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# Investigation of rainfall microstructure and variability using vertically pointing radar and disdrometer

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**Abstract.** In this study variability in the drop size distribution inside an area of 200 by 600 m is analyzed with a temporal resolution of 30 s using 3 Micro Rain Radars/disdrometers and a 2D-Video Disdrometer. Comparison of the instruments at different temporal scales allowed the estimation of measurement errors and necessary integration time. Deviations resulting from spatial and temporal variability could successfully be isolated from sampling effects and other errors. This opened the door for combining the instruments to measure inhomogeneity inside a volume corresponding to that illuminated by a conventional weather radar beam, and to study the temporal evolution of precipitation microstructure in single rain events.

## 1 Introduction

Ever since weather radar has been used for areal precipitation measurement, the quantitative estimation and investigation of rain rate from radar reflectivity has been hampered by:

1. the highly variable and ambiguous relation between rain rate and radar reflectivity, which depends strongly on the drop size distribution (DSD),
2. the occurrence of ice in the illuminated volume,
3. the evolution of rainfall from the height of the radar beam to the ground,
4. the dissimilar volumetric and temporal scales involved when measuring different rain characteristics.

These effects have been investigated in numerous publications, but the progress in applied areal rainfall measurement with radar has been modest. Often additional information is needed to correctly identify, predict and correct the named effects. Fabry et al. (1992) suggested the use of a network of low cost vertically pointing radars to enhance weather radar scans by measuring the vertical reflectivity profile and detecting the melting layer, which yields potential to counter the errors caused by issue 2 and 3. For issue 1, the measurement of the drop size distribution (DSD) allowed the investigation of methods to associate rainfall structure with DSD characteristics at ground level (Uijlenhoet et al., 2003). This represents a significant progress compared to separately measuring reflectivity with radar and rain rate with gauges, as this is too strongly affected by issue 4.

The vertical Doppler spectrum yields information on the DSD if an adequate relation between drop diameter and terminal falling velocity is given (Atlas et al., 1973; Gunn and Kinzer, 1949). A low cost vertically pointing Doppler radar may therefore be used to study drop populations at higher altitudes, leading to an improvement of Z-R relations. The change in both falling velocity and reflectivity in the melting layer is detectable in vertical profiles and allows an easier detection of the ice phase.

## 2 Description of the Experiment

The Micro Rain Radar 2 (MRR-2) was conceived for these applications. Only a short description of its functionality will be given here, more detail can be found in Peters et al.(2002). The MRR is a vertically pointing low cost FMCW radar at 24 GHz which measures the Doppler spectrum from 0 to 12 m/s. It is small (single 0.6 m diameter offset parabolic antenna with signal processing attached), has a low power consumption and an attached laptop or PC for operation. The standard real-time processing uses the relation given by Atlas et al. (1973) to attribute drop diameters to Doppler velocities. Mie theory is used to calculate drop numbers from the spectral volume reflectivity.

Corrections for oblate drops and lower air densities leading to higher falling velocities in high altitudes are applied. The DSD is calculated for falling velocities from 0.78 to 8.97 m/s in 43 intervals, corresponding to drop diameters

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**Table 1.** Instrumentation and contributors. WUR: Wageningen University & Research center, TUD: Technische Universiteit Delft, KNMI: Koninklijk Nederlands Meteorologisch Instituut.

| Instrument | Institute |
|---|---|
| **Wind Profilers** | |
| 1.29 GHz Windprofiler/RASS | KNMI |
| MODOS Sodar/RASS | IfT Leipzig |
| **Radars** | |
| 3 GHz FMCW Radar TARA | TUD |
| 24 GHz Micro Rain Radar (1) | Uni Bonn |
| 24 GHz Micro Rain Radar (2) | Uni Bonn |
| 24 GHz Micro Rain Radar (3) | WUR |
| 24 GHz Micro Rain Radar (4) | Uni Marburg |
| 35 GHz Cloud Radar | KNMI |
| C-Band radar De Bilt | KNMI |
| **Rain Gauges** | |
| 3 tipping bucket rain gauges | WUR |
| **Disdrometer** | |
| 2D-Video Disdrometer | WUR |

from 0.245 to 4.53 mm, which is the range where the signal to noise ratio is considered adequate. An attenuation correction necessary in moderately high rain rates is done by calculating Mie extinction from the derived DSD. Rain rate, LWC, and Rayleigh reflectivity $Z$ are calculated from the DSD, while mean falling velocity (first Doppler moment) and integral reflectivity (zeroth Doppler moment) are calculated directly from the measured Doppler spectrum. The MRRs range resolution can be set from 10 to 200 m in 30 height intervals. Attenuation at 24 GHz prevents the use of ranges higher than 6 km. The averaging time for one measurement can be set from 10 s up to several hours.

Being a compromise between versatility and low cost, issues like calibration, signal to noise ratio, and quality of the FMCW Doppler spectra as well as the validity of assumptions made in the MRR processing must be investigated. A unique occasion was given at the BALTEX Bridge Campaign (BBC-2)[1] in May 2003, during which a multitude of institutes contributed remote sensing and in-situ measuring equipment for intercomparison. The main focus of the campaign was on clouds, but precipitation measurements over an area approximately 600×200 m were made using 4 MRRs, 3 tipping bucket rain gauges, a 2D-Video disdrometer, and the Transportable Atmospheric Radar TARA. A pulsed 35 GHz cloud radar was useful for estimating height dependent biases of the FMCW radars. C-Band weather radar measurements were available in the form of pCAPPI-images and volume scans. Two wind profilers gave information for the correct interpretation of instantaneous and time-integrated measurements with respect to advection and wind induced error (see Table 1, Fig. 1).

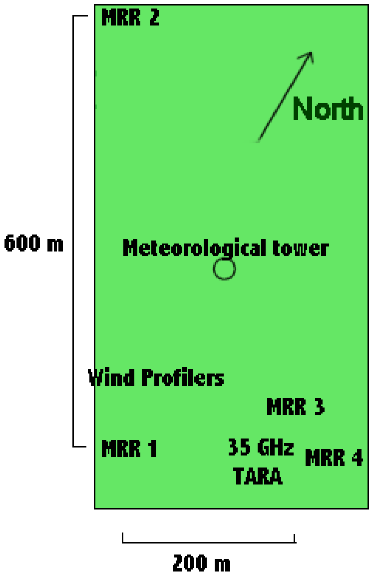

**Fig. 1.** Map of instrument layout at the meteorological observatory Cabauw.

## 3 Evaluation of instrument performance

### 3.1 Reflectivity measurements

The first assessment of MRR performance regards the integrated Doppler spectrum or radar reflectivity. Comparisons with the De Bilt C-Band weather radar volume products showed calibration errors in 2 MRRs (−8 and −3 dBZ), a smaller error in one MRR (+1 dBZ), and adequate calibration in the remaining one. Some evidence points towards a loss in antenna gain due to mechanical deformation being the origin of the deviations. If the MRR is placed within the range of a weather radar, such variations in calibration can easily be detected, but if no reference system is available, gross errors may arise in the derivation of quantities that depend on calibration.

The vertical reflectivity profiles measured by the MRRs were compared to weather radar volume scans at different beam heights, as well as the vertically pointing 35 GHz cloud radar and TARA. All MRRs displayed a loss in intensity of about −2 dBZ per kilometer altitude relative to the 35 GHz and weather radar volume scans, which is in agreement with the results of a previous comparison between another MRR and a weather radar of the Deutsche Wetterdienst (DWD). During separate test runs, 2 MRRs where operated with different range resolutions, which led to a bias of about 1 dBZ/km if the range resolution of one was doubled. The profiles showed a bias of less than 0.3 dBZ/km when operating at identical range resolution. A suggested explanation is imperfection in the frequency dependent transfer function, which compensates for the dependance of electronic system gain on frequency. Factors like attenuation, different behavior in the ice phase, Mie/Rayleigh scattering and changing

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[1] for more information see http://www.knmi.nl/samenw/bbc2/ or http://www.meteo.uni-bonn.de/projekte/4d-clouds/bbc2/

DSD shapes with height could be isolated and quantified as less prominent.

TARA is also capable of cloud measurements and operates at a frequency almost unattenuated by hydrometeors (3 GHz). Thus it is ideal for determining the top and bottom thresholds of MRR sensitivity, as well as evaluating the MRR attenuation correction algorithm. With comparisons at fixed heights, it was established that the noise level expressed in dBz was around −5 dBZ at ground level and rose to approx 5 dBZ at 2000 meters for MRR 1 and 2. However it rose from +5 dBZ at ground level to an unacceptable value of about +15 dBZ for MRR 3 and 4. The attenuation correction algorithm overcompensated slightly for the MRRs with adequate calibration, which may be linked to the observed height dependent bias. The intensities at ground level are obviously too high, which could propagate to higher altitudes in the attenuation correction. For the MRRs with more than -3 dBZ calibration error, the algorithm remained ineffective.

### 3.2 DSD measurement

The Joaneum 2D-Video Disdrometer was designed specifically for applications in radar meteorology. It is capable of measuring drop fall velocity, equivolumetric diameter, and oblateness. A description of the system's functionality is given in Kruger and Krajewski (2002). In our investigations total DSD accumulations as well as single radar reflectivity and rain rate values were calculated from DSDs obtained with one minute integration time in 22 0.2 mm intervals. The MRR DSDs were interpolated onto the same resolution for comparison. Figure 2 shows the resulting DSDs integrated over 5 days. The calibration differences in the MRRs become apparent, as well as a large disagreement in the smallest drop classes.

The disagreement between the MRRs was found to be caused by their different noise levels and calibration. Noise subtraction affects mostly drop numbers in "slow" Doppler bins. The video disdrometer counts significantly fewer drops at diameters between 0.2 and 0.6 mm, and more between 0.6 and 0.8 mm. The cause can not be determined with certainty, but an impediment of the disdrometer through horizontal wind has been suggested by Nespor et al. (2000). The optical resolution of the disdrometer is better than 0.22 mm, which leaves some uncertainty in drop class assignment. Similar behavior was found for shorter integration times of a few hours, except that the disdrometer did not give realistic drop numbers lower than $10/(\text{m}^3\ \text{mm})$ , whereas the MRRs continued to show agreeable drop numbers below $0.01/(\text{m}^3\ \text{mm})$. The disagreement for small drops was substantial enough to significantly influence integral rain rate, Z/R ratio, total drop number and mean drop diameter, as well as the first Doppler moment (mean falling velocity) during the absence of larger drops (see Fig. 7).

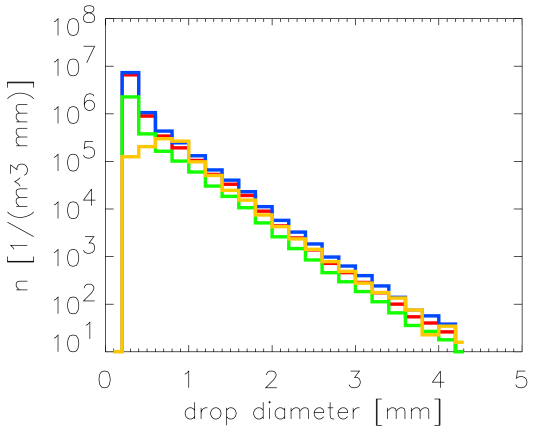


**Fig. 2.** Total drop numbers per cubic meter and diameter interval for a period of 5 days in 22 drop size classes with 0.2 mm interval. Measurements of MRR 1 (height 70 m) are shown in red, MRR 2 in blue, MRR 3 in green, the 2D-Video-Disdrometer in yellow.

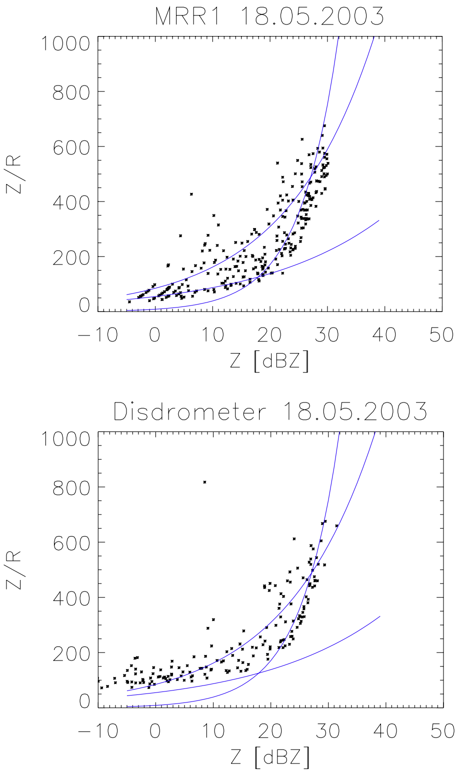
### 3.3 Precipitation measurement

The rain rate calculated from the MRR Doppler spectrum should agree better with in-situ precipitation measurements than any constant Z-R power law if the use of the MRR is justified. This was tested by deriving precipitation sums with one hour integration time, and calculating the correlation coefficient between rain gauges and MRR for DSD and Z-R rain rates. The correlation with gauges was 0.98 for rain rates derived from the DSD, and 0.94 for the best Z-R relation. Several other investigations and comparisons led to the following conclusions regarding MRR and rain gauges:

- The MRRs gave consistent rain rate estimates for integration periods down to 30 seconds, with good correlation between MRR locations in the case of homogenous rain and favorable wind advection. Spatial and temporal variability led to a clear dependence of correlation on integration time and distance between MRRs. Neither temporal variability below 5 min nor spatial variability within 200 or 600 m could be measured with the rain gauges due to lack of sensitivity (0.2 mm per pulse).

- For total rainfall accumulations over periods longer than several days the 3 rain gauges showed smaller deviations from each other (below 5%) than the 3 MRRs (more than 10%). This was not only caused by calibration errors but also by the dissimilar behavior of different MRRs in the noise correction at the "slower" end of the Doppler spectrum.

- Horizontal wind caused a detectable error in MRR rain rate assessment by shifting the Doppler spectrum if the vertical alignment of the radar beam was worse than ±3°. This could be measured using wind profilers and comparing all MRRs amongst themselves.



blue lines:
$Z = 450 \cdot R^{2.8}$ $Z = 480 \cdot R^{1.39}$ $Z = 150 \cdot R^{1.25}$

**Fig. 3.** Example of Z/R ratios and rain rate as a function of reflectivity during 3 h on May 18, 2003. Z-R power laws (blue dashed lines) could be fitted into short periods/rain types with very little scatter. Such temporarily constant Z-R behavior was observed in temporal scales from 10 min to several hours in homogeneous events.

## 4 Observations of rainfall characteristics in terms of radar reflectivity and rain rate

The drop size spectra measured by MRRs and 2D-Video Disdrometer are analyzed in terms of corresponding rain rate and radar reflectivity, without taking the detour of DSD parameterizations. Special attention is paid to systematic disagreements between instruments and their possible cause. Observations in three selected rain events exemplify the potential for studying rainfall microstructure with the used instruments and improving the conventional precipitation measurements of weather radar.

One event on May 18 consisted of two periods of increasing and decreasing rain intensity. The 30-second resolution MRR measurements at 70 m height (Fig. 3) formed near perfect Z-R power laws in periods of monotonic increase or decrease of reflectivity with time. While increasing, the reflectivity appeared to follow the power law $Z = 480 \cdot R^{1.39}$, whereas decreasing rain intensity displayed an evolution described by $Z = 450 \cdot R^{2.8}$ and $Z = 150 \cdot R^{1.25}$ with very little scattering. This behavior could be observed during two cycles of increasing and decreasing intensity in one convective system. This result is similar to what was observed by Uijlenhoet et al. (2003), except that it repeats itself.

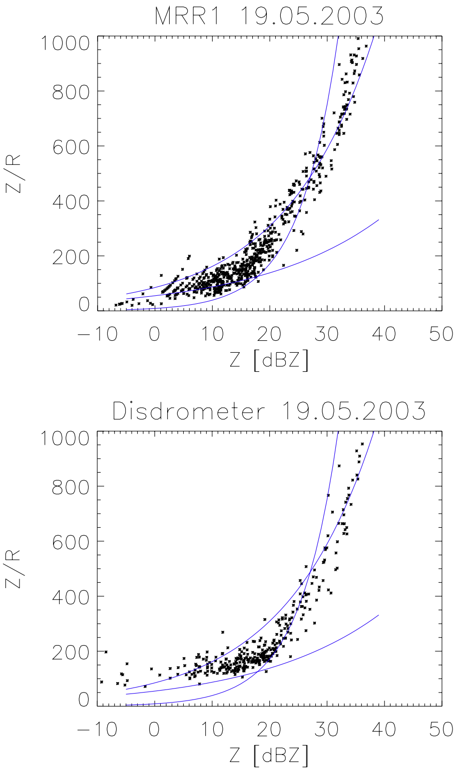


**Fig. 4.** Z/R ratios measured by MRR 1 and 2D-Video disdrometer on May 19. For better comparability the Z-R relations from the previous figure are also shown.

In a convective structure MRR drop spectra may be shifted and affected by the occurrence of strong vertical wind, which was not distinguishable from falling raindrops with the present wind profilers. The 2D-Video Disdrometer however shows a similar evolution of the Z-R ratio with time and rain intensity, although the power law is less well defined (temporal resolution of 1 min). The Z/R ratio is systematically higher during light rain but comparable to the MRRs' for stronger intensities, a consequence of the mentioned disagreement in small drops.

The other two examples of rain events (Figs. 4 to 7) display a dependency of instrument agreement on rain type. On May 19, large convective structures of high vertical extent gave Z/R ratios that followed the same power law at all stages. Again the same instrumental differences are observed for low Z/R ratios, which correspond to DSDs shifted towards small drop diameters. This instrumental difference does not manifest itself in the reflectivity values seen in Fig. 5.

On May 22, the vertical reflectivity profiles measured by the MRR showed very little vertical extent of the rain, and most precipitation formed without passing through a melting layer. The DSDs of the "warm" rain tended heavily towards small drop diameters, giving much smaller Z/R ratios than with visible melting layer. The low mean falling velocity of this kind of rain makes it easy to distinguish from the rain

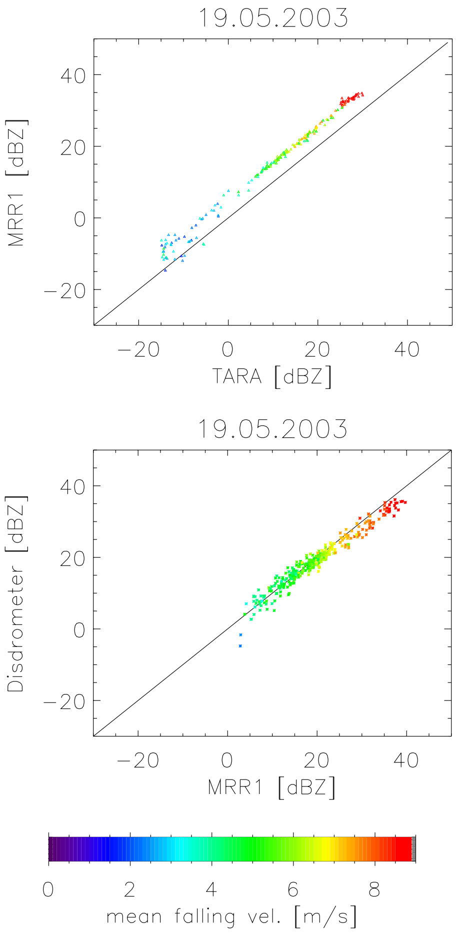


**Fig. 5.** MRR 1 reflectivity values compared to those measured by TARA and calculated from disdrometer spectra for May 19th. The bias between MRR and TARA is believed to be a combination of overestimation by the MRR and underestimation by TARA at low ranges caused by imperfect FMCW transfer functions and possibly insufficient beam overlapping of TARA's receiver and transmitter. The color coding shows the mean fall velocity measured by the MRR.

type of the previous examples. Comparisons of radar reflectivity displayed in Fig. 7 show that MRR and particularly the disdrometer fail to detect a portion of drops that move with low or no downward velocity. While the 2D-Video Disdrometer can only count drops falling through its measurement volume and the MRR is limited to positive falling velocities from 0.78 to 8.97 m/s, TARA also includes low and negative falling velocities in its reflectivity measurement. The underestimation of rain rate and reflectivity by the MRR for this example is much less dramatic than that of the disdrometer. Given the behavior of Z/R ratio, vertical extent, and a "catchment"-type instrument, this kind of rain may lead to underestimation by both weather radar, disdrometer and rain gauges. The identification of this rain regime can be effectively supported by MRR through both vertical reflectivity profile and DSD measurements, and eventually by applying recognition techniques on weather radar volume data.

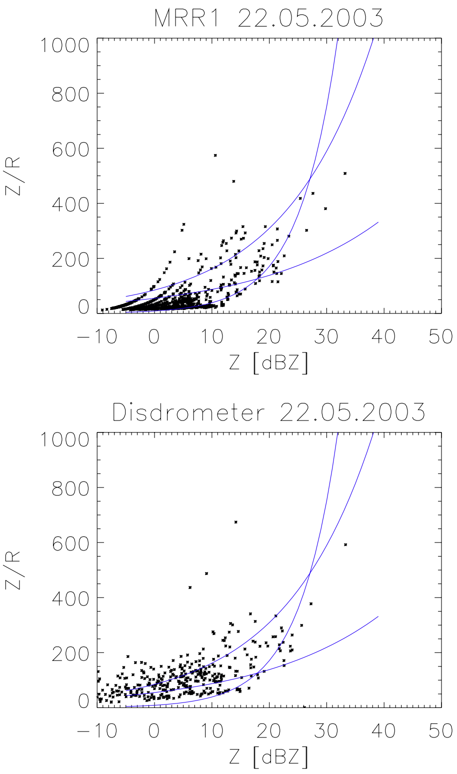


**Fig. 6.** Z-R ratios measured by MRR 1 and 2D-Video Disdrometer on May 22.

## 5 Resolving spatial and temporal variability of the drop size distribution

The unequal distribution of hydrometeors inside the illuminated volume of a radar beam is often named as an additional source of uncertainty in radar derived rainfall. To quantify the effect we can measure reflectivity at different spatial resolutions and estimate the bias caused by a non-linear Z-R relation, variability and spatial averaging. Capturing the inhomogeneity of the DSD inside a weather radar pixel has proven to be difficult with conventional disdrometers (Miriovski et al., 2004) due to necessary aggregation time, drop sorting, and sampling uncertainty. The use of vertically pointing radar to measure the drop spectrum allows both shorter integration time and sampling at the real location of the weather radar scan.

The main problem of assessing small scale variability is its distinction from systematic and random errors, or other instrumental differences. In our experiment the areal coverage by similar systems at different distances from one another, together with information on wind advection given by the SODAR/RASS systems, allowed the investigation of decorrelation of drop densities with range or by random errors. The correlation with other instruments in drop numbers for drops smaller than 1 mm remained low for MRR 3 and the disdrometer in all situations, the reason being an extremely high noise level for MRR 3 and probably horizontal wind for the disdrometer. For drops larger than 1 mm, all instruments

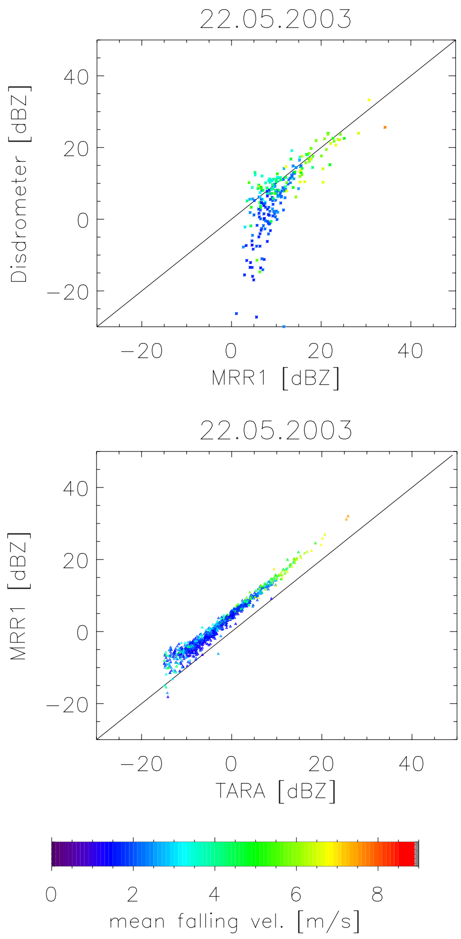


**Fig. 7.** MRR 1 reflectivity values compared to those measured by TARA and calculated from disdrometer spectra for May 22nd.

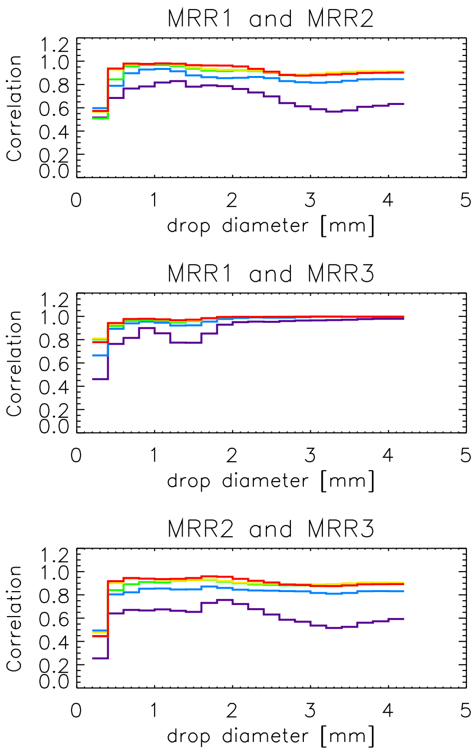


**Fig. 8.** Correlation of drop numbers in 22 drops size classes between the lowest MRR height bin at different integration periods. black: 1 min, blue: 5 min, green: 15 min, yellow: 30 min, red: 1 h . The stronger deviations in larger drops exhibited by MRR 2 against the other MRRs and the disdrometer result from the larger geographic distance.

showed good correlation when rain variability and wind advection created similar conditions within the averaging time. An example of decorrelation with range and random errors for 5 days of available disdrometer data is given in Figs. 8 and 9. Here the lower correlation with the more distant MRR 2 (see map in Fig. 1) is an indicator of spatial variability within 600 m. The fact that the correlation was lowered noticeably when introducing temporal offsets of ±1 min suggests that instrument precision is good enough to resolve temporal variability of rain contained in one minute. Longer averaging intervals smooth out variability, making it unmeasurable for instruments with low sensitivity and long aggregation time such as rain gauges.

## 6 Conclusions

This paper gives a short overview of the experience gained with MRR and 2D-Video Disdrometer during the BBC-2 campaign in Cabauw. Although instrumental problems such as calibration, noise levels, sampling errors and height dependent bias were uncovered, a high potential for important applications is demonstrated. We hope that analyzing the weaknesses of the systems will lead to a further improvement and will help researchers make best use of them.

Many investigations remain to be done with the recorded data, such as making use of the 2D-Video Disdrometer's capability to measure fall velocity, and combining radar with available ceilometer measurements to study the interaction of clouds and precipitation. Some questions regarding the evolution of MRR DSD measurements with height need to be addressed in more detail, like the effect of wind and turbulence, attenuation, the FMCW transfer function, the change of air density with height, and the issue of ambiguous backscattering signals in high and low altitudes.

The investigation of DSDs higher above ground level with the MRR is highly desirable and will be subject of further research. The lack of reference measurements has so far only resulted in investigations of consistency between MRRs. Instrumental differences between MRR and 2D-Video Disdrometer caused minor deviations in the appearance of variable Z-R relations at ground level, but the overall agreement between the two shows the possibility to study rainfall microstructure and variability with enough precision to improve quantitative weather radar measurements.

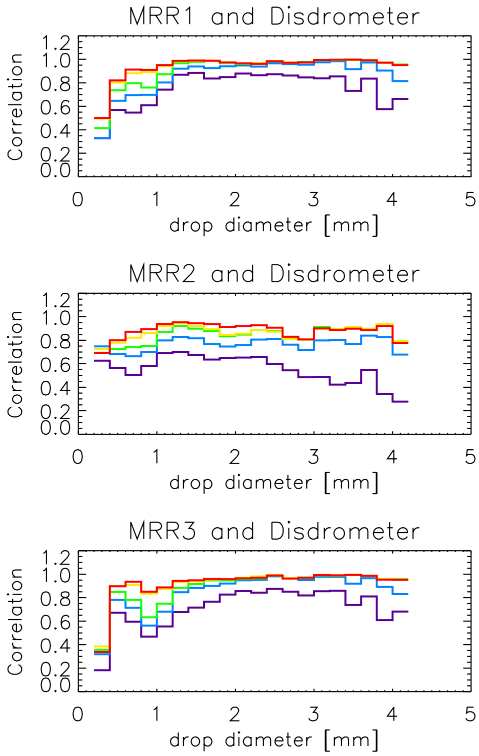


**Fig. 9.** Same as Fig. 9 comparing the 2D-Video Disdrometer spectra with the 3 MRRs. The lower correlation with MRR 2 in certain parts of the spectrum is again a consequence of greater distance.

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## References

Atlas, D., Srivastava, R., and Sekhon, R.: Doppler Radar Characteristics of precipitation at vertical incidence, Rev. Geophys. Space Phys.,11, p. 1–35, 1973.

Fabry, F., Austin, G. L., and Tees, D.: The accuracy of rainfall estimates by radar as a function of range, Quarterly Journal, Royal Met. Soc., 118, pp 435–453, 1992.

Gunn, R. and Kinzer, G.:The terminal velocity of fall for water droplets in stagnant air, J. Meteor., 6, pp 243–248, 1949.

Kruger, A. and Krajewski W. F.: Two dimensional video distrometer: a description, J. Atmos. Oceanic Technol. 19, p 602–617, 2002.

Miriovski, B. J., Bradley, A., Eichinger, W. E., Krajewski, W. F., Kruger, A., and Nelson, B. R.: An Experimental Study of Small-Scale Variability of Radar Reflectivity Using Disdrometer Observations, J. Appl. Meteor., 4, pp 106–118, 2004.

Nespor, V., Krajewski, W. F., and Kruger, A.: Wind-induced error of raindrop size distribution measurement using a two-dimensional video disdrometer, J. Atmos. Oceanic Technol., 17, p 1483–1492, 2000.

Peters, G., Fischer, B., and Andersson, T.: Rain observations with a vertically looking Micro Rain Radar (MRR), Boreal Environment Research, V.7 ,4, pp 353–362, 2002.

Uijlenhoet, R., Steiner, M., and Smith, J.: Variability of Raindrop Size Distributions in a Squall Line and Implications for Radar Rainfall Estimation, Journal of Hydrometeorology, pp 43–61, 2002.