Partitioning of Rain and Cloud water content by Ground-based observations with a multi-frequency microwave radiometer in synergy with a micro rain radar

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ABSTRACT

A new ground-based multi-frequency dual polarized microwave radiometer together with a methodology to retrieve simultaneously the cloud and rain liquid water path is presented. The instrument exploits the feature to measure brigtness temperature in vertical and horizontal polarization to retrieve the rain and cloud liquid path by means of the unique polarization difference signature. A retrieval algorithm based on a Bayesian inversion method is applied to the data set in order to retrieve the slant integrated water vapor, the cloud and rain liquid water from several rain events observed by the radiometer at 30° elevation angle. Moreover a colocated micro rain radar was used in order to have an insight into the rain structure under observation. The radar is used by the retrieval algorithm as minimum rain detection threshold as well as an independent validation of the rain component of the total liquid water path. A retrieval sensitivity on drop size distributions for case stuties is presented.

1. INTRODUCTION

Remote sensing by microwave radiometry is a fairly established technique to retrieve vertical integrated cloud liquid water path ($cLWP$) by multi-frequency radiometers with estimated accuracy of up to 15 g/m^2 (e.g. (1)), moreover liquid water profiles are also retrieved however this was recently questioned by (8) due to no information on vertical distribution of liquid water in the microwave observation.

Nevertheless when rain drops are presented then that may either wet the receiver antenna producing absorption losses directly at the antenna window or break down the applicability of Rayleigh approximation, according to which the extinction coefficient is essentially proportional to the mass of the particles so that the total optical thickness is directly proportional to the LWP. Cloud droplets produce a different mass extinction coefficient than raindrops because, in the Mie resonance region, the extinction cross sections remain higher than their Rayleigh counterpart. Therefore, the same amount of LWP but with a dominating rain component produces higher brightness temperature (TB). As a direct implication in LWP retrieval, the RMS and bias errors strongly increase in the presence of rain and can easily be higher than 100 g/m^2 even for total LWP less than 1 kg/m^2 (2). Nevertheless other authors have performed studies on the potential of retrieving rain parameters by standard multi-frequency ground-based radiometer measurements of precipitating clouds at zenith observations with some hardware improve in order to solve the contamination introduced by rain drops on the radiometer antenna (3).

Reference (4) has proposed ground-based microwave observations of brightness temperature at vertical (TB_v), horizontal (TB_h) polarization and the polarization difference ($PD = TB_v - TB_h$) to estimate the rain and cloud component of the total liquid water path. The same author has performed the first experimental approach to manage this by means of measurements with a single frequency (19 GHz) dual-polarization radiometer at 30° elevation angle, showing a negative polarization difference in presence of rain drops (5). This is explained by the idea that large rain drops have non-spherical shapes, which produce unique negative polarization signature. The amount of the effect mainly depends on the radiometer frequency, the distribution of hydrometeors, and the observation slant angle.

Recently (6) has showed the advantage of using the multi-frequency dual-polarization radiometer ADMIRARI to measure several rain events and the uneven sensitivity on different rain drop size distribution by polarization difference on the operational frequencies (10.65, 21.0 and 36.5 GHz). Furthermore (7) developed the first approach to retrieve rain, cloud liquid water path and integrated water vapor simultaneously from ADMIRARI measurements at the CESAR observatory in CABAUW.

In the present work the retrieval is presented for a case study together with a sensitivity study on different drop size distribution considered in the radiative transfer simulations.

2. EXPERIMENT DESCRIPTION

2.1. Instrumentation

The ADvanced MIcrowave RAdiometer for Rain Identification (ADMIRARI) was manufactured by Radiometer Physics GmbH (www.radiometer-physics.de). The radiometer consists on three independent modules which

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sense the atmospheric microwave signature at three frequencies i.e. 10.65, 21.0 and 36.5 GHz; every module includes an Ortho-mode transducer which splits the signal into vertical and horizontal polarization. The receiver optics for the 21.0 and 36.5 GHz modules is composed of a corrugate feed horn with an aperture lens, while for the 10.65 GHz module the full optic system is composed of a corrugated feed horn and an off-axis parabola antenna. Thus an antenna beam-width of 5° for every frequency is achieved. The aperture lenses as well as the off-axis parabola are coated with a water repellent film to avoid the sticking rain drops on the receiver surfaces. Furthermore every module is protected by a shield to avoid, when observing at low elevation angles, the wetting of the surfaces during rain and/or in some cases accumulation of snow. Every receiver module is thermally insulated to achieve a high stability with an accuracy of $< 0.05K$. The system performs a full internal calibration by using a built-in Dicke Switch hot target (absolute standard) in combination with an internal noise injection system which is used to calibrate the gain drifts. Noise diodes are secondary standards that are calibrated by sky tipping procedures regularly performed during clear sky conditions.

The system is mounted on a positioner which allows to scan the soil and sky in a full azimuth range (0° to 360°) and elevation (-90° to 90°) with an angular speed equal to 5°/sec and 3°/sec respectively. In order to permit easy transportation to campaign sites the whole system is installed on a trailer (www.meteo.uni-bonn.de/forschung/gruppen/admirari).

Since May 2008, a Micro Rain Radar (MRR) was installed aside ADMIRARI in order to have an insight into the rain structure at the same observation scene as the radiometer (see figure 1 in (6)). The MRR is a system manufactured by METEK GmbH (www.metek.de), it is a compact 24 GHz FM-CW-radar for the measurement of profiles of drop size distributions and, derived from this, rain rates, liquid water content and characteristic falling velocity resolved into 31 range gates (9). However, the standard MRR configuration is conceived for vertical observation, alike the products derived from its reflectivity measurements. On the other hand, ADMIRARI has been performing observations at a varied of scan configuration, instead of vertical. Therefore, most of the MRR products are useless or senseless due to they are derived using the relationship between terminal vertical fall velocity and drop diameter. Since we treat with observations in slant configuration, the only one parameter we can use is the radar reflectivity computed from the raw spectral power received by the MRR. The radar reflectivity was estimated according the procedures for the spectral reflectivity integration and noise level estimation indicated in (9). At the present work we focus on observations at 30° elevation angle.

In addition, ancillary data from standard meteorological stations available at the observation sites has been used for the present study.

2.2. Field campaigns

ADMIRARI has already participated in two field campaigns, during summer 2007 in the Convective and Orographically-induced Precipitation Study (COPS) taking measurements at the ARM Mobile Facility in the Murg Valley, Black Forest, south of Germany.

In 2008, ADMIRARI was deployed to the CESAR observatory in Cabauw, the Netherlands, in the frame of the EUCAARI campaign. The radiometer together with the MRR were taking measurements from beginning of May to beginning of December. The observation configuration for the whole measurement period was set up at a fixed azimuth and at 30° elevation angle. The analysis and the results in the current work is centered on measurements from this campaign.

3. RETRIEVAL TECHNIQUE

The inversion technique applied to ADMIRARI measurements in order to retrieve simultaneously integrated water vapor, cloud and rain liquid water path, is based upon a Bayesian approach. Considering the three physical quantities to be retrieved $\mathbf{X} = [\mathbf{iwv}, \mathbf{cLWP}, \mathbf{rLWP}]$ and the observation 6 dimensional vector $\mathbf{Y_o}$ composed by the down-welling TB and PD at the three ADMIRARI frequencies, together with the simulated observational vector $\mathbf{Y_s}(\mathbf{X_j})$, obtained from many realizations of the Goddard Cumulus Ensemble model, with j the index of the rainfall profile introduced at the radiative transfer code to simulate the synthetic TB and PD. These simulation are intended to cover the regime with high rain rates where 3D effects are relevant; in addition the data base has been enriched by representative simulations for low and medium rain, moreover profiles with only cloud have been also simulated. Thus under the assumption that the best estimated $\mathbf{X}$, given the set of observations $\mathbf{Y_o}$, is the expected value:

$$E(\mathbf{X}) = \sum_{\mathbf{j=1}}^{\mathbf{N_p}} \mathbf{X_j w_j} \tag{1}$$

with w_j, described in (7) equation (5), the probability density function which is proportional to the conditional probability that $\mathbf{X}$ represents the true atmosphere state given that $\mathbf{Y_s}$ is equal to the observed $\mathbf{Y_o}$.

The simulated TB and PD are obtained considering three different rain drop size distribution DSD (i.e. drizzle, Marshall-Palmer and Thunderstorm), as well as three different rain drop axial ratio parameterization and several observation positions relative to the precipitating cloud as explained in (7).

4. RETRIEVAL RESULTS

As example the retrieval applied to the observation from 2sd October 2008 is presented in figure 1. A period of time from 16:00 to 20:00 UTC is considered where no rain is observed at the beginning and end of the period together with several rain events from 16:15 until 19:20. From short showers to long stratiform with embedded convective rain is showed, with a maximum rain intensity at around 17:30 when the reflectivity is clearly affected by attenuation. A freezing level between 1 to 1.3 Km (2 to 2.6 km slant) is clearly seen from the MRR image. On the other hand the ADMIRARI measurements show an interesting behavior: the brightness temperature depicts the rainfall intensity within the radiometer observation volume with maximum values of 250, 200 and 80 K at 36.5, 21.0 and 10.6 GHz respectively, highly correlated with the MRR reflectivity values (color table at figure 1). During no rain cases (white areas at top in figure 1) the 21.0 GHz which is near a transparent water vapor absorption line becomes to dominate the signal over the 36 GHz where the emission is dominated only by the cloud liquid water component; this reflect the behavior which allows the retrieval of cloud LWP by standard technics.

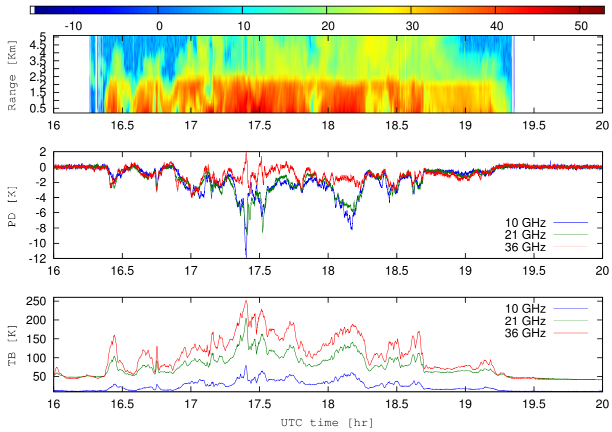

Figure 1. Observation from 2sd October 2008 at 30° elevation. Top: MRR reflectivity in dBz (white areas indicate no rain), Middle: ADMIRARI Polarization Difference, Bottom: Brightness Temperature

Nevertheless from the polarization signal is clear the advantage offered by the polarized radiometer ADMIRARI; the polarization difference at the selected frequencies shows the uneven effect on small droplets and large rain drops allowing the discrimination on: 1) cloud and rain liquid water path as suggested by (4) and 2) the variability of drop size distribution presented at different rain events. While the PD at 36.5 GHz shows the most negative values for light rain, the PD at 10.6 GHz has the most negative signal at strong rainfall, such is the case at approximately 17.4 and 18.3 UTC when the PD at 10.6 GHz reaches as negative values as -12 and -8 K respectively. On the other hand the PD at 36.5 GHz has a different behavior, at 17.4 UTC and around 17.5 the signal becomes positive (+2 K with the TB not yet completely saturated) while at 18.3 UTC the signal remains negative but around -2 K; this shows in the first case a convective rain with 3D effect and in the second case a stratiform rain which could be simulated just with a infinite plane parallel cloud approximation. The PD at 36.5 GHz is more negative than the other frequencies after 18.7 UTC when the event is mostly light rain as is corroborated by the MRR reflectivities (around 30 dBz).

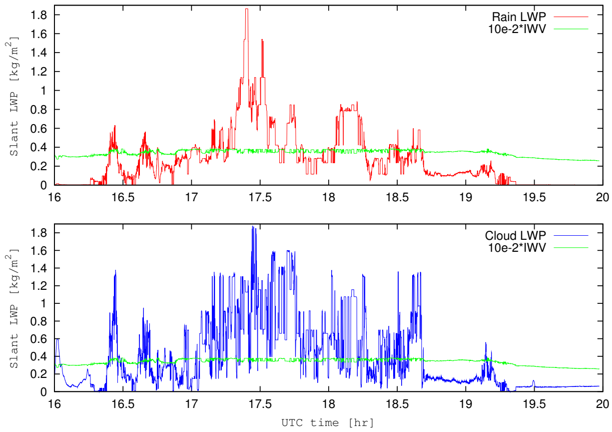

Figure 2. Retrieved for observations on figure 1, rain (top) and cloud liquid water path (bottom), together with integrated water vapor (greed line). All slant quantities.

The figure 2 shows the retrieval results from the observations in figure 1. Note that the slant $rLWP$ can be resolved to values as higher as 1.8 kg/m^2 corresponding to the most negative PD at 10.5 GHz, having a more constant values in stratiform rain like at 18.0 to 18.3 UTC and after 18.7 UTC. On the other hand, the $cLWP$ shows a higher variability mainly during strong rainfall, with values changing from lower than 0.4 kg/m^2 to high values as 1.8 kg/m^2 in a very short time. In figure 2 is also showed the retrieved slant IWV with a mean of 33.9 kg/m^2 and RMS of 3.5 kg/m^2.

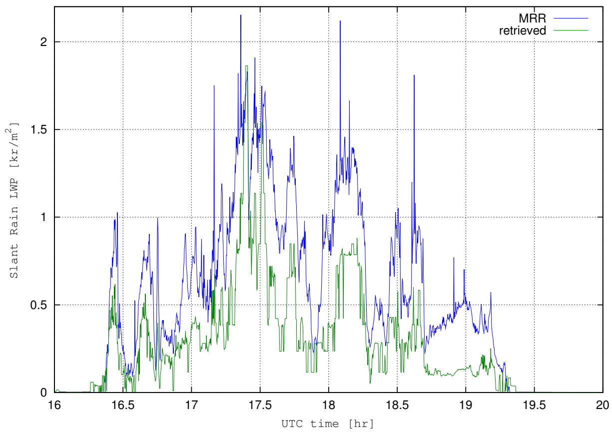

Figure 3. Two independent retrievals of rain liquid water path: MRR estimation (blue) and Bayesian algorithm from ADMIRARI (green)

In addition an independent $rLWP$ retrieval based only on the MRR measurements is presented together with the ADMIRARI retrieval in figure 3. The MRR $rLWP$

retrieval is obtained from a Rayleigh approximation $Z - rLWC$ relationship assuming the Marshall-Palmer DSD. Although the two retrievals show a correlation, the MRR based retrieval mostly overestimated the ADMIRARI $rLWP$, with the largest difference in the two stratiform rain events from 18.0 until 18.3 UTC and from 18.7 to 19.3 UTC.

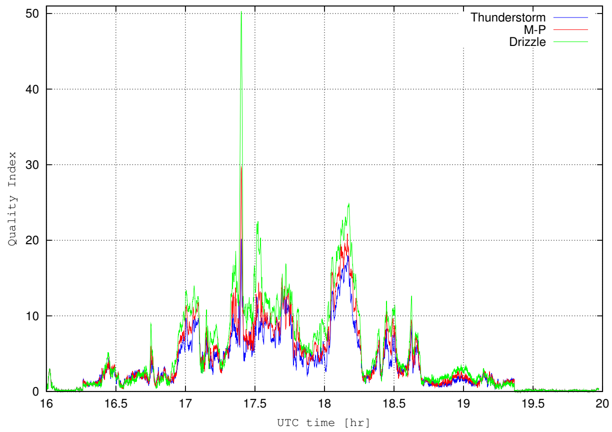

Figure 4. Retrieval quality index for three different DSD considered in the simulations. The lower the quality index, the best the retrieval.

Finally, by means of a retrieval quality index QI defined at (7) equation 6, which stand for the minimum euclidian distance between the observations and the simulations, a DSD sensitivity study has been performed. As indicated in section 3, three DSD has been considered on the simulations of the synthetic TB and PD; thus in figure 4 it sees that the different DSDs has a relevance in the retrieving of strong rain events where the QI corresponding to Thunderstorm DSD has the lowest values (high quality) and the corresponding to Drizzle has the highest values (low quality). Then the final retrieval showed in figure 2 is a selection of the lowest QI for the whole period. On the other hand for rain events like earlier than 16.9 UTC and later than 19.2 UTC the algorithm has a better performance with simulation considering a Drizzle DSD. The Marshall-Palmer DSD represent a mean QI between the Thunderstorm and the Drizzle. For no rain periods the simulations were performed only considering a Marshall-Palmer DSD.

5. CONCLUSIONS

A simultaneous retrieval of rain, cloud LWP and IWV based on a Bayesian approach has been implemented and applied to measurements by the radiometer ADMIRARI, highlighting the advantage to manage with the polarization difference in order to distinguish the uneven effect produced by different DSDs and rain rate regimes. Working in synergy with an active instrument like the MRR, the retrieval improves by selecting rainy observations at the radiometer slant field of view even if the rain cell is far away from the instrument site (unlike a rain sensor which indicates rain only for vertical observation), thus avoiding bias in the $rLWP$ retrieval during only cloudy conditions, further improve, showed by the QI, is introduced by considering three DSDs in the simulations. Finally the MRR gives a unique opportunity to improve the retrieval algorithm by including the reflectivity field to the Bayesian inversion technique which will be implemented in a future work.

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