A Statistical Method for Reducing Sidelobe Clutter for the Ku-Band Precipitation Radar on board the GPM Core Observatory

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ABSTRACT

A statistical method to reduce the sidelobe clutter of the Ku-band precipitation radar (KuPR) of the Dual-Frequency Precipitation Radar (DPR) on board the Global Precipitation Measurement (GPM) Core Observatory is described and evaluated using DPR observations. The KuPR sidelobe clutter was much more severe than that of the Precipitation Radar on board the Tropical Rainfall Measuring Mission (TRMM), and it has caused the misidentification of precipitation. The statistical method to reduce sidelobe clutter was constructed by subtracting the estimated sidelobe power, based upon a multiple regression model with explanatory variables of the normalized radar cross section (NRCS) of surface, from the received power of the echo. The saturation of the NRCS at near-nadir angles, resulting from strong surface scattering, was considered in the calculation of the regression coefficients.

The method was implemented in the KuPR algorithm and applied to KuPR-observed data. It was found that the received power from sidelobe clutter over the ocean was largely reduced by using the developed method, although some of the received power from the sidelobe clutter still remained. From the statistical results of the evaluations, it was shown that the number of KuPR precipitation events in the clutter region, after the method was applied, was comparable to that in the clutter-free region. This confirms the reasonable performance of the method in removing sidelobe clutter. For further improving the effectiveness of the method, it is necessary to improve the consideration of the NRCS saturation, which will be explored in future work.

1. Introduction

The Global Precipitation Measurement (GPM) mission is an international cooperative project to achieve highly accurate and very frequent global precipitation observations by satellite (Hou et al. 2014). The GPM mission consists of the GPM Core Observatory, which was jointly developed by the United States and Japan, and consists of constellation satellites that carry microwave radiometers provided by the GPM partner agencies. The GPM Core Observatory was successfully launched at 1837 UTC 28 February 2014. The Dual-Frequency Precipitation Radar (DPR) was developed by the Japan Aerospace Exploration Agency (JAXA) and the National Institute of Information and Communications Technology (NICT), and was installed on the GPM Core Observatory (Kojima et al. 2012). The DPR consists of Ku-band precipitation radar (KuPR) and Ka-band precipitation radar (KaPR). The level 2 (L2) product of the DPR, which was developed by the NASA–JAXA Joint Algorithm Team, provides the estimates of precipitation rates, radar reflectivity factors, and precipitation characteristics, such as the drop size distribution and precipitation type (Iguchi et al. 2010, 2012).

Precipitation rates are estimated through the radar backscattered power from hydrometeors within the antenna main lobe. Earth’s surface, however, is a strong source of backscattered power that can contribute to the

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received signal along the antenna sidelobe (Manabe and Ihara 1988; Hanado and Ihara 1992; Durden et al. 2001; Kozu et al. 2001; Tagawa et al. 2007). This surface clutter interferes with the radar return from hydrometeors and results in a degraded radar measurement that can severely affect retrieval accuracy. Although technology has made great strides in advancing antenna systems to suppress sidelobe effects, it is still difficult to entirely remove the surface sidelobe power via antenna design alone. The problem has become more pronounced as the desire for increased radar sensitivity has grown. As such, corrections to the surface clutter caused by antenna sidelobes are imperative in order to achieve the sensitivity and accuracy required for estimating the microphysical properties of rain and snow from space.

Figure 1 shows classification of surface clutter interference, when satellite altitude is 407 km: (a) clutter-free region, (b) main lobe clutter region, and (c) sidelobe clutter region.

2. Data and formulation

a. GPM/DPR instrument

The DPR, which consists of the KuPR and KaPR, is the first spaceborne dual-frequency precipitation radar on board the GPM Core Observatory (Kojima et al. 2012; Hou et al. 2014). Both the KuPR and KaPR are active-phased array radars, and they adopt a system design similar to that of the precipitation radar (PR) on board the Tropical Rainfall Measuring Mission (TRMM) (Kozu et al. 2001). The range resolution is 250 m, and the minimum detectable rain rate is 0.5 mm h$^{-1}$, for both the KuPR and KaPR in the matched beam scan area. Here, the pixels of the KaPR in the matched beam area are referred to as “KaMS,” where “MS” denotes the matched portion of the swath. When the KuPR scans the outer swath area, the KaPR scans the interlacing scan area with a range resolution of 500 m. The KaPR minimum detectable rainfall rate is 0.2 mm h$^{-1}$ in the interlacing scan area. These high-sensitivity pixels of the KaPR are referred to as “KaHS” in this paper. The beamwidth is about 0.71$^\circ$, and the horizontal resolution on the ground is 5.2 km for both KuPR and KaPR, when the orbit altitude is 407 km. The KaPR swath width is about 245 km, which corresponds to the 49 electrical beam scanning. The sampling interval of the KuPR for the range direction is 125 m from the surface up to the height of 14 km, and 250 m from heights of 14–19 km. In the L2 product, there are 176 range bins, corresponding to the 125-m sampling from the ground to 22-km altitude for both KuPR and KaMS. The sampling interval of the KaHS, however, is 250 m for all measurement ranges.
b. Analyzed data and period

A phase code in the phase shifters controls the antenna pattern of the KuPR. While the JAXA DPR project team tested 39 phase codes to examine the effect of the sidelobe clutter interference of KuPR, the operation of the phase code can be classified into three main types: 1) a phase code for 18 March–8 April 2014, 2) a phase code for 8 April–25 July 2014, and 3) a phase code for after 25 July 2014.

Phase code 3 was the final one and has been applied to all observations since 25 July 2014. In addition, the adjustment of the receiver attenuator was executed twice, that is, 6 dB on 28 April 2014 and 9 dB on 12 May 2014. These changes were related to a saturation issue of the normalized radar cross section (NRCS), which will be discussed in section 4.

To demonstrate the features of the sidelobe clutter, two periods corresponding to the above-mentioned operations, 26–31 March 2014 and 2–7 August 2014, are analyzed in sections 3 and 4. The period of 26–31 March 2014 corresponds to phase code 1 and the attenuator setting of 6 dB, which receives the most frequent sidelobe clutter and has the most frequent saturation issue. The period of 2–7 August 2014 corresponds to the final phase code and the final setting of the receiver attenuator. Version 03B of the DPR L1 and L2 product was used in this study.

c. Formulation of sidelobe clutter interference

In this subsection, the formulation of sidelobe clutter interference is summarized. Figure 2 shows the geometry for calculating the effects of sidelobe clutter interference through antenna sidelobe. The received power of sidelobe clutter $P_s$ can be calculated by integrating the following radar equation over the surface area $S$ at the same range gate (Hanado and Ihara 1992):

$$P_s = \frac{P^2}{4\pi} \int \frac{G^2(\theta, \phi)d\theta d\phi}{r^2} dS,$$

(1)

where $dS = r^2 \tan \theta d\theta d\phi$, $r = h_S/\cos \theta$, $G^2(\theta, \phi)$ is the antenna pattern, $h_S$ is the satellite altitude, $\sigma_m^0 = \sigma^0 A_S$ is the apparent NRCS of the surface, $\sigma^0$ is the rain-free NRCS of the surface, and $A_S$ is rain attenuation.

The azimuthal angle dependence of the antenna pattern is usually ignored, so the radar equation of (1) can be simplified and rewritten in terms of an integral over $\theta$ with a $\phi$-integrated squared antenna pattern:

$$P_s = \frac{P^2}{4\pi} \frac{1}{2h_S^2} \int_{\theta_S}^{\theta_F} F(\theta)\sigma_m^0(\theta) \sin 2\theta d\theta,$$

(2)

where

$$F(\theta) = \int_{-\pi}^{\pi} G^2(\theta, \phi) d\phi.$$

(3)

Figure 3 shows a geometric relationship of a spherical Earth approximation between satellite, radar scattering volume, Earth surface, and $\theta_S$. The law of cosines for the triangle ABC, the following equation is obtained:
where $R$ is Earth’s radius.

Thus, $\theta_5$ is a function of $r$ and $h_s$. The range $r$ depends on the angle bin numbers (which correspond to beam scan angles), range bin numbers (which correspond to altitudes), and satellite altitude. The DPR employs the variable pulse repetition frequency (VPRF) technique (Kobayashi and Iguchi 2003), and the distance from the satellite to a center of the first range bin varies with satellite altitude. Figure 4 shows $r$ and $\theta_5$ values with references to beam scan angles and altitudes when the satellite altitude is about 407 km. Note that the sidelobe power contributed from the near-nadir angle ($\theta_5 < 3^\circ$) is in the region adjacent to the clutter-free region, as shown in Fig. 1. As shown in the next section, the sidelobe clutter of the KuPR was frequently found in the region adjacent to the clutter-free region. This sidelobe clutter (referred to as “U shaped” type) is connected to the NRCS at nadir angles, from Fig. 4b. On the other hand, the other type (such as “radially spread” type, shown later) is connected to the NRCS at off-nadir angles. Thus, the quantity $\theta_5$ is useful for the determination of the relationship between the NRCS of the surface and the sidelobe clutter.

3. Features of sidelobe clutter in the KuPR

In this section, features of the sidelobe clutter in the KuPR are described using the KuPR observations. Figure 5 shows vertical cross sections of averaged received power of the KuPR over the ocean from 26–28 March 2014 (Fig. 5a) and 2–4 Aug 2014 (Fig. 5b) when precipitation is not present. For a comparison purpose, the results of the TRMM PR from 26 to 28 March 2014 are shown in Fig. 6. The measurement data with “no precipitation” for the KuPR and TRMM PR are determined based on the DPR/KaHS precipitation/no-precipitation classification result and the PR 2A25 product (Iguchi et al. 2000, 2009), respectively. In the
DPR scanning geometry described in section 2a, there are no KaHS data in the outer swath of the KuPR, and the edge information of the KaHS is used to cover the outer swath of the KuPR for the determination of no-precipitation cases. The intensities of the sidelobe clutter in the KuPR are 5–10 dB higher than the noise level (about $-112$ dBm) as shown in Fig. 5, while those in the TRMM PR are at most 1 dB higher than the noise level (about $-111.8$ dBm) as depicted in Fig. 6. These results reveal that the KuPR sidelobe clutter is much more severe than that of the TRMM PR. Both the U-shaped and radially spread sidelobe clutter of the KuPR are clearly shown in Fig. 5a. A sidelobe clutter level is directly related to $F(u)$ shown in (3). The term $F(u)$ was calculated from the antenna pattern measurement data derived from the ground test, and the sidelobe level of the TRMM PR antenna was lower than that of KuPR (K. Furukawa, JAXA GPM/DPR project team, 2015, personal communication). The basic radar system design is the same between the TRMM PR and the KuPR. However, the quality of the radar was uneven due to the actual hardware manufacturing result. This is the reason why the sidelobe clutter of the TRMM PR is weaker than that of the KuPR. Moreover, the transmitter power of the KuPR is higher than that of the TRMM PR (Kojima et al. 2012; Toyoshima et al. 2015). These factors lead to more severe effects of the sidelobe clutter.  

On the other hand, the intensities of radially spread sidelobe clutter (like cat’s whiskers) shown in Fig. 5b appear much weaker than those shown in Fig. 5a, although the intensities of the U-shaped sidelobe clutter remain relatively the same. The differences of the sidelobe clutter distributions between Figs. 5a and 5b are the results of the changes in the antenna patterns. Therefore, reduction of the intensities of radially spread sidelobe clutter shown in Fig. 5b resulted from using the final version of the phase code since 25 July 2014.

To examine the frequency of the sidelobe clutter occurrence, a flowchart for diagnosing sidelobe clutter was outlined in Fig. 7. First, the main lobe clutter was classified as range bins, which were closer to the ground than the lowest point free from main lobe clutter. The lowest point free from main lobe clutter is referred to as “binClutterFreeBottom” in the KuPR L2 product. In this study “binClutterFreeBottom – 1” was adopted as the lowest point free from main lobe clutter because of misidentification caused by the contamination of main lobe clutter at the “binClutterFreeBottom” of the V03B product. Next, the precipitation case and the no-precipitation case were classified by the KaHS. When no precipitation was determined, a further threshold was applied for the classification of “noise” and “sidelobe clutter.” The determination of this threshold is described as follows. The standard deviation of the fading noise $\sigma_N$ was approximated by the following equation, with the mean received power of the noise $P_{\text{noise}}$ for the number of independent echo samples $N$ and the number of independent noise samples $M$ (Kumagai et al. 1997):

$$\sigma_N = \frac{\pi P_{\text{noise}}}{\sqrt{6}} \sqrt{\frac{1}{N} + \frac{1}{M}}.$$  

Here, the sample numbers of the echo and the noise for the KuPR were set as 102 and 892, respectively, while the actual sampling numbers were variable by the VPRF technique,
\[ \sigma_N = \frac{\pi P_{\text{noise}}}{\sqrt{6}} \sqrt{\frac{1}{102} + \frac{1}{892}} = 0.134 P_{\text{noise}}. \]  

In the method of the precipitation/no-precipitation classification in the algorithm, \(3\sigma_N\), similar to the TRMM/PR algorithm (Kumagai et al. 1997; Takahashi and Iguchi 2008), was adopted as one of criteria of precipitation. Therefore,

\[
P_{\text{echo}} = P_{\text{signal}} + P_{\text{noise}} > P_{\text{noise}} + 3 \times 0.134 P_{\text{noise}}
\]

where \(P_{\text{echo}}\) is the received power of the echo and \(P_{\text{signal}}\) is the received power of the signal.

In decibels, the above-mentioned equation can be converted to

\[
P_{\text{echo}}(\text{dBm}) - P_{\text{noise}}(\text{dBm}) > 1.467.
\]

This was actually used to identify the sidelobe clutter that affects the precipitation/no-precipitation classification method.

After the sidelobe events were detected based on the procedures shown in the flowchart, the ratio of the sidelobe events to the total events was calculated at each range gate. Figure 8 shows the results of the ratio in the vertical cross sections. In the analysis for the case of land, an altitude relative to the land surface was adopted as the vertical axis. The pattern of the sidelobe clutter over the land was similar to the averaged power shown in Fig. 5, and the ratios with the values greater than 60% were widely spread. In contrast, patterns of the sidelobe clutter over the land were confined to U-shaped types. The occurrence ratios over the land were lower than those over the ocean, and there were few range bins with values greater than 60%.

These ocean–land differences can be explained by the differences of NRCS characteristics between ocean and land. Intensities of NRCS vary with the incident angles, and the NRCS at the nadir angle is strongest (e.g., Meneghini et al. 2000). The U-shaped sidelobe clutter is related to NRCS at nadir or near nadir, considering the \(\theta_N\) shown in Fig. 4b. On the other hand, the radially spread sidelobe clutter is associated with the NRCS at the off-nadir angles. Previous works, such as Seto and Iguchi (2007), showed that the NRCS over land was strong at the nadir angle and that it degraded quickly as the incident angle departed from the nadir. NRCS over the ocean peaked at nadir and maintained relatively large values at off-nadir angles. Weak NRCS at off-nadir angles over land leads to the weak radially spread sidelobe clutter. NRCS at the nadir angle over land varies widely with regions because of changes in land surface conditions (Seto and Iguchi 2007; Durden et al. 2012). For example, stronger NRCS was found over the Sahara and weaker NRCS was found over the Amazon forest based on TRMM PR observations (Seto and Iguchi 2007). It was also found that very strong NRCS often appears over ice-covered land as observed by the DPR. As a result, the strong NRCS at the nadir angle over ice-covered land or the desert could possibly lead to significant U-shaped sidelobe clutter.

4. Statistical method to reduce sidelobe clutter

a. Description of the method

In this subsection, a method to reduce the sidelobe clutter is described. As in (1) and (2), \(P_s\) is related to the NRCS of the surface. In (2), the azimuthal angle dependence is ignored to simplify the calculation. However, NRCS at \(C' (\sigma^0_m)\) with the angle of \(-\theta_N\), as illustrated in Fig. 3, is available for the KuPR observation, in addition to NRCS at \(C (\sigma^0_m)\) with the angle of \(\theta_N\), because the KuPR operates in a cross-track scanning geometry. As in (1), \(P_s\) can be calculated by integrating over \(S\), which includes both points \(C\) and \(C'\). Actually, a calculation using the antenna pattern measurement data derived from the ground test indicated that the total contribution to \(P_s\) from \(C'\) is sometimes larger than that from \(C\) (K. Furukawa, JAXA GPM/DPR project team, 2015, personal communication). Therefore, it is suitable to consider both \(\sigma^0_m\) and \(\sigma^0_{m'}\) to estimate the sidelobe clutter, and a multiple regression model with two explanatory variables is adopted in this study. In this model, the estimated received power of the sidelobe clutter \(\hat{P}_S\) is described using \(\sigma^0_m\) and \(\sigma^0_{m'}\):

\[
\hat{P}_S = a + b_1 \sigma^0_m + b_2 \sigma^0_{m'}. \tag{9}
\]

A multiple linear regression model with one \(y\) variable and two \(x\) variables is illustrated with a mean \(\mu\), covariance \(\sigma\), and correlation \(\rho\), as follows (e.g., Edwards 1984):

\[
\hat{Y} = a + b_1 X_1 + b_2 X_2, \tag{10}
\]

\[
a = \mu_Y - b_1 \mu_{X_1} - b_2 \mu_{X_2}, \tag{11}
\]

\[
b_1 = \frac{\sigma_{YX_1}}{\sigma_{X_1}} \frac{\rho_{X_1X_2}}{1 - \rho_{X_1X_2}^2}, \tag{12}
\]

\[
b_2 = \frac{\sigma_{YX_2}}{\sigma_{X_2}} \frac{\rho_{X_2Y}}{1 - \rho_{X_1X_2}^2}. \tag{13}
\]
When $\theta_s$ is equal to $0^\circ$, $\sigma_m^0 = \sigma_n^0$. Therefore, instead of the multiple regression model, a single regression model is adopted at the nadir angle, as follows:

$$P_S = a + b\sigma_m^0. \quad (14)$$

In addition, the single regression model is utilized when land/ocean surface types are different between $C$ and $C'$, which occurs in areas near coastlines. In this work, estimates from the water surface are used over those areas because of strong NRCS over the water surface.

In the calculation of the regression coefficients, cases with only “$P_{\text{signal}} = P_{\text{echo}} - P_{\text{noise}} > 0.134P_{\text{noise}}$” are used in order to reduce the effects of the fading noises. In addition, they should be calculated using nonprecipitation events of the KuPR. Therefore, the sample number in the regression model depends upon nonprecipitation events with $P_{\text{signal}} > 0.134P_{\text{noise}}$. For obtaining the reliable models, the coefficients were not calculated for sample numbers less than 50.

Based upon the abovementioned formulation, coefficients of the regression models are calculated in the KuPR scanning geometry (49 angle bins and 176 range bins) at every 1 km of satellite altitude, from 392.5 to 418.5 km. This means that there are a total of 232,848 ($49 \times 3 \times 176 \times 27$) sets of regression coefficients, although they are interpolated from neighboring range bins when the sample number is less than 50.

In Fig. 9 shows an example of the relationship between the NRCS and the sidelobe echo over the ocean. Here, the sidelobe echo was defined as $P_{\text{signal}}(>0.134P_{\text{noise}})$ with no precipitation judged by the KaHS. In this case study, the sidelobe echo of a range bin has a beam scan angle of $-4.97^\circ$ and an altitude (range-gate distance from surface) of 1.5 km, and the NRCS at the nadir angle was used for the period 26–28 March 2014. As shown in Fig. 9, there is good linear
correlation between the NRCS and the sidelobe echo for a weak or moderate NRCS with a correlation coefficient of 0.73 (sample number: 11,057). However, there are distinct deviations from a linear relationship in the case of a strong NRCS. The variability of the NRCS over the ocean is the result of the change in surface wind speed (Freilich and Vanhoff 2003; Li et al. 2004; Meneghini et al. 2004; Seto and Iguchi 2007). A strong NRCS at the nadir angle corresponds to a weak surface wind over a calm sea.

Deviations from the linear relationship are related to an engineering factor. The DPR transmits dozens of pulses per angle bin and receives reflective echo from surface, rain, and so on. Each received echo is converted to an 8-bit digital number called a “count value” on the DPR processing system. Then, these count values are averaged on board and are stored in the DPR L1 products. To avoid confusion, two count values are defined. One is “the independent echo,” which is obtained from the DPR’s transmitter wave corresponding to one pulse. The other one is “echoCount,” which is averaged with each independent echo on board. In the design of the DPR’s hardware, since the upper limit of the count value is 255, both count values are stored as an 8-bit digital number. Therefore, “echoCount = 255” could not reflect its true or appropriate value when that actual value exceeds 255. In addition, when echoCount < 255 but approaches 255, each independent echo may exceed 255 on the DPR processing system, and the echoCount might not reflect its true or appropriate value. This characteristic is referred to as “saturation,” and it occurs in the strong surface echo at the near-nadir angles over a calm sea, sea ice, or ice-covered land. Therefore, the linear relationship between NRCS and sidelobe clutter is not suitable for the strong NRCS because of the saturation issue.

One way to solve the problem of deviations from a linear relationship is to employ a higher-degree equation. The lowest-degree equation of a monotonic increase, except for the linear, is a cubic equation, that is,

\[
P_s = a + bX + cX^2 + dX^3,
\]

\[
X = \sigma_m^0.
\]

The green line in Fig. 9 shows the cubic fit, and this could represent well the regions for both the linear relationship and the deviations due to saturation. However, the method using the cubic fit is not straightforward to account for the rain attenuation \((A_s = \sigma_m^0 A_S)\) when an estimate of the sidelobe echo is applied to the precipitation signal.

Apparently, the attenuation is easily considered in a linear regression model because \(A_s\) is directly connected to the estimate. Therefore, a linear regression model classified with intensities of the echoCount for the NRCS was adopted in this study. The blue line in Fig. 9 shows a linear regression using events with an echoCount value of less than 252, and the purple line shows a linear regression using events with echoCount values greater than 252, respectively. Green line shows cubic fit.
the period 26–28 March 2014, and a minimum variance is found at echoCount = 252. Thus, echoCount = 252 was an optimal threshold and is therefore used in this study.

Frequencies of the echoCount ≥ 252 in the NRCS were examined with the distinction of beam scan angles, surface types (ocean or land), and periods. Figure 11 shows the ratio of echoCount ≥ 252 to total pixels in the NRCS for periods 26–28 March 2014 and 2–4 August 2014. Maximum values of the ratio were found at the nadir angle. The values were higher over the land than over the ocean at the nadir angle, while higher values were extended to the near-nadir angles (about 2°) over the ocean. The ratio of echoCount ≥ 252 for both overocean and overland was decreased for the period 2–4 August 2014. These results suggest the saturation was related to the NRCS at the near-nadir angles, and it was mitigated by the receiver attenuator with 12 dB since 12 May 2014.

A statistical method to reduce the sidelobe clutter was constructed based upon the analyzed results. Figure 12 depicts a flowchart, and the current method works as follows:

1) Determine whether sidelobe clutter appears frequently in the range bin. When the ratio of the sidelobe clutter events to total events in past DPR data is less than 10%, the method does nothing. The ratio is calculated as in Figs. 7 and 8, but for classification of every 1 km of satellite altitude, from 392.5 to 418.5 km.

2) Determine whether the received power of the echo in the range bin is greater than the standard deviation of the fading noise. The criterion is $P_{\text{signal}} > 0.134P_{\text{noise}}$. When it is not, the method does nothing.

3) Estimate the sidelobe echoes. The multiple regression model with two explanatory variables is adopted as a model function to represent the relationship between the NRCS and sidelobe clutter. The coefficients of the regression model are calculated from past DPR data. The value of echoCount = 252 was adopted as the optimum threshold dividing regression coefficients in order to correspond to the saturation issue of the NRCS.

4) Subtract the sidelobe estimates from the received power at corresponding range bins.

b. Evaluation of the method

In this subsection, the developed method was applied to the KuPR L2 algorithm. Here, coefficients of the regression models were calculated using the DPR data for 26–28 March 2014 and were applied to DPR data during 29–31 March 2014. In addition, the coefficients calculated using the data for 2–4, 2014 August were applied to the DPR data during 5–7 August 2014.

Figure 13 shows vertical cross sections of the received power of the echo over the ocean without use of the method (OFF) and with use of the method (ON). The received power is averaged from the data when
precipitation is not present as determined by the KaHS for 29–31 March. Figures 13a and 13c are similar to Figs. 5a and 5b, respectively. As compared with the OFF figures, the received power from the sidelobe clutter is largely reduced in the ON figure (Figs. 13b and 13d), and the received power from the U-shaped sidelobe clutter still remains though greatly reduced. This is mainly due to the lower effectiveness of the regression model in the saturation of the NRCS at near-nadir angles, as discussed in the previous subsection. Accuracies of the estimates of the sidelobe echo at the near-nadir angles decreases because of the saturation issue, leading to imperfect removal of the U-shaped sidelobe clutter.

The effects of this method on the precipitation estimates were also examined. The precipitation/no-precipitation classification method in the KuPR L2 algorithm was carried out in two steps. The first was to establish a threshold of $3\sigma_N$, as described in section 3. The other was to determine a successive number of range bins satisfying the abovementioned threshold along the range. In the KuPR L2 algorithm (version 03B), “precipitation” is classified when the successive number is equal to or greater than 6. Therefore, the criteria of the threshold of $3\sigma_N$ and the successive number are helpful also for reducing the contamination of the sidelobe clutter in the precipitation estimate.

As a case study, Tropical Cyclone Hellen, which occurred near Madagascar at 1750 UTC 30 March 2014, was selected. Figure 14 shows comparisons of horizontal distributions of the surface precipitation rate associated with Tropical Cyclone Hellen between without and with use of the correction method, that is, OFF and ON. In the OFF product (Fig. 14a), there appeared artificial precipitation estimates over the ocean, resembling wheel traces. The intensities of the artificial estimates over the ocean were less than 2 mm h$^{-1}$. These artificial estimates were not found over Madagascar because of weak NRCS over land, as evidenced by the ocean/land differences shown in Fig. 8. It is clearly seen that the artificial estimates were successfully removed in the ON figure (Fig. 14b) without affecting the estimates of the spiral rainbands of Tropical Cyclone Hellen depicted in Fig. 14b. Figure 15 shows vertical cross sections of measured radar reflectivity at the northern edge of Tropical Cyclone Hellen. In Fig. 15a, there were sidelobe clutter contaminations similar to Fig. 13a, in addition to precipitation signals related to Tropical Cyclone Hellen. In contrast, the sidelobe clutter contaminations were largely reduced by the method as shown in Fig. 15b. However, undercorrections (remaining sidelobe clutter contaminations) were sometimes found, for example, at 4-km altitude of the beam scan angles around $5^\circ$. Moreover, overcorrections (reduced precipitation signals) were also sometimes found in weak precipitation regions, such as at 7–8-km altitude of the beam scan angles around $-15^\circ$. For example, the vertical interpolation of the received power data for reducing the overcorrections was adopted in the DPR L2, version 4, product. Such additional methodology can be helpful in order to mitigate the overcorrections.
For statistical evaluations of the sidelobe clutter reduction in the KuPR for the precipitation/no-precipitation classification, three skill scores with reference to the KaHS were adopted in this work. Frequency bias (FB) is defined as the ratio of the number of the KuPR precipitation events to that of the KaHS precipitation events, that is, $FB = \frac{a + b}{a + c}$ in Table 1. Here, $FB = 1$ for unbiased estimates, indicating that the number of KuPR precipitation events is the same as the number of KaHS precipitation events. The probability of detection (POD) is the ratio of correct precipitation estimates to the number of precipitation events observed by the KaHS. POD was defined as $POD = \frac{a}{a + c}$, where elements $a$ through $c$ are the number of occurrences in Table 1. This statistic, also known as the hit rate, is an index of precipitation detection ability. The false alarm ratio (FAR) is the fraction of precipitation estimates that turned out to be wrong, or an index of false precipitation. The FAR was defined as $FAR = \frac{b}{a + b}$. The classification of precipitation/no precipitation (referred to as “flagPrecip” in the L2 product) in 25 angle bins in the Ku-/Ka-band matched beam area was used in this analysis.

Figure 16 shows FB values over the ocean in the OFF and the ON products during the periods 29–31 March 2014 and 5–7 August 2014. There was no sidelobe clutter at the near-nadir beams with scan angles less than 0.58, as shown in Fig. 1, and the line in ON agreed with that in OFF. At off-nadir angles, the values approached 1 in the ON product, while there were distinct biases at off-nadir angles in the OFF product. The results were summarized in Table 2. As shown in previous works (Kojima et al. 2012; Toyoshima et al. 2015), the sensitivity of the KaHS is higher than that of the KuPR, and therefore the FB values were less than 1 over the clutter-free region. The FB value in the clutter region in the ON was comparable to that of the clutter-free region. Analysis of the results confirms the reasonably effective performance of ON to remove the sidelobe clutter.

The FB may include offsets of undercorrections and overcorrections. Therefore, the POD and the FAR were analyzed during the periods as in Fig. 16. When the POD
FIG. 14. Horizontal distribution of surface precipitation rate for Tropical Cyclone Hellen near Madagascar at 1750 UTC 30 Mar 2014 (orbit number 483). (a) Results without the method (OFF) and (b) results with the method (ON). The horizontal resolution is 0.08° × 0.08° latitude by longitude. Unit is mm h⁻¹.
values are less than over the clutter-free region, it can be confirmed that the method reduces the correct precipitation estimates with the overcorrection. Figures 17a and 17b show POD values by the ON product over the ocean during 29–31 March 2014 and 5–7, 2014 August respectively. Actually, when the beam scan angle was 7.8°, the POD values were decreased when compared to others in both periods. This suggests the overcorrection occurred there. However, there were no similar decreases in the POD values of the other angles. Figures 17c and 17d show FAR values by the ON product. The FAR values in the clutter region during 5–7 August tended to be lower than those during 29–31 March, and this suggests that the sidelobe clutter contamination was mitigated by the final phase code and the final setting of the receiver attenuator.

The saturation issue of the NRCS was discussed in section 4a. Events when the echoCount of the NRCS at the nadir angle was above and below 252 are referred to as “HIGH” and “LOW,” respectively, and the FB values were calculated with the distinction between HIGH and LOW. Figure 18 shows the results for HIGH and LOW, and the results were summarized in Table 3. The LOW events were about 24 times more frequent than the HIGH events during 29–31 March and about 72 times more frequent during 5–7 August. Decreases of the HIGH events in August 2014 were consistent with the results of Fig. 11. The FB value in the clutter region for LOW events was comparable to that of the ON results in the clutter region in Table 2, because the LOW events occupied the majority. On the other hand, the FB values in the clutter region for HIGH events were higher than for LOW events during 29–31 March and 5–7 August. This suggests that the overestimation in the

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**FIG. 15.** Vertical cross section of measured radar reflectivity at the northern edge of the tropical cyclone Hellen (scan number 6290, orbit number 483) for (a) OFF and (b) ON. Unit is dBZ. Gray denotes range bins where the received power was below the noise level.

**TABLE 1.** A 2 × 2 contingency table for evaluation. Elements a–d are assigned the observed event counts in each category.

<table>
<thead>
<tr>
<th></th>
<th>KaHS: Precipitation</th>
<th>KaHS: No precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>KuPR: Precipitation</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>KuPR: No precipitation</td>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

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**FIG. 16.** Frequency bias over the ocean for the periods (a) 29–31 Mar and (b) 5–7 Aug 2014. Horizontal axis is beam scan angle (°). Dashed line denotes OFF and solid line denotes ON.
number of the KuPR precipitation events related to sidelobe clutter contamination is found when saturation of the NRCS at the nadir angle occurs. Thus, it will be necessary to improve the method for consideration of the NRCS saturation in a future work. The FB values in the clutter region for the HIGH events was 1.91 during 29–31 March and 1.18 during 5–7 August, which suggest the sidelobe clutter contamination was mitigated by the final phase code and the final setting of the receiver attenuator.

5. Summary

A statistical method to reduce sidelobe clutter in the GPM/KuPR was described and evaluated using DPR observations. The characteristics and features of the sidelobe clutter were analyzed for two periods, 26–28 March 2014 and 2–4 August 2014. The intensities of sidelobe clutter in the KuPR were 5–10 dB higher than the noise level, while those in the TRMM PR were 0.5–1 dB higher, and it was clearly demonstrated that the KuPR sidelobe clutter was much more severe than that of the TRMM PR. While both the U-shaped clutter and the radially spread sidelobe clutter were apparent during the period 26–28 March 2014, the radially spread sidelobe clutter was largely decreased during the period 2–4 August 2014 by using the final version of the phase code, as a result of the changes in the antenna patterns. The ratio of the sidelobe events that affected the precipitation/no-precipitation classification method to the total events was calculated for a frequency diagnosis of the sidelobe clutter. The patterns of sidelobe clutter over land were confined to U-shaped types, and the radially spread sidelobe clutter over the ocean was not seen over land. The values over the ocean were higher than those over land. These ocean–land differences could be connected to the NRCS characteristic.

The statistical method to reduce sidelobe clutter was constructed by subtraction of the estimated sidelobe powers based on the multiple regression model with explanatory surface NRCS variables. Because of the saturation of the NRCS at near-nadir angles, it was necessary

<table>
<thead>
<tr>
<th>Name</th>
<th>Data period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clutter-free region</td>
<td>0.84</td>
</tr>
<tr>
<td>Clutter region with OFF</td>
<td>9.92</td>
</tr>
<tr>
<td>Clutter region with ON</td>
<td>0.88</td>
</tr>
</tbody>
</table>

FIG. 17. POD over the ocean during (a) 29–31 Mar and (b) 5–7 Aug 2014, and FAR over the ocean during (c) 29–31 Mar and (d) 5–7 Aug 2014. Horizontal axis is beam scan angle (°). All lines denote ON results.
to calculate the regression coefficients with the threshold. The variable echoCount = 252 was adopted as the optimum threshold dividing the regression coefficients.

The developed sidelobe reduction method was implemented in the KuPR L2 algorithm and applied to the DPR observed data. After applying the procedure, the received power of the sidelobe clutter over the ocean was reduced to a great extent, while the received power from the U-shaped sidelobe clutter, though reduced, still remained at some locations. This is mainly due to the lower effectiveness of the regression model in the saturation of the NRCS at near-nadir angles. The method was tested on the case of Tropical Cyclone Hellen near Madagascar at 1750 UTC 30 March 2014, and artificial precipitation estimates over the ocean were successfully removed using this method. In statistical evaluations of the sidelobe clutter reduction using three skill scores (the FB, the POD, and the FAR) for the precipitation/no-precipitation classification, the number of KuPR precipitation events in the clutter region using the method was comparable to that in the clutter-free region. This confirms the reasonable performance of the method for removing sidelobe clutter. However, overestimation of the number of the KuPR precipitation events related to sidelobe clutter contamination was found when saturation of the NRCS at the nadir angle occurred, while it was mitigated by the final phase code and the final setting of the receiver attenuator. Therefore, it will be necessary to improve the method for consideration of the NRCS saturation in future work.

In this work, the method was evaluated using the KaHS. However, the KuPR swath is about 245 km in width, and the KaPR swath is about 125 km. Therefore, the pixels of the outer swath of the KuPR have not been able to be verified. For further verification of the method, the ground radar will be helpful, although an accumulation of KuPR data will be necessary for reliable verifications and several issues of the ground radar should be processed properly. Thus, verification using the ground radar is one of the future tasks.

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REFERENCES


