Assessment of Ground-Based X-Band Radar Reflectivity: Attenuation Correction and its Comparison With Space-Borne Radars Over the Western Ghats, India

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Abstract  Reflectivity measurements from X-band ground-based radar (GR) are assessed using observations from the Ku-band space-borne radars (SRs) onboard the Tropical Rainfall Measuring Mission and Global Precipitation Measurement satellites as a reference. The GR is at Mandhardev (18.04°N, 73.86°E) in the Western Ghats region, and the evaluation period is from June to September of 2014 and 2018. At X-band, the rainfall-induced attenuation leads to significant signal loss. The rain attenuation correction of GR is performed based on the relationship between specific attenuation and reflectivity. Using T-matrix scattering simulations, the specific attenuation and reflectivity are derived from the disdrometer data. Further, the systematic differences between reflectivity measured by GR and SR are minimized by performing the frequency scaling using scattering simulation. The comparison between corrected reflectivities of GR and SR is achieved by matching the resolution volumes and viewing geometry of both radars. The evaluation between corrected reflectivities of GR and SR shows reasonable agreement between them, indicating that the attenuation correction performs reasonably for GR. In rain regions, the GR bias lies between −2.6 and −1.8 dB for stratiform cases, while for convective samples, the GR bias varies from −2.4 to −0.7 dB relative to SR observations. The GR shows smaller reflectivity compared to SR at all heights. This study aims to implement the attenuation correction to long-term X-band radar data available in the Western Ghats region to study the orographic precipitation and convective system during monsoon.

1. Introduction

Understanding the physics of rainfall is essential for weather forecasting, cloud physics, agriculture, and microwave communications. Ground-based radars (GRs) measure rainfall with high temporal and spatial resolutions compared with other instruments such as rain gauges. However, GR suffers from reliability issues. Apart from ground clutter and beam blockage in radar measurements, the accuracy of radar reflectivity measurements needs to be examined for quantitative precipitation estimation (QPE), severe weather monitoring and nowcasting, and assimilation in numerical weather prediction models (Louf et al., 2019; Wang & Wolff, 2009; Wang et al., 2012; Xiao et al., 2007).

In recent time, the use of shorter wavelength radar-like X-band has attracted increasing attention attributable to the portability and cost-efficiency. However, due to a shorter wavelength, X-band radar signals suffer from severe attenuation caused by rainfall along the propagation path. Therefore, it is essential to correct the rain attenuation effect in radar operating at X-band before any quantitative applications that use power measurement like radar reflectivity factor. Algorithms have been developed to correct the rain attenuation using single-polarization radar measurements (Hitschfeld & Bordan, 1954), dual-wavelength radar measurements (Tuttle & Rinehart, 1983), and dual-polarization radar measurements (Bringi et al., 1990). With the availability of radar polarimetric measurements, there is a vast improvement in the accuracy and stability of the rain attenuation correction algorithm (Bringi & Chandrasekar, 2001). Calibration uncertainty is possibly the most severe problem in generating accurate rainfall products from radar observations. Houze et al. (2004) showed that a calibration offset of 2 dB could contribute an
uncertainty of 30% in the monthly rainfall estimation. Hence, it is necessary to determine the calibration bias for GR observations. The improvement in accuracy of radar QPE by comparing and correcting GR observations with space-borne radar (SR) paid much attention at present (Anagnostou et al., 2001; Cao & Qi, 2014; Liao et al., 2001; Liao & Meneghini, 2009; Wen et al., 2011, 2013). The precipitation radar (PR) operated at Ku-band (~13.8 GHz) onboard the Tropical Rainfall Measuring Mission (TRMM) was well calibrated, and the measured reflectivities have errors less than 1 dB (Shimizu et al., 2001; Takahashi et al., 2003; Takahashi & Iguchi, 2004). Recently, Warren et al. (2018) and Louf et al. (2019) used the Ku-band PR (KuPR) onboard TRMM and Global Precipitation Measurement (GPM) mission core observatory satellites for calibrating GRs in Australia.

Several researchers compared the reflectivities between SR and GR. For example, Bolen and Chandrasekar (2003) validated TRMM-PR reflectivity with Colorado State University CHILL radar observations. They found that TRMM-PR agrees within ~1 dB of GR observations with a standard deviation of 2–3 dB. Schumacher and Houze (2000) compared the reflectivity profiles between TRMM-PR and GR at Kwajalein and reported that PR undersampled weaker echoes associated with stratiform rain. Heymsfield et al. (2000) found that TRMM-PR compared very well with GR reflectivity for precipitation larger than PR footprint size and underestimated for convective cells smaller than PR footprint size. Anagnostou et al. (2001) showed that the differences between GR and TRMM-PR are mostly due to GR calibration errors. Wang and Wolff (2009) compared reflectivity between TRMM-PR and GR at four ground validation sites and found that PR agrees within ±1 dB of GR reflectivity. Liao and Meneghini (2009) evaluated TRMM-PR reflectivity observations with GR observations at Melbourne, Florida. They concluded that the PR has small biases near the storm top. The above cited studies demonstrated the utility of GR to test the detection accuracy of TRMM-PR and the performance of TRMM-PR attenuation correction algorithm. Kim et al. (2014) assessed the reliability of GR measurements in the Korean Peninsula region. They found that the time-averaged difference between TRMM-PR and GR lies between ~2.0 and +1.0 dB. Li et al. (2017) compared the GR reflectivity with TRMM-PR reflectivity above and below the bright band in stratiform precipitation. They found a negative bias in GR reflectivity above and positive bias below the bright band. Warren et al. (2018) and Crisologo et al. (2018) adapted the 3-D volume-matching method of Schwaller and Morris (2011) to quantify the calibration errors in GR by using SR overpasses over Sydney, Australia, and Subic, Philippines, respectively. They utilized the GR and SR reflectivity differences in the estimation of calibration errors. Louf et al. (2019) used an integrated approach with different calibrating techniques and found that the GR calibration error is less than 1 dB. Therefore, the above studies indicate that the SR measurement can serve as a reference to calibrate GR and hence detect the consistency of GR data.

In this study, we compare the reflectivity measurements between X-band GR and SR during June–September of 2014 and 2018. The motivation of this work is to reduce the source of uncertainty in quantitative applications of radar reflectivity data in hydrometeorology, weather forecasting, and assimilation in numerical weather prediction models. The calibration of attenuating wavelength radar in a regime such as the Indian monsoon is challenging. Here, we attempted for the first time to calibrate the reflectivity measurements of GR by comparing it with SR.

The paper is organized as follows. In section 2, X-band radar, disdrometer, TRMM-PR, and GPM-KuPR data description are presented. Section 3 then describes rain attenuation correction of GR reflectivity. The intercomparison between GR and SR is discussed in section 4. The findings of this work are summarized in section 5.

## 2. Instruments and Data

Data collected from X-band radar, Joss-Waldvogel disdrometer (JWD), along with Ku-band radar onboard TRMM and GPM are used in this study. This section describes the technical details of data sets used.

### 2.1. X-Band Radar

The present study uses data (June–September of 2014 and 2018) collected from ground-based X-band radar, manufactured by the Enterprise Electronics Corporation (EEC), Alabama, USA. The radar is deployed at Mandherdev (18.04°N, 73.86°E, and ~1.3 km above mean sea level [AMSL]), a remote location in the hilltop of Western Ghats, India. The X-band radar is a scanning system and mounted on a truck-trailer for mobile
use. The radar transmitter is a magnetron-based system operating at ~9.535 GHz with peak power of about 200 kW. The radar has a parabolic horn-type antenna of diameter 2.4 m and has a half-power beamwidth of 0.97°. The antenna is mounted on an elevation-over-azimuth pedestal. The radar signal is processed using the Enigma III+ signal processor. Detailed technical specifications are reported in Das et al. (2015) and Deshpande et al. (2015).

The reflectivity factor ($Z$, mm$^6$m$^{-3}$) measured by weather radar is an independent radar characterization of the target return and expressed as

$$Z = C_r \times P_r \times r^2$$

where $C_r$ is radar constant and depends on radar system parameters (transmitted power, wavelength, beam width, pulse duration, antenna gain, etc.), $P_r$ is the received backscattered power from the target, and $r$ is the distance between target and radar. The $Z$ is expressed in the logarithmic form (dBZ), and the above equation will be

$$10\log_{10}Z = 10\log_{10}C_r + 10\log_{10}P_r + 20\log_{10}r$$

Thus, any change in $C_r$ (varies with time due to degradation, maintenance, and replacement of various radar components) affects the radar reflectivity factor measurements. Therefore, regular testing of components is required, which can directly affect the value of $C_r$. Routine engineering calibrations are performed to maintain the radar system and thus reduce the possibility of errors in radar measurements due to variation in system parameters. Calibrations are performed for transmitted power and frequency, pulse width, and dynamic range. Transmitted power is calibrated using a power meter to attain the desired power level. Next, the transmitter frequency is adjusted using a spectrum analyzer. The pulse width is tested using an oscilloscope. The dynamic range calibration is performed using an external test signal generator. During the calibration process, it is assumed that the antenna gain and waveguide losses do not degrade with time and usually not re-measured and hence are taken to be constant.

The location of X-band radar system along with the topography of radar site is shown in Figure 1. The topography map is generated from the Shuttle Radar Topography Mission data, with one arc-second (~30 m) resolution (Farr et al., 2007). The windward side of radar site, Mandherdev, is surrounded by ocean. The

Figure 1. Topographical map of the Western Ghats of India generated using the Shuttle Radar Topography Mission data. The X-band radar is at Mandhardev (MDV) and Joss-Waldvogel disdrometer is at HACPL and shown with red stars.
X-band radar system was operated in the volume scan mode, which consists of a series of conical sweeps (plan position indicator [PPI]) with increasing elevation angles and collects 3-D data in every ~12 min. The radar performs PPI scans at elevation angles of 0.5°, 1.5°, 2.5°, 3.5°, 4.5°, 6°, 7.5°, 9°, 12°, 18°, 25°, 35°, 45°, 55°, 65°, 75°, 85°, and 90°. There are few small hillocks scattered around the radar site, which results in blocking the radar beam. The beam blockage fraction (BBF) is computed for each bin and each antenna azimuth and elevation angles based on the methodology proposed by Bech et al. (2003). To match the topography data with radar data which is in polar coordinates, the topography data are processed to 250-m resolution and 1° azimuth, extending to a maximum range of 125 km from radar center using spline interpolation technique. Figure 2 shows the BBF map for first four elevation angles.

There is no beam blockage above the fourth elevation angle. BBF of “1” corresponds to complete beam blockage of radar signal, and “0” represents that the radar signal is free from any obstruction. The BBF is high in the northeastern sector of radar site, indicating radar beam blockage in that area. There are few blockages on the southwestern side at 0.5° elevation angle. The BBF decreases with an increase in antenna elevation, and the obstruction is seen maximum up to 3.5° elevation angle. In the present study, reflectivities of GR and SR are neglected for the analysis where the radar beam blockage occurs.

### 2.2. Joss-Waldvogel Disdrometer

The JWD is a widely used instrument for analyzing the raindrop size distributions (DSDs) at the ground. The JWD used is disdrometer RD-80, manufactured by Distromet Ltd., Switzerland. JWD is an impact disdrometer, which converts the impact energy of falling drops to the size of each drop. The sampling
The cross-section area of JWD is a styrofoam cone with an area of ~50 cm². The raindrop falling at its terminal velocity has an impact (due to the falling raindrop momentum) on the styrofoam cone which is converted to an electrical impulse. The diameter of the raindrop is proportional to the amplitude of this electrical impulse. The JWD measures raindrops with size range from 0.3 to 5 mm in 20 size intervals. The disdrometer data are sampled at a time interval of 1 min. The accuracy of measurement is about ±5% of the measured raindrop diameter. Details of the measured DSDs can be found in Das et al. (2017) and Murali Krishna et al. (2017). JWD is deployed at the High Altitude Cloud Physics Laboratory (HACPL), Mahabaleshwar (17.92°N, 73.6°E, ~1.4 km AMSL), which is located in the complex mountain terrain of Western Ghats, India. The disdrometer site is about ~26 km from the radar site (Figure 1). The JWD data analyzed are for June–September of 2013–2015.

2.3. Space-borne radar

2.3.1. Tropical Rainfall Measuring Mission Precipitation Radar

The PR onboard TRMM was the first SR to measure rainfall from space. The TRMM-PR operated at Ku-band (~13.8 GHz) and orbited in a circular path with a nominal altitude of ~402.5 km and an inclination of ~35°, with a period of ~92.5 min. The TRMM-PR scans in the cross-track direction over ±17°, having a swath width of ~247 km. The TRMM-PR horizontal resolution is ~5 km, and the vertical resolution is 250 m at nadir. The effective signal-to-noise ratio of ~3 dB is obtained at reflectivity greater than 17 dBZ. Details of TRMM-PR can be found in Kummerow et al. (1998) and Liao and Meneghini (2009). We have considered TRMM-2A23 and TRMM-2A25 version 7 data during June–September 2014. TRMM-2A23 product provides the rain type classification, which is used to separate the GR reflectivity into stratiform and convective classes. TRMM-2A25 product has “correctZFactor” variable, which is the attenuation corrected reflectivity and is used to assess the corrected GR reflectivity. This data set contains quasi-vertical profiles of attenuation corrected reflectivity factor from 0 to 20 km. In TRMM-PR, the attenuation correction for reflectivity was carried out by estimating the path integrated attenuation (PIA) from two methods: Hitqschfeld-Bordan (HB) method (Iguchi & Meneghini, 1994) and the surface reference technique (Meneghini et al., 2000). Details of the attenuation correction algorithms can be found in Iguchi et al. (2000, 2009).

2.3.2. Global Precipitation Measurement Ku-Band Precipitation Radar

GPM is a joint mission between National Aeronautics and Space Administration (NASA) and Japanese Aerospace Exploration Agency (JAXA), which provides the next-generation observations of rain and snow within ±65° latitudes. The Ku-component (~13.6 GHz) of dual-frequency PR (KuPR) onboard the GPM core observatory satellite provides the quasi-vertical profiles of reflectivity within a swath width of ~250 km. The horizontal and vertical resolution of GPM-KuPR is ~5 km and 250 m. The GPM data are available from March 2014 onwards. Version 6 of 2AKu data for June–September of 2014 and 2018 is used. The GPM-2AKu contains the corrected reflectivity factor and the rain type classification data which are used in this work.

3. Attenuation Correction of X-Band Radar Reflectivity

Park et al. (2005) proposed an algorithm for rain attenuation correction for X-band radar based on T-matrix (transition matrix) scattering simulations (Barber & Yeh, 1975), if the quality of the polarimetric data is poor. The rain attenuation correction algorithm proposed by Park et al. (2005) is based on a power law relation between specific attenuation (A) and reflectivity (Z), where the proportionality constant depends on the raindrop size distribution and the exponent in the expression is sensitive to the temperature of raindrop. Krämer and Verworn (2009) proposed rain attenuation correction solely based on reflectivity data without any support of reference measurements like microwave links or mountain returns. In their method, the first range gate of radar reflectivity is corrected by using A-Z relationship by assuming fixed coefficient and exponent value (based on the scattering simulations using measurements of raindrop size distribution at the ground). The constant coefficient and exponent value is used as an initial guess for correction, and then an iterative calculation is applied until the stability in correction is achieved. This criterion provides the optimum coefficient and exponent value for A-Z equation to perform rain attenuation correction. Jacob and Heistermann (2016) modified the algorithm proposed by Krämer and Verworn (2009) by considering two constraints: first, PIA should not exceed 20 dB and second, the corrected reflectivity should not exceed 59 dBZ. In this work, the correction of radar reflectivity for rain attenuation is performed based on Jacob and Heistermann (2016) with modification, as discussed below.
The measured (attenuated) reflectivity \[ Z'(r) \] from X-band radar at a range \( r \) is related to corrected reflectivity \( Z(r) \) as follows (e.g., Hitschfeld & Bordan, 1954; Jacobi & Heistermann, 2016; Park et al., 2005):

\[
10 \log_{10} |Z'(r)| = 10 \log_{10} |Z(r)| - PIA
\]

Here, \( Z \) is in \( \text{mm}^6 \text{m}^{-3} \), \( A \) is in \( \text{dB/km} \), and \( PIA \) is path integrated attenuation. \( A \) is calculated using the T-matrix scattering theory by considering DSD data from JWD by assuming a non-spherical particle (Barber & Yeh, 1975; Bringi & Chandrasekar, 2001; Mishchenko, 2000). The parameters \( A \) and \( Z \) are parameterized as

\[
A = cZ^d
\]

The proper selection of coefficient \( c \) and exponent \( d \) is critical for estimation of \( A \), which can introduce substantial error and causes instability of gate-by-gate correction of reflectivity. In this work, we have used methodology from Park et al. (2005) to calculate the coefficient and exponent as discussed in Equation 5. It is known that \( c \) and \( d \) are sensitive to the large variability of DSD; therefore, we carried out scattering simulation for 1- and 11-min DSD data and parametrized \( A \) and \( Z \). Minimum of 1-min of disdrometer data is chosen to ensure a sufficient amount of raindrops for DSD calculation. As X-band radar repeats the volume scan at every \( \approx \)12-min, 11-min data are considered to cover the variation in DSD parameters for each volume scan. The coefficient and exponent from both relationships are used to calculate PIA. Figures 3a and 3b show the results of T-matrix scattering simulation calculations of \( A \) at X-band as a function of \( Z \) for 1- and 11-min DSD data, respectively. The scattering simulations are performed at 20°C with a fixed elevation angle of 0°. We considered that the distribution of canting angles of raindrops is Gaussian with a mean of 0° and a standard deviation of 10° (Beard & Jameson, 1983). The raindrop shape model proposed by Beard and Chuang (1987) is considered to calculate \( A \). It is to note that the coefficient and exponent of \( A-Z \) relation depend on DSD variability and are not affected much by the change in drop shape model and temperature for a specific location (Narayana Rao et al., 2018; Park et al., 2005). In general, \( A \) is increasing exponentially with \( Z \). Values of \( A \) are usually below 0.5 \( \text{dB km}^{-1} \) when \( Z \) is less than 45 dBZ. The shape and variability of \( A-Z \) scatter plot agree with the simulation results of Park et al. (2005). \( A \) and \( Z \) are parametrized \( (A = cZ^d) \) using power law fit (shown as a solid blue line) based upon Levenburg-Marquardt minimization method. The coefficient and...
The exponent is $c = 0.000169$ and $d = 0.78$ for 1-min average DSD data and $c = 0.000194$ and $d = 0.80$ for 11-min average DSD data, respectively. In this work, we used both the coefficients and exponents to find the optimum value of $c$ and $d$ based on the method discussed in Jacobi and Heistermann (2016). The minimum and maximum values of coefficient and exponent of $A$-$Z$ relationship are obtained from 1- and 11-min simulation, respectively. These minimum and maximum values are divided into 10 equal intervals. Initially, the attenuation correction algorithm is applied, and the PIA is calculated by considering the maximum value of coefficient and exponent in $A$-$Z$ relation. If the value of attenuation corrected reflectivity exceeds 59 dBZ or total PIA exceeds 20 dB threshold, the attenuation correction along the beam is considered as unstable. In this case, the coefficient and exponent are reduced (downward iterate) and the attenuation correction is performed until PIA, and attenuation corrected reflectivity becomes less than the threshold value. Once $A(s)$ is calculated at each range $r$, the corrected reflectivity $Z(r)$ can be calculated by substituting $A(s)$ into Equation 4.

Figure 4a shows the PPI image of measured reflectivity by X-band radar at an elevation of 1.5° from 18:54 UTC volume scan of 4 June 2014. The radar location (shown by a red star) is at the center. The range rings (dashed red line) are at every 25-km interval from radar. The beam blockage in the north-east direction to
radar is visible. The PPI image shows small and weak storm clusters in the radar surveillance area. In the northern direction, behind strong $Z (>35$ dBZ), there are weaker $Z$ values. This could be due to rain attenuation, where the radar beam does not propagate through the intense rain system. Figure 4b shows corrected $Z$ obtained after applying the rain attenuation correction algorithm to measured $Z$. Due to the rain attenuation correction, the small $Z$ values increased, especially in the north and south-east directions.

To better quantify the effect of rain attenuation, the slant range profiles of corrected (red) and measured (blue) $Z$ along 12° azimuth are plotted (see Figure 4c). The slant path is shown as a black dashed line in Figures 4a and 4b. It is observed that the rain attenuation effect becomes important after ~40 km. Figure 4d shows the PIA in the slant range along 12° azimuth. The total two-way attenuation is about 14 dB along the slant path.

4. Reflectivity Intercomparison Between GR and SR

4.1. Reflectivity Scaling Between X-Band and Ku-Band

The scattering characteristics of hydrometeors depend not only on their size, shape, orientation, and composition but also on wavelength (Cao et al., 2013; Jung et al., 2008; Ryzhkov et al., 2011). Therefore, the scattering characteristics are different at Ku- and X-band frequencies, and hence, the comparison of reflectivities need to accommodate this factor. To minimize the systematic differences between reflectivity measured by GR and SR due to different wavelengths, the reflectivity from Ku-band is scaled to X-band using scattering simulation. To better quantify the scattering differences between X- and Ku-band, the dual-frequency ratio (DFR) is computed as

$$DFR = Z(Ku) - Z(X)$$

Here, $Z$ is in dBZ and DFR is in dB. $Z(Ku)$ and $Z(X)$ represent the reflectivity at Ku-band and X-band, respectively. The calculation of DFR uses the same scattering simulation, as discussed in section 3. The variation of DFR in terms of Ku-band reflectivity is shown in Figure 5. Polynomial regression is fitted to all the data points, and the fitted DFR and Ku-band relation is

$$DFR = 18.19 - 2.141 Z(Ku) + 0.08533 Z(Ku)^2 - 0.001315 Z(Ku)^3 + 0.000006607 Z(Ku)^4$$

Using DFR, the SR reflectivity is scaled to GR reflectivity as

$$Z_s = Z(Ku) - DFR$$

Here, $Z_s$ is the reflectivity obtained after applying frequency scaling from Ku- to X-band.

4.2. Volume Matching of GR and SR Footprints

Direct comparison of GR with SR is challenging due to the viewing geometry, propagation paths, resolution volume size, and time synchronization mismatch (Bolen & Chandrasekar, 2003). Thus, to compare the GR data (a function of elevation, azimuth, and range to the surface) against SR measurements (a function of latitude, longitude, and height in the Earth coordinate system), the first step is to make both the data in a common coordinate system (Liao & Meneghini, 2009). The methodology proposed by Schwaller and Morris (2011) discussed the parallax correction of altitude (AMSL) and the horizontal location of each gate between GR and SR. In this method, the intersection of SR beam with GR elevation sweep is identified. The reflectivities of SR beam within GR beamwidth are averaged. Similarly, the GR reflectivities within SR beamwidth are averaged. The resulting averaged SR and GR reflectivities correspond to a single volume-matched sample. Full details of the procedure can be found in the appendix of Warren et al. (2018). The advantage of this
method is that it does not require any interpolation to match the GR data set with SR spatially. This step will minimize the spatial processing of two-radar data sets, and the source of error will be relatively less. In this work, we implemented the same technique proposed by Schwaller and Morris (2011) to match the resolution volume of GR with SR. This approach will maximize the sample size and makes the comparison results statistically more robust (Wang & Wolff, 2009). The minimum detectable threshold for SR is 18 dBZ, so the reflectivity values above this threshold are used for averaging reflectivities (in a linear unit) within the matched volume between GR and SR. In each volume sample, the fraction of SR and GR bins that meet the reflectivity criterion is noted. To minimize the non-uniform beam filling (NUBF) and low SR sensitivity, a threshold value is considered for a fraction of bins that fit the reflectivity criterion. In this work, volume-matched samples for which the fraction of GR or SR bins with reflectivities ≥18 dBZ is less than 0.7 are excluded from the analysis. The threshold value (0.7) considered is same as of Warren et al. (2018).

The matched cases of GR and SR reflectivity data are presented to observe the degree of agreement in the spatial patterns between attenuation corrected Z of GR and SR reflectivity. A total of 32 matched cases from TRMM (5,544 samples) and 54 matched cases (5,086 samples) from GPM are selected to compare the reflectivities between GR and SR. We considered each SR ray and GR ray within a 120-km range from the GR site.

Figure 6. Volume-matched sample of radar reflectivity distributions at 0.5° elevation from (a) TRMM, (b) GR, and (c) their difference for 23 July 2014. (d–f) Same as (a–c), but for GPM on 24 June 2018. The dotted circles represent the minimum (15 km) and maximum (125 km) ranges of the X-band radar measurements taken for the analysis. The solid black line represents the coastline. The dashed and solid line in magenta represents the central axis and edge of TRMM/GPM ground track, respectively.
4.3. Quantitative Assessment Between GR and SR Reflectivities

To understand the errors (bias) arising due to attenuation and calibration of GR measurements, we have shown reflectivity difference between corrected and measured by GR as a function of range from radar in rain region (below 4.5 km). Figure 7 shows the box plot distribution of bias between GR (measured and corrected) and SR in rain region. It is observed that the distribution of mean bias between measured and SR reflectivity increases with range. The bias varies between −20 and 15 dB for the measured reflectivity. The median value of bias increases up to 80 km and then decreases slightly after that. The slight decrease in bias after 80 km may be due to isolated convective cells that prevail over the ocean and Western Ghats region (Utsav et al., 2017), whereas the median value of bias with range remains almost the same in corrected reflectivity. The median value of bias lies between −2 and −3 dB for the corrected reflectivity.

Further, we examine whether the observed differences between GR and SR reflectivities are due to GR mis-calibration or errors in the attenuation correction. For this, the reflectivity differences between corrected GR and SR are calculated within the rain region. Here, the reflectivity differences are calculated only when the PIA is less than 1 dB, that is, when the attenuation is minimum. A total of 887 data points are available for the analysis. A calibration bias of −0.1 dB is observed in the rain region. This result shows that GR is well calibrated. Hence, the bias found in the corrected GR reflectivity to SR arises mainly due to errors in the rain attenuation correction algorithm for GR measurements.

The SR, while well calibrated, suffers from its errors. The SR in TRMM and GPM operates at Ku-band subject to substantial attenuation in heavy precipitation. Thus, the rain attenuation correction of reflectivity is taken into account for SR by a combination of the surface reference technique and HB method. However, the non-linear nature of radar attenuation equation and power law relations among specific attenuation, radar reflectivity, and precipitation rate is known to induce biases in PIA and thus bias in reflectivity retrieved (Short et al., 2013). Liao and Meneghini (2009) found that for stratiform rain, the TRMM-PR attenuation correction is adequate, whereas it underestimates for convective rain events. The other factor is the NUBF that needs to be considered in SR. NUBF refers to the radar signal over a volume that is not completely covered with the meteorological hydrometeors within the radar beam. In case of small, intense convective cells, the SR footprint (~5 km) is higher than the scale of some convective events. Thus, the non-uniform filling of SR antenna beam due to the weighting can bias the reflectivity measurement (Durden et al., 1998). Other sources of errors include non-Rayleigh scattering for large raindrop size, causing an error in reflectivity measurement of SR (Li et al., 2019). Ground clutter can contaminate the high reflectivity measurements at a lower height (below 2 km) especially over the orographic region which can introduce bias in reflectivity by frequently eliminating reflectivity measurement (Levizzani et al., 2020). The uncertainties associated with the systematic errors in SR measurements can be considered its limitation, and it is quite challenging to correct it as the actual measurement is not known. Further research is needed to quantify the relative contribution of the aforementioned error.

Figure 7. Box and whisker plot distribution of bias between measured GR and SR reflectivity (red) and corrected GR and SR reflectivity (black) as a function of range from the radar below 4.5-km height. Here, the box represents 25 and 75 percentile of the data, and whiskers show the data within 1.5 times the interquartile range. Within the box, the horizontal line represents 25 and 75 percentile of the data, and whiskers show the data function of range from the radar below 4.5 km height. Here, the box represents 25 and 75 percentile of the data, and whiskers show the data within 1.5 times the interquartile range. The zero bias is shown with a solid green line.
factors on the GR-SR comparison. Despite these limitations, comparisons with SR constitute a critical component in evaluating the accuracy of GR reflectivity measurement.

To understand errors in the rain attenuation correction algorithm, the reflectivity differences between GR and SR are presented at different heights and for different precipitation types. Figure 8a shows the box and whisker plot of reflectivity distribution of GR and SR data for all samples, stratiform and convective samples. The convective and stratiform separation is based on the rain type classification available in level 2 products of TRMM and GPM. In case of GR data classification, only the matched GR samples with SR are considered to identify the convective and stratiform pixels. The median values are shown with the horizontal line within the box, and filled circle within the box represents the mean value of the distribution. Overall, the GR reflectivities are smaller than the SR reflectivities. The mean value of Z is about 31.2 and 29.7 dBZ for convective samples in SR and GR, respectively. For stratiform samples, the mean value of Z is about 27.8 and 25.8 dBZ in SR and GR, respectively, which are smaller compared to convective samples. Therefore, the mean difference of Z between GR and SR is within $-1.5$ dB for convective samples and is $-2$ dB for stratiform cases. The standard deviation of convective samples is higher compared to stratiform cases (even though the mean Z is comparable in both GR and SR, the variation is higher for convective samples). However, for all cases, the GR agrees with the SR measurements with a mean difference within $-2$ dB.

To assess the potential bias between GR and SR measurements, the reflectivity differences between GR and SR ($\Delta Z = GR - SR$) are computed at all height levels. Figure 8b shows the box and whisker plot of $\Delta Z$ for all samples, stratiform and convective samples. At a glance, $\Delta Z$ varies between $-20$ and $20$ dB for all samples. The $\Delta Z$ between GR and SR measurements are mostly confined toward the negative values, indicating that the GR reflectivity values are smaller than SR reflectivities. For all samples, $\Delta Z$ varies between $-6$ and $+2$ dB with a median value of about $-2$ dB. The variability in $\Delta Z$ is relatively small for stratiform cases and higher for convective samples. The median value of $\Delta Z$ is about $-2$ dB for stratiform cases and is about $-1.5$ dB for convective events. The observed bias in corrected reflectivity may be attributed to errors in the rain attenuation correction algorithm for GR and matching errors between their temporal samples.

To further understand $\Delta Z$ variability with height and precipitation type, $\Delta Z$ is separated into below melting level/region (ML, below 4.5 km), within the ML (4.5–6 km), and above the ML (above 6 km) for all samples as well as for stratiform and convective samples. Figure 9a shows the $\Delta Z$ distribution below, within, and above the ML for all samples. The distribution of $\Delta Z$ shows higher variability below ML, and the variability decreases as height increases. The median value of $\Delta Z$ is about $-2.3$ dB below the ML, $-2.5$ dB within the ML, whereas it is about $+1$ dB above the ML. Figures 9b and 9c show the $\Delta Z$ distribution for stratiform and convective samples, respectively. Even in stratiform and convective samples, the median value of $\Delta Z$ is negative and higher in magnitude both below and within the ML and positive and smaller in
The ΔZ has a large spread for convective samples. This may be due to the small size and high spatial variability of the precipitation field and associated poorer volume matching in the convective samples. Despite the good calibration of SR, the SR also suffers from the relatively low spatial resolution, which may also cause the convective systems missed by the SR. This could also contribute to the large spread in ΔZ in the convective samples.

To observe the difference in the vertical structure of reflectivity differences between GR and SR, we constructed the mean vertical profile of ΔZ between GR and SR by linearly averaging the matched data at each altitude. Figure 10 shows the mean vertical profile of ΔZ between GR and SR. For total analyzed cases, the maximum ΔZ values are within −2.7 dB for all height levels. The ΔZ profile shows negative values below 7 km. It is observed that the magnitude of ΔZ is small at 2 km and increases with height up to 5 km and then decreases again after 5 km. The magnitude of ΔZ is higher for stratiform samples at all height levels compared to convective samples. The possible reasons for the discrepancy in the profile between GR and SR can be likely caused by under-correction of GR attenuation or mismatch between GR and SR due to time difference or inadequate detection of precipitation system or excessive attenuation correction by the SR. The ΔZ between GR and SR is positive at 7 km for stratiform samples, indicating that the GR reflectivity at 7 km is higher than the SR reflectivity. This may be due to random errors associated with the small sample size at higher altitudes.

5. Summary

GR can provide rainfall information at high spatiotemporal scales. However, accurate rainfall observations from weather radar are only possible if the radar system is well calibrated. The TRMM-PR operated at Ku-band was a well-calibrated radar system, and it has been used for the assessment of GR reflectivity in the past. In this study, we attempted to match and compare simultaneous observations between X-band GR and space-borne Ku-band radar (SR) onboard TRMM and GPM mission during June–September of 2014 and 2018. The X-band radar is deployed at Mandhardev, which is located in the complex terrain of Western Ghats region of India. This is the first study over complex mountain terrain where the radar data are corrected for rain attenuation and assessed against SR measurements during the Indian summer monsoon.

The radar signals at X-band are prone to attenuation due to rain. The rain attenuation correction for GR is performed using a power law.
relationship between specific attenuation and reflectivity based on the methodology proposed by Jacobi and Heistermann (2016) with modification. The specific attenuation is estimated from T-matrix scattering simulations, where the raindrop size distribution measurements are provided from JWD. Further, the rain attenuation corrected reflectivity of GR is volume matched with SR measurements using the volume-matching method of Schwaller and Morris (2011) to minimize the sampling errors arising due to the measurements from two different platforms (ground-based and spaceborne). The matched reflectivities between corrected GR and SR are quantitatively compared. We performed the frequency scaling to the SR data to account for differences in measurement frequency (X-band for GR, Ku-band for SR). The corrected GR reflectivity is quite consistent with SR reflectivity; however, GR reflectivity is smaller than SR. The bias in GR reflectivity decreases with height and is within −2.7 dB for all the samples taken collectively. Further, the mean reflectivity difference between GR and SR below the ML is −2.3 dB, within the ML is −2.5 dB, while +1 dB above the ML.

The proposed rain attenuation correction procedure could improve the GR reflectivity measurement and can recover much of the reflectivity information that is lost due to rain attenuation of radar beam. The primary goal of this study is to assess the accuracy of the GR reflectivity measurements. The corrected GR reflectivity can improve the quantitative application of reflectivity data to determine the precipitation product, separation of precipitation into different types, storm structure analysis, storm top height, severe weather monitoring and nowcasting, and assimilation in numerical weather prediction models.

The study region has heterogeneous topographic conditions. In the future, it will be interesting to examine whether the topography has any impact on the observed differences in the matched SR and GR data. While the corrected reflectivity results presented in this work are reasonable, still attenuation correction algorithm needs further improvement for better correction.

Data Availability Statement

The X-band radar and disdrometer data are archived at ITIM and are available online (ftp://103.251.184.52). These data sets can be made available for scientific collaborations upon requests. The authors acknowledge the NASA/Goddard space flight center for the provision of GPM data (https://gpm.nasa.gov/data-access/downloads/gpm). The TRMM and GPM data are freely available and can be downloaded from its archival.

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References

Anagnostou, E. N., Morales, C. A., & Dinku, T. (2001). The use of TRMM precipitation radar observations in determining ground radar calibration biases. Journal of Atmospheric and Oceanic Technology, 18(4), 616–628. https://doi.org/10.1175/1520-0426(2001)018<0616:TUOTPR>2.0.CO;2
Barber, P., & Yeh, C. (1975). Scattering of electromagnetic waves by arbitrarily shaped dielectric bodies. Applied Optics, 14(12), 2864–2872. https://doi.org/10.1364/AO.14.002864
Beard, K. V., & Chuang, C. (1987). A new model for the equilibrium shape of raindrops. Journal of the Atmospheric Sciences, 44(11), 1509–1524. https://doi.org/10.1175/1520-0469(1987)044<1509:ANMFTE>2.0.CO;2
Beard, K. V., & Jameson, A. R. (1983). Raindrop canting. Journal of the Atmospheric Sciences, 40(2), 448–454. https://doi.org/10.1175/1520-0469(1983)040<0448:RC>2.0.CO;2
Bech, J., Codina, B., Lorente, J., & Bebbington, D. (2003). The sensitivity of single polarisation weather radar beam blockage correction to variability in the vertical refractivity gradient. Journal of Atmospheric and Oceanic Technology, 20(6), 845–855. https://doi.org/10.1175/1520-0426(2003)020<0845:SBBCVT>2.0.CO;2
Bolten, S. M., & Chandrasekar, V. (2003). Methodology for aligning and comparing spaceborne radar and ground-based radar observations. Journal of Atmospheric and Oceanic Technology, 20(5), 647–659. https://doi.org/10.1175/1520-0426(2003)020<0647:MAACSS>2.0.CO;2
Bringi, V. N., & Chandrasekar, V. (2001). Polarimetric Doppler weather radar: Principles and applications. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511541094
Bringi, V. N., Chandrasekar, V., Balakrishnan, N., & Zrnić, D. S. (1990). An examination of propagation effects in rainfall on radar measurements at microwave frequencies. Journal of Atmospheric and Oceanic Technology, 7(6), 829–840. https://doi.org/10.1175/1520-0426(1990)007<0829:AEPEIF>2.0.CO;2
Cao, Q., Hong, Y., Qi, Y., Wen, Y., Zhang, J., Gourley, J. J., & Liao, L. (2013). Empirical conversion of the vertical profile of reflectivity from Ku-band to S-band frequency. Journal of Geophysical Research: Atmospheres, 118, 1814–1825. https://doi.org/10.1002/jgrd.50138
Cao, Q., & Qi, Y. (2014). The variability of vertical structure of precipitation in Huaimei River basin of China: Implications from long-term spaceborne observations with TRMM precipitation radar. Water Resources Research, 50, 3690–3705. https://doi.org/10.1002/2013WR014555
Crisologo, I., Warren, R. A., Mühlbauer, K., & Heistermann, M. (2018). Enhancing the consistency of spaceborne and ground-based radar comparisons by using beam blockage fraction as a quality filter. Atmospheric Measurement Techniques, 11(9), 5223–5236. https://doi.org/10.5194/amt-11-5223-2018
Das, S. K., Deshpande, S. M., Shankar Das, S., Konwar, M., Chakravarty, K., & Kalapureddy, M. C. R. (2015). Temporal and structural evolution of a tropical monsoon cloud system: A case study using X-band radar observations. *Journal of Atmospheric and Solar-Terrestrial Physics*, 132, 157–168. https://doi.org/10.1016/j.jastp.2015.05.009

Das, S. K., Konwar, M., Chakravarty, K., & Deshpande, S. M. (2017). Raindrop size distribution of different cloud types over the Western Ghats using simultaneous measurements from micro-rain radar and disdrometer. *Atmospheric Research*, 186, 72–82. https://doi.org/10.1016/j.atmosres.2016.11.003

Deshpande, S. M., Dhangar, N., Das, S. K., Kalapureddy, M. C. R., Chakravarty, K., Sonbawne, S., & Konwar, M. (2015). Mesoscale kinematics derived from X-band Doppler radar observations of convective versus stratiform precipitation and comparison with GPS radio-sounding profiles. *Journal of Geophysical Research: Atmospheres*, 120, 11,536–11,551. https://doi.org/10.1002/2014JD022995

Durden, S. L., Haddad, Z. S., Kitayakara, A., & Li, F. K. (1998). Effects of nonuniform beam filling on rainfall retrieval for the TRMM precipitation radar. *Journal of Atmospheric and Oceanic Technology*, 15(3), 635–646. https://doi.org/10.1175/1520-0426(1998)015<0635:ENONBF>2.0.CO;2

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., et al. (2007). The Shuttle Radar Topography Mission. *Reviews of Geophysics*, 45, RG2004. https://doi.org/10.1029/2005RG000183

Heymsfield, G. M., Geerts, B., & Tian, L. (2000). TRMM precipitation radar reflectivity profiles as compared with high-resolution airborne and ground-based radar measurements. *Journal of Applied Meteorology*, 39(12), 2080–2102. https://doi.org/10.1175/1520-0450(2001)040<2080:TRPRPF>2.0.CO;2

Hitchens, W., & Bordan, J. (1954). Errors inherent in the radar measurement of rainfall at attenuating wavelengths. *Journal of Meteorology*, 1(1), 58–67. https://doi.org/10.1175/1520-0469(1954)001<0058:EEITR>2.0.CO;2

Houze, R. A. Jr., Brodzik, S., Schumacher, C., Yuter, S. E., & Williams, C. R. (2004). Uncertainties in oceanic radar rain maps at KwaJalein and implications for satellite validation. *Journal of Applied Meteorology*, 43(6), 1114–1132. https://doi.org/10.1175/1520-0450(2004)043<1114:UIOJUL>2.0.CO;2

Iguchi, T., Kozu, T., Kwiatkowski, J., Meneghini, R., Awaka, J., & Okamoto, K. (2009). Uncertainties in the rain profiling algorithm for the TRMM precipitation radar. *Journal of the Meteorological Society of Japan*, 87A, 1–30. https://doi.org/10.2151/jmsj.87A.1

Iguchi, T., Kozu, T., Meneghini, R., Awaka, J., & Okamoto, K. (2000). Rain-profiling algorithm for the TRMM precipitation radar. *Journal of Applied Meteorology*, 39(12), 2038–2052. https://doi.org/10.1175/1520-0450(2000)040<2038:RPAFTT>2.0.CO;2

Iguchi, T., & Meneghini, R. (1994). Intercomparison of single-frequency methods for retrieving a vertical rain profile from airborne or spaceborne radar data. *Journal of Atmospheric and Oceanic Technology*, 11(6), 1507–1516. https://doi.org/10.1175/1520-0454(1994)011<1507:ISOAMF>2.0.CO;2

Jacobi, S., & Heistermann, M. (2016). Benchmarking attenuation correction procedures for six years of single-polarized C-band weather radar observations in South-West Germany. *Geomatics, Natural Hazards and Risk*, 7(6), 1785–1799. https://doi.org/10.1080/19475705.2016.1155080

Jung, Y., Zhang, G., & Xue, M. (2008). Assimilation of simulated polarimetric radar data for a convective storm using the ensemble Kalman filter. Part I: Observation operators for reflectivity and polarimetric variables. *Monthly Weather Review*, 136(6), 2228–2245. https://doi.org/10.1175/2007MWR2083.1

Kim, J.-H., Ou, M.-L., Park, J.-D., Morris, K. R., Schwaller, M. R., & Wolff, D. B. (2014). Global Precipitation Measurement (GPM) ground validation (GV) prototype in the Korean Peninsula. *Journal of the Korean Peninsula*. 31(9), 1902–1921. https://doi.org/10.1175/JTECH-D-13-0019.1

Krämer, S., & Verworn, H. R. (2009). Improved radar data processing algorithms for quantitative rainfall estimation in real time. *Water Science and Technology: a Journal of the International Association on Water Pollution Research*, 60(1), 175–184. https://doi.org/10.2166/wst.2009.282

Kummerow, C., Barnes, W., Kozu, T., Shiue, J., & Simpson, J. (1998). The Tropical Rainfall Measuring Mission (TRMM) Sensor Package. *Journal of Atmospheric and Oceanic Technology*, 15(3), 809–817. https://doi.org/10.1175/1520-0426(1998)015<0809:TRMMT>2.0.CO;2

Levičiūtė, V., Kidd, C., Kirschbaum, D. B., Kummerow, C. D., Nakamura, K., & Turk, F. I. (2020). Satellite precipitation measurement volume 2. Dordrecht: Springer Nature.

Li, N., Wang, Z., Chen, X., & Austin, G. (2019). Studies of general precipitation features with TRMM PR data: An extensive overview. *Remote Sensing*, 11(80). https://doi.org/10.3390/rs11010080

Li, N., Wang, Z., Xu, F., Chu, Z., Zhu, Y., & Han, J. (2017). The assessment of ground-based weather radar data by comparison with TRMM PR. *IEEE Geoscience and Remote Sensing Letters*, 14(1), 72–76. https://doi.org/10.1109/LGRS.2016.2626320

Liao, L., & Meneghini, R. (2009). Validation of TRMM precipitation radar through comparison of its multiyear measurements with ground-based radar. *Journal of Applied Meteorology and Climatology*, 48(4), 804–817. https://doi.org/10.1175/2008JAMC1974.1

Liao, L., Meneghini, R., & Iguchi, T. (2001). Comparisons of rain rate and reflectivity factor derived from the TRMM precipitation radar and the WSF-8D3 over the Melbourne, Florida, site. *Journal of Atmospheric and Oceanic Technology*, 18(12), 1959–1974. https://doi.org/10.1175/1520-0466(2001)018<1959:CRFRTT>2.0.CO;2

Louf, V., Protat, A., Warren, R. A., Collis, S. M., Wolff, D. B., Raunyiar, S., et al. (2019). An integrated approach to weather radar calibration and monitoring using ground clutter and satellite comparisons. *Journal of Atmospheric and Oceanic Technology*, 36(1), 17–39. https://doi.org/10.1175/JTECH-D-18-0007.1

Meneghini, R., Iguchi, T., Kozu, T., Liao, L., Okamoto, K., Jones, J. A., & Kwiatkowski, J. (2000). Use of the surface reference technique for path attenuation estimates from the TRMM precipitation radar. *Journal of Applied Meteorology*, 39(12), 2053–2070. https://doi.org/10.1175/1520-0450(2000)040<2053:UOTSRT>2.0.CO;2

Mishchenko, M. I. (2000). Calculation of the amplitude matrix for a nonspherical particle in a fixed orientation. *Applied Optics*, 39(6), 1026–1031. https://doi.org/10.1364/AO.39.010026

Murali Krishna, U. V., Das, S. K., Deshpande, S. M., Doiphode, S. L., & Pandithurai, G. (2017). The assessment of Global Precipitation Measurement estimates over the Indian subcontinent. *Earth and Space Science*, 4(8), 540–553. https://doi.org/10.1002/2017EA000285

Narayana Rao, T., Amaryothi, K., & Rao, S. V. B. (2018). Attenuation relations for monsoonal rain at the X band from disdrometer measurements: Dependency on temperature, raindrop size distribution and drop shape models. *Quarterly Journal of the Royal Meteorological Society*, 144(693), 64–76. https://doi.org/10.1002/qj.3291

Park, S.-G., Bringi, V. N., Chandrasekar, V., Maki, M., & Iwanami, K. (2005). Correction of radar reflectivity and differential reflectivity for rain attenuation at X band, Part I: Theoretical and empirical basis. *Journal of Atmospheric and Oceanic Technology*, 22(11), 1621–1632. https://doi.org/10.1175/JTECH1803.1
Ryzhkov, A., Pinsky, M., Pokrosky, A., & Khain, A. (2011). Polarimetric radar observation operator for a cloud model with spectral microphysics. *Journal of Applied Meteorology and Climatology, 50*(4), 873–894. https://doi.org/10.1175/2010JAMC2363.1

Schumacher, C., & Houze, R. A. (2000). Comparison of radar data from the TRMM satellite and Kwajalein oceanic validation site. *Journal of Applied Meteorology, 39*(12), 2151–2164. https://doi.org/10.1175/1520-0450(2001)040<2151:CORDFT>2.0.CO;2

Schwaller, M. R., & Morris, K. R. (2011). A ground validation network for the Global Precipitation Measurement Mission. *Journal of Atmospheric and Oceanic Technology, 28*(3), 301–319. https://doi.org/10.1175/2010jtecha1403.1

Shimizu, S., Ueno, K., Fujii, H., Yamada, H., Shirooka, R., & Liu, L. (2001). Mesoscale characteristics and structures of stratiform precipitation on the Tibetan Plateau. *Journal of the Meteorological Society of Japan, 79*(1B), 435–461. https://doi.org/10.2151/jmsj.79.435

Shaw Jr., H., Nakagawa, K., & Iguchi, T. (2013). Reduction of nonuniform beam filling effects by vertical decorrelation: Theory and simulations. *Journal of the Meteorological Society of Japan, 91*(4), 539–543. https://doi.org/10.2151/jmsj.2013-408

Takahashi, N., & Iguchi, T. (2004). Estimation and correction of beam mismatch of the precipitation radar after an orbit boost of the tropical rainfall measuring mission satellite. *IEEE Transactions on Geoscience and Remote Sensing, 42*(11), 2362–2369. https://doi.org/10.1109/TGRS.2004.837334

Takahashi, N., Kuroiwa, H., & Kawamishi, T. (2003). Four-year result of external calibration for precipitation radar (PR) of the Tropical Rainfall Measuring Mission (TRMM) satellite. *IEEE Transactions on Geoscience and Remote Sensing, 41*(10), 2398–2403. https://doi.org/10.1109/TGRS.2003.817180

Tuttle, J. D., & Rinehart, R. E. (1983). Attenuation correction in dual-wavelength analyses. *Journal of Climate and Applied Meteorology, 22*(11), 1914–1921. https://doi.org/10.1175/1520-0450(1983)022<1914:ACIDWA>2.0.CO;2

Utsav, B., Deshpande, S. M., Das, S. K., & Pandithurai, G. (2017). Statistical characteristics of convective clouds over the western ghats derived from weather radar observations. *Journal of Geophysical Research: Atmospheres, 122*, 10,050–10,076. https://doi.org/10.1002/2016JD026183

Wang, G., Liu, L., & Ding, Y. (2012). Improvement of radar quantitative precipitation estimation based on real-time adjustments to Z-R relationships and inverse distance weighting correction schemes. *Advances in Atmospheric Sciences, 29*(3), 575–584. https://doi.org/10.1007/s00376-011-1139-8

Wang, J., & Wolff, D. B. (2009). Comparisons of reflectivities from the TRMM precipitation radar and ground-based radars. *Journal of Atmospheric and Oceanic Technology, 26*(5), 857–875. https://doi.org/10.1175/2008JTECHA1175.1

Warren, R. A., Protat, A., Siems, S. T., Ramsay, H. A., Loud, V., Manton, M. J., & Kane, T. A. (2018). Calibrating ground-based radars against TRMM and GPM. *Journal of Atmospheric and Oceanic Technology, 35*(2), 323–346. https://doi.org/10.1175/JTECH-D-17-0128.1

Wen, Y., Cao, Q., Kirstetter, P.-E., Hong, Y., Gourley, J. J., Zhang, J., et al. (2013). Incorporating NASA spaceborne radar data into NOAA National Mosaic QPE system for improved precipitation measurement: A physically based VPR identification and enhancement method. *Journal of Hydrometeorology, 14*(4), 1293–1307. https://doi.org/10.1175/JHM-D-12-0106.1

Wen, Y., Hong, Y., Zhang, G., Schuur, T. J., Gourley, J. J., Flamig, Z., et al. (2011). Cross validation of spaceborne radar and ground polarimetric radar aided by polarimetric echo classification of hydrometeor types. *Journal of Applied Meteorology and Climatology, 50*(7), 1389–1402. https://doi.org/10.1175/2011JAMC2622.1

Xiao, Q., Kuo, Y.-H., Sun, J., Lee, W.-C., Barker, D. M., & Lim, E. (2007). An approach of radar reflectivity data assimilation and its assessment with the inland QPF of Typhoon Rusa (2002) at landfall. *Journal of Applied Meteorology and Climatology, 46*(1), 14–22. https://doi.org/10.1175/JAM2439.1