3R.2

IMPROVING RADAR RAINFALL ESTIMATES AT KWAJALEIN ATOLL, RMI THROUGH RELATIVE CALIBRATION ADJUSTMENTS

D. A. Marks[1,2,*], D. B. Wolff[1,3], D. S. Silberstein[1,2], J. L. Pippitt[1,2], and J. Wang[1,3]

[1]NASA Goddard Space Flight Center, TRMM Satellite Validation Office, Code 613.1, Greenbelt, Maryland 20771
[2]George Mason University, Center for Earth Observing and Space Research, Fairfax, Virginia 22030
[3]Science Systems and Applications, Inc., Lanham, Maryland 20706

1. INTRODUCTION

The TRMM Satellite Validation Office (TSVO) at the NASA Goddard Space Flight Center (GSFC) has developed a technique to quantify and apply Relative Calibration Adjustments (RCA) to reflectivity data from the Kwajalein Atoll S-band radar (KPOL) in the Republic of the Marshall Islands (RMI) for the TRMM Ground Validation (GV) program. The technique is based on the analysis of radar ground clutter pixels, and results in daily reflectivity calibration adjustments. Reflectivity measurements have been compared against the TRMM PR for independent validation of RCA magnitudes. Compared with previous rain rate estimates (Version 5, TRMM GV products), radar rain rate with applied RCA converges with rain rate estimates from rain gauges (by definition) and TRMM algorithms. In years with known and significant calibration issues (e.g. 2000 and 2003), radar rainfall estimation decreased by 30-50% after application of the RCA. Independent comparisons of these ground-based rain rate estimates with Version 6 TRMM PR (2A-25), TMI (2A-12), and COMBINED (2B-31) algorithms show significant bias decreases from prior GV estimates, thereby underscoring the importance of calibration stability in radar rainfall estimation.

2. RCA METHODOLOGY OVERVIEW

The KPOL radar calibration can change for different reasons. Mechanical and engineering issues (e.g. failed parts) in extremely harsh environmental conditions occur frequently. Incorrect calculation of system gains and other parameters, faulty operator adjustments, and calibration drift may also occur. The RCA technique employs the analysis of ground clutter targets to quantify daily reflectivity calibration adjustments relative to a known baseline. The mutually accepted calibration baseline was collectively determined by individuals from several groups (NASA, CSU, and Univ. of Wash.), by comparison of August 1, 1999 KPOL reflectivities with the TRMM PR. This collaboration revealed that KPOL was running 6 dB cold.

*Corresponding author address: David A. Marks, TRMM Satellite Validation Office, NASA Goddard Space Flight Center, Code 613.1 Greenbelt, MD 20771, e-mail: David.A.Marks@gsfc.nasa.gov

By adjusting KPOL reflectivity by +6 dB, the calibration baseline was established. Figure 1 shows a timeline of ground clutter analysis from years 2002 and 2003 that has been correlated with KPOL engineering events. As history has shown, not all KPOL engineering events are immediately detected by radar operators (such as arcing in the waveguide) nor are events consistently documented. Daily cumulative distribution functions (CDFs) of reflectivities from known ground clutter bins were extracted as a first step to detect events that impacted calibration. To segregate ground clutter from precipitation echo, the 95th percentile of the daily CDFs was selected. This subset captures significant as well as subtle calibration events, while excluding contamination from precipitation. For specific technical details on the development of this methodology, see Silberstein, et al (2005).

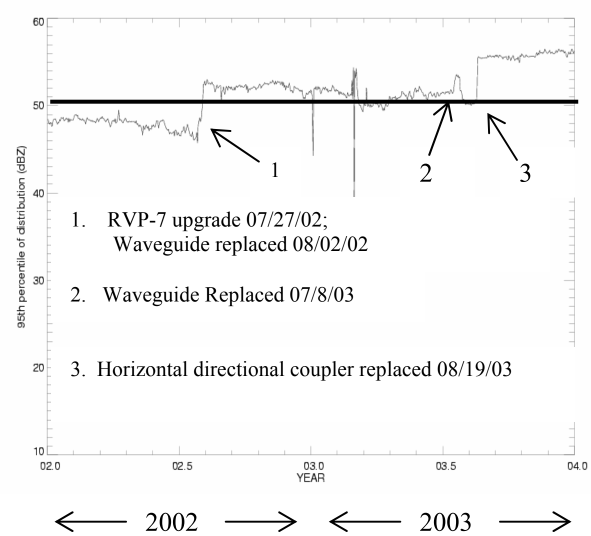

Figure 1. KPOL timeline of the 95th percentile of daily CDFs from ground clutter returns from 2002 and 2003. The dark horizontal line at 50 dBZ represents the calibration baseline to which the data was adjusted. Three distinct engineering events and their associated calibration impact are shown.

A ground clutter analysis was performed on all KPOL reflectivity data from Jan 1999 through Dec 2004, resulting in daily RCAs for the entire period. Table 1 shows approximate calibration adjustments relative to the August 1999 baseline.

Date Range	Approx RCA (dB)
Jan 1999 thru Jul 1999	KPOL very unstable
Aug 1999 thru Mid Mar 2000	+6 to +5
Apr 2000 thru Mid May 2000	+1
Mid May 2000 thru Jun 2000	-1 to –1.5
Jul 2000 thru Mid Sep 2000	+0.5 to –1.5
Remainder of Sep 2000	-3
Oct 2000 thru Mid Nov 2000	–1.5 to +0.5
Mid Nov 2000 thru Mid Dec 2000	-4
Mid Dec 2000 thru Jan 2001	+2
Feb 2001 thru Mar 2001	-0.5 to –1
Apr 2001 thru May 2001	+3
Jun 2001 thru Jul 2002	+2 to +3
Aug 2002 thru Feb 2003	-3
Mar 2003 thru Mid Jul 2003	+0.5 to –1.5
Mid Jul 2003 thru Mid Aug 2003	-3 to –0.5
Mid Aug 2003 thru Mar 2004	-6
Apr 2004 thru Dec 2004	KPOL very unstable

Table 1. Approximate Relative Calibration Adjustments (RCA) from 1999 through 2004.

3. VALIDATING RCA REFLECTIVITIES

To initially check the validity of the RCA results, a comparison was made with the KPOL calibration corrections presented in Houze et al (2004) (their Table 2 – not shown), which relied on the stability of the TRMM PR compared with KPOL. For several periods in the above referenced table, the RCA results compared quite favorably. As shown in Figure 2, both RCA and UW adjustments are initially +6 dB in early August 1999. Both RCA and UW offsets track each other within 1-2 dB. The UW offsets remain constant over large time periods (e.g. Dec 2000 to Aug 2001) until the next rainy PR overpass is analyzed in combination with engineering logs. In contrast, the RCA method computes calibration adjustments on a daily basis as individual engineering events are detected. The TSVO is confident that calibration jumps are being detected; however the magnitude of the resulting RCAs are still in question. For more comprehensive validation, the RCA-applied KPOL reflectivities were also statistically compared with PR reflectivities from 1999 through 2004. TRMM Standard Product (TSP) 2A-55 (SPRINT interpolated CAPPI planes – Mohr, et al. 1979) were created from the KPOL data. The original 2A-55 horizontal resolution of 2km x 2km was de-resolved to 4km x 4km for comparison with the PR (2A-25 V6). The vertical resolution of 2A-55 is 1.5 km. All comparisons were made above the brightband to avoid issues associated with PR attenuation, and all overpasses were weighted equally. Figure 3 shows comparisons of Ground Radar (GR; KPOL) and PR reflectivities for all rainy overpasses from years 2000 through 2003. On an instantaneous scale, average reflectivities from each 4km x 4km pixel were compared from each instrument. Biases in the range of +/- 2 dB are common, and fall within instrument uncertainty. Uncertainty in PR reflectivity factor is estimated to be within +/- 1 dB (Kummerow, et al. 1998). The resolution of the KPOL data is 0.5 dB due to formatting specifications within the TSVO Ground Validation System (GVS), and the *estimated* uncertainty associated with the RCA method is +/- 1 dB. As Figure 3 shows, the average PR reflectivity is generally higher than KPOL. Part of this difference may be explained by KPOL data gaps at higher CAPPI levels due to a lack of sufficient data for interpolation. The gap artifacts may be reducing KPOL averages within the 4km x 4km pixels. The next step after reflectivity comparison is Ze-R development and rain rate estimation.

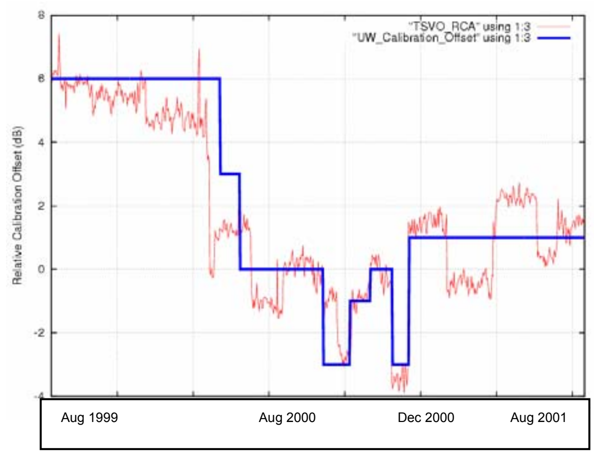

Figure 2. Timeline showing KPOL calibration offsets from the TSVO RCA and UW methods.

4. Ze-R DEVELOPMENT (VERSION 6)

The current GV test version (V6) of Window Probability Matching Method (WPMM, Rosenfeld, et al. 1994) Ze-R development from the Kwajalein site is composed of two main parts. First, the RCA method is applied to bring KPOL reflectivities to the calibration baseline, and second, instantaneous quality-controlled radar and rain gauge data for entire dry and wet seasons are combined for WPMM distributions. The dry season is defined as the months Jan-Jul, while the relatively wet season is defined as Aug-Dec. Separate Ze-R's are determined yearly for both dry and wet seasons from Jan 1999 through Jul 2004. No distinction is made for convective/stratiform classification. Figures 4 and 5 show the yearly variation in seasonal Ze-R's from dry and wet seasons, respectively. In all analyzed dry seasons (except 2003), it is evident that the Ze-R's are quite similar in the range from 20-43 dBZ (Fig. 4). The outlier season of 2003 is the result of significant rainfall that occurred in the Apr-Jul time period. In the analysis of wet season Ze-R's (Fig. 5), it is clearly evident that significant variation occurs from season-to-season.

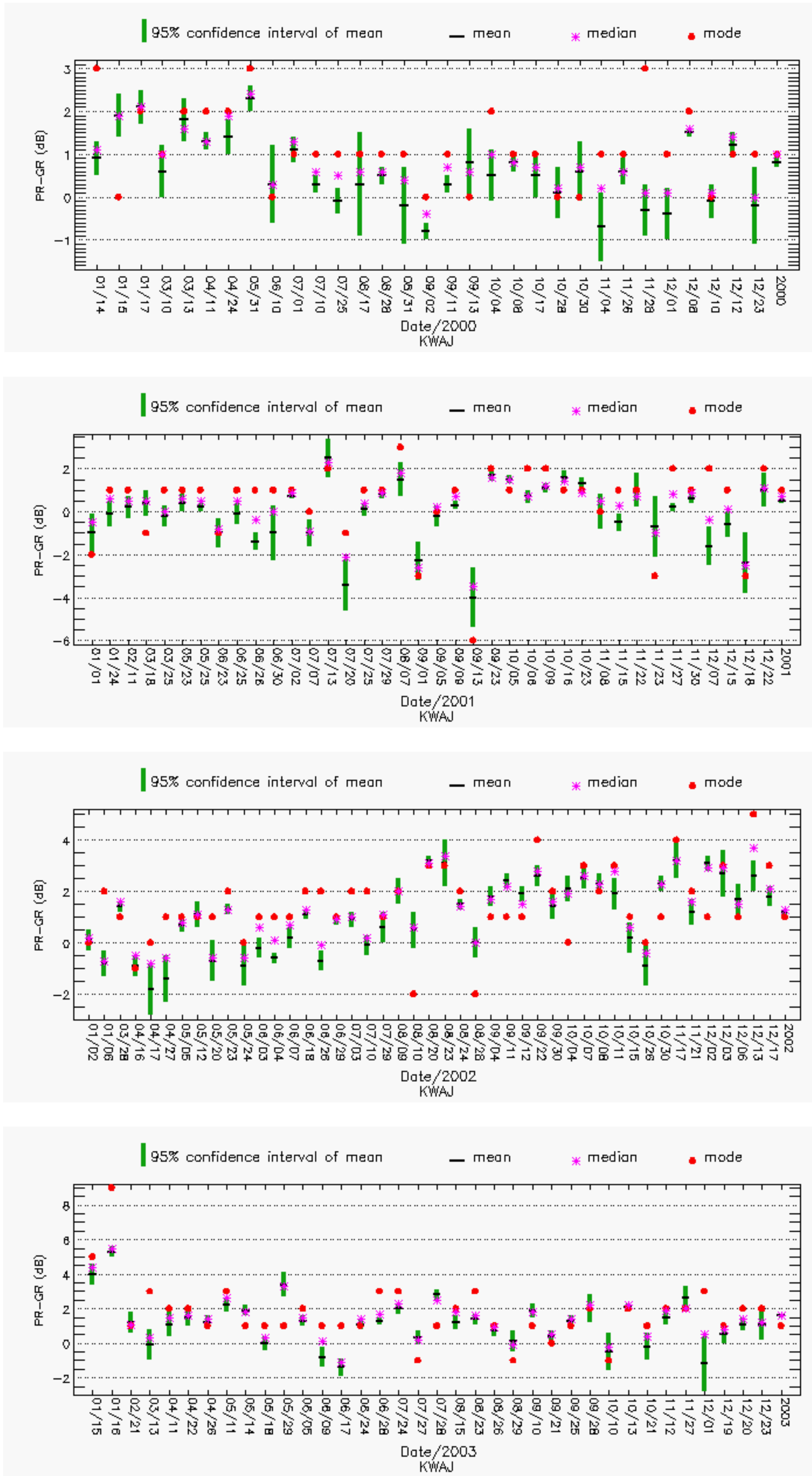

Figure 3. Reflectivity difference between PR and Ground Radar (GR, KPOL) on an instantaneous scale for years 2000-2003. Dates correspond to specific overpass events in which echo was detected from both instruments.

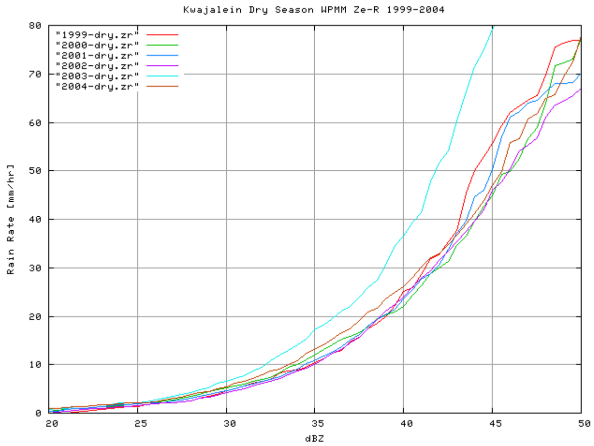

Figure 4. Yearly variation in WPMM gauge-adjusted Ze-R curves from the relatively dry season (Jan-Jul 1999-2004) at Kwajalein Atoll, RMI.

Why these variations are occurring might be related to a number of different factors, such as the varying quantity of "good" rain gauges from season-to-season used by WPMM (see Amitai, 2000 for gauge QC description), and the natural variability of rainfall within the scale of a radar pixel. Also, after application of the RCA, it is expected that KPOL calibration is stable although as discussed earlier, the magnitude of the adjustment is a potential source of error.

In contrast, an analysis of drop-size-distributions (DSDs) from season-to-season, (regardless of wet or dry), shows nearly identical drop size spectra for given reflectivities (pers. comm. Ali Tokay – JW disdrometers located at Kwajalein and Roi Namur). However, the similarities in DSDs from season-to-season may hold true only for the disdrometer, and may not be true of reflectivities aloft. During TOGA COARE, a particle-imaging probe on the NCAR Electra aircraft revealed distributions that were highly variable over the Western Pacific Warm Pool (Yuter and Houze, 1997). The TSVO Ze-R's are all developed from 1.5 km CAPPI data, so surface-based disdrometer distributions (and subsequently derived reflectivities) may not be representative of CAPPI radar reflectivities. The possible reasons associated with changing Ze-Rs from season-to-season (both microphysical and other) are still being addressed.

At this point, it could be questioned why the TSVO employs the RCA technique since WPMM gauge-adjustment is used in Ze-R development. By adjusting to gauges, are we negating the benefit of calibration-adjusted reflectivities? In-house studies by the TSVO group have shown that statistical inconsistencies are introduced into WPMM Ze-R development when uncorrected data with significant calibration jumps are included. The resulting Ze-R lookup table is then not representative for the data that was used in its development. While the WPMM does not require certainty in the absolute calibration of the radar, it absolutely requires stability in the relative calibration. By applying the RCA method, calibration adjusted reflectivities are used by WPMM and the statistical stability results in representative Ze-Rs. In addition, TSP 1C-51 and 2A-55 both contain corrected reflectivities.

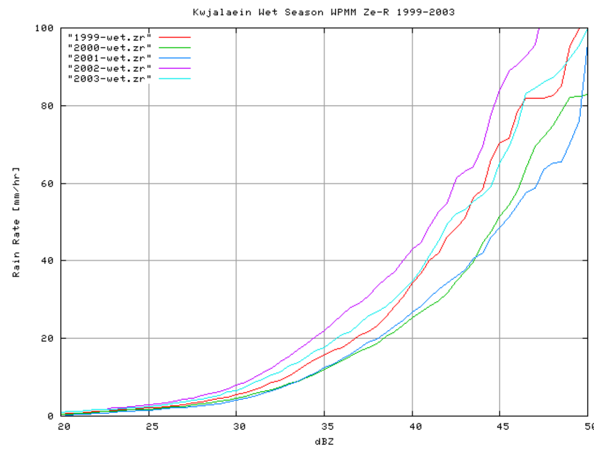

Figure 5. Yearly variation in WPMM gauge-adjusted Ze-R curves from the wet season (Aug-Dec 1999-2003) at Kwajalein Atoll, RMI.

5. VALIDATION OF TRMM RAIN RATE ESTIMATES

Independent comparisons of TRMM PR (2A-25), TMI (2A-12), and COMBINED (2B-31) Version 6 algorithms were performed against Versions 5 and 6 GV rain rate estimates. Satellite data are from the 0.5˚ x 0.5˚ gridded (3G-68) dataset, and the GV estimates (2A-53) were de-resolved into the same 0.5˚ x 0.5˚ grid. The Kwajalein site is considered 100% ocean, and only full-ocean (FO) pixels were considered for the comparison (see Fig. 6).

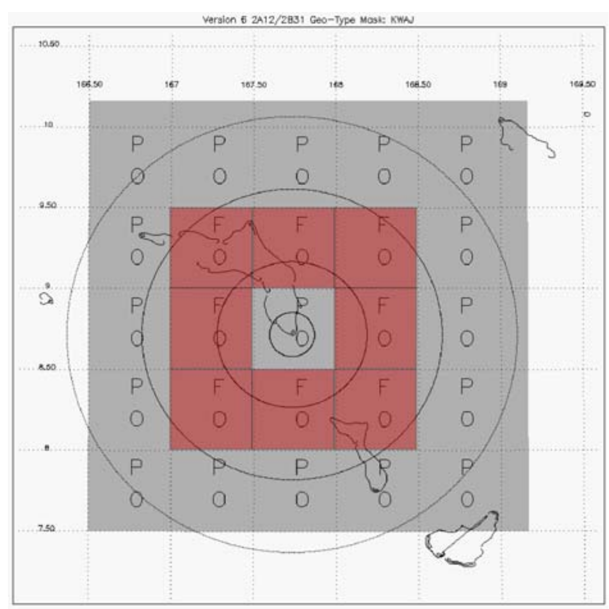

Figure 6. The Kwajalein Atoll GV site with full-ocean (FO) and part-ocean (PO) pixels. Comparisons are performed only within the FO pixels (shown in red).

FO pixels are defined as those that are located within approximately 100 km radius of the KPOL viewing area. Partial-ocean (PO) pixels are excluded. The center pixel is considered PO because of the 15 km exclusion ring at the radar site due to ground clutter contamination. Figures 7 through 10 show bias percentages, scatterplots, and rain rate comparisons between TRMM and GV from years 2000 through 2003. The comparisons in the left column are with GV Version 5, while the right column is with GV test Version 6. All TRMM algorithms are Version 6. The multi-bias percentage plots (top row of figures 7-10) are defined as follows: Given PR (2A-25), TMI (2A-12), COM (2B-31), and GV (2A-53) mean rain intensities, referred to as "Measurements" (M), the bias is calculated relative to some "Reference" (R), using the following equation:

Bias = (R-M) / M; where
M = {PR, TMI, COM, GV}
R = a) GV_Ref; b) Sat_Ref
GV_Ref = average GV estimate within 0.5° x 0.5° grid
Sat_Ref = (PR+TMI+COM)/3 within 0.5°x 0.5° grid

Bias percentage plots show both a GV_Reference and Sat_Reference. The GV bias calculations are interpreted as the percent bias of avg. GV rain rate estimates relative to other algorithms (or retrievals). For example, in year 2000 Version 5 GV rain rate estimates are approximately 65% higher than PR estimates, 60% higher than TMI, and 45% higher than COM estimates. Substantial lowering of these biases is seen when GV test Version 6 is compared (15%, 12%, and 2%, respectively). Table 2 summarizes the percent bias between GV and TRMM algorithms over four years. Positive biases indicate that GV shows higher rain rates than TRMM algorithms. All years (except 2001) show reduced biases from GV Version 5 to test Version 6. Comparisons with PR estimates show much more variability than comparisons with TMI and COM algorithms. These differences with the PR may be correlated with inherent DSD model assumptions and attenuation. From a validation perspective, more emphasis is being placed on comparisons with TMI and COM algorithms.

Year/ GV Version	PR	TMI	COM
2000 / GV V5	+65%	+60%	+45%
2000 / GV V6	+15%	+12%	+2%
2001 / GV V5	+8%	-1%	+3%
2001 / GV V6	+12%	+5%	+8%
2002 / GV V5	-4%	-8%	-12%
2002 / GV V6	+3%	-2%	-7%
2003 / GV V5	+75%	+53%	+58%
2003 / GV V6	+17%	+1%	+4%

Table 2. Bias percentage summary between GV (V5 and test V6) and TRMM rain rate algorithms. This table summarizes the bar charts in Figures 7-10.

Note the significant reduction in bias percentages from GV V5 to test V6 in years 2000 and 2003. Both of these years were characterized by extreme calibration fluctuations (refer to Table 1). The bias percentage differences in years 2001 and 2002 between GV V5 and test V6 were not as great due to better stability of the KPOL radar. Calibration jumps did occur in 2001 and 2002, but longer periods of stability (on the order of months) characterized these years. In all years presented, TMI and COM estimates track very well with GV estimates, although GV rain rates mostly run higher than satellite as shown in the biases and scatterplot regression analyses. The higher rain rates on a yearly basis can be traced to individual months throughout the years (Figures 7-10, bottom row). GV estimates are higher than all satellite estimates in months with higher mean rain intensity. Further study is needed to determine why, but one possible reason is that unresolved small-scale variability is enhancing the gauge accumulations to which GV radar data are adjusted. Differences may also be due to problems with satellite estimates in heavier rain events. Similar studies by the TSVO group from other GV sites (Houston, TX and Melbourne, FL – see Wolff, et al. 2005) indicate underestimation of heavy rain rates relative to GV over ocean pixels.

Additional information is provided in the bar charts of Figures 7 through 10 regarding the satellite algorithms. Sat_Reference is a statistical average of the satellite rain rate algorithms, and is defined as (PR+TMI+COM)/3. Satellite bias calculations can be interpreted as an internal consistency check among the TRMM algorithms. For example, in year 2003 the avg. satellite estimate is 10% higher than the PR, while being 5% and 3% colder than the TMI and COM estimates, respectively. In all four years of comparisons, satellite instrument estimates are within 10% of the avg. satellite estimates. These results are expected considering only FO pixels are considered (see Fig. 6).

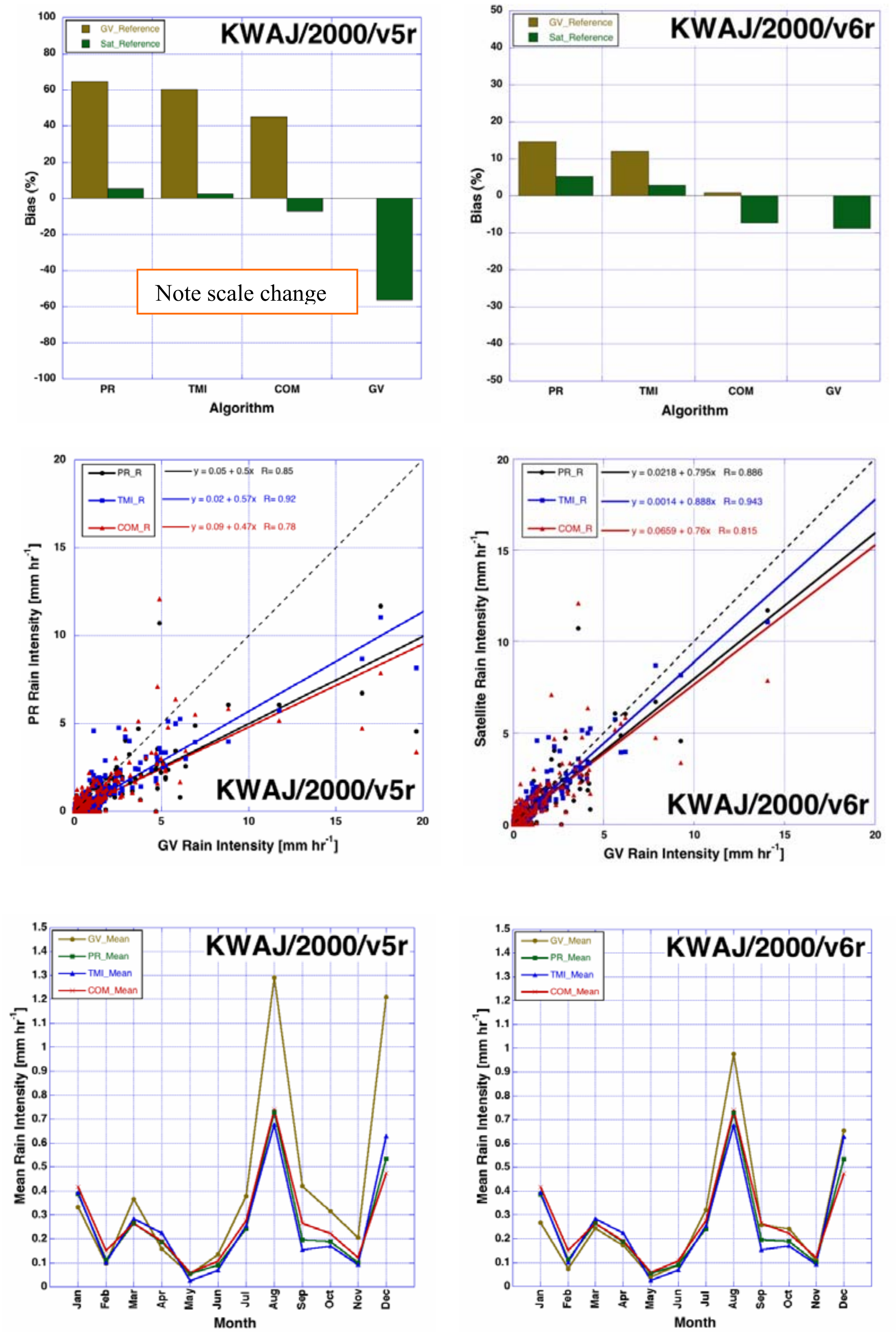

Figure 7. Comparison of TRMM PR (2A-25), TMI (2A-12), and COM (2B-31) rain rate algorithms against GV Version 5 (left column) and test Version 6 (right column) for year 2000. Algorithm biases are presented in the top row, scatterplot intensity comparisons in the middle row, and unconditional mean rate intensity by month in the bottom row. Note the improvement from GV Version 5 to test Version 6. See text for additional explanation.

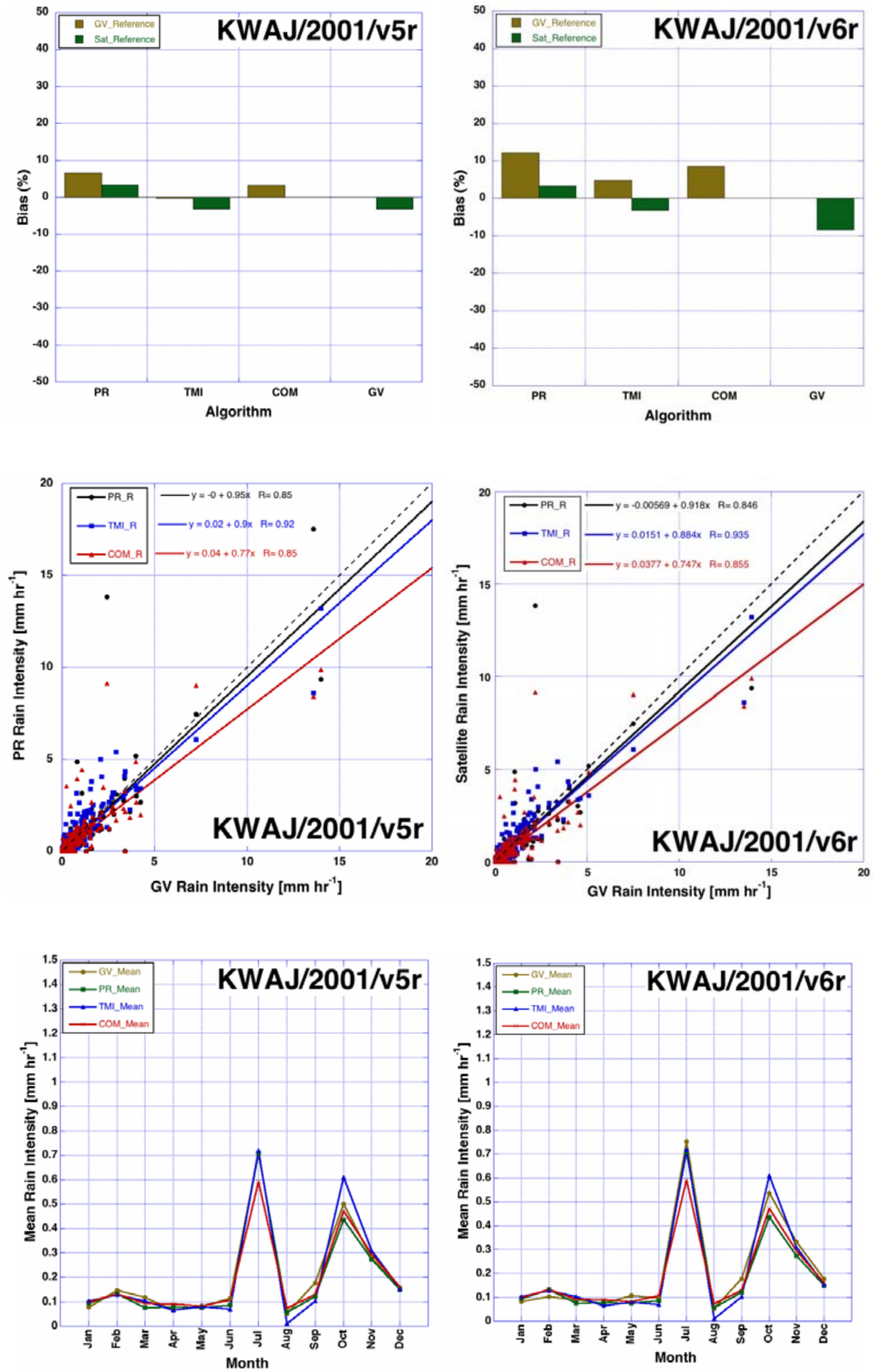

Figure 8. Comparison of TRMM PR (2A-25), TMI (2A-12), and COM (2B-31) rain rate algorithms against GV Version 5 (left column) and test Version 6 (right column) for year 2001. Algorithm biases are presented in the top row, scatterplot intensity comparisons in the middle row, and unconditional mean rate intensity by month in the bottom row. Results became slightly worse from Version 5 to test Version 6, but are still within acceptable bounds.
See text for additional explanation.

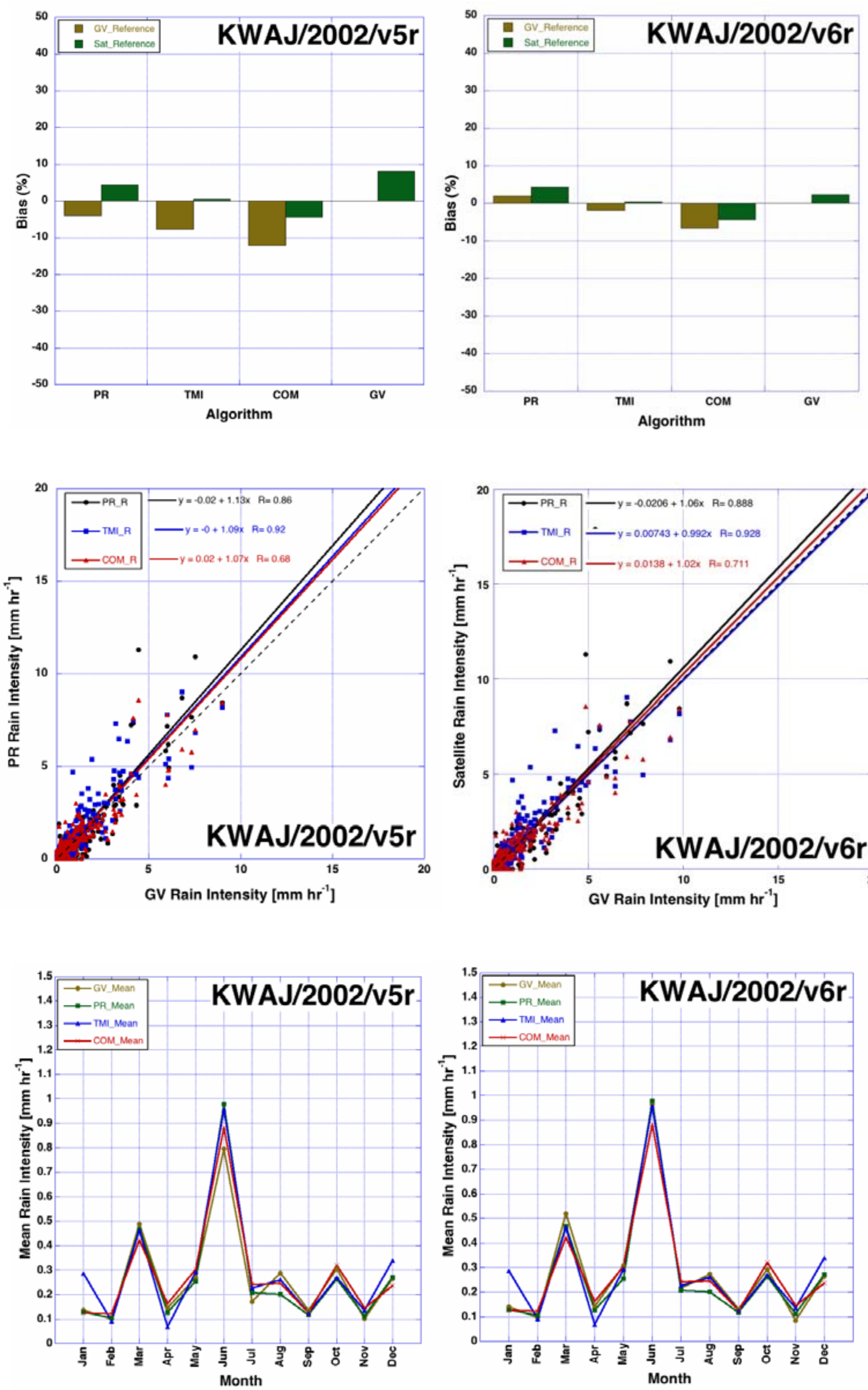

Figure 9. Comparison of TRMM PR (2A-25), TMI (2A-12), and COM (2B-31) rain rate algorithms against GV Version 5 (left column) and test Version 6 (right column) for year 2002. Algorithm biases are presented in the top row, scatterplot intensity comparisons in the middle row, and unconditional mean rate intensity by month in the bottom row. Note the improvement from GV Version 5 to test Version 6. See text for additional explanation.

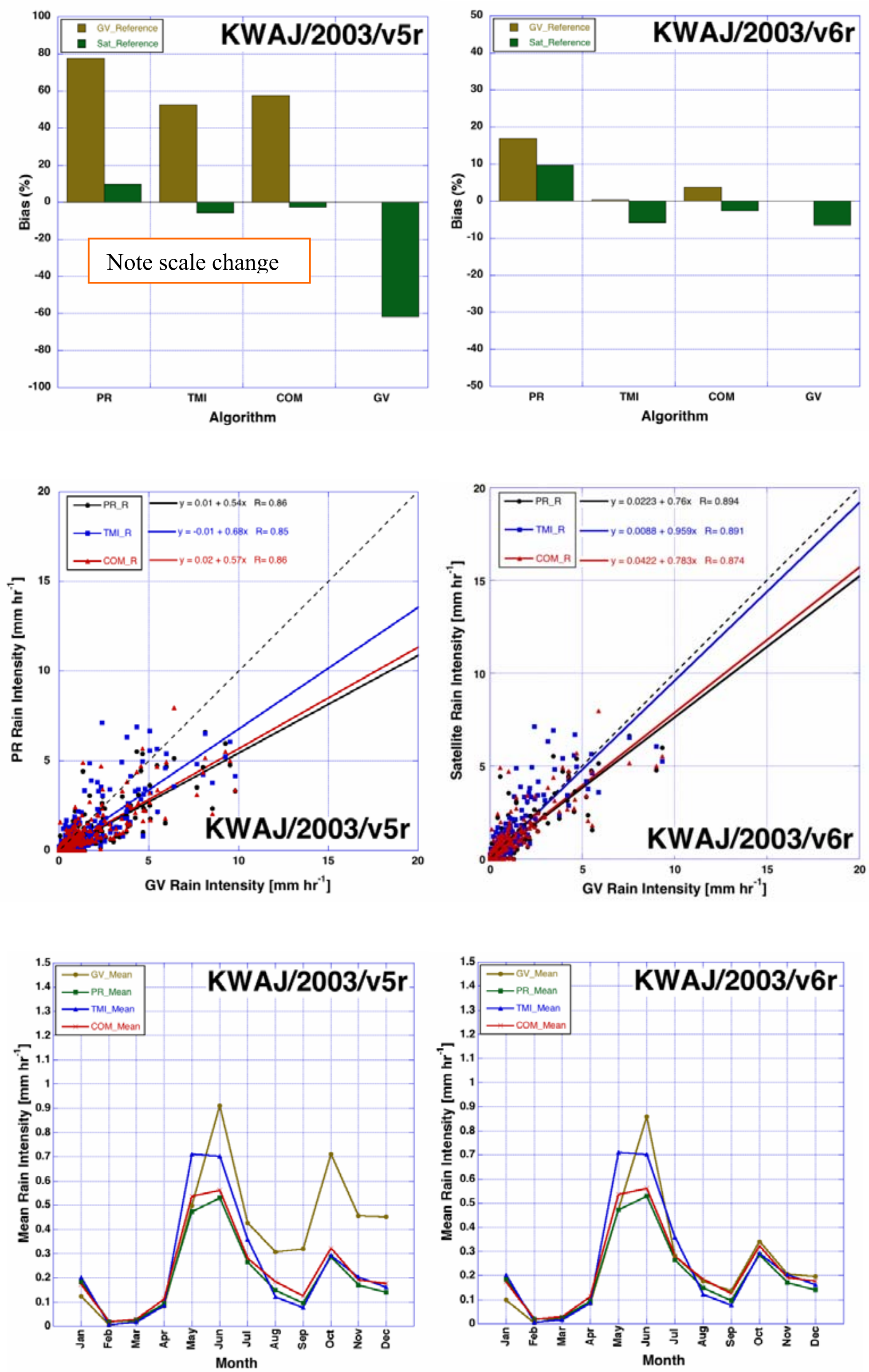

Figure 10. Comparison of TRMM PR (2A-25), TMI (2A-12), and COM (2B-31) rain rate algorithms against GV Version 5 (left column) and test Version 6 (right column) for year 2003. Algorithm biases are presented in the top row, scatterplot intensity comparisons in the middle row, and unconditional mean rate intensity by month in the bottom row. Note the improvement from GV Version 5 to test Version 6. See text for additional explanation.

5. CONCLUSIONS

There are several benefits of applying the RCA methodology to KPOL data. Through application of the RCA, it was subsequently determined that the TSVO Version *5* Ze-R rain rate estimates needed significant improvement. The RCA method has shown that the use of *uncorrected* KPOL data provides inconsistent results even when matched with rain gauge data using WPMM. The RCA method is instrumental in identifying questionable KPOL data through ground clutter analysis, is a valuable aid in the decision to exclude periods of radar instability, and is completely independent of rain gauges. Comparisons of TMI and COM algorithms with GV rain rate estimates are generally within 10% after application of the RCA. Results have shown that in years with significant KPOL calibration fluctuations (2000 and 2003 – see Table 1), applying the RCA method greatly reduces biases between satellite algorithms and GV. The RCA method results in smaller bias reductions in years that are punctuated by smaller calibration fluctuations (2001 and 2002) but are otherwise characterized by periods of stability on the order of several months. After the application of RCA, the yearly biases are dominated by events that occur in one or more months, and are not systematically higher or lower for all months. Both satellite and GV algorithm work is needed to understand these differences. The GV test V6 RCA method for calibration adjustment and Ze-R development have resulted in yearly rain rate bias differences that are within algorithm uncertainty levels at the Kwajalein Atoll GV site. It is hoped that the RCA methodology can be employed in a near real-time basis to provide better quality research data from KPOL. The knowledge learned in this application may potentially be extended to other radar sites in the GPM era.

6. ACKNOWLEDGMENTS

The authors wish to acknowledge Dr. Ramesh Kakar (NASA Headquarters), Dr. Robert Adler (TRMM Project Scientist), and Mr. Richard Lawrence (Chief, TSVO), for funding and support of this effort. The authors are appreciative to Dr. Ali Tokay for disdrometer results and discussions. David Makofski and Bart Kelley are acknowledged for computing support.

7. REFERENCES

Amitai, E., 2000: Systematic variation of observed radar reflectivity-rainfall rate relations in the tropics. *J. Appl. Meteor.* (Special Issue on TRMM), **39**, 2198-2208.

Houze, R. A., Jr., S. Brodzik, C. Schumacher, S. Yuter, and C. Williams, 2004: Uncertainties in oceanic radar rain maps at Kwajalein and implications for satellite validation. *J. Appl. Meteor.*, **43**, 1114-1132.

Kummerow, C., W. Barnes, T. Kozu, J. Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Technol.*, **15**, 809-817.

Mohr, C. G., L. J. Miller, and R. L. Vaughn, 1979: An economical procedure for Cartesian interpolation and display of reflectivity factor data in three-dimensional space. *J. Appl. Meteor.*, **18**, 661-670.

Rosenfeld, D., D. B. Wolff, and E. Amitai, 1994: The window probability matching method for rainfall measurements with radar. *J. Appl. Meteor.*, **33**, 682-693.

Silberstein, D. S., D. B. Wolff, D. A. Marks, and J. L. Pippitt, 2005: Using ground clutter to adjust relative radar calibration at Kwajalein, RMI. Preprints, *32nd Conference on Radar Meteorology*, Albuquerque, NM, AMS

Wolff, D. B., D. A. Marks, E. Amitai, D. S. Silberstein, B. L. Fisher, A. Tokay, J. Wang, and J. L. Pippitt, 2005: Ground validation for the Tropical Rainfall Measuring Mission (TRMM). *J. Atmos. Oceanic Technol.*, **22**, 365-380.

Yuter, S., and R. A. House, Jr., 1997: Measurements of raindrop size distributions over the Pacific warm pool and implications for Z-R relations. *J. Appl. Meteor.*, **36**, 847-867.