

Responses to Reviewer 2 Comments

Reviewer's comments are in black. Responses are in blue.

The authors are thankful to the Reviewer's constructive input and an appropriate acknowledgement for this has been added in the revised version.

The paper investigates how machine learning can improve rainfall estimates from an X-band weather radar, a system particularly sensitive to attenuation and calibration uncertainties. The authors design a two-step approach in which satellite radar observations are first used to adjust ground-based radar reflectivity measurements, aiming to reduce systematic biases and inconsistencies. In a second step, the adjusted radar signal is converted into surface rainfall using data-driven models trained on rain gauge measurements, thereby replacing traditional empirical relationships with learned nonlinear mappings. The methodology is tested over Cyprus, where the performance of different machine learning techniques is compared with standard reflectivity–rainfall conversions.

I have some major concerns regarding both the editorial and technical aspects.

General Response

We thank the reviewer for the thorough and constructive evaluation of our manuscript. We appreciate the detailed comments regarding both the methodological description and the presentation of the study. In response, we have substantially revised the manuscript to improve clarity, reproducibility, and the interpretation of the results.

The revised manuscript now provides additional information regarding the structure and dimensionality of the radar and satellite datasets, the volume-matching procedure between the ground-based X-band radars and the GPM DPR observations, the rationale behind the proposed two-stage framework, and the selection of radar-specific neural-network configurations. We have also expanded the discussion of the methodology and revised several sections to improve readability and transparency.

Furthermore, new figures have been added to better illustrate the volume-matching procedure, the reflectivity correction stage, and the relationships between radar reflectivity and rainfall observations. Existing figures have been revised to improve their interpretability, including the replacement of scatter plots with density-based visualizations where appropriate. Additional discussion has also been included to address the limitations and uncertainties associated with the proposed framework.

We believe that these revisions have significantly strengthened the manuscript and addressed the concerns raised by the reviewer. Detailed responses to each comment are provided below.

Comment:

I often found a lack of clarity in the prose that tends to obscure key methodological details. In a study like this, the **exact structure of the input data** is essential for interpreting the results and assessing reproducibility. For each model, it should be explicitly stated what the input tensor looks like (e.g., number of features, whether vertical profiles or single levels are used, spatial/temporal context, normalization). Without this, it is impossible to understand what the networks are actually learning or to compare fairly with alternative approaches.

Response:

Additional details regarding the model inputs have been added throughout Section 2 and Section 3. We now explicitly clarify that the study uses horizontal reflectivity observations

from volumetric radar scans. The input and output variables of each neural network are now more clearly described, together with the corresponding data sources, preprocessing steps, normalization procedures, and dataset splits. We also clarify the temporal coverage of the study and the rationale for selecting the 2019–2020 hydrological year. These additions improve the reproducibility and transparency of the proposed framework.

Added text (Section 2.2):

«This study uses horizontal reflectivity observations obtained from volumetric radar scans acquired by the two ground-based X-band radars.»

Added text (Section 3.2):

«Prior to model development, the input variables were normalized to the range [0, 1] using a Min-Max scaling approach. The dataset was subsequently divided into training, validation and test subsets.»

Comment:

Similarly, the absence of a clear description of the **volume matching procedure between ground radar and GPM DPR** is a major gap. This step is non-trivial and can strongly influence the results due to differences in resolution, viewing geometry, and sampling volumes.

Response:

The description of the volume-matching procedure has been expanded in the revised manuscript. The methodology follows the approach proposed by Bollen et al., further developed by Schwaller et al. and Warren et al., and implemented through the `gpmatch` Python library. The procedure identifies overlapping sampling volumes between the ground-based X-band radar and the GPM DPR Ku-band radar and computes weighted reflectivity averages within the common observation volume while accounting for differences in viewing geometry and sampling characteristics. Reflectivity conversion from Ku-band to X-band frequencies and clutter, speckle, and attenuation corrections were also applied prior to model development. For brevity, only a summary is included in the manuscript, while a detailed description is provided in Loulli et al. (2025b).

Added text (Section 2.4):

«Volume matching between the ground-based X-band radars and the GPM DPR Ku-band radar was performed using the `gpmatch` Python library following the methodology of Bollen et al., Schwaller et al., and Warren et al. The method identifies overlapping sampling volumes between the two radar systems and computes weighted reflectivity averages while accounting for differences in viewing geometry, beam characteristics, and sampling volumes. Reflectivity conversion from Ku-band to X-band frequencies and clutter, speckle, and attenuation corrections were applied prior to model development. Further details can be found in Loulli et al. (2025b).»

Comment:

The two-step design is introduced more as a procedural choice than as a **well-motivated strategy**. The authors should clearly explain *why* the problem is decomposed into (i) satellite-to-ground radar adjustment and (ii) radar-to-rainfall estimation, instead of, for example, a direct mapping from satellite observations to surface rainfall. A convincing motivation could be based on ideas such as domain adaptation, error separation (instrumental vs. microphysical), or leveraging higher-quality supervision (gauges) in an intermediate step—but none of these are articulated.

Response:

Additional motivation for the two-stage framework has been added to the revised manuscript. The first stage focuses on correcting systematic discrepancies in radar reflectivity observations and can therefore be used as a standalone reflectivity correction procedure. The second stage estimates rainfall from the corrected reflectivity using rain-gauge observations. This separation provides flexibility because the rainfall estimation model can be updated when new gauge measurements become available without requiring retraining of the reflectivity correction model. Furthermore, corrected reflectivity fields constitute useful products on their own, as they can support operational monitoring and forecasting applications where reflectivity patterns and storm evolution are of primary interest.

Added text (Section 3.1):

«The two-stage framework was selected to separate the reflectivity correction problem from the rainfall estimation problem. The first stage can operate as a standalone reflectivity correction procedure, while the second stage can be updated independently as additional rain-gauge observations become available. Furthermore, corrected reflectivity fields constitute useful products for operational monitoring and forecasting applications where reflectivity patterns and storm evolution are of primary interest.»

Comment:

The same applies to the **change in the number of layers for the models used for the two radars**; architectural decisions should be motivated (even briefly) in terms of the complexity of the mapping, input structure, or validation performance. Otherwise, it raises concerns about ad-hoc tuning or a lack of systematic model selection.

Response:

The neural-network architectures were selected through an iterative model-development process based on validation performance. Multiple configurations with different numbers of hidden layers and neurons were evaluated, and the final architectures were selected as a compromise between predictive skill and model complexity while avoiding signs of overfitting. The resulting configurations provided the best performance on the validation datasets and are therefore reported in the manuscript.

Added text (Sections 3.2.1 and 3.2.2):

«Several network architectures with different numbers of hidden layers and neurons were evaluated during model development. The final configurations were selected based on validation performance while maintaining a balance between predictive skill, model complexity, and robustness against overfitting.»

Comment:

Operations like the ones you mention (lines 199–201) appear as “black-box” preprocessing steps, and it is hard for the reader to assess the impact of these choices on the results.

Response:

We agree that the description of these calculations was not sufficiently clear. These calculations were originally included as reference analyses during model development and were not required for the final methodology. To improve clarity and avoid confusion, they have been removed from the revised manuscript.

Comment:

The overall quality of the figures should be improved. In particular, Figure 6 appears to contain visible artifacts that are not discussed in the text, making it difficult to determine whether they arise from the data, the processing chain, or the visualization itself. These features might be misleading and should either be explained or removed through improved plotting or preprocessing. In addition, the scatter plots are difficult to interpret due to overplotting and poor visual contrast; important structures (e.g., biases, spread, and conditional behavior) are not easily discernible.

Response:

To improve the presentation and interpretability of the results, several additional diagnostic figures have been included in the revised manuscript. In particular, density-based heatmap visualizations have been added to illustrate the relationships between raw radar reflectivity, corrected radar reflectivity, and GPM Ku-band reflectivity for both radars. These figures replace conventional scatter plots and provide a clearer representation of data density, spread, and agreement between datasets. Furthermore, boxplot analyses have been introduced to investigate the relationship between corrected reflectivity and gauge rainfall rates. These additions provide further evidence that the reflectivity correction stage improves agreement with the GPM observations while preserving a physically meaningful relationship between reflectivity and rainfall intensity.

Regarding the apparent artifacts visible in Figure 6, these are primarily associated with regions where rainfall estimates are extrapolated beyond areas adequately constrained by rain-gauge observations. This is particularly evident over marine areas surrounding Cyprus, where no gauge measurements are available for model training and validation. Consequently, rainfall estimates in these regions remain more uncertain than over land. This limitation is now explicitly acknowledged and discussed in the revised manuscript.

Added text (Section 5):

«Some localized features visible over marine areas may reflect increased uncertainty in regions where no rain-gauge observations were available for model training and validation. Consequently, rainfall estimates over the sea should be interpreted with greater caution than those over land.»

Newly added figures:

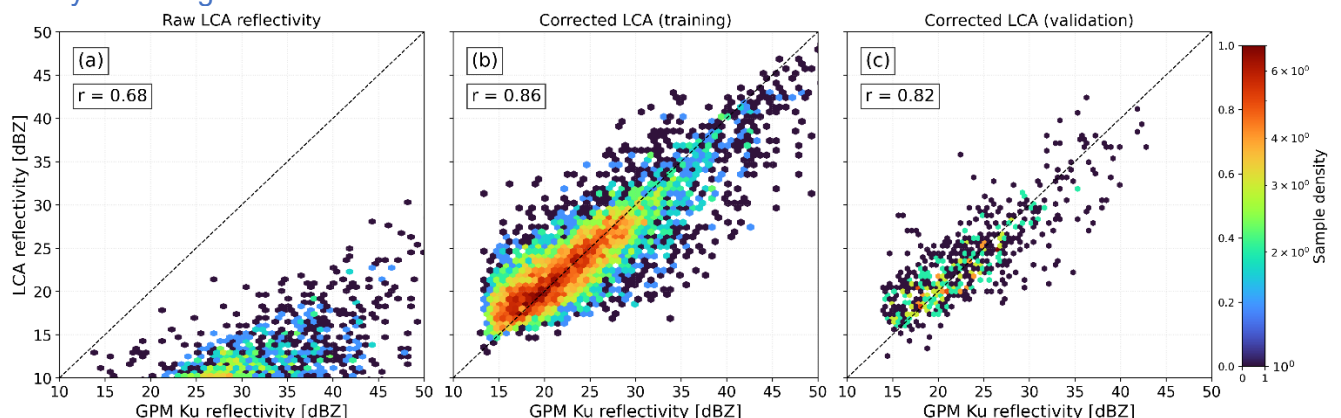


Figure 12. Joint distributions between GPM Ku-band reflectivity and LCA radar reflectivity: (a) raw reflectivity, (b) corrected reflectivity for the training dataset, and (c) corrected reflectivity for the validation dataset. The dashed line indicates the 1:1 relationship.

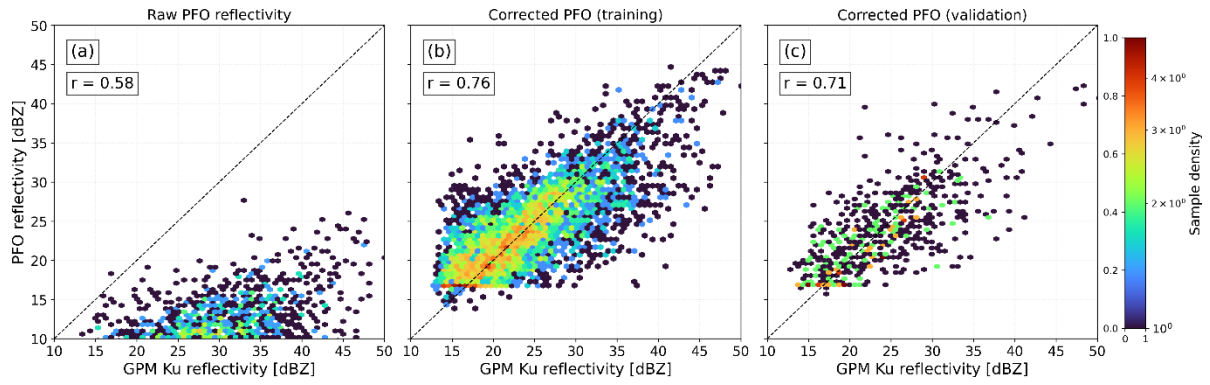


Figure 13. Joint distributions between GPM Ku-band reflectivity and PFO radar reflectivity: (a) raw reflectivity, (b) corrected reflectivity for the training dataset, and (c) corrected reflectivity for the validation dataset. The dashed line indicates the 1:1 relationship.

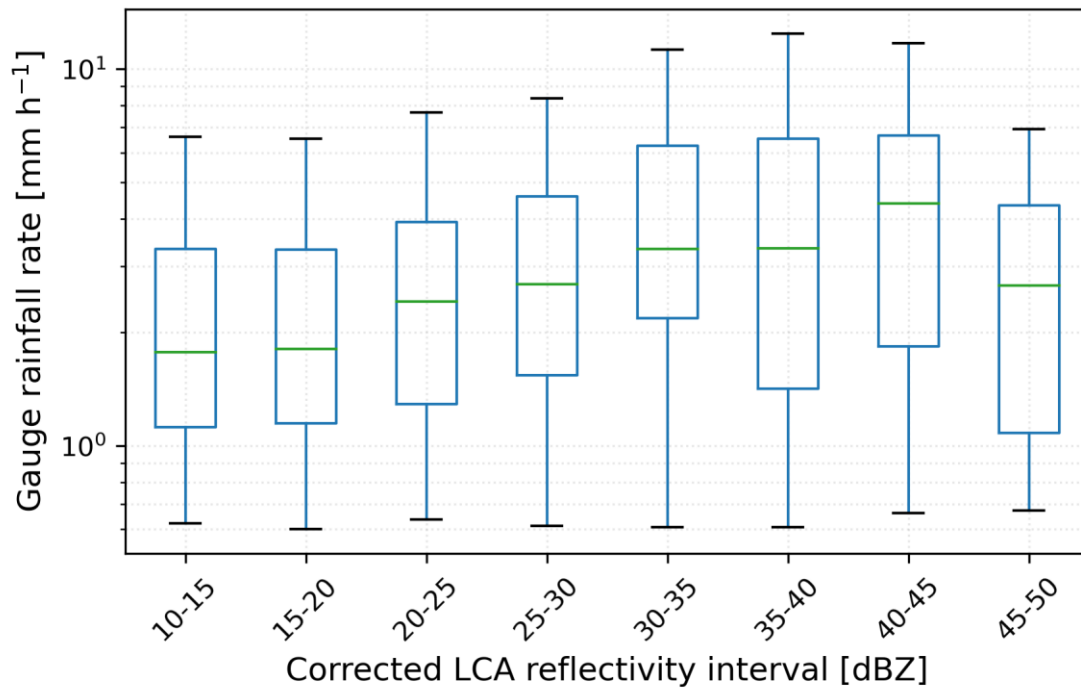


Figure 14. Boxplots of gauge rainfall rates grouped by corrected LCA reflectivity intervals.

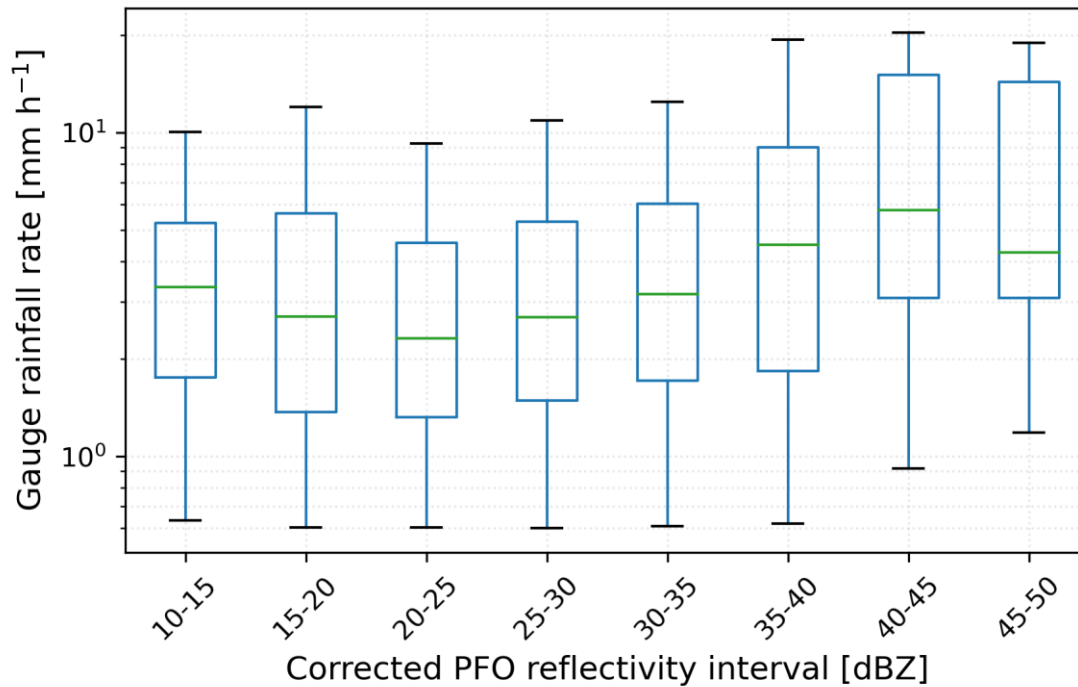


Figure 15. Boxplots of gauge rainfall rates grouped by corrected PFO reflectivity intervals.

Comment:

Line 15: What do you mean by weather radar? I would be more precise about which frequency you mean.

Response:

We agree that the term «weather radar» is too broad. The manuscript has been revised to specify the radar frequency bands commonly used in meteorological applications, namely **S-band (2–4 GHz), C-band (4–8 GHz), and X-band (8–12 GHz)** weather radars. We also explicitly state that this study focuses on an X-band weather radar operating within the X-band frequency range.

Revised text:

«Weather radars commonly operate in the S-band (2–4 GHz), C-band (4–8 GHz), and X-band (8–12 GHz) frequency ranges. This study utilizes two X-band weather radars, which offer high spatial resolution but are more susceptible to attenuation than lower-frequency systems.»

Comment:

Line 32: cite a reference to support this statement.

Response:

An additional reference has been included to support the statement regarding the characteristics and limitations of X-band weather radar observations.

Added reference:

Park, S.-G., Bringi, V. N., Chandrasekar, V., Maki, M., and Iwanami, K.: 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, 1621–1632, 2005.

Comment:

Line 32: “provide high spatial resolution” better restate as “provide data at high spatial resolution” or “that can perform high-resolution observations”.

Response:

The text has been revised accordingly.

Revised text:

«X-band weather radars provide data at high spatial resolution, making them particularly suitable for monitoring localized precipitation systems.»

Comment:

Line 75–77: Ground radar reflectivity: is this a map obtained from scans? Or a profile?

Response:

The text has been revised to clarify that the ground-radar reflectivity used in this study originates from volumetric radar scans acquired by the X-band radars rather than from individual profiles. To further clarify the data structure and the volume-matching procedure, a new schematic figure has been added illustrating the geometrical relationship between the ground-based radar sampling volume, the GPM DPR sampling volume, and the volume-matched observations used during model development.

Revised text:

«In this study, a two-stage ML framework is proposed for the estimation of near-surface rainfall from volumetric ground-based X-band radar observations over Cyprus. In the first stage, a feedforward NN is trained to correct ground-radar reflectivity using volume-matched reflectivity observations from the GPM DPR Ku-band radar. In the second stage, the corrected reflectivity is used as input to regression models for the estimation of near-surface rainfall rates using measurements from automatic weather stations.»

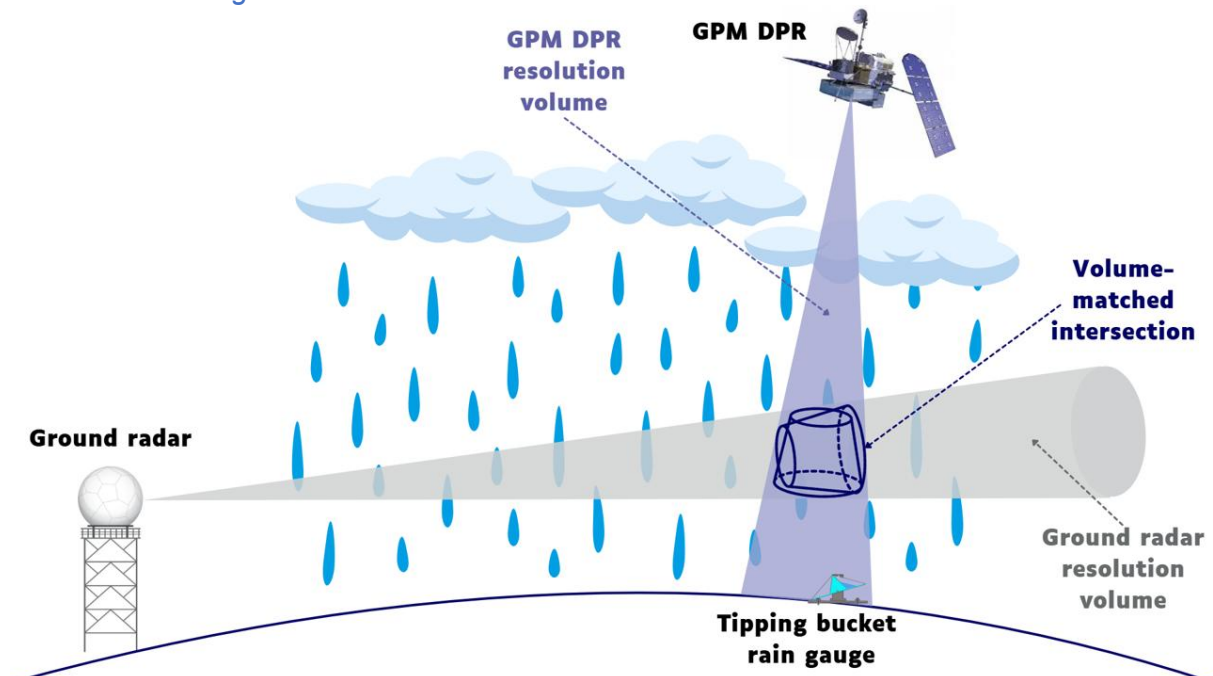


Figure X: Schematic representation of the volume-matching procedure between the ground-based X-band radar, the GPM DPR Ku-band radar, and the tipping-bucket rain gauge.

Comment:

Line 80: Reflectivity data is too generic: What type of data? Scans? Volumes? Profiles? What is the dimensionality? Unclear.

Response:

The manuscript has been revised to clarify that the study uses three-dimensional volumetric reflectivity observations from both the GPM DPR Ku-band radar and the ground-based X-band radars.

Revised text

«This study is based on volumetric Ku-band reflectivity observations from the GPM Dual-frequency Precipitation Radar (DPR), volumetric reflectivity observations from two ground-based X-band dual-polarization weather radars, and rainfall measurements from the network of Automatic Weather Stations (AWS) operated by the Cyprus Department of Meteorology. This section describes the datasets employed in the analysis.»

Comment:

Line 86–88: I think a figure would help to clarify which data you are considering.

Response:

A schematic figure illustrating the GPM DPR observation geometry and coverage has been added to improve the description of the satellite dataset employed in this study.

Added Figure:

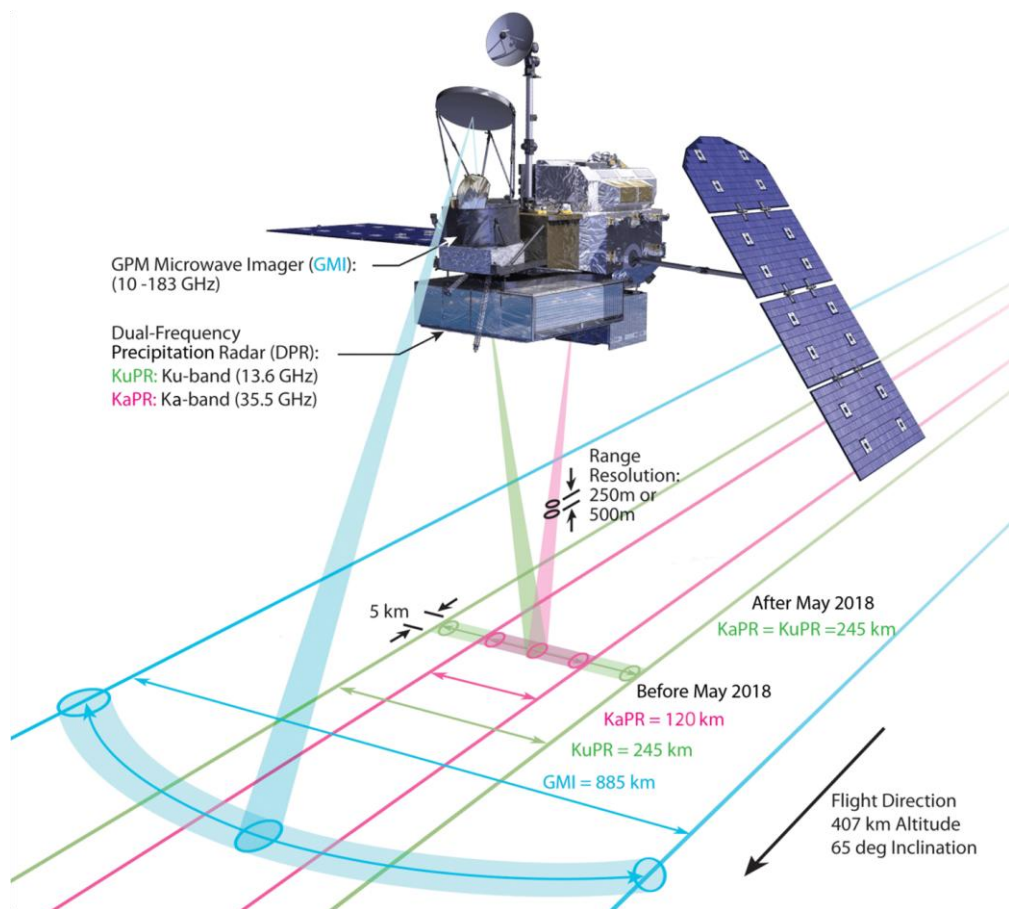


Figure X. Schematic diagram of the GPM Core Observatory's Dual-frequency Precipitation Radar (DPR) and GPM Microwave Imager (GMI) instruments. Source: NASA Global Precipitation Measurement (GPM) Mission (<https://gpm.nasa.gov/resources/images/swath-coverage-gpm-instruments>, last access: 13 June 2026).

Comment:

Line 89–92: What is the dimensionality of the GPM data you use?

Response:

The manuscript has been revised to clarify that the GPM DPR observations used in this study are three-dimensional volumetric reflectivity measurements.

Added text:

«Volumetric Ku-band reflectivity measurements from the GPM DPR Full Swath (FS) product were used and subsequently volume-matched with the ground-based X-band radar observations.»

Comment:

Line 130: How much data did you collect in the end?

Response:

The final number of samples has now been explicitly reported in the revised manuscript. After quality-control procedures and temporal matching, the final datasets comprised 25,741 samples for the LCA radar and 21,915 samples for the PFO radar.

Added text:

«After quality-control procedures and temporal matching, the final datasets comprised 25,741 samples for the LCA radar and 21,915 samples for the PFO radar.»

Comment:

What is the corresponding range to the ground radar? Unclear. How do you perform the volume matching? Showing some graphics to make people understand would help.

Response:

This issue is addressed in our response to the comment on Lines 75–77. To improve clarity, we have expanded the description of the volume-matching procedure and added a new schematic figure illustrating the geometrical relationship between the ground-based X-band radar sampling volume, the GPM DPR sampling volume, and the resulting volume-matched observations used during model development. Additional details have also been added to the manuscript clarifying the definition of the corresponding radar samples used in the matching procedure.

Comment:

Line 145: “corresponding” to what?

Response:

We thank the reviewer for identifying this ambiguity. The text has been revised to clarify that the term “corresponding” refers to the volume-matched GPM DPR observation associated with each ground-radar sample.

Revised text:

«The input vector of the first network (Stage 1) consisted of four variables: (i) the volume-matched raw ground reflectivity, (ii) the range of the corresponding ground-radar sample

from the radar location, (iii) the Path-Integrated Reflectivity (PIR) associated with the corresponding ground-radar sample, and (iv) the GPM overpass time.»

Comment:

Line 150–151: I don't understand. The output of the first network is the volume-matched Ku reflectivity, while the input to the second is called ground reflectivity. Are these two the same? If yes, why use two different names?

Response:

We thank the reviewer for identifying this ambiguity. The first-stage neural network is trained using volume-matched GPM Ku-band reflectivity as the target variable. Once trained, the model is applied to ground-radar observations to generate corrected ground reflectivities. These corrected reflectivities constitute the output of Stage 1 and are subsequently used as input to the rainfall estimation models in Stage 2. The text has been revised accordingly.

Revised text:

«The output vector consisted of one variable, namely the volume-matched GPM Ku-band reflectivity. Following model training, the neural network was applied to ground-radar observations to generate corrected ground reflectivities. These corrected reflectivities were subsequently used as input to the rainfall-estimation models of Stage 2.»

Comment:

General comment: you might clarify for a non-expert, what pulse data is, what the pulse tip is.

Response:

Additional clarification has been added to the manuscript. Pulse data from an automatic rainfall station correspond to the time-stamped measurements recorded whenever the tipping-bucket rain gauge collects a fixed amount of rainfall. Each pulse tip represents a predefined increment of accumulated rainfall and is subsequently used to derive rainfall intensity estimates.

Added text:

«Pulse data from an automatic rainfall station correspond to the time-stamped measurements recorded whenever the tipping-bucket rain gauge collects a fixed amount of rainfall. Each pulse tip represents a predefined increment of accumulated rainfall and is subsequently used to derive rainfall intensity estimates.»

Comment:

Line 159: Clarify what you mean by “lowest radar sweep”.

Response:

The manuscript has been revised to clarify that the lowest radar sweep refers to the radar scan acquired at the lowest elevation angle (0.5°). A radar sweep corresponds to a complete 360° rotation of the antenna at a fixed elevation angle.

Added text:

«The lowest radar sweep refers to the radar scan acquired at the lowest elevation angle (0.5°). A radar sweep corresponds to a complete 360° rotation of the antenna at a fixed elevation angle.»

Comment:

What is the criterion with which you decide the number of layers in the MLP?

Response:

This issue is addressed in our response to the comment regarding the use of radar-specific neural-network configurations (Section 3.2.2). As explained there, several network architectures with different numbers of hidden layers and neurons were evaluated during model development, and the final configurations were selected based on validation performance while maintaining a balance between predictive skill, model complexity, and robustness against overfitting.

Comment:

Line 330: You do not show any discussion on the choice of the optimal radius. If this is so relevant, then more information should be provided.

Response:

This issue is addressed in our response to the comments regarding the selection of the optimal averaging radius (Lines 253 and 330). As explained there, a sensitivity analysis was performed by evaluating multiple averaging radii around each rain-gauge location and assessing the resulting agreement between radar-derived variables and gauge rainfall observations. The selected radius corresponded to the configuration providing the most consistent relationship between radar observations and rainfall measurements while maintaining an adequate spatial representation of rainfall around the gauge location.

Comment:

Line 337–338: You do not explain why.

Response:

Additional discussion has been added to explain the lower performance observed for the PFO radar relative to the LCA radar.

Revised text:

«In terms of model complexity and performance, the PFO radar required a deeper NN architecture in both stages, yet it consistently yielded poorer results compared to the LCA radar. This difference may be attributed to the higher installation altitude of the PFO radar (392 m above mean sea level compared to 100 m for LCA), resulting in observations being acquired farther from the surface. Consequently, precipitation particles may undergo additional microphysical evolution before reaching the ground, weakening the relationship between radar observations and surface rainfall measurements. Differences in beam geometry, sampling characteristics, and local topographic influences may further contribute to the lower predictive performance observed for the PFO radar.»

Comment:

Line 159: Clarify what you mean by “lowest radar sweep”.

Response:

The manuscript has been revised to clarify the meaning of the term «lowest radar sweep».

Added text:

«The lowest radar sweep refers to the radar scan acquired at the lowest elevation angle (0.5°). A radar sweep corresponds to a complete 360° rotation of the radar antenna at a fixed elevation angle.»

Comment:

Why do you need a second stage? Couldn't you retrieve rain rates in the first stage? What's the added value and the motivation to add the second step?

Response:

The second stage was introduced to separate the reflectivity correction problem from the rainfall estimation problem. This design allows the reflectivity correction model to be used independently and updated separately from the rainfall retrieval model. In addition, corrected reflectivity fields represent a useful standalone product for operational applications where reflectivity information is required independently of rainfall estimates.

Added text (Section 3.1):

«The two-stage framework was selected to separate the reflectivity correction problem from the rainfall estimation problem. The first stage can operate as a standalone reflectivity correction procedure, while the second stage can be updated independently as additional rain-gauge observations become available. Furthermore, corrected reflectivity fields constitute useful products for operational monitoring and forecasting applications where reflectivity patterns and storm evolution are of primary interest.»

Comment:

Line 199–201: Totally unclear what all these manipulations are needed for.

Response:

We agree with the reviewer that these calculations were not essential for the methodology presented in this study. To improve clarity, they have been removed from the revised manuscript.

Comment:

Line 205–206: You said this already in your methodology section.

Response:

The redundant text has been removed from the revised manuscript.

Comment:

Section 3.2.2: Why do you need to define a specific model for the PFO site, which is different from the ones defined in the previous methodology section?

Response:

The rationale for using radar-specific model configurations has been clarified in the revised manuscript. The two radars operate under different observational conditions due to their differing elevations, beam geometries, and sampling characteristics. As a result, the relationship between radar observations and surface rainfall differs between the two sites. Therefore, radar-specific configurations were evaluated and selected based on their validation performance for each radar individually.

Added text:

«The two radars are located at substantially different elevations above mean sea level (100 m for LCA and 392 m for PFO), resulting in differences in radar beam geometry and sampling volumes. Consequently, the relationship between radar-observed reflectivity aloft and rainfall measured at the surface is not expected to be identical for the two sites. Precipitation particles sampled by the higher-elevation PFO radar are, on average, observed farther from the surface and may undergo additional microphysical evolution before reaching the ground. Furthermore, differences in beam height, viewing geometry, and local topographic influences can affect the representativeness of radar observations with respect to surface rainfall measurements. For this reason, radar-specific model configurations were explored and selected based on validation performance for each radar individually.»

Comment:

Section 3.3: I suggest putting these definitions in the appendix.

Response:

The definitions have been moved to the Appendix in the revised manuscript.

Comment:

Line 235: Missing "n".

Response:

We thank the reviewer for identifying this typographical error. It has been corrected in the revised manuscript.

Comment:

Line 249: Slight underestimation by whom? need to specify in the text... slight means what? Can you quantify it?

Response:

The text has been revised to explicitly state that the ground-radar reflectivities remain underestimated relative to the corresponding GPM observations by approximately 10 dBZ in the higher reflectivity ranges.

Revised text:

«The ground-radar reflectivities exhibited an underestimation relative to the corresponding GPM Ku-band observations, reaching approximately 10 dBZ in the higher reflectivity ranges. Nevertheless, the overall agreement remained acceptable across the majority of observations.»

Comment:

Line 253 / Line 330: How was the optimal radius selected?

Response:

Additional explanation regarding the selection of the averaging radius has been added to the manuscript. A sensitivity analysis was performed by evaluating multiple averaging radii around each rain-gauge location and assessing the resulting agreement between radar-derived variables and gauge rainfall observations. The selected radius corresponded to the configuration providing the most consistent relationship between radar observations and rainfall measurements while maintaining a representative sampling area around the gauge location. The adopted radius therefore reflects a balance between reducing sampling noise and preserving local rainfall variability.

Added text:

«The averaging radius was selected through a sensitivity analysis evaluating multiple radii around each rain-gauge location. The selected radius corresponded to the configuration providing the most consistent relationship between radar-derived variables and gauge rainfall observations while maintaining an adequate spatial representation of rainfall around the gauge location.»

Comment:

Fig. 6: There seem to be unrealistic features. Do you know what is causing them? For light green values.

Response:

The apparent features are mainly associated with regions where rainfall estimates are produced outside areas constrained by rain-gauge observations. This is particularly evident over marine areas surrounding Cyprus, where no gauge measurements are available for model training and validation. In addition, Figure 6 represents a merged rainfall product

combining estimates from both the LCA and PFO radars. Consequently, rainfall estimates in these regions remain more uncertain than over land and should be interpreted with caution. This limitation is now explicitly acknowledged in the revised manuscript.

Added text:

«Some localized features visible over marine areas may reflect increased uncertainty in regions where no rain-gauge observations were available for model training and validation. This is particularly relevant for the merged rainfall product, where estimates are generated over areas not directly constrained by gauge measurements. Consequently, rainfall estimates over the sea should be interpreted with greater caution than those over land.»

Comment:

Line 285: What is the criterion with which you decide the number of layers in the MLP?

Response:

Several neural-network architectures with different numbers of hidden layers and neurons were evaluated during model development. The final architectures were selected based on their performance on the validation dataset while maintaining a balance between predictive skill and model complexity. Architectures exhibiting signs of overfitting were discarded in favour of simpler configurations with comparable or improved validation performance. This clarification has been added to the manuscript.

Added text:

«Several network architectures with different numbers of hidden layers and neurons were evaluated during model development. The final configuration was selected based on validation performance while maintaining a balance between predictive skill, model complexity, and robustness against overfitting.»

Comment:

Line 330: You do not show any discussion on the choice of the optimal radius. If this is so relevant, then more information should be provided.

Response:

Additional explanation regarding the selection of the averaging radius has been added to the manuscript. Different radii around each rain-gauge location were evaluated and their impact on the agreement between radar-derived variables and gauge rainfall observations was assessed. The selected radius provided the most consistent relationship between radar observations and rainfall measurements while ensuring an adequate representation of rainfall conditions within the averaging area surrounding each gauge.

Added text:

«The averaging radius was selected through a sensitivity analysis evaluating multiple radii around each rain-gauge location. The selected radius corresponded to the configuration providing the most consistent relationship between radar-derived variables and gauge rainfall observations while maintaining an adequate spatial representation of rainfall around the gauge location.»