P3A.5 THE TRMM GROUND VALIDATION EFFORT AT NASA-GSFC: VALIDATING SURFACE RAINFALLESTIMATES

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1. INTRODUCTION

The primary function of the TRMM Ground Validation (GV) Program at NASA Goddard Space Flight Center (GSFC) is to provide ground-based surface rainfall estimates for validating satellite-derived precipitation retrievals from TRMM. Data quality, retrieval techniques, and processing methods are significant elements of TRMM GV rainfall estimation. A description of the data quality control effort, together with the science and processing methodologies employed at NASA-GSFC in the generation of reliable surface rainfall estimates is presented. Quality control (QC) procedures are first performed on radar and rain gauge data independently, then again in a combined manner. The quality of rain gauge data compared with extracted radar data is a determining factor in the decision to use specific gauges for Z_e-R development. The use of the Window Probability Matching Method in Z_e-R development and the subsequent generation of instantaneous rain rate maps are described. Monthly rainfall estimates have the additional concern of integration and data gap accountability. Internal validation statistics (dependent and independent) from the current version (5.0) of monthly GV rainfall validation products show marked improvement over previous estimates. The challenges of estimating and validating monthly surface rainfall from the Melbourne, Florida, and Kwajalein Atoll, Republic of Marshall Islands, both primary GV sites, and applications to future precipitation missions are discussed. The evaluation of instantaneous rain rate products is discussed in Amitai et al. 2001, and 2002.

2. DATA QUALITY CONTROL

The radar data QC algorithm is designed to remove non-precipitating radar echoes that may negatively impact the quality of higher-level TRMM GV rainfall products. QC is needed to remove non-precipitating echo such as clutter associated with insects, birds, chaff, wildfires, physical structures, and anomalous propagation (AP) as described in Robinson et al. (1999).

The QC algorithm chosen by the TRMM Science Team is a modified version of the algorithm developed by Rosenfeld et al. (1995). The algorithm uses eight adjustable parameters, three echo height thresholds, and five radar reflectivity thresholds in the determination of false echo. Algorithm parameters are highly sensitive, and are chosen based on site-specific experience of AP events (Kulie et al. 1999). The ability exists to remove a wide variety of false echo scenarios because of parameter flexibility. Specifically, it removes biological targets (e.g. birds), non-embedded AP and clutter specks, clear-air echo, and sea clutter. In addition, a velocity field masking technique is used to diminish multiple-trip echo. Tipping bucket rain gauge data are also quality controlled to obtain 1-minute resolution rates for comparison with reflectivity data. As described in Marks et al. 2000, official GV rainfall products are developed in discrete modular steps with distinct intermediate products. These developmental steps include: (1) extracting quality-controlled radar data over the locations of rain gauges; (2) merging gauge and radar data in time and space; (3) automated QC of radar and gauge merged data (Amitai, 2000); and (4) deriving Z_e-R lookup tables from the merged data. The final QC procedure (step 3) ensures that only objectively determined “good” gauges are used in Z_e-R development.

3. PROCESSING AND PRODUCT METHODOLOGY

Version 5 processing methodologies incorporate the Window Probability Matching Method (WPMM), (Rosenfeld et al. 1994), multiple-range techniques, strict CAPPI-based reflectivities, and rain rate integration variations tuned to specific GV sites. WPMM matches the probabilities of radar observed reflectivities, Z_e, and gauge measured rain intensity, R. The resulting Z_e-R functions are found to be curved lines in log-log space rather than a straight-line power law (Amitai, 2000).

3.1 Melbourne, Florida

At the Melbourne, Fl. GV site, monthly unconditional distributions ($R>0$) of Z_e and R from the QC merged data are used to derive specific month-to-month Z_e-R lookup tables. The KMLB WSR-88D is a very stable and well-calibrated radar, which allows the WPMM technique to be applied on a month-to-month basis.

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Multiple range techniques are also employed at the Melbourne GV site. Three distinct ranges from the KMLB WSR-88D radar have been defined as 15-50 km, 50-98 km, and 98-150 km. There are three rain gauge networks with gauges distributed throughout all ranges. For a given month, each range has its own uniquely determined WPMM Z_e-R lookup table based on the unconditional distributions of Z_e and R found within that range. There is currently no distinction between convective and stratiform classifications in Z_e-R development. Z_e distributions are obtained by extracting reflectivity from specific CAPPI heights directly over gauge locations. For the closest ranges (15-50, and 50-98 km), NCAR Sorted Position Radar Interpolation (SPRINT) interpolated reflectivities are extracted from the 1.5 km CAPPI height over gauge locations to define the Z_e distributions. For the outer range (98-150 km), SPRINT interpolated reflectivities are extracted from the 3.0 km CAPPI height over gauge locations. Resulting Z_e-R lookup tables are then applied directly to the same CAPPI levels from which they were derived to obtain instantaneous rain rate map products (TRMM Standard Product TSP 2A-53).

Monthly rainfall accumulation products (TSP 3A-54) are obtained by integrating the instantaneous rain rate maps over time. Integration parameters are defined by the time difference, ΔT, between successive radar volume scans. This scheme assumes that instantaneous rain rates remain constant for the duration of the specific radar scan up to a maximum ΔT of 10 minutes. When ΔT exceeds 10 minutes, the rain rate map immediately following the data gap is integrated for 5 minutes. The 5-minute period was chosen as it represents the approximate time of a volume scan in both VCP-21 (9 elevation angles in 6 minutes) and VCP-11 (14 elevation angles in 5 minutes) scanning modes.

3.2 Kwajalein Atoll, Republic of Marshall Islands

At the Kwajalein Atoll GV site (8.7°N, 167.7°E), unique circumstances require different techniques than at Melbourne. Monthly WPMM Z_e-R development is not attempted due to limited rain gauge data. On average, data from less than 7 "good" gauges are available each month. To circumvent this problem, and create adequate Z_e and R distributions, quality-controlled (QC'd) radar and gauge merged data from the entire year of 2002 were combined. This large-scale data compilation procedure, named "2002: A WPMM Odyssey", has captured a full spectrum of instrument events, and has provided adequate distributions for WPMM. Another alternative being considered is the development of seasonal WPMM Z_e-R relations. The seasonal relations would then be applied to the specific months from which they were derived.

Since most of the good gauges are within 98 km of the Kwajalein S-band polarimetric radar, we take a unique approach to the Z_e-R development. SPRINT-interpolated reflectivity data are extracted over the gauge locations from both the 1.5-km and 3.0-km CAPPI levels. Data from the 1.5-km (3.0-km) level are used in the Z_e distribution to develop a Z_e-R lookup table for the 15-98 km (98-150 km) range. By this technique, we are stating that the Z_e-R distributions obtained from radar and gauges within 98-km can be used to develop Z_e-R lookup tables which are applied to the areas both inside and outside 98-km.

The monthly rainfall accumulation scheme employed at Kwajalein is very similar to Melbourne in that the instantaneous rain rate maps are integrated over the time difference, ΔT, between successive radar volume scans. The maximum ΔT for integration is 15 minutes. If ΔT exceeds 15 minutes, the rain rates from the instantaneous map immediately following the gap are integrated for 10 minutes. The 10-minute period was chosen as it represents the approximate time between successive volume scans (with the current scanning strategy).

The stability of the Kwajalein radar is of significant concern. In 2002, the radar appears to have been relatively stable and without significant hardware and calibration issues. For this reason, 2002 was selected for the WPMM yearly technique. The *seasonal* Z_e-R development technique is also sensitive to calibration errors. Radar calibration fluctuations introduce a significant source of error into both instantaneous and monthly rainmaps. The NASA TRMM GV group is working to quantify and apply calibration offsets in such a manner that still allows independent evaluation/validation of TRMM satellite retrievals. One technique being considered is the application of a monthly radar-and-gauge determined bulk adjustment factor. The bulk-adjustment factor would shift the entire WPMM curve in log-log space without altering the slope, and would calibrate the Z_e distribution to match R from the gauges.

4. INTERNAL RAINMAP EVALUATION

Monthly rainfall accumulation products (TSP 3A-54) from Melbourne, Fl. are evaluated in both a *dependent* and *independent* manner. Scatterplots are generated showing the relationship between TSP 2A-56 gauge data and TSP 3A-54 monthly rainfall accumulation extracted directly above the gauges. Dependent validation simply means that the rain gauge data that were used to create the R distribution for the monthly WPMM Z_e-R, are then compared with the TSP 3A-54 radar rain rate accumulation. The gauge data are filtered for radar data gaps, and integrated for the corresponding time period as the radar data. Dependent validation is basically a sanity check to verify that algorithms are performing properly, the data have not become corrupt, and that resulting statistics are within acceptable bounds. Figure 1 is an example of dependent validation at Melbourne, Fl. for August 1998. QC'd rain gauge data (TSP 2A-56), which we consider to be the "ground truth" estimate of rainfall, is shown on the abscissa. Dependent validation (by definition) will result in a radar-to-gauge (R/G) ratio very close to unity (as shown in Figure 1). Statistical plot definitions are given above the figure.

Statistical plot definitions:
μ_G = avg. gauge accumulation (mm)
μ_R = avg. radar accumulation over gauge locations (mm)
σ_G = std. dev. of gauge accumulations
σ_R = std. dev. of radar accumulation over gauges
N_G = number of gauges
$\mu_{G-R} = \Sigma_{\text{all gauges}}(G-R)/N_G$
$\mu_{|G-R|} = \Sigma_{\text{all gauges}}|G-R|/N_G$
σ_{G-R} = std. dev. of gauge radar paired differences
r = correlation coefficient
MAE = $\mu_{|G-R|} / \mu_G$ (normalized mean absolute error)
R/G = μ_R/μ_G

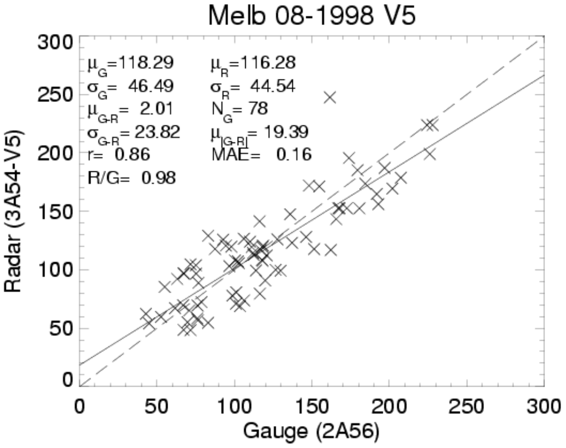

***Figure 1**. Dependent validation of August 1998 (version 5) monthly rainfall accumulation (TSP 3A-54) from Melbourne, Florida. The solid line represents linear regression (least-squares method).*

August 1998 is a unique month in that a *true independent* validation of the TSP 3A-54 is possible. *Independent* validation of this specific monthly rainmap is accomplished by validating against gauge data that were not used in Z_e-*R* development. The August 1998 results (Figure 2) are based on data from 15 independent gauges that were installed in the Melbourne vicinity for the Texas/Florida Underflight Experiment (TEFLUN-B) TRMM field campaign. These 15 gauges were not used in the operational WPMM Z_e-*R* development. Figure 2 shows an R/G bias of 1.08, or an 8% overestimation by the radar, and normalized MAE of 0.09.

True independent gauge data are not available every month, so a technique was devised for "quasi-independent" evaluation. Quasi-independent gauge data are obtained by withholding 10% of the dependent gauges from a particular month from the WPMM Z_e-*R* process. Gauges to be withheld are selected using a random number generator based on atmospheric noise (http://random.org). New Z_e-*R* lookup tables are developed and applied without these randomly selected gauges. The resulting monthly rainfall accumulation map is then compared directly with these withheld gauges. Technically, this method does not evaluate the official monthly rainfall product, *however*, significant changes to the Z_e-*R* distributions have *not* been noted due to the small percentage of gauges withheld.

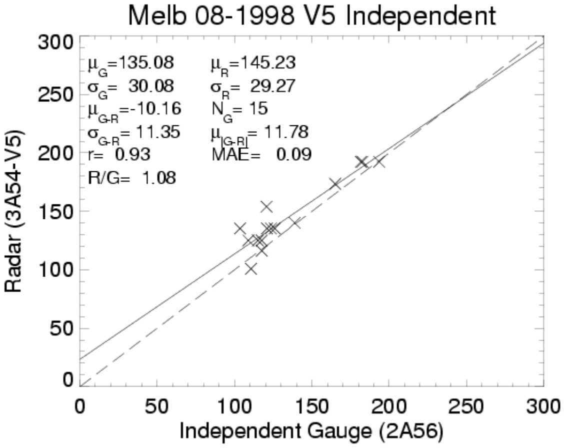

***Figure 2.** Independent validation of August 1998 (version 5) monthly rainfall accumulation (TSP 3A-54) from Melbourne, Florida. The solid line represents linear regression (least-squares method).*

Table 1 shows an 8-month summary of quasi-independent validation results from Melbourne, Fl. Relatively rainy months were chosen. The 8-month radar-to-gauge bias ($\Sigma R/\Sigma G$) is 1.002. Normalized MAE values range from 0.08 to 0.28. As explained in Amitai 2001, the natural variability of rain (within the scale of a radar pixel) and gauge instrument errors may explain a major fraction of the MAE. Point measurements from gauges are not at the same scale of a radar pixel, so gauge-based probability distribution functions (PDFs) of *R*, which are used as "ground truth", may not be representative of the actual *R* distribution at the scale of a radar pixel (Amitai et al. 2002). It is difficult to address this issue, as sufficiently dense gauge networks necessary to represent the distribution of *R* at a radar pixel size are not available at TRMM GV sites. For verification, the TRMM Satellite Validation is planning to establish a super-dense gauge network near the Kennedy Space Center in Florida. Additional scatterplots and validation statistics are posted on the TRMM Satellite Validation Office web site (see summary section for address).

Month/year	R/G bias	MAE	N_G
11/1998	0.94	0.08	6
05/1999	1.02	0.19	9
06/1999	0.95	0.17	10
08/1999	1.00	0.16	9
09/1999	1.10	0.21	9
10/1999	1.08	0.10	9
07/2000	0.94	0.25	10
09/2000	0.92	0.28	10

***Table 1:** Summary of quasi-independent validation statistics over an 8-month period at Melbourne, Fl. N_G represents the number of gauges randomly selected and withheld (see text).*

The specific quasi-independent validation approach just described (on a monthly scale) should not be applied to the Kwajalein Atoll site due to the limited number of rain gauges. However, it may be feasible to apply this technique to Houston, Texas; Darwin, Australia; and potentially new GV sites such as the Florida Keys (Wolff et al. 2003), and Wallops Island, Virginia. As the TRMM Satellite Validation Office evolves and adopts a more general philosophy of precipitation validation, lessons learned from TRMM will appertain to future missions, such as the proposed Global Precipitation Measurement (GPM) mission.

5.0 SUMMARY

The TRMM Ground Validation Program at the NASA Goddard Space Flight Center is responsible for the generation of *official* ground-based radar and rain gauge validation products for the Tropical Rainfall Measuring Mission. Data quality control is a significant aspect of this task. Many levels of quality control are employed before higher-level rainfall products are generated. Varying methodologies have been developed to accommodate unique circumstances at validation sites. The use of the Window Probability Matching Method, multiple-range techniques, constant altitude planes, and adjustable integration schemes reflect significant improvements to version 5 of the ground validation products. True independent and quasi-independent internal validation results from the Melbourne, Fl. validation site indicate that monthly rainfall accumulation products are in excellent agreement with “ground-truth” rain gauge data. Additional information can be obtained from the TRMM Satellite Validation Office web site (trmm-fc.gsfc.nasa.gov/trmm_gv/index.html).

6.0 ACKNOWLEDGEMENTS

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