A COMPREHENSIVE DATA ANALYSIS FROM TWO VERTICALLY POINTING RADARS

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Abstract

We collected high-resolution data using Doppler X- and S-band vertically pointing radars during the summer of 2002 in Iowa City, Iowa. The radars were collocated with impact and optical disdrometers and dual tipping-bucket rain gauges. The instruments sample at comparable but different spatial and temporal scales and we consider the how to reconcile the data in order to make meaningful comparisons. Both radars detected non-precipitating hydrometeors, and we used a simple but very effective filter that uses the Doppler velocities to identify noisy radar bins. We performed many comparative analyses and investigated the power spectrum and correlation of time series extracted from the data at several heights. We summarize the results and their implications for quantitative rainfall estimation, radar-rainfall error structure studies, and validation of remote sensing of rainfall.

Key Words: X-band radar, S-band radar, vertical profile, Doppler radar

Introduction

We collected high-resolution data using two vertically-pointing radars during the summer of 2002, at the Iowa City municipal airport, in Iowa City, Iowa. These were an X-band Doppler radar of The University of Iowa, and an S-band Doppler radar of the NOAA Aeronomy Laboratory. Table 1 summarizes important characteristics of the radars.

The operation of the X-band radar is straightforward. The PRF is 1,300 Hz, it averages 300 pulses for each bin, and writes the beam/dwell to disk every 300/1,300 = 230 ms. Thus, it samples the atmosphere slightly more than 4 times per second. The S-band radar produces 9-second samples. It operates in two modes. In the high-altitude mode the bin size is 90 m, while in the low altitude mode the bin size is 60 m. The S-band was operated primarily in the low altitude (60 m) mode with about 10% of the time in high-altitude mode (90 m bin sizes).

Table 1 Characteristics of the radars

<table>
<thead>
<tr>
<th></th>
<th>X-band</th>
<th>S-Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>3.2 cm</td>
<td>10.6 cm</td>
</tr>
<tr>
<td>Parabolic Dish Diameter</td>
<td>1.2 m</td>
<td>3.048 m</td>
</tr>
<tr>
<td>Sampling volume</td>
<td>150 m</td>
<td>60 m, 90 m (see text)</td>
</tr>
<tr>
<td>Beamwidth</td>
<td>1.9°</td>
<td>2.5°</td>
</tr>
</tbody>
</table>

The radars were colocated with a tipping-bucket rain gauge platform. The rain gauge platform consists of two identical rain gauges that are separated by about 1 m and this helps in early detection of many sensor malfunctioning problems. We also operated a Distromet Joss-Wal dov gel (JW) impact disdrometer as well as a Parsivel® 1-dimensional optical disdrometer, manufactured by PMTech AG, Pfinztal, Germany. An infrared laser in Parsivel’s transmitter head illuminates a
linear array of photodiodes that are housed in the Parsivel’s receiver head. The outputs of the photodiodes are digitized and processed with a digital signal processor (DSP). Hydrometeors that transit the measurement area cause variations in the photodiode outputs. The magnitude of the variation is related to the hydrometeor size while the duration of the variation is related to the hydrometeor’s transit time/fall velocity. The DSP calculates particle size and particle velocity from this information and categorizes the precipitation into different classes and a number of related variables: drops-size and velocity distribution, rain rate, radar reflectivity factor $Z$, and precipitation kinetic energy. All the equipment was within a 20 m radius.

**Event Selection and Time Series Extraction**

The datasets cover 47 days starting May 11, 2002 and ending June 26, 2002. While there are considerable periods where all the instruments were operational, there were some problems that resulted in data gaps. In some instances, one can use the whole data sets, while in other instances it makes more sense to use subsets of the data. To this end, we identified a number of periods with significant precipitation. Table 2 summarizes these periods. For time series analysis we extracted time series at three different heights: close to the ground (600 m), close to, but still below the bright band (2700 m), and close to, but above the bright band (4350 m).

**Table 2 Significant precipitation events. Values are approximate only**

<table>
<thead>
<tr>
<th>Event</th>
<th>Start Time (UTC)</th>
<th>Duration (minutes)</th>
<th>Gauge Accumulation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05/11/02 10:15</td>
<td>305</td>
<td>18.6</td>
</tr>
<tr>
<td>2</td>
<td>05/16/02 11:48</td>
<td>468</td>
<td>27.5</td>
</tr>
<tr>
<td>3</td>
<td>05/25/02 04:54</td>
<td>390</td>
<td>14.5</td>
</tr>
<tr>
<td>4</td>
<td>06/02/02 10:19</td>
<td>400</td>
<td>20.7</td>
</tr>
<tr>
<td>5</td>
<td>06/04/02 14:43</td>
<td>88</td>
<td>10.7</td>
</tr>
<tr>
<td>6</td>
<td>06/11/02 09:14</td>
<td>140</td>
<td>No Data</td>
</tr>
<tr>
<td>7</td>
<td>06/19/02 12:22</td>
<td>200</td>
<td>No Data</td>
</tr>
</tbody>
</table>

**Data Filtering**

The data from both radars contain noise and spurious signals. One source is aircraft 3–4 km aloft landing and taking off, which manifest as momentary high reflectivity signatures. Other sources are insects, fog, and particulates close to the ground (< 600 m). These manifest as salt-and-pepper noise that exhibit structure and display diurnal patterns. However, based on operator notes and data from the collocated rain gauge, one can conclude that these data do not correspond to precipitation. Since we are interested in precipitation, we filtered the data to remove these signals. One approach is to set a threshold of say 10 dBZ, and consider anything below that as “No Echo”. Another approach is to use a time-space filter where pixels that are isolated in the time-height plots are removed using a sliding window (Miriovsky, 2003). We used the following approach. Both radars provide Doppler information, and we treat bins that do not exhibit a mean fall velocity that makes it consistent with rainfall, as “No Echo” bins. Assuming a Marshall-Palmer (MP) drop size distribution (Rinehart, 1997), the mean velocity is (Sauvageot, 1992)

$$v_{\text{mp}}(Z) = 3.8Z^{0.072},$$

with $v_{\text{mp}}$ in m s$^{-1}$ and $Z$ in mm$^6$ m$^{-3}$. The filter removes data that violate the following condition.
\[ \frac{1}{3} v_{mp}(Z) \leq v \leq 3v_{mp}(Z), \]  

where \( v \) and \( Z \) are the velocity and reflectivity measured by the radar, and \( v_{mp} \) is the velocity computed assuming equation 2. We apply this filter up to 2900 meters. This removes most of the spurious bins. Next, stepping in time at a fixed height, if a bin is the only bin in a 5-bin window that exceeds 0 dBZ, then it is reclassified as “No Echo”. This second filter is applied to the whole dataset. Fig. 1 shows the effect of the filter. Note how the application of the filter removes the salt-and-pepper noise close to the ground and the effect of the noise on the accumulation obtained from the radar. Radar rain rates come from applying the MP Z-R relationship to the time series at 600 m.

**Fig. 1** Illustration of the effect of the noise filter. Top Left: Original S-band radar data showing salt-and-pepper noise and non-precipitating reflectors close to the ground. Bottom Left: Corresponding rain rate. Top Right: Bins where velocities do not correspond fall in a broad range implied by the MP distribution, were replaced with “No Echo” values. See text for details. Bottom Right: Corresponding rain rate. Data are for May 11, 2002.

**Averaging/Combining To Comparable Time and Spatial Scales**

The data were collected at different time and spatial scales. The S-band produces 9-second samples, the X-band 0.25-second samples, while the rain gauge tips at irregular intervals. Along its 2.5° beam, the S-band bin size is 60/90 meters, while the X-band bins are 150 m along its 1.9° beam. For meaningful comparative analysis, one has to average/combine and resample the data.
to get the time and spatial scales consistent. For the X-band radar, the sum of the “Echo” bins was divided by the number of bins in a 9-second window. Using this procedure, we put both radars on the same temporal scale.

The rainfall data collected from the two gauges is in the form of tip-time series. In order to convert the tips into rainfall rain rate, we used the interpolation method described and analysed by Habib et al. (2002) and Grzegorz (2002). With this method, the rain rate between two consecutive tips is assumed constant and is given by

\[ R(T_i - T_{i-1}) = \frac{\Delta V}{T_i - T_{i-1}}, \]  

(3)

where \( R \) is the rain rate, \( T_i \) and \( T_{i-1} \) is the times that the two consecutive tips occurred and \( \Delta V \) is the volume of the bucket (in our case \( \Delta V = 0.254 \text{ mm} \)). This method was applied to each of the tipping buckets individually and the final estimate of rainfall rate was obtained by averaging the resulting rain rates.

To make comparable spatial bins, we combine S-band radar’s bins to match the size of the X-band radar bins as best as possible. The bin size for the S-band is 60- or 90 m depending on whether it is in its low or high altitude mode, and the bin size for the X-band radar is 150 m. If the S-band radar it is in the low altitude mode, one must combine 3 bins to obtain a 180 m bin. When it is in high-altitude mode, one must combine 2 bins to obtain an 180 m bin. The first bin for the X-band radar is at 150 m and for the S-band it is at 375 m. The closest height to the ground where one can combine S-band bins and have good overlap with an X-band bin is at 600 m. Visual inspection of the data showed the existence of the bright band at 3 and 4 km. A good overlap close to, but below the bright band is at 2700 m. A good overlap above the bright band is at 4350 m.

When combining two volumes X and Y with mean (obtained from the radar) velocities \( v_x \) and \( v_y \), one can assume a MP distribution, and compute the number of hydrometeors \( N_x \) and \( N_y \) for each volume from the corresponding Z values. The velocity of the combined volume is given by

\[
\bar{v} = \frac{-1}{N_x + N_y} \left( \frac{N_x}{N_x + N_y} \sum v_x + \frac{N_y}{N_x + N_y} \sum v_y \right) = \frac{N_x}{N_x + N_y} v_x + \frac{N_y}{N_x + N_y} v_y
\]  

(4)

The spectral width values obtained from the radar represent the square roots of the variances \( \sigma_x^2 \) and \( \sigma_y^2 \) of the velocities \( v_x \) and \( v_y \). The variance of the velocities of the combined volume is

\[
\sigma^2 = \frac{N_x}{N_x + N_y} \left( \sigma_x^2 + (v_x - \bar{v})^2 \right) + \frac{N_y}{N_x + N_y} \left( \sigma_y^2 + (v_y - \bar{v})^2 \right)
\]  

(5)

The square root of (5) is the spectral width of the combined volume. These ideas are easily extended when combining more than two volumes.

**Descriptive and Comparative Data Plots**

A number of plots illustrate the data of the individual radars and also how the radars compare against each other. Where appropriate, some of the plots use the 9-second samples. In other cases, for example when comparing with rain gauge data, 1-minute averages are used.

Fig. 2 is a color-coded scatter plot of the X-band radar reflectivities against the S-band radar reflectivities. All the values for the seven events in Table 2 were used. X-band reflectivities are consistently about 10 dBZ higher than those seen by the S-band radar.
It is instructive to compare the radar data with the gauge data that were collected. Fig. 3 shows radar reflectivity and rain rates, plotted against rain rates obtained from the rain gauge. The integration interval is 1 minute. For the radars, 9-second reflectivity bins were averaged as described above. The MP Z-R relationship was then used to obtain rain rates. The 1-minute rain gauge data was obtained from the tips using the method described above. As expected, there is considerable scatter present in these 1-minute plots. As in Fig. 2, the X-band radar values are consistently higher than those seen by the S-band radar.
Fig. 3 Comparison with rain gauge data. The integration interval is 1 minute, and the MP relationship was used to convert $Z$ at 600 m values to rain rates.

Fig. 4 shows the autocorrelation function of the rain rate for the radars at the three heights: 600 m, 2700 m, and 4350 m. The data from both radars show a significant decrease in autocorrelation for lags less than 3 minutes (180 lags) and then the autocorrelation function flattens. There is some general agreement between the correlation functions of the radars at a given height. Nevertheless, the overall the correlation function for the S-band radar data is smoother. Compare for example, the S-band autocorrelation function for the 2700 m time series with the corresponding correlation function of the X-band radar. One possible source of the sharp decline of the autocorrelation at small lags, i.e., “nugget effect” is the presence of noise, and the more uncorrelated the noise, more pronounced the nugget. Another explanation is that the variability of the underlying process (precipitation) is higher than what the radars can sample. The difference between the S-band and X-band autocorrelation functions may be related to how each radar sample the atmosphere. As described above, we combine multiple S-band bins to get bins that are comparable with the X-band radar’s bins. However, the S-band radar’s beamwidth is 1.5 times larger, and at 600 m this translate to a 2.2 times larger volume. Thus, $Z$-values from the S-band come from significantly larger (more averaging) volumes that the corresponding X-band values. Both radars show that the correlation time above the bright band is very small, and the largest below the bight band. We are investigating these issues.
Fig. 4  Autocorrelation function for the two radars. Time series for 600 m for the complete data set were used, and the MP relationship was used to convert $Z$ at 600 m values to rain rates.

Concluding Remarks

In this extended abstract we summarized the data from the high resolution vertically pointing S-band and X-band radars, explained how the data were filtered, and presented a number of descriptive plots. We are continuing our analysis with results published on the project [website](http://example.com).

References


