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Validation and calibration of radar reflectivity measurements between ground-based weather radars and space-borne radar GPM over the East Coast and Southern Peninsula region, India

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Abstract

Weather radar reflectivity measurements are used for quantitative applications. Hence, the accuracy of the reflectivity data is crucial. In this study, we compare the radar reflectivity between space-borne radar (SR) GPM with ground-based radar (GR) to quantify the calibration bias. The difference in the viewing geometry of the two radars makes the comparison a challenging problem. Thus, a point-to-point contrast between the reflectivities of the two radars is obtained by matching the resolution volumes. Further, GPM and GR operate on different frequencies, promoting systematic differences between the observations in the two systems. These differences can be quantified using the dual-frequency ratio (DFR), which is used to scale GPM-Ku reflectivity to GR reflectivity. Beam blockage fraction is used as a quality index for SR-GR matching. This increases the consistency between the two measurements and, thus, the precision of calibration bias.

The comparison is carried out at various locations along India's Eastern coast and Southern peninsula. Here, we quantify the calibration bias for the first time by comparing GPM and GR measurements over such a large Indian domain. This study is essential for monitoring radar calibrations and quantifying calibration bias over long data sets. The study can be used to implement corrections to the GR reflectivity measurements and further our understanding of the convective systems. The study can be extended to examine the variation of bias across the range and height of the ground radar domain. Given the opportunity, further results of the analysis will be presented at the conference.

1 Introduction

GR provides a platform for the finest resolved measurements of atmospheric species (clouds, convection, and precipitation). However, these measurements are affected by various factors such as beam attenuation, ground clutter, beam blockage and thus can be unreliable. Uncertainty in the calibration of measurements is a severe problem in generating accurate products from radar observations. For example, an offset as low as 2 dB could lead to an uncertainty of approximately 30% in monthly rainfall estimates [1]. The reflectivity factor Z, a primary quantity measured by weather radar, can be expressed as

$$Z = C \times P_r \times r^2 \tag{1}$$

Where P_r denotes the power received from the target at a distance r and C is the radar constant which depends on the characteristics of the radar system. Any change in the assumed value of C will affect the value of Z. Thus, regular testing and maintenance of the radar components are required for the functioning of well-calibrated radar, which in turn affects the value of C. Frequent end-to-end calibration can be both time-consuming and expensive. The calibration can also not account for the previous datasets. Therefore, an alternate approach to compare the reflectivity measurements to an independent well-calibrated radar can be used.

One of the primary goals of weather and climate science services is the accuracy of quantitative precipitation estimates in the tropics. Reflectivity measurements from weather radars have various quantitative applications; thus, it is essential to quantify the calibration bias.

Comparing GR against SR is the most popular and convincing among all the reliable approaches for quantifying calibration bias. The Ku-band precipitation radar (PR) on the Tropical Rainfall Measuring Mission [2] satellite (from 1997 to 2014) and the Ku-band component of the Dual-Frequency Precipitation Radar (KuPR) on board the Global Precipitation Measurement Mission [3] Core Observatory satellite (from 2014 onwards) are shown to be accurate within 1 dB ([4]; [5]). Therefore, SR provides the best reference point to quantify and calibrate the GR reflectivity measurements.

Using the volume matching technique, Warren et al. [6] quantified calibration errors in GR reflectivity observations at Sydney, Wollongong, and New Castle using TRMM and GPM. For cross-validation, Crisologo et al. [7] used TRMM observations over Subic, Philippines, whereas Biswas and Chandrasekar [8] used GPM Ku- and Ka-band at 5 NEXRAD GR locations. Das et al. [9] discovered GR bias between 2.6 and 1.8 dB for stratiform cases and 2.4 to 0.7 dB for convective samples for X-band radar over the Western Ghats in India. The above studies indicate that the SR measurements can be used as a reference for GR calibration and thus help to improve the consistency of the dataset.

This study compares the GR and SR reflectivities at various locations along India's East Coast and Southern Peninsula region. Here, we quantify the calibration bias for the first time by comparing GR and SR measurements over such a large Indian domain. This study can thus be used to implement suitable calibration bias to GR datasets. This can improve the quantitative applications and thus further our understanding.

The paper is organized as follows: Section 2 presents ground-based radar (GR) data and space-borne radar (GPM) data descriptions, along with the methods used for the analysis. The comparison between GR and SR reflectivities is discussed in Section 3. The findings of this work are summarized in Section 4.

2 Data, Analysis, and Methods

2.1 Ground Radar Data

India Meteorological Department (IMD) operates a vast network of ground radars. This study uses high-resolution volumetric reflectivity measurements from various GR across the Eastern Coast and Southern Peninsula region of India. Quality control measures, like the removal of ground clutter and anomalous propagation echoes in the reflectivity data, are implemented by IMD. S-band Doppler weather Radar (DWR) deployed at Kolkata, Chennai Machilipatnam, and Karaikal is used in the analysis.

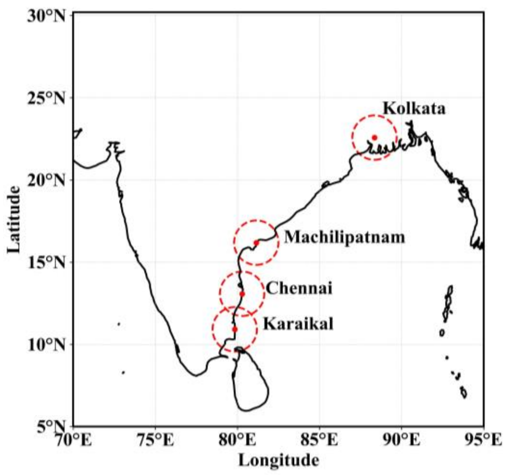

Figure 1. The location for the different ground radar sites Kolkata, Chennai, Machilipatnam, and Karaikal. The circle denotes the region having a radius of 150 km from the radar site.

India experiences Southwest (SW) monsoon (June - September) and Northeast (NE) monsoon (October - December). While the SW monsoon accounts for the majority of rainfall over the Indian landmass, the NE monsoon is more significant over the southern peninsula region. The data is thus analyzed from June to December to account for both SW and NE monsoons. Based on the availability of data, the comparison is carried out for the following year for the respective sites: Kolkata (2017), Chennai (2016), Machilipatnam (2020), and Karaikal (2020).

Volume scan consists of 10 elevation angles 0.2° to 21°. Each volume scan takes approximately 7 min, repeating every 10 min. Data within 150 km of radar range from the center is used to avoid the effects due to curvature of the earth and beam widening. Data within 5 km from the radar site is not considered. Further, attenuation correction is not necessary since S-band does not suffer attenuation in precipitation medium. Figure 1 illustrates the location of the different sites over the Indian domain used for analysis.

2.2 Space-borne Radar Global Precipitation Measurement (GPM)

GPM mission (successor of TRMM) is a joint mission between the National Aeronautics and Space Administration (NASA) and the Japanese Aerospace Exploration Agency (JAXA). GPM core observatory carries Dual-Frequency Precipitation Radar (DPR) which consists of Ku-band radar (13.6GHz) and Ka-band radar (35.5GHz).

For this study, we consider Ku-PR, which has a spatial resolution of about 5 km, a range resolution of 250 m, and a swath width of 245 km. GPM Ku-PR observations are available from March 2014 onwards. Level 2A product 2AKu (version 7) is used, which provides information about rain type classification and vertical profile of reflectivity factor with attenuation correction. Data for June – December is used for the following years 2016, 2017, and 2020.

2.3 Beam blockage fraction and quality index

GR measurements can be affected by the effects of beam blockage based on the topography of the location due to weakening or loss of signal as the radar beam interacts with the surface of the terrain. To quantify these effects, a beam blockage map is generated [10], which utilizes the Digital Elevation Model (DEM) to assess the extent of occultation. Shuttle Radar Topography Mission (SRTM) data, with 1 arc-second resolution, provides DEM, which is resampled to the coordinates of GR bin centroids to match the resolution of GR data. The beam blockage fraction (BBF) map and the corresponding quality map are generated for available elevation angles. The quality index Q_{BBF} is calculated from BBF using [11].

$$Q_{BBF} = \begin{cases} 1 & BBF \leq 0.1 \\ 1 - \dfrac{BBF - 0.1}{0.4} & 0.1 < BBF < 0.5. \\ 0 & BBF > 0.5 \end{cases} \quad (2)$$

As the antenna elevation increases, BBF decreases. BBF of 1.0 corresponds to complete beam blockage of the radar signal and a value of 0.0 to perfect visibility.

2.4 GR – SR volume matching and frequency scaling

SR and GR have different viewing geometries; thus, a direct comparison is not straightforward. The volume matching method provides a quantitative comparison between SR and GR reflectivities. Intersections between SR beam and GR elevation sweeps are identified. Firstly, the location of each SR bin with respect to GR is determined using parallax correction[12]. Reflectivity measurements from both SR and GR are averaged to equate the sample volumes[6]. SR data are averaged at the GR range of the intersection in range over the width of the GR beam, while GR data are averaged in the range–azimuth plane within the SR beam. The resulting pair of reflectivity measurements correspond to approximately the same volume of atmosphere. Since there is no interpolation or extrapolation of the data, the matched data is at the location of actual observation.

Moreover, SR and GR operate on different frequencies, promoting systematic differences between the reflectivity observations in the two systems depending on the scattering characteristics of particles within the sample volume. The scattering differences between GR and Ku-band can be quantified using the dual-frequency ratio (DFR). Since we are quantifying GR errors, we convert SR reflectivity observations from Ku to S-band.

$$Z_S = Z(Ku) - DFR \; = Z(Ku) + \sum_{i=0}^{4} a_i \, [Z(Ku)]^i \qquad (3)$$

Z_S is the reflectivity obtained after scaling is applied. DFR is calculated based on Cao et al. [13]. The coefficients a_i are specified for rain, snow, hail, dry snow, and dry hail at varying stages of melting. Constraints such as reflectivity threshold 18 dBZ (minimum value detected by SR) for SR and GR measurements are applied. A maximum time difference of 5 minutes is considered acceptable between the two measurements. Further, to minimize the non-uniform beam filling (NUBF) and low SR sensitivity, the matched samples having fraction of bins less than 0.7 are rejected for both SR and GR.

3 Result and Discussion

The location of the S-band radars and topography of the region, along with the BBF for the lowest elevation of 0.2˚, is illustrated in figure 2. Negligible BBF is observed for the smallest elevation angle for Kolkata and Karaikal. Some BBF can be seen for Machilipatnam, whereas significant BBF can be seen in the North West direction in case of Chennai. No BBF can be observed for Kolkata, Karaikal, and Machilipatnam for higher elevations. For Chennai, BBF is negligible above 1˚.

Further, three statistical indices, mean bias ($\overline{\Delta Z}$), mean absolute error (MAE), and Pearson's correlation coefficient (Corr), is used for evaluating GR observations with respect to SR. Mean bias gives the systematic bias in the observations, MAE quantifies the average magnitude of the error, and Corr gives information about how well the two observations are related. Mathematically,

$$\overline{\Delta Z} = \frac{1}{N}\sum_{n=1}^{N}(Z_{GR} - Z_{SR}\;) \qquad (4)$$

$$MAE = \frac{1}{N}\left|\sum_{n=1}^{N}(Z_{GR} - Z_{SR}\;)\right| \qquad (5)$$

$$Corr = \frac{\sum_{n-1}^{N}(Z_{GR}-\overline{Z_{GR}})\,(Z_{SR}-\overline{Z_{SR}})}{\sqrt{\sum_{n-1}^{N}(Z_{GR}-\overline{Z_{GR}})^2(Z_{SR}-\overline{Z_{SR}})^2}}. \qquad (6)$$

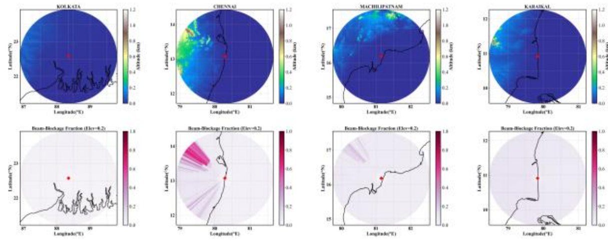

Figure 2. The topography and beam blockage fraction at the lowest elevation of 0.2° for (a) Kolkata, (b) Chennai, (c) Machilipatnam, and (d) Karaikal. The red point in the center signifies the radar location. The radar domain having a radius of 150 km from the site is shown.

GPM and GR reflectivity scatter diagram for all the locations and corresponding statistical indices are shown in figure 3. For better understanding of attenuation correction, the total matched samples are classified as stratiform and convective rain based on flagprecip parameter of SR data set (result not shown).

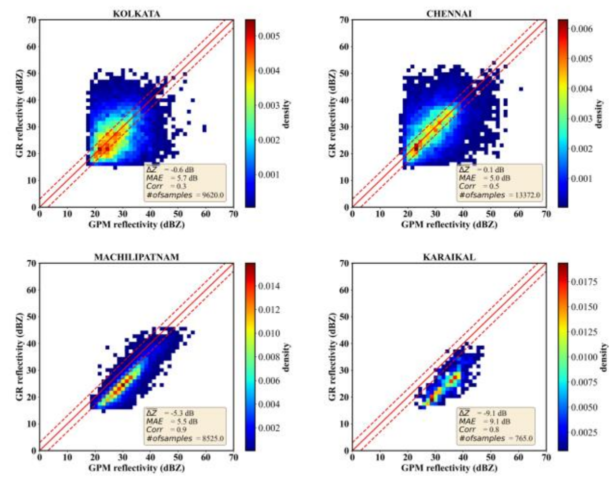

Figure 3. GPM and GR reflectivity scatter diagram and corresponding statistical indices for Kolkata, Chennai, Machilipatnam, and Karaikal. The solid red line is 1:1 line. Dotted red lines are ±3 dB lines.

A total of 20 matched cases (9620 samples) for Kolkata, 8 matched cases (13372 samples) for Chennai, 17 matched cases (8525 samples) for Machilipatnam, and 3 matched cases (765 samples) for Karaikal are selected. Mean bias is computed with and without BBF as a quality index. The bias does not change in the case of Kolkata and Karaikal. A negligible variation of order 10^{-3} is observed for Machilipatnam. For Chennai, the mean bias reduces to 0.07 from 0.1. Thus, BBF as a quality index does not account for much significance in our case (figure not shown).

For Kolkata and Chennai, it can be observed that the majority distribution of samples is around the 1:1 line with a ±3 dB variation. Whereas, in case of Machilipatnam and Karaikal, the majority distribution can be observed at a slope similar to 1:1 line but at a lower value. Similar trends are observed for stratiform and convective samples (figure not shown). The negative value of $\overline{\Delta Z}$ signifies that the GR underestimates the value of reflectivity compared to SR.

A bias of -0.6 is observed in the case of Kolkata, whereas 0.1 is observed in the case of Chennai. For Machilipatanam and Karaikal, bias up to -5.3 and -9.1 is observed. Although the bias is high, a high Corr is observed in both cases. The high value of bias can be attributed to the fewer number of cases identified for these locations. A statistical method is implemented over the GR dataset to reduce this mean bias, and improved results are illustrated in figure 4.

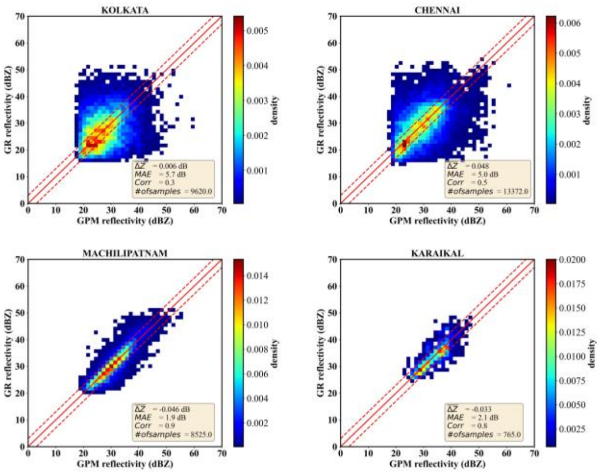

Figure 4. GPM and GR reflectivity scatter diagram and corresponding statistical indices after correction for Kolkata, Chennai, Machilipatnam, and Karaikal. The solid red line is 1:1 line. Dotted red lines are ±3 dB lines.

4 Summary

In this study, we compare the reflectivity measurements of S-band radar GR and GPM Ku-band radar (SR) at various locations along the Eastern coast and Southern peninsula region of India to quantify calibration bias.

A direct comparison of the two measurements is not straightforward. In this study, we use volume matching method and frequency scaling to obtain a point-to-point comparison between the two measurements. Further, the beam blockage fraction is used as a quality index in the analysis. Density scatter plots are obtained for matched samples. A statistical method is used to account for the bias, obtained, and improved results $\overline{\Delta Z} < |1| dB$ is observed.

The study can be extended to examine the variation of bias across the range and height of the ground radar domain. Individual analysis for stratiform and convective samples will be discussed in detail. Given the opportunity, further results of the analysis will be presented at the conference.

This study provides a valuable tool that can be utilized to monitor radar calibrations and even quantify the calibration bias over long series of data, improving the consistency. Corrected GR reflectivity measurements can help us improve the quantitative application of GR data and thus further our understanding of convective systems.

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