Narrowing the Blind Zone of the GPM Dual-Frequency Precipitation Radar to Improve Shallow Precipitation Detection in Mountainous Areas

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ABSTRACT: The Dual-Frequency Precipitation Radar (DPR), which consists of a Ku-band precipitation radar (KuPR) and a Ka-band precipitation radar (KaPR) on board the GPM Core Observatory, cannot observe precipitation at low altitudes near the ground contaminated by surface clutter. This near-surface region is called the blind zone. DPR estimates the clutter-free bottom (CFB), which is the lowest altitude not included in the blind zone, and estimates precipitation at altitudes higher than the CFB. High CFBs, which are common over mountainous areas, represent obstacles to detection of shallow precipitation and estimation of low-level enhanced precipitation. We compared KuPR data with rain gauge data from Da-Tun Mountain of northern Taiwan acquired from March 2014 to February 2020. A total of 12 cases were identified in which the KuPR missed some rainfall with intensity of \( >10 \text{ mm h}^{-1} \) that was observed by rain gauges. Comparison of KuPR profile and ground-based radar profile revealed that shallow precipitation in the KuPR blind zone was missed because the CFB was estimated to be higher than the lower bound of the range free from surface echoes. In the original operational algorithm, CFB was estimated using only the received power data of the KuPR. In this study, the CFB was identified by the sharp increase in the difference between the received powers of the KuPR and the KaPR at altitude affected by surface clutter. By lowering the CFB, the KuPR succeeded in detection and estimation of shallow precipitation.

SIGNIFICANCE STATEMENT: The Dual-Frequency Precipitation Radar (DPR) on board the GPM Core Observatory cannot capture precipitation in the low-altitude region near the ground contaminated by surface clutter. This region is called the blind zone. The DPR estimates the clutter-free bottom (CFB), which is the lower bound of the range free from surface echoes, and uses data higher than CFB. DPR consists of a Ku-band precipitation radar (KuPR) and a Ka-band precipitation radar (KaPR). KuPR missed some shallow precipitation more than \( 10 \text{ mm h}^{-1} \) in the blind zone over Da-Tun Mountain of northern Taiwan because of misjudged CFB estimation. Using both the KuPR and the KaPR, we improved the CFB estimation algorithm, which lowered the CFB, narrowed the blind zone, and improved the capability to detect shallow precipitation.

KEYWORDS: Precipitation; Orographic effects; Algorithms; Satellite observations

1. Introduction

An important feature of spaceborne radar is its capability to view precipitation in regions where ground radar data are generally unavailable, such as in mountainous terrain and open ocean (Hirose et al. 2017). Spaceborne precipitation radars, such as the Precipitation Radar on board the TRMM satellite (TRMM PR) and the Dual-Frequency Precipitation Radar on board the GPM Core Observatory (GPM DPR), estimate precipitation rate from the received power of the microwave signal backscattered by raindrops (Nakamura 2021). Because echoes scattered by the ground surface (surface clutter) contaminates the zone just above the ground, spaceborne precipitation radars cannot capture precipitation in the low-altitude zone near the ground surface, which is a region called the blind zone. Surface clutter is a major cause of error in precipitation estimation by spaceborne precipitation radars, especially over

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mountainous regions where the blind zone extends to high altitude (Arulraj and Barros 2021). In mid- to high-latitude mountainous regions, shallow precipitation clouds often exist in stable environments during the winter months, causing errors in spaceborne precipitation radar observations. With the coverage of GPM DPR observations extending to higher latitudes than TRMM PR, the capability of detecting shallow orographic precipitation has become more important than ever before. Aoki and Shige (2021) showed that DPR underestimates the frequency of precipitation over the coastal mountains in Alaska at high latitudes because of surface clutter obstruction.

The DPR original operational algorithm estimates the clutter-free bottom (CFB), which is the lower bound of the range free from surface echoes, and uses data at the CFB to estimate near-surface precipitation. DPR observes precipitation by changing the angle at which it emits microwave signals, while the CFB also changes depending on the observing angle (Kubota et al. 2016). For near-nadir data, the CFB is low and it is relatively easy to observe precipitation at low altitudes. Conversely, for off-nadir data, the CFB is higher than that of near-nadir data, making it difficult to estimate near-surface precipitation and detect shallow precipitation. Using 5-yr DPR precipitation data, Hirose et al. (2021) showed that precipitation data obtained at larger incidence angles were underestimated in comparison with data acquired at smaller incidence angles nearer the satellite nadir.

Research has been conducted to improve estimation of near-surface precipitation by DPR. For example, Hirose et al. (2021) estimated the off-nadir precipitation profile in the blind zone using near-nadir data, which are affected less by surface clutter, and their work improved both detection of shallow precipitation and estimation of low-level enhanced precipitation. Arulraj and Barros (2021) improved DPR precipitation estimation in the Appalachian Mountains using machine learning with ground-based radar data, the GPM Microwave Imager (GMI), a precipitation detection model, and a precipitation regime classification model.

Because the algorithm for CFB estimation has not changed substantially from that used by the TRMM PR (Awaka et al. 2000), which is the previous generation of the GPM DPR, there remains scope for further improvement. This study improved the CFB estimation in the operational algorithm and narrowed the blind zone by changing the CFB to as low as possible to detect missed shallow precipitation hidden in the blind zone.

The DPR consists of Ku-band precipitation radar (KuPR) operating at 13.6 GHz and Ka-band precipitation radar (KaPR) operating at 35.5 GHz. In this study, to narrow the blind zone, the CFB estimation algorithm was improved from the profile data of the received power by utilizing the inherent difference in sensitivity to surface clutter between the KuPR and the KaPR, taking advantage of the strength of the DPR in operating at two different frequencies.

2. Data

Da-Tun Mountain and the vicinity in northern Taiwan (25.07°–25.34°N, 121.43°–121.73°E) (shown in Fig. 1) were chosen for a detailed analysis of the problem of distinguishing between returns from surface clutter and precipitation in this study. From March 2014 to February 2020, a total of 426 cases were detected in which the GPM Core Observatory overpassed Da-Tun Mountain. In this study, KuPR level 2, version 06A, data (Seto et al. 2021) were used for precipitation rate, radar reflectivity, and terrain elevation because the KuPR is more sensitive to precipitation in comparison with the KaPR (Toyoshima et al. 2015). For CFB estimation, we used the received power data of the KuPR and KaPR level 1, version 05A (1 March 2014–21 May 2018), 05B (21 May–30 September 2018), and 05C (30 September 2018–29 February 2020) products (Masaki et al. 2020), which were the latest versions available at the time at which the study was conducted. In the most recent KuPR level 2, version 07A, data, sidelobe clutter discrimination is improved while CFB estimation remains unchanged from that of the KuPR level 2, version, 06A data. The footprint is 5 km in diameter and the vertical spacing of range data is 125 m. KuPR data comprise data in 49 scanning-angle bins arranged in the cross-track direction, while KaPR data consist of the innermost 25 scanning-angle bins from March 2014 when the DPR commenced observations, but KaPR full scan mode data were extended to 49 scanning-angle bins from May 2018 (Awaka et al. 2021). The KaPR data of innermost 25 scanning-angle bins were used in this study.

Da-Tun Mountain of northern Taiwan represents an excellent natural laboratory for exploring the problem of the CFB, not only because Da-Tun Mountain is the area in Taiwan with the most concentrated area of heavy rainfall during typhoons and wintertime northeasterly monsoons (Yu and Cheng 2008, 2014; Cheng and Yu 2019), but also because a high-density, automatic rain gauge network [the Da-Tun rain gauge network (DTRGN); Cheng and Yu 2019] has been deployed over this mountain barrier since 2011 (white circles in Fig. 1). DTRGN is constructed with 22 tipping-bucket rain gauges. In addition, the wintertime precipitation over Da-Tun Mountain is typically shallow in nature, with the layer of orographic enhancement of precipitation confined mostly to the lowest 1 km over mountain slopes (Cheng and Yu 2019; Yu et al. 2022). This study used the rain gauge data to identify cases for which the KuPR misses shallow precipitation with intensity of ≥10 mm h⁻¹ over Da-Tun.
To investigate the cause of the missed precipitation by KuPR, we used the S-band (10 cm) Doppler radar (WSR-88D) on Wu-Fen-San (WFS) located southeast of Da-Tun Mountain (solid star in Fig. 1). The characteristics of the DTRGN and the WFS radar data are described in Cheng and Yu (2019) and Yu et al. (2018). The interpolated data spacing of the WFS radar is 1 km, but in this study, the resolution of the WFS radar was matched up with that of the KuPR for the comparison of both data. A distance-weighted average of the precipitation rate of WFS radar in the neighborhood of the KuPR footprint was performed. The CFB of the WFS radar for each matched KuPR footprint was calculated as the average of the lowest height at which WFS radar observation data existed.

Of the 426 cases in which the GPM Core Observatory overpassed, 216 cases were detected in which both KuPR and KaPR observations were obtained. We identified 12 cases in which the KuPR missed precipitation even though rain gauges captured strong rainfall with intensity of $\geq 10$ mm h$^{-1}$ among the 426 cases (described in section 3). Of the 12 cases, KaPR and ground-based radar observations are obtained for five cases. The five cases were used for defining the CFB estimation algorithm to detect the shallow heavy precipitation missed by the KuPR original operational algorithm. The 211 cases, excluding 5 of the 216 cases, were used for testing the CFB estimation algorithm to avoid mistakenly recognizing surface clutter as precipitation echoes.

3. Shallow precipitation in the blind zone

We compared KuPR near-surface rain data with rain gauge data for the total of 426 cases in which the GPM Core Observatory overpassed Da-Tun Mountain. The method adopted for comparing the rain gauge and KuPR data was adapted from Terao et al. (2017). The rain gauge data were matched up with KuPR observation data whose centers were within the matching radius $D$. The rain gauge precipitation accumulation was calculated within the time interval of $t + \tau - \Delta t$ to $t + \tau + \Delta t$, where $t$ is the DPR scanning time, $\tau$ is the time lag of rain drops falling from the CFB to the surface and $\Delta t$ is the half length of the time window. These values, taken to maximize the correlation coefficient between the KuPR and rain gauge precipitation rates, were determined as $D = 4.5$ km, $\tau = 120$ s, and $\Delta t = 300$ s.

We identified 12 cases in which the KuPR missed precipitation even though rain gauges captured strong rainfall with intensity of $\geq 10$ mm h$^{-1}$ among the 426 cases (Table 1). In cases 1–4, 6, 8, 9, and 11, the KuPR missed precipitation within the inner swath (angle bin 13–37) over which concurrent KaPR observational data exist. Case 6 was not considered in this study because the ground-based radar only observed a small area. Cases 4 and 11, in which the KaPR did not observe the entire analysis area due to its narrower swath, were also excluded because this study uses both the KuPR and KaPR data to improve precipitation detection. We used cases 1, 2, 3, 8, and 9 (shown in boldface in Table 1) for developing the CFB estimation algorithm. Because the observation time of the ground-based radar deviates from that of the KuPR by only 1–2 min, we compared both datasets measured at approximately the same time.

Figures 2a–c show the horizontal distributions of precipitation rate observed by the KuPR, rain gauges, and ground-based radar for case 9, respectively. The KuPR missed rainfall near the nadir for this case. The rain gauges detected heavy precipitation of 4–10 mm h$^{-1}$ over Da-Tun Mountain (Fig. 2b), and the ground-based radar similarly captured precipitation over the mountainous area (Fig. 2c). However, KuPR did not detect any precipitation at all as shown in Fig. 2a. Figure 2d shows the precipitation rate profile of the ground-based radar in a vertical cross section that is along the near-nadir scanning angle of KuPR (bin 24). Spaceborne precipitation radars were capable of observing heavy orographic rainfall associated with low precipitation-top heights (Shige and Kummerow 2016), but in this case, the KuPR missed shallow precipitation occurred within the blind zone that is the layer below the estimated CFB. KuPR misjudged the precipitation echoes as surface clutter and estimated the CFB higher than the actual lower bound of the range free from the surface echo. In cases 1, 2, 3, and 8, the shallow precipitation was also missed by KuPR by estimating the CFB high. Cheng and Yu (2019) documented the dominance of shallow precipitation over Da-Tun Mountain during winter and attributed it to a stable environment that prevents deep convection. In this study, 7 of the 12 cases of interest occurred during November–January.

Hamada and Takayabu (2014) showed that extremely strong precipitation in the Himalayan mountains detected by the TRMM PR version 7 product was actually misinterpretation of surface clutter as precipitation echoes. To avoid mistakenly recognizing surface clutter as precipitation echoes, the KuPR has estimated the CFB in a more conservative way, which might in turn cause the overestimation of the CFB. In view of this, we attempted to improve the operational CFB estimation algorithm by estimating the CFB to the altitude just above the contaminated zone of surface clutter to better capture shallow precipitation over Da-Tun Mountain.

4. Estimation of CFB

The original operational algorithm estimates the CFB using KuPR level 1 received power data. However, in this study, we estimated the CFB using both KuPR and KaPR level 1 received power data. The dual-frequency ratio between the

<table>
<thead>
<tr>
<th>Case</th>
<th>Time</th>
<th>Orbit</th>
<th>Angle bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0451 (0449) UTC 8 Jun 2014</td>
<td>1564</td>
<td>26</td>
</tr>
<tr>
<td>2</td>
<td>0746 (0745) UTC 9 Nov 2014</td>
<td>3962</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>0528 (0528) UTC 17 Nov 2014</td>
<td>4085</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>0607 UTC 23 Aug 2015</td>
<td>8426</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>0927 UTC 27 Sep 2015</td>
<td>8973</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>1802 UTC 12 Oct 2016</td>
<td>14906</td>
<td>25</td>
</tr>
<tr>
<td>7</td>
<td>2008 UTC 26 Dec 2016</td>
<td>16074</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>1210 (1207) UTC 31 Oct 2017</td>
<td>20875</td>
<td>32</td>
</tr>
<tr>
<td>9</td>
<td>0328 (0328) UTC 30 Nov 2017</td>
<td>21336</td>
<td>24</td>
</tr>
<tr>
<td>10</td>
<td>2156 UTC 18 Dec 2017</td>
<td>21628</td>
<td>38</td>
</tr>
<tr>
<td>11</td>
<td>1627 UTC 6 Jan 2018</td>
<td>21920</td>
<td>36</td>
</tr>
<tr>
<td>12</td>
<td>2252 UTC 8 Nov 2018</td>
<td>26684</td>
<td>42</td>
</tr>
</tbody>
</table>
received power \( P_r \) of the KuPR \( P_r(\text{Ku}) \) and that of the KaPR \( P_r(\text{Ka}) \), DFRP, is defined as follows:

\[
\text{DFRP}[i] = 10 \log_{10} \frac{P_r(\text{Ku})}{P_r(\text{Ka})} = 10 \log_{10} \left[ \frac{P_r(\text{Ku})}{P_r(\text{Ka})} \right],
\]

where \( i \) is the range bin number. The range bin \( i = 1 \) is approximately 22 km from the geoid surface that is closest to the satellite. The \( P_r \) value of a precipitation echo can be expressed as follows:

\[
P_r = P_t G_0^2 \lambda^2 \theta_0^2 \Delta r 10^{-\Delta V/10} \sum \sigma \Delta V
\]

where \( P_t \) is transmitted power, \( G_0 \) is antenna gain, \( \lambda \) is wavelength, \( \theta_0 \) is the 3-dB beamwidth, \( \Delta r \) is range resolution, \( r \) is range, \( A \) is two-way path-integrated attenuation, \( \sigma \) is the scattering cross-section of precipitation particles, and \( \Delta V \) is unit volume (Okamoto 2001). The ratio of \( P_r(\text{Ku}) \) to \( P_r(\text{Ka}) \), is expressed as follows:

\[
\frac{P_r(\text{Ku})}{P_r(\text{Ka})} \approx \frac{P_t(\text{Ku}) G_0^2 \lambda^2 A(\text{Ku})^2 \theta_0^2 (\text{Ku})^2 \sum \sigma(\text{Ku})}{P_t(\text{Ka}) G_0^2 \lambda^2 A(\text{Ka})^2 \theta_0^2 (\text{Ka})^2 \sum \sigma(\text{Ka})} \times 10^{-[A(\text{Ka})−A(\text{Ku})]/10}.
\]

Since \( G_0(\text{Ku}) = G_0(\text{Ka}) \) and \( \theta_0(\text{Ku}) = \theta_0(\text{Ka}) \),

\[
\frac{P_r(\text{Ku})}{P_r(\text{Ka})} \approx \frac{P_t(\text{Ku}) \lambda A(\text{Ku})^2 \sum \sigma(\text{Ku})}{P_t(\text{Ka}) \lambda A(\text{Ka})^2 \sum \sigma(\text{Ka})} 10^{-[A(\text{Ka})−A(\text{Ku})]/10}.
\]

The \( P_r \) of the surface echo at its peak at an off-nadir incidence angle can be expressed as follows:

\[
\text{FIG. 2. For case 9, (a) KuPR near-surface precipitation rate, (b) rain gauge precipitation rate and terrain height, (c) ground-based radar near-surface precipitation rate, and (d) vertical cross section of ground-based radar precipitation rate along the black line shown in (c). The black line in (c) is along the KuPR near-nadir scanning angle (bin 24). The CFB estimated by the KuPR with the original operational algorithm (black curve) and the terrain elevation from DPR (green curve) are shown in (d). The scale for the color shading used in (a)–(d) is shown to the right of (b) and (d).}
\]
the DFRPs of precipitation echoes and surface clutters is not Rayleigh scattering. The DFR may become very large. In such cases, because the difference between DFRP_precip and DFRP_srf becomes small, the proposed method may not work well so that the original CFB is used instead of the DFRP-derived CFB.

Figure 3a shows the $P_r$(Ku), $P_r$(Ka), and DFRP profiles of shallow precipitation in case 9 in which the precipitation-top height is lower than 4 km. The DFRP value increases sharply with range at an altitude of approximately 1.5 km, which is affected by surface clutter. We examined the DFRP values from altitudes of approximately 22 km down to the surface to detect any sharp increase in the DFRP values. We estimated the CFB at the range bin at which the DFRP increase satisfies following equation (hereinafter, DFRP CFB):

$$\text{DFRP}[i + 1] - \text{DFRP}[i] > 2.3 \text{ dB.}$$  \hspace{1cm} (9)

The threshold value of 2.3 dB in Eq. (9) was set empirically to be safe so as to avoid lowering the CFB too much and misjudging surface clutter as precipitation echoes in the shallow precipitation cases by testing with 211 cases described in section 2. Because the sharp increase of DFRP caused by the surface clutter is independent of the attenuation, the CFB estimation using the DFRP can be applied to cases with deep precipitation. Figure 3b shows a footprint with deep precipitation, and a sharp DFRP increase with range due to the surface clutter appears at the altitude of approximately 1.0 km. Lowering the CFB would improve precipitation estimation in deep precipitation cases.

The CFB estimation algorithm developed in this study (hereinafter, the DFRP algorithm) consists of the three processes illustrated in Fig. 4. In the first process, we determine a temporary CFB as the first DFRP increase in which Eq. (9) is satisfied. The range bin $i$ at the temporary CFB is defined as $i_{\text{tmp}}$. If there is no increase in which Eq. (9) is satisfied, we determine the CFB to be the original CFB.

In the second process, we examine cases in which uncontaminated data exist below $i_{\text{tmp}}$. Figure 3c shows a case in which $i_{\text{tmp}}$ is determined at the increase in the DFRP values attributable to the sidelobe clutter at 1.5 km and usable data exist below $i_{\text{tmp}}$. In this process, we check for the presence of uncontaminated data below $i_{\text{tmp}}$. The check to detect uncontaminated data is conducted using the following conditions:

$$\text{DFRP}[i] < 2 \text{ dB for } i = i_{\text{tmp}}, \ldots, i_{\text{tr}} - 5,$$  \hspace{1cm} (10)

$$\text{DFRP}[i] - \text{DFRP}[i - 1] < 0 \text{ dB for } i = i_{\text{tmp}}, \ldots, i_{\text{tr}} - 5, \text{ and}$$  \hspace{1cm} (11)

$$P_r(Ku) < -100 \text{ dBm for } i = i_{\text{tmp}}, \ldots, i_{\text{tr}} - 5.$$  \hspace{1cm} (12)

We estimated the CFB by using the DFRP increase due to the surface clutter.

For heavy rainfall or ice precipitation, the scattering by precipitation particle may not be Rayleigh scattering. The DFRP of precipitation due to the Mie scattering may deviate from that calculated assuming Rayleigh scattering, but the deviation, which is equal to the dual-frequency ratio (DFR) of KuPR’s to KaPR’s radar reflectivity factors, remains less than a few dB for most realistic rainfall (Liao et al. 2020). Therefore, the increase of DFRP_precip is sufficiently smaller than the DFRP_srf – DFRP_precip of approximately 16.7 dB even in cases of heavy rainfall where scattering by raindrops may not be Rayleigh scattering. In a heavy ice precipitation case or rainfall with exceptionally large drops case in which scattering by precipitation particles is not Rayleigh scattering, DFR may become very large. In such cases, because the difference between DFRP_precip and DFRP_srf becomes small, the proposed method may not work well so that the original CFB is used instead of the DFRP-derived CFB.

Table 2. The values and ratios of $P_r$, $\lambda$, and $P_r\lambda^2$ between KuPR and KaPR.

<table>
<thead>
<tr>
<th></th>
<th>KuPR</th>
<th>KaPR</th>
<th>Ratio (Ku/Ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_r$</td>
<td>1012.0 W</td>
<td>146.5 W</td>
<td>6.908</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>2.20 x 10^{-2} m</td>
<td>8.84 x 10^{-2} m</td>
<td>2.61</td>
</tr>
<tr>
<td>$P_r\lambda^2$</td>
<td>0.490 W m^2</td>
<td>1.04 x 10^{-2} W m^2</td>
<td>46.9 = 16.7 dB</td>
</tr>
</tbody>
</table>

$$P_r = \frac{P_0 G_0^2 \lambda^2 \theta_0 \Delta r}{2 \pi^2 S_0^2 \sqrt{2 \ln(2)} \rho^3 \sin \theta} 10^{-A/10} \sigma^0,$$  \hspace{1cm} (5)

where $\theta$ is the incidence angle and $\sigma^0$ is the scattering cross section of the surface (Okamoto 2001). The $P_r$ of a surface clutter for the nadir incidence angle differs from Eq. (5) in some respects, such as the distance resolution dependence, but these values do not affect DFRP because they cancel out when taking the ratio of $P_r$(Ku) and $P_r$(Ka). For scattering by the surface, $\sigma^0$ is almost independent of $\lambda$ (in particular for sea surface) and the ratio of $P_r$(Ku) to $P_r$(Ka) can be expressed as follows:

$$\frac{P_r(Ku)}{P_r(Ka)} \approx \frac{P_r(Ku)\lambda(Ku)}{P_r(Ka)\lambda(Ka)} 10^{-A(Ku) - A(Ka)/10},$$  \hspace{1cm} (6)

The values of $P_r$, $\lambda$, and $A$ of the KuPR are different from those of the KaPR. The values of $P_r$ and $\lambda$ of the KuPR [i.e., $P_r(Ku) = 1012.0$ W, $\lambda(Ku) = 2.20 \times 10^{-2}$ m] are both larger than those of the KaPR [i.e., $P_r(Ka) = 146.5$ W, $\lambda(Ka) = 8.44 \times 10^{-2}$ m] as shown in Table 2. Because $P_r\lambda^2(Ku) = 0.490$ W m^2 and $P_r\lambda^2(Ka) = 1.04 \times 10^{-2}$ W m^2 (shown in Table 2), $P_r(Ku)$ is larger than $P_r(Ka)$. The difference between the DFRPs of precipitation echoes and surface clutters is expressed as follows:

$$\text{DFRP}_{srf} - \text{DFRP}_{precip} = 10 \log_{10} \left[ \frac{P_r(Ku)}{P_r(Ka)} \right]_{srf} - 10 \log_{10} \left[ \frac{P_r(Ku)}{P_r(Ka)} \right]_{precip} + 10 \log_{10} \left[ \frac{P_r(Ku)}{P_r(Ka)} \right]_{srf} - 10 \log_{10} \left[ \frac{P_r(Ku)}{P_r(Ka)} \right]_{precip} = 10 \log_{10} \frac{\sum A(Ka)}{\sum A(Ka)},$$  \hspace{1cm} (7)

indicating that it is independent of the values of attenuation. If the scattering by precipitation particles is assumed as Rayleigh scattering, $\sigma \propto \lambda^{-2}$, Eq. (7) is expressed as follows:

$$\text{DFRP}_{srf} - \text{DFRP}_{precip} = 10 \log_{10} \frac{\sum A(Ka)}{\sum A(Ka)} = 10 \log_{10} \frac{A(Ka)}{A(Ka)} = 16.7 \text{ dB.}$$  \hspace{1cm} (8)
where \( i_{tmp} \) is the range bin at the terrain height provided from the DPR products. If at least one DFRP value exists at range bin \( i \) in which all Eqs. (10)–(12) are satisfied, the operation returns to the first process because uncontaminated data exist at altitudes lower than range bin \( i_{tmp} \). Conversely, if there are no data in which all Eqs. (10)–(12) are satisfied, there are no usable data and the height at the range bin \( i_{tmp} \) is determined as the CFB.

The third process is to check whether the DFRP-estimated CFB is applied instead of the original CFB. Figures 3d and 3e show cases in which DFRP-estimated CFB was not applied. First, the attenuation of KuPR should be larger than that of KaPR because of \( \lambda(Ka) > \lambda(Ku) \), but in the deep precipitation case shown in Fig. 3d, DPR had the anomalous data in which the path-integrated attenuation of KuPR estimated by the surface reference technique is larger than that of KaPR, and for unknown reasons, increases in DFRP due to the surface clutter do not show up clearly at approximately 1.5 km where \( P_r(Ku) \) and \( P_r(Ka) \) increase sharply. By calculating precipitation rate using the method presented in section 5, precipitation rate of KuPR using the DFRP CFB is 93 mm h\(^{-1}\), while that of ground-based radar is 4.7 mm h\(^{-1}\). It indicates that the DFRP CFB is estimated at the altitude where the echo is contaminated by the surface clutter in this case. Therefore, in the DFRP algorithm, we use the original CFB for the deep precipitation cases in which both conditions \( A(Ku) > A(Ka) \) and \( A(Ku) > 1.0 \) dB are satisfied. Deep precipitation was defined so that mean received power from the range bins of 2–4 km above the terrain satisfies following equation:

\[
\frac{\sum_{j=15}^{32} P_r(Ku)(i_{tmp} - j)}{10 \log_{10}(17)} > -106 \text{ dBm}.
\] (13)

Second, Fig. 3e shows a case where the CFB estimated by DFRP is estimated too high because the sharp increase of DFRP due to ice precipitation echo is misidentified as that due to surface clutter. The increase of DFRP due to the Mie scattering in heavy ice precipitation is approximately equal to that of DFR. DFR due to heavy ice precipitation is so large that is used to detect the heavy ice precipitation (Iguchi et al. 2018; Akiyama et al. 2019) that makes it difficult to estimate the CFB by the sharp increase of DFRP. Therefore, in this algorithm, if the CFB estimated using the DFRP is at least three range bins higher than the CFB estimated by the original operational algorithm, the original CFB is applied.
The altitude at the largest range bin \( i_{\text{tmp}} \) that goes through the entire processes is estimated as the DFRP CFB. The precipitation rate data at the DFRP CFB is used as the near-surface precipitation.

5. Results

a. Case study

The CFBs in cases 1 and 9 estimated by the KuPR using the original operational algorithm, by the DFRP algorithm, and by the ground-based radar are shown in Figs. 5a–f. Over Da-Tun Mountain (i.e., nearby the center of the analyzed domain), the original operational algorithm estimates the CFB as above 2000 m (Figs. 5a,b), whereas the DFRP-estimated CFB is an altitude of approximately 1500 m (Figs. 5c,d), that is, lower by 500 m than that of the original CFB. The ground-based radar CFB is lower than 1000 m southeast of analysis area (Figs. 5e,f), where is near to the ground-based radar installed location (solid star in Fig. 1). On the other hand, in locations far from the ground-based radar installed location, the transmitted waves are blocked by the terrain, and the ground-based radar CFB becomes higher than 1200 m. Therefore, the DFRP-derived CFB, which is below 1000 m, is lower than ground-based radar CFB, which is about 1200–1300 m mainly over the ocean (Figs. 5c,d).

In determining the presence or absence of precipitation based on the radar reflectivity measurements, we used the threshold value of 15.46 dBZ, which is identical to the threshold at which KuPR can detect precipitation. If precipitation is present in two or more consecutive range bins, the original operational algorithm flags it as precipitation (Iguchi et al. 2020). Using our algorithm, only when precipitation is present in four or more consecutive range bins, we flag it as precipitation to avoid misjudging sidelobe clutter as precipitation echo.

To estimate near-surface rainfall for KuPR and ground-based radar, radar reflectivity needs to be converted to precipitation rate. To investigate the possible difference in precipitation rate among KuPR using the original CFB, KuPR using the DFRP CFB, and ground-based radar, the common \( Z-R \) relationship was used. We simply calculated the near-surface rainfall by converting the measured radar reflectivity to precipitation rate. An
attenuation correction must be considered when calculating the precipitation rate of deep precipitation with strong attenuation. The future goal of this study is to incorporate DFRP algorithm into the KuPR original operational algorithm, but for simplicity in this study, we excluded the footprints of attenuation of $>5$ dB when we compare the precipitation rate of KuPR to that of ground-based radar or rain gauges. Using the $Z-R$ relationship used in the KuPR original operational algorithm shown later, attenuation of $>5$ dB results in a difference in precipitation rate of more than 2 times relative to the value when no attenuation is considered. There were 19 footprints with attenuation of $>5$ dB out of a total of 7652 footprints for 216 cases in which both KuPR and KaPR observations are obtained. For the cases of attenuation of $\leq 5$ dB, precipitation rate was calculated without considering attenuation correction. The $Z-R$ relationships for convective precipitation and stratiform precipitation (Kozu et al. 2009) used in the KuPR original operational algorithm to convert radar reflectivity ($Z$, $\text{mm}^6 \text{m}^{-3}$) to precipitation rate ($\text{mm h}^{-1}$) are as follows:

$$Z = 185R^{1.43}$$  \hspace{1cm} \text{for convective precipitation and} \hspace{1cm}  
$$Z = 300R^{1.38}$$  \hspace{1cm} \text{for stratiform precipitation.}  \hspace{1cm} (14)$$

Because shallow precipitation over mountainous areas contains many small precipitation particles, and because the drop size distribution is different from that in nonmountainous areas, the $Z-R$ relationship of shallow precipitation over mountainous areas is different from that of precipitation in nonmountainous areas. Cheng and Yu (2019) used the $Z-R$ relationship expressed in Eq. (15) to calculate the precipitation rate over Da-Tun Mountain:

$$Z = 32.5R^{1.65}.$$  \hspace{1cm} (15)$$

The horizontal distribution of precipitation rate for case 9 calculated by using Eqs. (14) and (15) are shown in Figs. 6a and 6b, respectively. Rain gauges captured precipitation with the intensity of $\geq 8$ mm h$^{-1}$ at 5 stations, but precipitation rate of KuPR calculated by using Eq. (14) was 2.9 mm h$^{-1}$ at most. On the other hand, precipitation rate of KuPR calculated by Eq. (15) was 7.2 mm h$^{-1}$ at most and improved the precipitation estimation compared to that calculated by Eq. (14).

Since case 9 was a shallow precipitation case in which Eq. (13) was not satisfied, Eq. (15) was used to calculate precipitation rate. However, it is not appropriate to use Eq. (15) to calculate precipitation rate for deep precipitation cases. In this study, Eq. (15) was used for shallow precipitation while Eq. (14) was used for deep precipitation, which is defined by using Eq. (13). We calculated the bias ratio of KuPR precipitation rate to that of rain gauges for the 216 cases except for the footprints with attenuation of $>5$ dB. The bias ratio is calculated as follows:

$$r = \frac{\sum N (R_{\text{gauge}} - R_{\text{Ku}})}{\sum N R_{\text{gauge}}} \times 100\%,$$  \hspace{1cm} (16)$$

where $N$ is the number of rain gauge data. The bias ratio of KuPR precipitation rate using only Eq. (14) is $-57\%$. By calculating the precipitation rate using both Eqs. (14) for deep precipitation and (15) for shallow precipitation, the bias ratio is $-25\%$. It indicates that the combined use of Eqs. (14) and (15) can reduce the underestimation.

The precipitation rates observed by the KuPR at the original CFB, by the KuPR at the DFRP CFB, and by the ground-based radar for cases 1–3, 8, and 9 are shown in Fig. 7. In cases 2, 8, and 9, the KuPR at the original CFB missed the shallow precipitation over Da-Tun Mountain (Figs. 7b,d,e) that was captured by the ground-based radar (Figs. 7l,n,o), but the DFRP CFB successfully detected the precipitation equally as well as the ground-based radar did (Figs. 7g,i,j).

In case 1, the KuPR using the DFRP CFB captured precipitation at Jian Shan Hu (JSH, shown as square in Figs. 7f,k), and Jin Shan (JS, shown as circle in Figs. 7f,k), but ground-based radar did not. Figure 8 shows the precipitation rates of rain gauges in case 1. The rain gauge at JSH captured precipitation with intensity of 3.0 mm h$^{-1}$. On the other hand, the rain gauge at JS did not capture precipitation when KuPR observed precipitation, but the tipping-bucket rain gauge tipped

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**Fig. 6.** Precipitation rate distribution in case 9 observed by the KuPR at the DFRP CFB calculated using (a) Eq. (14) and (b) Eq. (15). (c) Precipitation rate observed by the rain gauges. The scale for the color shading in (a)-(c) is shown to the right of (c).
FIG. 7. Precipitation distribution for cases 1–3, 8, and 9 estimated by (a)–(e) the KuPR at the original CFB, (f)–(j) the KuPR at the DFRP CFB, and (k)–(o) the ground-based radar, respectively. The square and the circle in (f) and (k) indicate the locations of Jian Shan Hu (JSH) and Jin Shan (JS) shown in Fig. 8, respectively. The star in (c) is the footprint shown in Fig. 9 where the original operational algorithm underestimated precipitation.
7 min before and 15 min after KuPR observation, indicating that weak precipitation might be present.

Figure 9 shows the received power profiles at the footprint where precipitation estimation was improved by lowering the CFB in case 3 (star in Fig. 7c). The KuPR using the original CFB at 1.9 km estimated the precipitation with intensity of 20 dBZ (2.1 mm h$^{-1}$) as compared with the estimate of 7.8 mm h$^{-1}$ by the ground-based radar. By lowering the CFB by approximately 700 m, the KuPR using the DFRP CFB at 1.2 km succeeded in revealing low-level enhanced shallow precipitation of 31 dBZ (8.7 mm h$^{-1}$) closer to the ground (Fig. 7h). Because the precipitation rates of KuPR using original CFB and DFRP CFB are calculated by using the same $Z$–$R$ relationship, the difference of precipitation rate is only due to the difference of CFB.

We introduced the threat score (TS), probability of detection (POD), false alarm ratio (FAR), and frequency bias (FB) (e.g., Mega and Shige 2016) to evaluate the extent to which precipitation detection by the KuPR matched that of the ground-based radar. These evaluation metrics are defined by the following equations:

$$TS = \frac{N_1}{N_1 + N_2 + N_3}, \quad POD = \frac{N_1}{N_1 + N_2},$$

$$FAR = \frac{N_3}{N_3 + N_4}, \quad FB = \frac{N_3 + N_2}{N_1 + N_3}.$$  \hspace{1cm} (17)

where $N_1$ is the number of pixels where both the KuPR and the ground-based radar detected precipitation, $N_2$ is the number of pixels where the KuPR did not detect precipitation but the ground-based radar did, $N_3$ is the number of pixels where the KuPR detected precipitation but the ground-based radar did not, and $N_4$ is the number of pixels where neither the KuPR nor the ground-based radar detected precipitation. The threshold value of ground-based radar was set to the same value as that of KuPR for comparison of precipitation detection with the

KuPR. POD is the probability that KuPR detects precipitation when ground-based radar detects precipitation. TS is an evaluation value that further takes the false precipitation detection of KuPR into consideration for the POD, and is evaluated worse if there are false precipitation detection cases as well as missed ones. The closer TS is to 1, the less false precipitation detection and misses of precipitation by KuPR. FAR is the probability that KuPR falsely detects precipitation when ground-based radar does not. FB is the ratio of precipitation frequency detected by KuPR to that detected by ground-based radar and FB greater than 1 indicates that KuPR is overdetecting precipitation, while FB less than 1 indicates underdetecting precipitation.

Table 3 shows the TS, POD, FAR, and FB values of precipitation presence at the original CFB and the DFRP CFB compared with that of the ground-based radar for cases 1–3, 8, and 9. The POD values were improved in all five cases. The TS, FAR, and FB values for case 1 became worse. However, this could not be because DFRP CFB was too low and falsely captured surface clutter as precipitation, but because DFRP CFB was lower than that of ground-based radar over the northern ocean (shown in Figs. 5c,e) and captured the shallow precipitation missed by ground-based radar. The FAR become

Table 3. TS, POD, FAR, and FB values at the original CFB/DFRP CFB in five cases for which the KuPR missed precipitation and in 216 cases for which both KuPR and KaPR observations were obtained.

<table>
<thead>
<tr>
<th></th>
<th>TS</th>
<th>POD</th>
<th>FAR</th>
<th>FB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.64/0.60</td>
<td>0.70/0.90</td>
<td>0.043/0.22</td>
<td>0.80/1.4</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.083/0.50</td>
<td>0.091/0.55</td>
<td>0.042/0.042</td>
<td>0.18/0.64</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.67/0.74</td>
<td>0.67/0.78</td>
<td>0.00/0.056</td>
<td>0.67/0.83</td>
</tr>
<tr>
<td>Case 8</td>
<td>0.33/0.38</td>
<td>0.38/0.54</td>
<td>0.087/0.22</td>
<td>0.54/0.92</td>
</tr>
<tr>
<td>Case 9</td>
<td>0.00/0.67</td>
<td>0.00/0.73</td>
<td>0.00/0.048</td>
<td>0.00/0.82</td>
</tr>
<tr>
<td>216 cases</td>
<td>0.44/0.45</td>
<td>0.56/0.68</td>
<td>0.035/0.067</td>
<td>0.83/1.2</td>
</tr>
</tbody>
</table>
worse for cases 1–3, 8, and 9, but there are no footprints in which KuPR using DFRP CFB captured extremely strong precipitation by misjudging surface clutter as precipitation echoes (shown in Fig. 7).

b. Statistical study

In section 5a, we confirmed that the KuPR using DFRP CFB succeeded in detecting the shallow heavy precipitation with intensity of $\geq 10$ mm h$^{-1}$ missed by that using original CFB. In this section, we compared KuPR using DFRP CFB and ground-based radar for the 216 cases in which both KuPR and KaPR observations were obtained to ensure that there were no footprints where the CFB was estimated to be too low and where the KuPR captured extremely strong precipitation by misjudging surface clutter as precipitation echoes (Hamada and Takayabu 2014).

The TS, POD, FAR, and FB values calculated based on the original CFB were 0.44, 0.56, 0.035, and 0.83, respectively, and those calculated based on the DFRP CFB were 0.45, 0.68, 0.067, and 1.2, respectively (shown in Table 3). While the TS and POD values were improved, the FB and FAR values became worse, but this could be not necessarily because KuPR mistakenly captures the surface clutter as precipitation echo, but as already mentioned, because DFRP CFB is lower than that of ground-based radar such as cases 1 and 9 (Figs. 5c–f) and KuPR captures the precipitation missed by ground-based radar.

We compared the precipitation rate observed by the ground-based radar with those of the KuPR at the original CFB (Fig. 10a) and that at the DFRP CFB (Fig. 10b). In Fig. 10b, there is a footprint for which the KuPR using DFRP CFB detected heavy precipitation with intensity of $\geq 10$ mm h$^{-1}$ that was not detected by the ground-based radar. This particular case is shown in Fig. 11. For the footprint where the KuPR using the original CFB falsely detected heavy precipitation, the ground-based radar did not detect precipitation and the KuPR using the DFRP CFB detected weak precipitation with intensity of $\leq 4$ mm h$^{-1}$ (star in Fig. 11c). For this footprint, the KuPR with the version 06A standard product estimated precipitation with intensity of approximately 25 mm h$^{-1}$ and the KuPR with the latest version 07A standard product, for which sidelobe clutter distinction is improved, also estimated precipitation with intensity of approximately 46 mm h$^{-1}$. The received power profiles for this footprint (Fig. 11d) indicate that the KuPR using the original CFB incorrectly detected sidelobe clutter as strong precipitation by misjudging the CFB. The DFRP algorithm avoids the false precipitation detection by estimating the CFB at altitudes below the sidelobe clutter.

The correlation coefficients between the ground-based radar and the KuPR was 0.49 for the DFRP CFB, while that for the original CFB was 0.42, indicating that the estimation of precipitation improved. The bias ratio between the ground-based radar and the KuPR was 26% for the DFRP CFB, while that for the original CFB was −19%. The bias ratio compared to the ground-based radar become larger, but the bias ratio between the rain gauges and KuPR was also calculated and that of the KuPR was −18% for the DFRP CFB, while that for the original CFB was −51%, indicating that the bias ratio was improved. In case 9, precipitation rate of KuPR using DFRP CFB was overestimated compared to that of ground-based radar (Figs. 7j,p), but was underestimated compared to that of rain gauges (Fig. 6c). Since rain gauges directly observe precipitation on the ground, improvement of precipitation estimation compared to rain gauges suggests that the increase of precipitation rate estimated by KuPR using DFRP CFB is not due to the error of CFB estimation.

6. Summary

Analysis using spaceborne precipitation radars have revealed that heavy rainfall in mountainous areas is frequently
associated with low precipitation-top heights (Shige and Kummerow 2016), leading to the subsequent improvement of passive microwave radiometer rain retrievals in mountainous areas (Shige et al. 2013, 2014; Taniguchi et al. 2013; Yamamoto and Shige 2015; Yamamoto et al. 2017). However, they cannot observe precipitation associated with shallow clouds present over mountains where the blind zone caused by surface clutter extends to higher altitudes. In this study, we identified 12 cases in which KuPR missed precipitation with intensity of $10 \text{ mm h}^{-1}$.

In five of these cases, shallow heavy precipitation occurred in the blind zone over Da-Tun Mountain in northern Taiwan. This error occurred because the KuPR signal was judged to arise from the surface instead of the precipitation, causing the CFB to be estimated higher than the actual lower bound of the range free from surface echoes. To improve KuPR precipitation detection and estimation, this study refined the CFB estimation algorithm using received power data from the KuPR and the KaPR.

Since the received power ($P_r$) depends on the transmitted power ($P_t$), wavelength ($\lambda$), attenuation ($A$), and scattering cross section, the received power of KuPR (1012.0 W, 13.6 GHz) is different from that of KaPR (146.5 W, 35.5 GHz). For scattering by the precipitation particles, scattering cross section ($\sigma$) depends on $\lambda$. Therefore, the DFRP, the ratio of $P_r$(Ku) and $P_r$(Ka), depends on $\sigma$ for the precipitation echo. On the other hand, DFRP for the surface clutter is independent of scattering cross section ($\sigma^0$), since $\sigma^0$ is independent of $\lambda$. Because of the difference of scattering cross section dependency, DFRP$_{surf}$ is larger than DFRP$_{precip}$. With this relationship, it was established that the DFRP value sharply increases at altitudes affected by surface clutter. We estimated the CFB at the altitude where the DFRP increases to more than the threshold of 2.3 dB. By improving the CFB estimation algorithm, the CFB was lowered by approximately 500 m in the mountainous areas where precipitation had been missed by the KuPR using the original operational algorithm, and it became lower than that of the ground-based radar in some areas such as northern ocean.

The shallow precipitation rate was calculated using the $Z$–$R$ relationship applicable over Da-Tun Mountain (Cheng and Yu 2019), and the deep precipitation rate was calculated using the $Z$–$R$ relationship with the original operational algorithm. The DFRP algorithm improved precipitation detection and mitigated precipitation underestimation. Comparison of the KuPR precipitation rates at the DFRP CFB with those of the original CFB in all 216 cases for which both the KuPR and the KaPR measurements covered Da-Tun Mountain revealed

![Figure 11](https://example.com/figure11.png)

**FIG. 11.** Precipitation distribution for orbit 1309 measured by (a) the KuPR at the original CFB (1959 UTC 22 May 2014), (b) the KuPR at the DFRP CFB, and (c) the ground-based radar (1956 UTC 22 May 2014). The star in (c) indicates the footprint for which the KuPR misjudged sidelobe clutter as precipitation echoes. (d) Received power profiles in footprint denoted by the star in (c).
that the TS, POD and correlation coefficient values were improved, while the FB and FAR value became worse. However, the worse FB and FAR for the DFRP CFB could be because DFRP CFB is lower than that of ground-based radar in some areas, and KuPR captured shallow precipitation missed by ground-based radar. By investigating the cases in which the KuPR with the DFRP algorithm detected strong precipitation that the ground-based radar did not, we confirmed that there were no cases for which the DFRP algorithm estimated the CFB as being too low and misjudged surface clutter as precipitation echoes. Conversely, there was a case for which KuPR using the original CFB falsely captured heavy precipitation as being too low and misjudged surface clutter as precipitation echoes, which was not corrected even in the latest version of the KuPR. On the other hand, the KuPR using the DFRP CFB avoids falsely capturing heavy precipitation.

This study used KaPR data from March 2014 to February 2020 with 25 angle bins in the innermost swath. However, the KaPR full scan mode data since May 2018 has 49 angle bins (Awaka et al. 2021). Because the CFB is higher for larger angles, we expect greater improvement in detecting shallow precipitation when applying the DFRP algorithm to the KaPR full scan mode data.

The DFRP algorithm cannot estimate CFB for heavy ice precipitation cases with large DFRP shown in Fig. 3e. Future research is needed to improve CFB estimation in heavy ice precipitation cases.

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Data availability statement. The GPM DPR data used in this study can be downloaded from the JAXA Globe Portal System (G-Portal) at https://gportal.jaxa.jp/gpr/index/index. The Wu-Fen-San radar observations from the Taiwan Central Weather Bureau are available from the Data Bank for Atmospheric and Hydrologic Research (https://dbar.pccu.edu.tw/) sponsored by National Science and Technology Council of Taiwan. Because of confidentiality agreements, surface rainfall data from the rain gauge network over Da-Tun Mountain (i.e., DTRNG) can only be made available to bona fide researchers subject to a nondisclosure agreement. Access to these data is available from one of the coauthors for this article (Cheng-Ku Yu, email: yuku@nsu.edu.tw) at the Department of Atmospheric Sciences, National Taiwan University.

REFERENCES


