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1 **Development of precipitation type classification**
2 **algorithms for a full scan mode of GPM Dual-Frequency**
3 **Precipitation Radar**

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Abstract

The Global Precipitation Measurement (GPM) Dual-Frequency Precipitation Radar (DPR) has operated in full scan (FS) mode in both the Ku-band and Ka-band since May 2018. This FS mode can enable about 245 km full swath dual-frequency processing for the first time, whereas previous algorithms enabled dual-frequency processing in the narrower inner swath, having a width of approximately 125 km. This paper describes the classification (CSF) module in newly developed DPR level 2 V06X experimental algorithms corresponding to the FS mode. The CSF module classifies precipitation as three major types, stratiform, convective, and other, and provides bright-band (BB) information.

One-month statistics show that a significant jump occurs in the Ka-band precipitation type counts at the edges of the inner swath due to the different sensitivity of Ka-band radar in Ka-band Matched Scan (Ka-MS) mode compared with that in Ka-band High Sensitivity (Ka-HS) mode. However, precipitation type counts indicate that dual-frequency processing works well not only in the inner swath but also in the outer swath. Statistics on BB counts show a significant improvement in BB detection, especially in the outer swath, when dual-frequency processing is performed.

In addition, the V06X Ku-band algorithm solves two problems related to the CSF module: (a) appearance of a very large near-surface precipitation rate of stratiform precipitation

reclassified by the slope method and (b) a rare case of misjudging BB peak as an upper part of surface echo.

The data structures of GPM DPR algorithms were drastically changed in V06X. The new data structures introduced in V06X will be used in V07A and later. In this regard, the V06X CSF module outlined in this paper is a prototype of future versions of each CSF algorithm.

Keywords radar; precipitation type; algorithm; dual-frequency ratio; GPM; DPR

66 **1. Introduction**

67 Dual-Frequency Precipitation Radar (DPR) is operating in the Ku-band and Ka-band at
68 the core observatory of the Global Precipitation Measurement (GPM) mission (Kojima et al.
69 2012; Hou et al. 2014; Kubota et al. 2014; Skofronick-Jackson et al. 2017; Iguchi 2020;
70 Nakamura 2021). The GPM core observatory was launched into orbit on February 28, 2014
71 (Japan Standard Time). It flies in a non-Sun-synchronous orbit, and observes precipitation
72 in the latitude ranging from 65°N to 65°S. Furthermore, the GPM core observatory
73 comprises two sensors: DPR and GPM Microwave Imager (GMI) (Hou et al. 2014;
74 Skofronick-Jackson et al. 2017).

75 The Ku- and Ka-band radars have almost the same antenna beam shape and observe
76 precipitation with the same footprint size, which is approximately 5.2 km at the nadir. The
77 pulse width of the Ku-band radar is 1.6 μ s, and the range resolution is 250 m. The Ka-band
78 radar operates with two pulse-widths: 1.6 and 3.2 μ s (Kojima et al. 2012; Iguchi et al. 2020).
79 In the Matched Scan (MS) mode, the Ka-band radar operates with the 1.6 μ s pulse-width,
80 making the range resolution 250 m. In the High Sensitivity (HS) mode, the Ka-band radar
81 operates with the 3.2 μ s pulse-width that makes the range resolution 500 m. The sensitivity
82 of Ka-band radar in HS mode operation is higher than that of MS mode operation because
83 the energy contained in a radar pulse becomes larger as the radar pulse-width increases.
84 Thus, the Ka-band radar in HS mode operation achieves high sensitivity at the expense of
85 range resolution.

86 There are three DPR level 2 (L2) algorithms that output physical data derived from the
87 DPR level 1 engineering data: there are two single frequency (SF) algorithms and one dual
88 frequency (DF) algorithm. Each algorithm consists of modules (Iguchi 2020; Iguchi et al.
89 2020). The DF algorithm is applicable only when the radar beam of Ku-band radar and that
90 of the Ka-band radar match. Notably, radar beam matching is essential for applying the DF
91 algorithm; if the range resolutions are different, interpolated data can be used for the DF
92 processing.

93 Until May 21, 2018 (approximately 1600 UTC), the Ka-band radar observed
94 precipitation in a narrow inner swath of about 125 km with two antenna scan modes called
95 Ka-band Matched Scan (Ka-MS) mode and Ka-band High Sensitivity (Ka-HS) mode,
96 whereas the Ku-band radar observed precipitation in a full swath of approximately 245 km.
97 The DF algorithm modules only processed the inner swath data until May 21, 2018.

98 Figure 1(a) displays the antenna scan pattern of DPR before May 21, 2018. The
99 Ku-band radar scanned the radar beam in a cross-track direction by pointing its beam in 49
100 directions. In one antenna scan, each antenna beam direction is specified by a quantity
101 called angle bin number, which takes values from 1 to 49. The full swath data consist of 49
102 angle bin data. At angle bin number 25, the antenna beam points to the nadir. In this paper,
103 the angle bin number is counted with respect to that of the Ku-band radar.

104 The Ka-band radar observed precipitation in the inner swath whose angle bin number
105 ranges from 13 to 37 where the antenna beam of Ka-band radar and that of Ku-band radar

106 were matched. However, when the Ku-band radar observed precipitation in the outer swath,
107 which can be specified by angle bin numbers 1-12 and 38-49, the Ka-band radar observed
108 precipitation in HS mode in the inner swath whose angle bin number takes a half-integer
109 ranging from 13.5 to 36.5. Therefore, the Ka-HS mode and the Ku-band antenna beams
110 were not matched.

111 On May 21, 2018, the antenna scan pattern of the Ka-band radar was changed to
112 observe precipitation in the outer swath in Ka-HS mode. Figure 1(b) shows the antenna
113 scan pattern of DPR after the Ka-band antenna scan pattern change. After May 21, 2018,
114 the Ka-band radar also observes precipitation in the full swath, with its antenna beam being
115 matched with the Ku-band beam (Iguchi 2020; Iguchi et al. 2020). Thus, at the cost of
116 abandoning the Ka-HS mode observation of precipitation in the inner swath, full swath data
117 for DF processing have been available since May 21, 2018. However, as far as the DF data
118 are concerned, the current DPR L2 algorithms version 06A (V06A) released in October
119 2018 could only process the inner swath DF data, but not the full swath DF data. Thus, the
120 current V06A algorithms continue to process data after the Ka-HS antenna scan pattern
121 was changed by assuming that Ka-HS data are missing. Conversely, full swath DF
122 processing is performed by the newly developed DPR L2 V06X experimental algorithms,
123 which were released in June 2020. Consequently, the DPR L2 V06X algorithms are only
124 applicable to data obtained after the Ka-HS antenna scan pattern was changed, but the
125 subsequent V07A algorithms planned to be released in 2021 can handle data obtained both

126 before and after the modification to the Ka-HS antenna scan pattern.

127 The DPR L2 algorithms consist of several modules (Iguchi et al. 2020), including the

128 classification (CSF) module, where precipitation is classified into three major types:

129 stratiform, convective, and other (Awaka et al. 2016). The paper's primary purpose is to

130 show how the V06X CSF module handles the full swath Ka-band data. This paper shows

131 for the first time what the full swath statistics of the Ka-band and DF precipitation type

132 counts look like.

133 The rest of this paper is arranged as follows. Section 2 describes the data structures

134 and overviews the algorithms in V06A and V06X. Next, Section 3 outlines the V06X CSF

135 modules, and Section 4 presents CSF-related V06A problems mitigated in V06X. Notably,

136 Section 5 highlight the statistical results of V06X CSF output data. Finally, Section 6

137 summarizes the conclusion and addresses future work.

138

139 **2. Data structures and overview of algorithms in V06A and V06X**

140 Figure 2 exhibits the data structures of the current V06A and new experimental V06X

141 DPR L2 algorithms. Both V06A and V06X algorithms consist of two single frequency (SF)

142 algorithms (i.e., Ku- and Ka-band algorithms) and one DF algorithm. In V06A shown in Fig.

143 2 (a), the Ku-band SF algorithm outputs Ku-band Normal Scan (Ku-NS) data, the Ka-band

144 SF algorithm outputs Ka-MS and Ka-HS data, and the DF algorithm outputs DPR-NS,

145 DPR-MS, and DPR-HS data. Only Ku-NS and DPR-NS are full swath data, while the rest

146 are inner swath data. Though DPR-NS data consist of full swath Ku-band-related data, DF
147 processed data can only be found in the inner swath portion of the DPR-NS data. The
148 current DPR L2 V06A algorithms continue to process the data obtained after the Ka-band
149 antenna scan pattern was changed on May 21, 2018, but with the Ka-HS and DPR-HS data
150 missing. In V06X, the SF and DF algorithms output full swath Ku-FS and Ka-FS as well as
151 DPR-FS data, respectively, as shown in Fig. 2 (b). The Ka-FS data are obtained in MS
152 mode in both inner and outer swaths. Therefore, “MS mode” in Fig. 2 (b) should be
153 understood as a shorthand notation for “normal sensitivity inner swath MS mode” and “HS
154 mode” for “HS outer swath MS mode.” The DPR L2 V06X algorithms are the first ones that
155 process the full swath data obtained after the Ka-HS antenna scan pattern was changed on
156 May 21, 2018. Though not used in V06X, the DPR L2 V06X algorithms prepare Ka-HS and
157 DPR-HS data structures so that the algorithms can handle the data obtained before the
158 Ka-HS antenna scan pattern was changed.

159 Figure 3 shows the data flow of the V06A (or V06X) Ku-band SF algorithm that handles
160 Ku-NS (or Ku-FS) data. The Ku-band SF algorithm consists of the preparation (PRE)
161 module, vertical profile (VER) module, CSF module, drop size distribution (DSD) module,
162 surface reference technique (SRT) module, and solver (SLV) module (Iguchi et al. 2020).
163 The PRE module provides the measured radar reflectivity factor,
164 precipitation/no-precipitation classification, and clutter mitigation (Kubota et al. 2016). The
165 VER module computes the path-integrated attenuation (PIA) due to nonprecipitation

166 particles (piaNP) and generates a radar reflectivity factor corrected for piaNP (Kubota et al.
167 2020). The CSF module classifies precipitation types and obtains BB information. This
168 study focuses on the CSF module, which is later described in detail. The SRT module
169 estimates PIA for precipitation pixels (Meneghini et al. 2015). Finally, the SLV module
170 numerically solves the radar equations and obtains DSD parameters and precipitation rates
171 at each range bin (Seto et al. 2013; Seto and Iguchi 2015; Seto et al. 2021).

172 The Ku-band SF algorithm has a loop structure, and the data go through the modules
173 within the loop twice. In other words, the data return to the start point of the loop only once.

174 The data flow of the Ka-band SF algorithm is the same as that shown in Fig. 3 except
175 for the fact that the starting point of the loop is after the PRE module in the Ka-band SF
176 algorithm. In the V06A algorithms, Ka-MS data and Ka-HS data are separately processed
177 by a data flow similar to that shown in Fig. 3. In V06X algorithms, Ka-FS data are processed
178 by a data flow similar to that shown in Fig. 3.

179 The data flow of the DF algorithm is the same as that shown in Fig. 3 but without the
180 loop structure. In the V06A CSF module, the DF processing developed based upon Le and
181 Chandrasekar (2013a, 2013b) is applied to the combination of Ka-MS and the inner swath
182 of the Ku-NS data and to the combination of Ka-HS and the corresponding interpolated Ku
183 data, respectively. In the V06X CSF module, however, updated DF processing is applied to
184 the combination of Ka-FS and the corresponding Ku-FS data. New output items related to
185 the V06X CSF module are summarized in Appendix A.

186

187 **3. Overview of the V06X CSF modules**

188 In the GPM DPR L2 V06X algorithms, there are three CSF modules: two SF CSF
189 modules (Ku-FS CSF module and Ka-FS CSF module) and one DF CSF module (DPR-FS
190 CSF module). The main purposes of the CSF modules are to detect bright band (BB) and
191 classify precipitation as three major types: stratiform, convective, and other.

192 Figure 4 shows the precipitation type decision flow in the Ku-FS CSF module, which
193 includes two main methods for precipitation type classification: the vertical profiling method
194 (V-method) and the horizontal pattern method (H-method) (Awaka et al. 2009, 2016). The
195 precipitation type decision is completed on a “pixel” basis so that a precipitation type is
196 given to each antenna beam as a whole (i.e., does not change along the antenna beam),
197 and each antenna beam is mapped to each corresponding pixel.

198 BB is detected first in the V-method because its existence is a good indicator of
199 stratiform precipitation (Battán 1973; Houze 1993). The V-method can detect BB because
200 BB can be characterized by a unique, strong peak near the freezing height in the height
201 profile of the radar reflectivity factor (Z) near the freezing height (Klaassen 1988; Fabry and
202 Zawadzki 1995). In the V-method, detection of BB is made by a peak search of Z in a BB
203 search window determined by the height of the 0°C isotherm. The 0°C height is estimated
204 in the VER module using the global analysis data (GANAL) of the Japan Meteorological
205 Agency (JMA) (Kubota et al. 2020). The BB search window is from 0°C height – 2 km to

206 0°C height + 1 km. This choice of BB search window is based on a statistical finding by the
207 Tropical Rainfall Measuring Mission (TRMM) precipitation radar that the BB peak appears
208 about 0.5 km below the 0°C height on average (Awaka et al. 2009). Rigorously speaking,
209 what is used in the detection of BB is Z-factor corrected for attenuation by nonprecipitation
210 (NP) particles, $Z_{NPcorrected}$ (Iguchi et al. 2020).

211 The V-method also examines $Z_{NPcorrected}$ along the antenna beam. The V-method
212 makes the following decision on the precipitation type of the pixel being considered. (1) If
213 BB is detected, the precipitation type is basically stratiform but is convective when
214 $Z_{NPcorrected}$ of precipitation close to the surface is exceptionally strong (i.e., when $Z_{NPcorrected} >$
215 46 dBZ). (2) If BB is not detected, then $Z_{NPcorrected}$ of precipitation echo along the antenna
216 beam is examined. If the maximum value of $Z_{NPcorrected}$ along the beam exceeds the
217 convective threshold (set to 40 dBZ), the precipitation type is convective. (3) If the
218 precipitation type is neither stratiform nor convective, the precipitation type obtained by the
219 V-method is other.

220 Table 1 summarizes the V-method and also lists the percentages of each precipitation
221 type for July 2020. The main target of the V-method is the detection of stratiform
222 precipitation that accompanies detectable BB. Another target of the V-method is the
223 detection of strong convective precipitation. But the above two targets do not cover all
224 cases. The table lists 76.9% of precipitation types as being other, which means that
225 precipitation types of a large number of precipitation pixels are left undecided. The following

226 H-method clears this indecisive situation.

227 Based on the University of Washington convective/stratiform separation method
228 (Steiner et al. 1995; Yuter and Houze 1997), the H-method examines the horizontal pattern
229 of $Z_{\max}$ (i.e., maximum value of $Z_{\text{NPcorrected}}$ along the antenna beam in the rain region), which
230 means $Z_{\max}$ is obtained from $Z_{\text{NPcorrected}}$ below the BB region when BB exists. The reason
231 why the CSF module uses $Z_{\max}$ is as follows. The University of Washington
232 convective/stratiform separation method was developed for analyzing the data obtained by
233 a ground-based radar to classify precipitation into two categories, and the method
234 examines the horizontal pattern of Z at a given height. To examine Z at a given height is
235 appropriate for ground-based radars, but it is inappropriate for the GPM DPR because it
236 observes precipitation over the ocean and land. Over the ocean, it would be easy to
237 examine Z at a given height by the DPR. However, it would become impossible for the DPR
238 to select the appropriate data height over land when it observes precipitation over very high
239 mountain regions. Nevertheless, it is requested that the DPR analyze the data over high
240 mountain regions and decide on precipitation types. In order to solve this problem, the
241 H-method in the CSF module uses $Z_{\max}$ in place of Z at a given height.

242 The main target of the H-method is the detection of the convective type. Thus, the
243 H-method starts with the detection of a convective center.

244 When either of the following conditions is satisfied, the pixel being considered is judged
245 to be a convective center.

- 246 (1) $Z_{\max}$ of the pixel exceeds the convective threshold (which is 40 dBZ in V06X); or
247 (2) $Z_{\max}$ of the pixel stands out against those in the surrounding background area.

248 In (2), $Z_{\max}$ is compared with Z_{bg} , an average value of $Z_{\max}$ in a surrounding background
249 area. If the following inequality is satisfied, then it is said that $Z_{\max}$ satisfies the stand-out
250 condition:

251

$$252 \quad Z_{\max} - Z_{bg} > a \cos\left(\frac{1}{b} \cdot \frac{\pi Z_{bg}}{2}\right), \quad (1)$$

253

254 where a and b are parameters. The analytical formula on the right side of Eq. (1), described
255 in Yuter and Houze (1997), can reasonably approximate the formula given by Steiner et al.
256 (1995). Since the right side of Eq. (1) is continuous, it is easy to use. The parameter values
257 used in the Ku-band H-method are $a = 9.0$ and $b = 43.75$. For simplicity, those values are
258 also used in the Ka-band H-method.

259 The precipitation type of the convective center is convective, and the precipitation type
260 of four pixels adjacent (not diagonally) to the convective center is also convective when the
261 adjacent pixel is a precipitation pixel. When not convective, the H-method precipitation type
262 is stratiform if $Z_{\max}$ exceeds a predetermined noise threshold. Otherwise, it is other. Thus,
263 the other type obtained by the H-method means a case where $Z_{NPcorrected}$ in the rain region
264 is noise (e.g., realized in case of clouds only). The introduction of the other category is
265 needed for the H-method because it should handle the case when there is no precipitation

266 on the surface, but there is precipitation in the upper region. The noise threshold used in
267 the Ku-FS H-method is 12.0 dBZ. For simplicity, the noise threshold of 15.0 dBZ is used in
268 the Ka-FS H-method for both inner and outer swath. However, a smaller threshold value
269 should be used in the outer swath where Ka-band radar operates in HS mode, which is an
270 issue for V06X.

271 The V-H precipitation type is obtained as follows from the V- and H-method precipitation
272 types:

273 (1) When the V-method precipitation type is stratiform, the V-H precipitation type is
274 stratiform because BB is detected by the V-method.

275 (2) When the V-method precipitation type is convective, the V-H precipitation type is
276 convective because Z is strong.

277 (3) When the V-method precipitation type is other, the H-method precipitation type is the
278 V-H precipitation type.

279 Table 2 summarizes the V-H precipitation type with percentages obtained by using the
280 July 2020 V06X data. Through process (3) above, the V-method other type that occupies
281 76.9% of precipitation pixels in the July 2020 V06X statistics (see Table 1) is broken down
282 into 64.3% stratiform, 7.3% convective, and 5.3% other. Thus, the overall percentage of the
283 V-H precipitation types are 83.9% stratiform, 10.8% convective, and 5.3% other.

284 As shown in Fig. 4, the V-H precipitation types undergo unification by consulting the
285 results of small size precipitation detection, shallow rain detection, and Heavy Ice

286 Precipitation (HIP) detection. But the V-H other type is not affected by the unification; if the
287 V-H precipitation type is other, then the unified precipitation type is other even when a small
288 size cell, shallow rain, or HIP is detected,

289 Small-sized precipitation is defined as (a) a single precipitation pixel surrounded by
290 no-precipitation pixels or (b) two adjacent precipitation pixels surrounded by
291 no-precipitation pixels. The type of small-sized precipitation could not be stratiform because
292 the smallness of the precipitation size disagrees with the wide-spreading nature of
293 stratiform precipitation. Therefore, if small-sized precipitation is detected, the unified type of
294 small-sized precipitation is convective when the V-H precipitation type is not other.
295 Small-sized precipitation was detected in 2.6% of V06X Ku-FS precipitation pixels in July
296 2020.

297 Shallow rain is defined as precipitation whose storm top height is lower than the
298 freezing level height by at least 1 km (Awaka et al. 2016; Iguchi et al. 2020). When shallow
299 rain is detected, the unified precipitation type is convective when the V-H precipitation type
300 is not other. Shallow rain was detected in 9.1% of V06X Ku-FS precipitation pixels in July
301 2020.

302 Iguchi et al. (2018) conceived the idea of HIP. Since version 05 (V05) was released in
303 May 2015, the CSF modules have been looking for HIP in the upper region of a storm
304 where the temperature is lower than -10°C . The definition of HIP is different for Ku-, Ka-,
305 and DPR-data processing, as listed in Table 3. For Ku-FS data, HIP is defined as

306 precipitation consisting of ice particles that produce a large measured Z factor (Z_m) (i.e., Z_m
307 > 35 dBZ). If HIP is detected, the unified precipitation type is essentially convective.
308 However, if the V-H precipitation type is stratiform because of BB being detected, the
309 unified precipitation type is stratiform even when HIP is detected. In this case, the upper ice
310 region is convective because of the detected HIP, but the lower rain region is stratiform
311 because of the detected BB. For the purpose of precipitation rate retrieval, the precipitation
312 type in the lower precipitation region matters; therefore, the unified precipitation type is
313 stratiform in this case. If the V-H precipitation type is other, then the unified precipitation
314 type is other even when HIP is sensed. HIP was detected in 0.5% of V06X Ku-FS
315 precipitation pixels in July 2020.

316 Houze and Brodzik (2017, private communication) noticed that the V05 Ku-band CSF
317 module incorrectly classified many stratiform pixels as convective pixels. They developed a
318 “slope” method to solve the problem. The method examines the Z profile above the 0°C
319 isotherm for convective precipitation, and if the slope resembles that in the upper part of BB,
320 the convective type is reclassified as the stratiform type. As shown in Fig. 4, the slope
321 method is implemented in the last part of the V06X Ku-FS CSF module. The slope method
322 was first introduced in the V06A Ku-NS CSF module, whose data flow is the same as
323 shown in Fig. 4.

324 The V06X Ka-FS CSF module has the same data flow as shown in Fig. 4, except
325 that there is no slope method in the Ka-band module. The reason why the V06X Ka-FS

326 CSF module does not include the slope method is because the strong rain attenuation of
327 the Ka-band makes the detection of convective type infrequent, and there is no need to
328 reclassify convective type to stratiform by the slope method. The slope method is
329 considered most necessary in the outer swath where the BB peak smears and some BB
330 peaks may be masked by smeared surface clutter. In the inner swath, strong Ka-band rain
331 attenuation and slightly lower sensitivity of the Ka-MS mode radar reduce the chances of
332 detecting convective type, so that reclassification from the convective type to stratiform by
333 the slope method is unnecessary. Notably, the slope method is introduced to solve the
334 problem of too many convective type counts in the V06A Ku-band data. This problem
335 originates from the fact that the V-method does not detect some smeared BBs. If the
336 smeared BB is not identified, then the type is not decided as stratiform, and the V-method
337 proceeds to examine $Z_{NPcorrected}$ along the entire radar beam. Furthermore, if the peak value
338 of $Z_{NPcorrected}$ exceeds the Ku-band convective threshold, then the V-method decides that
339 the type is convective though, in reality, it is stratiform because there is the smeared BB
340 that the V-method fails to detect. The slope method remedies this problem by examining
341 the slope of $Z_{NPcorrected}$ above the 0°C isotherm. In the case of Ka-band data, however, a
342 large attenuation makes the peak values of $Z_{NPcorrected}$ small. Therefore, the chances of
343 $Z_{NPcorrected}$ exceeding the convective threshold are small even when the Ka-band V-method
344 fails to detect a smeared BB. Thus, in the case of Ka-band, precipitation type for missed BB
345 would mostly be stratiform. Notably, the V06A Ka-MS data do not exhibit the “too many

convective type” problem. However, the next version of the Ka-FS CSF module includes the slope method if necessary since the Ka-FS mode is a full swath mode and has high sensitivity data in the outer swath.

The DPR-FS CSF module uses the method developed based upon Le and Chandrasekar (2013a, b) of Colorado State University (CSU). Their method is based on using the measured Dual-Frequency Ratio (DFR_m) for precipitation type classification. The definition of DFR_m is as follows:

$$\text{DFR}_m = Z_m(\text{Ku}) - Z_m(\text{Ka}), \quad (2)$$

where $Z_m(\text{Ku})$ and $Z_m(\text{Ka})$ are the measured Z (in dB) in the Ku-band and Ka-band, respectively. This paper calls Le and Chandrasekar’s method the CSU DFR_m method to differentiate it from any other method that also uses DFR_m. The CSU DFR_m method not only classifies precipitation types but also detects melting layer (ML) boundaries. The ML concept has a wider meaning than BB in a sense that BB is a subset of ML because the melting of solid particles causes BB and because ML exists in both stratiform and convective precipitations. In the case of stratiform precipitation, ML can be identified with BB.

Figure 5 shows an example of the DFR_m height profile that shows a clear “bump” near the 0°C isotherm. The figure shows key points B and C for the CSU DFR_m method. At point B, DFR_m takes a local maximum value, and at point C, DFR_m takes a local minimum value.

The CSU DFR_m method is applied to the precipitation pixel where both Ku-band and

366 Ka-band precipitation echoes exist. When these DF precipitation echo data exist, then the
 367 CSU DFRm method examines precipitation echo data in a possible ML region near the 0°C
 368 isotherm. Here, the possible ML region means the height region between 0°C height - 2 km
 369 and 0°C height + 1 km, where 0°C height is the estimated height obtained by using the
 370 GANAL data. If there is not enough precipitation echo data in the possible ML region, then
 371 the CSU DFRm method skips the processing. If not skipped, then the CSU DFRm method
 372 looks for the points B and C, defined in Fig. 5, of the DFRm “bump” in the possible ML
 373 region. It is requested that the following condition is satisfied:

374

$$375 \quad \text{diffDFRm} = \text{DFRm}(\text{max}) - \text{DFRm}(\text{min}) \geq \text{THdiff}, \quad (3)$$

376

377 where DFRm(max) is the DFRm value at point B, DFRm(min) is located at point C, and
 378 THdiff is a threshold. In V06X, THdiff = 2.0. If points B and C are determined, which satisfy
 379 the above Eq. (3), then the following quantities (i.e., V_1 and V_2) are calculated. The
 380 definition of V_1 is

381

$$382 \quad V_1 = \frac{\text{DFRmLIN}(\text{max}) - \text{DFRmLIN}(\text{min})}{\text{DFRmLIN}(\text{max}) + \text{DFRmLIN}(\text{min})}, \quad (4)$$

383

384 where DFRmLIN(max) is the linear value of DFRm at point B, and DFRmLIN(min) is the
 385 linear value of DFRm at point C. By Eq. (4), the difference DFRm(max)-DFRm(min) is

386 mapped to V_1 because V_1 is uniquely determined by $\text{DFRmLIN}(\text{max})/\text{DFRmLIN}(\text{min})$, and
387 this mapping is one-to-one. In Eq. (4), the linear value of DFRm is used so that V_1 is
388 guaranteed only to take on a value between zero and one.

389 The definition of V_2 is

390

$$391 \quad V_2 = |\text{mean slope of DFRm in rain region}|, \quad (5)$$

392

393 where DFRm in the rain region corresponds to DFRm below point C (see Fig. 5), and the
394 slope is measured with respect to height in km. If V_2 is smaller than 0.5 dB/km, then the
395 DFRm processing is skipped. Otherwise, the following V_3 is calculated.

396

$$397 \quad V_3 = \frac{V_1}{V_2}. \quad (6)$$

398

399 The CSU DFRm method determines precipitation type by the following rule:

$$400 \quad \text{If } V_3 < C_1, \text{ then the precipitation type is convective,} \quad (7a)$$

$$401 \quad \text{If } V_3 > C_2, \text{ then the precipitation type is stratiform,} \quad (7b)$$

$$402 \quad \text{If } C_2 \geq V_3 \geq C_1, \text{ then the precipitation type is transition.} \quad (7c)$$

403 In the above, C_1 and C_2 are empirical parameters and take the following values:

$$404 \quad C_1 = 0.18 \text{ and } C_2 = 0.20 \text{ in the inner swath,} \quad (8a)$$

$$405 \quad C_1 = 0.19 \text{ and } C_2 = 0.22 \text{ in the outer swath.} \quad (8b)$$

406

407 After the precipitation type decision, the CSU DFRm method performs ML detection.
408 First, the CSU DFRm method examines the DFRm profile exhibiting the “bump” that
409 satisfies Eq. (3). In this examination, if a point where the absolute value of the DFRm slope
410 becomes largest is found in the possible ML region then the point is judged as the ML top,
411 and point C is regarded as the ML bottom.

412 As shown in Fig. 6, as the CSU DFRm method alone could not handle all precipitation
413 cases, the V06X DPR-FS CSF module also uses the Ku-FS results (or Ka-FS results when
414 Ku-FS results are not available) for determining unified precipitation types. The CSU DFRm
415 method classifies precipitation into three types: stratiform, convective, and transition. If the
416 CSU DFRm precipitation type is transition, the Ku-FS CSF decision is used for the unified
417 precipitation types. The precipitation types by the CSU DFRm method are 7.6% stratiform,
418 2.6% convective, and 0.6% transition in the July 2020 V06X statistics.

419 As shown in Fig. 4, the Ku-FS CSF module performs additional decisions on
420 small-sized precipitation, shallow rain, and HIP. In the V06X DPR-FS CSF module,
421 small-sized precipitation and shallow rain decisions are copied from the Ku-FS CSF module
422 but not from the Ka-FS CSF module because a large Ka-band rain attenuation and a lower
423 sensitivity of Ka-band data, particularly in the inner swath, cause unreliable Ka-FS results
424 on small-sized precipitation and shallow rain. On the other hand, however, the V06X
425 DPR-FS CSF module adds a DFRm decision to HIP (see Table 3). The HIP decision is

426 made at a later part of the flow, as shown in Fig. 6. Furthermore, a winter convection
427 detection that examines DFRm at and around the storm top follows after the HIP decision
428 and examines whether HIP exists nearby (see Iguchi et al. 2020 for details). The V06X
429 DPR-FS CSF module uses the HIP information and winter convection detection results to
430 produce the final outcome of unified precipitation types. Incidentally, the addition of the
431 DFRm decision to HIP is also made in V06A.

432 The right hand side of Fig. 6 indicates that precipitation type is other if the condition
433 “precipitation at Ku but no precipitation at Ka” is not satisfied, which is a bug. If this
434 condition is not satisfied, Ka-band single frequency precipitation type should be used
435 instead of other. The effect of this bug is apparent as shown later in Fig. 11. The bug is fixed
436 in V07A.

437

438 **4. CSF-related V06A problems mitigated in V06X**

439 There are two significant CSF-related problems in the standard V06A products: one
440 concerns the slope method and the other concerns the detection of a clutter-free bottom in
441 the PRE module that affects BB detection and is thus CSF-related. The V06X algorithms
442 solve both problems.

443 *4.1 Improvement of the slope method*

444 The slope method examines the Ku-band Z profile of convective precipitation. When
445 the absolute value of the slope of $Z_{NPcorrected}$ relative to height is very large above the 0°C

446 isotherm, the convective type is reclassified as the stratiform type. The slope method is
447 implemented in the V06A (and V06X) Ku-band CSF module.

448 Immediately after the release of V06A data, the near-surface precipitation rate (P_{NS}) of
449 the reclassified stratiform type was found to sometimes become very high because the
450 V06A slope method only examines the height region above the 0°C isotherm. However, it is
451 difficult to imagine that stratiform precipitation accompanies a very high precipitation rate
452 near the surface. Therefore, to solve this problem, a limit was set on the slope method's
453 input so that the technique could be applied to convective precipitation whose P_{NS} is
454 smaller than a threshold, which is 20 mm/h in V06X (Awaka and Brodzik 2019). The idea
455 behind this is as follows: if convective precipitation having a smaller P_{NS} were reclassified
456 as stratiform, the P_{NS} of the reclassified stratiform precipitation would also be small.

457 Figure 7 displays the P_{NS} of the reclassified stratiform precipitation in the form of a
458 histogram. The figure is based on July 2020 data. Figure 7 (a) shows the histogram of P_{NS}
459 obtained by the V06A slope method and clearly shows that the reclassified stratiform
460 precipitation produces appreciable numbers of large P_{NS} (> 50 mm/h). Figure 7 (b) shows
461 the corresponding histogram obtained by the improved V06X slope method. In Fig. 7 (b),
462 the large P_{NS} (> 50 mm/h) disappears. Therefore, it can be concluded that the improved
463 V06X slope method works well. However, though the threshold of 20 mm/h is introduced
464 into the V06X slope method, Fig. 7 (b) shows that the P_{NS} of the reclassified stratiform
465 precipitation still exceeds the threshold in a small number of cases. The following explains

466 this behavior.

467 As shown in Fig.3, since the CSF module is placed in an earlier part of the flow in the
468 loop, the CSF module can use P_{NS} obtained by the SLV module in the 1st loop (P_{NS} (1st
469 loop)) but not that obtained in the 2nd loop (P_{NS} (2nd loop)). Users can use P_{NS} (2nd loop)
470 but not P_{NS} (1st loop) because the latter is an internal quantity. The P_{NS} quantity in Fig. 7 is
471 P_{NS} (2nd loop). Furthermore, the non-uniform beam filling (NUBF) effect (Seto et al. 2021)
472 is included in the SLV module in the 2nd loop but not in the 1st loop. Consequently, P_{NS}
473 (2nd loop) can generally become greater than P_{NS} (1st loop). In the V06X slope method, a
474 limit is imposed on P_{NS} (1st loop) because the method could not access P_{NS} (2nd loop).
475 Therefore, in Fig. 7 (b), P_{NS} (2nd loop) may sometimes exceed the limit imposed on P_{NS} (1st
476 loop).

477 *4.2 Improvement in the decision on a clutter-free bottom*

478 Due to a bug in the Ku-band V06A PRE module, a few cases occur where a BB peak is
479 misjudged as the upper part of surface echo. When this happens, a clutter-free bottom is
480 falsely set at an altitude higher than the BB peak height, which eliminates the opportunity to
481 observe BB and rain below BB. This problem has thus far been found in the following two
482 cases: (a) high BB case and (b) low BB case.

483 (a) High BB case

484 The problem mentioned above can be found in the V06A data over mountainous areas
485 where the surface echo takes a complicated and broadened shape. Figure 8 shows

486 examples where the profile of Ku-band Z_m is plotted for a few angle bins. Figure 8 (a) shows
487 some V06A Z_m profiles where each BB at angle bin numbers 31-34 is regarded as a part of
488 surface echo. Figure 8 (b) shows the bug-fixed V06X results that clearly distinguish BB
489 from the surface.

490 (b) Low BB case

491 The problem mentioned above could occur near nadir in winter when BBs appear very
492 close to the surface. Notably, Watters et al. (2018) reported this problem. Figure 9 shows
493 Ku-band Z_m profiles for low BB, where Figure 9 (a) shows the Z_m profiles before the bug fix
494 (V06A), and Fig. 9 (b) shows those after the bug fix (V06X).

495

496 5. Statistical results

497 Figure 10 shows one-month (July 2020) statistics on precipitation type counts obtained
498 by the V06X single frequency modules: Ku-FS and Ka-FS results are shown by thin and
499 thick lines, respectively. The abscissa shows the angle bin number, which indicates the
500 antenna beam direction within one antenna scanning plane that is perpendicular to the
501 direction of satellite movement; the angle bin number 25 corresponds to the nadir direction.
502 The figure shows that among the counts of three major precipitation types for both Ku-FS
503 and Ka-FS, the stratiform count is the largest, followed by the convective count and then
504 the other count. Notably, each type count of Ka-FS exhibits a stepwise change at both
505 edges of the inner swath because the Ka-band radar operates in low-sensitivity Ka-MS

506 mode in the inner swath, but the radar operates in high sensitivity Ka-HS mode in the outer
507 swath (Masaki et al. 2020).

508 Though unclear in the figure, the other type count of Ka-MS is not zero. The other count
509 of Ka-MS in the figure is approximately 1000 for each angle bin in the inner swath. We
510 simply interpret that this occurs because the low sensitivity of Ka-MS makes the detection
511 of weak precipitation very difficult. Surprisingly, the other type count of Ka-HS is larger than
512 that of Ku-FS in the outer swath. We think this occurs because the noise threshold for the
513 Ka-HS is 15.0 dBZ, which is the value used for Ka-MS. Since the Ka-HS data is obtained by
514 HS mode operation, the noise threshold for the Ka-HS should be smaller than 15.0 dBZ.
515 This is a parameter tuning issue, and V07A data is processed using appropriate
516 parameters.

517 Figure 10 also indicates the following very interesting fact. If we add up all three type
518 counts at each angle bin, we obtain the precipitation count at each angle bin because
519 precipitation consists of three types of precipitation. Then we can conclude that the
520 precipitation counts of Ku-FS data are higher than those of Ka-HS data. However, it is
521 reported that the sensitivity of HS mode Ka-band radar is higher than that of Ku-band radar
522 (Masaki et al. 2020). Though HS mode Ka-band radar has higher sensitivity, its
523 precipitation counts are lower than Ku-band radar. The main reason for this would be that
524 the radars observe not only rain but also ice and snow. If the radars observe only rain, the
525 HS mode Ka-band radar would observe weaker rain that the Ku-band radar cannot detect.

526 However, the situation is different for the observation of ice and snow. Liao and Meneghini
527 (2011) showed that the reflectivity of solid particles at Ka-band could be smaller than that at
528 Ku-band by more than a few dB. There may be other reasons, but Liao and Meneghini's
529 findings may be the main reason that the Ku-band radar can detect precipitation more than
530 the higher sensitivity Ka-band radar. The strong attenuation at the Ka-band would not be
531 the reason for the higher precipitation count of Ku-FS radar because strong attenuation is
532 caused by moderate or intense rain, then the upper part of such precipitation should be
533 observed by both Ka- and Ku-band radars.

534 The angle bin dependence of each unified precipitation type count obtained by the
535 V06X DPR-FS CSF module (thick lines) is shown in Figure 11. The thin lines plot the
536 corresponding Ku-FS results for comparison. Compared to the Ku-FS results, the DPR-FS
537 stratiform count is slightly lower (almost parallel-shifted downward), whereas the DPR-FS
538 convective count is slightly higher (almost parallel-shifted upward). The almost parallel-shift
539 behavior observed above in stratiform curves and convective curves indicate that the CSU
540 DFRm method works well in the outer swath. This finding is important because the CSU
541 DFRm method is applied to the outer swath data for the first time in V06X.

542 Figure 11 shows that the DPR-FS other type count is much greater than the
543 corresponding Ku-FS count in the outer swath because of the V06X bug described at the
544 end of Section 3. When the bug is fixed, the bump of the other count by DPR-FS
545 disappears, and stratiform and convective counts by DPR-FS slightly increase in the outer

546 swath. The bug fix is made in V07A.

547 Figure 12 is essentially the same as Fig. 11 but shows the statistics separately over
548 the ocean and land. The general trend of the curves in Fig. 12 (a) is almost the same as
549 that in Fig. 12 (b), although the statistics shown in Fig. 12 (a) have larger counts than those
550 in Fig. 12 (b); nothing strange seems to occur over the ocean or land. This fact implies that
551 the CSF module V06X works well over ocean and over land.

552 Incidentally, Fig. 12 shows that the difference of each type count between Ku-FS and
553 DPR-FS over land is smaller than that over the ocean. However, care should be taken that
554 precipitation statistics over land are susceptible to sampling errors and seasonal biases.

555 Figure 13 depicts the angle bin dependence of the BB counts obtained by the V06X
556 Ku-FS CSF module (thin line) and the V06X DPR-FS CSF module (thick line). The
557 advantage of DF processing is evident, particularly in the outer swath, as shown by the
558 thick line.

559 Table 4 summarizes the improvement of BB detection because of the introduction of
560 DF processing. The following quantity assesses the enhancement:

561
$$(B - A) / A, \quad (9)$$

562 where A is the BB count obtained by the V06X Ku-FS CSF module, and B is the BB count
563 obtained by the V06X DPR-FS module. The table shows the 22.1, 12.0, and 68.9%
564 improvement in the full, inner, and outer swaths, respectively, confirming the advancement
565 of BB detection in the outer swath using DF processing in the outer swath.

566 In the V06X DPR-FS CSF module, the CSU DFRm method makes an “extension” to
567 ML detection. The detection of ML can be made by THdiff, whose value is different from the
568 value used to determine precipitation type. If ML is not detected using THdiff = 2.0, which is
569 used to find the precipitation type, the ML detection is attempted using THdiff = 0.5. The
570 “extension” means that the detection of ML is made using THdiff = 0.5. In V06X, the
571 information about whether ML is detected by the “extension” or not is given to a quality flag.
572 From Eq. (3), it is understood that the use of a smaller value of THdiff means the detection
573 of ML is made for the data showing less clear DFRm “bump,” signifying that the reliability of
574 ML detected by the “extension” could be low. Consequently, a trial to identify ML as BB is
575 not performed for the ML detected by the “extension” in V06X. Introducing a BB
576 identification process for ML detected by the “extension” would increase the number of
577 detected BBs, but this is a matter for V07A.

578

579 **6. Conclusions**

580 This paper described the CSF modules in GPM DPR L2 V06X that were released in
581 June 2020. The V06X algorithms were developed to process full swath Ka-band data that
582 have been obtained since May 18, 2018, when the antenna scan pattern of the Ka-band
583 radar was changed.

584 The following problems related to the CSF module are solved in the V06X Ku-band
585 algorithm: (a) appearance of a very large near-surface precipitation rate (P_{NS}) of stratiform

586 precipitation reclassified by the slope method and (b) a rare case of misjudging BB peak as
587 an upper part of surface echo.

588 One-month statistics show that a significant jump occurs in the Ka-band precipitation type
589 counts at the edges of the inner swath because the sensitivity of Ka-band radar in Ka-MS
590 mode differs from that in Ka-HS mode. In the V06X DPR-FS CSF module, the CSU DFRm
591 method is applied to DF data in the outer swath for the first time. The statistics show that
592 the CSU DFRm method works well not only in the inner swath but also in the outer swath.
593 The statistics also show a considerable improvement in BB detection in the outer swath
594 when using DF data.

595 The following two tasks are also undertaken as part of algorithm development for V07A
596 to be released in 2021.

597 (1) Improvement of BB detection in both SF and DF modules

598 This is a long-standing issue. An interesting possibility of improving BB detection in the DF
599 CSF module is related to “*MixedPhaseTop*” in Appendix A.

600 (2) Re-examination of weak stratiform precipitation not accompanying BB

601 This is also a long-standing issue. If BB is not detected, some stratiform precipitation
602 determined by the current CSF module may be convective, which can occur in winter data,
603 for example. Studies on this issue should be continued.

604

605

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611

612 **Appendix A. New output items related to the CSF module in DPR L2 V06X**

613 This appendix briefly describes the new output items of the V06X CSF modules. Details
614 can be found in Iguchi et al. (2020).

615 *A.1 Additional information about Heavy Ice Precipitation (HIP)*

616 In V06X, the following new items relating to HIP were introduced to present information
617 about the ranges where HIP is detected.

618 a) binHeavyIcePrecipTop

619 b) binHeavyIcePrecipBottom

620 c) nHeavyIcePrecip

621 Notably, a) shows the range bin corresponding to the top height where HIP is detected,
622 b) shows the range bin corresponding to the bottom height where HIP is detected, and c)
623 shows the number of HIP events detected in the range between binHeavyIcePrecipTop and
624 binHeavyIcePrecipBottom. These items were added to Ku-FS, Ka-FS, and DPR-FS
625 outputs.

626 *A.2 flagGraupelHail (Experimental)*

627 This flag shows the existence of graupel and hail detected by the method developed by Le
628 and Chandrasekar (2019, 2021). Since the method uses DFRm information, this flag is only
629 available in DPR-FS output.

630 *A.3 MixedPhaseTop (Experimental)*

631 This flag shows the location where the phase of precipitation particles turns from solid
632 (ice) to liquid (water). Details are described in Iguchi et al. (2020). As DFRm information is
633 needed for determining the location above, this flag is only available in DPR-FS output.

634 The method for detecting MixedPhaseTop is apparently applicable to BB detection once
635 certain modifications are made to the method. Then there arises a very interesting
636 possibility that BB and melting layer (ML) detections could be separated in a future DPR-FS
637 CSF module. BB detection would then become straightforward, whereas BB detection
638 using dual-frequency data is currently made indirectly using information about ML.

639

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727 the Pacific warm pool and implications for Z–R relations. *J. Appl. Meteor.*, **36**, 847–867.

728 **List of Figures**

729 Fig. 1 Antenna scan pattern of DPR (a) before May 21, 2018, and (b) after May 21, 2018.
730 The Ku-band radar points its beam in 49 directions. Each antenna beam direction is
731 specified by a quantity called angle bin number, which takes values from 1 to 49. At angle
732 bin number 25, the antenna beam points to the nadir. The Ka-band radar scans region
733 marked by hatched lines.

734

735 Fig. 2 GPM DPR L2 (a) V06A and (b) V06X data structures. In V06X, full swath
736 dual-frequency processing becomes possible for the first time. In the figure, NS, MS, HS,
737 and FS denote Normal Scan, Matched Scan, High Sensitivity, and Full Scan, respectively.

738

739 Fig. 3 Data flow of the GPM DPR L2 Ku-band single frequency algorithm.

740

741 Fig. 4 Data flow of the V06X single frequency Ku-FS CSF module. The other type in the
742 output of unification and V-H precipitation type (V-H precip. type) units is the same because
743 the unification unit does not alter the other type. The data flow of the Ka-FS CSF module is
744 identical to that shown in the figure except for the slope method. The slope method is only
745 installed in the Ku-FS CSF module. HIP in the figure means Heavy Ice Precipitation. In this

746 figure and later figures, stratiform and convective are abbreviated as Stra. and Conv.,
747 respectively.

748

749 Fig. 5 An example of the DFRm height profile. The figure shows key points B and C for the
750 DFRm data processing. At point B, DFRm takes a local maximum value; at point C, DFRm
751 takes a local minimum value.

752

753 Fig. 6 Data flow of the V06X dual-frequency DPR-FS CSF module.

754 (*) Other in the right hand side of the figure is a V06X bug.

755

756 Fig. 7 Histogram of near-surface precipitation rate (P_{NS}) of reclassified stratiform
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775 and Ka-FS data (thick green lines). The Ka-band radar operates in HS mode in the outer
776 swath (angle bin numbers 1 to 12 and 38 to 49), whereas it operates in MS mode in the
777 inner swath (angle bin numbers 13 to 37). Given the higher sensitivity of HS mode, each
778 thick curve shows jumps at the boundaries between the inner swath and outer swath. At
779 angle bin number 25, the radar beam points toward the nadir.

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783 between Ku-FS and DPR-FS is small, and each type count displays almost parallel-shift
784 shapes. Consequently, the CSU DFRm method works well in the inner swath (which is
785 known in V06A and prior) and also in the outer swath. At angle bin 25, the radar beam
786 points toward the nadir. See the text for bumps of the DPR-FS other type counts in the

787 outer swath.

788

789 Fig. 12 Identical to Figure 10 except (a) the angle bin dependence of type counts is
790 presented over the ocean and (b) land.

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792 Fig. 13 Angle bin dependence of BB counts obtained by the Ku-FS CSF module (thin black
793 line) and DPR-FS CSF module (thick purple line).

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798 Fig. 1 Antenna scan pattern of DPR (a) before May 21, 2018, and (b) after May 21, 2018.

799 The Ku-band radar points its beam in 49 directions. Each antenna beam direction is
800 specified by a quantity called angle bin number, which takes values from 1 to 49. At angle
801 bin number 25, the antenna beam points to the nadir. The Ka-band radar scans region
802 marked by hatched lines.

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807 Fig. 2 GPM DPR L2 (a) V06A and (b) V06X data structures. In V06X, full swath
808 dual-frequency processing becomes possible for the first time. In the figure, NS, MS, HS,
809 and FS denote Normal Scan, Matched Scan, High Sensitivity, and Full Scan, respectively.

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814 Fig. 3 Data flow of the GPM DPR L2 Ku-band single frequency algorithm.

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818 Fig. 4 Data flow of the V06X single frequency Ku-FS CSF module. The other type in the
 819 output of unification and V-H precipitation type (V-H precip. type) units is the same because
 820 the unification unit does not alter the other type. The data flow of the Ka-FS CSF module is
 821 identical to that shown in the figure except for the slope method. The slope method is only
 822 installed in the Ku-FS CSF module. HIP in the figure means Heavy Ice Precipitation. In this
 823 figure and later figures, stratiform and convective are abbreviated as Stra. and Conv.,
 824 respectively.

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829 Fig. 5 An example of the DFRm height profile. The figure shows key points B and C for the
830 DFRm data processing. At point B, DFRm takes a local maximum value; at point C, DFRm
831 takes a local minimum value.

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837 Fig. 6 Data flow of the V06X dual-frequency DPR-FS CSF module.

838 (*) Other in the right hand side of the figure is a V06X bug.

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902 Table 3 HIP conditions. $Z_m(\text{Ku})$, $Z_m(\text{Ka})$, and DFR_m are understood as those in the upper
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912

V-method type (Percentage)	Description
Stratiform (19.7%)	BB is detected (and Z near surface is not very strong).
Convective (3.4% with (1): 0.01% (2): 3.4%)	(1) BB is detected but Z near surface is very strong or (2) Z along the beam exceeds convective threshold.
Other (76.9%)	Neither stratiform nor convective

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917 Table 2 A summary of the V-H precipitation type in the V06X Ku-FS module.

918 Numbers in the table are based on July 2020 V06X data.

919

920

	H-stra.	H-conv.	H-other
V-stra.	Stra. 17.5%	Stra. 2.1%	Stra. 0.04%
V-conv.	Conv. 0.04%	Conv. 3.4%	Conv. 0.0%
V-other	Stra. 64.3%	Conv. 7.3%	Other 5.3%

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924 Table 3 HIP conditions. $Z_m(Ku)$, $Z_m(Ka)$, and DFR_m are understood as those in the upper
925 ice region where the temperature is below -10°C .

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Ku-FS	$Z_m(Ku) > 35 \text{ dBZ}$
Ka-FS	$Z_m(Ka) > 30 \text{ dBZ}$
DPR-FS	$Z_m(Ku) > 35 \text{ dBZ}$ or $Z_m(Ka) > 30 \text{ dBZ}$ or ($Z_m(Ku) > 27 \text{ dBZ}$ and $\text{DFR}_m > 7 \text{ dB}$)

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930

931 Table 4 BB counts.

932 Numbers in the table are based on July 2020 V06X data.

933

		full swath	inner swath	outer swath
Ku-FS	A	2,184,558	1,798,618	385,940
DPR-FS	B	2,666,539	2,014,531	652,008
Improvement	(B-A)/A	22.1%	12.0%	68.9%

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