Application of a modified digital elevation model method to correct radar reflectivity of X-band dual-polarization radars in mountainous regions

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Abstract:
This study focuses on the application of a modified digital elevation model (DEM) method that not only considers geometrical power losses but also addresses effects such as power losses caused by ground-clutter filtering and the radar system’s calibration errors. X-band dual-polarization radars operated by the Ministry of Land, Infrastructure, Transport and Tourism of Japan are located near mountainous terrain in the southern part of the Kanto region in Japan, at Fujinomiya and Shizukita. Both radars suffer from problems caused by partial beam shielding at various low-elevation angles, which lead to underestimation of the amount of rainfall. After correcting for reflectivity attenuation, a modified DEM method was applied to correct for bias reflectivity in the presence of beam-shielding problems. Validation of the corrected reflectivity based on comparison tests shows that the modified DEM method significantly improved the bias reflectivity caused by partial beam blocking.

KEYWORDS complex terrain; radar observation; reflectivity; partial beam blockage; DEM method

INTRODUCTION

Polarimetric variables, including the horizontal reflectivity ($Z_H$), the specific differential phase ($K_{dp}$), and the differential reflectivity ($Z_{dr}$), have been considered to estimate rainfall rates. They have been used to derive various relationships (e.g., Zrnic and Ryzhkov, 1996; Vivekanandan et al., 1999; Carey et al., 2000; Lang et al., 2009), whose advantages and disadvantages have been discussed extensively (e.g., Zrnic and Ryzhkov, 1996; Vivekanandan et al., 1999; Giangrande and Ryzhkov, 2005; Maki et al., 2005). Some studies showed that $K_{dp}$ is relatively unaffected by either beam blockage or anomalous propagation (Zrnic and Ryzhkov, 1996; Vivekanandan et al., 1999; Carey et al., 2000; Giangrande and Ryzhkov, 2005; Friedrich et al., 2007). However, particularly during periods of low rain rate, $K_{dp}$ is affected by several uncertainties (Zrnic and Ryzhkov, 1996; Vivekanandan et al., 1999; Illingworth et al., 2000), which then lead to uncertainties in rainfall estimates. In such cases, quantitative estimates of the precipitation based on $K_{dp}$ are not applicable and $Z_H$ must be used instead.

$Z_H$ is a widely used parameter to estimate rainfall rate; many studies have used it to generate models that closely follow ground-truth data, especially for light to moderate rain (Park et al., 2005; Kim and Maki, 2012; P.C. et al., 2013). However, radar estimates of rainfall using $Z_H$ in areas of beam blockage are clearly biased in comparison with the ground-truth data (Zrnic and Ryzhkov 1996; Vivekanandan et al., 1999; Kucera et al., 2004; Krajewski et al., 2006; Friedrich et al., 2007; Lang et al., 2009; P.C. et al. 2013). This problem of beam blockage is a major issue affecting radar hydrology and meteorology in mountainous areas. Complex topography, which includes irregular features and high mountains, can shield the radar beam, affecting observations. Several methods have been developed to address this problem in mountainous regions (e.g., Vivekanandan et al., 1999; Dinku et al., 2002; Kucera et al., 2004; Krajewski et al., 2006; Friedrich et al., 2007; Lang et al., 2009; P.C. et al., 2013). Most of these methods use a simple digital elevation model (DEM) method, and in many cases the results show good agreement with ground-truth data, particularly for C- and S-band weather-radar systems (Vivekanandan et al., 1999; Dinku et al., 2002; Kucera et al., 2004; Krajewski et al., 2006; Lang et al., 2009). A recent study (P.C. et al., 2013) has shown that many known and unknown errors are associated with radar observations, which implies that application of the DEM method alone is not sufficient to correct the reflectivity in mountainous regions, an issue that is of particular concern in relation to X-band weather-radar data.

To correct for bias reflectivity in the presence of partial beam blockage, a new method, referred to as the “modified DEM method”, was proposed by P.C. et al. (2013), based on application of the method in a mountain range in central Japan using X-band dual polarization Ebina radar (MP-X). These authors used the DEM method to determine how the reflectivity was affected by partial beam blockage (PBB) by the mountains and compared this reflectivity with ground reflectivity data. Their results clearly showed that the DEM method alone is insufficient to correct the biased reflectivity. They found that the modified DEM method resulted in good corrections of the reflectivity under different partial beam-blockage conditions. Their method was well suited to the research radar of the National Research Institute for Earth Science and Disaster Prevention (NIED; located in Ebina city, Kanagawa prefecture, Japan).

The previous work left certain issues unresolved. For example, it did not establish whether the modified DEM method can be applied to radars other than that in Ebina or in what way the method could be validated in the absence of ground-truth data. Furthermore, the equations established in the previous work were not tested in different environments. The present work explores these issues by reporting...
the application of the modified DEM method to two different radars and comparing the corrected reflectivity on a point-by-point and area-by-area basis in the absence of ground-truth data. First, the attenuation correction is validated using comparisons between observations obtained with different radars. Subsequently, an application of the modified DEM method is analyzed.

METHOD

PBB correction using the modified DEM method

The DEM method is widely used to correct for bias reflectivity in the PBB zone. The general equation pertaining to the DEM method, in logarithmic form, is given by

\[ 10 \log Z_{\text{H, dem}} = 10 \log Z_{\text{H, rad}} - 10 \log (1 - BBR) \]  

(1)

where \(Z_{\text{H, dem}}\) is the corrected reflectivity resulting from application of the DEM method, \(Z_{\text{H, rad}}\) is the attenuation-corrected reflectivity, and \(BBR\) is the fractional beam-blockage rate. P.C. et al. (2013) noted that factors such as the data filtering process and ground clutter may cause additional problems in the presence of PBB in mountainous regions. They modified Equation (1) as follows:

\[ 10 \log Z_{\text{H, mod, dem}} = 10 \log Z_{\text{H, rad}} - 10 \log (1 - BBR) - 10 \log F \]  

(2)

\(F\) represents the power loss in the mountainous area caused by unknown errors, which is taken to be zero in the absence of PBB. BBR is calculated from the DEM data by integrating the area of the terrain projected onto the beam’s cross-section for the relevant azimuth and elevation angles (P.C. et al., 2013). Although, it is difficult to estimate the factor \(F\), a straightforward relationship that can be used to solve two unknown factors appears in Equation (2). A true reflectivity is equal to attenuation-corrected reflectivity in the presence of no PBB at any nearest elevation angle. Mathematically, we can write the assumption required to solve Equation (2) expressed as

\[ Z_{\text{H, mod, dem}}(\theta) = Z_{\text{H, rad}}(\theta^*) \]  

(3)

where \(\theta\) is the antenna elevation angle affected by the PBB, and \(\theta^*\) is a minimum elevation angle at which no PBB occurs. \(Z_{\text{H, rad}}(\theta^*)\) may vary from one elevation angle to another depending on the height of the mountain, as well as distance from the radar location. Based upon this assumption, we can rewrite Equation (2) as

\[ \Delta Z_{\text{H}} = 10 \log (1 - BBR(\theta)) + 10 \log F(\theta) = 10 \log Z_{\text{H, rad}}(\theta) - 10 \log Z_{\text{H, rad}}(\theta^*) \]  

(4)

\(\Delta Z_{\text{H}}\) in Equation (4) depends on the BBR, and an empirical relationship can be derived by statistical analysis of the last term of Equation (4) using observed radar data. Having established the relationship between \(\Delta Z_{\text{H}}\) and BBR, reflectivity in the PBB zone can be corrected using Equation (3). A detailed description of the method is presented in Supplement Document S1.

Comparison of radar reflectivity

A comparison of radar reflectivity can help to check the data quality obtained from different radars in the area in common or at the intersection of both radar beams. This method is an important tool in the absence of ground-truth data; however, at least two radars within a common area are needed. The reflectivity profile for a given elevation of the first radar is compared with that of the second radar in some common area at the same (or an equivalent) elevation. However, the locations of the radar systems, their antenna scanning modes, the region’s topography, the scanning time, and the surrounding environment may introduce uncertainties that could affect the comparison.

In this study, point-by-point and area-by-area comparisons are performed (Figure 1). Point-by-point comparison is a direct method based on polar coordinates. It involves the selection of common ranges and beams that pertain to both radars, which are then compared with each other. This method depends upon the locations of the radars, as well as on their azimuth angles and ranges. Area-by-area comparison is a comparatively indirect method. It involves the selection of a common area (boundary) defined by the coverage of the two radars. The radar reflectivity of the selected area is then extracted in Cartesian coordinates using both radars. Subsequently, the same numbers of data points can be compared for the points in common.

To compare the corrected and observed data, the correlation coefficient (COR), normalized bias (NB) and normalized error (NE) were calculated. In this study, the observed and expected reflectivity values were considered separately on a case-by-case basis.

STUDY AREA

The two X-band weather radars considered here are at Fujinomiya and Shizuoka–Kita (hereafter Shizukita). They are respectively 209 m and 73 m above mean sea level; both are close to the complex, mountainous terrain of central Japan. Their coverage range profiles are shown in Figure 2. They are operated by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT). The scan elevations for the Fujinomiya radar were 1.4°, 3.3°, 4.0°, and 5.0°; the equivalent angles for the Shizukita radar were 1.6°, 3.1°, 3.6°, and 4.0°. One full scan by both radars took around
Because of the presence of complex mountainous areas near the radar locations, it is not possible to use low elevation angles or small gaps between elevation angles. Increasing the elevation angles may increase the uncertainties at long distances from the radar locations. Keeping this in mind, a common area was chosen, located within 30 km of both radars (Red rectangle in Figure 2).

Data were collected for three rainfall events (Case_1, Case_2, and Case_3) for both radars (Table I). Noise, ground clutter, and non-meteorological echoes were eliminated to maintain the quality of the radar data. Details about the filtering of the polarimetric variables are reported by Maesaka et al. (2011).

### RESULTS

#### Comparison of attenuation correction

It is important to know about the accuracy of attenuation correction before calculating and inspecting other errors and biases. Figure 4 shows a time series of instantaneous data sets at common points (black squares and triangles in the inset) for the two radars. The time series for these points shows good agreement for the two radars for the same elevation angles. To derive a more general comparison of the accuracy of the attenuation correction, all data for the selected area in common to both radars were compared using a 10 minute time-averaged basis. It should be noted that 2 minutes and 30 seconds per scan at each elevation. Both radar systems cover a common mountain range, but from different locations. Figure 3 shows the spatial distribution of the BBR and the corresponding reflectivity profiles at the second of the four elevations for both systems. Both radars suffer from beam shielding at the lowest elevation. The reflectivity distribution pertaining to the higher BBR zone exhibits a sudden decrease of reflectivity. However, neither radar is affected by PBB at higher elevations.

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Figure 5. Comparison of attenuation-corrected reflectivity of the Fujinomiya and Shizukita radars at an elevation angle of 4.0° for an 8 hour period on 2 May 2012 (Case_3)

that this selected area is suitable for two reasons: 1) it is a common area and close to both radars, and 2) it contains complex mountain terrain. Figure 5 compares the attenuation-corrected reflectivity for the two radars for an elevation of 4.0° for Case_3. For the comparison, the logarithm of the frequency density (FD) was used on account of the large number of sample data. Overall, most points follow the 1:1 locus, which suggests close similarity of $Z_{H_{\text{att}}}$ values for both radars for Case_3. Similar results were obtained in the comparison tests of the attenuation corrections for Case_1 and Case_2. Overall these results suggest that the attenuation corrections of the reflectivity were applied properly.

Calculation of the empirical equation of the modified DEM method

In this study, the full range of azimuth angles can be considered by virtue of the presence of mountains surrounding the radars. Figure 6 shows the relationship between $\Delta Z_H$ and $BBR$ for all three events within 2–30 km for all azimuth angles. Note that for $BBR > 90\%$, $Z_{\text{H_{un}}}$ was disregarded in the derivation of $\Delta Z_H$. To obtain the empirical equations in the modified DEM method, many events and instantaneous data sets were used. Note that a simple straightforward relationship i.e. linear equation was obtained based on the concentration pattern of reflectivity gradients at each case. As the trend lines for individual events for each radar are close to each other, the average relationships between $\Delta Z_H$ and $BBR$ obtained for both radars are:

$$\Delta Z_H = \begin{cases} -15.1 \times BBR, & \text{Fujinomiya radar} \\ -17.6 \times BBR, & \text{Shizukita radar} \end{cases}$$

(5)

From the Shizukita radar, most beams are projected normal to the orientation of the major mountain ranges. Although the presence of electricity or telecommunications towers on mountain peaks could also block the beams, these are not considered in deriving the $BBR$ map. This could be one of the reasons for deviation of $\Delta Z_H$ at Shizukita radar.

PBB correction using the modified DEM method

Figure 7 shows plan position indicators of $BBR$, $Z_{\text{H_{un}}}$ and $Z_{\text{H_{mod_dem}}}$ for elevations of 3.3° and 3.1° (Fujinomiya and Shizukita, respectively) for the radar observations using a $250 \times 250$ m² mesh resolution. Significant differences can be observed between $Z_{\text{H_{att}}}$ and $Z_{\text{H_{mod_dem}}}$ over the PBB zone in the mountainous region. Note that the area covered in Figure 7 is the same as that used for the validation of the attenuation correction (Figure 4). The selected common area has an additional advantage for validation, because the correction for attenuation was calculated and inspected. $Z_{\text{H_{un}}}$ at an elevation of 3.1° for the Shizukita radar shows a band of decreased reflectivity. The patterns of $Z_{\text{H_{mod_dem}}}$ in the PBB zone and of $Z_{\text{H_{un}}}$ in the non-PBB zone for both radars look similar (Figure 7). Moreover, the distributions of $Z_{\text{H_{mod_dem}}}$ at different elevation angles for both radars show similar patterns of reflectivity.

To investigate the accuracy of the spatial distribution of the reflectivity across the PBB zone in more detail, the reflectivities ($Z_{\text{H_{un}}}$ and $Z_{\text{H_{mod_dem}}}$) for low and high elevations for both radars were compared. The PBB-zone elevation angle for all azimuth angles and the corresponding non-PBB zone elevation angle were compared using 10 min averages. The $Z_{\text{H_{un}}}$ for blocked and unblocked elevations show clear systematic biases for both radars. When the modified DEM method is applied, $Z_{\text{H_{un}}}$ for a given unobstructed...
elevation and $Z_{\text{H,mod, dem}}$ clearly follow the 1:1 locus, characterized by a significant bias reduction (Supplement Figure S1). Statistical values for all cases are listed in Supplement Tables SI and SII.

**Validation of PBB correction**

The lowest tested elevations of both radars over the selected common area yielded very high BBR values. Therefore, the second-lowest elevations (i.e., 3.3° (Fujinomiya) and 3.1° (Shizukita)) were used to assess the accuracy of the corrected reflectivity (Figure 7, BBR). Point-by-point comparisons were conducted at two points: the black triangle and circle in Figure 7. The triangle marks a location characterized by a BBR value based on the Shizukita observations, but with zero BBR based on the Fujinomiya data. The circle marks a location where the situation is reversed. Figure 8 shows a time series of $Z_{\text{H,att}}$ and $Z_{\text{H,mod, dem}}$ for the period from 1500 to 2300 UTC on 2 May 2012 for these two points. In both cases, $Z_{\text{H,mod, dem}}$ (PBB) is in good agreement with $Z_{\text{H,att}}$ (non-PBB).

For a more general check, Figure 9 compares the reflectivities ($Z_{\text{H,att}}$ and $Z_{\text{H,mod, dem}}$) at the same elevations over the same period (Case_3). A comparison of $Z_{\text{H,att}}$ between both radars shows less correlated values: COR 0.59, NB 7%, and
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NE 19%. Pockets of points clearly resulted from the small PBB zone pertaining to the Fujinomiya radar. $Z_{\text{HH}} \text{DEM}_{\text{HH}}$ showed COR 0.82, NB 1%, and NE 10%. Application of the modified DEM method to data from both radars led to significantly improved statistical errors for Case_3, and correcting the reflectivity using the modified DEM method was shown to work well for both radars. A comparison of the statistical summaries of the data from both radars at the second-lowest elevations for all three events (Supplement Table SIII) shows that strong correlations were observed despite the possible effects of environmental conditions, radar locations, and scanning times.

SUMMARY AND CONCLUSIONS

It is impossible to correct the radar reflectivity in an area of perfect beam shielding, such as behind a high mountain. One solution involves the use of a second or third radar, which can be employed to observe such an area. The main purpose of this work was to address issues related to the application of the modified DEM method proposed by P.C. et al. (2013). This study reached important conclusions about the previously unresolved issues.

The modified DEM method was then applied to two different radars to test its broad applicability. Relationships between $\Delta Z_{\text{HH}}$ and $B\text{BR}$ for the two radars were obtained that were different from each other and also different from that derived in the previous study, and this is difficult to explain. (The empirical equations pertaining to the Fujinomiya and Shizukita radars are $\Delta Z_{\text{HH}} = -15.1 \times B\text{BR}$ and $\Delta Z_{\text{HH}} = -17.6 \times B\text{BR}$, respectively, which compare with $\Delta Z_{\text{HH}} = -21.8 \times B\text{BR}$ found previously for the MP-X radar.) The obtained empirical equations are clearly different for each radar system. Therefore, special observations are recommended before the modified DEM method is applied to a given radar system. The differences in the relationships can be attributed to the different conditions of nearby mountain topography and also to the characteristics of the individual radar systems. For example, both radars considered here scanned some common area, but the beam of the Fujinomiya radar was perpendicular to the mountain range, while scanning by the Shizukita radar was mainly normal to the range.

The corrected reflectivity resulting from both methods was tested in different ways. The biased reflectivity was corrected and compared with $Z_{\text{HH,un}}$ of the unblocked elevation for both radars. Point-by-point and area-by-area comparisons were also conducted. The results from both methods clearly show that the corrected reflectivity at an elevation pertaining to both radars yielded good matches, clearly emphasizing the accuracy of the modified DEM method. Therefore, the modified DEM method demonstrated broad applicability to different radars in various environments.

The method was validated in the absence of ground-truth data via comparisons, which were conducted to validate the reflectivity corrected for attenuation and partial beam blockage. This method appears useful for application in complex, mountainous regions, where ground observations are difficult. One of the key issues of the comparison method for X-band radar is the accuracy of the rainfall attenuation correction. The accuracy of the modified DEM method for two different radars cannot be ascertained unless the rainfall attenuation correction is evaluated. The results of the rainfall attenuation correction by the specific differential phase show that the reflectivities measured by two radars agree well with each other in the common area. We conclude that such comparisons could be used to validate the PBB-correction method.

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SUPPLEMENTS

Document S1. Detailed description to apply the modified DEM method
Table S1. Statistics describing the relationship between $Z_{\text{HH}}$ for an elevation of 4.0° and the reflectivity for 3.3° for the Fujinomiya radar for all three events
Table SII. Statistics describing the relationship between $Z_{\text{HH}}$ for an elevation angle of 3.6° and the reflectivity for 3.1° for the Shizukita radar for all three events
Table SIII. Statistical summary of the comparisons for three events
Figure S1. Comparison of reflectivity at unblocked and the corresponding blocked elevation angles for Fujinomiya (left) and Shizukita (right) radar observations for the period 1500–2300 UTC on 2 May 2012 (Case_3)

REFERENCES

Carey LD, Rutledge SA, Ahijevych DA, Keenan TD. 2000. Correcting propagation effects in C-band polarimetric radar observations of tropical convection using differential propagation phase. Journal of Applied Meteorology 39: 1405–1433. DOI: 10.1175/1520-0450(2000)039<1405:CPEICB>2.0.CO;2.
Dinku T, Anagnostou EN, Borga M. 2002. Improving radar-based estimation of rainfall over complex terrain. Journal of Applied Meteorology 41: 1163–1178. DOI: 10.1175/1520-0450(2002)41<1163:IREORC>2.0.CO;2.
Friedrich K, Germann U, Gourley JJ, Tabary P. 2007. Effects of partial beam blockage on rainfall estimation for the polarimetric C-band radar. Journal of Atmospheric and Oceanic Technology 24: 1839–1859. DOI: 10.1175/JTECH2085.1.
Giangrande SE, Rydzkov AV. 2005. Calibration of Dual-Polarization Radar in the Presence of Partial Beam Blockage. Journal of Atmospheric and Oceanic Technology 22: 1156–1166. DOI: 10.1175/JTECH1766.1.
Illingworth AJ, Blackman TM, Goddard JWF. 2000. Improved rainfall estimates in convective storms using polarisation diversity radar. Hydrology and Earth System Science 4: 555–563. DOI:10.5194/hess-4-555-2000.
Kim DS, Maki M. 2012. Validation of composite polarimetric parameters and rainfall rates from an X-band dual-polarization radar network in the Tokyo metropolitan area. *Hydrological Research Letters* 6: 76–81. DOI: 10.3178/HRL.6.76.

Krajewski WF, Ntelekos AA, Goska R. 2006. A GIS based methodology for the assessment of weather radar beam blockage in mountainous regions: Two examples from the U.S. NEXRAD network. *Computer & Geoscience* 32: 283–302. DOI: 10.1016/j.cageo.2005.06.024.

Kučera PA, Krajewski WF, Young CB. 2004. Radar beam occultation studies using GIS and DEM technology: An example study of Guam. *Journal of Atmospheric and Oceanic Technology* 21: 995–1006. DOI: 10.1175/JTECH1133.1.

Maesaka T, Maki M, Iwanami K. 2011. Operational rainfall estimation by X-band MP radar network in MLIT, Japan. Preprints: 35th Conference on Radar Meteorology, September 26–30, 2011 Pittsburgh, USA; 11–142.

Maki M, Iwanami K, Misumi R, Park SG, Moriwaki H, Maruyama K, Watabe I, Lee DI, Jang M, Kim HK, Bringi VN, Uyeda H. 2005. Semi-operational rainfall observations with X-band multi-parameter radar. *Atmospheric Science Letters* 6: 12–18. DOI: 10.1002/asl.84.

Park SG, Maki M, Iwanami K, Bringi VN, Chandrasekar V. 2005. Correction of radar reflectivity and differential reflectivity for rain attenuation at X band. Part II: Evaluation and application. *Journal of Atmospheric and Oceanic Technology* 22: 1633–1655. DOI: 10.1175/JTECH1804.1.

P.C. S, Maki M, Shimizu S, Maesaka T, Kim DS, Lee DJ, Iida H. 2013. Correction of reflectivity in the presence of partial beam blockage over a mountainous region using X-band dual polarization radar. *Journal of Hydrometeorology* 14: 744–764. DOI:10.1175/JHM-D-12-077.1.

Vivekanandan J, Yates DN, Brandes EA. 1999. The influence of terrain on rainfall estimates from radar reflectivity and specific propagation phase observations. *Journal of Atmospheric and Oceanic Technology* 16: 837–845. DOI: 10.1175/1520-0426(1999)016<0837:TIORFE>2.0.CO;2.

Zrnic DS, Ryzhkov A. 1996. Advantages of rain measurements using specific differential phase. *Journal of Atmospheric and Oceanic Technology* 13: 454–464. DOI: 10.1175/1520-0426(1996)013<0454:ARUOFP>2.0.CO;2.