Rain Type Classification Algorithm Module for GPM Dual-Frequency Precipitation Radar

JUN AWAKA
Tokai University, Sapporo, Japan

MINDA LE AND V. CHANDRASEKAR
Colorado State University, Fort Collins, Colorado

NAOFUMI YOSHIDA AND TOMOHICO HIGASHIWATOKO
Remote Sensing Technology Center of Japan, Tsukuba, Japan

TAKUJI KUBOTA
Japan Aerospace Exploration Agency, Tsukuba, Japan

TOSHIO IGUCHI
National Institute of Information and Communications Technology, Koganei, Japan

(Manuscript received 12 January 2016, in final form 17 May 2016)

ABSTRACT

The Global Precipitation Measurement (GPM) Dual-Frequency Precipitation Radar (DPR) algorithms consist of modules. This paper describes version 4 (V4) of GPM DPR level 2 (L2) classification (CSF) modules, which consist of two single-frequency (SF) modules—that is, Ku-only and Ka-only modules—and a dual-frequency (DF) module. Each CSF module detects bright band (BB) and classifies rain into three major types, that is, stratiform, convective, and other. The Ku-only and Ka-only CSF modules use algorithms that are similar to the Tropical Rainfall Measuring Mission (TRMM) rain type classification algorithm 2A23. The DF CSF module uses a new method called the measured dual-frequency ratio (DFRm) method for the rain type classification and the detection of BB. It is shown that the Ku-only CSF module and the DF CSF module produce almost indistinguishable rain type counts in a statistical sense. It is also shown that the DFRm method in the DF CSF module improves the detection of BB.

1. Introduction

The GPM Core Observatory carries the Dual-Frequency Precipitation Radar (DPR) operating at Ku band and Ka band (Kobayashi and Iguchi 2003; Kubota et al. 2014). Rain type classification is very important for accurate measurement of precipitation rate by the DPR because the reflectivity factor $Z$ and the attenuation due to precipitation depend on rain types (e.g., Battan 1973; Meneghini and Kozu 1990).

In the GPM DPR algorithms, rain type classification is made in three classification (CSF) modules: two single-frequency (SF) modules—that is, Ku-only and Ka-only modules—and a dual-frequency (DF) module. Since the electrical properties of the Ku-band radar are very similar to those of the Tropical Rainfall Measuring Mission (TRMM) Ku-band Precipitation Radar (PR), the Ku-only CSF module uses the algorithm flow that is similar to that of the TRMM PR rain type classification algorithm 2A23 (Awaka et al. 1997, 1998, 2007, 2009), which detects bright band (BB) and classifies rain into three major types, that is, stratiform, convective, and

Corresponding author address: Jun Awaka, Sapporo Liberal Arts Education Center, Tokai University, Minami-ku, Minami-sawa 5-1-1-1, Sapporo 005-8601, Japan. E-mail: awaka@tsc.u-tokai.ac.jp

DOI: 10.1175/JTECH-D-16-0016.1

© 2016 American Meteorological Society
other. Stratiform rain is weak but widespread and accompanies BB, in which the solid particles aloft melt and change to raindrops. The bright band appears near 0°C height and returns a strong echo when observed by radar. Convective rain is strong but has a small localized area. The other type of rain is characterized by no rain near the surface but radar echo exists in the high cloud region. The Ka-only CSF module is developed by applying necessary changes to the Ku-only CSF module. Contrary to this, the DF CSF module incorporates a new method called the measured dual-frequency ratio (DFRm) method (Le and Chandrasekar 2013a,b) for the rain type classification and the detection of the melting layer (ML) that is assumed to be equivalent to the detection of BB in the case of stratiform rain.

This paper describes details of the most recent version, version 4 (V4), codes of CSF modules. Some statistical results obtained by using the recent V4 data are also shown.

2. Outline of GPM DPR L2 algorithm structure

There are three GPM DPR level 2 (L2) algorithms: two SF algorithms (Ku-only and Ka-only algorithms) and a DF algorithm. Though the three algorithms are different, their data flow structures are similar as shown in Fig. 1. Each algorithm consists of the preparation (PRE) module, the vertical profile (VER) module, the CSF module, the drop size distribution (DSD) module, the surface reference technique (SRT) module, and the solver (SLV) module (Seto and Iguchi 2011, 2015). The purpose of this paper is to give a detailed description of the CSF module.

In the PRE module, a rain or no-rain decision is made after the separation of rain echo from main-lobe surface clutter and the rejection of sidelobe clutter. In the VER module, correction for attenuation by atmospheric gases and water vapor is made to the measured reflectivity factor. In the VER module, the height of the 0°C isotherm is also estimated from the global analysis data (GANAL) of the Japan Meteorological Agency (JMA). In the CSF module, detection of BB and rain type classification is made. In the DSD module, the drop size distribution is estimated. In the SRT module, the total attenuation of propagation from the radar to the surface is obtained by the surface reference technique. Finally, in the SLV module, the rainfall rate is calculated.

In the single-frequency algorithms—that is, in the Ku-only and Ka-only algorithms—the process from the VER module to the SLV module is repeated twice in order to obtain reliable attenuation correction to Z. In the DF algorithm, however, such repetition is not made because the DF algorithm uses the outputs from the single-frequency algorithms where reliable attenuation correction is already made.

3. Rain type CSF module

The main objectives of the CSF modules, which are similar to those of the TRMM PR standard algorithm 2A23, are as follows:
1) detection of BB,
2) classification of rain type into three major categories, and
3) detection of shallow rain.

Figure 2 shows the concept of rain type classification in each CSF module. Figure 2a shows the rain type classification flow of the Ku-only or Ka-only CSF module, and Fig. 2b shows that of the dual-frequency CSF module. In the CSF modules, the rain type classification is made on pixel basis. Hence, the rain type is the same along a radar beam. Some details of each CSF module are discussed below.

a. Ku-only CSF module

The Ku-only CSF module uses computer codes whose logic is similar to that of the TRMM PR 2A23 algorithm; that is, the rain type is determined by using the vertical
profile method (V method) and the horizontal profile method (H method). In the V method, detection of BB is made first. After the detection of BB, the V method classifies rain into three categories: stratiform, convective, and other.

Detection of BB is made by a peak search of $Z$ in a BB search window that is determined by the height of the $0^\circ C$ isotherm estimated in the VER module using the GANAL data. The BB search window is from 1 km above to 2 km below the $0^\circ C$ height. This choice of BB search window is based on the empirical TRMM PR result that, statistically speaking, BB peak appears about 0.5 km below the $0^\circ C$ height on average (Awaka et al. 2009).

When a BB is detected, the width of the BB (BBwidth) is computed from the upper (BBtop) and lower boundaries (BBbottom) of the BB. The upper and lower boundaries are determined by examination of the reflectivity profile. The BBbottom is determined first and has a similar definition to that of Fabry and Zawadzki (1995). The BBtop is determined next and has a definition somewhere between that given by Fabry and Zawadzki (1995) and that by Klaassen (1988).

At nadir, BBwidth is computed using

$$BBwidth = r_{BBbottom} - r_{BBtop},$$  

where $r_{BBbottom} > r_{BBtop}$ because the range is measured from the spaceborne radar down to Earth.

At other antenna beam directions, BBwidth is computed by the following empirical formula (Awaka et al. 2009):

$$BBwidth = \left[ r_{BBbottom} - r_{BBtop} - \left( L_o F/\cos^2\theta \right) \sin\theta \right] \cos\theta,$$

where $\theta$ is the local zenith angle, $r_{BBbottom}$ and $r_{BBtop}$ are the quantities obtained for the off-nadir radar beam, $L_o$ is the diameter of the antenna beam footprint, and $F (<1)$ is an empirical correction factor ($F = 0.5$ in the source program).

When a BB is detected, the pixel is normally considered stratiform, but it is classified as convective if $Z$ corrected for attenuation by nonprecipitation (NP) particles $Z_{NPcorrected}$ below BB exceeds a convective threshold (which is set to be 39 dBZ). The calculation of $Z_{NPcorrected}$ is done in the VER module. If there is no BB detected, then the pixel is classified as convective if $Z_{NPcorrected}$ below the storm top exceeds the convective threshold; otherwise, the pixel is classified as other.

In the Ku-only CSF module, the rain type is also determined by the H method, which examines $Z$ horizontally. The H method is based on the University of Washington convective/stratiform separation method (Steiner et al. 1995; Yuter and Houze 1997), which we will call the original H method. In practice, however, some modifications to the original H method are necessary for making the method suitable for analyzing the spaceborne radar data. First and foremost, what is examined in the H method is not $Z$ at a constant altitude, but the maximum value of $Z$ along a given antenna beam in a range from 1.5 km below the $0^\circ C$ level to the lowest clutter-free point above the surface. Let $Z_{maxH}$ denote the maximum value of $Z$ thus obtained. In colder regimes (i.e., when the height 1.5 km below $0^\circ C$ drops lower than the clutter-free bottom), the H method uses $Z$ of the clutter-free bottom as $Z_{maxH}$. If $Z_{maxH}$ for a given pixel stands out against the background $Z_{maxH}$ of the surrounding pixels or exceeds a predetermined threshold (40 dBZ for both Ku and Ka bands), then the pixel is regarded as a convective center. Pixels adjacent to the convective center are also classified as convective. If the $Z_{maxH}$ value is considered noise, then the pixel is classified as other. If the rain type is neither convective nor other, then the pixel is classified as stratiform.

In addition to that mentioned above, the Ku-only CSF module also detects shallow rain and small-cell-size rain. A pixel is considered to have shallow rain if the storm top is more than 1 km below the $0^\circ C$ height estimated from the GANAL data and no BB is detected. The small cell size indicates a small horizontal extent (i.e., a single pixel

---

**FIG. 2.** Outline of rain type classification by each CSF module: (a) the Ku-only or Ka-only CSF module and (b) the DF CSF module.
or two adjacent rain pixels surrounded by no-rain pixels). When shallow rain or small cell size is detected, the pixel is classified as convective.

The Ku-only rain type unification is very similar to the rain type unification made by the TRMM PR standard algorithm 2A23, and the unified rain type consists of three major categories: stratiform, convective, and other. The unified rain type other means that the radar echo in the lower rain region is noise, which occurs, for example, in the cloud-only case. Figure 3 shows how the Ku-only rain type unification is made. When the V method detects BB and classifies the rain type as stratiform, the unified rain type is stratiform unless the type is overwritten by the detection of shallow rain and/or small-cell-size rain. When the V method classifies rain type as convective (with or without BB), the unified rain type is convective (with or without BB). When the V method classifies the rain type as other, the unified rain type is that of the H method unless the type is overwritten by the detection of shallow rain and/or small-cell-size rain. Figure 3 is also applicable to the Ka-only rain type unification.

Though the Ku-only rain type unification and the 2A23 rain type unification are similar, there are two main differences between them. In the TRMM 2A23 algorithm, rain types are expressed by three digits, but in the GPM DPR CSF modules, rain types are expressed by eight digits (see the appendix for details). Another difference is in the rain type of shallow rains.

In the TRMM 2A23 decision, shallow isolated is convective but shallow nonisolated is either convective or stratiform. In the GPM CSF decision, however, both shallow isolated and shallow nonisolated are convective. This change of rain type for shallow nonisolated is based on the analysis by Funk et al. (2013).

b. Ka-only CSF module

The Ka-band PR operates in two types of scan: one is a matched beam scan (MS) in which beams are matched to the central 25 beams of Ku-band PR and the other is a high-sensitivity-mode scan (HS) in which the high sensitivity is realized by using a wider range resolution, one that is twice as large, than that of the matched beam scan. The HS beams are interlaced within the scan pattern of the matched beams. Though there are differences between Ka-band data and Ku-band data, the basic algorithm flow of the Ka-only CSF module is the same as that of the Ku-only CSF module. However, since the profile of BB at Ka band becomes less clear than that at Ku band, which makes the use of Ka-band data unfavorable to the detection of BB, the Ka-only CSF module uses a simplified BB detection code and tries to detect only clear BB. On the other hand, at MS rain type classification, the detection of shallow rain, and the detection of small-cell-size rain by the Ka-only CSF module are very similar to those by the Ku-only CSF module. In particular, the basic parameters, such as convective threshold, are the same as those of Ku-only CSF module.

The Ka-only CSF module outputs the unified rain type that consists of three major categories: stratiform, convective, and other. The unified rain type other means that the radar echo in the lower rain region is noise. The principle of rain type unification is the same as that of the Ku-only CSF module.

c. DF CSF module

The DF CSF module uses the DFRm method, developed by Colorado State University (CSU; Le and Chandrasekar 2013a,b), in the inner swath, where the dual-frequency data are available. The DFRm method takes advantage of using dual-frequency data. The DFRm method detects ML, the concept of which has a wider meaning than that of BB, and classifies the rain type into three categories: stratiform, convective, and transition, the last of which is a new rain type category. However, the DF CSF module unifies the rain type by the (MS or HS) DFRm method and by the single-frequency (Ku-only or HS Ka-only) method, and the DF CSF module outputs the unified rain types, which are stratiform, convective, and other.

1) RAIN TYPE BY DFRM METHOD

The DFRm method uses the so-called measured dual-frequency ratio (DFRm), which is defined as follows:

$$DFRm = Zm(Ku) - Zm(Ka),$$

where Zm(Ku) and Zm(Ka) are the measured reflectivity factor (dBZ) at Ku band and Ka band, respectively. The DFRm method examines the vertical profile of DFRm.
Figure 4 shows an example of the DFR<sub>m</sub> profile with key points A–D (Le and Chandrasekar 2013a, b). At point A, the slope of DFR<sub>m</sub> takes a peak value; at point B, DFR<sub>m</sub> takes a local maximum value; at point C, DFR<sub>m</sub> takes a local minimum value; and point D indicates the lowest boundary above which DFR<sub>m</sub> is available.

DFR<sub>m</sub> method continues; otherwise, the DFR<sub>m</sub> method is skipped (at part B in Fig. 5).

Next, the quantities variable 1 (V1) and variable 2 (V2) are calculated. The definition of V1 is

\[
V1 = \frac{\text{DFR}_m(\text{max}) - \text{DFR}_m(\text{min})}{\text{DFR}_m(\text{max}) + \text{DFR}_m(\text{min})},
\]

where DFR<sub>m</sub>(max) and DFR<sub>m</sub>(min) are the linear values of DFR<sub>m</sub>(max) and DFR<sub>m</sub>(min), respectively. The definition of V2 is as follows:

\[
V2 = \text{abs(mean slope of DFR}_m\text{ in rain region}),
\]

where abs(·) means to take the absolute value of the quantity inside the parentheses, and the slope is measured with respect to height (km); therefore, the quantity V2 has a dimension of decibels per kilometer and the rain region means the height interval between points C and D in Fig. 4. If V2 is smaller than 0.5 dB km<sup>−1</sup>, then the DFR<sub>m</sub> method is skipped (at part B in Fig. 5); otherwise, variable 3 (V3) is calculated, which is defined as

\[
V3 = \frac{V1}{V2}.
\]

The DFR<sub>m</sub> method classifies rain into three categories: stratiform, convective, and transition, the last of which is a new concept. The DFR<sub>m</sub> rain type decision is made as follows (see part C of Fig. 5):

\[
V3 > C2: \text{rain type is stratiform,}
\]

\[
V3 < C1: \text{rain type is convective, and}
\]

\[
C1 \leq V3 \leq C2: \text{rain type is transition,}
\]

where C1 and C2 are empirical parameters. Parameter tuning was made after the first public release of the GPM DPR products, and the parameter values (km dB<sup>−1</sup>) are C1 = 0.18 and C2 = 0.20 in the V4 DF code.

The abovementioned DFR<sub>m</sub> method is applied not only to the MS data but also to the HS data. In the case of the HS data handling, Ka-band data having a 125-m range bin interval are interpolated from the HS data, whose range bin interval is 250 m; the corresponding Ku-band data are estimated from the normal scan (NS) data of the nearest four pixels that surround the HS pixel; and then DFR<sub>m</sub> is calculated using (3) and these interpolated data.

2) DETECTION OF ML BY DFR<sub>m</sub> METHOD

When DFR<sub>m</sub> pair exists, that is, both DFR<sub>m</sub>(max) and DFR<sub>m</sub>(min) exist, a search is made for the range bin where the slope of DFR<sub>m</sub> takes a peak value, that is, a search for point A in Fig. 4, is made. When point A is
3) DETECTION OF BB IN DF CSF MODULE

When ML is detected by the DFRm method, the algorithm assumes tentatively that BB is detected. The height of BB is defined as the height at which Ku-band $Z_{NP}\text{corrected}$ takes the maximum value within the range determined by the upper and lower boundaries of ML.

Since BB detected by the Ka-only CSF module is not trustworthy, a unification between BB determined by the DFRm method and the HS Ka-only method is not made.

4) UNIFICATION OF RAIN TYPES IN DF CSF MODULE

In the new V4 algorithm, the rain type by the DFRm method and that by the single-frequency method are unified (for the numbering of unified rain types, see the appendix).

In the outer swath of NS, the rain type of the DFRm module is the copy of the corresponding rain type of the Ku-only CSF module.

In the inner swath of NS, the rain type by the DFRm method and that by the Ku-only CSF module are unified. When the rain type by the DFRm method is stratiform or convective, this decision is respected and used as the unified rain type in most cases. However, there are three exceptions. 1) When BB is detected, the unified rain type is basically stratiform; however, if $Z_{NP}\text{corrected}$ in the lower part of rain region below BB is strong enough to be convective, then the rain type is convective. 2) When shallow rain is detected, the unified rain type is convective. 3) When small-cell-size rain is detected, the unified rain type is convective. When the rain type by the DFRm method is transition, the unified rain type is the rain type by the Ku-only CSF method.

Since BB detected by the Ku-only CSF module is not trustworthy, a unification between BB determined by the DFRm method and the HS Ka-only method is not made.

FIG. 5. Flowchart of rain type classification by the DFRm method. When the decision tree reaches part A or part B, the DFRm rain type classification is skipped. The actual DFRm rain type classification is made at part C. For quantities V2, V3, C1, and C2, see the text.
When DFRm is skipped at part A or part B in Fig. 5, the unified rain type is that by the Ku-only CSF module. In the 2014 public release codes, when the DFRm method is skipped at part A, the unified rain type is that by the H method; and when DFRm method is skipped at part B, the rain type is determined by another single-frequency decision. These are conceptual bugs and should be fixed because when the DFRm method is skipped, the DF CSF module uses a single-frequency decision that should be consistent with other reliable single-frequency decisions—that is, with the Ku-only CSF decision—but not with the Ka-only CSF decision, which may be unreliable. These bugs are fixed in the new DF CSF module.

The unified rain type by the DF CSF module again consists of stratiform, convective, and other. The unified rain type other means that the radar echo in the lower rain region is noise. The unification between rain type by the HS DFRm method and that by the Ka-only HS method is made similarly.

4. Statistical results

This section shows some statistical results of the output data of CSF modules. It also shows the single-frequency Ku-only NS results and the DF NS results. The DFRm method is used in the inner swath of DF NS data. (Since the Ka-only data are kind of supplementary as far as the rain type classification is concerned, the Ka-only results are not shown here.)

Figure 6a shows the angle bin (i.e., antenna beam direction) dependence of each unified rain type count obtained by the V3 2014 public release algorithms. The figure plots the data of one month (July 2014). The dotted line shows the count determined by the single-frequency CSF module, and the solid line shows the count determined by the DF CSF module. Among the counts of three major rain types, the stratiform rain count is the largest, the convective rain count is the second largest, and the other rain count is the smallest. At scan edges (i.e., at angle bins 1 and 49), the convective count slightly decreases, whereas the stratiform and other counts increase because the small-cell-size decision cannot be made at the scan edges (and small-cell-size rain is not classified as convective there). The dips and spikes in the rain type counts around angle bins 15–19 and 31–35 are due to the Ku-band sidelobe clutter rejection. In the inner swath region—that is, at angle bins 13–37, where the DFRm method is applied—one can notice a discernible difference between the Ku-only NS result and the DF NS result. It is known that the difference occurred due to bugs in some parts of the V3 2014 public release codes. The bugs are fixed in the new V4 codes.

Figure 6b shows the angle bin dependence of each unified rain type count obtained by the new V4 codes. Figure 6a shows the angle bin dependence of each unified rain type count obtained by the V3 2014 public release algorithms. The figure plots the data of one month (July 2014). The dotted line shows the count determined by the single-frequency CSF module, and the solid line shows the count determined by the DF CSF module. Among the counts of three major rain types, the stratiform rain count is the largest, the convective rain count is the second largest, and the other rain count is the smallest. At scan edges (i.e., at angle bins 1 and 49), the convective count slightly decreases, whereas the stratiform and other counts increase because the small-cell-size decision cannot be made at the scan edges (and small-cell-size rain is not classified as convective there). The dips and spikes in the rain type counts around angle bins 15–19 and 31–35 are due to the Ku-band sidelobe clutter rejection. In the inner swath region—that is, at angle bins 13–37, where the DFRm method is applied—one can notice a discernible difference between the Ku-only NS result and the DF NS result. It is known that the difference occurred due to bugs in some parts of the V3 2014 public release codes. The bugs are fixed in the new V4 codes.
between the dotted and solid lines can occur only in the inner swath. However, the figure does not show any appreciable difference between the dotted and solid lines in the inner swath region. Each Ku-only NS rain type count is almost identical to the corresponding DF NS rain type count. To understand this, it is necessary to study the inner swath data in detail.

Table 1 shows the counts of DFRm rain types obtained in the inner swath of DF NS data, which are based on the same one month of data used for Fig. 6b. The DFRm rain type can be retrieved from the eight-digit unified rain type as shown in the appendix. The table shows that the main part of the DFRm method (which is indicated by part C in Fig. 5) works for only about 14% of the inner swath data, and the remaining about 86% of data are skipped from the main DFRm processing. When the DFRm method skips the data, the single-frequency Ku-only decision is used for the unified rain type. This fact may partly explain the good agreement between dotted and solid lines in Fig. 6b. Nevertheless, Fig. 6b implies that the DFRm rain types are close to the Ku-only rain types. This is important because good agreement between the rain types by different methods implies that both the Ku-only rain type decision and the DFRm rain type decision are reliable.

A comparison of Figs. 6a and 6b shows that the update of algorithms gives rise to noticeable changes in rain type counts. In particular, the count of the rain type other becomes appreciably smaller mainly because of the improvement of sidelobe clutter rejection algorithm in the VER module.

Figures 7a and 7b show the angle bin dependence of each unified rain type count obtained by the new codes for the data over ocean and that over land, respectively. Here, the data over ocean mean the data where the landSurfaceType flag is zero and the data over land

<table>
<thead>
<tr>
<th>DFRm rain type</th>
<th>Count</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Stratiform</td>
<td>446,845</td>
<td>Total count processed at part C: 636,954 (14.1%)</td>
</tr>
<tr>
<td>2: Convective</td>
<td>161,835</td>
<td></td>
</tr>
<tr>
<td>4: Transition</td>
<td>28,274</td>
<td></td>
</tr>
<tr>
<td>8: Skipped at part B</td>
<td>1,585,095</td>
<td>Total count skipped: 3,893,181 (85.9%)</td>
</tr>
<tr>
<td>9: Skipped at part A</td>
<td>2,308,086</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 7](image_url)
mean the data where the landSurfaceType flag is positive (therefore, the data over land include the data over coastline). If the data in Fig. 7a and that in Fig. 7b are added, then Fig. 6b is obtained. As far as the figure layout is concerned, Figs. 7a and 7b are the same as Fig. 6b. Figures 7a and 7b show that the stratiform and convective curves over land are more flat than over ocean. Since the rain type other means that the radar echo in the lower rain region is noise, let us not consider the rain type other any longer and concentrate only on stratiform rain and convective rain.

In the GPM DPR CSF modules, shallow rains are classified as convective. It would be interesting to separate shallow rain from convective rain and examine the angle bin dependence of the count of each of them. Figures 8a and 8b show the angle bin dependence of the shallow convective rain count (dotted curve) and that of the convective but not the shallow rain count (solid curve): Fig. 8a shows the count over ocean and Fig. 8b shows that over land. For simplicity, the figures show the count determined by the Ku-only CSF module. To make a comparison between Figs. 7a and 8a (or between Figs. 7b and 8b) easy, the angle bin dependence of the stratiform rain count is also shown in Figs. 8a and 8b.

Figures 8a and 8b show that the shallow convective rain count has a strong dependence on the angle bin number because rain echo having a low storm top becomes masked by a smeared surface echo whose smearing effect becomes larger as the antenna scan angle increases (Awaka et al. 2007, 2009). Contrary to this, the nonshallow convective count shows only weak dependence on angle bin numbers. Figure 8a shows that, over the ocean, the population of shallow convective rain is comparable to that of non-shallow convective rain, whereas Fig. 8b shows that, over the land, the population of shallow convective rain is much smaller than that of nonshallow convective rain. This observation indicates that shallow rain mainly occurs over the ocean (this fact was first noticed in the TRMM observations of rain; Short and Nakamura 2000).

Figure 9 shows the angle bin dependence of stratiform rain using the Ku-only V4 data over ocean. The stratiform count without any constraint of storm top shows a strong dependence on angle bin number despite the fact that stratiform rain does not include shallow rain (because the CSF module classifies shallow rain as convective). It should be noted, however, that nonshallow rain does not necessarily mean that the storm top is high; it only means that the storm-top height does not satisfy the shallow condition, that is, the condition that the storm-top height is 1 km or more lower than the estimated 0°C height. If the estimated 0°C height is very low, then the storm-top height can be very low even if the storm-top height does not satisfy the shallow condition, and the rain echo can be masked by the smearing of the strong surface echo at larger antenna scan angles.

Figure 9 also shows the counts with the following conditions that the storm-top height $H_{\text{storm}}$ is higher than 4, 6, and 8 km. When the lower bound of height imposed on $H_{\text{storm}}$ becomes higher, the stratiform rain count decreases, and the most noticeable change in the curve is
that the count becomes almost flat with respect to the angle bin number. When the storm top is higher than 4 km, the smearing of surface echo does not affect the existence of rain even at scan edges where the smearing of surface echo becomes the broadest.

Figure 10 shows the BB count and also the stratiform count as a reference. The dotted curve shows the count obtained by the Ku-only CSF module and the solid curve shows that obtained by the DF CSF module. The figure clearly shows that the BB count is increased by the DF CSF module in the inner swath where the DFRm method is applied. This fact indicates an advantage of the use dual-frequency data.

Figure 10 shows that the BB count is smaller in the outer swath; the BB count in the outer swath should be improved in the future update of the CSF module.

5. Future plans

The current DFRm method does not use the dual-frequency data fully. It is expected that the dual-frequency data give us useful information about the phase of particles in the upper part of storm (e.g., Liao and Meneghini 2011). If we develop a method to analyze the DFRm in the upper part of storm extensively, then we may be able to use that information, for example, for the type classification of the almost snow-only case in the mid- and high latitudes in winter.

Other future plans include the following:
1) Improvement of the detection of BB, in particular in the Ku-band outer swath;
2) Improvement of the Ka-only CSF module, which currently uses the code similar to the Ku-only code and with the parameters of Ku-only module; and
3) Experimental use of SLV module output for the rain type classification. As shown in Fig. 1, the single-frequency algorithms have a loop structure. However, the current Ku- and Ka-only CSF modules do not use the attenuation-corrected SLV module output.

6. Conclusions

This paper describes the most recent CSF modules for the GPM DPR data processing. There are three CSF modules: Ku only, Ka only, and dual frequency (DF). The CSF modules classify rain into three major unified types: stratiform, convective, and other. The CSF modules also detect BB. The Ku-only and Ka-only CSF modules use algorithm structures that are very close to the TRMM rain type classification algorithm 2A23. The DF CSF module uses the DFRm method for rain type classification and also for detecting BB through detecting ML.
Among the CSF modules, this paper focuses on the NS Ku-only CSF module and the NS DF CSF module. It is shown statistically that the unified rain type counts by the NS Ku-only CSF module are very close to those by the NS DF CSF module. It is also shown statistically that the detection of BB by the NS Ku-only CSF module is improved by the combined use of the Ku-only method and the DFRm method.

Among the future plans shown in section 5, a possible extension of the DFRm method for the purpose of precipitation type classification in the snow-only case in winter has the highest priority.

Acknowledgments. This work is supported by the Japan Aerospace Exploration Agency (JAXA) Precipitation Measuring Mission (PMM) research program under Grant JX-PSPC-418726. The authors thank JAXA and the National Aeronautics and Space Administration (NASA) for allowing them to use the GPM DPR data and algorithm sources.

APPENDIX

Numbering of Rain Types

In the TRMM 2A23 algorithm, rain types are expressed with three digits. In the GPM DPR CSF modules, however, rain types are expressed with eight digits as shown in Fig. A1. The rule of the rain type numbering is the same for the Ku-only, Ka-only, and DF CSF modules. In the GPM DPR algorithms, the rain type number is stored in the typePrecip flag.

As shown in Fig. A1, the first digit (i.e., the leftmost digit) of the rain type number expresses the unified rain type. For most users of the GPM DPR data, therefore, an examination of the first digit of the rain type number would be sufficient.

The second digit of the rain type number indicates the decision made by the DFRm method. In the new algorithm, 8 (which means the DFRm decision is skipped at part B in Fig. 5) is added as a valid member to the second digit of the rain type number.

REFERENCES


