Rainfall observations and assessment using vertically pointing radar and X-band radar
N. Mazari, H. O. Sharif, H. Xie, A. E. Tekeli, J. Zeitler and E. Habib

ABSTRACT
Two years of K-Band micro rain radar-2 (MRR) data are used to investigate the vertical variability of rain in an atmospheric column and assess MRR rainfall estimates accuracy from both direct rainfall measurement using the Mie Theory (i.e., MRR RR) and a Z-R relationship (Z = 300 R^{1.4}) (i.e., MRR Rz). Two different height resolutions (HR) settings are used. A nearby Doppler weather radar KEWX (S-band) using the same Z-R relationship is found to underestimate rainfall by up to 32.2%, while MRR estimates are much closer to collocated gauge measurements. For the first three gates, MRR RR underestimates rainfall by 5.7%–60.1% for the HR of 35 meters and by 31.2%–47.9% for the 100 meter resolution, while MRR RR overestimates rainfall for higher gates at the 100 m resolution, and MRR Rz underestimates rainfall at all gates due to errors of the Z-R relationship (Z = aR^b). Gates higher than 2,000 m are affected by bright band and mixed phase rainfall. Examination of the rainfall statistics suggests that the 100 m HR produces better rainfall estimates, and that the gate centered at 300 m has better performance than the gate centered at 70 m.

Key words | gauge, MRR, NEXRAD, rainfall, reflectivity, variability

INTRODUCTION
Rainfall is among the most important inputs in hydrometeorological and water resources studies. In addition to traditional measurement devices such as rain gauges, weather radar has evolved into a viable complementary (or alternative) method for applications in atmospheric research, weather prediction, and hydrometeorology. Radar rainfall estimations were significantly improved with the deployment of the WSR-88D Next Generation Radar (NEXRAD) network in the early 1990s (Neary et al. 1997). This network of some 146 radars across the United States has been instrumental in improving rainfall measurements quantitatively and spatially, by covering large and remote areas that may be sparsely covered by rain gauges. Rain gauges take samples of precipitation at a point, while radar takes samples of precipitation within a volume and estimates the average accumulation over an area. As a result, there are differences in precipitation estimates from these two methods (Ciach & Krajewski 1999; Habib et al. 2004; Xie et al. 2006; Wang et al. 2008). Also, weather radar estimates rainfall aloft from reflectivity returns, while gauges measure rainfall at ground level. Rain gauges also suffer from a number of measurement errors, wind may be the most important of these errors (Rodda & Dixon 2012), others include evaporation, splash or sometimes mechanical failure in the gauge tipping bucket system.

Weather radar measures rainfall remotely using the quantity known as the reflectivity factor Z, with units
of mm$^6$ m$^{-3}$. Compared with rain gauges rainfall rate (mm hr$^{-1}$), or accumulation (RA, in mm), the radar rainfall measurements are estimated through a relationship between the reflectivity (Z) and the rain rate (R). Two approaches are used to derive the Z-R relationship, the rain’s drop size distribution (DSD) approach and the optimization approach (Krajewski & Smith 2002). In the DSD approach, Z-R relationships are derived from raindrop size distributions measured at the surface, and estimates of rainfall rates are derived from the drops fall velocity, raindrop size distribution and count within a volume. The optimization approach is based on relating radar reflectivity measured in the atmosphere to surface observations of rainfall, typically from rain gauge networks.

Weather radar rainfall products still suffer from biases and limitations due to hardware, software and processing algorithms, and simply to the presence of other hydrometeors in the atmosphere along with water droplets (Fabry 2004; Sharif et al. 2004, 2006; Mazari et al. 2013). The recent introduction of dual polarization capability to the NEXRAD network is expected to enhance rainfall estimation through classification of hydrometeors (e.g., rain, graupel), discrimination of precipitation types and separation between hydrometeor and non-hydrometeor, and finally an improvement in radar data quality and resolution (NEXRAD Now 2010). The NEXRAD rainfall products, such as Level III and the Digital Storm-total Precipitation product are based on Level II reflectivity (Mazari et al. 2013; Wang et al. 2013). Other products, such as the Multi-sensor Precipitation Estimator or Stage III rainfall products, are a multi-sensor mix of radar, rain gauges, and satellites. Nevertheless, the WSR-88D rainfall estimates are range dependent and carry errors from the Z-R relationship. The radar reflectivity, which is the basis of rainfall measurement, is more sensitive to raindrop diameter and DSD distribution than the rain rate (Chumchean et al. 2008). Different DSDs will produce different reflectivities, even if the rain rate remains the same.

Standard horizontally-scanning weather radar cannot detect rainfall variability in an atmospheric column. Understanding vertical variability may help adjust radar estimates that are made well above ground level. Vertically pointing radar (VPR) such as the micro rain radar (MRR) (Peters et al. 2002, 2005; METEK 2004, 2005) measure DSDs, reflectivity (Z), rainfall rates (R), and other parameters in an atmospheric column, therefore, they are complementary to standard, horizontally-scanning weather radar and in situ rain measuring devices (Tokay et al. 2009; Prat & Barros 2010). Characterizing the rainfall’s microphysical processes is essentially based on the understanding of the DSD distribution (Lee et al. 2009). This DSD distribution throughout an atmospheric column can only be practically investigated through the use of a VPR. Although a disdrometer can provide DSD distributions, this sensor typically is limited to measurements at ground level.

Peters et al. (2002) have shown good agreement ($\rho = 0.87$) between rain gauge observations and MRR estimates at a height of 500 m above the rain gauges. For total rainfall events, agreement between the two sensors was within 5%, but for instantaneous measurements the results showed deviations up to a factor of two between MRR and rain gauge estimates. Tokay et al. (2009) suggested the second gate of the MRR (centered at 70 m) is the first reliable gate for comparison between an MRR and a disdrometer. They found good overall agreement between the MRR and the disdrometer, but MRR estimates deteriorate during intense convection, probably due to attenuation. They cautioned that the MRR Reflectivity estimates are not reliable above 500 m. Rollenbeck et al. (2007) reported an MRR underestimated rain rates by about 32% when compared to a rain gauge. They also compared MRR to a local weather radar, and found that the rain rate correlation between the MRR and the radar was $R^2 = 0.59$ for the hourly averaged rain rates, and $R^2 = 0.72$ for daily averaged rain rates, and $R^2 = 0.62$ for the daily rainfall totals. Prat & Barros (2010) used two MRRs and several tipping bucket rain gauges at two locations. The comparison of the total accumulated rainfall for the collocated gauges with the MRRs indicated one MRR severely underestimated rainfall at one site in the summer and fall. In contrast, the second MRR overestimated the total rainfall by about 200%. These and previous results (Löffler-Mang et al. 1999; Peters et al. 2002) show that calibration and/or attenuation may be a major source of error for MRR rainfall estimation. Another MRR source of error may be the ambiguity in differentiating between snow and rain (Cha et al. 2007).
especially during convective rainfall (Peters et al. 2005; Bendix et al. 2006; Tridon et al. 2011). Raindrop velocity is also affected by horizontal air motion which can also introduce errors.

In this paper, rainfall measurements from MRR at two height resolution (HR) settings (35 and 100 m) are compared and evaluated against observations by a collocated tipping bucket rain gauge and rainfall derived from the Level II reflectivity product from the nearest weather radar (KEWX). The MRR estimates of rainfall are derived from DSD and from reflectivity. MRR rainfall measurements at different gates are examined. For the purpose of the study, we will follow the manufacturer’s suggestions and keep the same MRR calibration constant to investigate rainfall measurements at different heights.

The KEWX radar

The KEWX radar is an S-band radar with a frequency ranging from 2.7 to 3.0 GHz located 58.5 km from the MRR/KEWX radar. The KEWX radar is an S-band radar with a frequency ranging from 2.7 to 3.0 GHz located 58.5 km from the MRR/KEWX radar (Fulton et al. 1997). The KEWX radar has a 2.7 to 3.0 GHz frequency range and uses several beam elevation angles (0.5° to 19.5°) to cover an area in a 230 km radius. The first and most basic NEXRAD product is the Level II base reflectivity available in increments of 0.5 dBZ. The Level II data product is a major component of the NEXRAD Precipitation Processing System, which incorporates radar raw data preprocessing and corrections, including a partial beam blockage correction, ground clutter and anomalous propagation removal, and correction for hail and range degradation. The WSR-88D rainfall algorithm and processing system is described by Fulton et al. (1998).

The estimation of rainfall rate from radar reflectivity is accomplished through a Z-R relationship \( Z = aR^b \) (Battan 1973; Doviak & Zrnic 1984; Fulton et al. 1998), where \( Z \) is the radar reflectivity in units of mm\(^6\) mm\(^{-3}\) and \( R \) is the rain rate (mm hr\(^{-1}\)). The values of the coefficient \( a \) range from 75 to 300 and the values of the exponent \( b \) from 1.2 to 2.0. The national weather service (NWS) has a preselected set of values for \( a \) and \( b \) depending on rainfall regime and climate. The default NEXRAD (also true for the KEWX) settings are coefficient \( a \) is 300 and the exponent \( b \) is 1.4 (i.e., \( Z = 300 \ R^{1.4} \) (Battan 1973; Doviak 1983; Doviak & Zrnic 1984; Fulton et al. 1998).

MRR

The MRR is a compact 24 GHz K-band radar (wavelength of 1.25 cm). It transmits radiation vertically into the atmosphere, where a small portion is scattered back to the antenna from raindrops or other hydrometeors. The MRR is able to measure the reflectivity \( Z \) (in units of dBZ), the rain rate (in units of mm hr\(^{-1}\)), the liquid water content (in units of g m\(^{-3}\)) and the falling velocity of the raindrops (m s\(^{-1}\)). These measurements are resolved into 30 range bins or gates. The backscattered signal consists of a distribution of different Doppler frequencies or raindrop diameters. Spectral analysis of the received signal yields a wide distribution corresponding to the Doppler frequencies of the signal. The temporal resolution for this spectrum is about 10 seconds and integration over the entire drop spectrum results in the actual rain rate and liquid water content. The MRR is capable of detecting very light precipitation below the threshold of conventional rain gauges (up to 0.01 mm hr\(^{-1}\)). The droplet number concentration in each drop-diameter bin is derived from the backscatter intensity in each corresponding frequency bin. A summary of the specifications of the two radars is shown in Table 1.

The MRR rainfall parameters are computed according to the following equations. The DSD is described by the number of raindrops \( N(D) \) per volume for a given diameter which is computed by:

\[
N(D) = \frac{\eta(D)}{\sigma(D)}
\]

(1)

where \( \sigma(D) \) is the single particle backscattering cross section, and \( \eta(D) \) is the spectral reflectivity as a function of the drop diameter \( D \).

The reflectivity is estimated from the DSD using the equation below:

\[
Z = \frac{\pi}{6} \int_0^\infty N(D) D^6 \, dD
\]

(2)

where \( Z \) is referred to as the Equivalent Radar Reflectivity factor with units of mm\(^6\) mm\(^{-3}\).
Rain rate ($R$) can be calculated as a function of fall velocity spectra $\nu(D)$ and the DSD $N(D)$ as:

$$R = \frac{\pi}{6} \int_0^\infty N(D) D^3 \nu(D) \, dD$$  \hspace{1cm} (3)

METHODS AND DATA

The gauge and the MRR were installed on the main campus of the University of Texas at San Antonio. The elevation of the site is 324 m above mean sea level, and is located 58.5 km from the nearest NEXRAD radar (KEWX) near New Braunfels, Texas. The lowest elevation (0.5 degree) beam for the LEVEL II reflectivity product was used. The KEWX 0.5 degree midpoint beam centerline elevation is approximately 2,438 m above the MRR/rain gauge site. The corresponding MRR gate (considering a HR of 100 m) for this NEXRAD beam is the gate numbered 24 with an elevation centered at 2,400 meter above ground. Observations started on December 18, 2009 (for both the MRR and rain gauge) and ended on July 31, 2012. Data collection was interrupted several times during this period due to rain gauge or MRR failure. The tipping bucket rain gauge used for this study is a Campbell Scientific TB4, with a 0.254 mm (0.01 in) funnel and the gauge temporal resolution was set to one minute. It scans for tips every 10 seconds, and records the time stamp and the number of tips for each minute through the data logger (Campbell Scientific CR3000 series). The MRR produces measurements every minute.

A set of statistics is used to compare estimates from the three sensors at different time scales. The main statistics are the Pearson correlation coefficient ($\rho$) and the bias ($\beta$). The statistics are described below.

**Correlation coefficient ($\rho$).** This is the ratio of the sample covariance of two variables (e.g. $R_g$ and $R_{MRR}$) to the product of the two standard deviations and is expressed as

$$\rho = \frac{\text{COV}(R_{MRR}, R_g)}{\sigma(R_{MRR})\sigma(R_g)}$$  \hspace{1cm} (4)

where $\text{COV}(R_{MRR}, R_g)$ is the covariance of the collocated radar gauge rainfall amounts (both are non-zero), $\sigma (R_{MRR})$ is the conditional standard deviation of the MRR rainfall estimates (non-zero) and $\sigma (R_g)$ is the conditional standard deviation of the gauge rainfall estimates (non-zero).

**Bias between the two sensors ($\beta$).** For this statistic (with units of mm) we consider the rain gauge as the reference sensor representing the ground truth for the rainfall rate and accumulation,

$$\beta = \frac{1}{n} \sum_{i=1}^{n} (R_{i g} - R_{i MRR})$$  \hspace{1cm} (5)

where $n$ is the number of paired measurements.

**Weighted absolute bias $|\beta_W|$.** This statistic (with units of mm) includes weights that depend on the values of $R$ such that the events with higher accumulations have more impact on the computed bias (Tokay et al. 2009). The statistic is computed as

$$|\beta_W| = \frac{1}{n} \sum_{i=1}^{n} w_i |(R_{i g} - R_{i MRR})|$$  \hspace{1cm} (6)

### Table 1: Specifications for the WSR-88D weather radar, and the MRR-2

<table>
<thead>
<tr>
<th>Specification</th>
<th>MRR</th>
<th>NEXRAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit frequency</td>
<td>24 GHz (K-band)</td>
<td>2,700–3,000 MHz (S-band)</td>
</tr>
<tr>
<td>Beam width</td>
<td>1’ (or 2 two way, 6 dB)</td>
<td>0.48’ ~ 0.925’</td>
</tr>
<tr>
<td>Antenna</td>
<td>Offset-parabolic 0.6 m diameter</td>
<td>Parabolic 10 m diameter</td>
</tr>
<tr>
<td>Modulation</td>
<td>FM-CW</td>
<td>Polarization: linear horizontal</td>
</tr>
<tr>
<td>Transmit power</td>
<td>50 mWatt</td>
<td>750 KWatt (peak)</td>
</tr>
<tr>
<td>HR</td>
<td>10–1,000 m</td>
<td>Azimuth increment 1 degree</td>
</tr>
<tr>
<td>Averaging time</td>
<td>10–3,600 s</td>
<td>4 ~ 12 minutes</td>
</tr>
<tr>
<td>Height range</td>
<td>10 ~ 30,000 m (along 30 gates)</td>
<td>Range increment 250 m (230 km max.)</td>
</tr>
</tbody>
</table>
where \( w_i \) is the weighting function and is calculated as shown below:

\[
w_i = \frac{R_{tg}}{\sum_{i=1}^{n} R_{tg}}
\]

(7)

Normalized absolute bias \( |\beta_N| \). This bias is unitless. If the rain gauge is considered to be the reference sensor then it will be calculated as follows:

\[
|\beta_N| = \frac{\sum_{i=1}^{n} (R_g - R_{MRR})}{\sum_{i=1}^{n} (R_g)}
\]

(8)

Rainfall events

The start and end time of a rainfall event is determined by the rain gauge data. The rainfall event separation requirement is defined as at least two hours of no rain between consecutive events (or gauge tips); in our case, this arbitrary period is the most practical and efficient choice to separate between different rain events. We match the gauge events to both MRR and WSR-88D’s Level II (KEWX) data for comparison. No data are time-shifted, and the rainfall event time stamps are in local Central Daylight Time in summer or Central Standard Time in winter. The MRR HR was set to 35 m for the period from December 18, 2009 to May 17, 2010. We then changed the resolution to 100 m for all data collected from November 26, 2011 to July 31, 2012. We use the HR35 and HR100 for referring to the two HRs used. The number of total rainfall events was 52 for HR35, and 43 for HR100.

RESULTS

Comparison of rainfall events totals

Seventy-five events were recorded during the deployment period, 15 of which recorded rainfall totals greater than 10 mm. The comparison of rainfall between all sensors is based on these 75 events. Figure 1 shows the total accumulated rainfall for the two periods with different HRs as estimated by the three sensors. In this figure and most of the following figures, the MRR rainfall estimates (RR and Rz) are plotted as a function of the gate height.

Over the study period, the rain gauge recorded 312.2 hours of rainfall, from the 75 events with an event total of more than 2 mm. The gauge accumulated rainfall was 863.6 mm, while KEWX reported 585.6 mm (based on Level II reflectivity data). MRR RR and Rz accumulated rainfall are shown for the first four gates in Table 2 for both HR35 and HR100. As shown in Figure 1, at the 100 m HR MRR total rainfall accumulations (RR) varied from 227.9 mm to 1,563.7 mm (depending on MRR gate), while the rain gauge had only 437.6 mm of total rainfall for all events for the same HR. In contrast the MRR Rz totals for the same HR were from 255.6 mm to 300.9 mm.

It can be seen from Figure 1 that MRR RR overestimated the total rainfall accumulations (RAs) from the fifth gate and above for HR35, and for the last 10 gates for HR100. In Figure 1(a), where the accumulation totals are plotted at HR35, the first three gates underestimated rainfall by 5.7 to 60%, and the fourth gate underestimated by only 2.7% (11.4 mm), followed by the fifth gate (175 m) which overestimated the total accumulation by 2.9% (12.4 mm). For the HR100, it is the gate at 1,000 m (Figure 1(b) and 1(c)) that agrees best with the gauge with an underestimation of only 1.3%, followed by the 15th gate (1,500 m) with an overestimation of 2.4%, then the 18th gate with an overestimation of 2.8%. The first five gates at this resolution (100–500 m) underestimated the total rainfall by 16.4 to 47%, with the first gate having the highest underestimation.

MRR Rz underestimated the total rainfall for all gates and the underestimation increased steadily after the second or third gate. At HR35, it is the third gate (105 m) that had the lowest underestimation (45.1%); for HR100, it is the second gate (200 m) that had the lowest underestimation compared to the rain gauge, with a difference of 31.2%. For the KEWX, it underestimated the total rainfall by about 33.8% for accumulation at HR35 and by 30.6% for total rainfall at HR100.

A closer inspection of the rainfall totals by height (Figure 1) reveals that for the last ten gates (840 to 1,050 m at HR35 and 2,100 to 3,000 m at HR100) the MRR overestimated rainfall by differences ranging from 130.5 (for the gate centered at 2,100 m) to 926.0 mm (for the gate centered at 2,500 m above ground). Interestingly only six events, two at HR35 and four at HR100 had severe overestimation of rainfall by the MRR RR, while
the KEWX totals were nearly always below rain gauge totals. These events are shown in Tables 3 and 4, with total accumulated rainfall for the last seven gates. Results suggest that the severe overestimation of rainfall by the MRR occurred only for the MRR RR, in contrast MRR Rz underestimated rainfall for most events (except for the December 24, 2009 and March 20, 2012 events). The six events with higher overestimation are removed from further comparison and we are investigating some of them in a later section of this paper.

**Rainfall variability with height**

The variability of RR and Rz with height is shown in Figure 2, for all 75 events over the two periods (HR35 and HR100). These figures show the random
pattern of the variability by height for all events above 10 mm of total accumulated rainfall, while for smaller accumulations the total rainfall decreased with height for RR and it is almost constant for Rz. The variability is more pronounced and random for the case of RR.

Rainfall statistics

The comparison between the different rainfall estimates can be summarized using the statistics described in Equations (5) through (8) in the Methods and data section. The statistics are computed for each MRR gate at both HRs for all

Table 2  Total accumulated rainfall events (in mm) for the 75 events used in the study, the first 34 events from December 18, 2009 to May 17, 2010 with a HR of 35 meters, and from November 21, 2011 to July 31, 2012 with HR of 100 meter

<table>
<thead>
<tr>
<th>MRR</th>
<th>Events</th>
<th>Hours</th>
<th>Minutes</th>
<th>Gauge</th>
<th>KEWX</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR</td>
<td>34</td>
<td>128.9</td>
<td>5,571.4</td>
<td>426.0</td>
<td>281.8</td>
<td>170.0</td>
<td>346.6</td>
<td>401.5</td>
<td>414.6</td>
</tr>
<tr>
<td>Rz</td>
<td>34</td>
<td>128.9</td>
<td>5,571.4</td>
<td>426.0</td>
<td>281.8</td>
<td>144.5</td>
<td>230.2</td>
<td>234.0</td>
<td>227.6</td>
</tr>
</tbody>
</table>

Table 3  Six rainfall events with unusually high MRR RR rainfall: the table shows the last seven gates (heights shown are in meters above antenna)

<table>
<thead>
<tr>
<th>HR35 HR100</th>
<th>Height (m)</th>
<th>Storm began</th>
<th>Storm ended</th>
<th>TB4</th>
<th>KEWX</th>
<th>840</th>
<th>2,400</th>
<th>875</th>
<th>2,500</th>
<th>910</th>
<th>2,600</th>
<th>945</th>
<th>2,700</th>
<th>980</th>
<th>2,800</th>
<th>1015</th>
<th>2,900</th>
<th>1050</th>
<th>3,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12/24/2009</td>
<td>01:43</td>
<td>12/24/2009</td>
<td>02:51</td>
<td>3.8</td>
<td>2.2</td>
<td>72.9</td>
<td>85.3</td>
<td>100.6</td>
<td>102.5</td>
<td>93.8</td>
<td>90.0</td>
<td>98.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3/24/2010</td>
<td>23:27</td>
<td>3/25/2010</td>
<td>00:09</td>
<td>3.6</td>
<td>0.1</td>
<td>51.2</td>
<td>44.6</td>
<td>48.6</td>
<td>48.4</td>
<td>43.7</td>
<td>43.4</td>
<td>44.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12/10/2011</td>
<td>14:26</td>
<td>12/11/2011</td>
<td>02:54</td>
<td>15.5</td>
<td>20.3</td>
<td>425.8</td>
<td>430.7</td>
<td>366.1</td>
<td>290.8</td>
<td>264.4</td>
<td>243.3</td>
<td>274.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12/21/2011</td>
<td>19:28</td>
<td>12/22/2011</td>
<td>02:39</td>
<td>19.3</td>
<td>16.3</td>
<td>458.2</td>
<td>506.2</td>
<td>441.4</td>
<td>326.0</td>
<td>249.3</td>
<td>203.3</td>
<td>180.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/30/2012</td>
<td>15:20</td>
<td>1/30/2012</td>
<td>18:53</td>
<td>8.1</td>
<td>8.0</td>
<td>46.4</td>
<td>66.1</td>
<td>68.5</td>
<td>66.6</td>
<td>59.6</td>
<td>48.2</td>
<td>39.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2/10/2012</td>
<td>04:12</td>
<td>2/10/2012</td>
<td>05:45</td>
<td>6.9</td>
<td>7.4</td>
<td>51.2</td>
<td>50.6</td>
<td>52.4</td>
<td>48.7</td>
<td>50.7</td>
<td>58.0</td>
<td>58.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4  Six rainfall events with unusually high MRR Rz rainfall: the table shows the last seven gates (heights shown are in meters above antenna)

<table>
<thead>
<tr>
<th>HR35 HR100</th>
<th>Height (m)</th>
<th>Storm began</th>
<th>Storm ended</th>
<th>TB4</th>
<th>KEWX</th>
<th>840</th>
<th>2,400</th>
<th>875</th>
<th>2,500</th>
<th>910</th>
<th>2,600</th>
<th>945</th>
<th>2,700</th>
<th>980</th>
<th>2,800</th>
<th>1015</th>
<th>2,900</th>
<th>1050</th>
<th>3,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12/24/2009</td>
<td>01:43</td>
<td>12/24/2009</td>
<td>02:51</td>
<td>3.8</td>
<td>2.2</td>
<td>4.7</td>
<td>5.5</td>
<td>6.1</td>
<td>6.4</td>
<td>6.1</td>
<td>5.4</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3/24/2010</td>
<td>23:27</td>
<td>3/25/2010</td>
<td>00:09</td>
<td>3.6</td>
<td>0.1</td>
<td>4.3</td>
<td>4.2</td>
<td>4.4</td>
<td>4.4</td>
<td>4.3</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12/10/2011</td>
<td>14:26</td>
<td>12/11/2011</td>
<td>02:54</td>
<td>15.5</td>
<td>20.3</td>
<td>21</td>
<td>16.7</td>
<td>13.2</td>
<td>10.9</td>
<td>10.3</td>
<td>10.5</td>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/30/2012</td>
<td>15:20</td>
<td>1/30/2012</td>
<td>18:53</td>
<td>8.1</td>
<td>8.0</td>
<td>7.5</td>
<td>7.1</td>
<td>6.2</td>
<td>5.3</td>
<td>4.2</td>
<td>3.2</td>
<td>2.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2/10/2012</td>
<td>04:12</td>
<td>2/10/2012</td>
<td>05:45</td>
<td>6.9</td>
<td>7.4</td>
<td>3</td>
<td>2.7</td>
<td>2.6</td>
<td>2.5</td>
<td>2.4</td>
<td>2.6</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
69 rainfall events retained. Differences among the events are also illustrated from events 1 to 32 (for the HR35), at the second and third gates centered at 70 and 105 m, respectively, and from event number 33 to 69 (for the HR100), at the gates centered at 100, 200 and 300 m (first, second and third gates, respectively).

The correlations between the rain gauge and MRR RR and Rz and between KEWX and MRR RR and Rz for the rainfall totals are presented in Figure 3. The correlation between MRR RR estimates and estimates by the rain gauge decreases significantly with height. The values of the correlation coefficients range between 0.59 and 0.96. The maximum correlation occurs at the first gate for the 35 m HR. The correlation is lower for the 100 m resolution with values of \(\rho\) between 0.18 and 0.70 and a maximum at the fourth gate (400 m). The correlations with MRR Rz are more stable and significantly higher than with MRR RR for the 35 m resolution. The correlation coefficient for Rz ranges between 0.86 and 0.95 for 35 m HR and between 0.53 and 0.81 for the 100 m HR. For the first resolution (HR35) the correlation is best at the first gate (35 m), while for HR100, the best correlation occurred at the 28th gate (2,800 m) with \(\rho = 0.81\). The correlation with KEWX (Figure 3(c) and 3(d)) shows a similar decreasing trend with height. Correlations for the HR35 are lower in the KEWX case than the rain gauge. For the HR100, the trend in the correlation coefficient with height is similar to the gauge and MRR case, but with higher overall minimum values.

The correlation coefficient may not be enough to determine the MRR gate that best agrees with either the
rain gauge or KEWX. Habib et al. (2004) and Tokay et al. (2009) stated that this statistic is not strong enough to derive any conclusions from its values, as it only shows the agreement of the trend of the compared data sets. Scatter plots for comparison of estimates from MRR and the rain gauge are constructed for all gates. The overall results shows that in general estimates from the higher gates are noisier and agree less with the rain gauge measurements.

Scatter plots for the first three gates are shown in Figure 4 (HR35) and Figure 5 (HR100). For HR35 the best agreement with the rain gauge occurs at the first gate for MRR RR and Rz. In contrast, for HR100, the second and third gates agree most with the rain gauge for MRR RR while the third gate agrees better for the MRR Rz.

Comparison of MRR RR and MRR Rz with KEWX rainfall estimates produced similar results for both HRs. This is not surprising as the correlation between the rain gauge and KEWX is high ($\rho = 0.89$). However, the comparison of rainfall totals between the gauge and KEWX (Figure 6) shows a clear underestimation by the weather radar. The high correlation indicates that the KEWX radar could adequately capture the rainfall variability but produced biased estimates of total RAs. This agrees with studies (e.g. Skinner et al. 2009; Mazari et al. 2013) that...
observed underestimation by weather radars at distances similar to the distance between KEWX and the study site (less than 60 km).

The cumulative rainfall depth estimated by the three sensors is shown in Figure 7 for two events from each HR. Both MRR and KEWX radars had captured the
time evolution or variability of rainfall quite well and their cumulative rainfall follows closely the rain gauge observations for the majority of the events. However, the MRR RR estimates are significantly better than KEWX’s. Like KEWX, MRR Rz underestimated rainfall in most of the events and its performance was better for the first and seventh events. Both radars used the same Z-R relationship which can be the cause of this underestimation.

The standard deviation increases with height for the paired records of gauge and MRR RR, while the paired records of gauge and MRR Rz show a reverse trend for both HRs (Figure 8). The same is true for the paired records of KEWX and MRR RR (not shown).

For the first HR (35) as shown in Figure 8, the standard deviation increases with height for both MRR RR estimates compared to gauge or KEWX rainfall estimates (not shown in figures), the values for the standard deviation ranged from 13 to 29.1 mm. In contrast, the standard deviation for the MRR Rz compared either with gauge or KEWX decreases with height.

Considering the gauge as the reference sensor, the bias is found to decrease with height, which means a decrease of MRR RR and gauge rainfall agreement accuracy with height. While in the case of MRR Rz, the bias is slightly increasing with height. This shows that MRR reflectivity is less reliable or has more attenuation for higher gates. The weighted and normalized bias (Figure 8) increases with height either for MRR RR or MRR Rz.

At the HR100, the standard deviation is also increasing with height for MRR RR and decreases with height for MRR Rz, with values ranging from 11.9 to 18.1 mm for the gauge and MRR comparison, and from 3.1 to 7.4 mm for the MRR and KEWX comparison.

![Figure 6](image_url) Scatter plot of total rainfall for gauge (TB4) and KEWX rainfall measurements derived from the Z-R relationship ($\rho = 0.89$).
Similar to the previous HR, the bias decrease with height is more significant for the MRR RR than the MRR Rz. For the weighted and normalized bias, there is more fluctuation with height, while the trend is slightly increasing, either for MRR RR or MRR Rz. The same is true if MRR RR or MRR Rz is compared to KEWX rainfall estimates (not shown). This result may be due to the MRR higher sampling volume and higher attenuation, especially in the case of the MRR Rz rainfall estimates.

The impact of bigger rainfall events is higher in the absolute weighted bias statistics. The results show that the weighted bias ($\beta_w$) overall increased with height specifically for the HR of 35 m, and its values are much higher than the regular bias. For MRR RR estimates as compared with gauge measurements, $\beta_w$ varies between 8.2 and 31.1 mm (HR35), and between 11.8 and 20.6 mm (HR100). For MRR Rz estimates as compared with gauge measurements, $\beta_w$ varies between 13.3 to 25.1 mm and between 11.9 and 18.1 mm for HR35 and HR100, respectively. $\beta_w$ values of MRR RR and MRR Rz show similar patterns and magnitudes when KEWX estimates are taken as the reference for both resolutions (not shown in figures).

The last statistic used is the normalized bias ($\beta_N$), which eliminates the weight of bigger events. Results for $\beta_N$ are...
shown in Figure 8(g) and 8(h). Similar to the weighted bias, \( \beta_N \) increases with height in all cases. The values of \( \beta_N \) are lower for MRR Rz than MRR RR. The normalized bias is higher for HR35 resolution estimates for all cases. The agreement between the MRR and the weather radar rainfall is lower for both RR and Rz.

The previous statistics have shown that the second and third gates agreed best with the rain gauge estimates; these are the gates centered at 70 and 105 m (HR35) and the gates centered at 200 and 300 m (HR100). Statistics for these two gates are compared for individual events in Figures 9 and 10. The bias (Equations (5)–(8)) for MRR RR is smaller for the gate centered at 200 m than the gate centered at 70 m as can be seen in Figure 9.

The bias varies from −4.66 mm to 13.37 mm, and the absolute weighted bias is from 0.0 to 0.6 mm, while the normalized bias is from 0.07 to 2.49 for the gate at 70 m, meanwhile the gate at 200 m has a significantly lower statistics range, −2.53 to 8.03 for the bias, 0.00 to 1.93 mm for the absolute weighted bias, and 0.04 to 4.5 for the normalized bias. The bias of MRR Rz estimates shows similar patterns as seen in Figure 9. When taking
KEWX as a reference, the bias of MRR estimates (not shown) is similar in magnitude. The gate centered at 200 m has better agreement with KEWX estimates than the 70 m gate.

The bias of MRR RR rainfall at the third gates (105 m and 300 m) is also lower for the HR100, that is, the third gate at 300 m is better than the gate at 105 m (Figure 10). The average values are 1.10, 0.09 and 0.04 mm, for the bias, the weighted bias and the normalized bias, respectively, at the 105 m gate, while the 300 m gate have average values of 0.43, 0.12 and 0.52 mm, respectively, for the same statistics. The same conclusions apply to MRR Rz estimates (Figure 10) and when taking KEWX as the reference (not shown).

Figures 9 and 10 clearly show that MRR RR and MRR Rz estimates of the gate at 70 m (second gate) have higher bias statistics than those of the gate at 105 m (third gate) for HR35. However, for HR100, MRR RR and MRR Rz
estimates of the third gate have higher bias statistics than those of the second gate. Overall, the third gate (300 m height) has the best rainfall estimates when compared to the rain gauge estimate.

The event of December 21–22, 2011

To investigate one of the six excluded events cited in Tables 3 and 4, we select the event of December 21–22, 2011 because this event had the highest rainfall accumulation as measured by the gauge, while it had the second highest rainfall overestimation by MRR (Table 3). The MRR RR recorded a total rainfall of 180.5 to 506.2 mm for this event at the last seven heights (2,400 to 3,000 m), while the gauge had only 19.3 mm of total rainfall and the KEWX 16.3 mm. This indicates an overestimation of about 161.2 to 486.9 mm in comparison to the rain gauge. The plots in Figure 11 show the rainfall parameters as derived by the MRR; the rain rate is shown to be very high (over 45 mm hr⁻¹) from the height of 2,100 m to the 3,000 m, while closer to the ground the rainfall rate is lower than 10 mm hr⁻¹ or closer to 0 mm hr⁻¹ (especially between 00:15 to 00:45 and before 01:00; Figure 11(c)). This high variation in the rainfall rate can only be related to what seems to be the bright band above 2,100 m. In fact, the appeared bright band (dark brown color in Figure 11(b) and 11(d)) appears to be
wider than the melting phase which has lower rainfall rates (yellow to green color in the figure). The bright banding was present at various levels in the KEWX reflectivity for the 21–22 December, 2011 event. Figure 12 clearly shows the bright band at a radius of approximately 50 km from KEWX, on the 2.4 degree elevation slice at 0722 UTC on 22 December, 2011. The beam centerline elevation over the MRR (and rain gauge) is approximately 2,438 m above ground level. The higher reflectivity in the bright band due to water-coated snowflakes at that altitude results in anomalously high reflectivity, and thus a significant overestimation of precipitation using a standard Z-R relationship.

Rainfall drops fall velocity shows that for the same region, the fall velocity is lower than 2 ms\(^{-1}\), which is consistent with snowfall velocity (rainfall velocities are between 2 to 8 ms\(^{-1}\)). The liquid water content is also higher at the region from 2,100 to 3,000 m. While the reflectivity surface plot does not show a clear bright band signature, it seems that there is a mixed phase of snow and rain. This may explain the higher rainfall rates and low reflectivity values for this event. In comparison with the event of December 21–22, 2011, Figure 13 shows a regular rainfall event that occurred on January 15, 2010. This rainfall event clearly shows higher rain rates at the lower heights. The same is true for drops velocities, liquid water content, and reflectivity, which are all higher for gates closer to the ground.

In Figure 14, we plot the drop size distribution (DSD) for the event of December 21–22, 2011, at two heights (500 and 2,300 m). The plot shows significant differences between the two DSDs in terms of number of drops per volume and drops diameter. At 500 m a lower number of drops is found, but a larger drop diameter (right tail of plot), while at 2,300 m,
there are more drops per volume but with smaller diameters. This suggests coalescence is dominant at lower heights.

CONCLUSIONS AND DISCUSSION

Rainfall estimates, by a K-band MRR 2 with two HR settings (35 m and 100 m) and a collocated tipping bucket rain gauge, were collected from December 18, 2009 to February 21, 2012. Estimates from the nearest NEXRAD weather radar (KEWX, New Braunfels, TX) were also compiled. MRR estimates were based on the measured raindrop size distribution and drop fall velocities (MRR RR) and the measured radar reflectivity (MRR Rz). Furthermore, MRR estimates were based on two HRs (35 m and 100 m). The study enabled the examination of the rainfall variability along an atmospheric column and its effect on rainfall estimates as compared to the ground observations by the gauge and estimates by the weather radar.

Taking the rain gauge observations as the ground truth, KEWX underestimated rainfall by 32.2%. MRR RR estimates were much closer to the rain gauge observations than those of MRR Rz. On average, MRR RR estimates at the first, second, and third gates were 60.1%, 18.6%, and 5.7% less than the rain gauge estimates, respectively, for the HR35. HR100 MRR RR estimates were 47.9%, 33.9%, and 31.2% less than the rain gauge estimates, for the first, second and third gates, respectively. For higher gates, MRR RR overestimated rainfall by 10.1 to 211.6%. On the other hand, MRR Rz underestimated gauge-measured rainfall at all gates. The underestimation of MRR Rz was between 45.1% and 70.3% for HR35, and 31.2% to 72.7% for HR100, and the MRR Rz underestimation of rainfall increased with height after the third gate. This result agrees with Tokay et al.’s (2009) conclusion that MRR reflectivity was not reliable at more than 500 m above the antenna. Above that, estimates with the 100 m resolution suffered from higher overestimation than those with the 35 m resolution. MRR Rz estimates with the two HRs were comparable.
Examination of the vertical variability of instantaneous MRR RR estimates or at the event level reveals that it is highly random and varies considerably with time and among events. This observation suggests the existence of strong turbulence caused by vertical winds as observed in other studies (e.g. Peters et al. 2002, 2005). In addition to the variability of raindrop size distribution, coalescence and breakup may probably be the main causes of errors in MRR RR estimates. The vertical variability of MRR Rz is smaller and might be the result of the variability of raindrop size distribution and reflectivity attenuation. It is known that, in convective systems, spatial and temporal variability of rainfall are affected by two main factors: the large-scale atmospheric forcing and the system-scale microphysical properties. Thus, there are large uncertainties associated with the effects of rain microphysics on surface rainfall and vertical profiles along an atmospheric column (Wang & Georganakos 2005). These uncertainties should be explored in more detail in future research.

Examination and combination of all the error statistics for the total rainfall for selected events suggest that the HR100 produced better MRR rainfall estimates. This might be due to the fact that a larger volume of sampling produces better estimates of rainfall that is characterized with significant variability over space and time. Considering the statistics by events it seems that the third gate at HR100 produces the best MRR RR estimates. However, the MRR Rz estimates are slightly better for the second gate, probably due to higher attenuation at the third gate. Comparison with KEWX leads to the same conclusion. This contradicts other results that concluded that the lowest reliable gates were at 500 m or 600 m (Peters et al. 2002; Prat & Barros 2010). The differences in their results and ours are probably due to the differences of rainfall types and MRR calibration. The study also reveals that MRR rainfall measurements in some instances can be very inconsistent as compared to ground rainfall (gauge), and
that investigation of bright band or mixed rainfall phase is useful to correct MRR rainfall estimates. The MRR also is very valuable for investigating drop size distribution and to determine the dominant microphysical rainfall processes.

More studies of this type would result in the development of methodologies that maximize the benefits of the use of MRR in rainfall estimation. A good calibration could improve MRR estimates and a better Z-R relationship (e.g. with a higher exponent) would have significantly improved MRR Rz estimates. Sensitivity of MRR estimates to the event size has to be explored. Due to reliability concerns for tipping bucket rain gauge measurements, more than one rain gauge should be used for calibration. The role of horizontal and vertical winds on MRR estimates needs to be examined in detail.

ACKNOWLEDGEMENTS

This study was partly supported by the NOAA/UCAR/COMET grant No. Z10-83385 and the NASA grant (#NNX11AE42G).

REFERENCES


First received 13 July 2015; accepted in revised form 1 March 2017. Available online 27 March 2017.