An Approach to Estimate Rainfall Rates Aloft from Millimeter Wavelength Cloud Radar Measurements

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Introduction

Millimeter wavelength cloud radars (MMCRs) have been used for several years by the Atmospheric Radiation Measurement (ARM) Program for remote sensing of clouds. A number of different remote sensing methods that use radar measurements were developed for retrieving cloud microphysical parameters. Though precipitation (including rainfall and snowfall) is also observed by MMCR, very few attempts have been made to quantitatively retrieve rainfall/snowfall parameters. Precipitation is a crucial part of the water cycle, and adding a capability for retrieving quantitative precipitation information from routine MMCR measurements would benefit the ARM scientific community.

This study shows possibilities of using MMCR reflectivity measurements to retrieve low-resolution vertical profiles of rainfall rates. The suggested approach is based on attenuation of radar signals in rain rather than on relations between radar backscatter and rainfall rates that conventional radar-based approaches rely on. The attenuation-based approach was initially tested using data form MMCR that belongs to the Environmental Technology Laboratory. It is intended to apply this approach to ARM MMCR data from different testbed sites.

Relating Attenuation and Rainfall Rate at K_a-band

At K_a-band (i.e, the MMCR frequency), the attenuation coefficient, *a*, and the rainfall rate, *R*, are related practically linearly. This linear relation is rather stable and exhibits very little variability due to details of drop size distributions (DSD) and the nature of rain (e.g., convective vs. stratiform). Figure 1 shows *a*-*R* relations obtained by calculations using the T-matrix approach for non-spherical drops and DSDs collected during the Wallops and Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment (CRYSTAL-FACE) field projects. About 4000 different DSDs were collected in both field campaigns using an impact disdrometer. Most of the Wallops rain events were stratiform ones with a clearly defined bright band (Matrosov et al. 2002). The CRYSTAL-FACE data, on the other hand, were comprised by DSDs corresponding to convective rains that are typical for this geographical location (Matrosov 2005).

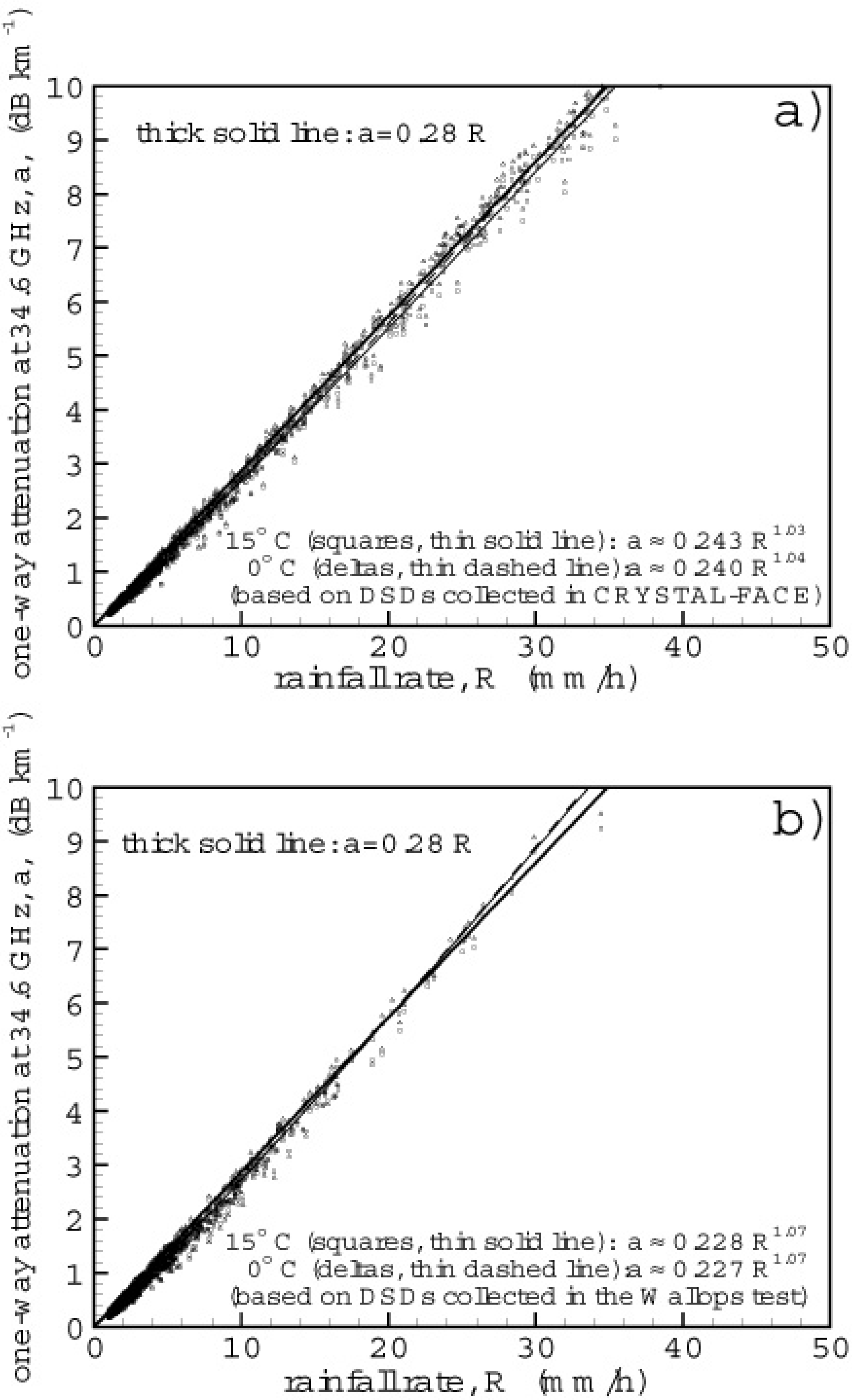

Figure 1. Attenuation-rainfall rate relations at 35 GHz.

An average linear relation between a and R is:

$$a \text{ (dB/km)} = c\, R \text{ (mm/h)} \quad (c{=}0.28) \tag{1}$$

The relative standard deviation (RSD) of individual data points around the mean linear relation (Eq.1) is generally less than 10%. Other important characteristics of a-R relations at K_a-band are their very low sensitivity to drop shapes at the vertical radar beam incidence and temperature. The practical linearity of a-R relations and their insensitivity to other factors make them suitable for rainfall rate retrievals in situations when attenuation effects dominate the variability of non-attenuated reflectivity, Z_e. Note that the traits of a-R relations are rather unique and Z_e-R and a-Z_e relations at K_a-band (not shown here) are non-linear and exhibit a significant data scatter and a noticeable temperature dependence.

Examples of Millimeter Wavelength Cloud Radar Reflectivity Measurements in Rain

Due to a high rate of rain attenuation at Ka-band, vertical changes in measured reflectivity, Z_{em}, at a sizeable height interval are often dominated by signal attenuation and not by the variability in non-attenuated reflectivity, Z_e. Figure 2 shows a time-height cross-section of MMCR reflectivity data during a time period with two convective showers. The height of the freezing level during these observations was about 5 km, so nearly all observed convective rain was warm. The radar signals were not totally extinguished during the first shower at around Julian Day (JD) 205.69, so a thin layer of cloud reflectivity could be seen at a height of 7.5 km even during the time when the shower was the heaviest. The second shower observed at around JD 205.64 completely attenuated the radar signals, so no cloud aloft could be seen.

Figure 3 shows several consecutive vertical profiles of measured reflectivity in the MMCR precipitation mode during the second convective shower discussed above. Rainfall rates were changing quite rapidly during this shower. The saturated data are clearly seen for different profiles. During the heaviest rain (JD 205.6388), radar signals were in saturation up to the altitudes of 2.5- 3 km. Depending on the time of the profiles the total extinction of radar signals was achieved at levels from about 3 km (JD 205.6408) to about 5 km. Rain rate retrievals are possible at heights where MMCR reflectivity data are neither in saturation nor in complete extinction.

Retrievals of Rainfall Rates

An average rainfall rate in a vertical layer with a thickness Δh can be estimated as:

$$\mathrm{R} = k(2c)^{-1}(\Delta Z_{em}/\Delta h) \tag{2}$$

where k accounts for the air density changes. The relative importance of the effects of signal attenuation over the vertical variations of non-attenuated reflectivity increases with the vertical resolution of retrievals. Typical resolutions (Δh) of the attenuation-based rainfall retrievals are about 0.5 – 1 km.

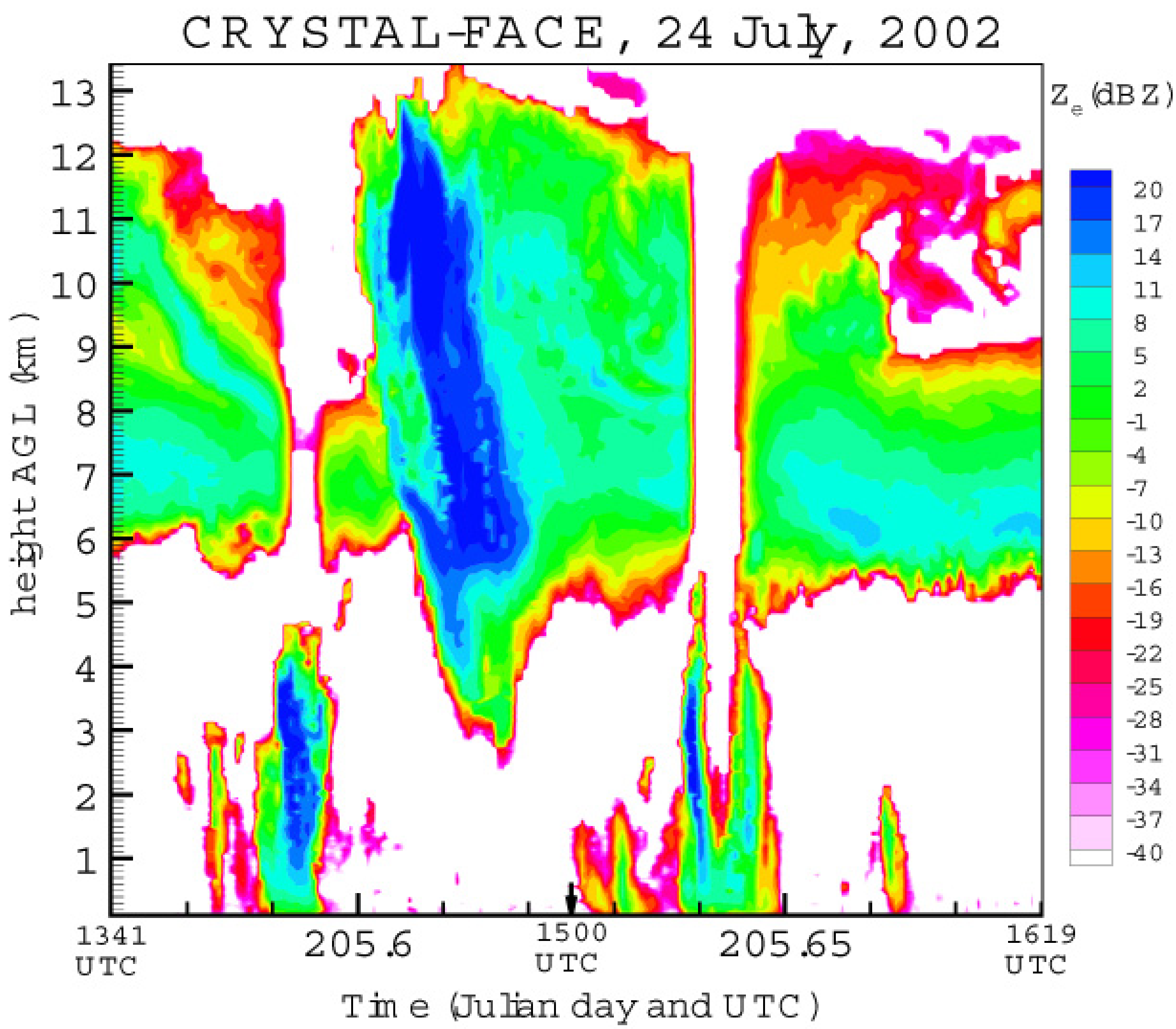

Figure 2. MMCR reflectivity time-height cross section data during periods of convective rains.

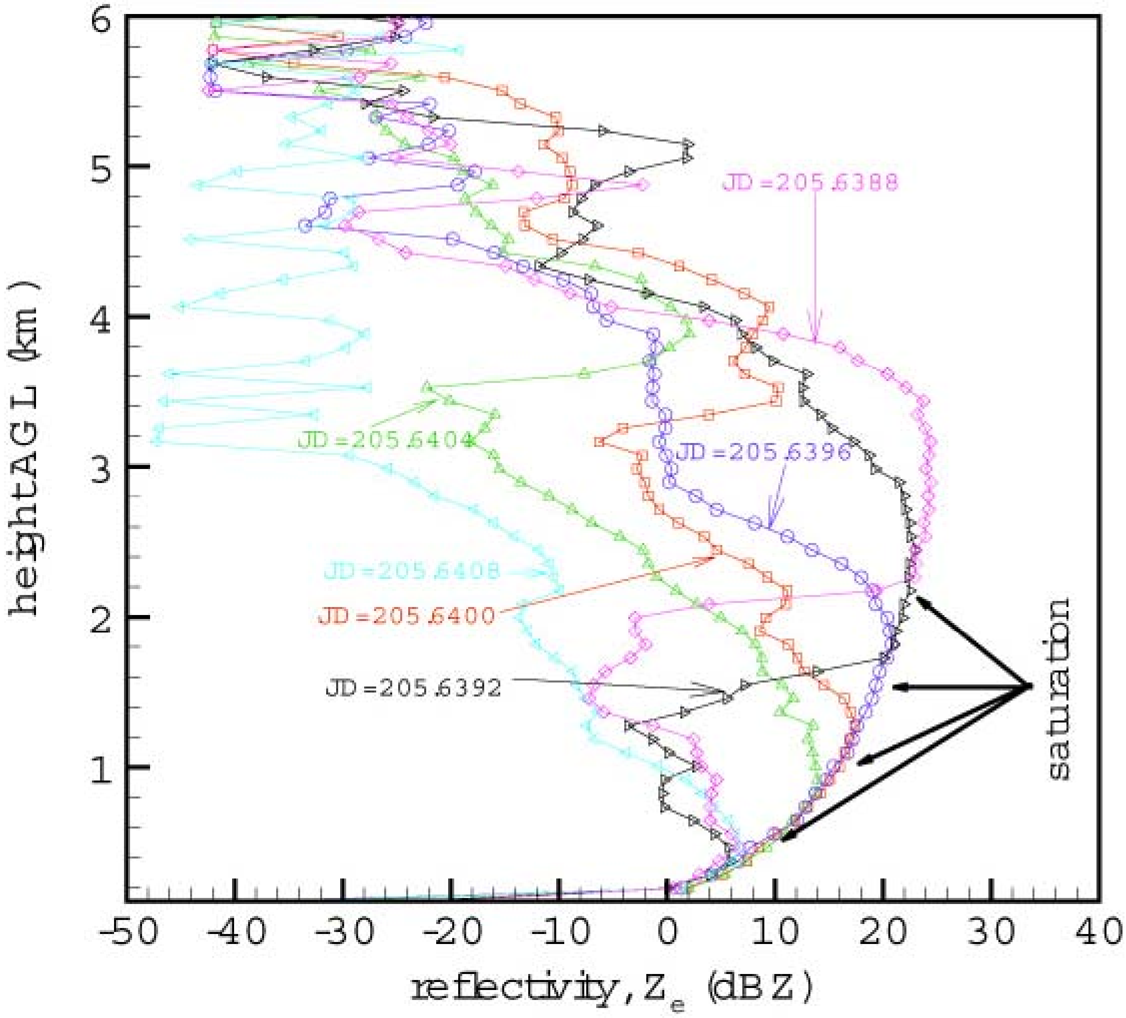

Figure 3. Vertical profiles of MMCR reflectivity in heavy rain.

Figure 4 presents the retrieval results for the second convective shower (JD 205.6396). Though retrievals for this shower below 2 km are not generally available due to saturation, the rapid decrease of rainfall rates below and above a maximum value reached at 2.5 km indicates that the strongest rain was isolated aloft in a layer, which was about 1 km thick. This was confirmed by the ground observations, which showed no substantial rain at the ground at JD 205.6396 but a strong rain just a few minutes later. Figure 5 shows comparisons of rainfall rates at the 2.5 km height retrieved from MMCR measurements and ground estimates of *R* from impact disdrometer data. The ground and elevated rainfall rate peaks are separated by about 5 minutes, which is the time required for rain to come down from the altitude of 2.5 km.

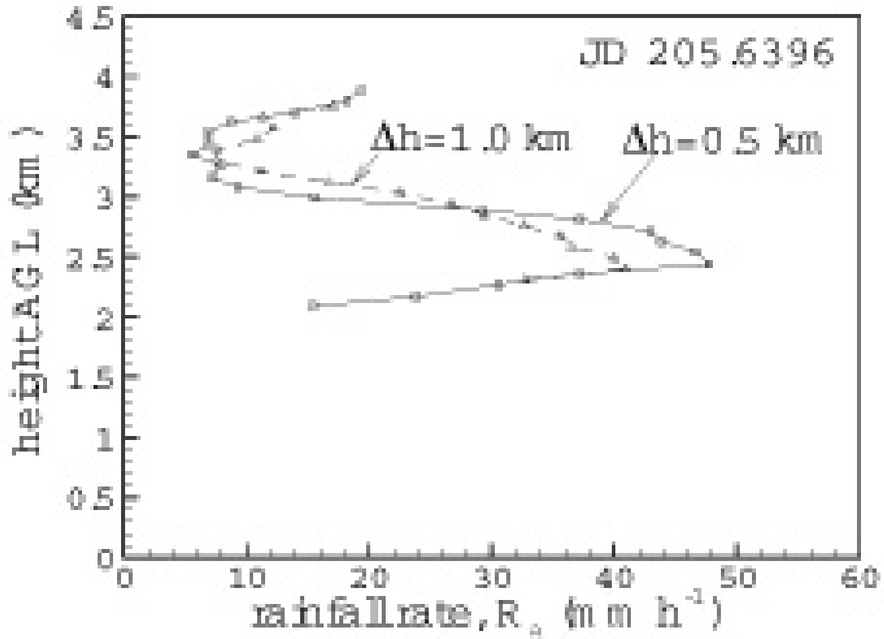

Figure 4. Rainfall rate profile retrievals.

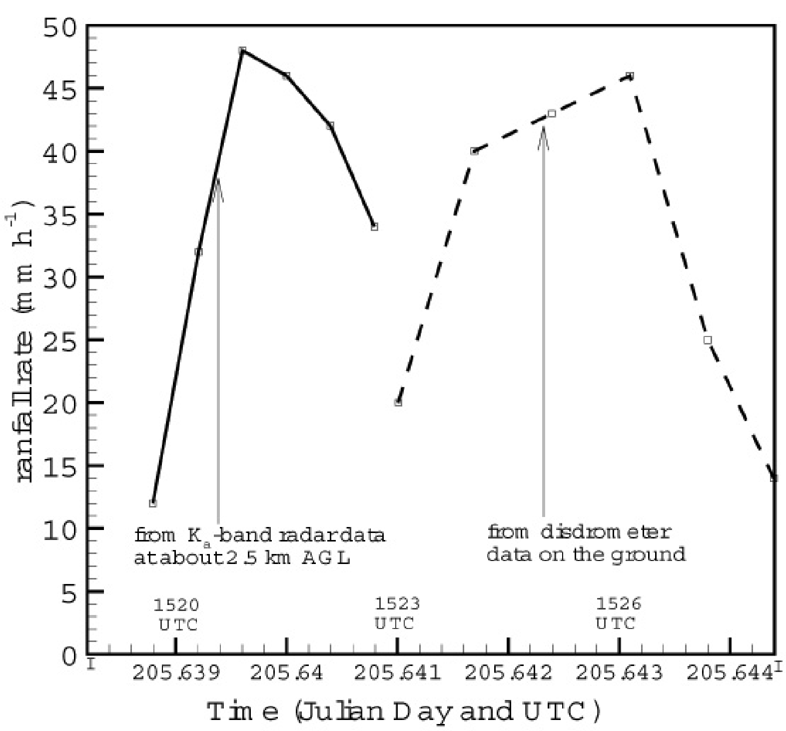

Figure 5. Comparisons of retrievals of rain aloft with ground data.

In the event when a reference high cloud reflectivity, Z_{er}, is available during the rain event, a whole layer average rainfall rate can be estimated. The high cloud reflectivity at 7.6 km for the first convective shower at around JD 205.69 was available during the whole rain period. Before and after rain this reflectivity was about 5 dBZ, and in the middle of the rain shower, it was about -30 dBZ due to the rain attenuation. Given that this shower was 4.5 km thick, it can be estimated from Eq. (1) that its average rainfall rate was about 11 mm h^{-1}.

Assessments of Accuracies of Rainfall Rate Retrievals

Errors of the attenuation-based retrievals of rainfall rates mostly depend on the uncertainty of the non-attenuated reflectivity differences (δZ_{el}) in the beginning and at the end of the vertical resolution interval, the length of the resolution interval (Δh), the uncertainty of the coefficient c in Eq. (1), and the rainfall rate, R. Figure 6 shows estimates of the retrieval errors for different values of the contributing factors. The relative importance of the attenuation effects compared to the variability in non-attenuated reflectivity increases with rainfall rate and the path length, the retrieval errors diminish as Δh and R increase. It can be seen from Figure 6 that for larger values of Δh and heavier rainfall rates, the retrieval errors approach 10%, which is close to the uncertainty of the coefficient c in the linear a-R relations.

It is expected that typical values of δZ_{el} at a 1 km resolution in stratiform rains could be about 1 dB or so. In convective rains, vertical variability of non-attenuated reflectivities is generally higher than in stratiform rains and one can expect typical values of δZ_{el} to in a range of 1-2 dB for a 1 km resolution (e.g., Smyth and Illingworth 1997). More accurate rainfall estimates can be performed at the expense of more coarse vertical resolution of the retrievals.

Figure 6c corresponds to Δh=4.5 km and can be used to estimate retrieval errors for the average rainfall rates R_a in convective rain shafts when the high cloud reference reflectivity is available as in the first shower in Figure 2. In this case δZ_{el} is the uncertainty in the reference reflectivity. It can be seen that even a rather high value of δZ_{el}= 5 dB results in reasonable retrieval errors for R_a > 6 mm h^{-1}.

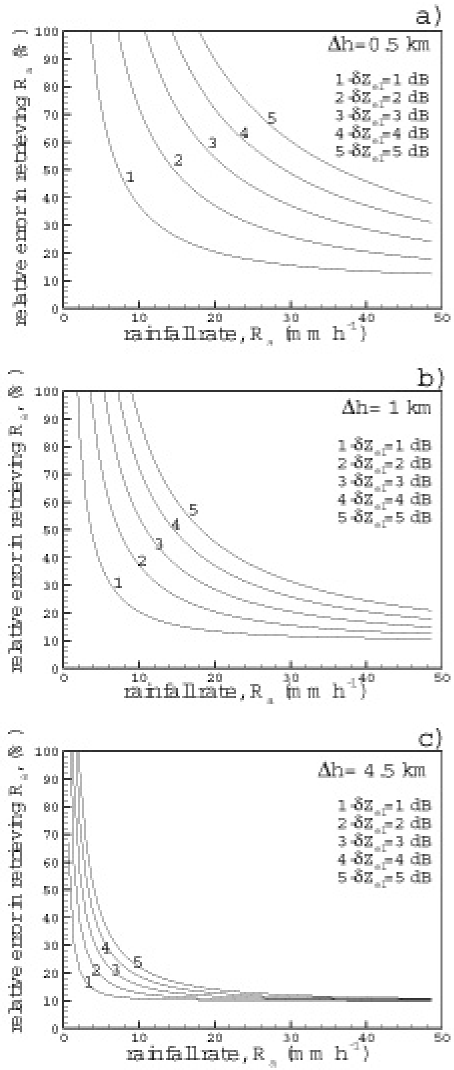

Figure 6. Estimates of rainfall retrieval errors.

Conclusions

The suggested approach for retrieving rainfall rates aloft uses routine MMCR measurements in precipitation mode. The retrievals are available when radar returns are neither in saturation nor in total extinction. The retrieval accuracies decrease as the rainfall rate increases. These accuracies also depend on the vertical resolution and lower errors can be achieved at the expense of a more coarse resolution. The attenuation-based retrievals do not depend on the radar absolute calibration, and they are not influenced by such limiting factors as a wet radome.

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References

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