The Utilization of Surface Reference Technique for the GPM/DPR Retrieval Algorithm

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To retrieve rain rates from the Dual-frequency Precipitation Radar (DPR) of the Global Precipitation Measurement (GPM), backward retrieval method (BRM) is available, but BRM requires an accurate surface reference technique (SRT). Mardiana et al. developed a retrieval method (Ma04) which does not require SRT, but Ma04 cannot give correct solutions for medium to heavy rainfall. We modified Ma04 into SZ to remove the bias, but random error is still large. In this study, Ma04 and SRT are combined to get more accurate solutions. Two methods are proposed; one method (iSRT) is the same with MA04, but PIA in the first iteration is given by the SRT. Another method (iDSRT) is the same with iSRT, but the difference of PIA between the two frequencies is constrained by SRT in the second iterations and later. The advantages of iDSRT against iSRT are not to require the single-frequency PIA's and to work better as long as the errors in PIA correlate well positively between the two frequencies.

Key Words: GPM, DPR, Surface Reference Technique

Nomenclature

σ^0	:	surface backscattering cross section
Z	:	radar reflectivity factor
N	:	the number of range bins

1. Introduction

The core satellite of the Global Precipitation Measurement (GPM) mission will be launched in 2013 with the Dual-frequency Precipitation Radar (DPR) on. The DPR consists of KuPR (frequency: 13.6 GHz) and KaPR (frequency: 35.5 GHz). The swath width of KuPR is about 250 km (wide swath), but that of KaPR is about 120km (narrow swath). In narrow swath, KuPR and KaPR observe the same pixel simultaneously. It is expected that the simultaneous observations of DPR will enable us to retrieve drop size distribution (DSD) more flexibly and accurately than the single-frequency observation of the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR), which has been working for more than 13 years. In this study, on dual-frequency retrieval method, which is applied for the simultaneous observations by DPR to retrieve DSD and rain rates, previous methods are reviewed and new methods are introduced.

2. Reviews of Dual-frequency Retrieval Methods

2.1. Backward retrieval method (BRM)

Meneghini et al. (1992)[1] developed a retrieval method which requires surface reference technique (SRT). Their method is called backward retrieval method (BRM) in this study. SRT is to estimate path integrated attenuation (PIA), which is the total attenuation occurring along with the two-way path between the radar and the earth surface, from the change in backscattering cross sections (denoted as σ^0) between the current raining pixel and other (usually non-raining) pixels. For the simplicity, throughout this study, let us assume that radar reflectivity factor is always measurable free from ground clutters. For the lowest range bin (just above the earth surface), by adding PIA to the measured radar reflectivity factor (Z_m), non-attenuated radar reflectivity factor (Z_e) is obtained. From Z_e's at the two frequencies of KuPR and KaPR, two unknown parameters of DSD are retrieved. There are two nonlinear equations with two unknowns, mathematically speaking, but the corresponding solutions are not generally unique. In the case of multiple solutions, by limiting the range of DSD parameters, a solution is selected. Then, attenuation occurring within the lowest range bin is reduced from PIA for the attenuation correction at next upper range bin. This process is continued until DSD is retrieved at all the range bins.

BRM relies heavily on SRT, but the accuracy of SRT is generally not very satisfactory. SRT[2,3] is also used in the standard algorithm[4,5], but there are some problems to be resolved in the SRT[6]. Particularly over land, high variability of land surface conditions both in time and space degrades the accuracy of SRT and sometimes cause severely large biases in PIA.

2.2. Iterative backward retrieval method (IBRM)

Mardiana et al. (2004)[7] applied a new retrieval method without the use of SRT. Their method is called Ma04 in this study. Ma04 is a kind of iterative backward retrieval method (IBRM). In IBRM, PIA is assumed arbitrarily instead of SRT (this PIA is denoted as PIA*). With PIA*, BRM is applied and PIA is calculated from the retrieved DSD (this PIA is denoted as PIA$^\#$). When PIA$^\#$ is not equal to PIA*, PIA* can be judged as incorrect. There are various ways how to assume PIA*. In Ma04, at the first iteration, PIA* is set to be 0dB (in other words, the first guess of PIA is 0dB in Ma04). At the second and later iterations, PIA* is set to be PIA$^\#$ of the previous iteration.

Several studies[8),9)] tested Ma04 with simulation datasets under idealized conditions, but they claimed that Ma04 did not work properly for medium to heavy rainfall. In Ma04, rain rates (if "rain rates" is simply noted hereafter in this study, it means rain rates at the lowest range bin) tend to be underestimated. The authors objectively explained the mechanism of the underestimation[10)]. Without the use of SRT, the dual-frequency retrieval is to solve a set of 2*N* nonlinear equations with 2*N* unknown parameters (*N* is the number of range bins). Generally, the equations have no unique solutions because of their high nonlinearity. This suggests that no retrieval methods can always obtain the right solution. Ma04 searches a solution with the first guess of 0 dB PIA, which is an underestimates for any precipitation cases. Therefore, Ma04 tends to select a solution with the smallest PIA among multiple solutions and it fails to select the right solution in the case of heavy rainfall. The height of precipitation also affects the accuracy. If the rain rates are the same, higher precipitation is more difficult to be retrieved accurately than lower precipitation, because of the accumulation of the numerical error.

2.3. Stepwise IBRM method

The authors improved Ma04[11)]. Even when Ma04 underestimates rain rates at the lowest range bin, it usually estimates correctly at top several range bins. The vertical profile of Z_e shows a rapid decrease at lower range bins. In a new method called SZ, a vertically constant profile of Z_e is preferred. The process of SZ is shown below.

SZ means "a stepwise IBRM with constant $\underline{Z}_e$". SZ consists of *N* steps. In the 1st step, Ma04 is applied only for the top range bin (called range bin 1; hereafter range bin *i* indicates the *i*th range bin from the top). Attenuation occurring at range bin 1 is denoted as PIA(1) [PIA(*i*) denotes the attenuation occurring at range bins from 1 to *i*], and PIA(1) is updated instead of PIA. The first guess of PIA(1) is 0 dB as well as PIA is set to be 0 dB in the original PIA. In the 1st step, it is expected that PIA(1) is accurately retrieved as the number of range bins is as small as one.

In the 2nd step, Ma04 is applied for range bins 1 and 2 to estimate PIA(2). The first guess of PIA(2) is not 0dB, but is set so that Z_e at range bin 2 is equal to Z_e at range bin 1, which is retrieved in the 1st step. Note that retrieved Z_e's are not necessarily the same between range bins 1 and 2. The assumption of constant Z_e's is used just as the first guess, not as constraints. In the following steps, the number of range bins is increased one by one.

In the final (N^{th}) step, Ma04 is applied for all the range bins. The difference between the N^{th} step of SZ and the original Ma04 lies only in the first guess of PIA. In the N^{th} step of SZ, PIA is set so that Z_e at range bin *N* is equal to Z_e at range bin (*N*-1), while PIA is always 0 dB in the original Ma04. Note that in SZ, DSD at any range bins is determined in the N^{th} step, and results in the 1st to $(N\text{-}1)^{th}$ steps are reflected only on the first guess of PIA in the N^{th} step.

As shown later, the first guess of PIA affects the accuracy of rain rate estimates very much. A small bias in PIA can be adjusted by IBRM, but a large bias in PIA may cause IBRM to select a false solution when there are multiple solutions. SRT does not give the perfect PIA estimates, but if the bias is within an allowable range, it can be used as the first guess of IBRM. In the next section, the utilization of SRT in IBRM is introduced.

3. The Utilization of SRT in IBRM

3.1. The utilization of single-frequency SRT

Probably, a new method called iSRT is the simplest utilization of SRT in IBRM. The first guess of PIA is given by the SRT at each frequency. Except for the first guess, iSRT is the same with Ma04.

3.2. The utilization of dual-frequency SRT

With DPR, SRT is applied not only for the single-frequency PIA, but for the difference of PIAs between the two frequencies. The difference of PIAs is denoted as dPIA [dPIA=(PIA at KaPR)-(PIA at KuPR)]. SRT to estimate dPIA is called DSRT[12)]. It is expected that dPIA is estimated more accurately than PIA at single frequency. The reason is given as follows. Essentially, errors in SRT are caused by the variation of σ^0. The difference in σ^0 between the current pixel and referenced pixels becomes the error in PIA in the case of a primitive SRT. Particularly over land, the variations of σ^0 are large as well as those of the land surface conditions. However, an airborne radar experiment showed that the variations of σ^0 are similar between different frequencies. It means the errors in PIA can be largely cancelled by taking the difference between the two frequencies as dPIA.

A new method called iDSRT is introduced. The first guess of PIA is set 0 dB at KuPR and dPIA dB at KaPR (as shown later, absolute value at single-frequency PIA does not matter as long as dPIA is equal to the value given by DSRT). At the 2nd and later iterations, PIA* at KuPR is set to be PIA$^\#$ in the previous iterations, but PIA* at KaPR is set to be (PIA* at KuPR) + dPIA so that dPIA is conserved.

4. Simulation Dataset

The above five methods (BRM, Ma04, SZ, iSRT, and iDSRT) are divided into two groups: those with the use of SRT (BRM, iSRT, and iDSRT) and those without the use of SRT (Ma04, SZ). Among the five methods, only BRM does not have iterations so that PIA$^\#$ is not necessarily equal to PIA*. The other four methods are kinds of IBRM, and a big difference among them lies in the first guess of PIA. Table 1 summarizes the characteristics of the five methods.

The five methods are applied to a DPR simulation dataset. The simulation dataset is the same with those used in Seto and Iguchi (2011b)[11)], where you can find the details of the dataset. Briefly speaking, DSDs in liquid precipitation range bins are taken from the TRMM PR standard product. From the DSD, Z_e's at the two frequencies are calculated according to the Mie scattering theory and Z_m's are simulated considering attenuation by liquid precipitation particles. Effects of ground clutter, measurement errors in Z_m's, and attenuation by other particles than liquid precipitation particles are all ignored to check and compare the performance of methods under idealized conditions. Land surface is assumed to be located just under the lowest range bin. PIA calculated by DSD is regarded as the truth, but errors can be added to them to see the effects of biases in PIA on rain rate estimates. The simulation dataset is produced by a 1-month TRMM/PR products (July 2001) and the average of rain rates is 2.98 mm/h.

Before the evaluation of the new methods in the next section, the evaluation results of Ma04 and SZ are shown in Fig. 1 and Fig. 2, where the horizontal (vertical) axis is for true (estimated) rain rates. 2-D histogram is shown as background; Denser gray is for higher population. Lines are the averages of estimated rain rates and different colors are used for different categories of the height of liquid precipitation (denote as NL; N multiplied by the width of range bin L = 250m).

In Ma04, severe underestimation is seen when true rain rates are higher than 10 mm/h even for NL < 1 km. For NL > 4km, underestimation is seen for more than 3 mm/h. The total bias is -1.21 mm/h and corresponds to about 40% of the average of the truth.

In SZ, almost no biases are seen when rain rate is less than 10 mm/h even for high NL. For short precipitation (NL<2km), estimates have no large biases even for heavy precipitation. The total bias is -0.37 mm/h, which corresponds to about 12 % of the truth. Compared with Ma04, SZ shows smaller biases. This suggests that the first guess of PIA is given well in (the N^{th} step) of SZ.

5. Evaluation of the utilization of SRT

5.1. In case of perfect SRT

Three retrieval methods with the use of SRT (BRM, iSRT, and iDSRT) are tested with the simulation dataset by assuming SRT is perfect (Fig. 3). BRM performs almost perfectly. The total bias in BRM is as small as -0.03 mm/h. Underestimation for light rain rates (less than 1mm/h) is seen as well as in the other methods. This is almost unavoidable errors and the errors for such light rain rates are not a severe problem. If we try to avoid this error, larger errors are caused for heavy rain rates.

iSRT is expected to yield the same results with BRM as long as the SRT is perfect, but iSRT shows some biases for heavy rain rates (> 10mm/h). At the 1st iteration, PIA# is not judged to be equal to PIA* because of numerical errors and PIA becomes different from the truth during iterations. The same problem should lie in Ma04 and SZ. Therefore, underestimation for heavy rain rates in these methods is caused not only by inappropriateness of the first guess of PIA, but by numerical errors. The total bias in iSRT is -0.26 mm/h and not very different from that of SZ (-0.37 mm/h).We can say that the first guess of PIA is well given in SZ.

iDSRT gives similar results with BRM. As dPIA is constrained during iterations, iDSRT does not modify PIA wrongfully as iSRT does for heavy rain rates.

5.2. In case of biased SRT

Next, the three methods are applied with a biased SRT (+1dB for PIA at KuPR and +2dB for PIA at KaPR; +1dB for dPIA). In BRM, the rain rates are directly affected by biases in SRT regardless of the true rain rates. iSRT is not affected by biases in SRT when the true rain rates are less than 3 mm/h, but is affected for larger rain rates. It means that the same amount of biases in the first guess of PIA can be adjusted by IBRM for weak rain rates, but cannot be adjusted for heavy rain rates. In similar to BRM, iDSRT is affected by biases of DSRT regardless of the true rain rates. In iDSRT, as dPIA is conserved, the errors in dPIA are never modified by IBRM.

Fig. 5 is the same as Fig. 4 but SRT is negatively biased (-1dB for PIA at KuPR and -2dB for PIA at KaPR; -1dB for dPIA). In BRM and iDSRT, rain rates are always negatively biased. In iSRT, the rain rates are not affected by biases when rain rates are less than 3 mm/h, but are affected for heavier rain rates.

5.3. Comparison of methods

Fig. 7 shows biases in rain rates for different biases in PIAs at KuPR and KaPR; the biases in PIA are set between -5 dB and 5 dB (with a step of 1 dB) and independently from each other. Because of the limitation of our computer resources, the simulations for this figure are not for one month but for one orbit (orbit number 20675). Contours are the biases of the rain rates and those corresponding to the biases in Ma04 and SZ are shown by green and purple, respectively. In any methods with the use of SRT, to give smaller biases than SZ, SRT should be accurate. Some combinations of PIAs make the bias in rain rates zero, but RMSE is far from zero except for the case that SRT is perfect.

In BRM, rain rates are affected by biases in PIA at KaPR rather than those in PIA at KuPR. In iSRT, biases in rain rates look generally smaller than those in BRM. We can confirm by this that iSRT is less affected by SRT than BRM. In iDSRT, the contours are parallel to the 1:1 line. It means that only dPIA affects the results and PIA at single-frequency is not important. Therefore, it is not necessary to divide dPIA into single-frequency PIAs for iDSRT. But, dPIA should be accurate enough for iDSRT to get better results than SZ.

6. Summary

For the GPM/DPR, new retrieval methods with the use of SRT as the first guess of PIAs in IBRM are proposed. The new methods are applied to the simulation dataset as some previous methods. It depends on the accuracy of the SRT which methods perform best. The advantage of iDSRT is to require only dPIA estimates and not to require PIA at each frequency. As long as dPIA is estimated accurately, iDSRT gives good estimates of rain rates. Surface backscattering observations by airborne radars are to provide information on the accuracy of SRT and DSRT, and are necessary for us to develop the algorithm.

Table 1. Characteristics of retrieval methods.

Methods	PIA* in the first iteration (the first guess of PIA)	PIA* in the 2^{nd} and later iterations
BRM	PIA* given by SRT	(no iterations)
Ma04	PIA*=0dB	PIA*=PIA#
SZ (Nth step)	Ze at range bin (N-1) – Zm at range bin N	PIA*=PIA#
iSRT	PIA* given by SRT	PIA*=PIA#
iDSRT	dPIA* given by DSRT	PIA*=PIA# (at KuPR) PIA*=(dPIA by DSRT)+PIA# (at KaPR)

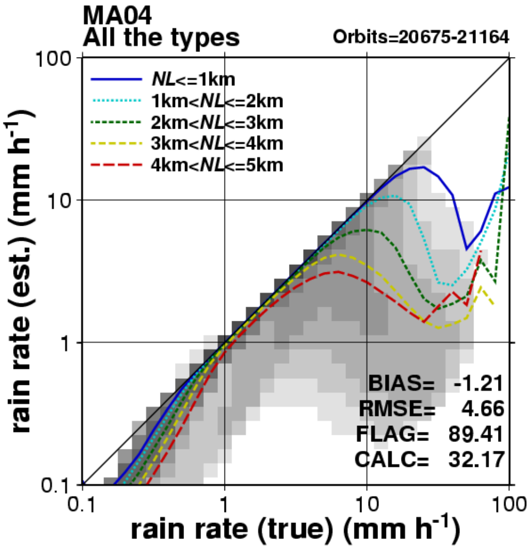

Fig. 1. The evaluation results of Ma04 by the simulation dataset.

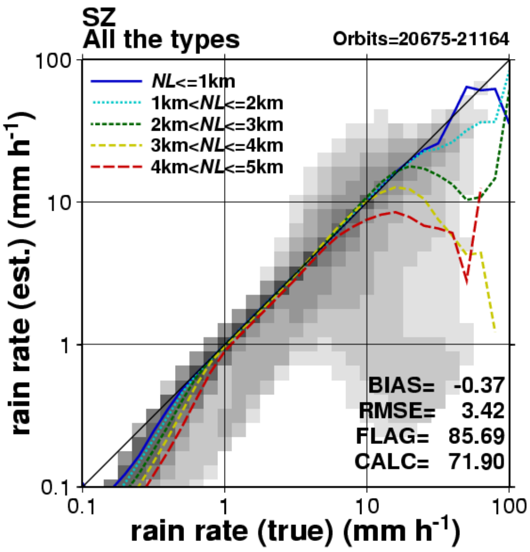

Fig. 2. The same as Fig. 1, but for SZ.

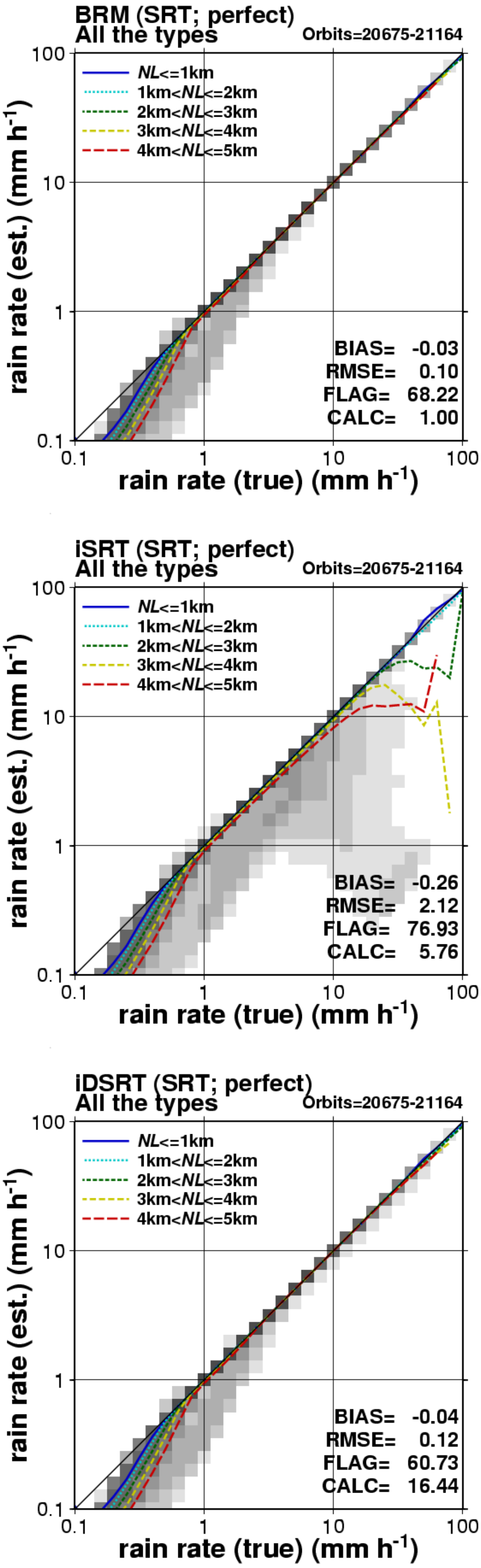

Fig. 3. The evaluation results of BRM(upper), iSRT(middle), and iDSRT(lower) in the case that SRT is perfect.

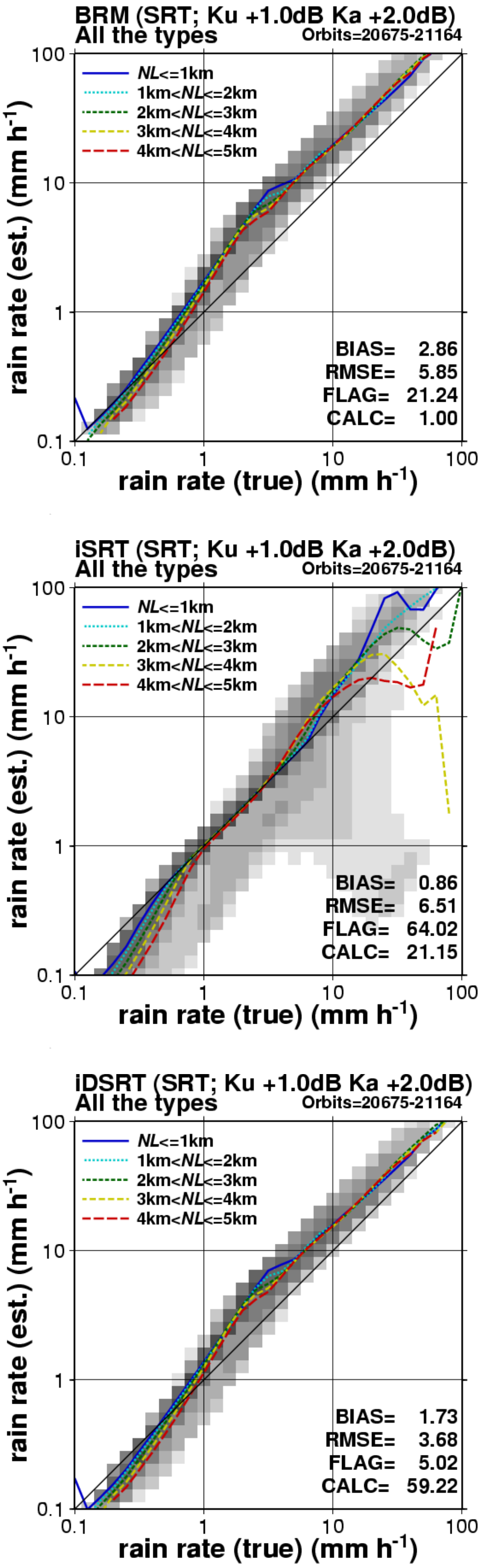

Fig. 4. The same as Fig. 3, but for the case that SRT is positively biased.

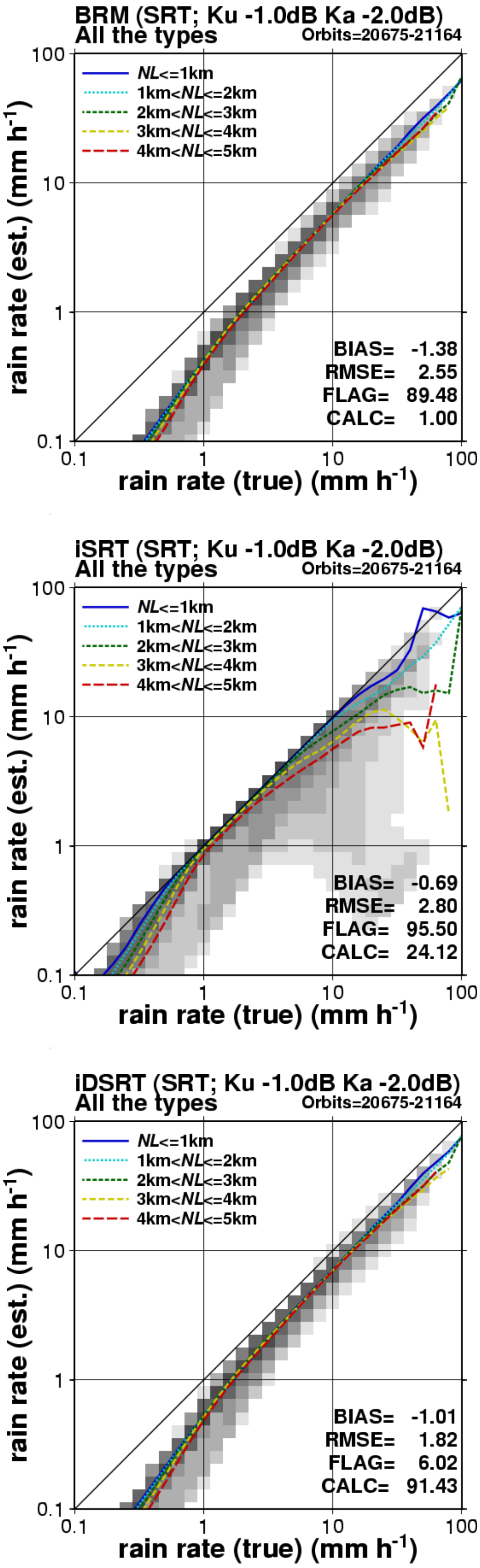

Fig. 5. The same as Fig. 3, but for the case that SRT is negatively biased.

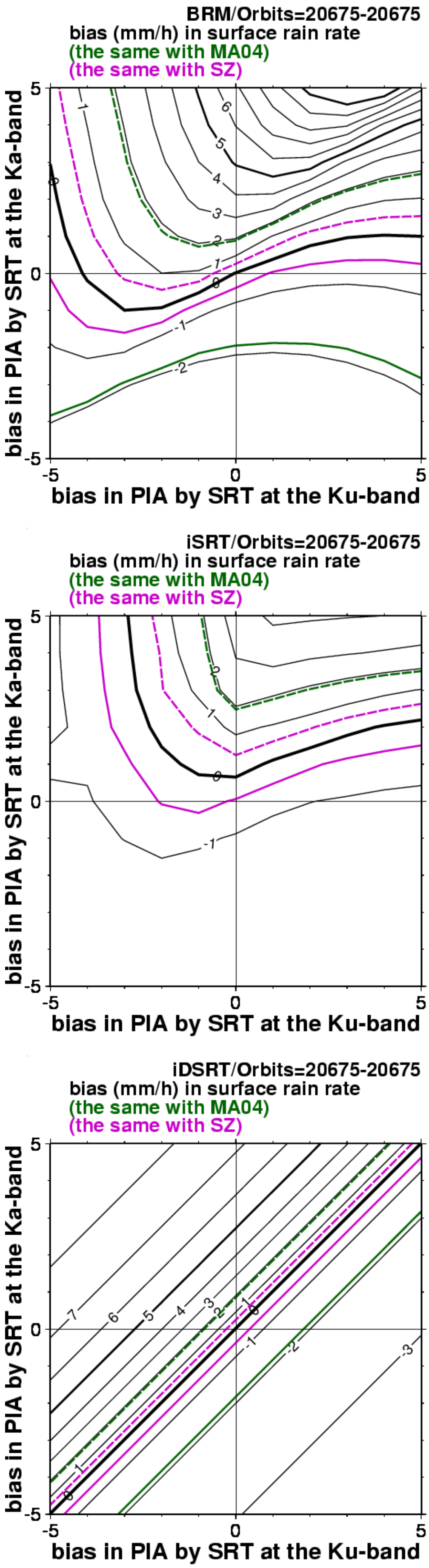

Fig. 6. The biases in rain rates for different biases in SRT.

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