The Influence of Terrain on Rainfall Estimates from Radar Reflectivity and Specific Propagation Phase Observations

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ABSTRACT

The effect of beam blockage on rainfall estimates derived from radar reflectivity and specific propagation phase was evaluated from measurements of a convective rainfall event from the National Center for Atmospheric Research’s S-band polarized (S-Pol) radar. This storm produced a flash flood in a mountainous watershed to the southwest of Denver, Colorado, and widespread rainfall over the plains. A beam blockage map of the region, based on a digital elevation model and characteristics of the S-Pol radiation pattern, was computed. Rain-rate estimates over both low and high beam-blockage areas were compared. Results supported the hypothesis that specific propagation phase–based quantitative precipitation estimates tend to be less influenced by terrain than reflectivity-based precipitation estimates are.

1. Introduction

The use of weather radar to perform quantitative precipitation estimates (QPEs) has been touted as a useful tool for reducing the risk of flood-related damage and injury. This is especially important in areas of complex terrain, in which the risk of flash flooding is particularly high because of enhanced orographic effects during strong summertime convective storms and the subsequent routing of floodwaters through narrow canyons. Consistently reliable, precise, and accurate QPEs from weather radar are yet to be realized. The WSR-88D Next Generation Weather Radar (NEXRAD), operated by the National Weather Service (NWS), relies primarily on reflectivity- (power) based methods for estimating precipitation. The current NEXRAD precipitation processing system (PPS) uses an $R(Z_H)$ relationship, in which $R$ is the rainfall rate and $Z_H$ is the radar reflectivity factor at horizontal polarization.

The NWS is in the process of evaluating the added benefit of polarization radar technology for a possible upgrade for WSR-88D radar. Polarimetric measurements provide additional information about drop size distribution, hail, and ground clutter contamination. The measurements can be used for obtaining independent precipitation estimates using both power and phase measurements. Each of these estimates has a specified statistical error that is a function of drop size distribution and radar measurement error (Ryzhkov and Zrnić 1995). It is likely that both reflectivity and specific propagation phase measurements will be used in a complementary mode, using the strengths of each to improve rainfall estimates. The effect of beam blockage on precipitation estimation over hilly terrain is yet to be compared using radar reflectivity- and phase-based estimates.

Harrold et al. (1974) suggest a simple correction scheme for reflectivity-based rainfall when beam blockage is less than 60%. Beyond the blocked terrain, when no ground clutter is present, the simple correction scheme for reflectivity might be feasible. In general, reflectivity is the sum of precipitation reflectivity and ground clutter reflectivity at the radar resolution volume. The actual bias in the measured reflectivity due to beam blockage depends on 1) the amount of beam blockage and 2) the reflectivity difference between precipitation and the ground clutter echo. It is difficult to estimate accurately the bias due to beam blockage, especially for the radar resolution volume that has clutter. Zrnić and Ryzhkov (1996) discussed advantages of specific propagation phase–based measurements for rainfall estimation, noting that the specific propagation phase approach is not affected by the absolute calibration of the radar system, attenuation, and beam blockage. Comparing radar-based rain-rate estimation and gauge measurements, Zrnić and Ryzhkov (1996) showed that the specific propagation phase–based rain estimate is not affected by the beam blockage, whereas reflectivity underestimated the precipitation.

In this paper, we examine and analyze the influence of beam blockage on reflectivity rainfall estimates using observations from the National Center for Atmospheric Research’s S-band polarized (S-Pol) radar.
Research’s (NCAR) S-Pol radar (Lutz et al. 1997). We assume that a reflectivity-based precipitation estimate is more influenced by beam blockage when compared with a phase-based measurement. We used this assumption to perform a relative comparison of the two measurement methods in regions of both high and low beam blockage (Zrnić and Ryzhkov 1996).

The S-band polarized radar (S-Pol) is capable of measuring both reflectivity ($Z_H$) and specific differential propagation phase ($K_{DP}$). The data analyzed in this paper were collected during PRECIP 96 [an S-Pol radar field program in the summer of 1996 (Brandes et al. 1997a)]. A brief description of PRECIP 96 is presented in section 2. Reflectivity and specific propagation phase–based precipitation estimates for a convective event are described in section 3. The computation of a radar beam-blockage map for the Front Range of Colorado and the influence of beam blockage on precipitation estimates are presented in section 4. Finally, the paper ends with a summary of the results in section 5.

2. PRECIP 96

During the summer of 1996, NCAR first fielded its new polarimetric S-Pol radar. The radar supported a hydrological field program (PRECIP 96) whose primary goals were 1) to improve the present WSR-88D radar reflectivity-based algorithms for estimating rainfall and 2) to determine benefits that might be gained if WSR-88Ds are modified for dual-polarization capability. During PRECIP 96, S-Pol was placed at 285° azimuth and at a 2-km range from the WSR-88D that services the Denver metropolitan area. The site was approximately 35 km east of downtown Denver and 60 km east of the Colorado foothills, as shown in Fig. 1. Temporal samples at 0.5° elevation were obtained at intervals of 1 min and 50 s. The spatial resolution of the radar measurements was 0.15 km in range by 1° azimuth.

The S-Pol is a dual-polarization radar, transmitting and receiving horizontally and vertically polarized pulses. The radar uses a high-performance transmitter and sidelobe parabolic antenna with good isolation between horizontal and vertical channels. A dual-channel receiver with an NCAR-designed radar signal processing system is used for both Doppler and polarization signal measurements (Lutz et al. 1997; Randall and Loew 1997). For ease in interpreting measurements, the radar system includes a product generator for real-time display of Doppler and polarization observations, rain rate, and microphysical products.

3. Rainfall estimates with reflectivity ($Z_H$) and specific propagation phase ($K_{DP}$)

Radar reflectivity measurements at horizontal polarization were converted to rainfall rates using the NEXRAD reflectivity-based relationship [$R(Z_H)$], $R = 0.017Z_H^{0.14}$. A lower bound of 25 dBZ was used to prevent “clear-air” return signals from outflow boundaries and convective rolls from contributing to the accumulated totals. A hail threshold of 51 dBZ was used; that is, all reflectivity values greater than 51 dBZ were assumed to be contaminated by hail and were reset to 51 dBZ. The specific propagation phase–based rainfall [$R(K_{DP})$] rate was estimated using the relation $R = 40.56K_{DP}^{0.87}$ (Sachidananda and Zrnić 1987). The specific propagation phase measurement has a standard error of 0.2°–0.4°. The rainfall rate was accumulated only if the reflectivity value was greater than 25 dBZ. Measurement uncertainties in $K_{DP}$ increase at low rainfall intensities. Thus, at lower rain rates ($<20$ mm h$^{-1}$), $R(Z_H)$ might
be more accurate than $R(K_{DP})$ (Blackman and Illingworth 1997).

The study region included a large area of Colorado’s Front Range, just to the west of the S-Pol radar site (Fig. 1). We selected a strong summertime convective storm event (13 July 1996) that was within the scanning range of the S-Pol radar. This storm produced a flash flood in the Buffalo Creek watershed, located approximately 45 km to the southwest of the Denver metropolitan area, leading to two fatalities and millions of dollars in property damage. The Buffalo Creek watershed was about 75 km from the S-Pol radar site, at an approximate azimuth angle of 233°. Figures 2 and 3 are the 4-h and 23-min rainfall totals estimated using the reflectivity and specific propagation phase methods, respectively (Brandes et al. 1997a). These figures include the location of the radar as well as the watershed boundary of Buffalo Creek. Both rainfall estimates were based on 0.5° elevation scans.

Two regions within the study area were selected as areas of particular interest for the analysis and are labeled regions 1 and 2 (Figs. 2 and 3). These were selected because both contained strong precipitation events and had differing terrain features. Region 1 consisted of relatively smooth topographic characteristics—hence, low blockage values—while region 2 included the Buffalo Creek watershed area and was characterized by high blockage values.

Systematic measurement bias (i.e., $Z_H$ and/or $K_{DP}$ consistently under- or overpredicting the rainfall amount exclusive of blockage) was first determined in order to compare the two rainfall estimation methods. We assumed that this bias could be determined in regions in which there was negligible beam blockage (region 1). The power- and phase-based 4-h and 23-min rainfall totals were compared with observations from 38 rain
Fig. 3. Total precipitation accumulation estimate (mm) for the 4-h and 23-min storm using the phase-based measurement \( R(K_{DP}) \) from the S-Pol radar in the study domain. Region 1 (low-blockage area) and region 2 (high-blockage area) are identified by the boxes within the study domain, while the Buffalo Creek watershed is highlighted in red at the lower left-hand corner of the figure. The lowest elevation contour starting at 1600 m, with 250-m elevation contours included.

gauges operated by the Urban Drainage and Flood Control District of Denver. The gauges have tipping buckets and record in 1-mm increments. To reduce the impact of local ground clutter, gauges with greater than 15-dBZ ground clutter on a clear-air day were eliminated from the comparison. Mean system bias was computed for the study domain (including both regions 1 and 2; the low- and high-blockage areas, respectively) as the ratio between averages of gauge and radar estimates. The radar estimates were derived as the average around a 1 km\(^2\) area of each gauge location. The bias for reflectivity was 0.78, and the corresponding value for specific differential phase was 0.74. Hence, both parameters overestimated the precipitation.

Since we were interested only in a relative comparison between the power- and phase-based precipitation estimates, we computed an adjustment factor that forced the difference between \( R(Z_H) \) and \( R(K_{DP}) \) to be near zero in the low-beam-blockage area (region 1). This adjustment was computed for the QPEs by deriving the spatially averaged precipitation of the 4-h and 23-min storm total for both estimation methods based on those locations in which the beam blockage was less than 10%. The bias was then found by dividing the average reflectivity-based rain estimate by the average specific propagation phase–based estimate, which resulted in a slight bias adjustment of 1.1. The reflectivity rainfall field was multiplied by this factor. This systematic bias is attributed to either weather-related microphysical variations or hardware calibration: for example, not knowing the correct antenna gain and/or overall system gain. It should also be noted that reflectivity and specific phase–based rain estimates might differ because they are independent estimates. The standard errors on \( R(Z_H) \) and \( R(K_{DP}) \) depend on the standard errors on the \( Z_H \) and \( K_{DP} \) measurements and the temporal and spatial averaging scheme used for estimating the precipitation map. For the S-Pol radar, the measurement accuracies of reflectivity and specific propagation phase are ±1 dB and 0.2°, respectively. For instantaneous rate estimation, the
corresponding fractional standard errors for $R(Z_H)$ and $R(K_{DP})$ are 40% and 24%, respectively (Goddard and Cherry 1984; Ryzhkov and Zrnić 1995). These errors might be smaller for estimates of accumulated precipitation if they had been temporally averaged.

4. Influence of terrain on $Z_H$ and $K_{DP}$ observations

A difference between the $Z_H$- and $K_{DP}$-based rainfall estimates was expected as the beam propagated into the mountainous area and became increasingly blocked by high terrain features. As beam blockage increases, the reflectivity-based rainfall estimate should become smaller relative to the phase-based estimates because less energy is reflected back to the receiver. The specific propagation phase estimate of precipitation should be less influenced by blockage because it is a ratio of power and hence is less sensitive to the absolute value of the backscattered power. So the ratio of the $Z_H$ to $K_{DP}$-based rainfall estimate should generally decline as the beam-blockage percentage increases, implying a reduced $R(Z_H)$ in regions of significant beam blockage. To test this, we generated a blockage map of the study region and then derived a percent difference map $[\Delta R/R(K_{DP})]$ between the $R(Z_H)$ and $R(K_{DP})$ rain estimates, in which $\Delta R$ is the difference between the $R(Z_H)$ and $R(K_{DP})$ rain estimates.

4. Generation of the blockage map

The blockage map (Fig. 4) represents the fraction of the radar beam that was obstructed by terrain features as the beam propagated in the outward direction (0%, no blockage; 100%, full blockage). This map is based on the U.S. Geological Survey (USGS) 1:250 000 scale Digital Elevation Models (DEMs), which were converted to the IDRISI (Eastman 1995) Geographical Information System (GIS) format for processing. Once the DEM of the region was entered into the GIS, azimuth angle intervals of 0.5$^\circ$ were used to generate elevation profiles. These profiles were made by sampling the DEM along each profile transect, from the radar site to the

Fig. 4. Blockage map of the study domain, given as a percentage of beam blocked (0%—no beam blockage; 100%—complete blockage). Regions where apparent discontinuities exist in the radial direction are artifacts of the interpolation scheme used to generate the smoothed blockage map from the discrete radials.
outer boundary of the radar coverage. This process produced approximately 720 elevation profiles that were used to determine the percentage of the beam blocked. The GIS was not used directly to determine the percentage of the beam blocked because of the outwardly propagating nature of the radar beam. Instead, blockage was determined separately for each radial, where the height of the beam axis above the ground and the elevation angle of the beam were determined from (1):

\[ H' = H'_{i+1} + \Delta R \sin(\theta') \]

\[ n'(H' + R_i) \cos(\Theta') = \text{constant}, \]

where \( i \) is the horizontal increment along the specific radial, \( R_i \) is the radius of the earth, \( H' \) is the elevation height of the radar beam center above the ground (km), \( \Delta R \) is the horizontal increment along the beam axis (km), \( \Theta' \) is the elevation angle of the refracted beam (radians) at \( H' \). The refractive index, \( n' \), is a function of height and approximates the atmospheric influence on the beam.

Denver radiosonde observations at 0000 UTC on 13 July 1996 were used for computing the refractive index profile. The radiosonde observations were closest to the rain event that produced widespread precipitation along the Front Range between 0000 and 0423 UTC. The actual elevation angle of the radar beam is influenced by the atmosphere through refraction of the radio waves (described by the refractive index profile). An approximate equation (Bean and Dutton 1966)

\[ \theta_{i+1} = \sqrt{\theta_i^2 + \frac{2\Delta h}{H'_{i+1} + R_i} - 2(n_i - n_{i+1})}, \quad \text{radians} \]

was used for computing the elevation angle of the beam at \( \Delta h \) increments in height. The factor \( n_i - n_{i+1} \) is the incremental change in the refractive index over the \( \Delta h \) interval, and \( (\theta_{i+1} - \theta_i) \) is the corresponding change in elevation angle of the beam.

Blockage was defined by the fraction of the beam that encountered a terrain barrier along the local vertical profile and was based on a Gaussian distribution (Zrnić and Ryzhkov 1996) describing radiation intensity [(3) and Fig. 5a]:

\[ g(\theta) = \exp\left(-\frac{\theta^2}{2\sigma^2}\right), \]

where \( \sigma \) is the standard deviation of the distribution and is related to the 3-dB beamwidth of the radiation pattern. The same antenna is used for both transmission and reception for a two-way Gaussian radiation pattern:

\[ g(\theta) = \exp\left[-8 \ln 2 \left(\frac{\theta^2}{\theta_1^2}\right)^2\right], \]

\[ 2\sigma^2 = \frac{\theta_1^2}{8 \ln 2}, \]

\[ \theta = \frac{\Delta z}{r} \quad \text{(radians), and} \]

\[ \theta_1 = 3\text{-dB beamwidth} = 0.97^\circ \]

\[ = 0.97\left(\frac{\Pi}{180}\right) \quad \text{(radians),} \]

with the beamwidth \( \theta_1 \) and the distance along the beam axis \( r \) defining the shape of the distribution (Doviak and Zrnić 1993). The vertical distance measured from the beam axis is \( \Delta z \). It is positive upward and negative downward (Fig. 5b). Blockage at each point along the radial is given by

\[ B(r) = \int_{-\infty}^{E_i} \exp\left[-8 \ln 2 \left(\frac{\Delta z}{r\theta_1}\right)^2\right] d\Delta z \]

except when \( B(r_i) < B(r_{i+1}) \); then \( B(r_i) = B(r_{i+1}) \). Here \( E_i \) is the elevation of the terrain at location \( i \) along the

![Fig. 5. (a) General Gaussian distribution with \( \sigma = 0.3 \), (b) Vertical Gaussian distribution based on the 3-dB beam angle \( (\theta_1 = 0.97^\circ = 0.017 \text{ rad}) \) and at horizontal distances of 20 and 50 km.](image)
given radial. Equations (4) and (5) specify a two-way radiation pattern and blockage computation in terms of local coordinates (see Fig. 5). This procedure, when applied to all of the radii, produced thousands of blockage points over the study region. These blockage values were then entered back into the GIS, in which spatial interpolation was used to create a “smoothed” blockage map at the same resolution as the precipitation maps (Fig. 4).

b. Comparison of reflectivity versus specific propagation phase–based rainfall estimates

Figures 6a and 6b are histograms of the percent of beam blocked and the corresponding percent difference in the precipitation estimate for region 1, respectively. This region was characterized by smaller amounts of beam blockage, with the southern area containing blockage values between roughly 1% and 20%, and the northern area becoming completely unblocked (Fig. 4). The percent difference in $R(Z_{dp})$ and $R(K_{dp})$ was normally distributed, with a mean of approximately 0.3% and a standard deviation of about 18%, exhibiting a weak correlation ($\sim 0.30$) between blockage and the measurement technique.

As the amount of beam blockage increased, $R(K_{dp})$ was less influenced by terrain, whereas the $R(Z_{dp})$ estimate decreased. This result is supported by Figs. 7a and 7b, in which the beam blockage increased and the distribution $\Delta R/R(K_{dp})$ lost its normally distributed shape and skewed to the left. The mean value of the percent difference was $-18\%$, with a standard deviation of 18% and a correlation of $-0.62$ between blockage and $\Delta R/R(K_{dp})$. This was a more significant relationship between beam blockage and the measurement method than was found in region 1—the area with less blockage.

Table 1 gives the storm total average (mm), the root-mean-square error (mm) between $R(Z_{dp})$ and $R(K_{dp})$, and the average blockage (percentage) for both regions 1 and 2. These statistics show the smaller variation between the precipitation estimates in the low-blockage region 1, when compared to the estimate made in the

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<th>Region 1</th>
<th>Region 2</th>
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<tr>
<td>$R(Z_{dp})$</td>
<td>13.0</td>
<td>16.4</td>
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<tr>
<td>$R(K_{dp})$</td>
<td>14.4</td>
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<td>rmse</td>
<td>4.2</td>
<td>9.6</td>
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<td>Avg block</td>
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high-blockage region 2. Also, the overall $R(K_{DP})$ precipitation estimate was higher in the high-blockage region relative to the overall $R(Z_H)$ precipitation estimate.

Figure 8 is a scatterplot of beam blockage versus $\Delta R/R(K_{DP})$ and contains all of the points in region 2, in which both $R(Z_H)$ and $R(K_{DP})$ were greater than 15 mm. The solid boxes are the average percent difference for each 10% increment of the blocked beam. This was done to extract the general trend of a decreasing $\Delta R/R(K_{DP})$ as the percentage of beam block increased. The vertical bars give the ±1 standard deviation within each 10% blockage band. This graph supported the trend of a decreased QPE in the region of higher beam blockage for the reflectivity-based method. Explained variance of 0.32, measured as the $r$ squared ($R^2$) between beam blockage and $\Delta R/R(K_{DP})$, suggested a statistically significant relationship between blockage and the estimate method. As alluded to earlier, bias variation for a specified blockage might be due to reflectivity differences between precipitation and clutter. Higher $R^2$ values are likely unattainable because of weather-related microphysical variations that are chaotic in nature and tend to produce random variability in the measurements.

5. Conclusions

We analyzed the effect of beam blockage on two independently derived S-Pol radar-based rainfall estimates: namely, reflectivity $[R(Z_H)]$ and specific propagation phase $[R(K_{DP})]$. Blockage maps and bias-corrected $R(Z_H)$ and $R(K_{DP})$ maps were developed and compared. The S-Pol antenna beam pattern was approximated using a Gaussian distribution function. Two study areas were chosen: 1) a region with a relatively low amount of radar beam blockage and 2) a mountainous region with comparatively high radar beam blockage. Beam blockage throughout the combined study region varied between 0% and 70%. In the region of low beam blockage (region 1), it was found that the percent difference between $R(Z_H)$ and $R(K_{DP})$ was normally distributed with an approximate mean value of zero. This implied that when systematic measurement bias was removed in the low-blockage region, $R(Z_H)$ and $R(K_{DP})$ gave similar estimates, and where differences did exist and could most likely be explained by meteorological phenomena.

In the high beam-blockage area (region 2), $R(Z_H)$ tended to underestimate rainfall when compared with $R(K_{DP})$. The percent difference between $R(Z_H)$ and $R(K_{DP})$ lost its normally distributed shape, skewing leftward and revealing a tendency of lower $R(Z_H)$ values relative to $R(K_{DP})$. Rain gauge measurements at Buffalo Creek agreed most closely with the $R(K_{DP})$ estimate (Brandes et al. 1997b). Thus, the results support the initial hypotheses that the specific propagation phase measurements tend to be less influenced by beam blockage. The $R(K_{DP})$ and $R(Z_H)$ estimates at Buffalo Creek are 63 and 41 mm, respectively, and were derived by averaging a 1 km$^2$ area around the rain gauge at Buffalo Creek. This rain gauge reported 68 mm of accumulation for this event, more closely matching the $R(K_{DP})$ estimate.

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