Effect of Non-Uniform Beam-filling on TRMM PR Rainfall Measurements

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Abstract -- We investigate effects of non-uniform beam-filling on TRMM PR rain retrieval using data from the NASA/JPL Airborne Rain MApping Radar (ARMAR) acquired during TOGA COARE in early 1993. Our approach is to simulate TRMM PR observations using the ARMAR data and compare the radar observable and retrieved rain rate from the simulated PR data with those corresponding to the high-resolution radar measurements.

INTRODUCTION

The Tropical Rainfall Measuring Mission will include a Precipitation Radar (PR) for rainfall measurement. Because the 4.3 km diameter of the PR footprint is larger than the size of many convective cells, it is possible that rainfall estimates may be biased, Such biases in radar retrieved rain rate due to non-uniform beam-filling (NUBF) have been found by a number of authors [1],[2],[3]. We study the statistical nature of NUBF effects using a large data set acquired by the NASA/JPL Airborne Rain MApping Radar (ARMAR) [4] during the Tropical Oceans Global Atmosphere Coupled Ocean Response Experiment (TOGA COARE). Data from ARMAR is well--suited for such a study because it operates with the same 13.8 GHz frequency and downward-looking geometry as the TRMM PR but has substantially better spatial resolution (0.8 km at the surface). Our approach is to simulate TRMM PR observations using the ARMAR data and compare the radar observable and retrieved rain rate from the simulated PR data with those corresponding to the high-resolution radar measurements.

BACKGROUND

Algorithms for retrieving rain from spaceborne radar typically use a form of the Hitschfeld-Bordan technique, in combination with the path-integrated attenuation (PIA) measured by the Surface Reference Technique (SRT) [5], [6]. These algorithms assume uniformity of the rain rate across the antenna beam. When this is not the case, the goal must then be retrieval of the horizontally-averaged rain rate, as discussed in [2]. Unfortunately, because of non-linearity in the Z-R relation and the relation between PIA and rain rate, the measured PIA and reflectivity profile do not correspond to the average rain rate profile. Consequently, if NUBF is present, the radar measurements and the resulting retrieved rain rates can be biased.

DATA ANALYSIS TECHNIQUE

To quantify the effects of NUBF, we simulate TRMM PR observations using ARMAR TOGA COARE data. First, the ARMAR data is resampled to a uniform Cartesian grid. Second, a multi-dimensional Gaussian function is convolved with the resampled data, The Gaussian is chosen so that it approximates both the range resolution and the two-way antenna pattern. The simulation procedure does not explicitly include attenuation since the attenuation experienced by a simulated PR bin is essentially the same as the attenuation already experienced by the ARMAR measurement.

For the analysis of NUBF effects we consider only data at nadir and do not add thermal or fading noise so that the results depend only on NUBF effects. Furthermore, only the 2-D simulation is used, so that the simulated TRMM PR data has the PR resolution along-track and the ARMAR resolution across-track. In this case all averaging uses ARMAR data acquired at the same scan angle, so no assumptions about surface wind speed and backscatter models are needed.

The errors due to NUBF effects are found by comparing "true" and "apparent" radar observable: the SRT-derived PIA, the near-surface reflectivity (altitude 0.5 km), and the rain-top reflectivity (4 km). The "apparent" radar observable are taken directly from the output of the simulation. In addition to the radar observable, corresponding rain rates are also compared. The apparent path-averaged rain rate (PARR) is derived from the apparent PIA using a k-R relation. The apparent rain rate at 4 km is derived from the apparent reflectivity using a Z-R relation; attenuation is neglected. The apparent rain rate at 0.5 km altitude is derived by normalizing the apparent reflectivity by the apparent SRT-derived PIA, as done in both the kZS algorithm [6] and the alpha-adjustment method used in the TRMM algorithm [5]. The resulting, corrected reflectivity is then converted to rain rate using a Z-R relation. The k-R and Z-R relations are not adjusted based on the measured PIA. This approach follows the kZS algorithm [6].

Derivation of the "true" radar observable, corresponding to the horizontally-averaged rain rate, requires the high-resolution rain rate. We first perform vertical averaging of the ARMAR data to the PR range resolution so that the errors found in this study are due solely to horizontal variability of the rain. The high-resolution rain rates are then retrieved from these data and averaged over the PR footprint, using precisely the same antenna pattern as for the reflectivity data in the PR simulator. Once the horizontally-averaged rain rates have been computed, the "true" radar observable are computed using the radar equation and k-R and Z-R relations.

RESULTS

Table 1 shows the mean, standard deviation, minimum, and maximum of NUBF errors ("apparent" minus "true") over all of TOGA COARE. These statistics are based on the 1397 simulated PR footprints with a true PARR of more than 2 mm/h. While the means and standard deviations of the errors in all quantities are relatively small, the distributions have long tails, i.e., there are some cases with very large errors. The range between minimum and maximum error is always much larger than the standard deviation. Also, for some quantities the errors are only positive or only negative. The PIA and PARR errors are always smaller than the true; i.e., the TRMM PR would always underestimate PIA and PARR. The greatest underestimation is 12 dB for the PIA and 21 mm/h for the PARR. Previous studies using simulated data and smaller sets of real radar data have also noted underestimation of the PIA [1],[2],[3]. If we compute the average PARR over all 1397 footprints, we find that the average using the apparent PARR is underestimated by 4%.

The reflectivity and rain rate at 4 km altitude are always overestimated. Since attenuation is neglected in retrieving the rain at 4 km, these results are characteristic of rain retrieval using a Z-R relation. Previous authors have also noted overestimation due to the non-linearity of the Z-R relation (e.g., [1],[2]). When comparing the TOGA COARE average rain rates using both the high-resolution rainfall and the rainfall from the simulated TRMM PR, we find an overestimation by 3%, similar to the findings of Amayenc et al. [2] for the Z-R algorithm.

The near-surface reflectivity errors are both negative and positive, extending from -12.3 dB to +10.5 dB. The mean is very close to zero, and the distribution is fairly symmetric about the mean. Both underestimation and overestimation of the near-surface reflectivity are possible due to the presence of the competing effects of the Z-R relation, causing overestimation, and the attenuation, causing underestimation. The near-surface rain rate errors are more negative than positive and there are a few cases with negative errors as large as -79 mm/h. The maximum positive error is much smaller at approximately 18 mm/h. The average rain rate at the surface, computed over all 1397 footprints, is underestimated by 11 %, similar to the findings in [2] for the kZS algorithm at 35 GHz. The reason that the near-surface rain rate is typically underestimated even though the near-surface reflectivity error has zero mean is that the rain rate is derived by correcting the reflectivity by the PIA, which is always underestimated. Thus, the PIA error causes the non-zero mean error, i.e., the bias in the near-surface rain rate.

Fig. 1 shows a scatter plot of the PIA measurement errors versus the standard deviation of the high resolution PIA within the footprint. The two quantities are correlated (correlation coefficient r = -0.77). We also examined the relation of other quantities to the high-resolution measurement variability. The error in the 4 km altitude reflectivity is correlated with the standard deviation of the high resolution 4 km altitude reflectivity (r = 0.86). The near-surface reflectivity error is not correlated with the PIA standard deviation. Its mean remains close to zero even for large PIA standard deviation, However, the absolute value of the error does increase with increasing PIA standard deviation.

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Table 1: Statistics of NUBF Errors

	Mean	SD	Min	Max
PIA (dB)	-0.2	0.8	-11.7	0.0
PARR (mm/h)	-0.4	1.5	-20.6	0.0
Rain-top Z (dBZ)	0.3	0.5	0.0	4.7
Rain-top R (mm/h)	0.1	0.1	0.0	2.3
Near-surf Z (dBZ)	0.0	0.8	-12.3	10.5
Near-surf R (mm/h)	- .	5.5	-78.7	18.1

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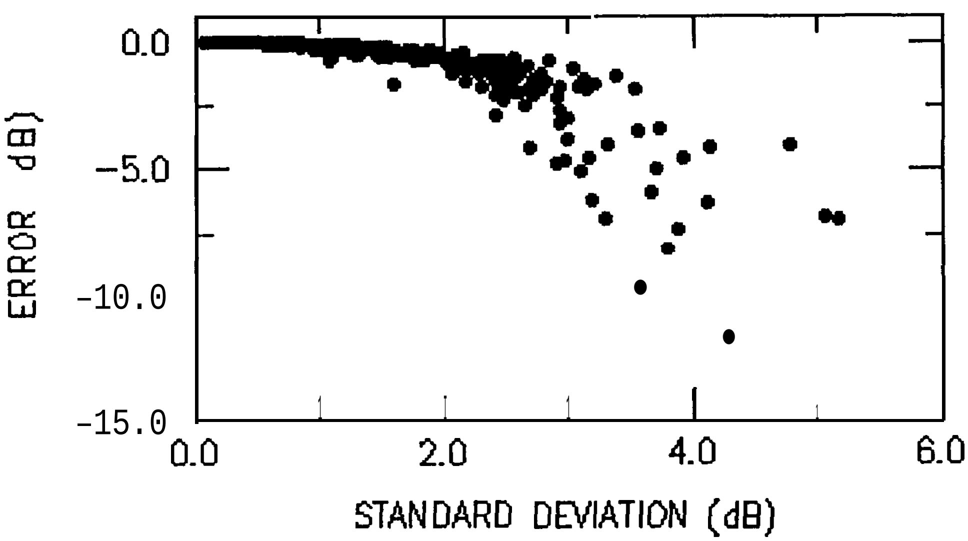

Figure 1. Scatter plot of the PIA error ("apparent" minus "true") versus the standard deviation of the high resolution PIA within the footprint.