Rainfall Profiling Using ARM Millimeter Wavelength Cloud Radars

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Introduction

The Atmospheric Radiation Measurement (ARM) Program Data Archive contains detailed vertically resolved radar measurements representing echoes from clouds and precipitation. Since it earlier days, the ARM Program has invested heavily (both financially and intellectually) in the development of remote sensing methods to retrieve cloud microphysical parameters. No significant development for retrievals of precipitation parameters using the standard ARM instrumentation has occurred, except for some attempts to retrieve parameters of weak drizzle using millimeter wavelength cloud radar (MMCR) reflectivity measurements. Precipitation, however, is a crucial part of the water cycle, and adding a capability for retrieving quantitative precipitation information from routine ARM measurements would benefit the scientific community and overcome a certain inadequacy in characterizing the vertical atmospheric column above the ARM remote sensing sites.

One reasons for the lack of ARM precipitation retrievals is that the 34.6 GHz frequency of the MMCR ARM radars is not suitable for traditional reflectivity-based rainfall estimations because of the high rate of attenuation of the radar signals at this frequency in rain. While the absolute reflectivity measurements from the MMCR can hardly be used for retrieving the quantitative information about rainfall, some non-traditional approaches can be suggested for estimating rainfall using available MMCR measurements in a relative sense. While attenuation is a limiting factor for applying reflectivity – rainfall rate relations, it can be used as the useful information in a method that relates rainfall rate to range derivative of reflectivity as a function of height above the ground.

Theoretical Background

Rainfall rate, R, is proportional to the product of the drop terminal velocity, V_t, and the rainwater mass, which in its turn is proportional to the third moment of the drop size distribution (DSD) spectra:

$$R \sim \langle V_t(D) D^3 \rangle ,$$

where D is the equal-volume spherical raindrop diameter and the angular brackets indicate integrating over DSD, which is usually denoted as $n(D)$. Figure 1 shows the product of $V_t(D)D^3$ as a function of D. The calculations in Figure 1 are performed for the mean bin sizes (shown as symbols in Figure 1) of a typical impact-type Joss-Waldfogel disdrometer (JWD) that is often used to measure rain DSD spectra. It can be seen from the presented calculations and a power-law approximation that:

$$R \sim \langle D^{3.68} \rangle .$$

An ideal rain rate estimator should be based on a radar measurable parameter which is proportional to the same moment of the DSD as the rainfall rate (i.e., the 3.68th moment). The attenuation coefficient at 34.6 GHz (K_a-band), a, provides a very close approximation for such a parameter. This coefficient is given in terms of the imaginary part of the forward scattering amplitude, f:

$$a = 2\lambda \int \mathrm{Im}\,[f(D)]\, n(D) dD ,$$

where λ is the radiation wavelength, the integration is performed over DSD and the maximum drop size in the integration is 7 mm. Figure 1 also shows values of Im $[f(D)]$ at K_a-band as a function of the rain drop diameter. It can be seen from a power-law fit that Im $[f(D)]$ can be approximated by the 3.63rd moment of DSD thus:

$$a \sim \langle D^{3.63} \rangle .$$

Since both the rainfall rate and the attenuation coefficient at K_a-band are approximately proportional to the same moment of the DSD, a practically linear a-R relation exists. The deviations of the empirical a-R relations from linearity typically do not exceed 10%, and for the MMCR frequency of 34.6 GHz the linearized relation can be given as (Matrosov 2005):

$$a(\mathrm{dB\ km^{-1}}) = 0.28\, R\, (\mathrm{mm\ h^{-1}}).$$

Unlike for longer radar wavelengths, the attenuation coefficient at K_a-band is nearly independent on temperature, and, at vertical incidence, it practically does not depend on the drop shape model. Note also that the linearity of the a-R relation is a unique feature of the K_a-band, which does not hold for other radar frequency bands.

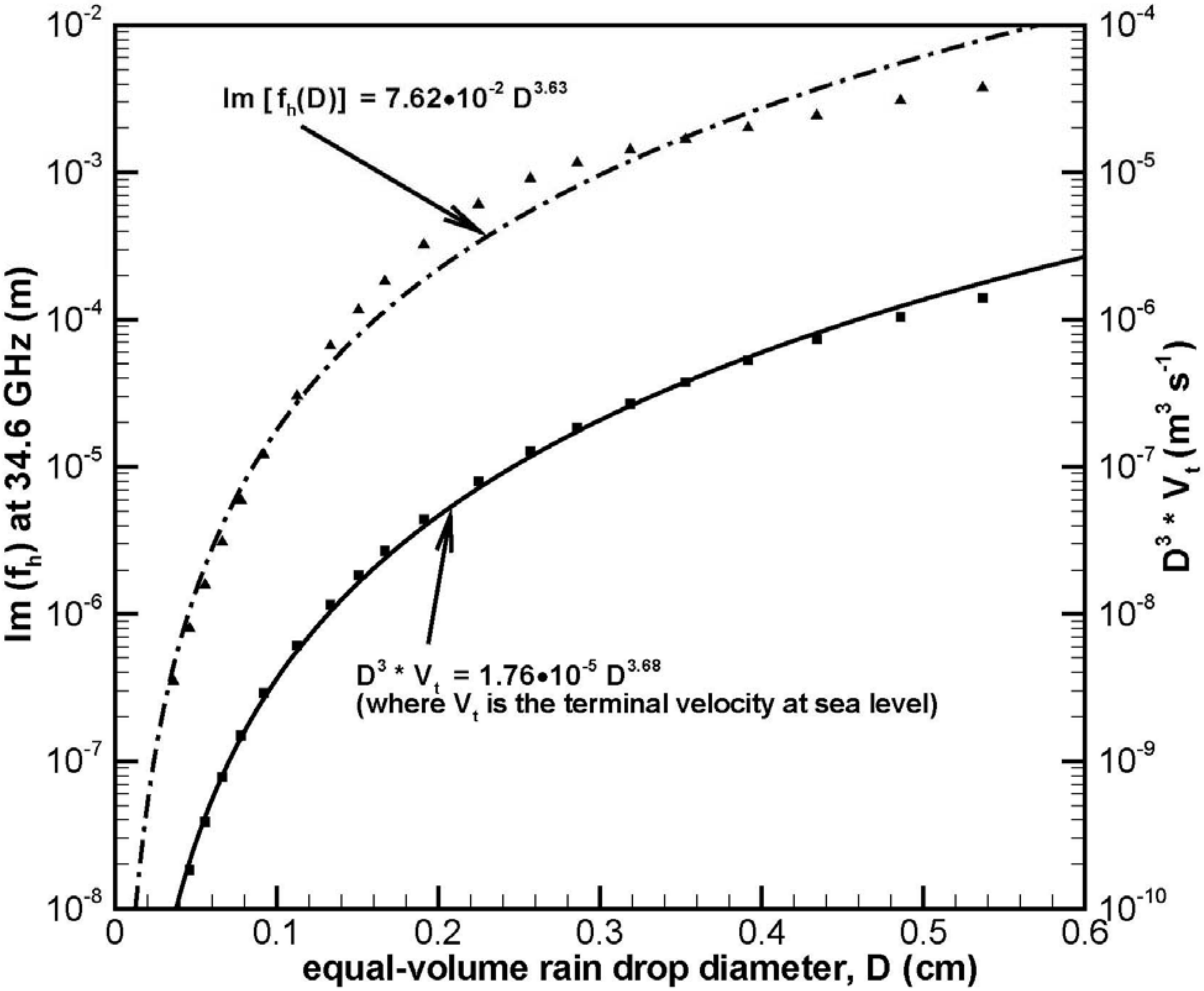

Figure 1. Imaginary part of the forward radar amplitude at the MMCR frequency of 34.6 GHz and the product D^3V_t as functions of the equal-volume drop diameter. Symbols represent calculations at the JWD bin sizes and lines represent the power-law approximations.

Rainfall Rate Estimator

Being a very convenient parameter from which to infer rainfall rate, the attenuation coefficient, however, is difficult to measure. In the attenuation-based method (Matrosov 2005), *a* is calculated as a range (height) derivative of the reflectivity measurements at vertical incidence. The heaviest assumption involved in these calculations is that the changes in the vertical profile of the apparent (i.e., measured) reflectivity due to attenuation generally prevails over those due to nonattenuated reflectivity variations.

This assumption becomes progressively more substantiated as rainfall rate and/or the resolution interval grow larger. The variability in nonattenuated reflectivity constitutes the main source of retrieval uncertainties which were estimated in (Matrosov 2005).

Because of the statistical noise in the MMCR data and variability in nonattenuated reflectivity, a least square estimator is used to obtain the rainfall rate. The routine is briefly described below. After the effective resolution of retrievals, Δh is chosen, the vertical changes of measured reflectivities Z_e are considered at an interval $h \pm \Delta h/2$, where h is a height of the resolution bin center. Z_e data points within this vertical interval that correspond to no-rain echoes and those that are outside the linear regime of the radar receiver (i.e., either below the receiver noise level or in the saturation regime) are rejected from further analysis. If the number of remaining data points after such thresholding is more than 50% of the original number of points in the interval, the estimate of rainfall rate R at the height h is calculated as a slope of a linear fit:

$$R(h) = -\frac{k(h)}{2c} \frac{\sum_i Z_e[h(i)]\, h(i) - \{\sum_i Z_e[h(i)] \sum_i h(i)\} N^{-1}}{\sum_i h(i)^2 - [\sum_i h(i)]^2 N^{-1}},$$

where the summation is performed over all remaining N data points in the interval $h \pm \Delta h/2$. If the number of the remaining data points after thresholding is less than 50% of the original number of points, the rainfall estimate for such an interval is deemed unreliable. The reflectivities in the equation above are in the logarithmic scale (dBZ), the coefficient c=0.28 dB km^{-1} mm^{-1}h, and the dimensionless coefficient k accounts for the raindrop fall velocity changes due to changing air density, ρ aloft.

Rainfall rate estimates based on attenuation are performed using a sliding "window" Δh for all MMCR resolution gates, which are typically spaced at 90 m apart in a rain layer. As a result, the apparent vertical resolution of retrievals is 90 m, though the effective (actual) resolution corresponds to the interval Δh, which is typically chosen to be about 1 km. Only data from the so-called "precipitation" mode of the routine MMCR measurements are used here for retrievals. This mode has the largest range of unambiguous Doppler velocity estimates (±15.14 m s^{-1}), which allows accurate measurements of precipitation echoes using the standard spectral processing employed with the ARM radars. Retrievals are available when MMCR data are neither in the noise nor in the saturation range of the radar receivers.

Retrievals of Rainfall Rates

The retrieval accuracies of the attenuation-based rainfall rate profiling method strongly depend on uncertainties in the vertical profiles of nonattenuated reflectivity and the effective resolution interval Δh, and they decrease as rainfall rate increases. The variability in the nonattenuated reflectivities is expected to be minimal in stratiform rain events which are characterized by relatively modest rainfall rates (typically less than about 15 mm h^{-1}), relatively strong radar bright bands, extensive spatial coverage and long duration. Assuming a typical 1 dB uncertainty in the nonattenuated K_a-band reflectivity profiles for such events (at Δh,=1 km), the relative errors for the discussed method can be estimated as 40% for R=4 mm h^{-1}, 20% for R=10 mm h^{-1}, 15% for R=15 mm h^{-1}. It can be expected that the variability of nonattenuated reflectivities in convective rains are higher. Rainfall rates in convective rains are generally higher than those during the stratiform events.

Figures 2 and 3 show time height cross sections of MMCR measurements and rainfall rate retrievals during a stratiform event at the Southern Great Plains (SGP) site. Also shown is a convective event at the Tropical Western Pacific (TWP) Darwin site. For the stratiform event (Figure 2), the average thickness of a layer where rainfall rates retrieved from MMCR data were available is about 1.3 km. The center of this layer is located at about 1.35 km above ground level. A time series of the mean rainfall rate, R_m, in this layer is shown in Figure 4. This figure also depicts the rainfall accumulations calculated using R_m and as recorded by the ground-based high-resolution (0.01”) tipping bucket-type rain gauge deployed at the SGP site near the MMCR. For this approximately 7-hour rain event, the total radar-derived accumulation (using R_m) is about 29 mm which corresponds to a time-average R_m value of about 4 mm h^{-1}. As mentioned above, the expected retrieval accuracies of rainfall rate at such modest values of R are around 40% for the resolution used (Δh = 1 km). Given this and the fact that surface rain gauges are usually calibrated within 10-15%, the general agreement between surface gauge and radar-retrieved accumulations is good.

The MMCR retrievals at the TWP Darwin site can be compared to results of the C-band scanning radar (C-Pol) data. This scanning polarimetric radar is located at about 20 km away from MMCR and it regularly performs range – height indicator (RHI) scans over the MMCR. As an example, the vertically resolved MMCR retrievals for decimal 13.82 Universal Time Coordinates (UTC) (a time for a C-Pol RHI scan over the MMCR site) are shown in Figure 5. This figure also depicts a corresponding profile of C-Pol reflectivities, Z_{ec}, that were corrected for slant attenuation effects in rain (which are much smaller at C-band compared to K_a-band) using a standard differential phase shift correction approach. The subscript “c” stands in Z_{ec} for the C-band. Note that due to non-Rayleigh scattering effects, even nonattenuated K_a-band reflectivities are smaller than those at C-band. Two types of rainfall rate estimates were available from C-Pol: (1) estimates that are based on Z_{ec} –R relations for C-band, and (2) estimates that are based on differential phase shift (K_{DP}) measurements. It can be seen from Figure 5 that MMCR retrievals for the most part are bracketed by the C-Pol estimates of these two types.

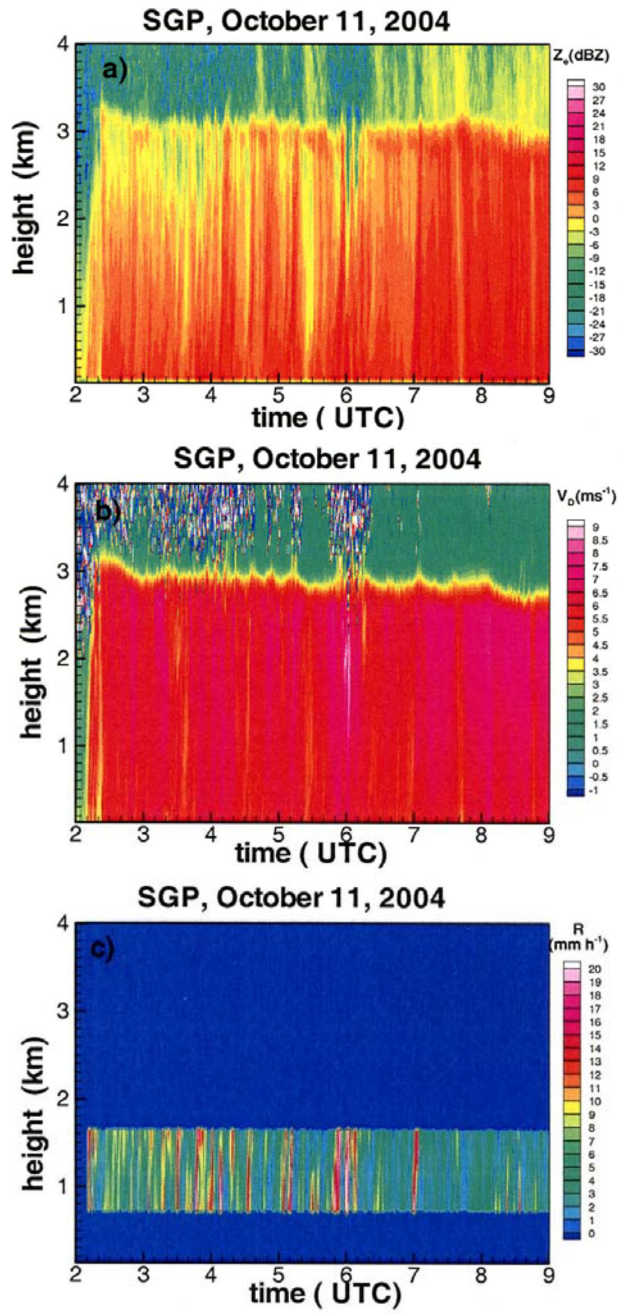

Figure 2. Time-height cross sections of (a) MMCR measured reflectivity, (b) mean Doppler velocity, and (c) retrieved rainfall rates for the SGP event observed on 11 October 2004.

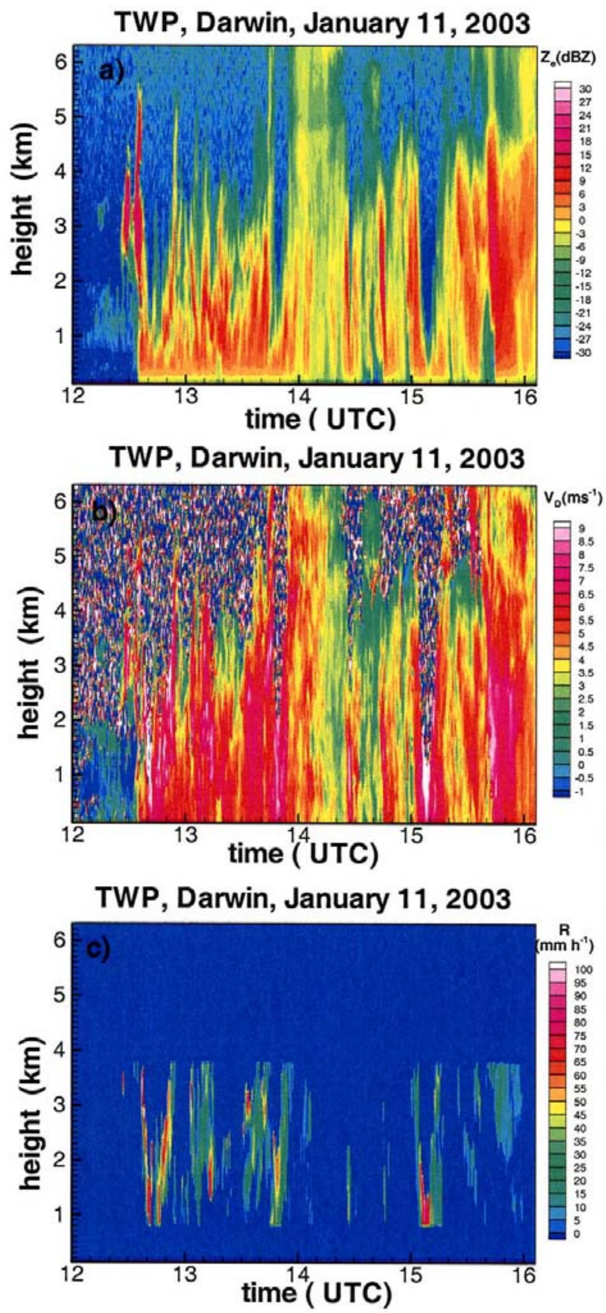

Figure 3. Time-height cross sections of (a) MMCR measured reflectivity, (b) mean Doppler velocity, and (c) and retrieved rainfall rates for the TWP Darwin event observed on 11 January 2003.

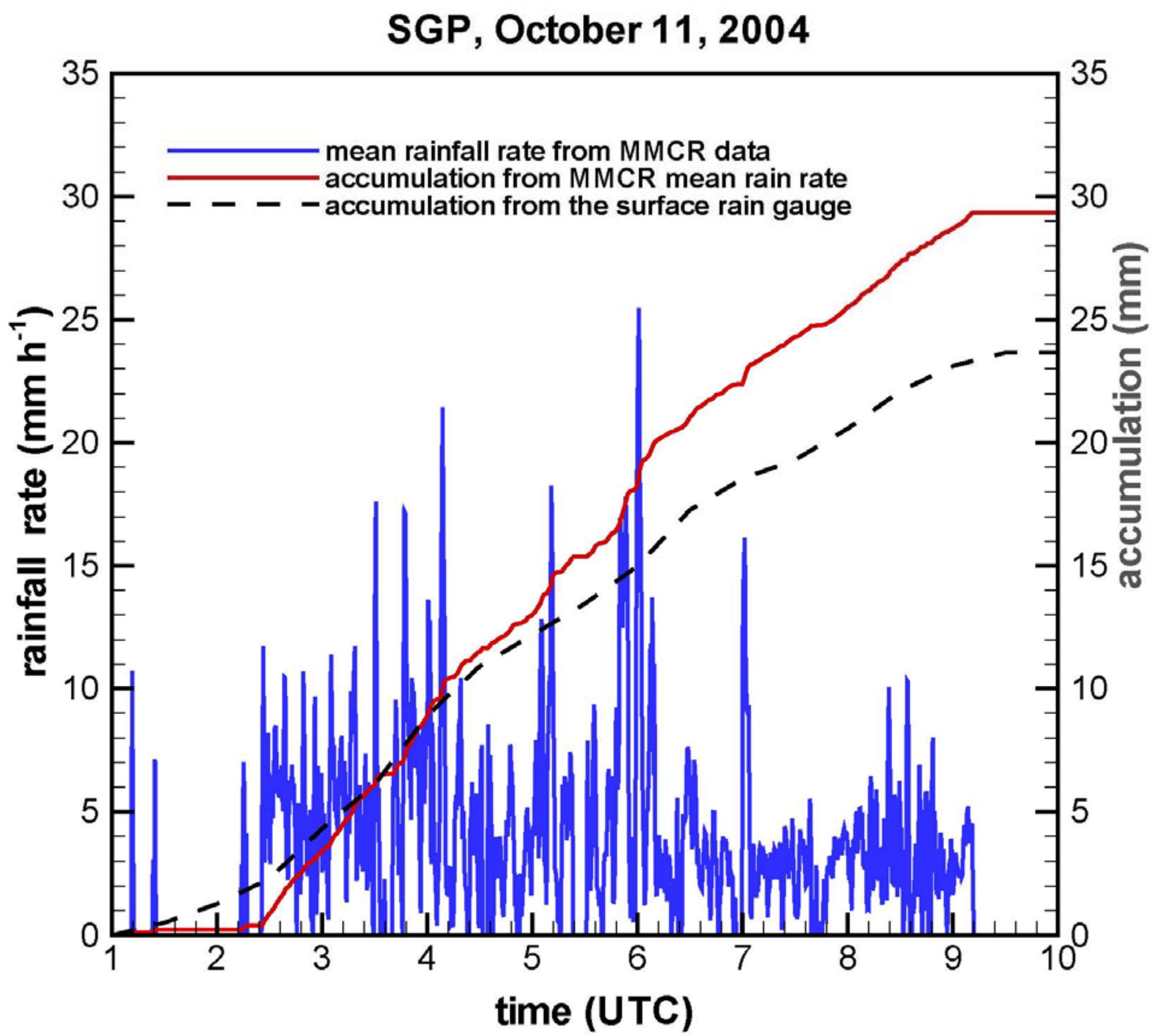

Figure 4. Mean layer retrieved rainfall rates and accumulations from MMCR data and from the surface rain gauge for the event observed on 11 October 2004 at the SGP site.

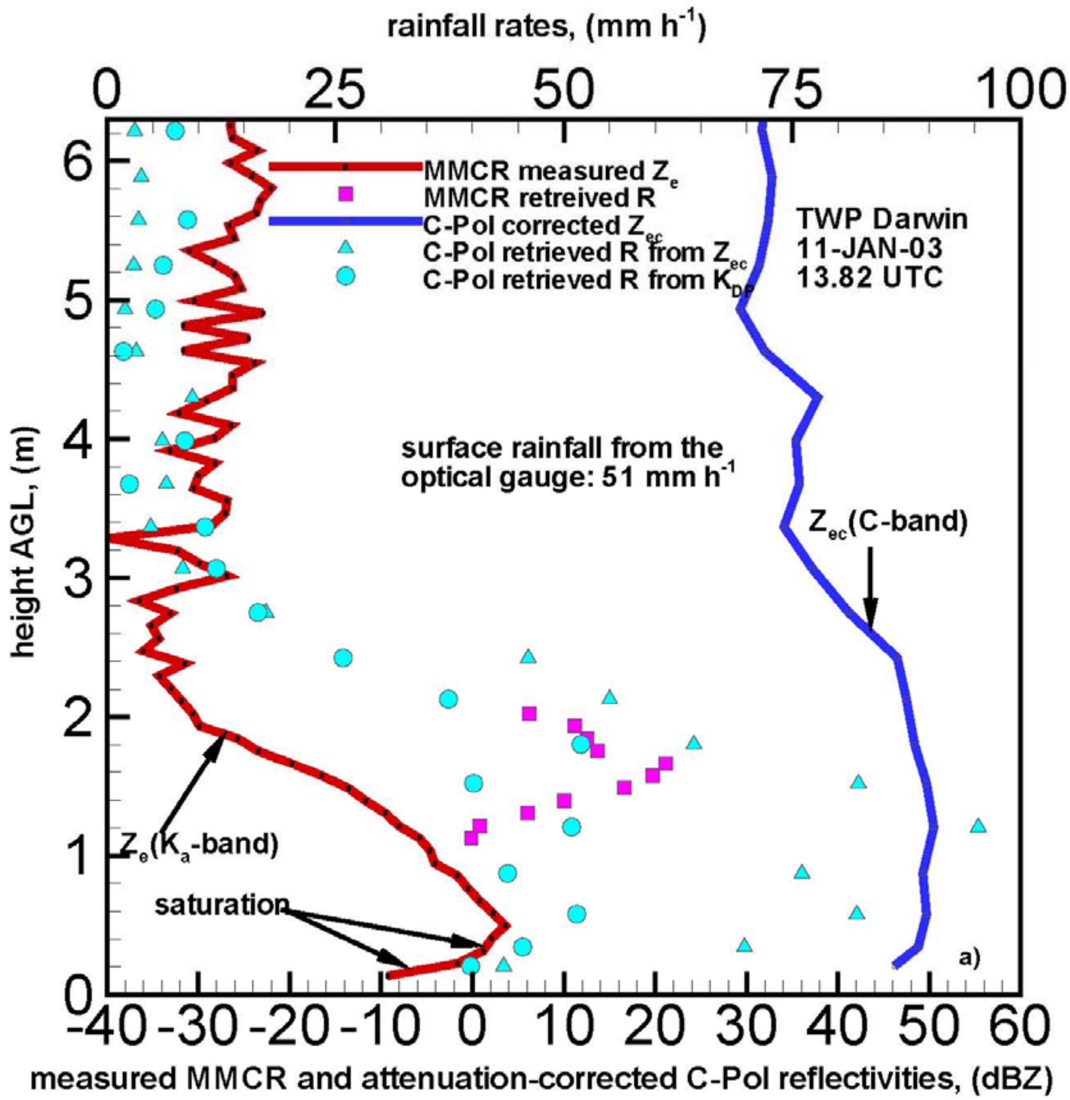

Figure 5. MMCR measured and C-Pol corrected reflectivity profiles over the TWP Darwin site (upper X-axes) and the corresponding rainfall rate retrievals (lower X-axes) from MMCR (squares), from C-Pol using Z_{ec}, (triangles), and form C-Pol using K_{DP} (circles); 11 January 2003 13.82 UTC.

Conclusions

A method to retrieve vertical profiles of rainfall from MMCR precipitation mode measurements is suggested. This method is based on relative attenuation effects not on absolute measurements. The rainfall information can be provided with the same time resolution and spacing as ARM cloud products. Initial comparisons with available ground and scanning precipitation radar data indicate the general robustness of the suggested attenuation–based method to infer precipitation information from ARM MMCR data.

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References

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