.85</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>3.89 (5.65)</td>
<td>0.57 (0.33)</td>
<td>6.04</td>
</tr>
<tr>
<td></td>
<td>60 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>2.43</td>
<td>0.73</td>
<td>2.43</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>2.41 (3.33)</td>
<td>0.55 (0.36)</td>
<td>2.54</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>2.32 (3.50)</td>
<td>0.56 (0.33)</td>
<td>2.63</td>
</tr>
<tr>
<td></td>
<td>120 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(Z_H)$</td>
<td>1.73</td>
<td>0.72</td>
<td>1.62</td>
</tr>
<tr>
<td>$R(Z_H, Z_{DR})$</td>
<td>1.89 (2.64)</td>
<td>0.55 (0.35)</td>
<td>1.9</td>
</tr>
<tr>
<td>$R(Z_H, \tilde{\zeta}_{DR})$</td>
<td>1.81 (2.77)</td>
<td>0.56 (0.33)</td>
<td>1.96</td>
</tr>
</tbody>
</table>

the self-consistency constraint between $Z_H$ and $K_{DP}$. This method is simpler than other existing methods and not affected by the calibration of other polarimetric parameter such $Z_{DR}$. The $Z_{DR}$ calibration biases are obtained by two methods; vertically pointing measurement and $Z_H$–$Z_{DR}$ relationship from measured DSDs. The vertically pointing measurement is a direct technique to derive the calibration bias but this requires special observation strategy. However, the $Z_H$–$Z_{DR}$ technique can be applied for a volume scan and does not require a special scan.

The vertically pointing measurements are only performed three times during the analysis period. Thus, the monitoring of $Z_{DR}$ bias highly depends on the technique of $Z_H$–$Z_{DR}$ relationship and the vertically pointing measurements are used to verify the consistency between the two methods. The verification for the improvement of accuracy in rainfall rate estimation through the calibration of $Z_H$ and $Z_{DR}$ is performed by using the dense rain gauge network data (eight gauges within an area of 1.6 km $\times$ 1.25 km).

The calibration bias of $Z_H$ is obtained from July 11, 2010 to October 8, 2011. The averaged calibration bias is −1.6 dB and the calibrations bias varies from
−3.39 dB to 0.82 dB for each rain event. The variation of the bias within a rain event is about 0.5–0.8 dB which is within the uncertainty of this technique (~1 dB, Lee and Zawadzki 2006). The sudden jump of the calibration bias of $Z_H$ is noticed because of the hardware maintenance.

The $Z_{DR}$ calibration bias derived from vertically pointing measurement changes from 0.7 dB in 2010 to 0.47 dB in 2011. This $Z_{DR}$ calibration is applicable for a reflectivity of 38 dBZ. The two calibration methods (vertically pointing observation and average $Z_H$–$Z_{DR}$ relationship) provide consistent results.

$Z_H$ and $Z_{DR}$ calibration method in this study can be used for C-band or X-band radar with proper climatological relationships and attenuation correction. However, this method is more applicable for lower reflectivity to avoid resonance effects. The error of rainfall estimation is reduced by using the areal average rainfall from eight gauges and the application of adaptive calibration bias is the most effective in reducing radar rainfall errors in particular for rainfall estimators with both $Z_H$ and $Z_{DR}$. Thus, the determination of the calibration bias of $Z_H$ and $Z_{DR}$ is essential to improve the accuracy of radar rainfall estimation. The rainfall estimators with $Z_H$ and $Z_{DR}$ derived from the disdrometric data lead to rainfall overestimation by 34 %–37 %. This may be due to the yearly variation of average DSDs and the small data set of disdrometer used in this study. Thus, the rainfall estimators are adjusted with gauges and provide nearly no bias.

**Acknowledgment**

This research is supported by “Development and application of Cross governmental dual-pol. radar harmonization (WRC-2013-A-1)” project of Weather Radar Center, Korea Meteorological Administration in 2014 and the Korea Meteorological Administration Research and Development Program (Grant No. CATER 2013-2040).
Appendix

To verify the $Z_{DR}$ calibration method using $Z_H$–$Z_{DR}$ relationship, the disdrometer data in Section 2.3 was used. The same method was applied to the $Z_H$ and $Z_{DR}$ simulated from disdrometer data. The temporal variation of $Z_{DR}$ bias is shown in Fig. A1. In this figure $Z_{DR}$ is equal to $Z_{DR}$ bias. The dot symbol is $Z_{DR}$ bias from raw data and the diamond symbol represents $Z_{DR}$ bias calculated by using the method presented in Section 3.2.b. The result show the stable variation of $Z_{DR}$ when the standard deviation and mean absolute error were applied. The averaged standard deviation and mean absolute error were within 0.1 dB.

The comparison of $Z_{DR}$ biases between $Z_H$–$Z_{DR}$ relationship and vertically pointing measurements were performed to evaluate the stability of this method. Moreover, we simultaneously compared $Z_{DR}$ bias using the simulated data from the 2D-video disdrometer (2DVD, Schönhuber et al. 2008). The $Z_{DR}$ value was calculated using T-matrix scattering (Bringi et al. 1990; Vivekanandan et al. 1991) with the assumption in Table 3 and by using the DSDs measured from 2DVD. The $Z_{DR}$ calculated from 2DVD was compared with $Z_{DR}$ measured from radar. The radar measured $Z_{DR}$ was averaged 3° by 11 gates (1.2 km × 1.375 km) to reduce measurement noise. The 2DVD was located at the KNU observation field, 23 km away from the radar. The 2DVD was operated on June 30 and October 24, 2012. The vertically pointing observation was performed for seven days during 2012.

Figure A2 shows the temporal variation of $Z_{DR}$ calibration biases. The $Z_{DR}$ biases from 2DVD and vertically pointing method systematically differ from $Z_H$–$Z_{DR}$ relationship method. The $Z_{DR}$ bias calculated from vertically pointing method was approximately 0.17 dB larger than the bias from average $Z_H$–$Z_{DR}$ relationship. This systematic bias is applied to the $Z_{DR}$ bias from $Z_H$–$Z_{DR}$ relationship. The physical reasons for the systematic difference between vertically pointing measurements and $Z_H$–$Z_{DR}$ relationship is not certain. Possible reasons can be the inaccurate representation of the $Z_H$–$Z_{DR}$ relationship derived from DSD and side lobe contamination in $Z_{DR}$.

References

Al-Khatib, H. H., 1979: Differential reflectivity and its use in the radar measurement of rainfall. The Ohio State University.


Bringi, V., V. Chandrasekar, D. Zmic, and C. Ulbrich, 2003: Comments on “The need to represent raindrop size spectra as normalized gamma distributions for the


