Evaluation of Precipitation Estimates by at-Launch Codes of GPM/DPR Algorithms Using Synthetic Data from TRMM/PR Observations

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Abstract—The Global Precipitation Measurement (GPM) Core Observatory will carry a Dual-frequency Precipitation Radar (DPR) consisting of a Ku-band precipitation radar (KuPR) and a Ka-band precipitation radar (KaPR). In this study, “at-launch” codes of DPR precipitation algorithms, which will be used in GPM ground systems at launch, were evaluated using synthetic data based upon the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data. Results from the codes (Version 4.20131010) of the KuPR-only, KaPR-only, and DPR algorithms were compared with “true values” calculated based upon drop size distributions assumed in the synthetic data and standard results from the TRMM algorithms at an altitude of 2 km over the ocean. The results indicate that the total precipitation amounts during April 2011 from the KuPR and DPR algorithms are similar to the true values, whereas the estimates from the KaPR data are underestimated. Moreover, the DPR estimates yielded smaller precipitation rates for rates less than about 10 mm/h and greater precipitation rates above 10 mm/h. Underestimation of the KaPR estimates was analyzed in terms of measured radar reflectivity ($Z_{mr}$) of the KaPR at an altitude of 2 km. The underestimation of the KaPR data was most pronounced during strong precipitation events of $Z_{mr} < 18$ dBZ (high attenuation cases) over heavy precipitation areas in the Tropics, whereas the underestimation was less pronounced when the $Z_{mr} > 26$ dBZ (moderate attenuation cases). The results suggest that the underestimation is caused by a problem in the attenuation correction method, which was verified by the improved codes.

Index Terms—Algorithms, attenuation, Global Precipitation Measurement (GPM), rain, simulation, snow, spaceborne radar, Tropical Rainfall Measuring Mission (TRMM).

I. INTRODUCTION

The Global Precipitation Measurement (GPM) Mission consists of a Tropical Rainfall Measuring Mission (TRMM)-like nonsun-synchronous orbiting satellite (GPM Core Observatory) and a constellation of satellites carrying microwave radiometer instruments [1]. The GPM Core Observatory, which will be launched in early 2014, carries the Dual-frequency Precipitation Radar (DPR) developed by the Japan Aerospace Exploration Agency (JAXA) and the National Institute of Information and Communications Technology (NICT) [2], and the GPM microwave imager (GMI) provided by the U.S. National Aeronautics and Space Administration (NASA). The DPR consists of two radars: Ku-band (13.6 GHz) PR (KuPR) and Ka-band (35.55 GHz) radar (KaPR). To obtain a higher sensitivity, the DPR employs the variable pulse repetition frequency (VPRF) technique [3], [4]. The DPR is expected to advance precipitation science by expanding the coverage of observations to higher latitudes than those obtained by the TRMM Precipitation Radar (PR), by measuring snow and light rain via high-sensitivity observations from the KaPR, and by providing drop size distribution (DSD) information based on the differential scattering properties of the two frequencies. The combined use of PR and the TRMM microwave imager (TMI) onboard the TRMM satellite has greatly improved the technique of rainfall estimation [5]–[12]. By simultaneous observation with the DPR, the GMI will improve the accuracy of rainfall/snowfall estimates, and work as a bridge between the highly accurate observation by the GPM Core Observatory and frequent observations by constellation satellites with microwave radiometers.

For operational productions of precipitation datasets, it is necessary to develop computationally efficient, fast-processing DPR Level-2 (L2) algorithms that can provide estimated precipitation rates, radar reflectivity factors, and precipitation information, such as the DSD and precipitation type. The L2 algorithms have been developed by the DPR Algorithm Development Team under the NASA-JAXA Joint Algorithm Team [13], [14]. As a test bed for the DPR L2 algorithms, synthetic DPR Level-1 (L1) data are needed before the launch of the GPM Core Observatory. Previous work on algorithm development relied on airborne dual-frequency radar data [15]–[20], ground-based radars [21]–[23], numerical model simulations [24]–[26], and data simulated from the TRMM/PR [27]–[31]. In this paper, we
use the last of these approaches. The primary advantage is that measured Ku-band data from the TRMM/PR, obtained under a wide variety of meteorological conditions, forms the basis of the simulation. As such, the results can be compared directly to the standard TRMM/PR retrievals. The disadvantage is that the hydrometeor particle size distribution and phase state are derived from the PR algorithm results to convert the Ku-band measured reflectivity factors to those at Ka-band.

This paper presents evaluations of “at-launch” codes of the DPR algorithms using the synthetic data generated from the TRMM/PR observations. Section II describes the data and methods related to the GPM/DPR algorithms and synthetic radar data from the PR data. Section III presents an evaluation of the at-launch codes. Section IV provides the horizontal distribution of frequencies in the simulated radar reflectivity of the KaPR. Section V discusses reasons for the underestimates in the KaPR data found in the current code. Section VI presents an overall summary of this research.

II. DATA AND METHODS

A. Antenna Scanning Geometry of the DPR

The antenna scanning geometry of the DPR is needed to generate the synthetic data. Fig. 1 shows the antenna scanning geometry of the KuPR and the KaPR [2]. The KuPR beam scanning from the 13th to the 37th angle-bins and the KaPR beam scanning from the 1st to the 25th angle-bins is performed synchronously to provide matched KuPR and KaPR beams within an accuracy of 1 km. The range resolution is 250 m, and the sensitivity is 0.5 mm/h for both the KuPR and the KaPR in this matched beam portion of the swath. Here, the pixels of the KaPR are referred to as “KaMS,” while “MS” denotes the matched portion of the swath. During the time when the KuPR scans the outer swath area (from the 1st to the 12th and from the 38th to the 49th angle-bins) with a range resolution of 250 m, the KaPR scans the interlaced scan area (from the 26th to the 49th angle-bins) with a range resolution of 500 m. The KaPR minimum detectable precipitation rate is 0.2 mm/h in the interlaced scan area. The high-sensitivity pixels of the KaPR are referred to as “KaHS” in this paper. For all the modes and for both frequencies, the beam width is about 0.7°, and the horizontal resolution on the ground is about 5.2 km for both the KuPR and the KaPR when the orbit altitude is 407 km. The KuPR swath width is approximately 245 km, which corresponds to ±17° electrical beam scanning. The KaPR swath width is approximately 125 km, which corresponds to ±8.5° electrical beam scanning. The sampling interval of the KuPR along the range direction is 125 m from the surface up to a height of 14 km, and 250 m for heights from 14 to 19 km. The sampling interval of the KaMS is the same as that of the KuPR, and it is 250 m for all heights in the KaHS.

B. “At-launch” Codes of GPM/DPR Level-2 Algorithms

The “at-launch” codes of the DPR-L2 algorithms will be used in GPM ground systems at the launch for the production of the precipitation datasets. The L2 algorithms will produce three sets of outputs: 1) KuPR-only products, 2) KaPR-only products, and 3) DPR products using both KuPR and KaPR data. It is important to develop algorithms applicable to both PR and KuPR in order to produce a long-term continuous dataset. Thus, the L2 algorithms consist of KuPR, KaPR, and DPR algorithms. The KaPR-L2 algorithm generates the KuPR-L2 product from the KuPR-L1 product that includes Ku-band radar received power data. The KaPR-L2 algorithm generates the KaPR-L2 product from the KaPR-L1 product that includes Ka-band radar received power data. The KaMS and the KaHS data are processed as a single file in the KaPR-L1 or L2 product. The DPR-L2 algorithm generates the DPR-L2 product from the KuPR-L2 and the KaPR-L2 products.

While the single-frequency L2 algorithms have been developed based on TRMM/PR standard algorithms [32]–[36], there are several features in the newly developed DPR-L2 algorithm. In the classification module, which classifies precipitation types and bright band information, the KuPR and KaPR algorithms use a concept similar to the PR 2A23 algorithm [36]. However, the DPR algorithm uses the dual-frequency ratio (DFR) method [37], [38]. In the surface reference technique (SRT) module, which estimates the path-integrated attenuation (PIA) for precipitation pixels, the KuPR and KaPR algorithms employ an approach similar to the PR 2A21 algorithm [33], [34], whereas the DPR algorithm uses a dual-frequency SRT (DSRT) based upon the differential path attenuation between the Ku-band and Ka-band [20], [39]. In the Solver (SLV) module, which numerically solves the radar equations and obtains DSD parameters at each range bin, the KuPR and KaPR algorithms use a combination of the Hitschfeld–Bordan attenuation correction method (HB method) and the SRT method, similar to the PR 2A25 algorithm [32], [35]. The DPR algorithm uses a combination of the HB method, the DFR method, and the SRT method [31], [40].

C. KaPR Sampling Experiments by TRMM/PR

Since November 1997, the first spaceborne PR (PR) has been operating on the TRMM satellite. The TRMM/PR operates at a frequency of 13.8 GHz [41], [42], whereas the KuPR of the DPR will operate at 13.6 GHz. The peak transmit power of the TRMM/PR is 500 W, while that of the KuPR is 1012 W.

The antenna scanning geometry of the TRMM/PR and the KuPR, as described in Section II-A, are identical. On the other hand, the scanning geometry of the KaPR is different from that of TRMM/PR. An experiment, in which the scanning geometry of
the TRMM/PR was modified to that of the KaPR, was desirable in order to produce synthetic data simulating the KaPR scanning geometry. Therefore, JAXA carried out the experiment of the TRMM/PR on March 15, 2007 [43]. The scan angles and the measurement sequence of the PR were modified by sending operational control commands from the ground system. This was referred to as the “KaPR sampling experiment.” There were two kinds of operational modifications for the simulation of the KaPR sampling in the experiment. One was a change in the scanning angles and another was a change in the recording range bins. Scanning angles from 1st to 12th and from 38th to 49th were changed by replacing phase codes from the ground system for collecting interlaced footprint data. By this procedure, the TRMM/PR scan range was narrowed from \( \pm 17 \) to \( \pm 8.5^\circ \). The experiment was executed for 7 orbits (orbit numbers from 53159 to 53165). For this experiment, the TRMM/PR L1 algorithm was modified to account for changes in the scan angles and altitude limits. Fig. 2 shows examples of measured radar reflectivity factor \((Z_{\text{m}})\) data of the TRMM/PR over the southwestern Pacific in (a) matched beams, (b) interlaced beams, and (c) all beams in the TRMM orbit number 53\(^{\circ}\) 160 during the KaPR sampling experiment. Black circles denote pixels where the received power was below the noise level.

D. Development of Synthetic Radar Data

This section describes how the synthetic DPR L1 data are generated from the PR data. Here, the DSD, \(N(D)\) was modeled by a gamma distribution function of a drop diameter \(D\), as shown in the following equation:

\[
N(D) = N_0D^p \exp\left[-(3.67 + \mu)D/D_0\right]
\]

Two DSD parameters \((N_0, D_0)\) were retrieved from the effective radar reflectivity factor \((Z_{\text{e}})\) and specific attenuation \((k)\) obtained in the PR 2A25 product based upon the method of Seto et al. [31]. Third parameter of the DSD function \(\mu\) was assumed to be 3 in this study, because PR 2A25 and current DPR-L2 algorithms adopt this assumption. For each range bin, \(k/Z_{\text{e}}\) can be converted to \(D_0\) using the theoretical relationship between \(k/Z_{\text{e}}\) and \(D_0\); \(N_0\) is then obtained from \(D_0\) and \(Z_{\text{e}}\). The current relationship was identical to that used in the algorithms. When
is not a monotonic function of $D_0$, the smaller $D_0$ is selected. Estimates of nonprecipitating constituents of the atmosphere such as water vapor (WV), molecular oxygen ($O_2$), and cloud liquid water (CLW) were based upon atmospheric information obtained from a Global Objective Analysis from the Japan Meteorological Agency (GANAL). Attenuation due to WV was estimated by a formulation presented in previous work [44]–[46], and attenuation due to $O_2$ was estimated by a formulation presented in similar and other previous work [45]–[47]. Attenuation due to CLW was estimated for nonprecipitating pixels from GANAL and for precipitating pixels from a CLW database generated by global cloud-resolving model simulations as a function of surface precipitation rate, temperature, and precipitation type [48]. Thus, $PIA$ and $Z_o$ of $KuPR$ and $KaPR$ were calculated from the estimated DSD with attenuations.

In the surface echo simulation at the Ka-band, it is necessary to consider differences of the normalized radar cross section (NRCS) between the Ku-band and the Ka-band frequencies. In this study, statistical mean differences of the NRCS, which are dependent upon incidence angles, were used from dual-frequency airborne radar results [19], [20]. This simple assumption is reasonable over the ocean background because quasi-specular scattering dominates when the incident angle is less than 20°. On the other hand, the NRCS of over the land background is often modeled by the soil surface and vegetation cover [49]–[52] and this assumption may be problematic here. The relationships between the $KuPR$ and the $KaPR$ for $Z_o$ and the NRCS, described in Appendix A, were used in the calculation. For the values of $Z_o$ at the surface, the difference in $Z_o$ between the $KuPR$ and the $KaPR$ is directly related to the difference between the NRCS at the two frequencies. Furthermore, the surface echo at the Ka-band was calculated considering differences of $PIA$ by the precipitation and nonprecipitation between the Ku-band and Ka-band frequencies. In the simulation, the surface echo at $KuPR$ was assumed to be the same as that of the TRMM/PR.

Using these atmospheric and surface models, the radar return power can be calculated from $Z_m$ at $KuPR/KaPR$ according to the appropriate radar equation. In this study, constant noise levels were taken to be $-109.50$ dBm at $KuPR$, $-109.47$ dBm at $KaMS$, and $-112.48$ dBm at $KaHS$. Finally, the received power data were resampled using the VPRF table and archived in the $KuPR/KaPR$ L1 format. Fig. 3 shows comparisons of $Z_m$ in the DPR synthetic data at a 2 km altitude over the southwestern Pacific. Due to higher attenuation at Ka-band by precipitation and other atmospheric constituents, $Z_m$ values at Ka-band were lower in stronger precipitation areas than $Z_m$ values at Ku-band. Note that the synthetic data were computed at pixels where the PR algorithm identified “rain” (i.e., data were recorded with a “rain certain” flag). Therefore, radar reflectivity data diagnosed as “no-rain” or “rain possible” by the PR L1 algorithm were not calculated in the current simulation. This was done because the simulation is based on $Z_o$ data in the 2A25 product. Thus, weak signals diagnosed as “no-rain” or “rain possible” in the PR were omitted in $KuPR/KaPR$ $Z_m$, as shown in Fig. 3. This constitutes a limitation of the current synthetic dataset.

Fig. 3. Same as Fig. 2, except for $Z_m$ of the GPM/DPR synthetic data for (a) matched beams, (b) interlaced beams, (c) all beams at the Ka-frequency, and (d) matched beams at the Ku-frequency.
Following the methodology described above, synthetic DPR L1 data were produced for 1 month from April 1 to 30, 2011 based upon the PR version 7 (V7) products. These datasets, along with the data from the KaPR sampling experiment data on March 15, 2007 described in Section II-C, were used as test data for the DPR level-2 algorithms.

III. EVALUATION OF GPM/DPR LEVEL-2 “AT-LAUNCH” ALGORITHMS

This section provides evaluations of the at-launch codes of KuPR, KaPR, and DPR L2 algorithms (version 4.20131010) which were submitted in early October 2013. The precipitation rate calculated from the DSD assumed in the synthetic data and a drop size/fall-speed relationship [53] is regarded as the true value in this study. The PR V7 algorithm takes into account non-uniform beamfilling (NUBF) effects [22], [35], [54], whereas the PR V6, KuPR, KaPR, and DPR L2 algorithms do not. Therefore, the NUBF effects were not considered in the calculation of the true values. Thus, the current KuPR, KaPR, and DPR L2 products are compared with the true value data. The radar rain echoes from near the surface are hidden by the surface clutter echo, and precipitation estimates at the lowest point in the clutter-free region (clutter-free bottom) are taken to be near-surface precipitation rates (“nearSurfRain” in the PR 2A25 and “precipRateNearSurface” in DPR L2 algorithms). However, a routine to detect the surface clutter and the clutter-free bottom, which is one of the new features of the algorithms for the KaPR, is still in the developmental stage. In addition, the clutter-free bottoms can be different between the KuPR and KaPR. While precipitation rates at the actual surface are estimated by the algorithms assuming a slope in the clutter region (“e_surfRain” in the PR 2A25 and “precipRateEsurface” in DPR L2 algorithms), the results depend upon the location of the clutter-free bottom and the different assumptions used in the PR and DPR algorithms. Thus, a precipitation rate at an altitude of 2 km was adopted as an index of the surface precipitation rate for purposes of the comparisons made for the KuPR, KaPR, and DPR products in this study.

Analyzed precipitation rates at the KuPR and DPR were confined within the KaPR observation swath width, i.e., the 13th to the 37th angle-bins (see Section II-A), for a comparison of the algorithms. Precipitation rates over the interlaced scan area were analyzed in the KaPR product, while those in the DPR product were not. This study focused on over-ocean estimates because the surface echo simulation at Ka-band may be problematic over the land, as was noted in the previous section. Another reason we focused on the ocean is that the surface clutter detection routine is also problematic over the land because of difficulties introduced by complex terrains. This will be one of the future tasks in upgrading the algorithms.

Fig. 4 shows the comparisons made for the precipitation rates at an altitude of 2 km over the southwestern Pacific for TRMM orbit number 53 160 during the KaPR sampling experiment. This specific case study showed that KuPR/DPR-estimates were similar to the true values, while the KaPR estimates were clearly smaller in strong precipitation areas. A comparison between Figs. 3 and 4 suggests that the KaPR estimates obtained by the current algorithm underestimated in stronger precipitation areas.
Fig. 5 shows probability density functions (pdfs) for precipitation rates at an altitude of 2 km over the ocean for the 7 orbits of the KaPR sampling experiment. Vertical axes are precipitation rates of (a) KuPR, (b) KaMS, (c) DPR, and (d) KaHS. All horizontal axes are precipitation rates from the true values. A unit of both axes is a decibel of the precipitation rate dBPr, i.e., $10 \times \log_{10}$ (precipitation rate). The values $-10, 0, 10,$ and $20$ dB Pr correspond to $0.1, 1.0, 10.0,$ and $100$ mm/h, respectively. Contours show labeled values.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>KuPR</th>
<th>KaMS</th>
<th>KaHS</th>
<th>DPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficients</td>
<td>0.92</td>
<td>0.51</td>
<td>0.47</td>
<td>0.84</td>
</tr>
<tr>
<td>RMSE (mm/h)</td>
<td>0.34</td>
<td>0.72</td>
<td>0.84</td>
<td>0.52</td>
</tr>
</tbody>
</table>

A targeting variable is a precipitation rates at an altitude of 2 km. Statistics were analyzed for over-ocean events during the KaPR sampling experiment.

Table I

Fig. 5 shows probability density functions (pdfs) for precipitation rates at an altitude of 2 km over the ocean for the 7 orbits of the KaPR sampling experiment data. The units of both axes are taken to be the precipitation rate in decibels dBPr, i.e., $10 \times \log_{10}$ (precipitation rate). The results for the correlation coefficients and the root mean square errors (RMSEs) are summarized in Table I. The KuPR estimates were in good agreement with the true values. For the KaPR results, distinct underestimates were found for precipitation rates of more than 6 dBPr (about 4 mm/h), while overestimates were found for precipitation rates of less than about 4 mm/h. Differences between the KaMS and the KaHS results were small. This is the result of the fact that no weak signals occur in the synthetic data, as noted in Section II-D. In Fig. 5(c), estimates of the DPR show underestimation in the precipitation rate for values less than 10 mm/h, and overestimation for precipitation rates of above 10 mm/h. The performances of the DPR shown in Table I were slightly worse than those of the KuPR. The DSD in the synthetic data were estimated from the PR 2A25 product, and the relationship between $k/Z_o$ and $D_0$ in the synthetic data was identical to that used in the algorithms, as described in Section II-D. Thus, the assumptions used in the KuPR-only algorithm are consistent with the assumed DSD.
which provides an accuracy to the KuPR-only algorithm better than what normally can be expected.

The KaPR estimates were further analyzed using the intensity of $Z_m$ of the KaPR ($Z_{mKa}$) at an altitude of 2 km. Fig. 6 shows pdfs of the KaMS when the values of $Z_{mKa}$ fall into the following categories: less than 18 dBZ, 18–22 dBZ, 22–26 dBZ, and more than 26 dBZ. When the $Z_{mKa}$ is greater than 26 dBZ, the KaPR estimates display good correspondence with the true values [Fig. 6(d)]. Results for the correlation coefficients are summarized in Table II. When the $Z_{mKa}$ is between 18 and 22 dBZ or between 22 and 26 dBZ, the pdfs show a dependence on the magnitude of the true value [Figs. 6(b) and (c)]. When the true value decreases, the attenuation due to the precipitation also decreases and the KaPR estimates correspond well with the true values. However, underestimation of the KaPR is clearly evident for higher intensities of the true value, corresponding to heavier attenuation along the path. When the $Z_{mKa}$ is less than 18 dBZ, two clusters are found in the pdf [Fig. 6(a)]. One of these corresponds to weak precipitation events of less than 1 mm/h. The other corresponds to stronger precipitation events greater than 4 mm/h that are associated with heavy attenuation. The underestimation of the KaPR most clearly appears during heavy precipitation events where

![Figure 6](image-url)

**Fig. 6.** Same as Fig. 5, except for the KaMS when the $Z_m$ of the KaPR was (a) less than 18 dBZ, (b) between 18 and 22 dBZ, (c) between 22 and 26 dBZ, and (d) more than 26 dBZ.

**TABLE II**

<table>
<thead>
<tr>
<th>Threshold (Unit: dBZ)</th>
<th>$18 &lt; Z_{mKa}$</th>
<th>$18 \leq Z_{mKa} &lt; 22$</th>
<th>$22 \leq Z_{mKa} &lt; 26$</th>
<th>$Z_{mKa} \leq 26$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficients</td>
<td>0.12</td>
<td>0.65</td>
<td>0.72</td>
<td>0.83</td>
</tr>
<tr>
<td>Sample number</td>
<td>9619</td>
<td>10322</td>
<td>10605</td>
<td>3345</td>
</tr>
</tbody>
</table>

A targeting variable is a precipitation rates at an altitude of 2 km. Sample numbers are also listed in the table. Statistics were analyzed for over-ocean events during the KaPR sampling experiment.
The value is not always directly connected to a precipitation rate. The was calculated from the by the attenuation correction method and a precipitation rate was calculated from the considering the DSD. However, the results suggest that underestimation is caused by a problem in the attenuation correction method, because the underestimation was obvious when the (heavy attenuation cases) but less pronounced when the (moderate attenuation cases). Thus, the classification by the is related to that of the PIA to some extent. In addition, the classification by the can be connected to characteristics of the precipitation, a topic which will be discussed further in Section IV.

Global monthly results are shown in Fig. 7 where the difference in the surface precipitation among KuPR, KaPR, and DPR and the true values are shown. Large underestimations were found in the KaPR, whereas the differences were small in the KuPR and DPR. The underestimations of the KaPR were clear in tropical areas with precipitation amounts heavier than 100 mm/month, whereas the discrepancies were less clear in the mid-latitude areas of the Northern Hemisphere. This is directly related to the frequency of strong precipitation, which is higher in the Tropics than in the mid-latitudes. This feature will be discussed in Section IV. Fig. 8 shows zonally averaged surface precipitation rates over the ocean. Estimates among the PR V6 and V7, KuPR, DPR, and true values were similar in the Tropics, whereas the KaPR algorithm yielded underestimates. In this and following analyses, PR estimates are presented for both the PR V6 and 7 products. Precipitation amounts for the PR V7 estimates, which take the NUBF effects into account, were highest in the Tropics.

Fig. 9 shows the cumulative histogram of precipitation rates at an altitude of 2 km over the ocean during April 2011. As in previous figures, Fig. 9 shows that for the KaPR, there was overestimation at the smaller precipitation rates and underestimation at the larger precipitation rates. On the other hand, the KuPR estimates were larger than the true values for precipitation rates less than 40 mm/h. With reference to the true values, both curves approached similar values for precipitation rates higher than 40 mm/h. These data suggest that the frequencies of stronger precipitation in the KuPR estimates were smaller than those of the true values in the current evaluation. In the histogram, accumulations of the DPR estimates were smaller compared to the

\[ Z_{mKa} < 18 \text{ dBZ} \]  

The \( Z_{mKa} \) value is not always directly connected to a precipitation rate. The \( Z_e \) was calculated from the \( Z_{mKa} \) by the attenuation correction method and a precipitation rate was calculated from the \( Z_e \) considering the DSD. However, the results suggest that underestimation is caused by a problem in the attenuation correction method, because the underestimation was obvious when the \( Z_{mKa} < 18 \text{ dBZ} \) (heavy attenuation cases) but less pronounced when the \( Z_{mKa} > 26 \text{ dBZ} \) (moderate attenuation cases). Thus, the classification by the \( Z_{mKa} \) is related to that of the PIA to some extent. In addition, the classification by the \( Z_{mKa} \) can be connected to characteristics of the precipitation, a topic which will be discussed further in Section IV.

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true values and the PR estimates for precipitation rates less than about 13 mm/h and larger for precipitation rates more than about 13 mm/h, while the total precipitation amount was similar between the DPR and PR estimates. This is consistent with the results showing underestimations for precipitation rates less than 10 mm/h and overestimations for precipitation rates above 10 mm/h in Fig. 5(c). Seto et al. [31] indicated that estimates of precipitation rates were severely underestimated for rates above 10 mm/h in the HB-DFR method, which does not use the SRT method. The at-launch codes use the HB-DFR-SRT method which is the combination of the DFR, the HB, and the SRT methods. Therefore, larger estimates in precipitation rates above 10 mm/h can be connected to the incorporation of the SRT method. Improvements in the HB-DFR-SRT method for the DPR algorithm will be one of the future tasks conducted for the algorithms.

IV. HORIZONTAL DISTRIBUTION OF FREQUENCIES IN THE SIMULATED \( Z_{\text{mm}} \) OF THE KAPR

In Section III, distinct underestimations were found in estimates of the KaPR. The analyses show the underestimation was related to the intensity of \( Z_{\text{mm}} \) at an altitude of 2 km. In this section, the behavior of the KaPR estimates is discussed from the viewpoint of the horizontal distribution of \( Z_{\text{mm}} \). Fig. 10(a) shows ratios of occurrences in \( Z_{\text{mm}} \) larger than 26 dBZ for all precipitation occurrences at a 2 km altitude over the ocean averaged over all data from April 2011. Here, the ratio is referred to as “\( RA_{26} \leq Z_{\text{mm}} \)” , where the subscript denotes the threshold. Through a comparison of precipitation amounts shown in Fig. 7(a), higher \( RA_{26} \leq Z_{\text{mm}} \) values indicate a “horseshoe” pattern in the Pacific, which is located in areas neighboring heavy precipitation regions. Lower ratios were found in the subtropical Pacific Ocean where shallow weak precipitation is dominant. In addition, higher ratios were found in the mid-latitudes and in small areas of the Atlantic and Indian Oceans. Fig. 6(d) shows good correspondence with reference to the true precipitation rate over the area with this threshold.

Fig. 10. Ratios of occurrences in \( Z_{\text{mm}} \) of the KaPR a) larger than 26 dBZ and b) between 18 and 26 dBZ for all precipitation occurrences at an altitude of 2 km over the ocean averaged during April 2011. The unit is a percentage (%).

Ratios of occurrences in the \( Z_{\text{mm}} \) between 18 and 26 dBZ (\( RA_{18} \leq Z_{\text{mm}} < 26 \)) were relatively high throughout the TRMM domain, except for regions in the subtropical waters of the Pacific and Atlantic Oceans, and the Arabian Sea [Fig. 10(b)].

In the analysis of the ratios of \( Z_{\text{mm}} \) for values smaller than 18 dBZ, the intensity of the true precipitation rate was used because Fig. 6(a) showed two clusters that depended on the magnitude of the true precipitation rate. A threshold of 4 mm/h in the precipitation rate at an altitude of 2 km was adopted here. Fig. 11(a) shows \( RA_{Z_{\text{mm}} < 18 \& Pr > 4} \) with precipitation rates stronger than 4 mm/h. This threshold corresponds to a clear underestimation of the KaPR due to stronger precipitation attenuation, as shown in Fig. 6(a). The horizontal pattern of the \( RA_{Z_{\text{mm}} < 18 \& Pr > 4} \) corresponds to occurrences of heavy attenuation, which are similar to the distribution of large differences of precipitation rates between the KaPR estimates and the true values as in Fig. 7(c).

Fig. 11. Ratios of occurrences in \( Z_{\text{mm}} \) of the KaPR smaller than 18 dBZ for all precipitation occurrences at an altitude of 2 km over the ocean averaged during April 2011. Ratios were classified with precipitation rates of the true values (a) larger than 4 mm/h and (b) smaller than 4 mm/h. The unit is a percentage (%).

Higher ratios of the \( RA_{Z_{\text{mm}} < 18 \& Pr > 4} \) were found in the Tropics, but not in the mid-latitude area of the Northern Hemisphere. This can be related to the frequency of strong precipitation, which is higher in the Tropics than in mid-latitudes. Fig. 11(b) shows \( RA_{Z_{\text{mm}} < 18 \& Pr \leq 4} \) with precipitation rates less than 4 mm/h. In this figure, higher ratios were clearly found in subtropical waters of the Pacific Ocean, the Atlantic Ocean, and the Arabian Sea.

Thus, classification by the \( Z_{\text{mm}} \) with the precipitation thresholds demonstrated important characteristics of the precipitation, even though the \( Z_{\text{mm}} \) value is not always directly connected to the precipitation rate.

V. DISCUSSION

In the evaluations using the at-launch codes (version 4.20131010) of the KaPR L2 algorithm, distinct underestimations were found for precipitation rates of more than about 4 mm/h, as
described in Section III. The underestimation of the KaPR data was most pronounced during strong precipitation events where \( \text{Z}_{\text{minK}} < 18 \text{ dBZ} \) (high attenuation cases) which occurred in heavy precipitation areas of the Tropics. Underestimation was less pronounced in the moderate attenuation cases where \( \text{Z}_{\text{minK}} \geq 26 \text{ dBZ} \). The results suggested that the underestimation was caused by a problem in the attenuation correction method.

In order to verify this, results from the upgraded code (version 4.20131129) of the KaPR L2 algorithm, which was submitted as the operational at-launch code at the end of November 2013, are analyzed in this section. In the version 4.20131129 code, the SLV module uses an improved version of the attenuation correction method. Fig. 12 shows pdfs of the KaMS from the version 4.20131129 code using 7 orbits of the KaPR sampling experiment data. In contrast with Fig. 6, the KaMS estimates from this version were in good agreement with the true values for moderate values of the attenuation, whereas the KaMS estimates underestimate for precipitation intensities above about 15 dBPr (about 32 mm/hr) in precipitation events for which \( \text{Z}_{\text{minK}} < 18 \text{ dBZ} \) [Fig. 12(a)]. Results for the correlation coefficients are summarized in Table III. In the comparisons shown in Tables II and III, the correlation coefficients were higher for version 4.20131129 than for version 4.20131010 in all \( \text{Z}_{\text{minK}} \) ranges. These results clearly show that the underestimates in version 4.20131010 code were caused by deficiencies in the attenuation correction method of the SLV module and that this problem has been resolved in the latest version of the SLV module.

### Table III

<table>
<thead>
<tr>
<th>Statistics</th>
<th>( 18 &lt; \text{Z}_{\text{minK}} )</th>
<th>( 18 \leq \text{Z}_{\text{minK}} &lt; 22 )</th>
<th>( 22 \leq \text{Z}_{\text{minK}} &lt; 26 )</th>
<th>( \text{Z}_{\text{minK}} \leq 26 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficients</td>
<td>0.78</td>
<td>0.86</td>
<td>0.84</td>
<td>0.86</td>
</tr>
<tr>
<td>Sample number</td>
<td>9619</td>
<td>10322</td>
<td>10605</td>
<td>3345</td>
</tr>
</tbody>
</table>

VI. Summary

In this study, the “at-launch” codes of the GPM/DPR L2 algorithms (version 4.20131010) were evaluated using synthetic data generated from TRMM/PR data. There are three sets of L2
The DPR products during April 2011 were similar in the Tropics, whereas the KaPR underestimated precipitation in this region. The DPR estimates were smaller for precipitation rates less than 10 mm/h and larger for precipitation rates above 10 mm/h compared to the true values, whereas the total precipitation amount from the DPR was similar to the true value. Improvement of the combination of the HB, the DFR, and the SRT methods in the DPR algorithm will be one of future tasks.

Precipitation rates of the KaPR showed an underestimation at higher precipitation rates. Underestimation of the KaPR estimates was analyzed by using the intensity of $Z_{mK_a}$ at an altitude of 2 km. The quantity of $Z_{mK_a}$ is related to the PIA to some extent, and can be connected to characteristics of the precipitation. The underestimation was clear when $Z_{mK_a} < 18$ dBZ (heavy attenuation cases) but less obvious when the $Z_{mK_a} \geq 26$ dBZ (moderate attenuation cases). The results suggested that the underestimation was caused by a problem in the attenuation correction method. This was verified by the version 4.20131129 code, in which the SLV module uses an improved version of the attenuation correction method. In the results of the version 4.20131129 code, the KaPR estimates were in good agreement with the true values for moderate values of the attenuation, whereas the KaPR estimates underestimate for precipitation intensities above about 32 mm/h where $Z_{mK_a} < 18$ dBZ.

The estimates, classified according to the intensity of $Z_{mK_a}$, are useful in interpreting the characteristics of the errors. The regions where $Z_{mK_a} \geq 26$ dBZ form a “horseshoe” pattern in the Pacific. Other areas that satisfy this condition occur in the mid-latitudes and in small regions of the Atlantic and Indian Oceans. Regions where $Z_{mK_a}$ is less than 18 dBZ with precipitation rates more than 4 mm/h correspond to strong precipitation events and found in the Tropics with heavy precipitation amount. In contrast, areas where $Z_{mK_a}$ is less than 18 dBZ, with precipitation rates less than 4 mm/h, are frequently observed over the subtropical waters of the Pacific Ocean, the Atlantic Ocean, and the Arabian Sea.

The performances of the DPR were slightly worse than that of the KuPR in this study, while previous works [28], [55] demonstrated better skill by the dual-frequency algorithms than by the single-frequency algorithms. One reason for this discrepancy is that the DSDs in the synthetic data were estimated from the PR 2A25 product, and that the relationship between $k/2Z_e$ and $D_0$ in the synthetic data was identical to that used in the algorithms. Thus, the assumptions used in the KuPR-only algorithm are consistent with the assumed DSD which provides an accuracy to the KuPR-only algorithm better than what normally can be expected. Moreover, while the DSD estimated from the PR algorithms was regarded as a true value here, there are possible errors in the PR algorithms, which can lead to biases in the estimated DSD. In addition, differences between evaluations of the KaMS and the KaHS were small. This can be attributed to the lack of weak signals in the synthetic data. These limitations of the current synthetic data lead to a poorer performance of the DPR relative to that of the single-frequency Ku-band retrieval.

This study focused on evaluations of over-ocean estimates because the surface echo simulation at Ka-band may be problematic over the land using this method. The over-land detection routine for the KaPR is still in the developmental stage because of difficulties introduced by complex terrains. Over-land evaluations of the algorithms will be one of the future tasks. In this study, the DSD parameter $\mu$ was assumed to be 3 for the generation of the synthetic data, which is consistent with the assumption used in the current DPR-L2 algorithms. Varying the values of $\mu$ and quantifying its effect on the accuracy of the L2 algorithms, will be one of the future tasks. Current evaluations were limited to the 36 S–36 N domain observed by the TRMM satellite. Evaluations of the algorithms at higher latitudes are also planned along with a greater emphasis on snow retrievals and on modeling of snowflakes with complex and irregular shapes [56], [57].

**APPENDIX A**

**RELATIONSHIP BETWEEN EQUIVALENT RADAR REFLECTIVITY AND NRCS AT THE SURFACE FOR THE DPR**

Following previous works for a cross-track scanning geometry [33], [58], the return power $P_r$ from the surface at an incidence angle $\theta$ with respect to nadir at a height $H$ above the surface is related to the normalized radar cross section (NRCS) $\sigma^0_L$ of the surface by the approximation in a simple case in which the sampling is done just at the center of the antenna beam

$$P_r(\theta) = \frac{P_0\lambda^2G^2L\sigma_L^0(\theta)\cos\theta\phi_B\theta_B}{512(\ln 2)^2\pi^2H^2}$$

where $\phi_B$ and $\theta_B$ are the along- and cross-track beam widths, $P_0$ is the transmit power, $G$ is the antenna gain, $L$ is the system loss factor, $\lambda$ is the radar wavelength, and $a$ is the atmospheric attenuation along the main lobe. Also

$$\theta_B = (\theta^2 - \theta^2_p)^{-0.5}$$

and

$$\theta_p = \frac{ct}{2H\theta}$$

where $c$ is the speed of light.

The return power can be also expressed with equivalent radar reflectivity $Z_e$, and range from the antenna $r$ (e.g., [46])

$$P_r = \frac{n^3P_0G^2LZ_e^2K_w^2ac\tau\phi_B\theta_B}{2^{10}(\ln 2)^2\lambda^3\tau^2}$$

where $K_w$ is the refractive index of water, and $c$ is the speed of light.

At the surface ($r = H$), $P_r = P_T$. Therefore, an equation at Ku-band for $Z_e$ ($Z_{eK_a}$) and $\sigma_L^0$ ($\sigma_{K_a}^0$) and an equation at Ka-band for $Z_e$ ($Z_{eK_a}$) and $\sigma_L^0$ ($\sigma_{K_a}^0$) are established at the surface. A
combination of both equations satisfies following relationship at an incidence angle $\theta$

$$Z_{e,Ka} = Z_{e,Ku} \frac{\sigma^2_{Ka}}{\sigma^2_{Ku}} C_{KaKa} \cdot f(\theta)$$

$$C_{KaKa} = \frac{\lambda^4}{\lambda^4} \frac{|KuKa|^2}{|KuKa|^2} \frac{T_{Ka}}{T_{Ka}}$$

$$f(\theta) = \frac{\theta_{BKu} \theta_{BKu}}{\theta_{BPu} \theta_{BPu}} = \sqrt{\frac{\theta_{BKu}^2 + \left(\frac{2}{\sigma_{Ka}} H^2\right)^2}{\theta_{BKu}^2 + \left(\frac{2}{\sigma_{Ka}} H^2\right)^2}} \theta_{BKu}$$

where subscripts of Ku or Ka denote Ku-band or Ka-band. Specifications of the DPR used in the current calculation are summarized in Table A.1, and $|KuKa|$, $|KuKa|$, and $H$ are assumed to be 0.9255, 0.8989, and 400 (km), respectively, here. Thus, constant “$C_{KaKa}$” is $-16.606$ (dB) at the KaMS and $-19.603$ (dB) at the KaHS. $\tau$ is identical between the KuPR and the KaMS, and so $f(\theta) = 1$ in the KaMS. In the KaHS, $f(\theta)$ varies with incident angles, as shown in Fig. A.1. When $\theta$ is larger, $f(\theta)$ is approaching to 3 dB, which works as an offset to differences of the constant $C_{KaKa}$ between the KaMS and the KaHS. Thus, relationship of $Z_e$ and $\sigma^2$ between the KuPR and the KaPR is obtained and it was used in the surface echo simulation at Ka-band.

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**REFERENCES**


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