University of Washington Kwajalein Ground Validation Rain Maps:

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1. Introduction

The purpose of this document is to explain and describe the revised and expanded University of Washington Ground Validation rain maps for Kwajalein. A full set of products for July-December 1999 is being submitted herewith to the DAAC. These products replace all products generated previously by the University of Washington for these months. Products for other months since the TRMM launch are also being reprocessed and will soon also be on the DAAC. Table 1 lists the products generated for each month of Kwajalein GV data. A more detailed documentation of the specifications of each product is provided at

www.atmos.washington.edu/gcg/MG/KWAJ/UWproductsOnDAAC.html

This new product set is the result of ~15 years of research on the development of TRMM ground validation products. It is also the result of a long effort to install and operate scientifically credible ground validation instrumentation at Kwajalein, a very remote location. Besides being remote, it is an atoll with extremely limited locations for rain gauges. Ground validation is intrinsically challenging because of the inherent uncertainties in both radar and rain gauge data under the best of conditions. Difficulties operating at Kwajalein make the ground-validation measurements even more problematic. Nevertheless, the uniqueness of the site makes it invaluable for long-term oceanic ground-validation for satellites. We have taken care to document carefully all the sources of uncertainty in the ground validation data set from Kwajalein. The new University of Washington Ground Validation product set is the first in which the sources of uncertainty are identified separately, and each is evaluated quantitatively as an error bar for the best estimate maps. Our product consists of a set of low and high estimates associated with each source of uncertainty as well as providing a best estimate of the rain maps at Kwajalein.

There are four different sources of uncertainty in the rain maps: the calibration of the radar, the vertical profile of reflectivity below the lowest beam of the radar, the *Z-R* relation implied by the drop size distribution, and gaps in the data collection. The new University of Washington Ground Validation product takes all four uncertainties into account independently in the monthly rain map for Kwajalein.

These four sources of uncertainty are often lumped together in a *Z-R* relationship. We choose to separate them, since they are independent sources of error. The calibration error is a bias with no random error (calibration error is generally constant for a given radar volume). The variation with height depends on precipitation type and atmospheric conditions and has a bias and random error. The variation in the drop spectrum also has a bias and a random component. By separating the sources of error, we help the user understand how to interpret the data, and we obtain a more clear indication of where improvements are needed.

To produce new monthly rain maps for Kwajalein, all the individual base reflectivity maps have been reprocessed, and instantaneous rain maps re-computed. The re-computed instantaneous surface rain maps are computed by a series of steps in which each factor affecting rain rate is treated separately. First, we obtain the best estimate of the reflectivity field before converting to rain rate, by applying the best estimate of the radar's instrumental calibration. Next, the reflectivity at the lowest elevation angle is extrapolated empirically to near the surface via climatological vertical profiles of radar echo to obtain the best estimate of the rain rate at the ocean or land surface. This step removes range effects owing to the typical upward tilt of the radar beam. Then, and only then, do we convert the surface reflectivity field to rain rate. For this step, we use a Z-R relation based on the typical drop-size distribution measured by disdrometers at Kwajalein. The final step corrects the rain maps for periods of missing data during the month. This data-gap filling method is primarily an interpolation procedure.

The University of Washington Ground Validation monthly product, obtained by applying these steps, consists of a netcdf file on a 151×151 grid of 2-km square pixels. As indicated in Table 1, there are nine fields on this grid:

- Best estimate of monthly rain accumulation
- Low and high estimates resulting from calibration uncertainty
- Low and high estimates based on assumed vertical profile of reflectivity below lowest beam
- Low and high estimates resulting from uncertainty in drop-size distribution
- Low and high estimates resulting from uncertainty in gap filling algorithm

In Sections 2-5 below, we explain how we obtained the best, low, and high estimate rain maps for each category of uncertainty.

2. Calibration uncertainty

A meteorological radar's calibration should be monitored against a stable standard, which is difficult to obtain at Kwajalein. While a network of several hundred rain gauges can serve as a calibration standard (Joss et al. 1998), such a network is logistically not practical to set up at Kwajalein Atoll. Most of the area surveyed by the radar is ocean, most of the islands have smaller area than an individual radar pixel, and only a handful of the islands are sufficiently large as to be not awash with sea water during storms. Data from the approximately 10 rain gauge/radar pixel pairs usually available from the atoll region are inadequate for statistical monitoring of the calibration. The TRMM satellite precipitation radar (PR) is the most consistently available comparison standard for the Kwajalein ground validation radar. Unfortunately, this inverts the role of the satellite and ground radar to a large extent. The Kwajalein radar is no longer an independent check on the precipitation radar (PR). The Kwajalein radar, calibrated against the PR, however remains an important ground validation site for the TRMM microwave imager (TMI) as well as for other satellites, such as the planned AQUA and GPM. Also, the Kwajalein radar can still be used to validate the PR in terms of vertical profile of reflectivity, attenuation correction, convective-stratiform separation, and sampling limitations of the satellite. We have employed a simple method to determine the gross calibration changes that have occurred at Kwajalein since the TRMM launch in November 1997.

We have determined the calibration correction required to make the area covered by echo > 17 dB*Z* at the 6-km level (ice region) consistent between the TRMM PR and the Kwajalein ground validation radar. This level is not subject to the uncertainty of attenuation correction since it is above the melting layer. The last column of Table 2 lists the calibration correction required to obtain consistency between the Kwajalein ground validation radar and the PR according to our simple analysis. The middle column of Table 2 lists major changes in the status of the Kwajalein radar that appear to be associated with the abrupt changes in calibration correction.

Bolen and Chandrasekar (2000) have developed a program that makes an exhaustive three-dimensional layer comparison between the Kwajalein GV radar and the TRMM PR. The few calculations available from their method so far are generally consistent with the values listed in Table 2. We have obtained the software to make these comparisons as a regular check of the results of our more simple echo-area comparisons. The only number in Table 2 that is considered final at this point in time is the +5 dB correction for 22 June 1999-1 January 2000. Before the next release of data to the DAAC, we will make further checks on the calibration correction via the method of Bolen and Chandrasekar (2000) .

The quality of the GV radar/satellite calibration adjustment is a function of the radar echo area (i.e., sample size) during the set of overpasses used to calculate the adjustment. During the Kwajalein dry season of Jan-May, there is much less radar echo than during the rest of the year. Calibrations derived for the dry periods are subject to more error than those derived during wet periods.

The calibration corrections in Table 2 remove the major part of the calibration bias associated with changes in the status of the radar equipment. Our best estimate rain maps are computed using the calibration corrections indicated in Table 2.

After the gross calibration correction has been made according to Table 2, an uncertainty remains regarding the engineering calibration once these gross corrections have been made. The basic operation of the radar is monitored by standard methods. Aeromet Kwajalein makes daily measurements of the transmitter performance (peak power, modulator current, and magnetron current) and of servo performance. Antenna gain and alignment measurements using a solar scan measurement technique are also made daily to monitor the performance of the receiver and the antenna. A receiver calibration is performed about once a month by putting known power levels into the system with a signal generator. Sphere calibrations have proved unfeasible because of typical strong winds. A standard-gain horn calibration has been performed as part of a comprehensive radar hardware assessment in October 1999, March 2000, and March 2001. Given these measurements, a conservative (rather than optimistic) estimate of typical hardware calibration uncertainty at Kwajalein is ±2 dB (personal communication with P. Smith, E. Mueller, and V. N. Chandrasekhar) . This uncertainty is consistent with the magnitudes of the estimated calibration corrections in Table 2, which suggest that the instrumental calibration of the Kwajalein radar undergoes sporadic changes of the order of a few dB.

The 1999-2000 Kwajalein disdrometer data set used in Section 4 to obtain the *Z-R* relation is used again here, to determine the uncertainty in rain rate associated with the apparent calibration uncertainty of ±2 dB. The best-estimate *Z-R* relation derived from the disdrometer data set is used to calculate $[R(\text{dB}Z\pm2)/R(\text{dB}Z)] \times 100\%$. This calculation yields the percentage error for reflectivity under- and overestimated by 2 dB. The percentages are 130% for dBZ+2 and 70% for dBZ-2. Therefore, our high- and low-estimate maps are obtained by multiplying the best estimate pixels by 1.3 and 0.7, respectively.

3. Vertical profile uncertainty

One of the principal uncertainties in estimating surface rain rate from radar is in the change in reflectivity with height below the lowest beam of the radar (Joss and Waldvogel 1990; Vignal et al. 2000). Over tropical oceans, this effect is assumed to be small because of the generally high humidity below cloud base. Nonetheless, the drop-size spectrum continues to evolve by coalescence, breakup, and sedimentation below the lowest elevation angle. Moreover, this effect becomes greater with increasing range, as the beam tilts upward relative to the surface of the earth. The height of the 0.4^{o} beam (typically the lowest scan of the Kwajalein radar) reaches almost 2.5 km above sea level 150 km away from the radar. Kwajalein does not have enough reliable gauges to adjust the range dependency of the radar for measurements of surface precipitation. Therefore, to estimate this effect we have calculated the most probable values of the dBZ difference between the lowest elevation angle and the surface for both convective and stratiform precipitation. We apply these to the lowest scan of the Kwajalein radar to extrapolate the radar data to the surface before calculating the Kwajalein rain maps.

The reflectivity-profile correction values are derived by a procedure similar to that of Vignal et al. (2000). The method is applied to 1,313 three-dimensional volumes of data obtained by the Kwajalein ground validation radar between August 1998 and January 2001. The data volumes are all those obtained by the Kwajalein ground radar during TRMM TMI overpass times during this period. These volumes thus constitute a randomly selected sample of sufficient size to represent a wide range of conditions at Kwajalein. We consider radar data only out to 50 km from the radar to insure sufficient vertical resolution and coverage down to the 0.5-km altitude. The volumes were interpolated to 0.5 km in the vertical and 2×2 km in the horizontal. Table 3 contains the reflectivity difference between the 0.5-km level and the indicated beam height as determined from this data set. These values are the modes for the entire 1,313 volume data set. These values imply the most probable shape of the vertical profile of reflectivity below a beam height of 2.5 km. The profiles for convective and stratiform regions are shown in Fig. 1. The curves are extended to the surface (0 km) by extrapolating the portion of the curve between 0.5 and 1 km down to the surface.

Convective and stratiform pixels are identified by the TRMM ground-validation program's convective-stratiform separation algorithm. To apply the vertical profile correction, the height of the center of the beam of the lowest elevation scan is computed for each radar pixel. From this height and the classification of the pixel as convective or stratiform, the surface reflectivity is estimated according to the empirical profiles in Fig. 1. An appropriate Z-R relation is then applied to this vertical-profile-corrected map as described in the section below to yield the associated rain maps. For the map representing the "low" estimate, the stratiform correction value is used for all echo regions. For the "high" estimate map, the convective correction value is used for all echo regions.

4. Drop size distribution (*Z-R*) uncertainty

The drop size distribution of the rainfall sampled by radar is not constant. Therefore the rain rate estimated from reflectivity is always an educated guess, based on the statistics of the drop size spectra that occur in the region of the radar site. How the statistics of the drop size spectra are applied to make a guess of the rain rate depends on how the radar data are to be applied. Every measurement of the drop size spectrum implies a relationship between the rain rate *R* and the Rayleigh-scattering properties of the drops (i.e., their reflectivity *Z* at the wavelengths of weather radar). The best guess of the instantaneous rain rate is derived from the modal value of the rain rate associated with a given *Z*. The best estimate of the net rain accumulation over a long time period and area is derived from the mass-weighted mean of the number distribution of the rain rate associated with a given *Z*. Since the rain rate over tropical oceans tends to be log-normally distributed, the mode, mean, and mass-weighted means may differ substantially. Hence we must choose our *Z-R* relation based on the application we have in mind. Since the goal of TRMM is to produce accurate climatological rain accumulations over large time and space scales (Simpson et al. 1988), we have chosen a *Z-R* relation that gives the best time-area integrated climatology. It should be recognized that this relation may differ from that which gives the best instantaneous rain mapping.

To derive the *Z-R* that will give the best climatological rainfall results for Kwajalein, we use drop size data collected by a Joss-Waldvogel distrometer at Kwajalein in the wet seasons of 1999 (KWAJEX) and 2000. We compare two data sets, the *R* values calculated directly from the DSD (i.e., calculated *R*) versus the *R* values derived using the *Z-R* relation with the *Z* calculated from the DSD as input (i.e., derived *R*).

The procedure for determining the best estimate of the instantaneous rain rate would be to minimize error in an individual sample (i.e., one pixel in one instantaneous map or 1 disdrometer sample). The associated metric would be a root mean square error between the calculated and derived *R*, so the "best" *Z-R* for this application has the lowest root mean square error. We did not do this because we seek the *Z-R* that will produce the best climatological rain accumulation over the Kwajalein region. Instead, we minimized error in rain accumulation over many samples. The associated metric weights heavier rain rates more as they contribute more to the accumulation. In this case, we examine the ratio of the accumulation of the calculated *R*s and the accumulation of the derived *R*s. The "best" *Z-R* is the one for which the ratio is 1.

For the *Z-R* relation we use the standard form, $Z=aR^{1.5}$. Use of a fixed exponent was proposed by Smith and Joss (1997) and was tested extensively by Doelling et al. (1998) and Steiner and Smith (2000). To obtain values for the coefficient *a*, we looked at the disdrometer data collected in the 1999 and 2000 wet seasons and arrived at the "best" values of the coefficient *a* for each summer independently and the two summers treated as one large data set. This superset had 13,153 1-min rain samples. We accumulated these into consecutive 10-min subsets to minimize sampling error in the calculation of *Z* and *R* (see Smith et al. 1993). To obtain the *Z-R* we used 891 10 min samples totaling 869 mm of rain. The result is:

$$\text{Best: } Z=175R^{1.5}$$

The high and low estimates were obtained by comparing the "best" *a* values for the 1999 and 2000 samples independently. The difference between these is an estimate of yea- to-year variability in the calculation, which is sensitive to the rain rate distribution occurring in a particular year. The rain rate distribution at any one spot is not exactly reproducible year to year.We are assuming that the fundamental nature of rainfall at Kwajalein did not change from 1999 to 2000. We then apply this estimate of year-to-year variability, rounding up slightly from 13.5 to 15 units of coefficient *a* to obtain our high and low estimates for the rain maps:

$$\text{Low: } Z=190R^{1.5}$$
$$\text{High: } Z=160R^{1.5}$$

We recognize that use of data from only two years gives a poor estimate of year-to-year variability but this is all the data we have so far. This uncertainty in our estimate is why we rounded from 13.5 to 15 "*a* units" to obtain our high and low estimates. As more data is collected at Kwajalein we may need to refine our high and low estimates. But based on examination of data from other sites, we are reasonably confident in our error bounds and that data from future years will be within them.

5. Gap filling uncertainty

For each radar volume during a month, if the time to the next volume is less than 20 min, then that volume's instantaneous rainrate map is applied to the gaptime and the accumulation is added to the monthly accumulation. If the time between two radar observation volumes exceeds 20 min, the gap is filled by interpolation. First we determine the average rain rate over a time period equal to that of the gap for the times both preceding and following the gap. The lower rain rate is extrapolated across the gap to provide a low estimate of conditions in the gap, while the higher average is extrapolated across the gap to provide a high estimate of conditions in the gap. The best estimate of conditions in the gap is obtained by linear interpolation (averaging) of the low and high values across the gap.

6. Summary

The best estimate monthly rainfall product listed in Table 1 (raccumbest) is based on:

- applying a calibration correction based on matching the size of the echo covered area (>17 dB*Z*) seen by the TRMM PR and the Kwajalein ground-based radar, fine tuned by the method of Bolen and Chandrasekar (2000),
- extrapolating the observed reflectivity from the lowest elevation angle to the surface using a climatological convective or stratiform reflectivity correction value,
- using a disdrometer-based *Z-R* from 2 wet seasons at Kwajalein and fitting the *Z-R* to maximize the accuracy of the monthly accumulation over the entire radar-viewed area, and
- filling radar data gaps by interpolation.

The monthly rainfall products with suffixes "lo" and "hi" in Table 1 quantify the uncertainties in the best estimate as follows:

- For the calibration correction, the engineer estimate of a 2-dB instrumental calibration uncertainty was used to estimate low and high estimates.
- For the vertical profile correction, the precipitation is assumed to be all stratiform (convective) to produce a low (high) estimate.
- For the distrometer based *Z-R*, the statistics for the two years of data were taken as an indication of the year-to-year variability to produce a low and high estimate.
- For gap filling, the rain rate on the less (more) rainy side of the gap is extrapolated across the gap to give a low (high) estimate of the rain in the gap.

By separating the sources of uncertainties and quantifying them to the degree possible, we hope to guide users of the Kwajalein ground validation radar toward an appropriate application of the data set. We also provide a clear indication of where improvements in the Kwajalein data need to be made.

References

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Table 1. The University of Washington ground validation product set archived on the DAAC. DZ is reflectivity, CZ is corrected reflectivity, VR is radial velocity, YYYY is the year, MM is the month, DD is the day, HH is hour, MM is minutes, SS is seconds, uf indicates universal format, cdf indicates netcdf format. Field names: DZ--reflectivity, CZ--corrected reflectivity, VR--radial velocity, maxdz--reflectivity, rainr--rain rate, convsf--indicator of whether echo is convective or stratiform, raccumbest--overall best estimate of accumulated rainfall, raccumgaplo/hi--lower and upper limits owing to gap filling uncertainty, raccumzrlo/hi—lower and upper limits owing to *Z-R* relation uncertainty, racccumcallo/hi—lower and upper limits owing to calibration uncertainty, raccumvplo/hi lower and upper limits owing to vertical profile uncertainty. Asterisk (*) indicates only for volumes of interest (i.e., volumes within +/-15 minutes of overpass times and volumes with significant rainfall (areal rainfall rate ≥ 0.15mm/hr).

Product	**Naming Convention**	**Field(s)**	**Hor. Res**	**Hor. Domain**	**Vert. Res**	**Vert. Domain**
Corrected Reflectivity	1C51UW.kwaj.YYYYMMDD.HHMM.uf	DZ, CZ, VR	N/A	N/A	N/A	N/A
Base Reflectivity Maps	baseUW.kwaj.YYYYMMDD.HHMMSS.cdf	maxdz	2 km	150×150 km	N/A	N/A
Instantaneous Rainmaps	2A53UW.kwaj.YYYYMMDD.HHMMSS.cdf	rainr	2 km	150×150 km	N/A	N/A
Convective/ Stratiform Maps	2A54UW.kwaj.YYYYMMDD.HHMMSS.cdf	convsf	2 km	150×150 km	N/A	N/A
3-D Interpolated Volumes*	2A55UW.kwaj.YYYYMMDD.HHMMSS.cdf	maxdz and radial velocity	2 km	150×150 km	1 km	2-15 km
Month Rainmaps	3A54UW.kwaj.YYYYMM.cdf	raccumbest raccumgaplo raccumgaphi raccumzrlo raccumzrhi raccumcallo raccumcalhi raccumvplo raccumvphi	2 km	150×150 km	N/A	N/A

Table 2. Calibration corrections and their association with various changes in status of the Kwajalein ground validation radar. Asterisk indicates tentative value. The time period during which KWAJEX occurred is the only fixed nontentative estimate. The other values will become fixed in future releases, when the products for those periods are generated.

Time period (YYMMDD)	**Change of Radar Status**	**Calibration correction (dB)**
980805-981013		+2*
981022-981228	azimuth motor replaced 981013-9810211, yearly hardware assessment 9810	0*
990110-990519	transmitter diode replaced 981228-990109	+2*
990520-990621	pulse filament transformer changed 990519	bad
990622-000101 (KWAJEX)	separate V channel installed, polarization switch removed, pulse burst aligned, stalo adjusted 990621	+5
000101-000331	high voltage power supply fails in Jan, radar operates in limited mode, power supply is replaced in March, yearly hardware assessment March 2000	?*
000401-000821	azimuth tachometer shutdown 000319, azimuth belt maintenance 000406	+1*
000822-001212	Pulse forming network (PFN) replaced 000822	–3*
001213-010105	Pulse forming network (PFN) replaced 001212	+4*
010106-010301		?*
010302-010519	thyratron replaced 010301, yearly hardware assessment March 2001	+2*

Table 3. Modal values of reflectivity difference between the beam height and the 0.5-km level. Based on data from all TMI overpasses between August 1998 and January 2001.

Beam height (km)	**Difference between reflectivity at 0.5 km and the reflectivity at beam height**	
	Convective	**Stratiform**
2.5	3.04	0.21
2.0	2.33	0.40
1.5	1.56	0.47
1.0	0.86	0.44

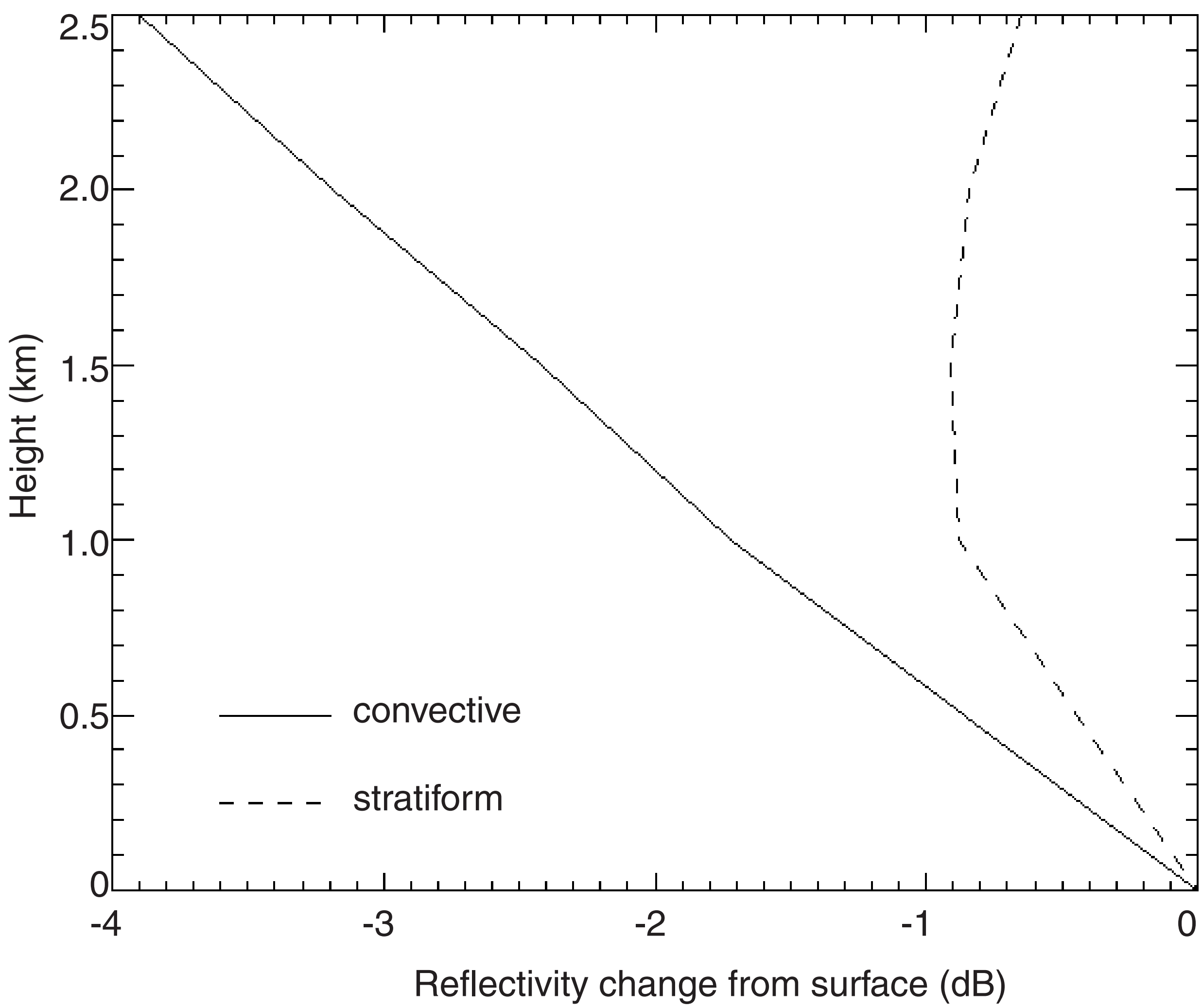

Figure 1. Most probable vertical profiles of reflectivity at Kwajalein.