Ground Clutter as a Monitor of Radar Stability at Kwajalein, RMI

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(Manuscript received 12 September 2007, in final form 2 April 2008)

ABSTRACT

There are many applications in which the absolute and day-to-day calibrations of radar sensitivity are necessary. This is particularly so in the case of quantitative radar measurements of precipitation. While fine calibrations may be made periodically by a variety of techniques such as the use of antenna ranges, standard targets, and solar radiation, knowledge of variations that occur between such checks is required to maintain the accuracy of the data. This paper presents a method for this purpose using the radar on Kwajalein Atoll to provide a baseline calibration for the control of measurements of rainfall made by the Tropical Rainfall Measuring Mission (TRMM). The method uses echoes from a multiplicity of ground targets. The daily average clutter echoes at the lowest elevation scan have been found to be remarkably stable from hour to hour, day to day, and month to month within better than ±1 dB. They vary significantly only after either deliberate system modifications, equipment failure, or other unknown causes. A cumulative distribution function (CDF) of combined precipitation and clutter reflectivity (Ze in dBZ) is obtained on a daily basis, regardless of whether or not rain occurs over the clutter areas. The technique performs successfully if the average daily area mean precipitation echoes (over the area of the clutter echoes) do not exceed 45 dBZ, a condition that is satisfied in most locales. In comparison, reflectivities associated with the most intense clutter echoes can approach 70 dBZ. Thus, the level at which the CDF reaches 95% is affected only by the clutter and reflects variations only in the radar sensitivity. Daily calculations of the CDFs have recently been made beginning with August 1999 data and are used to correct 7.5 yr of measurements, thus enhancing the integrity of the global record of precipitation observed by TRMM. The method is robust and may be applicable to other ground-based radars.

1. Introduction

A vital task of all those working on the Tropical Rainfall Measuring Mission (TRMM) or using the resulting data is the validation of the accuracy of the rainfall measurements by the precipitation radar (PR) on board the TRMM satellite. This is a primary responsibility of the Ground Validation (GV) Team at the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center. One of our goals has been the review and correction of the observations made by the Kwajalein polarimetric S-band weather radar (KPOL) on Kwajalein Atoll. The radar's specifications are shown in Table 1. Changes in radar sensitivity [see Eq. (2)] can be caused by either deliberate system modifications, equipment failures, or unknown causes.

The best checks of system sensitivity have been made from time to time using observations of solar radiation and standard targets (Atlas and Mossop 1960). However, sensitivity changes have occurred on other occasions that have produced errors in the precipitation re-

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DOI: 10.1175/2008JTECHA1063.1

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TABLE 1. Characteristics of the Kwajalein (KPOL) radar located on Kwajalein Island at the southern tip of Kwajalein Atoll in the Republic of the Marshall Islands.

Frequency	2800 MHz
Wavelength	10.71 cm
Peak power	700 kW
Normal power	500 kW
Pulse width	1.67×10^{-6} s
Pulse repetition frequency	264–1536 Hz
Radar range (maximum)	450 km (243 nm)
Velocity	150 km (81 nm)
Antenna gain	43.8 dB
Antenna diameter	8.2 m (27 ft)
Antenna beamwidth	1.1°
Height to center of antenna	20.7 m (68 ft)
Input power	110/220-V single phase at 7.5–10.0 kW

flectivity and thus in the estimated rainfall. It was therefore necessary to find a means of correcting such errors on a routine basis, even daily. We chose to use echoes from fixed ground structures (ground clutter), as had been done previously in a more limited manner by Rinehart (1978). Indeed, echoes from well-defined structures have been used since World War II as a qualitative measure of radar performance.

The present approach involves the use of the statistics of the clutter-area reflectivity at the lowest elevation scan on rain-free days and similar statistics of the combination of clutter and precipitation reflectivity when raining. A change in system sensitivity alters the features of the probability distributions in a well-defined manner. The goals of this work are 1) to develop the method, 2) to demonstrate the manner in which this method determines changes in system sensitivity whenever they occur, 3) to provide a long-term record of the system sensitivity changes, and 4) to indicate how we plan to correct the KPOL observations and thereby enhance the integrity of the decade-long global archive of rainfall measured by TRMM.

2. Background

A comprehensive review of the nature of ground clutter in a variety of environments is available in Skolnik (2001, chap. 7). Further details may be found in the papers by Billingsley and Larrabee (1991) and Billingsley (1993) as well as others in the Skolnik review. For present purposes it suffices to know that most of the significant clutter echoes at low angles come from spatially localized or discrete vertical features associated with high regions of the visible landscape (e.g., trees, buildings, or towers). A view of the main island of Kwajalein Atoll from space is shown in Fig. 1. Except

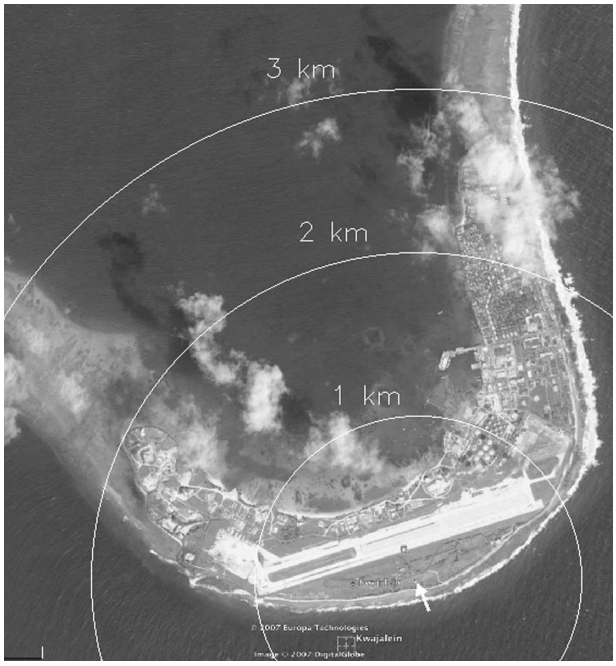

FIG. 1. Aerial view of Kwajalein Island. The KPOL radar, indicated by the arrow, is located at the southern edge of the island. Range rings are drawn at 1-km intervals from the radar site.

for the case of echoes from wind-driven trees, the echoes included in the statistical analysis do not fluctuate as do those from precipitation. The reader is referred to Skolnik (2001, Table 7.1 and Figs. 7.4 and 7.5) for details on the typical strength of clutter echoes from various types of terrain as a function of wavelength. In addition, we acknowledge the existence of sea clutter around the island but note that observed maximum sea clutter reflectivities of 30–35 dBZ are insufficiently intense to affect our analysis.

In what follows the Sigmet Corporation's RVP8 signal processor averages the echoes and produces a digital measure of the reflectivity factor 10log$Z$ (in dBZ). The processor does the same for ground clutter with or without the presence of precipitation.

Using the radar equation,

$$\mathrm{Pr} = CZ/R^2, \tag{1}$$

where Pr is the echo power, R is the range, Z is either the sum of the rain reflectivity (Zr) and the clutter reflectivity (Zc) or the clutter alone, and C includes all the "constant parameters" of the radar such as transmitted power, beamwidth, and pulse width. Taking common logarithms,

$$10 \log Z = 10 \log \mathrm{Pr} + 20 \log R - 10 \log C \ (\mathrm{dB}Z). \tag{2}$$

TABLE 2. Distribution of clutter points as a function of range from KPOL.

Distance from radar (km)	No. of clutter points	Cumulative percentage
1	296	22
2	307	46
3	202	61
4	132	71
5	81	77
6	48	81
7	42	84
8	15	85
9	9	86
10	8	86
>10	183	100
Total points	1323	

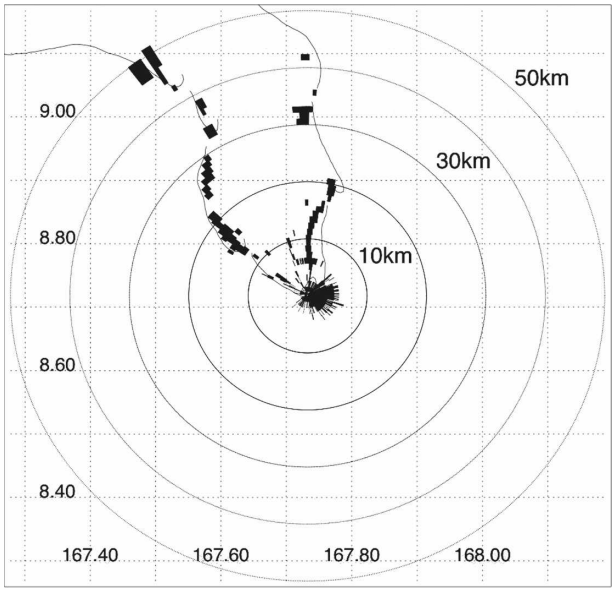

FIG. 2. Map of the clutter field at Kwajalein. Range rings are drawn at 10-km intervals from the radar site.

In accord with common practice in radar meteorology, we simply refer to $10\log Z$ as Z in dBZ. Since the range is known for all precipitation targets, $10\log C$ represents the radar sensitivity (in dB) so that any change in system sensitivity will shift the probability density function (PDF) of the echoes by $\Delta(10\log C)$ dB.

Each clutter echo element is the sum of the reflections from structures within a half pulse length and the beamwidth. Only if the surface features were uniform would we find a systematic range variation such as the inverse third power reported by Skolnik (2001). On the main island of Kwajalein Atoll, the clutter is due almost entirely to human-made structures, so that the range dependence is a function only of the characteristics of those structures. Table 2 contains the distribution of the number of clutter points as a function of range. Twenty-two percent of the points are within 1 km of the radar, 61% within 3 km, 77% within 5 km, and 86% within 10 km. Figure 1 illustrates the high concentration of targets within 3 km of the radar. In general, we need not be concerned with their range dependence, but only with their day-to-day stability (see section 4a). This is to say that the constancy of the clutter echoes indicates the constancy of the radar sensitivity provided only that 1) no changes in surface-based structures on the main island are made, 2) the radar elevation angle at which the clutter is measured remains constant, and 3) the daily area-averaged precipitation echoes do not dominate the clutter. The slight variations of the lowest elevation angle from the nominal value of 0.4° (as seen in the observations to follow) are thought to be responsible in large part for the noise in the day-to-day relative sensitivity.

Because the method requires the constancy of the probability distribution function (PDF) of the clutter reflectivity, we have examined the possible effects of anomalous propagation over all relevant intervals from hours to months and found no significant variations. This is probably due to the oceanic tropical environment of Kwajalein.

3. Specifics of the relative calibration adjustment (RCA) method

A clutter map was developed by constructing a mask where there is a relatively high probability of echo detection in the absence of precipitation. Using the lowest elevation scan of 0.4°, these regions were identified according to range and azimuth from the radar and a database was constructed containing 1323 range–azimuth pairs. This database was used to establish a clutter map, displayed in Fig. 2, that is used for purposes of the quality control of the precipitation measurements. The outline of the clutter does not correspond to Kwajalein Island alone but to the group of islands composing the entire atoll. The 1323 range–azimuth pairs are from observations at intervals of 1° of azimuth and 1 km in range. While data azimuth angles are indexed from scan to scan, there may be slight differences between true and reported azimuths. For each degree of azimuth, the observed reflectivity, hereafter referred to as reflectivity, is recorded at individual gates with 264-m spacing (200-m gate spacing after 1 March 2005). The raw, unfiltered reflectivity at each gate was extracted from the TRMM standard product 1C-51 data. This product is described more fully in Wolff et al.

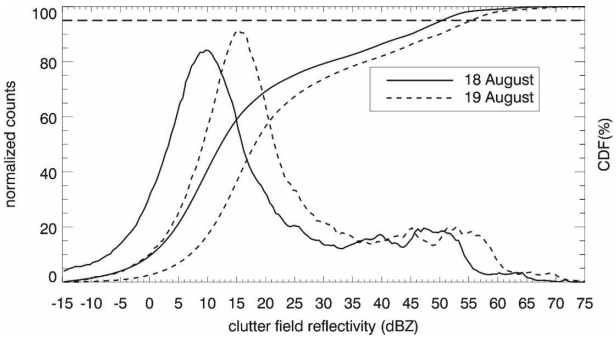

FIG. 3. Comparison of two daily PDFs/CDFs from August 2003. The horizontal dashed line represents the 95th percentile of the CDFs. Failure of the CDF curves to converge at the upper percentiles of the reflectivity is an indication of a calibration shift.

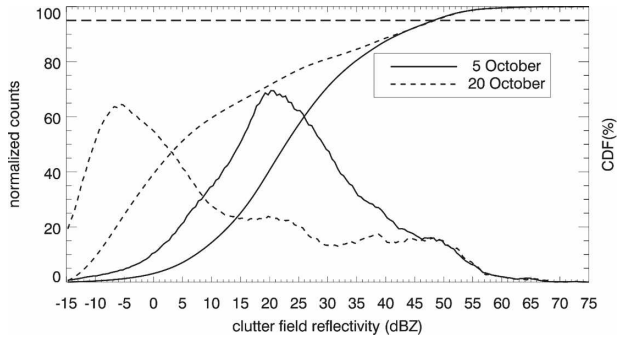

FIG. 4. Comparison of two daily PDFs/CDFs from October 2001. The horizontal dashed line represents the 95th percentile of the CDFs. Distinctly different meteorological conditions exist on the two dates displayed, yet the CDF curves converge at the upper percentiles of the reflectivity, indicative of stable radar calibration.

(2005). Because there are roughly four gates per kilometer, this extraction provides approximately 5000 reflectivity measurements (more than 6500 after 1 March 2005) within the clutter region for a full sweep of the radar. During the course of a day, with volume scans approximately every 6 min, there can be up to 240 scans resulting in daily clutter datasets containing more than 10^6 samples.

In this study, the PDF and corresponding cumulative distribution function (CDF) are based on an entire day of data. Those for consecutive days from August 2003 are shown in Fig. 3. The shift in the mode of the PDF between 18 August (solid curve) and 19 August (dashed) is the same as that throughout the entire CDF. It is worth noting that the meteorology on these two dates is quite similar with only widely scattered rainfall on both dates; however, the CDFs for these two consecutive dates differ considerably at higher reflectivities, indicating a change in 10log$C$. Independent engineering logs provided by 3D Research Corporation (3DRC) reveal that this particular change is related to the replacement of a directional coupler on 19 August.

In the second half of 2001, it was generally accepted that the KPOL radar was operating in a relatively stable mode as determined by engineering logs. The PDFs and CDFs for 5 and 20 October are displayed in Fig. 4. Visual inspection of radar images for these dates indicates that very different meteorological conditions existed on these 2 days. On 5 October (solid curve), numerous organized rainbands traversed the site, while on 20 October (dashed curve), precipitation was generally light and widely scattered. Because reflectivity associated with precipitation rarely exceeds 45 dBZ (and is much smaller for the daily area mean) at Kwajalein, the combined CDF of Zc and Zr approaches 100% close to that level under ordinary circumstances, that is, the most representative absolute value of C. However, when C changes with a sensitivity change, the new combined CDF will attain 100% at either a smaller or larger reflectivity value depending upon whether 10log$C$ increases or decreases, respectively. Empirical tests have shown that the 95th percentile of the CDF is a very reliable indicator of such changes and provides robust sampling based upon $\approx$ 50 000 values per day. This is the level to which we refer through the remainder of this paper. An evaluation of the 95th percentile of daily CDFs over the 7.5 yr of data processed is displayed in Fig. 5. It is evident that there are periods of great stability of the radar sensitivity and others when the sensitivity has changed significantly. Most of these obvious changes in sensitivity have been directly tied to significant engineering events such as the failure or replacement of major radar components and not to any atmospheric phenomena. The power of the RCA method will be demonstrated subsequently.

To provide daily data adjustments, we must track the

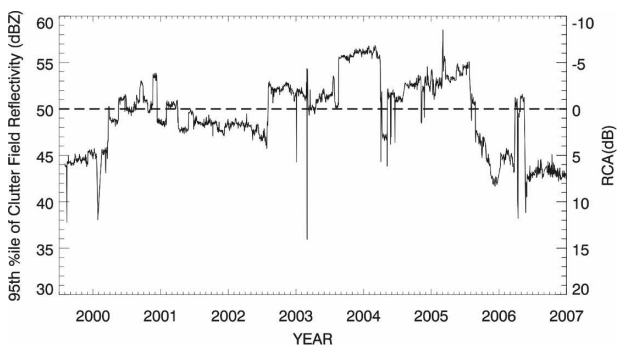

FIG. 5. Time record of the 95th percentile of daily CDFs of clutter field reflectivity at Kwajalein. The RCA, displayed on the vertical scale to the right of the figure, is calculated by subtracting the 95th percentile value from the baseline value of 50 dBZ.

95th percentile of the CDF routinely. A baseline measurement must also be determined, requiring a high degree of confidence in the calibration at a specific time. Fortunately, as a result of the intensive Kwajalein Experiment (KWAJEX) field campaign conducted in 1999 (Yuter et al. 2005) and subsequent collaboration among several institutions [NASA, the Colorado State University, and the University of Washington (UW)], a consensus was reached among researchers that the radar was running about 6 dB too low, based on comparisons with the TRMM precipitation radar (PR), on-site sphere calibrations, and other methods, during the month of August 1999. The RCA baseline was thus established by adding 6 dB to the 95th percentile value of 1 August 1999, making that value the standard to which all subsequent days would be compared. The original value on 1 August is 44 dBZ; therefore, the baseline value was set to 50 dBZ. To calculate the RCA, the daily 95th percentile value is subtracted from the baseline value. The result of this calculation for the period of August 1999–2006 is displayed on the right-hand scale of Fig. 5. It is clear that there are periods during which the radar sensitivity runs low and positive adjustments are required; the converse is true when the sensitivity is high. It is remarkable that the change in radar sensitivity between 2004 and 2006 amounted to ≈14 dB. Even though there are relatively stable periods, it is worth noting that almost every day may require some adjustment, as the RCA is rarely equal to zero. Given that the majority of the daily data will undergo at least some revision with major adjustments in certain cases, it is vital to assess the extent to which engineering issues affect the continuity and stability of KPOL data and demonstrate how the RCA can produce accurate precipitation measurements.

To check the validity of the RCA results initially, a comparison was made with the KPOL calibration corrections presented in Houze et al. (2004, their Table 2). The latter relied on the documented stability of the TRMM PR (Kozu et al. 2001). For several periods in the above-referenced table, the RCA results compared quite favorably. As shown in Fig. 6, both RCA and UW adjustments were initially +6 dB in early August 1999. Both RCA and UW offsets usually track each other within 1–2 dB. The UW offsets remain constant over long time periods (e.g., December 2000–August 2001) until the analysis of the next rainy PR overpass in combination with engineering logs. Because only a small number of TRMM overpasses with substantial rain occur in any month, the UW method can result in missed calibration changes and uncertain timing of appropriate adjustments. In contrast, the RCA method computes calibration adjustments on a daily basis using a ground clutter analysis of every volume scan during the day, thereby ensuring that all fluctuations (documented and undocumented) are detected. An example of the ability to detect engineering events via the RCA is presented in Fig. 7, with a display of four separate incidents (marked a–d) occurring during 2000 and 2001. The nature of each event was obtained from radar logs and is summarized in Table 3.

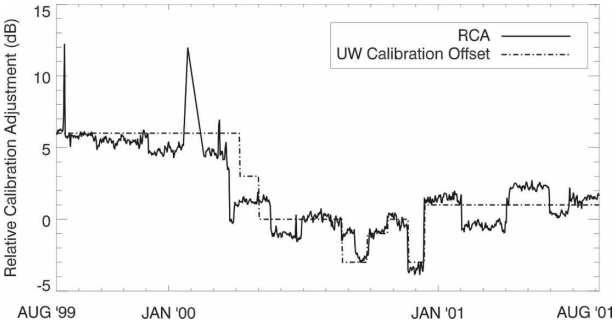

FIG. 6. Time record showing KPOL calibration offsets from the TRMM-GV RCA method compared with the UW offset.

4. Other factors

a. *Sensitivity of ΔRCA: Maximum range and day to day*

To examine the effects of using clutter at three maximum range intervals (1, 5, and 10 km with 22%, 77%, and 86% of the clutter, respectively), we developed Table 4 for a 10-day period in July 2007. We see that the 1-km maximum range shows the greatest stability with an average day-to-day fluctuation in magnitude of only 0.07 dB. The average increases to only 0.22 dB at 5-km maximum range and remains steady at 0.21 dB for 10-

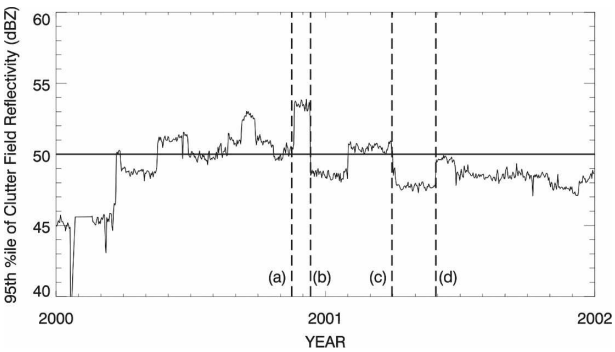

FIG. 7. Time record of the 95th percentile of the clutter field reflectivity for 2000 and 2001. The letters a–d mark four separate events described in Table 3 where engineering issues impacted the time record. The solid horizontal line at 50 dBZ represents the baseline reflectivity used in the calculation of the RCA.

TABLE 3. Description of engineering events depicted in Fig. 7.

Event	Date	Radar log account	Magnitude of change (dB)
a	19 Nov 2000	Pulse forming network replaced	≈3
b	12 Dec 2000	Pulse forming network replaced	≈4.5
c	2 Apr 2001	Antenna gain decrease	≈3
d	31 May 2001	Antenna gain increase	≈2

km maximum range. It is likely that the shorter range interval is dominated by a few very strong and stable targets. Any of these ranges are acceptable although the somewhat greater ranges appear to be slightly more susceptible to fluctuations due either to slight variations in antenna elevation angle, earth curvature, or atmospheric conditions.

b. Calibration case study

The PDFs and CDFs for 2 days in May 2004, another period of unstable radar calibration, are displayed in Fig. 8. Although the meteorological conditions on these 2 days are similar with widely scattered showers, the PDFs reveal that there is a substantial jump in the calibration from 7 May (solid lines) to 8 May (dashed lines). The shift in 10log$C$ of approximately 8 dB at the 95th percentile is one of the largest changes observed on consecutive days. As was the case with the August 2003 example described in section 3, a portion of the calibration change during May 2004 can be tied to a documented engineering event: the changing of the directional coupler loss from 50.47 to 48.1 dBZ on 7 May. We do not imply that the coupler loss alone is entirely responsible for the 8-dB change in 10log$C$; rather that there are very likely other undocumented factors affecting the radar performance during this period.

TABLE 4. Day-to-day ΔRCA (dB) during July 2007 illustrating the range effect.

Date	ΔRCA (1-km limit)	ΔRCA (5-km limit)	ΔRCA (10-km limit)
11 Jul	−0.12	−0.46	−0.41
12 Jul	0.01	0.02	0.03
13 Jul	0.06	0.22	0.23
14 Jul	0.19	0.26	0.31
15 Jul	−0.05	0.12	0.10
16 Jul	−0.09	−0.19	−0.18
17 Jul	0.08	−0.28	−0.28
18 Jul	−0.04	0.33	0.25
19 Jul	−0.04	0.13	0.15
20 Jul	0.03	−0.20	−0.19
Avg magnitude	0.07	0.22	0.21

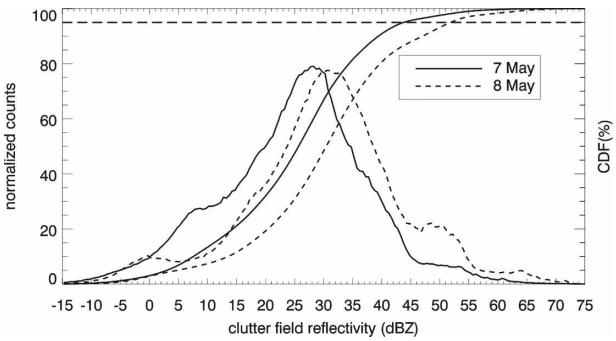

FIG. 8. Comparison of two daily PDFs/CDFs from May 2004. The horizontal dashed line represents the 95th percentile of the CDFs. Failure of the CDF curves to converge at the upper percentiles of the reflectivity is an indication of a calibration shift.

The impact of such a sudden and extreme change in calibration can also be seen in the actual radar imagery. Two radar images, taken almost exactly 24 h apart, are presented in Figs. 9a and 9b. It is evident from a comparison of these two figures that a significant change in sensitivity had occurred. The 8 May reflectivity values appear considerably larger in the area of the sea clutter and across the entire radar domain.

c. Controlled KPOL calibration offset test

In February 2007, in cooperation with the 3DRC radar operations staff, a test was performed to examine whether the RCA could accurately depict a prescribed calibration offset at KPOL. The test was structured so that within a span of 3 days, during a meteorologically quiescent period with no other engineering tasks scheduled, the operator first decreased both the horizontal and vertical calibration offsets by 2 dB from their nominal values and then increased calibration offsets by 2 dB above their nominal values. The PDFs and CDFs for 3 days are presented in Fig. 10. The results clearly show that for reflectivities typical of clutter there is an approximate shift about the 8 February PDF of ±2 dB. The direct impact of this shift in the PDFs can be seen more clearly in the plot of the daily RCA values over this period, depicted in Fig. 11. The RCA value on 10 February is approximately 2 dB greater than the 8 February value, as one would expect for a decrease in calibration offset (a leftward shift of the PDF), while the 11 February RCA value is approximately 2 dB less than the 8 February value as one would expect for an increase in calibration offset (a rightward shift of the PDF). This result indicates that in the absence of major engineering issues, such as an inaccurately pointed radar beam, the RCA has the capability to track a drift in radar sensitivity.

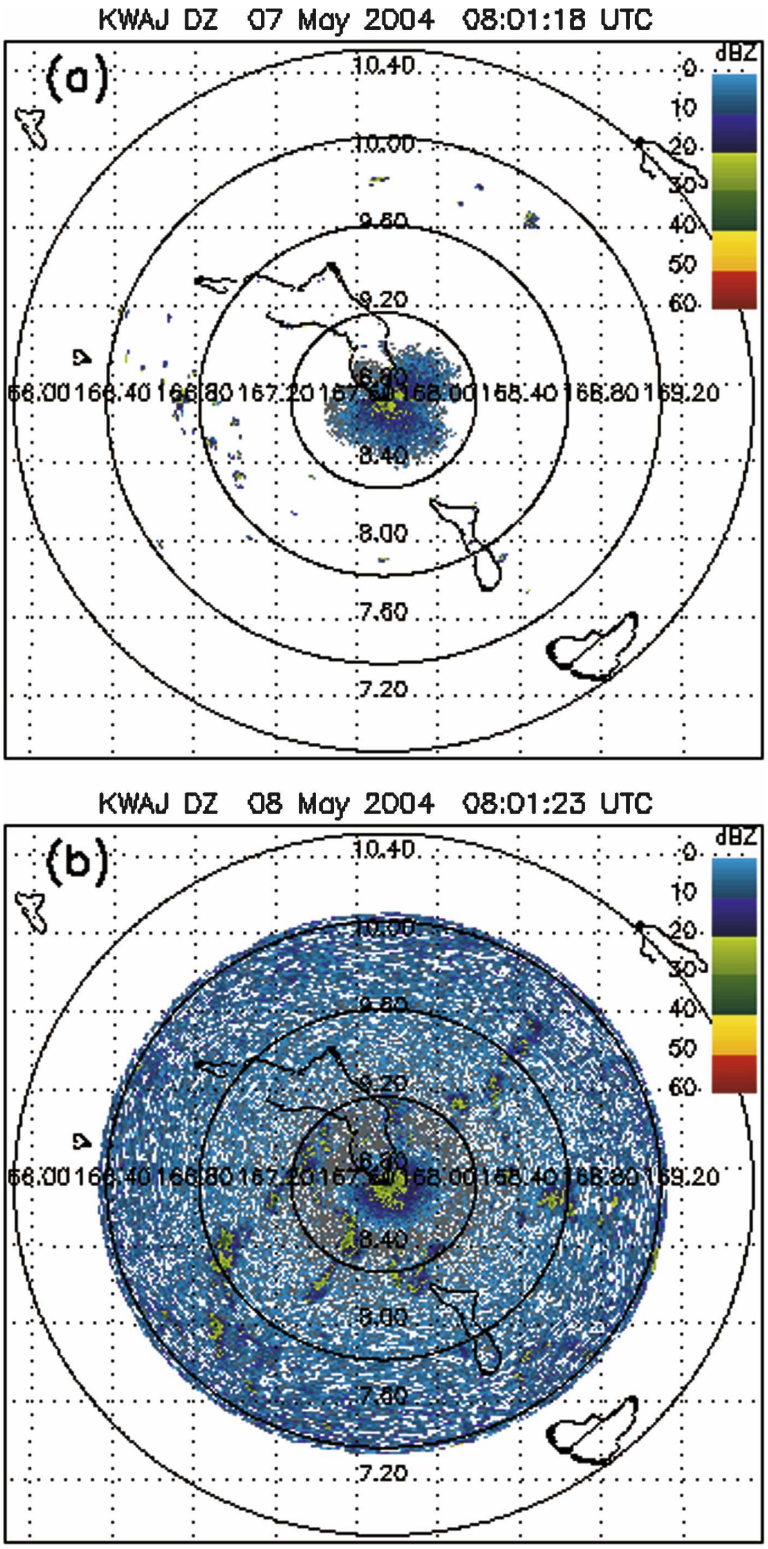

FIG. 9. Raw reflectivity images displaying evidence of a sensitivity shift between (a) 0800 UTC 7 May 2004 and (b) 0800 UTC 8 May 2004. Identical reflectivity color tables are used for both images. Range rings are plotted at 50-km intervals.

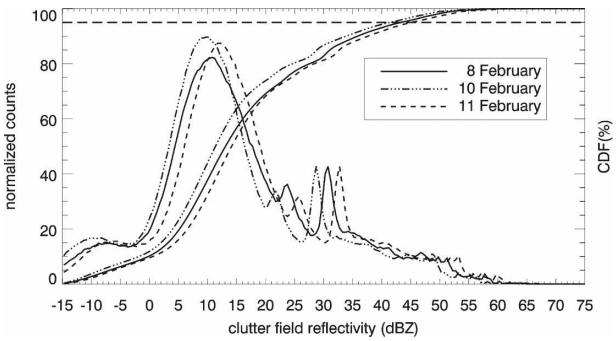

FIG. 10. Comparison of three daily PDFs/CDFs illustrating the effects of a prescribed ±2 dB radar calibration offset (February 2007).

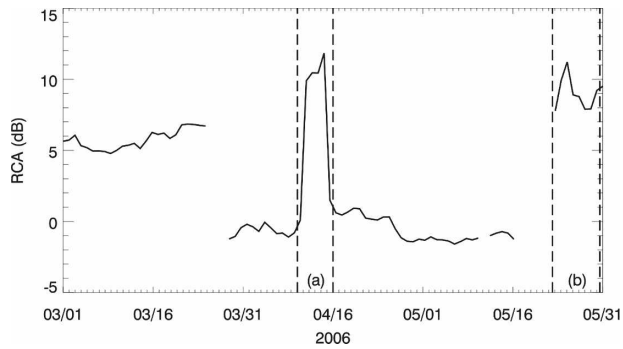

FIG. 12. Time record of the RCA displaying radar elevation angle modification during periods marked a and b.

5. Detecting elevation angle offsets

A series of events in 2006 further highlighted the capability of the RCA to detect changes in the actual pointing angle of the KPOL radar. Two prominent spikes in the reflectivity time record can be seen in Fig. 5 during early 2006. This portion of the time record is expanded in Fig. 12 to display the period from March through May of 2006. In the first period of interest (marked a), the RCA jumps to a value approaching 12 dB before settling back to a value near 0 dB within a span of 5 days. Clearly, a major engineering event occurred during this period and a careful examination of the radar logs provided the explanation. Testing of a new solar calibration software utility (Sigmet's SUNCAL) indicated that the antenna's elevation offset was not on track. On 10 April, the antenna offset was adjusted from −18° to −17.2°, and then reset to −18° on 15 April. As a result, we realized that we were not only dealing with changes in calibration, but also with changes in the elevation angle of the radar beam. The sensitivity is such that for every 0.1° increase in beam elevation angle, the RCA increases approximately 1 dB.

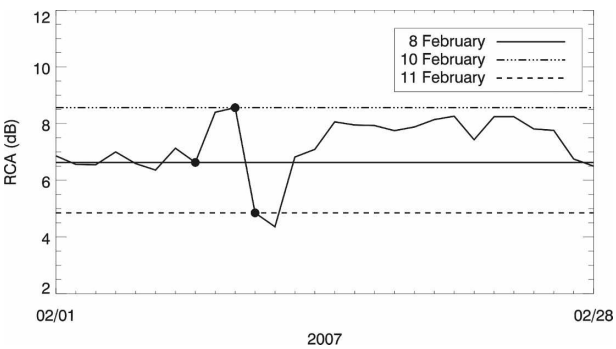

FIG. 11. Time record of the RCA illustrating how it tracks a prescribed ±2-dB radar calibration offset.

In addition, another event occurred at the end of May that demonstrated the impact of changes in the elevation angle. During May 2006, a calibration team arrived at Kwajalein to perform their yearly investigation (Smith et al. 2007). While there, they ran the Sigmet solar calibration utility and as a result of their findings the antenna offset was adjusted from −18° to −17.25°. Evidence of this change is clearly seen in Fig. 12 (marked b), concurrent with another substantial increase (≈ 9 dB) in the RCA. This confirms that elevation angle modification can alter the RCA greatly. The overshooting of ground clutter targets has a major effect, thus reemphasizing the importance of maintaining the stability of the elevation at the lowest level scan.

6. Summary and conclusions

This paper presents a method for monitoring the sensitivity of a radar from day to day. It uses a large set of echoes from ground clutter at the lowest beam elevation to provide a stable reference cumulative distribution function (CDF) of equivalent reflectivity Zc of the clutter echoes that reflects the change in radar sensitivity. This is done automatically, on a daily basis, regardless of the presence or absence of precipitation within the clutter area. The CDF in the presence of rain is due to the sum of the rain reflectivity Zr plus Zc. However, because the technique employs the daily area-averaged echoes, the precipitation reflectivity does not alter the CDF significantly. Any change in radar sensitivity displaces the entire CDF by an amount corresponding to that change. We have shown that the dBZ shift in the 95th percentile of the CDF of (Zr + Zc) is a remarkably reliable measure of the change in sensitivity.

The primary conditions required for the stability of the method are that 1) no changes in surface-based structures responsible for the clutter are made, 2) the radar elevation angle at which the clutter is measured

remains constant, and 3) the daily area-averaged precipitation echoes do not dominate the clutter. The best results occur when the surface targets are within the radar horizon.

The relative calibration adjustment (RCA) method has been used to provide a long-term record of system sensitivity for the KPOL radar at Kwajalein, the only rainfall ground truth radar in the tropical Pacific for the Tropical Rainfall Measuring Mission (TRMM). It has revealed previously undetected changes in sensitivity due either to intentional or unknown causes, such as system modifications, antenna offsets, alterations of the receiver, or the data processor. We have used this approach to correct the 7.5 yr of radar rainfall measurements by TRMM, thus ensuring the integrity of the near-global climatology of the water budget. The RCA method is applicable to any ground-based radar that does not use Doppler filtering of clutter and is not subject to intense and frequently recurring anomalous propagation in radar vicinity. Readers interested in learning more about the GV program's near-real-time monitoring of KPOL performance may access the team's Web site (http://trmm-fc.gsfc.nasa.gov/KWAJ/RCA) for further information.

Acknowledgments. This study was funded by NASA Grant NNG07EJ50C. The authors thank Dr. Ramesh Kakar (NASA Headquarters), Dr. Robert Adler (TRMM project scientist), and Mr. Richard Lawrence (chief, TRMM Satellite Validation Office) for their guidance and support of this effort. We are grateful to Dr. Merrill Skolnik for discussions of ground clutter, to Mr. Bartie Kelley for developing the suite of routines in the Radar Software Library (RSL in IDL) used in this study, and the support of David Makofski and Marcella Shupp. We also acknowledge the valuable comments of the reviewers.

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