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Estimation of Rain Rate by Microwave Radiometry and Active Radar during CLEOPATRA '92

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Abstract

Microwave radiometers operating at wavelengths 0.3, 0.8, 1.35 and 2.25 cm were used to estimate rain rates from ground during CLEOPATRA (Meischner et al., 1993). The systems were similar to those planned for the forthcoming PRIRODA mission. They were mainly operated looking at a fixed elevation of 75°. A model for estimation of the microwave emission of a rain layer taking into account polarization effects is briefly described. Originally designed for the evaluation of space borne measurements it was modified for ground based measurements and used to retrieve different rain parameters of interest. Intercomparisons with simultaneous measurements by the polarimetric Doppler radar POLDIRAD of DLR (Deutsche Forschungsanstalt für Luft- und Raumfahrt) and rain gauges provided the base for validation of the algorithm for rain rate estimations. Agreement strongly depends on the type of rain event characterized by the homogeniety of the rain clouds and by different drop size distributions influencing especially the radar measurements. Passive microwave radiometer measurements and active polarimetric radar measurements ideally complement each other in rain rate estimations from space as well as from ground. Ground based active radar is of importance in estimating small scale structures in time and space, such reducing possible errors of the radiometer measurements and for the selection of appropriate parameters for the rain model.

Zusammenfassung

Abschätzung von Niederschlagsraten durch Mikrowellenradiometrie und aktives Radar während CLEOPATRA '92

Ein Mikrowellenradiometersystem mit den Wellenlängen 0,3; 0,8; 1,35 und 2,25 cm wurde eingesetzt, um Regenraten am Grund während CLEOPATRA (Meischner et al., 1993) zu messen. Das System entspricht einer Konfiguration, die mit der zukünftigen PRIRODA Mission auf der russischen Raumstation MIR fliegen soll. Die Messungen wurden weitgehend unter einem festen Elevationswinkel von 75° durchgeführt. Ein Modell zur Bestimmung der emittierten Mikrowellenstrahlung unter Berücksichtigung polarimetrischer Effekte wird kurz beschrieben. Dieses, ursprünglich für Messungen aus dem Weltraum entwickelte Modell wurde modifiziert, um Regenparameter aus den Messungen vom Boden aus abzuleiten. Vergleiche mit gleichzeitig durchgeführten Regenmessungen mit dem Polarisations Doppler Radar POLDIRAD der DLR sowie Regenmessern am Boden ermöglichten eine Prüfung der Methode. Es zeigte sich, daß der Grad der Übereinstimmung stark von der Art des Niederschlages abhängt. Hierbei sind die Homogenität des Regens und die Variabilität der Tropfengrößenverteilungen, die inbesondere die Radarmessungen beeinflussen sensitive Parameter. Passive Mikrowellenradiometermessungen und aktive polarimetrische Radarmessungen zur Bestimmung von Regenraten stellen sowohl für Anwendungen vom Weltraum als auch am Boden eine gute Ergänzung dar, indem sie jeweils für unterschiedliche Tropfengrößenbereiche besonders empfindlich sind. Ein aktives Bodenradar kann darüberhinaus die kleinräumigen und zeitlichen Strukturen der Regenwolken quantifizieren und damit zur Korrektur der über größere Bereiche gemittelten Radiometermessungen beitragen und es kann die Wolkenparameter bestimmen, die in das Regenmodell eingehen.

1 Introduction

Among others, the objectives of the field experiment CLEOPATRA (Cloud Experiment Oberpfaffenhofen and Transports, May 11–July 31, 1992) were to quantify water vapor transports from soil and vegetation to the atmosphere in dependence on precipitation events and the state of vegetation, and to improve remote sensing methods from ground, aircraft and space for observing such elements of the hydrological cycle (Meischner et al., 1993).

The Russian module PRIRODA for earth observations is scheduled for launch in March 1995 to be connected with the space station MIR. PRIRODA will have a complementing package of active and passive optical and microwave instrumentation including different packages of microwave radiometers (Armand, 1991). Similar microwave radiometers as planned for PRIRODA were used during CLEOPATRA at ground and on aircraft to estimate rain rates, water vapor distributions in the troposphere and soil moisture. The aims of these measurements were to test the algorithms as developed for space-borne measurements and to intercompare the results with measurements by ground based systems of well known characteristics. The different conditions for observations from space or from ground were taken into account. In this paper we report on the rain measurements; an accompanying paper describes observed water vapor structures (Meischner et al., this issue).

A model for the retrieval of rain parameters from multichannel microwave measurements was developed and tested by comparison with the results of microwave emission simulations by Smirnov (1984) and Kutuza and Smirnov (1991). The model and the data processing techniques were developed primarily for satellite experiments. Up to now, no testing or verification, especially for the rain-filled atmosphere by measurements from ground have been performed. Intercomparisons by simultaneous measurements with the DLR polarimetric Doppler radar POLDIRAD and rain gauges were used for this purpose.

Rain measurements from space especially over land suffer from large uncertainties which should be reduced by the combination of passive and active methods. On the other hand, rain rate estimation by active radar from ground will profit by complementation with passive methods. The results of the measurements performed during CLEOPATRA '92 will contribute to this discussion.

2 The Model of Microwave Emissions from a Rain Layer

For the retrieval of rain parameters from multifrequency microwave radiation measurements we need to knoww the relationship between the signals measured at that frequencies and the parameters which characterize the rain. This relation can be obtained by empirical regressions or by a model using known physical relations between given rain layer parameters and the emitted radiation. The model we use is given by an equation describing the dependency of the brightness temperatures at different wavelengths from the main parameters of the atmosphere containing rain including the physical properties of the underlying surface. The advantage of such a model is the possibility to adjust it easily to different measurement conditions.

According to Smirnov (1984) and Kutuza and Smirnov (1991) the brightness temperature of the downwelling emission T_b^d and the upwelling emission T_b^u from a rain layer with an average thermodynamic temperature T above a surface with the reflection coefficient r_s and the temperature T_s (see Figure 1):

$$\begin{aligned} T_b^u &= T_r + (1 - r')\, r_s T_b^d q + (1 - r')\,(1 - r_s) T_s q \\ T_b^d &= T_r + r'\,(1 - r_s)\, T_s + r\, r_s T_r \end{aligned} \qquad (1)$$

For the upwelling radiation

1 – $T_r = T(1 - q - r)$ – the brightness temperature of the rain layer neglecting any boundary effects;

2 – the emission of the rain layer, reflected from the ground surface;

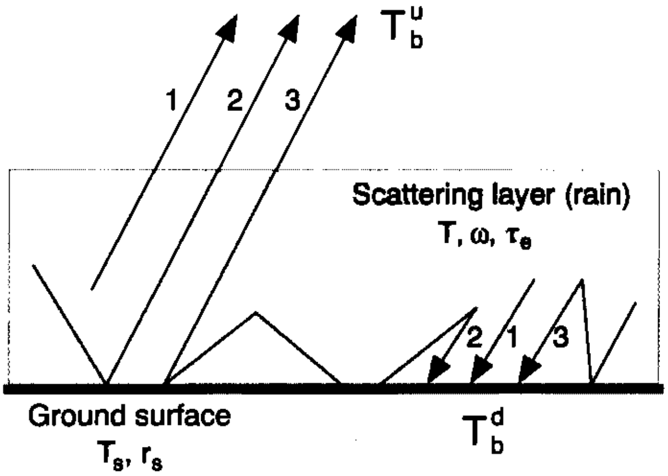

Figure 1 Definition of the scattering of the up- and downwelling radiation temperature.

3 – the ground surface emission, reflected by the rain layer and reflected again by the surface into the direction of the receiver.

For the downwelling radiation

1 – the brightness temperature of the rain layer;
2 – the emission of the surface, reflected by the rain layer;
3 – the rain layer emission reflected by the surface and then from the rain layer into the direction of the receiver.

The coefficients r and q describe the reflection and transparency of the rain layer. They are predicted by a one-dimensional scattering model (Sobolev, 1956):

$$q = \frac{(1 - r_0^2)\exp(-k\tau_e)}{1 - r_0^2\exp(-2k\tau_e)}$$

$$r = r_0\frac{1 - \exp(-2k\tau_e)}{1 - r_0^2\exp(-2k\tau_e)} \qquad (2)$$

where $r_0 = (1 - k)/(1 + k)$, $k = (1 - \omega)^{1/2}$, τ_e is the total extinction and ω the single scattering albedo of the rain layer. $r' = 0.64\,r$ is a semi-empirical equivalent reflection coefficient taking into account three-dimensional scattering.

The Mie theory is used for calculating τ_e. In a simplified form τ_e may be approximated by the equation

$$\tau_e = (\tau_o + c_1Q + c_2W + AR\,\alpha H)/\sin\Theta \qquad (3)$$

where Q is the total water vapor content, W the cloud liquid water content, τ_o the absorption by oxygen, c_1 and c_2 are coefficients, R is the rain rate and H is the thickness of the rain layer. A and α are coefficients depending on the wavelength and drop size distribution and Θ is the elevation angle of the observation (Smirnov, 1984).

Figure 2 shows the results of calculations of T_b^d versus rain rate for different rain rates. It demonstrates that the set of wavelengths used in this experiment allows to estimate rain rates up to about 100 mm/h. The accuracy is higher for low rain rates because of larger differences for the different wavelengths. The most reliable results however are expected for rain rates between 0 and 15 mm/h.

Falling raindrops are oblate in shape with a known axial ratio depending on the mean equivalent drop diameter (Pruppacher and Pitter, 1971). They further show a high degree of orientation during their fall through the atmosphere with the smaller axis being oriented vertically. Therefore the scattering and extinction coefficients differ for horizontal and vertical polarizations. These differences of the scattering and extinction coefficients for emission of oblate raindrops were calculated for horizontal and vertical polarizations (Smirnov, 1984). The approximation for τ_e and ω versus R, H and the angle ϕ between the observation direction and the drop axis was formulated similar to (3) as

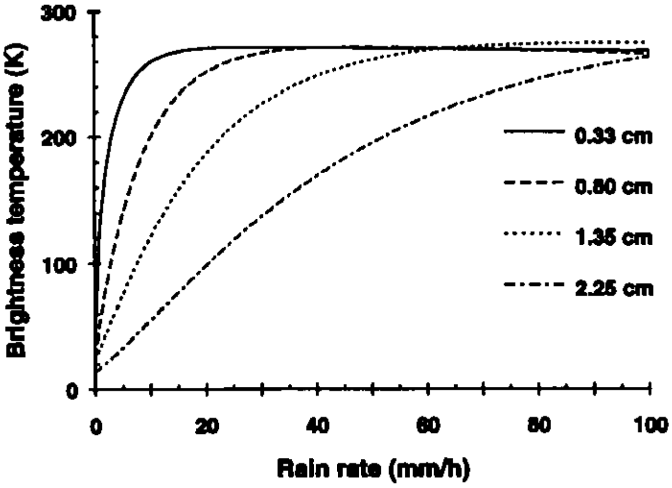

Figure 2 The model dependence of T_b^d on R at wavelengths used in the experiment (H = 2 km, T = 15 °C, elevation angle 35°).

$$\tau_r^h = A_h R\,\alpha_h H$$
$$\tau_r^v = A_v R\,\alpha_v H \sin^2\phi \qquad (4)$$

Sensitivy studies with the model given by the Eqs. (1–3) have shown, that for rain rate estimations by passive microwave measurements the parameters rain rate R, rain layer thickness H and rain layer temperature T are the most important ones. The measured brightness temperatures are less sensitive to the drop size distribution including the cloud droplets (Smirnov, 1984).

The accuracy of the described model previously has been estimated theoretically by comparison with results of simulations of the rain layer emission (Smirnov, 1984; Vinokurova et al., 1991). These simulations were performed using Monte Carlo calculations for different rain types.

The most simple case was the assumption of a homogeneous layer of scatterers above a homogeneous flat surface. This system was characterized by different values of T, ω, τ, T_s and e_s the surface emissivity. An example comparing the brightness temperatures for the model and the Monte Carlo simulation is shown in Figure 3. An excellent agreement can be stated.

A more detailed model did include a temperature profile and various reflection properties of the

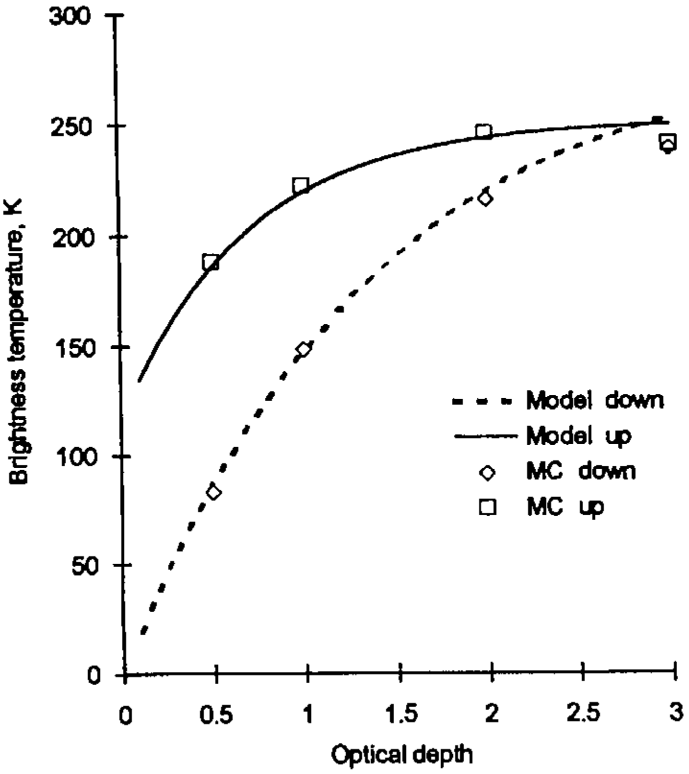

Figure 3 Comparison of brightness temperatures using the described model and a Monte Carlo (MC) simulation.

ground surface. The most detailed model used for these intercomparisons took into account a number of horizontally limited rain cells. The scattering properties of the rain drops were described by Mie phase functions and the extinction coefficients were calculated for oblate raindrops according to Smirnov (1984).

Depending on the rain model used for the simulations, the differences in the brightness temperatures between the model calculations and Monte Carlo simulations were found to be between 3 and 5 K for wavelengths between 0.5 and 6.0 cm. For the wavelength of 0.3 cm the difference is somewhat higher. In general we state an uncertainty of no more than 3 K for the frequency range of interest.

3 Passive Microwave Measurements and Data Processing

The ground based passive microwave system designed and constructed by the Institute of Radioenigneering and Electronics, Moscow, was operating at wavelengths 0.3, 0.8, 1.35 and 2.25 cm. The radiometers were located at the Lichtenau site in Southern Bavaria, Germany. The radiometers were installed as a block on the remotely controlled turnable platform which provided the possibility to perform measurements for different azimuthal and elevational directions. For 2.25 cm wavelength the intensity of the emission was measured for both horizontal and vertical polarizations. A short description of the system can be found in Meischner et al., in this issue.

The multichannel microwave measurement data evaluation consists of two parts: The calibration procedure and the estimation of the geophysical parameters of interest. The corresponding technique of data processing has been developed primarily for satellite measurements (Petrenko, 1991; Petrenko, 1992). This method was slightly modified for the ground based measurements. The main difference is, that for satellite measurements the calibration and the estimation of the geophysical parameters of interest are combined in one algorithm, using a priori informations, whereas for the measurements from ground a separate calibration procedure was used as follows:

It is assumed that the measured brightness temperatures for different wavelengths are:

$$T_{b\lambda} = T_{b\lambda}(\mathbf{X},\Theta) + \delta T_{b\lambda} \tag{5}$$

where $T_{b\lambda}(\mathbf{X},\Theta)$ is the brightness temperature, calculated by the model (1), $\delta T_{b\lambda}$ is the calculation error at wavelength λ and $\mathbf{X}$ is the vector of the geophysical parameters which determine the measured brightness temperature. In our case $\mathbf{X}$ consists of such parameters as R, T, H, total water vapor content Q, cloud liquid water content W, etc. Some of these parameters may be retrieved and some of them must be known a priori.

The aim of the calibration is to determine the coefficients a_λ and b_λ of the linear relation between the measured brightness temperatures of the atmosphere $T_{b\lambda}$ and the raw radiometric signals u_λ for each wavelength λ of interest:

$$a_\lambda + b_\lambda T_{b\lambda} = u_\lambda + \delta u_\lambda \tag{6}$$

where δu_λ is the measurement error, taking into account e.g. instrumental noise and antenna sidelobe effects.

For the ground based measurements the calibration was performed by measurements of the brightness temperatures under clear air conditions at different elevation angles. For this purpose time periods for cloudless conditions (R = 0, W = 0) and known profiles of the meteorological parameters including Q from radiosonde data were selected.

Then the following equation was used for determining the coefficients a_λ and b_λ:

$$\sum_{\Theta} (\mathbf{a} + \mathbf{b}\mathbf{T}_b(\mathbf{X},\Theta) - \mathbf{u})^T \Delta_u^{-1} (\mathbf{a} + \mathbf{b}\mathbf{T}_b(\mathbf{X},\Theta) - \mathbf{u}) = \min \qquad (7)$$

where **a**, **b**, $\mathbf{T}_b$, **u** are vectors of the corresponding variables, index T denotes a matrix transposition and Δ_u^{-1} is an interchannel covariance matrix of the measurement errors.

The second step of data evaluation then is to find those values of the vector of the geophysical parameters **X** which best fit the estimated relation between the measured microwave radiometric signals and the wavelengths used. A retrieval of the model parameters from a number of values u_λ was performed using the equation:

$$\sum_{\Theta} (\mathbf{a} + \mathbf{b}\mathbf{T}_b(\mathbf{X},\Theta) - \mathbf{u})^T \Delta_u^{-1} (\mathbf{a} + \mathbf{b}\mathbf{T}_b(\mathbf{X},\Theta) - \mathbf{u}) + (\mathbf{X} - \mathbf{Y})^T \mathbf{Z}^{-1} (\mathbf{X} - \mathbf{Y}) = \min \qquad (8)$$

where **Y** is a mathematical expectation value of **X** and **Z** is the covariance matrix of **Y**. $\delta T_{b\lambda}$ is considered by use of an additional formal component of the vector **X**.

Due to essential nonlinearity of the radiative transfer model we used an iterative gradient method to retrieve the vaiues of the parameters. The analysis of the inverse problem for the retrieval of the rain parameters shows, that from a number of values of brightness temperatures at the used wavelengths only the rain rate and the rain layer temperature may be estimated with an acceptable accuracy. In our experiment, the altitude of the radar bright band as determined from POLDIRAD-RHI images was used for the estimation of H.

Measurements were performed during two periods of intense observations of CELOPATRA in May–July 1992. Measurements during rainfall were made at a fixed elevation angle of approximately 35° in northern direction. Horizontal averaging due to the antenna pattern was about 3–4 km depending on the rain layer thickness. Time series of the brightness temperatures for the wavelengths used, measured on July 22, 1992 during rainfall are presented in Figure 4. The retrieved rain rate for 22 July 1992 is presented in Figure 5.

The results of the rain rate retrievals by the multifrequency microwave measurements were compared with the independent measurements by a rain gauge installed near the microwave radiometer system and by the weather radar POLDIRAD. These results will be discussed in paragraph 5.

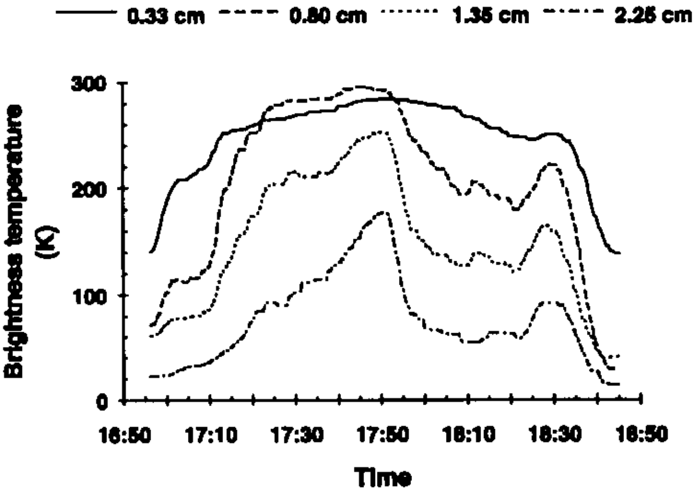

Figure 4 The sample of measured brightness temperatures at 22 July 1992 during rainfall.

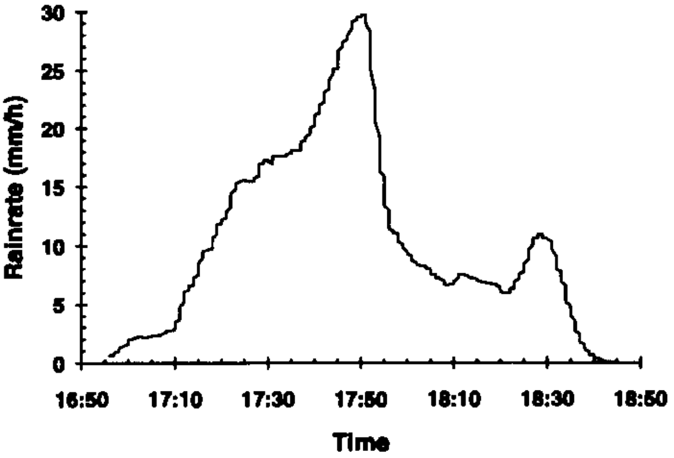

Figure 5 Retrieved rain rates from the data shown in Figure 4.

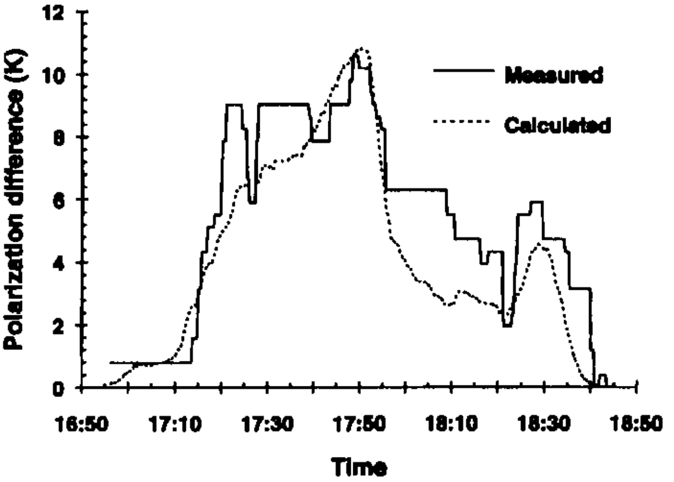

Figure 6 Measured and calculated polarization difference for the case study at 22 July 1992.

Further, nearly independent measurements useful for intercomparison were performed by the polarization measurements at 2.25 cm wavelength. For this purpose calculations of the difference of the brightness temperatures for horizontal and vertical polarizations as described above were performed, using R as retrieved from the multifrequency measurements. Figure 6 shows, that the measured difference is in very good agreement with the calculations giving evidence for the self-consistency of the model. This finding further suggests to use the polarization difference of the emission radiation of oblate raindrops as an additional parameter in solving the general inverse problem.

4 Radar Measurements

The DLR polarimetric Doppler weather-radar (Schroth et al., 1988) was located about 27 km north-east of the site of the ground based microwave radiometer system. The radar frequently scanned in PPI mode about 600 m above the radiometers. Products from the radar are – besides others – the reflectivity for horizontal (Z_{HH}) and vertical polarization (Z_{VV}). The presented radar data are average values of an aera of 2 by 2 km^2 centered above the radiometers.

Three different methods were applied for rain rate estimations from radar data. The first one uses a relationship between reflectivity Z and rain rate R (Z – R relation)

$$Z_{HH} = aR^b \tag{9}$$

where Z_{HH} is the reflectivity in mm^{6}m^{-3} and R is the rain rate in mm/h, a and b are coefficients varying with the type of precipitation. For Southern Germany a and b are reported to be 231 and 1.43, respectively (Aniol et al., 1980). This method assumes a standard exponential rain drop size distribution (Marshall and Palmer, 1948).

In the second approach we use additional information which is provided by the differential reflectivity Z_{DR}. Z_{DR} is the ratio between Z_{HH} and Z_{VV} which is, in the case of rain, mainly determined by the shape of the raindrops and their common alignment (Seliga and Bringi, 1976). Because of the known relationship between the size and the mean elliptical shape of falling drops (Pruppacher and Pitter, 1971), Z_{DR} contains additional information on the presence of larger drops in the raindrop size distribution. A relation between the radar parameters Z and Z_{DR} and the rainrate (Z – Z_{DR} –R relation) will give a better estimation of the rain rate in situations where the drop size distribution deviates from the distribution assumed for the Z – R relations. Numerical simulations of the backscatter of various raindrop size distributions show that

$$R = 2.1 \cdot 10^{-3} Z_{HH}^{0.96} Z_{DR}^{-1.17} \tag{10}$$

with Z_{DR} in dB (Aydin et al., 1989). However, attenuation effects especially in heavy rain or hailfall can reduce Z_{DR} considerably which in turn will overestimate the rain rate.

The third approach to estimate the rainrate by polarimetric measurements is performed as proposed by Seliga and Bringi (1976). They used the differential reflectivity Z_{DR} to estimate the median-diameter D_0 of a gamma dropsize distribution

$$N(D) = N_0 D^{\mu} e^{-\frac{3.67+\mu}{D_0} D} \tag{11}$$

with μ as a shape factor. This shape factor will be set to 2 (Ulbricht and Atlas, 1984). For an exponential dropsize distribution μ is zero. Knowing D_0 and μ, N_0 can be estimated with the reflectivity Z. For a given Z and Z_{DR} the rainrate R in mm/h can now b computed

$$R = 6\pi \cdot 10^{-4} \int_0^{\infty} N(D)\, D^3 v(D)\, dD, \tag{12}$$

with v(D) the terminal fall velocity of the raindrops. This approach for the rainrate estimation allows more flexibility in retrieving the rainrate from polarimetric radar measurements. The effect of overestimation of the rainrate by low Z_{DR} is not so pronounced as with the use of Eq. (10). In the further text we will refer to this technique as the $R(N_0, D_0)$ estimation.

No attempt was made to correct for propagation effects because of the moderate or even low rain intensity along the path of the radar beam from the radar site to the radiometer site as can be seen on Figures 7 and 10.

A further promising method of rain rate estimation by Doppler measurements is discussed by Richter (1994).

5 Intercomparison of Results

The different techniques of rain rate estimations were applied to measurements on 22 July and 25 July, 1992. These days represent two quite different meteorological situations. 22 July was characterized

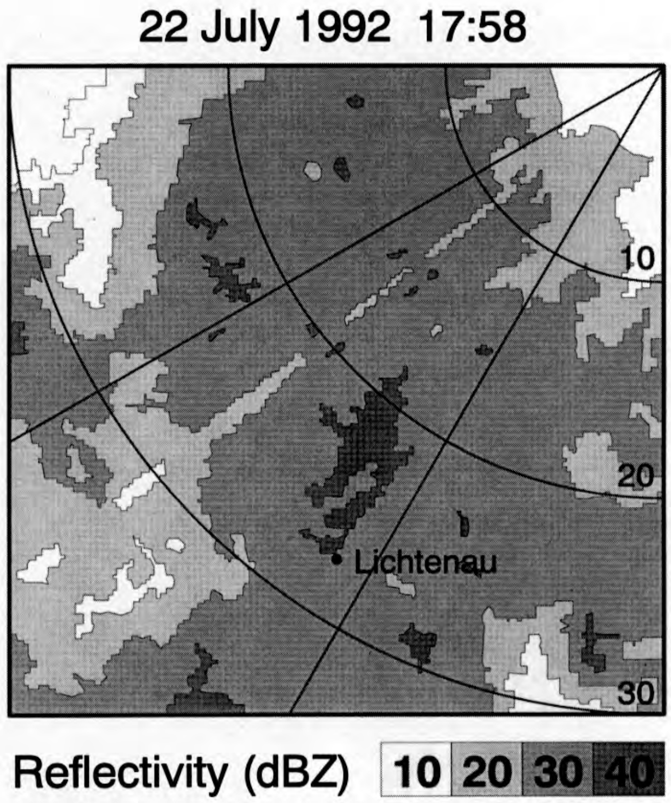

Figure 7 Image of the radar reflectivity (Z_{HH}) at 22 July 1992. South-west sector of a PPI scan at 2.5° elevation. Distances in kilometers. The location of the Lichtenau is marked.

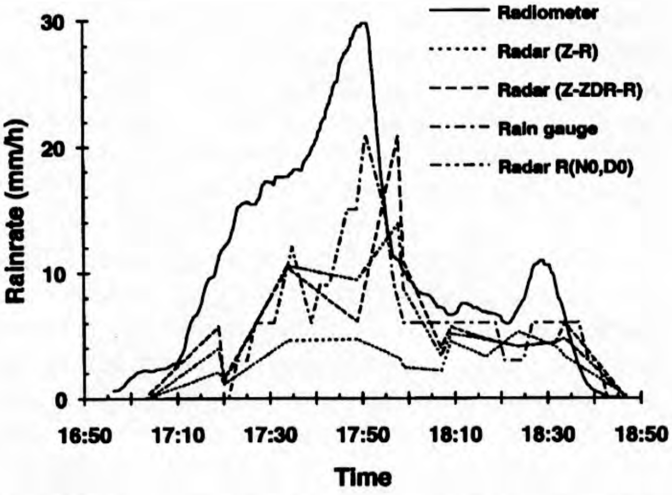

Figure 8 Comparison of rain retrieved by radiometry, rain gauge and polarization radar at 22 July 1992. Z–R and Z–Z_{DR}–R denote the different retrival techniques for radar data.

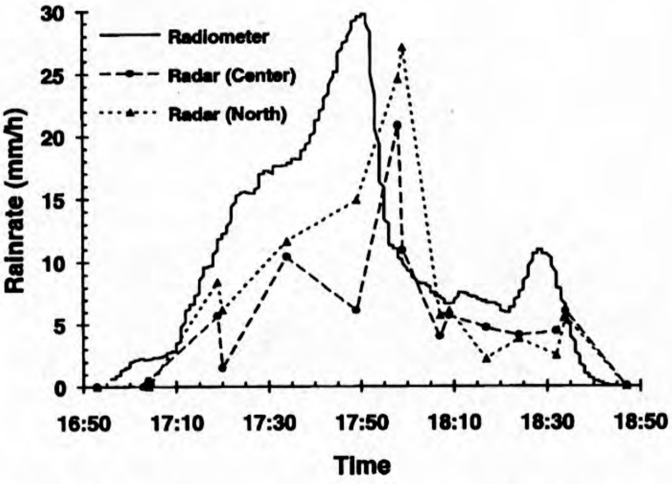

Figure 9 Rain rates retrieved by radiometry and polarization radar. Radar data are for two different 2 by 2 km^2 cells located above the Lichtenau and north of the Lichtenau.

by widespread precipitation with embedded weak showers, whereas the second day showed convective activity with heavy showers. The radar measurements presented as PPI images in Figures 7 and 10 represent the different characteristics of the rain cells for these two case studies. On both days the rain layer was about 2 km deep.

When intercomparing the rain rates as determined by the three systems their quite different temporal and spatial measurement characteristics need to be considered. The radiometers continuously measured the integral over a slanted path of about 35° elevation in northern direction through the rain layer. Horizontal averages of 2 by 2 km^2 were sampled by POLDIRAD at a heigth of about 600 m above the radiometer location in a time sequence of some minutes whereas the rain gauge measurements represent continuous 2 minute averages for one point at the ground.

For the case of July 22, 1992 the rain rate estimation (Figure 8) using the $Z - Z_{DR} - R$ and the $R(N_0, D_0)$ relation gives good agreement with the rain gauge measurements and fair agreement with the passive radiometer measurements during high rain rates at the beginning of the precipitation event. The time offset for the different measurements is caused by the different locations of measurements and different integration times. The large difference between the radiometer measurements and the other sensors mainly is due to the heavier precipitation in the north of the Lichtenau (Figure 7). In Figure 9 we show the radar derived rain rates ($Z - Z_{DR} - R$) for the 2 by 2 km^2 square area just north of the radiometer site (central). Within this area the radar derived rain rates are higher and very similar to those derived by the radiometer measurements.The $Z - R$ relation shows rather weak precipitation for that time.

Later on, for lower precipitation intensities all methods show similar results. At that time the embedded convective activity has decreased, resulting in more homogeneous precipitation in time and space as assured by the frequent radar observations, not shown here. This reduces the error due to the different spatial and temporal measurement characteristics. The agreement between the Z – R and the Z – Z_{DR} – R as well as the R(N_0,D_0) rainrate estimation is interpreted in such a way that the drop size distribution now is close to an exponential one. During the onset of the intense convective precipitation the drop size distribution can remarkably deviate from a standard exponential distribution, e.g. due to evaporation of small drops or the separation due to high vertical air velocities. Here the additional use of Z_{DR} is necessary to retrieve more accurate rain rates by radar measurements. The high precipitation rates are connected with a low Z_{DR} in combination with a high Z. This indicates a drop size distribution with a relatively large number of smaller drops (smaller than about 1.5 mm in diameter). Drops of this size are expected to be spherical and do not contribute to Z_{DR}. Both polarimetric techniques show similar results, R(N_0,D_0) gives a D_0 of 0.9 mm for the time of the intense rainfall.

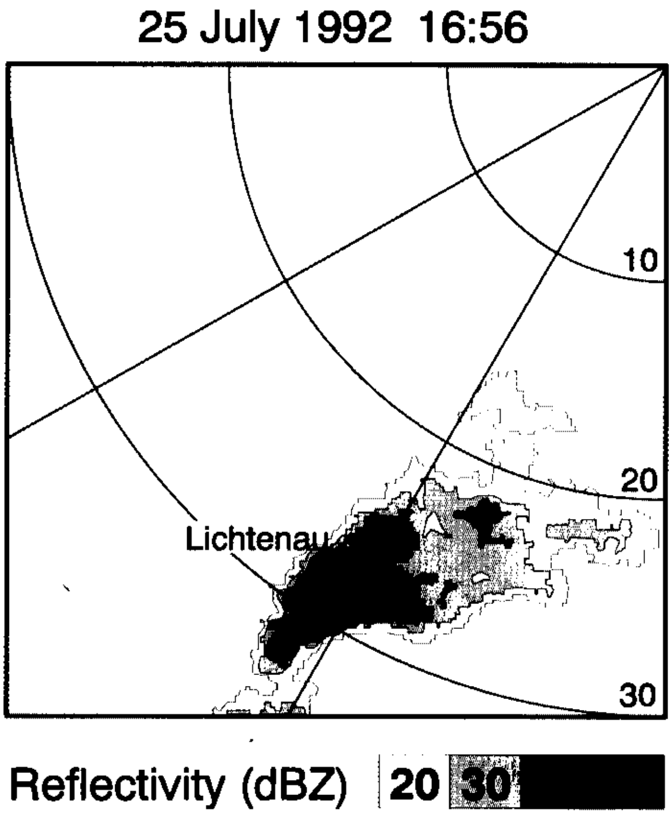

Figure 10 Image of the radar reflectivity (Z_{HH}) at 25 July 1992. South-west sector of a PPI scan at 2.5° elevation. Distances in kilometers. The location of the Lichtenau is marked.

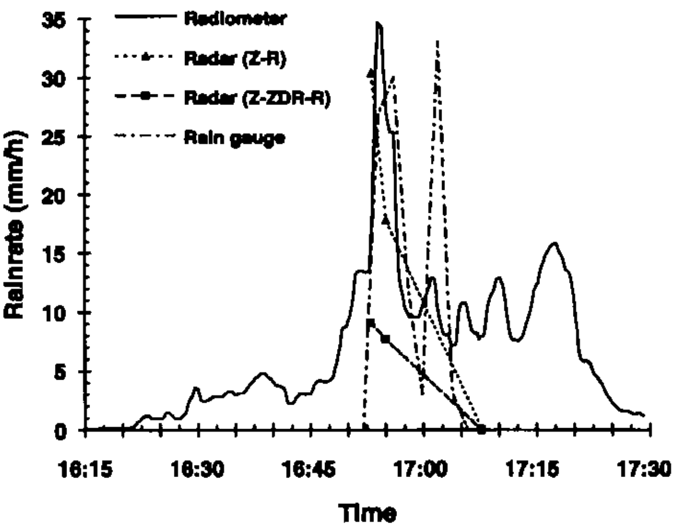

Figure 11 Comparison of rain rates retrieved by radiometry, rain gauge and polarization radar at 25 July 1992. Z–R and Z–Z_{DR}–R denote the different retrival techniques for radar data.

On 25 July 1992 the radar measurements started at 16:54 local time (Figure 10). At this time a precipitation cell reached its mature state just near the Lichtenau with its northern edge above the site. Subsequently it moved to the south-east and decreased in intensity. Radiometers and rain gauges show good agreement during the passage of the main precipitation shaft (16:50 to 16:58 local time) (Figure 11). The comparison with the radar estimated rain rates shows remarkable differences. The Z – R relationship gives good agreement, whereas the Z – Z_{DR} – R relationship failes for this study. The reason is a high Z_{DR} of about 3.2 dB. According to numerical studies and observations a Z_{DR} of about 1.5 dB is expected for rainrates of about 30 mm/h (Bringi et al., 1991). The high Z_{DR} can be explained by the presence of a monodisperse drop size distribution with a mean diameter of about 4.5 mm (Meischner et al., 1991). These big drop zones are frequently observed in the inflow region of thunderstorms. Due to the high local variability of the precipitation cell and the different spatial and temporal resolutions of the different sensors the differently estimated rain rates show quite different values for the low rain rates starting at about 16:58 local time. The radar observed smaller showers north of the Lichtenau during that time. They may cause the fluctuating values around 10 mm/h for the radiometer measurements. Furthermore, these estimations suffer from the fact that the rain cell cannot be assumed to be horizontally uniform and that the depth of the rain layer is uncertain and highly variable within a rain shower.

6 Discussion and Conclusions

Simultaneous measurements by a ground based passive multichannel microwave radiometer system similar to a system to fly on the forthcoming PRIRODA mission, the polarimetric Doppler radar POLDIRAD and a rain gauge as part of the CLEOPATRA experiment gave an excellent possibility to intercompare the different techniques of rain rate estimation and to assess methods of spaceborne observations.

A model for estimation of the microwave radiation emission upwards and downwards from a rain layer was validated experimentally for the downwelling microwave emission for rather stratiform as well as for more convective situations. The results agree reasonably well with active and gauge measurements of the rainrate if the different sampling characteristics are considered. So it can be concluded that the model and the retrieving method will be applicable for space borne observations too. Nevertheless the main areas of uncertainty need to be considered. These are the variation of surface emissivity in time and space which contribute to the upwelling radiation and the small scale variability of cloud and precipitation systems themselves. The results of the experiment clearly demonstrate that active radar is of urgent need for description of the character and structure of the precipitating system. Parameters as rain layer height, horizontal cloud extend and cloud distributions, all essential for the underlying rain model, can be derived by active radar. So passive microwave radiometers (from space as well as from ground) and active radar are complementing methods, increasing the accuracy and, more important, the reliability of rain rate measurements because of the possibility to be adapted to different rain characteristics. Another important point of complementation is, that multichannel microwave radiometer rain measurements are most sensitive for small rain rates (Figure 2) whereas polarimetric radar measurements are especially suited for higher rain rates. However, as shown by the example of 25 July 1992, additional interpretation can be necessary to understand the polarimetric signals. Vertical pointing Doppler measurements (Richter, 1994) further contribute to quantitative rain rate measurements.

The results gained during the CLEOPATRA field experiment as presented here, represent an important step in using the forthcoming PRIRODA mission for investigating cloud and precipitation systems over southern Germany. Especially the strategy of combined measurements and intercomparisons will be defined on the base of this findings.

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