Comparison between Pludix and impact/optical disdrometers during rainfall measurement campaigns

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Abstract

The performances of two couples of disdrometers based on different measuring principles are compared: a classical Joss–Waldvogel disdrometer and a recently developed device, called the Pludix tested in Ferrara, Italy, and Pludix and the two-dimensional video disdrometer (2DVD) tested in Cabauw, The Netherlands. First, the measuring principles of the different instruments are presented and compared. Secondly, the performances of the two pairs of disdrometers are analysed by comparing their rain amounts with nearby tipping bucket rain gauges and the inferred drop size distributions. The most important rainfall integral parameters (e.g. rain rate and radar reflectivity) and drop size distribution parameters are also analysed and compared. The data set for Ferrara comprises 13 rainfall events, with a total of 20 mm of rainfall and a maximum rain rate of 4 mm h⁻¹. The data set for Cabauw consists of 9 events, with 25–50 mm of rainfall and a maximum rain rate of 20–40 mm h⁻¹. The Pludix tends to underestimate slightly the bulk rainfall variables in less intense events, whereas it tends to overestimate with respect to the other instruments in heavier events. The correspondence of the inferred drop size distributions with those measured by the other disdrometers is reasonable, particularly with the Joss–Waldvogel disdrometer. Considering that the Pludix is still in a calibration and testing phase, the reported results are encouraging. A new signal inversion algorithm, which will allow the detection of rain drops throughout the entire diameter interval between 0.3 and 7.0 mm, is under development.

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1. Introduction

The observed variability in the drop size distribution (DSD) or its integrated parameters is attributable to two main sources: instrumental effects and natural (spatial or temporal) variability. If there is more than one disdrometer at the same location, then the variability between the instruments at a given time gives the measurement fluctuations which are not physical variabilities. Since each instrument has its own principle of operation and sampling volume, differences between them are not surprising. In any case, it is important to compare different kinds of disdrometers in order to determine whether the DSD variability is due to nature or to differences among the instruments. Another important task is to ascertain if the different kinds of disdrometers respond in the same manner to different kinds of precipitation. In addition, accurate measurements of the
DSD are required for various applications, and since the true DSD is not known, the only way to understand the instrumental limitations of each instrument is by an intercomparison of their samples.

The aim of the present study is to compare the performances of various disdrometers, based on different measuring principles, in the rainfall-rate \( (R) \) and DSD estimates. In particular, it aims to test a recent device, called the Pludix. To reduce other sources of possible differences among the measurements, the methods of data processing used for the instruments are the same.

Classically the DSD is measured by an electromechanical disdrometer called Joss–Waldvogel (hereinafter JW) (Joss and Waldvogel, 1967). Despite advances in disdrometer technology, the JW disdrometer is still considered to be the standard instrument for DSD measurements at the ground surface. The JW disdrometer suffers, however, from underestimation of drop concentrations due to the acoustical noise produced by the rain itself.

The Pludix is a rain-gauge/disdrometer based on the analysis of an X-band (9.5 GHz) continuous wave radar signal backscattered by hydrometeors. It provides more detailed information than a classical tipping-bucket rain-gauge (hereinafter TB-RG) and some disdrometers, providing information about the precipitation type. It was employed over three months, from May 13 to August 13, 2003 in the BBC-2 (Baltex Bridge Cloud Campaign 2) at CESAR (Cabauw Experimental Site for Atmospheric Research) in The Netherlands, near Utrecht. The campaign was a large cloud measurement campaign, organized by the Royal Netherlands Meteorological Institute (KNMI), involving different kinds of instruments. One of the aims of the ground precipitation analysis was to compare different kinds of disdrometers in order to measure and parameterise the rainfall microstructure. Also used in the experiment were a two-dimensional video disdrometer (2DVD), two optical (infrared) disdrometers and different TB-RGs. For the first time, the Pludix was used alongside optical disdrometers.

Moreover, several events are analysed at the Ferrara (Italy) site (Dept. of Physics–University of Ferrara), where the Pludix has been located since November 2001 alongside a JW impact disdrometer. A TB-RG is also used to validate the rain measurements. Many more samples of simultaneous Pludix and JW measurements than in previous studies (Prodi et al., 2000a,b,c) were collected, in order to provide a more robust DSD parameterization and to study the instrumental dependency on the relationships between rainfall integral parameters and precipitation types for different rain regimes. This is the first time that the JW disdrometer and the Pludix have been compared over such an extended time period.

Previous comparisons of rainfall-rate and DSDs measured by the Pludix and the JW disdrometer were realized, but for shorter time periods. Since September 1999 the instrument has been in operation together with a tipping-bucket and a weighting scale rain-gauge in downtown Bologna. More than 200 rainfall events have been detected, and a subgroup of 21 events has been investigated in order to study the time variability and the precipitation type as observed by the Pludix. It was found that stratiform rain is well matched by a Marshall and Palmer (1948) exponential DSD, while in mixed and convective rain the Marshall and Palmer is still followed, but some episodes were found in which a three parameters gamma DSD would probably fit better. A correlation between the Pludix and the tipping-bucket data has shown that, for stratiform and mixed rain, there is a fairly good correspondence, while for convective episodes, especially very heavy rains, the tipping-bucket is a less reliable instrument because of the bucket mechanism, while the Pludix is still recording (Prodi et al., 2000b,c).

All the instruments analysed here are collocated: although numerous previous studies on drop size distributions have used various types of disdrometers, only a few have compared simultaneous DSD measurements performed by collocated disdrometers (Tokay et al., 2001). Donnadieu (1980) has presented 14 min of composite DSDs from simultaneous observations of a JW and an optical disdrometer. His results revealed the presence of more drops in the JW, except in the very first size range. Therefore, the integral parameters such as liquid water concentration, rain rate and reflectivity were higher in the JW than in the optical disdrometer. Löffler-Mang and Joss (2000) compared 10 min of composite DSDs from simultaneous observations of collocated optical and JW disdrometers. They reported a good agreement between measurements of optical disdrometers and JWs for the drop size of 0.7–2.0 mm diameter. The presence of more drops in the range from 1.5 to 2.8 mm diameter in JW measurements suggests a higher rain rate and reflectivity in the JW. The presence of many more drops in sizes less than 0.7 mm in optical disdrometer measurements, on the other hand, results in a higher total number concentration in the optical disdrometer. Sheppard and Joe (1994) conducted a comprehensive comparative study of DSDs from in situ disdrometer measurements. Their experiment included an optical array probe (Knollenberg, 1970), a JW
disdrometer, and an X-band Doppler radar (named POSS). Sheppard and Joe presented simultaneous measurements of DSDs at different rain intensities. The rain rate computed from the Knollenberg spectra was much lower (57%) than the one computed from the JW spectra. This difference was due mainly to the deficit of the drops in the 1 to 3 mm size range of the probe spectra. Campos and Zawadski (2000) used a similar setup but with a different type of optical disdrometer, rather than a Knollenberg optical array probe. A close examination of 5-min-averaged DSDs showed a good agreement among the three different sensors’ spectra.

Recent works on the intercomparison between impact and optical disdrometers have been presented by Williams et al. (2000), Tokay et al. (2001) and Tokay et al. (2002). Williams et al., during the second phase of the TRMM ground validation program, compared a JW disdrometer, a 2DVD and a vertically pointing profiler in Florida. They found that, while the instruments show a general agreement for larger drops sizes \((D > 1.5 \text{ mm})\), the agreement is poor for smaller drop sizes. The 2DVD disdrometer measures significantly fewer small drops \((D < 1.5 \text{ mm})\) than the other instruments, even if corrected for the dead-time problem. The 2DVD underestimates the number of small drops during windy conditions. Tokay et al. (2001) compared two 2DVD and one JW disdrometer along with eight TB-RGs in Florida, in the frame of the TRMM ground validation program. They found that both disdrometers underestimate the rain total, while the agreement is better between the 2DVD and the gauges. A good agreement is found in the DSD comparison, even if the 2DVD counts more small drops in rainfall rates greater than 20 mm h\(^{-1}\). At light to moderate rainfall rates, more medium-size drops were observed in 2DVD spectra than in JW spectra. As part of the TRMM mission Tokay et al. (2002) have compared optical and impact disdrometers in Brazil, confirming the previous results. A very recent work of the IIHR-Hydrosience and Engineering team of the University of Iowa, describes an intercomparison of four disdrometers (JW, single-beam optical-spectropluviometer, POSS and 2DVD) during the XPOW field experiment, which began on October 2001 in Iowa (Miriovsky et al., 2004). However, these instruments were not collocated. Subsequently, Krajewski et al., submitted for publication conducted probably the most comprehensive comparative study of DSDs from in situ disdrometer measurements. The DEVEX (Disdrometer Evaluation Experiment) yielded a unique data set, employing four disdrometers (a 2DVD, an optical disdrometer Parsivel, the classical JW disdrometer and the new dual beam spectro-pluviometer), an S-band vertically pointing profiler and several TB-RGs platforms located at the Iowa City Municipal Airport, Iowa City, IA (US) during the spring and summer of 2002. The results showed a good agreement between the disdrometers after the application of correction algorithms on each instrument. For further details, see Krajewski et al. (submitted for publication).

2. Description of the disdrometers used in the present work

2.1. The rain-gauge/disdrometer Pludix

The Pludix (PLUviometro-Dlisdrometro in X-band, 9.5 GHz) is a bistatic Doppler rain-gauge disdrometer for monitoring and characterizing atmospheric precipitation at the ground (Prodi, 1994), manufactured jointly by ADA s.r.l. and NUBILA s.a.s., Bologna (Italy) (www.nubila.net). Its functions are to:

- identify precipitation type (rain, snow, hail, drizzle...);
- provide hydrometeor size distribution (for drops, snowflakes, hailstones);
- measure the instantaneous rainfall rate;
- give the total rainfall in a given time interval.

It can operate automatically and can be connected in networks for operation in remote areas.

The detection and characterization of a precipitation is based on the fact that each precipitation type (rain, snow, hail) has its own Doppler spectrum. Thus, for each hydrometeor type, a different algorithm has to be selected to determine the size distribution and the rain intensity. The instrument provides the size distribution and rain intensity for water drops. It is hoped that the instrument’s capability can be extended in the future to measure the DSD for snow and hail. Like a rain-gauge, the Pludix also provides the instantaneous rainfall rate and the total rain amount in a given time interval, integrating the disdrometric function. As a disdrometer, it measures the size of the drops falling in a well-defined volume (3 m high and 1 m wide) above it. The measurement volume is defined by an average antenna gain. The drops are classified in constant size intervals \((0.3 \text{ mm})\). For each size, the instrument gives the average concentrations \([\text{m}^{-3}]\) and its contribution to the total precipitation intensity \([\text{mm h}^{-1}]\). The diameter interval varies from 0.8 to 7.0 mm. The advantages are: with respect to optical disdrometers, simplicity and lack of maintenance and lower cost; with respect to
electromechanical disdrometers, no difficulty in distinguishing simultaneously or almost simultaneously falling drops; with respect to rain-gauges, low precipitation intensity detected, no clogging of the funnel by leaves, feathers or other objects, no maintenance (waterproof bell-shaped radome), disdrometric ability.

The instrument consists of a sensor located in a waterproof fibreglass container to be placed outside, and connected by a cable to the power supply/signal processing unit (see Fig. 4a). The upper part of the container (dome) is shaped in order to minimize dry deposition and can be heated. The length of the cable connecting the sensor with the power supply/signal processing unit can be extended to several tens of meters. The signal processing unit receives, elaborates and stores the signal coming from the sensor. It can communicate to the user in three different ways: a serial port RS232C, Ethernet and modem. A dedicated software pack in Visual Basic has been developed to establish a direct connection between a PC and the signal processing unit, allowing the data visualization and storage via all the three connection options. The program pack works on Windows-based systems, but it can easily be interfaced with a different OS-based system.

2.1.1. Principle of operation

The sensor is an X-band continuous wave, low power (10 mW) Doppler radar (9.5 GHz frequency of operation). The MW beam emitted by an upward oriented antenna is backscattered by hydrometeors in free fall. The geometry of operation is shown in Fig. 1. The transmitting and receiving antennas are very close to each other and the volume of measurement is immediately above them. The target (a hydrometeor) moves vertically toward the instrument. Near the ground each hydrometeor reaches an aerodynamic equilibrium and falls at a constant terminal velocity only as a function of its size, in the absence of vertical wind. When it enters the measurement volume, it produces a signal whose frequency is a function of its velocity. In fact, the frequency depends on the velocity at which the object crosses the equi-phase surfaces, the surfaces made by the points having \( R_1 + R_2 = \text{const.} \) (Fig. 1). Therefore, the backscattered signal at the receiving antenna is comprised of many components that are shifted in frequency by the transmitted signal depending on the hydrometeors’ terminal velocities (Doppler effect) and their location in the measurement volume. The amplitude of such components is a function of the reflectivity of the hydrometeors, and their concentrations and location in the volume seen by the sensor. Since a given drop at terminal velocity does not generate a constant but rather a variable Doppler frequency shift depending on its position in space, a special algorithm has been developed to obtain the drop size distribution from the signal spectrum and hence the parameters characterizing the precipitation.

The physical characteristics of hydrometeors affecting the output signal are the backscattering cross section \( \sigma \) and the fall velocity \( v \). Both are related to the size, phase (liquid, solid, mixed) and composition (water, air) of hydrometeors. The fall speed is considered in a model with complete absence of wind. The effects of wind, especially horizontal wind, whose effect is to flatten the spectrum, will be the subject of future work. Due to its position (a few tens of centimetres from the ground), it is correct to assume that the Pludix is not affected by winds, since the vertical velocity is one order of magnitude lower than the horizontal one. The knowledge of \( \sigma \) and \( v \) as a function of \( D \) is needed to generate an inversion algorithm which associates the output signal to the characteristics of precipitation. The frequency analysis of the signal provides information on the sizes (which are \( v \) dependent). From the power response, related to \( \sigma \), information on the precipitation intensity is available. \( N(D) \), the hydrometeor size distribution, is the direct final result. Once \( v(D) \) is known for the case of rain, the rainfall intensity is indirectly determined.

\[ \sigma \text{ and } v \text{ as a function of } D \]

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Fig. 1. Pludix antennas and equi-phases surfaces (T=transmitting, R=receiving antenna).
To estimate correctly the instrument response to a natural precipitation and determine the drop size distribution, measurements on monodisperse droplets are performed in controlled conditions and a calibration procedure is constructed (Prodi et al., 2000a,b). Drops are considered spherical up to 1 mm in diameter. The scattering diagram is calculated for a relatively large number of drop size classes using a T-Matrix code (Prodi et al., 1999). If a natural rain, as a superposition of monodisperse rains is considered, its spectral intensity $S_{\text{real}}$ is:

$$S_{\text{real}} = \int_{D_{\text{min}}}^{D_{\text{max}}} N(D)S_{\text{mon}}(D)dD$$

(1)

where $S_{\text{mon}}$ is the spectral intensity generated by a monodisperse rain of diameter $D$, divided by the number of drops which has caused it, and $N(D)$ is the distribution function, i.e. the relative contribution of that size to the real spectral intensity $S_{\text{real}}$. If the above equation is discretized in frequency and diameter, it gives:

$$S_{f_{i}} = C_{f_{i},D_{j}}N_{D_{j}}$$

(2)

where $N$ is a column vector whose elements are the number of drops per unit volume in diameter interval $D_{j}$. $C$ is the matrix of the contributions to power of monodisperse drops of diameters $D_{j}$ (column index) at frequencies $f_{i}$ (row index), divided by the average number of monodisperse drops. The normalized contribution of a monodisperse rain of a given diameter is an “average signal”, i.e. it has the average characteristics from the drop falling in various regions of the measurement volume. For the inversion problem solution, advantage can be gained from known relationships and hypotheses: the Gunn and Kinzer (1949) empirical law is used to connect fall velocity with drop size; a statistical hypothesis is made that droplets have an equal probability of falling on a horizontal surface above the instrument. If the $C$ matrix is constructed in such a way that the number of size and frequency intervals are chosen to be the same, it is possible to deduce the drop size distribution $N(D)$ by the real spectrum $S$ by inverting only the square matrix $C$. The inversion problem is therefore reduced to inverting a square matrix.

In the current inversion, algorithm $C$ is a matrix of dimensions $21 \times 21$. As result of the inversion, a drop size distribution is determined. The rainfall intensity, through drop concentration, is related to the intensity of the signal, accumulated in a given time interval (1 min).

Consider now the hydrometeors type identification. As known, drops fall with a terminal velocity that, near the ground, is approximately constant. This velocity depends on the drop dimensions through the empirical Gunn and Kinzer (1949) relationship: $v = 9.65 - 10.3e^{-0.6D}$, with $0.2 < D < 7.0$ mm, in which $v$ is the velocity [m s$^{-1}$] and $D$ is the diameter [mm]. This formula is effective under standard atmospheric temperature and pressure. The drops cause a Doppler echo whose frequency shift $f$ is proportional to the terminal velocity $v$: $f = 2v/\lambda$, where $\lambda$ is the radar wavelength (in our case $\lambda = 0.0315$ m). Also for snow and hail, empirical relationships between $D$ and $v$ (Pruppacher and Klett, 1998) were proposed. For dry snow: $v = 0.098D^{0.31}$, and for hail: $v = 5.123D^{0.5}$, with $v$ the velocity in m s$^{-1}$ and $D$ the flakes dimensions, in mm.

Fig. 2 shows the plots corresponding to the previous formulae.

It can be seen that at the Pludix frequencies (9.5 GHz) the Doppler frequencies of all the hydrometeors (snow, rain, hail, ...) are between 0 and 1 kHz. For simplicity, the frequency interval is divided in three parts: a low part, between 0 and 200 Hz (snow band); a central part, between 200 and 600 Hz (rain band); a high part, over 600 Hz (hail band). However, it is important to explain that these values are very indicative and that the low band also represents the contribution of the smallest rain drops (like drizzle and fog), while in the high band the contribution of the smallest iced particles is superimposed on the contribution of the largest particles.

Normally the power spectrum has a characteristic maximum whose frequency is higher as the rain intensity grows. For each intensity there is therefore a drop diameter that gives the maximum contribution to the spectrum, and this diameter grows with the increasing intensity. The precipitation intensity is above all characterized by the spectrum amplitude, which depends on the total power reflected from the drops in the measured volume; but it is also characterized by the maximum frequency than usually grows with the increasing intensity. The spectrum shape therefore strongly depends on the precipitation type. In November 2000, the instrument was selected by DWD (Deutscher Wetterdienst) with other disdrometers and rain gauges for a field test of evaluation and intercomparison at a test site (Offenbach, Germany). The main characteristic of this experiment was the availability, every minute, of reports of a professional observer on the present weather conditions according to the WMO codes. As a result, a valuable amount of data was collected, which made possible the construction of a tutorial for qualitative observations. The tutorial is dedicated to all applications in which the knowledge of
the present weather is of relevance. The whole tutorial is composed of 44 different typical hydrometeors falls, commented in terms of the intensity spectral profile (including stratiform rain; convective rain; rain shower with drop break-up; drizzle and fog; frozen drizzle; fall of pristine ice crystals; rain and snow; drizzle and snow; heavy rain with hail; melting snow; dry snow).

A presentation of the software data-processing interface is shown in Fig. 3. Each stored data file contains binary data, which are converted mainly into graphs and integrated numerical data. Every file is subdivided into cycles, each of them 60 s long. The first graph (labelled 1) describes the spectral power (i.e., power transformed with FFT) of the selected cycle as a function of frequency. This curve is divided into three parts, of which only the median (grey line) reveals the presence of rain. This is very useful for roughly discriminating the region in which a backscattered signal is caused by the presence of snow (left black line), or hail (right black line). The Y-axis is in dB (10 dB div$^{-1}$), and the X-axis is in Hz (100 Hz div$^{-1}$). The X-axis range is from 0 to 1023 Hz. The second diagram (on the left) shows the histogram of the aforementioned spectral power divided into 21 selected frequency bands (the Y-axis is in dB, while the X-axis represents the 21 bands). The third one (on the right) is the conversion of the power divided by band into a drop size distribution (the Y-axis is the number of droplets m$^{-3}$, and the X-axis represents the corresponding 21 diameter bands). The black line shows the MP distribution for the given precipitation intensity, while the other lines represent the MP relative to fixed rainfall-rate values (0.01, 0.1, 1, 10 and 100 mm h$^{-1}$). The diagram at the bottom shows the time evolution of the retrieved rain rate for each cycle, calculated from the drop size distribution (the Y-axis is in mm h$^{-1}$, and the X-axis represents the cycle; 1 cycle = 1 min).

Even if they have not yet been fully investigated, some of the problems common to small CW bi-static Doppler radars like the Pludix include the following (see for reference Doviak and Zrnic, 1993; Germann, 1999; Sheppard, 1990):

1. run-off and vibration of raindrops on the radome;
2. variable absorption losses due to water on the radome;
3. the effect of horizontal winds on the retrieval of DSDs.

Fig. 2. Relationships between the hydrometeors diameter D [mm] and the Doppler frequency [Hz] for rain, snow, hail.
(4) sampling errors caused by the non-uniform response from different locations in the measurement volume.

Regarding the Pludix, these problems were attenuated or corrected as follows:

1. a microwave transparent sponge was set on the radome to avoid vibrations. The radome was built with elliptical base.
2. the bell-shaped form of the Pludix radome avoids water deposition of the radome.
3. no correction for the wind effects was carried out on the Pludix; the assumption was made that, due to its position (a few tens of centimetres from the ground) Pludix is not affected by vertical winds. This aspect will be investigated in future work.
4. the Pludix measurement volume is defined by an average antenna gain; if any drop falls out of the optimal antenna gain, it is discarded.

2.1.2. Estimation of hydro-meteorological parameters

The Pludix output is \( n_i \), the number of drops measured in drop size class \( i \) m\(^{-3}\). To calculate the drop size distribution \( N(D) \) [m\(^{-1}\) m\(^{-3}\)], it is sufficient to divide \( n_i \) by 0.3 mm, the diameter interval \( \Delta D_i \) of each drop size class. The average diameter \( D_i \) of the diameter class \( i \) [mm] is given in Table 1 (21 drop size classes). The time interval for one measurement is set to

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subdivision of the 21 drop size classes measured by the Pludix</td>
</tr>
<tr>
<td>Pludix drop size classes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of band</th>
<th>Average drop diameter in class ( i ) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1</td>
<td>0.95</td>
</tr>
<tr>
<td>Band 2</td>
<td>1.25</td>
</tr>
<tr>
<td>Band 3</td>
<td>1.55</td>
</tr>
<tr>
<td>Band 4</td>
<td>1.85</td>
</tr>
<tr>
<td>Band 5</td>
<td>2.15</td>
</tr>
<tr>
<td>Band 6</td>
<td>2.45</td>
</tr>
<tr>
<td>Band 7</td>
<td>2.75</td>
</tr>
<tr>
<td>Band 8</td>
<td>3.05</td>
</tr>
<tr>
<td>Band 9</td>
<td>3.35</td>
</tr>
<tr>
<td>Band 10</td>
<td>3.65</td>
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<td>Band 11</td>
<td>3.95</td>
</tr>
<tr>
<td>Band 12</td>
<td>4.25</td>
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<tr>
<td>Band 13</td>
<td>4.55</td>
</tr>
<tr>
<td>Band 14</td>
<td>4.85</td>
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<td>Band 15</td>
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<td>Band 18</td>
<td>6.05</td>
</tr>
<tr>
<td>Band 19</td>
<td>6.35</td>
</tr>
<tr>
<td>Band 20</td>
<td>6.65</td>
</tr>
<tr>
<td>Band 21</td>
<td>6.90</td>
</tr>
</tbody>
</table>
60 s. For the terminal velocity, the well-known Gunn and Kinzer (1949) formula is used \([\text{m s}^{-1}]\). The rainfall rate \(R\), expressed in \(\text{mm h}^{-1}\), is derived from the drop size distribution as:

\[
R = 6\pi 10^{-4} \sum_{i=1}^{21} D_i^3 \cdot n_i \cdot v(D_i).
\]

(3)

2.2. The Joss–Waldvogel type disdrometer RD-80

The RD-80 disdrometer (JW disdrometer) has the ability to transform the vertical momentum of an impacting raindrop into an electric pulse whose amplitude is a function of the drop diameter. It was originally developed by Joss and Waldvogel (1967) and is manufactured by Distromet of Basel, Switzerland. According to the operating principle, the disdrometer measures the size distribution of raindrops falling on the sensitive surface of the transducer. The JW data consist of the number of raindrops \(n_i\) of diameter \(D_i\) in 20 categories, which are not of uniform size, ranging from 0.3 to 5.6 mm. The intervals increase from about 0.1 mm for the smallest drops to 0.5 mm for the largest drops (Table 2). The temporal resolution is 30 s or 1 min.

<table>
<thead>
<tr>
<th>JW drop size classes</th>
<th>Lower threshold of drop diameter ([\text{mm}])</th>
<th>Average diameter of drops in class (i) ([\text{mm}])</th>
<th>Fall velocity of a drop with diameter (D_i) ([\text{m s}^{-1}])</th>
<th>Diameter interval of drop size class (i) ([\text{mm}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.313</td>
<td>0.359</td>
<td>1.435</td>
<td>0.092</td>
</tr>
<tr>
<td>2</td>
<td>0.405</td>
<td>0.455</td>
<td>1.862</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td>0.505</td>
<td>0.551</td>
<td>2.267</td>
<td>0.091</td>
</tr>
<tr>
<td>4</td>
<td>0.596</td>
<td>0.656</td>
<td>2.692</td>
<td>0.119</td>
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<tr>
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<td>0.715</td>
<td>0.711</td>
<td>3.154</td>
<td>0.112</td>
</tr>
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<td>6</td>
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<td>0.913</td>
<td>3.717</td>
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<tr>
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<td>0.999</td>
<td>1.116</td>
<td>4.382</td>
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<td>1.232</td>
<td>1.331</td>
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<tr>
<td>9</td>
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<td>1.506</td>
<td>5.423</td>
<td>0.153</td>
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<td>1.582</td>
<td>1.665</td>
<td>5.793</td>
<td>0.166</td>
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<td>11</td>
<td>1.748</td>
<td>1.912</td>
<td>6.315</td>
<td>0.329</td>
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<tr>
<td>12</td>
<td>2.077</td>
<td>2.259</td>
<td>7.009</td>
<td>0.364</td>
</tr>
<tr>
<td>13</td>
<td>2.441</td>
<td>2.584</td>
<td>7.546</td>
<td>0.286</td>
</tr>
<tr>
<td>14</td>
<td>2.727</td>
<td>2.869</td>
<td>7.903</td>
<td>0.284</td>
</tr>
<tr>
<td>15</td>
<td>3.011</td>
<td>3.198</td>
<td>8.258</td>
<td>0.374</td>
</tr>
<tr>
<td>16</td>
<td>3.385</td>
<td>3.544</td>
<td>8.556</td>
<td>0.319</td>
</tr>
<tr>
<td>17</td>
<td>3.704</td>
<td>3.916</td>
<td>8.784</td>
<td>0.423</td>
</tr>
<tr>
<td>18</td>
<td>4.127</td>
<td>4.350</td>
<td>8.965</td>
<td>0.446</td>
</tr>
<tr>
<td>19</td>
<td>4.573</td>
<td>4.859</td>
<td>9.076</td>
<td>0.572</td>
</tr>
<tr>
<td>20</td>
<td>5.145</td>
<td>5.373</td>
<td>9.137</td>
<td>0.455</td>
</tr>
</tbody>
</table>

The RD-80 disdrometer consists of three main units (Distromet LTD, 2001):

- the transducer, which is exposed to the rain (sensor);
- the processor;
- a plug-in power supply for powering the system.

The analog to digital converter of the signal processing unit has an exponential conversion characteristic: the approximate relation between the drop diameter \(D\) and the amplitude of output voltage pulse: \(U_{\text{out}}=0.94D^{1.47}\), \(U_{\text{out}}\) in \(V\), \(D\) in mm.

To compute the drop size distribution, the quantity \(N(D_i)\), the number density of drops with diameters corresponding to size class \(i\) per unit volume, must first be calculated from the data for every drop size class, according to the following formula:

\[
N(D_i) = \frac{n_i}{A \cdot v(D_i) \cdot \Delta D_i}
\]

(4)

where \(n_i\) is the number of drops measured in drop size class \(i\); \(D_i\) is the average diameter of the drops in size class \(i\) [mm]; \(A\) is the size of the sensitive surface of the disdrometer (50 cm\(^2\)); \(t\) is the time interval for one measurement (here set to 60 s); \(v(D_i)\) [m s\(^{-1}\)] is the fall velocity of a drop with the diameter \(D_i\); \(\Delta D_i\) is the diameter interval of drop size class \(i\) [mm] (see Table 2). For the terminal velocity, the well-known Gunn and Kinzer (1949) formula is used.

The following quantities are displayed during the data acquisition process, obtained by the DISDRODATA program running on a PC connected to the processor: \(n_i\) (number of drops measured in every drop size class \(i\) during time interval \(t\)); \(R\) (rainfall rate in \(\text{mm h}^{-1}\)); \(RA\) (rain amount in mm); \(W\) (liquid water content in \(g \text{ m}^{-3}\)); \(Z\) (radar reflectivity factor in dBZ); \(EF\) (energy flux in \(J \text{ m}^{-2} \text{ h}^{-1}\)); \(D_{\text{max}}\) (larger drop collected in mm); \(N(D_i)\) (the number density of drops with diameters corresponding to size class \(i\) per unit volume [\(\text{mm}^{-1} \text{ m}^{-3}\)]); the two parameters of the exponential distribution, \(N_0\) [\(\text{mm}^{-1} \text{ m}^{-3}\)] and \(A\) [\(\text{mm}^{-1}\)].

The quantities \(R\), \(W\), and \(Z\) are computed using the following formulae:

\[
R = 6\pi 10^{-4} \frac{1}{A \cdot t} \sum_{i=1}^{20} n_i D_i^3
\]

\[
W = \frac{\pi}{6} \frac{1}{A \cdot t} \sum_{i=1}^{20} n_i v(D_i) \cdot D_i^3
\]

(5)

\[
Z = \frac{1}{A \cdot t} \sum_{i=1}^{20} n_i v(D_i) \cdot D_i^6
\]

To compute \(N_0\) and \(A\), parameters of an exponential DSD with the same values for \(W\) and \(Z\) as the measured
distribution, the following formulae are used (Waldvogel, 1974):

\[
N_0 = \frac{1}{\pi} \left( \frac{6!}{\pi} \right)^{4/3} \left( \frac{W}{Z} \right)^{4/3} W
\]

\[
A = \left( \frac{6!}{\pi} \right)^{1/3} \left( \frac{W}{Z} \right)^{1/3}
\]

There are three different sources of errors affecting the measurement of small drops with the JW disdrometer: wind, acoustic noise from the surroundings due to the rain, thunder, machines, etc., and ringing of the styrofoam cone when it is hit by large drops (known as the disdrometer dead time). The influence of the first two sources can be reduced to a minimum by a proper installation of the transducer. The last effect cannot be reduced by any preventive measure, but it can be corrected by mathematical methods. The following empirical function was developed by several authors for computing a correction for this dead time (Sheppard and Joe, 1994; Sauvageot and Lacaux, 1995):

\[
N_{i,\text{corr}} = N_i \exp \left[ \frac{0.035}{T} \sum_{D_i = 0.85D_c} \ln \left( \frac{D_i}{0.85(D_i - 0.25)} \right) \right]
\]

\(N_i\) is the number of drops in size class \(i\) without correction;

\(N_{i,\text{corr}}\) is the number of drops in size class \(i\) with correction;

\(T\) is the sampling time in seconds.

Fig. 4. (a) The instruments installed on the roof of the Department of Physics–University of Ferrara. Pludix (rain-gauge/disdrometer in X-band) (left) and Joss–Waldvogel disdrometer (right). (b) The 2DVD outdoor part, as installed in the Netherlands–Cabauw site (Utrecht), during the BBC2 campaign, together with a sonic anemometer (right) and a TB-RG (left).
It is important to point out that the algorithm was provided in a “personal communication” from A. Waldvogel, and prior to 1994 it had not previously been published in the literature.

A drop in size class $k$ causes a dead time for all channels $i$, where:

$$D_k \geq 0.85D_i.$$  \hspace{1cm} (8)

Applying the dead time correction has the effect of increasing the numbers of small raindrops, mainly in spectra where many large drops are present, i.e. at high rain rates. The result of applying the correction is that lower order moments (which depend more strongly on the numbers of small drops than higher order moments) are increased at higher rain rates, whereas they remain largely unaffected at lower rain rates (when less large drops are present). Although the influence of these corrections on the number of drops can be very large, quantities such as the rainfall rate or the reflectivity factor do not change markedly.

Fig. 5. (a) 1-min temporal rainfall-rate evolution for April 11, 2002 in Ferrara (dashed line = JW; solid line = Pludix). (b) 1-min time evolution for the April 12, 2002 event in Ferrara.
However, if there are no drops in a given channel, the correction matrix does not add any drop; rather it significantly increases the high moments of the DSD, such as the rain rate. The problem derives from the correction matrix, and is the reason why it was decided not to implement it in this study. There are plans to test the effects of the dead time problem correction algorithm in a future work.

2.3. The two-dimensional video disdrometer (2DVD)

The 2DVD is an optical disdrometer, developed by Joanneum Research in Graz, Austria, which records the characteristics (size, velocity, shape) of each single hydrometeor falling through its sensing area. The instrument therefore works on an optical basis. A detailed description of the instrument is given in Urban (1996) and Schönhuber et al. (1994, 1995, 1996). Něspor et al. (2000) studied the wind effect on the disdrometer measurements. Kruger and Krajewski (2002) also describe their experience in operating the instrument over several years. The three main units are:

- the sensor unit containing the two optical systems, for measuring the front and side view of the hydrometeors;
- the outdoor electronics unit has to be located close to the sensor unit. The outdoor electronics unit controls the two line scan cameras and acquires and pre-processes the raw data;
- the indoor user terminal stores the data and simultaneously offers various analyses in online mode to the user.

Optionally a three-dimensional ultrasonic type wind sensor and a TB-RG may also be connected to the system (as in Fig. 4b).

To obtain a front and side view of each particle falling through the measurement area, two optical systems are used. The optical systems are orthogonally aligned against each other with a height offset of some 6 mm. Each optical system consists of a high-speed line scan camera and a background illumination device. By means of a Fresnel lens, the light of a standard halogen bulb is focused onto the camera, yielding intense background illumination and the particle causes a blockage of a certain number of the camera’s pixels. To the cameras, any particle falling through the beam of light will appear as a dark silhouette against the bright background. Only particles seen in both cameras are counted. The 2DVD employs a virtual measuring area to avoid counting splashes. Only the inner part of the measurement inlet is taken for data processing. The outer part, which is influenced by splashes from the edges, is ignored. The virtual measuring area is located some few centimeters beneath the rims of the collecting funnel, thus avoiding the unwanted effect of splashing from these rims into the virtual measuring area.

The rainfall rate \( R \) is obtained by dividing the rain amount by the corresponding time interval:

\[
R = 6\pi 10^{-4} \frac{1}{\Delta t} \sum_{i=1}^{n} \frac{V_i}{A_i} \quad (9)
\]

where \( \Delta t \) is the integration time interval in seconds (varies from 15 s to 24 h), \( i \) the drop number, \( n \) the total number of fully visible drops measured in the time interval \( \Delta t \) (here set to 60 s), \( V_i \) the volume of drop \( i \) in mm\(^3\), \( A_i \) the effective measuring area for drop \( i \) in mm\(^2\).

Table 3

Overall rainfall-rate and rain-amount comparison for the different instruments (TB-RG, JW and Pludix) and correlation coefficient between the rainfall-rates of the two disdrometers (JW and Pludix)

<table>
<thead>
<tr>
<th>Day</th>
<th>RA (TB) [mm]</th>
<th>RA (JW) [mm]</th>
<th>RA (px) [mm]</th>
<th>&lt;R&gt;(JW) [mm h(^{-1})]</th>
<th>&lt;R&gt;(px) [mm h(^{-1})]</th>
<th>Correlation coefficient, ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 27, 2001</td>
<td>1.0</td>
<td>0.84</td>
<td>0.64</td>
<td>0.83</td>
<td>0.63</td>
<td>0.89</td>
</tr>
<tr>
<td>Nov 27, 2001</td>
<td>1.4</td>
<td>1.29</td>
<td>1.19</td>
<td>1.55</td>
<td>1.43</td>
<td>0.80</td>
</tr>
<tr>
<td>Jan 24, 2002</td>
<td>1.8</td>
<td>1.48</td>
<td>1.72</td>
<td>1.45</td>
<td>1.69</td>
<td>0.62</td>
</tr>
<tr>
<td>Jan 24, 2002</td>
<td>3.2</td>
<td>3.13</td>
<td>2.77</td>
<td>2.04</td>
<td>1.81</td>
<td>0.46</td>
</tr>
<tr>
<td>Feb 7, 2002</td>
<td>0.8</td>
<td>0.69</td>
<td>0.78</td>
<td>0.94</td>
<td>1.07</td>
<td>0.90</td>
</tr>
<tr>
<td>Apr 12, 2002</td>
<td>3.8</td>
<td>3.36</td>
<td>2.93</td>
<td>3.42</td>
<td>2.98</td>
<td>0.79</td>
</tr>
<tr>
<td>Apr 16, 2002</td>
<td>0.6</td>
<td>0.65</td>
<td>0.77</td>
<td>1.70</td>
<td>2.03</td>
<td>0.79</td>
</tr>
<tr>
<td>Apr 16, 2002</td>
<td>0.6</td>
<td>0.58</td>
<td>0.38</td>
<td>1.84</td>
<td>1.20</td>
<td>0.71</td>
</tr>
<tr>
<td>Apr 20, 2002</td>
<td>1.8</td>
<td>1.37</td>
<td>1.35</td>
<td>3.43</td>
<td>3.39</td>
<td>0.88</td>
</tr>
<tr>
<td>Apr 23, 2002</td>
<td>0.6</td>
<td>0.55</td>
<td>0.47</td>
<td>2.09</td>
<td>1.78</td>
<td>0.82</td>
</tr>
<tr>
<td>Apr 27, 2002</td>
<td>1.2</td>
<td>1.24</td>
<td>0.88</td>
<td>2.99</td>
<td>2.11</td>
<td>0.82</td>
</tr>
<tr>
<td>May 12, 2002</td>
<td>1.8</td>
<td>1.84</td>
<td>2.28</td>
<td>2.12</td>
<td>2.63</td>
<td>0.67</td>
</tr>
<tr>
<td>May 20, 2002</td>
<td>1.4</td>
<td>1.52</td>
<td>1.55</td>
<td>3.81</td>
<td>3.89</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Total 20.0 19.40 18.10
Calculation of DSD is performed as follows:

\[ N(D_i) = \frac{1}{\Delta D_i \Delta t} \sum_{j=1}^{n_i} \frac{1}{A_j v_j} \]  

(10)

where \( i \) denotes the particular drop size class, \( j \) denotes the particular drop within size class \( D_i \) and time interval \( \Delta t \), \( n_i \) is the number of drops within the size class \( i \) and time interval \( \Delta t \), \( D_i \) is the mean diameter of size class \( i \) [mm], \( \Delta t \) is the time interval [s], \( \Delta D_i \) is the width of drop size class \( i \) [mm], \( A_j \) is the effective measuring area for drop \( j \) [m\(^2\)] and \( v_j \) is the fall velocity of the drop \( j \) [m s\(^{-1}\)]. \( A_j \) is approximately twice the JW measuring area. Also available are the raindrop oblateness, orientation angles, front and side view and the horizontal velocity of each drop. Since such information is not used in this work, details on these parameters are not considered.

3. Instrumental set-up and methodology

The Pludix and JW were operated during the period November 2001–May 2002 at the Physics Department of the University of Ferrara. There is approximately 0.5 m of separation between the two instruments. For the collocation site, see Fig. 4a. The measurements were taken at 1-min intervals, for each instrument. A TB-RG with buckets are calibrated to tip after each 0.2 mm was used to validate the rain measurements. The TB-RG was positioned approximately 3 m from the two disdrometers.

No on-site calibration was performed on the JW disdrometer, as the sensor head used during the experiment was new and calibrated by the manufacturer. No correction is applied to the DSD to account for the dead time problem of the instrument. In order to

<table>
<thead>
<tr>
<th>Time=59 min</th>
<th>JW</th>
<th>Pludix</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R ) [mm h(^{-1})]</td>
<td>3.42</td>
<td>2.98</td>
</tr>
<tr>
<td>( Z ) [dBZ]</td>
<td>30.60</td>
<td>28.25</td>
</tr>
<tr>
<td>( A ) and ( b ) of ( Z-R ) relation</td>
<td>360.85</td>
<td>227.21</td>
</tr>
<tr>
<td>( Z ) [mm(^6) m(^{-1})] ( R ) [mm h(^{-1})]</td>
<td>1.05</td>
<td>1.12</td>
</tr>
<tr>
<td>( N_0 ) [mm(^{-1}) m(^{-3})]</td>
<td>8.25 ( \times ) 10(^3)</td>
<td>1.22 ( \times ) 10(^4)</td>
</tr>
<tr>
<td>( A ) [mm(^{-1})]</td>
<td>3.27</td>
<td>3.82</td>
</tr>
<tr>
<td>( m ) [( \times )]</td>
<td>11.3</td>
<td>4.90</td>
</tr>
<tr>
<td>( N_0 ) [mm(^{-1}\cdot m(^{-3})]</td>
<td>4.47 ( \times ) 10(^6)</td>
<td>6.42 ( \times ) 10(^5)</td>
</tr>
<tr>
<td>( A ) [mm(^{-1})]</td>
<td>10.2</td>
<td>7.47</td>
</tr>
</tbody>
</table>
operate the JW disdrometer, the transducer was installed taking into account the following conditions:

- it was set up in quiet surroundings;
- it was mounted with its top covered by a platform, reducing the effect caused by strong winds, producing turbulence at the edges of the transducer and creating background noise that underestimates drops less than 2 mm in diameter. The upper platform was covered with some damping material to prevent splashes and reduce the acoustic noise;
- it was set up in order to avoid flooding;
- it was set away from objects which can resonate when hit by raindrops;
- some wires were also fixed around the top of the sensor, and a square also made of wires, like a primitive spider web, with a hole in the middle around the top of the sensor was fixed, to keep off birds.

Fig. 7. (a) Mean percentage rainfall rate contribution in JW (dashed) and Pludix (solid) diameter classes for the April 12, 2002 event in Ferrara. (b) Counts in rainfall rate classes (from 0.0 to 12.0 mm h$^{-1}$, with 0.5 mm h$^{-1}$ steps) for the two instruments (solid=Pludix, dashed=JW) for the April 12, 2002 event in Ferrara.
The Pludix data in Ferrara (as in Cabauw) consist of the number of raindrops $n_i$ of diameter $D_i$ in 21 categories, ranging in size from 0.8 to 7.0 mm, in constant steps of 0.3 mm. The Pludix was installed with its sensor field of view clear of any obstacle on a stable base without vibrations. The ideal collocation of the sensor is in the open field, without surrounding objects (above all, objects in motion, like trees) in a beam of 5–10 m. Interferences of a physical nature (for example objects in motion) cause spectra with only low frequencies, since the objects causing them move at low speeds. The ground noise (Pludix spectrum in absence of precipitation) is in practice all contained in the lower part of the spectrum (under 200 Hz). The data collected in Ferrara were contaminated by ground noise signals (especially physical noise due to an anemometer present at the site, and to tree movement in the area of the instrument) that were present at the lowest frequencies (<50 Hz). This noise was present on days with and without precipitation and was more intense during windy conditions, requiring its elimination from each measurement. The noise removal was accomplished by detecting a characteristic noise spectrum during a non-rainy day and subtracting it from the measured spectrum when precipitation was detected.

To gain automatic and continuous access to the Pludix data, an automatic procedure to download the data on a work-station was also created, using the Mirror Software.

From the overall data set, four light rainfall events and nine moderate rainfall events were selected and analysed. The performances of the two instruments in both rainfall-rate and DSD measurements were tested. Different Pludix calibration approaches are still under testing and are only mentioned here. An average DSD in each time period of each event was considered. The $N_0$ [mm$^{-1}$ m$^{-3}$] and $\Lambda$ [mm$^{-1}$] parameters of the exponential DSD (Marshall and Palmer, 1948; hereinafter MP) were computed using the Waldvogel (1974) method. The $m$, $N_0$ [mm$^{-1}$ m$^{-3}$] and $\Lambda$ [mm$^{-1}$] values of a gamma DSD (Ulbrich, 1983) were computed following the Tokay and Short (1996) method of moments. The rainfall rate $R$ [mm h$^{-1}$] and the reflectivity $Z$ [dBZ] were computed by the observed $N(D)$, here truncated at $D_{\text{min}} = 0.3$ mm, $D_{\text{max}} = 5.5$ mm for JW and at $D_{\text{min}} = 0.8$ mm, $D_{\text{max}} = 7.0$ mm for the Pludix, and were subsequently compared. The $Z$–$R$ relationships from the measured spectrum when precipitation was detected.

![Z-R relationship at Ferrara site (Italy)](image)

Fig. 8. Overall $Z$–$R$ relationship for the JW (crosses) and Pludix (squares), at the Ferrara site. The grey line is the MP (1948) relationship: $Z = 200R^{1.6}$.
were computed by a linear regression method for each instrument.

In addition, a 2DVD (ESA-ESTEC property) and Pludix, installed at the Cabauw site (The Netherlands), with a time resolution of 60 s, were compared (see Fig. 4b for the measurement site). There were approximately 10 m of separation between the two disdrometers. Several rain-gauges were used to validate the rain measurements. The two instruments were operated during the period May 13, 2003–August 13, 2003.

The 2DVD data in Cabauw consist of number of raindrops $n_i$ of diameter $D_i$ in 22 categories, ranging in

---

**Fig. 9.** Comparison of the DSDs of the two instruments (black bars=JW; grey dashed bars=Pludix) for the April 12, 2003 event in Ferrara.

**Fig. 10.** Average coincident measurements of the two instruments (dashed line = Pludix; solid line = JW) for all coincident observations in Ferrara.
size from 0.2 to 4.4 mm, in constant steps of 0.2 mm. Special care was taken during the installation of the instrument to avoid splashing onto the optical surfaces (mirrors and lenses), since such splashes are seen by the cameras, giving rise to permanent shadow sections. As a result, the data rate would increase dramatically, causing overflows and outages of the data acquisition process. Due to the carefully designed mechanical protection in “normal” precipitation, no splashing reaches the optical surfaces. However, in “extreme” storm events (high rain-rates combined with high wind speeds), a few splashes do reach the mirrors. For that reason, eight ceramic rod heaters were used, evaporating any water droplets on the mirrors within seconds.

From the overall data set, nine events were selected, most of which were intense (\(R>20\) mm h\(^{-1}\)). The performances of the two instruments were tested in both \(R\) and DSD measurements. Different rainfall integral and DSD parameters were computed and compared for the analysed events, following the procedure used for the Ferrara data set.

4. Results of the comparison

4.1. Comparison of the Pludix and JW in Ferrara: rainfall rate and DSD analyses

4.1.1. Rainfall rate comparison

The aim of this part of the work is to compare the performances of the two instruments in the rainfall rate estimates. The TB-RG is taken as a reference. During the seven months from November 2001 to May 2002, the two instruments continuously monitored the precipitations falling at the meteorological station of the Department of Physics (Ferrara). A systematic study on the precipitation estimates of both instruments was recently performed for all the considered months (Caracciolo et al., 2002; Caracciolo, 2004). For each analysed period, only rainfall rate values greater than 0.2 mm h\(^{-1}\) were considered. Thirteen precipitation events were subsequently selected and a detailed comparison was realized. Here, only a significant period taken as a reference is shown. The results are reported in Fig. 5a as 1-min rainfall rate time evolution. Of the thirteen events, only the April 12, 2002 event is commented here.

The rainfall rate analysis over the entire seven month data set shows that the Pludix generally tends to underestimate the less intense precipitation events and to overestimate the more intense precipitation events, compared to the TB-RG and JW (see Fig. 5a for April 11, 2002). The light–moderate rain events are characterized by more small drops (between 0.3 and 0.8 mm), which the Pludix does not consider,

<table>
<thead>
<tr>
<th>Day</th>
<th>RA(2DVD) [mm]</th>
<th>RA(Pludix) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 17, 2003</td>
<td>1.21</td>
<td>1.20</td>
</tr>
<tr>
<td>May 18, 2003</td>
<td>3.66</td>
<td>4.71</td>
</tr>
<tr>
<td>May 19, 2003</td>
<td>3.76</td>
<td>4.05</td>
</tr>
<tr>
<td>June 2, 2003</td>
<td>0.82</td>
<td>1.26</td>
</tr>
<tr>
<td>June 2, 2003</td>
<td>6.76</td>
<td>16.64</td>
</tr>
<tr>
<td>June 10, 2003</td>
<td>3.24</td>
<td>6.76</td>
</tr>
<tr>
<td>June 19, 2003</td>
<td>1.31</td>
<td>1.00</td>
</tr>
<tr>
<td>June 19, 2003</td>
<td>0.38</td>
<td>0.72</td>
</tr>
<tr>
<td>July 24, 2003</td>
<td>4.04</td>
<td>12.08</td>
</tr>
<tr>
<td>Total</td>
<td>25.18</td>
<td>48.42</td>
</tr>
</tbody>
</table>

Table 6
Integral and DSD parameters for the May 18 and 19, 2003 events in Cabauw

<table>
<thead>
<tr>
<th>May 18, 2003 (51 min) 17:53 – 18:30</th>
<th>2DVD</th>
<th>Pludix</th>
<th>May 19, 2003 (289 min) 12:18 – 17:44</th>
<th>2DVD</th>
<th>Pludix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z [dBZ]</td>
<td>29.10</td>
<td>30.54</td>
<td>20.49</td>
<td>23.52</td>
<td></td>
</tr>
<tr>
<td>(R) [mm h(^{-1})]</td>
<td>5.77</td>
<td>7.27</td>
<td>0.78</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td>RA [mm]</td>
<td>3.66</td>
<td>4.71</td>
<td>3.76</td>
<td>4.05</td>
<td></td>
</tr>
<tr>
<td>RA-TB [mm]</td>
<td>4.4</td>
<td>4.4</td>
<td>3.2</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>(A) and (b) of (Z-R) relation</td>
<td>242.6</td>
<td>237.60</td>
<td>325.16</td>
<td>275.78</td>
<td></td>
</tr>
<tr>
<td>(Z) [mm(^2) m(^{-3})] (R) [mm h(^{-1})]</td>
<td>1.30</td>
<td>1.11</td>
<td>1.38</td>
<td>1.11</td>
<td></td>
</tr>
<tr>
<td>(N_0) [mm(^{-1}) m(^{-3})]</td>
<td>2.26·10(^4)</td>
<td>5.33·10(^6)</td>
<td>4.37·10(^5)</td>
<td>4.03·10(^5)</td>
<td></td>
</tr>
<tr>
<td>(A) [mm(^2)]</td>
<td>4.02</td>
<td>4.30</td>
<td>4.47</td>
<td>4.19</td>
<td></td>
</tr>
<tr>
<td>(m) [−]</td>
<td>12.79</td>
<td>5.27</td>
<td>11.61</td>
<td>3.97</td>
<td></td>
</tr>
<tr>
<td>(N_0) [mm(^{-1}) m(^{-3})]</td>
<td>8.64·10(^8)</td>
<td>4.11·10(^6)</td>
<td>5.17·10(^9)</td>
<td>1.10·10(^5)</td>
<td></td>
</tr>
<tr>
<td>(A) [mm(^2)]</td>
<td>15.50</td>
<td>8.16</td>
<td>16.26</td>
<td>6.96</td>
<td></td>
</tr>
</tbody>
</table>
which is probably the reason for the underestimation. In the more intense events, large drops are present and the Pludix gives rain values higher than those of the JW and more similar to those of the TB-RG (often higher than the TB-RG). In this case, the Pludix values are supposed to be more realistic, because JW counts drops only until $D = 5.3$ mm, and during heavy events the TB-RG is a less reliable instrument because of the bucket mechanism. The JW dead time effect may also play a role.

Fig. 11. 1-min temporal rainfall-rate evolution for (a) May 18, 2003 and (b) May 19, 2003 in Cabauw (solid line=Pludix; dotted line=2DVD).
The thirteen selected events (Table 3) are characterized by light to moderate rainfall rate intensities. The shape of the Pludix power spectrum (here not shown) has varying characteristics depending on the different precipitation types. The stratiform and winter precipitation has broad maxima. The convective precipitation usually has relatively flattened spectra, with narrowed and emphasized maxima at higher frequencies, often with irregular shape. For all the events considered here, the maxima are relatively broad and confined between

![Graph](image-url)
300 and 600 Hz, indicating a stratiform precipitation. Some representative spectra taken from the Ferrara data set are given in Fig. 6.

The total depth of rainfall is determined by the TB-RG and compared with the total depth of rainfall measured by the two disdrometers. Table 3 shows that the rain total measured by the JW disdrometer is less than that observed by the rain-gauge in most of the events. The overall rain total is also less. This result is partially due to the underestimation of drops of small diameters in

Fig. 13. Counts in rainfall rate classes for the two instruments (grey=Pludix, black=2DVD) for the May 18, 2003 (a) and May 19, 2003 (b) events in Cabauw.
The limit of maximum drop size may also play a role. This will be evaluated in future work through a simulation truncating a MP DSD (or any other model) at the JW maximum, and examining the effect. However, there is better agreement between the JW and the TB-RG than between the Pludix and the TB-RG. The integrated precipitation over each time period is generally less in the Pludix with respect to the JW and TB-RG. The Pludix
records 9.5% less rain amount, while the JW records 3% less rain amount than the TB-RG. Table 3 also shows high values of the correlation coefficient between the rainfall rate estimates of the two disdrometers.

In Fig. 5b, the 1-min rainfall rate time evolution of the two instruments is given for an event taken as a reference (April 12, 2002). Different rainfall integral and DSD parameters are also computed for all of the analysed rain events (see Table 4 for the April 12 event). An average DSD in each time period of each event is considered.

In Fig. 5b, it can be seen that the Pludix tends generally to underestimate the rainfall rate with respect to JW (see also Table 4). This is probably due to the fact that the minimum diameter detected by the Pludix is 0.8 mm, and that for all the analyzed events the total number of drops per unit volume is always less than the JW counts (not shown). Another explanation is that (see Fig. 7a) for the Pludix the drops contributing most to the rainfall rate are included in the first diameter classes (average diameter of 0.95 mm). In Fig. 7b the data are presented in terms of the number of minutes spent in rainfall rate classes (from 0.0 to 12.0 mm h\(^{-1}\), with 0.5 mm h\(^{-1}\) steps) for the two instruments. The frequency distributions of JW and Pludix rain occurrence show that the Pludix records a higher percentage of light rain than the JW, for the corresponding measurements.

The Pludix tends also to underestimate Z as compared to the JW (Table 4). The light/moderate events analysed here are characterized by more small drops and less large drops. It is expected that the situation will invert for heavy events, because of the maximum Pludix detected diameter equal to 7 mm. Another important aspect is that, the Pludix tends to count a lot of drops, especially in the 0.8–1.5 mm diameter interval for almost all the events (see Fig. 7a). This interval contributes most to the rainfall rate, while there is a presence of more large drops in the JW, except in the very first size ranges. The underestimation of small drops by the JW also has a limited effect on Z, because this parameter is related to the higher moments of the DSD.

To show the instrumental dependence on the coefficients of the Z–R relationship, Z–R relations obtained from DSD measurements by the two disdrometers are examined. Recently, Campos and Zawadski (2000) found that the Z–R relationship is highly instrument dependent; the differences found in the relationship comparing a JW disdrometer, POSS and an optical spectro-pluviometer are of the same order of magnitude as those generally encountered in distinct climatic regions. In the present study, the comparison of Z–R relations derived from Pludix and JW measurements shows quite good agreement (see Table 4 for April 12, 2002). If one considers two DSDs, at the same R, the spectrum that has more large drops turns out to have a higher coefficient A than the spectrum with less large drops, assuming a constant exponent b. 

![Z-R relationship at Cabauw site (The Netherlands)](image_url)

Fig. 15. Overall Z–R relationship for 2DVD (crosses) and Pludix (dots) for the Cabauw site.
comparison, the Pludix \( A \) coefficient is generally lower than the JW \( A \) coefficient, while the Pludix \( b \) coefficient is nearly always lower than the JW \( b \) coefficient. This is also confirmed in Fig. 8 where it can be noted that almost all the Pludix \( Z \) values during the period of interest lie below the JW disdrometer values. Otherwise, the Marshall and Palmer (1948) relationship for stratiform rain fits well both sets of data.

4.1.2. Drop size distribution comparison

Simultaneous measurements of DSDs by the JW and the Pludix are performed for the thirteen selected events. The composite DSDs derived for all these observations show a good agreement between the two instruments (see Fig. 9 for the April 12 event). The DSDs for the two instruments are similar for the same diameter classes. Qualitatively, the measurements in the mid-diameter range (1 < \( D \) < 3 mm) of DSD behave similarly, with a concentration relatively lower in the Pludix than in the JW. The Pludix is able to detect large drops not measured by the JW, although the concentration of large drops is very small, because of light rains. There are also differences in drop concentrations at \( D < 1 \) mm, mainly due to the underestimation of small drops by the JW (dead time problem), and to the relatively large concentration of drops in the first Pludix diameter class of 0.95 mm.

To examine the characteristics of the DSD of the two disdrometers, the coincident DSDs of the two instruments for three different rain intervals (\( R < 2, 2 < R < 5, 5 < R < 10 \) mm h\(^{-1}\)) and for the total rain range (see Fig. 10) are also averaged. Good agreement is found between the two disdrometers at all three scales, especially for \( R < 2 \) mm h\(^{-1}\), with a slightly smaller concentration of medium size drops in the Pludix (here not shown). Fig. 10 shows that the two measurements agree well each other, with a slightly lower concentration of medium size drops in the Pludix. This result suggests

![Fig. 16. Comparison of the DSDs of the two instruments (black bars=Pludix; grey dashed bars=2DVD) for May 18, 2003 (a) and May 19, 2003 (b) in Cabauw.](image)
that both disdrometers can be used to investigate the differences in DSD in different rainfall rate regimes. The ability to measure very large drops with the Pludix, as with any radar having a large measurement volume, should also be considered a substantial improvement in DSD research.

To parameterise the DSD, the exponential and gamma functions are applied to each average DSD. The parameters of the exponential and gamma DSD derived from the Pludix spectra (see Table 4 for April 12, 2002) are often higher than those derived from the JW spectra (the DSD is narrow). This result suggests the presence of more small drops and fewer medium-size drops in the Pludix than in the JW (consequence of the minimum detected diameter, equal to 0.8 mm). As the rainfall rate increases, more large drops are found in the Pludix spectra than in the JW spectra. It is also found that the Pludix DSD is better parameterized by an exponential distribution, while the JW DSD is better parameterized by a gamma distribution. For diameters less than 0.5 mm, the JW shows \( N(D) \) deviating from the exponential model. As the rainfall rate increases, the DSDs show increasing curvature relative to the exponential model: the number concentrations of both small (JW dead time effect) and large drops are smaller. A gamma DSD fits better the data. For the Pludix, the shape of all the curves represents an exponential distribution rather well, except in the case of large diameters, especially at high rainfall rates. This is probably due to an under-sampling of large diameter drops. Otherwise, for diameters between 2 and 5 mm the Pludix generally shows \( N(D) \) deviating from the exponential model.

4.2. Comparison between the Pludix and 2DVD in Cabauw: rainfall rate and DSD analyses

4.2.1. Rainfall rate comparison

Table 5 shows the rain amount comparison between the two disdrometers for the nine selected events in Cabauw. Two significant events (May 18 and 19, 2003) were subsequently selected to undergo analysis. Unfortunately, the gauge data were available only for these two events. Table 6 reports the rainfall integral and DSD parameters for the two selected events. The rain amount analysis over the entire data set (Table 5) reveals that the Pludix generally tends to underestimate the less intense precipitation events, as found for the Ferrara data set, and to overestimate greatly the most intense events.

![Fig. 17. Histograms of \( m, N_0 \) and \( \Lambda \) values of a gamma DSD, for all the coincident observations in Cabauw (grey bars = 2DVD; black bars = Pludix).](image-url)
intense precipitation events. Such behaviour is probably due to Pludix splash effects during the extreme rain events, producing many small-medium drops which contribute most to the rainfall rate. This aspect is analysed in greater detail below. In any case, a better agreement is found between the Pludix and TB-RG rain amounts for the May 18, 2003 event (very heavy rain) than in the May 19, 2003 event (moderate rain), for which there is a better agreement between the 2DVD and TB-RG rain amounts.

Fig. 11 shows the Pludix and the 2DVD rainfall-rate 1-min time evolution for the May 18 and 19, 2003 events occurring in Cabauw, taken as the most representative. In general, it was found that for the less intense events, the Pludix tends to underestimate the rainfall rate with respect to the 2DVD. Otherwise, for the heavy events ($R > 10 \text{ mm h}^{-1}$) the Pludix tends generally to overestimate the rainfall rate (see also Table 6). Such behaviour is partly attributable to the different size classes of the two instruments and to the minimum detected diameter (0.8 mm for the Pludix and 0.2 mm for the 2DVD). The maximum Pludix detected diameter of 7.0 mm may influence the final result for the heavy rain events.

Regarding the comparison of the radar-reflectivity values (see Fig. 12), a good agreement is found between the two instruments (see also Table 6). This means that, because the reflectivity is the sixth moment of the drop size distribution and is therefore sensible to the largest drops, the smallest drops are the ones accounting for the biggest differences between the two instruments. Such behaviour is also confirmed in Fig. 13, which shows the frequency distributions of 2DVD and Pludix rain occurrences. It can be seen that the Pludix records an higher percentage of light rain than the 2DVD, for the corresponding measurements. Moreover, in Fig. 14, it can be seen that the Pludix tends to count a lot of drops, especially in the 1.0–1.5 mm diameter interval for both the events. This interval contributes most to the rainfall rate, while there is a presence of more large drops in the 2DVD, thus confirming the above consideration as to the possibility of splash effects in the Pludix during heavy rain events.

To show the instrumental dependence on the coefficients of the $Z-R$ relationship, $Z-R$ relations obtained from DSD measurements by the two disdrometers were examined. As for the Ferrara data set, comparison of $Z-R$ relations derived from the Pludix

![Average DSD (590 1-minute spectra) - Cabauw site (The Netherlands)](image)

Fig. 18. Average coincident measurements of the two instruments (solid line = Pludix; dashed line = 2DVD) for all coincident observations in Cabauw.
4.2.2. Drop size distribution comparison

Simultaneous measurements of DSDs by the 2DVD and Pludix were performed for the nine selected events. The composite DSDs derived for all these observations show a good agreement between the two instruments (see Fig. 16 for the May 18 and 19 events), especially for the less intense rain events. The measurements in the mid-diameter range (1.0 – 3.3 mm) of DSD behave similarly, with a relatively lower concentration in the Pludix than in the 2DVD. The Pludix is able to detect large drops not measured by the 2DVD. There are also differences in drop concentrations at D<1 mm, mainly due to the large concentration of drops in the first Pludix diameter class of 0.95 mm.

To parameterise the DSD, the exponential and gamma functions are applied to each average DSD. As for the Ferrara data set, the Pludix DSD is better parameterized by an exponential distribution, while the 2DVD DSD is better parameterized by a gamma distribution. The parameters of the gamma DSD derived from the Pludix spectra (see Table 6 for May 18 and 19, 2003) are smaller than those derived from the 2DVD spectra (the DSD is broad), while the Pludix exponential DSD parameters are slightly higher. This result suggests the presence of more small drops and fewer medium-size drops in the Pludix than in the 2DVD (consequence of the minimum detected diameter equal to 0.8 mm, and to splash effects during very heavy events). As the rainfall rate increases, more large (but very few) drops are found in the Pludix spectra than in the 2DVD spectra, but also more drops with 1 mm diameter due to the splash effect. Fig. 17 shows the histograms of the three gamma DSD parameters, for all the coincident observations in Cabauw; as previously noted, many Pludix spectra are characterised by smaller values of the three parameters than those of the 2DVD.

The coincident DSDs of the two instruments for the total rain range (see Fig. 18) were also averaged. A good agreement is found between the two disdrometers, especially in the range 1.5 – 3.5 mm, with a great concentration of drops about 1 mm diameter in the Pludix. This result suggests that both disdrometers can be used to investigate the differences in DSD in different rainfall rate regimes. The ability to measure very large drops with the Pludix should also be considered a substantial improvement in DSD research.

5. Conclusions and further work

Two types of disdrometers based on different measuring principles installed in Ferrara (Italy) and in Cabauw (The Netherlands) were compared: a classical JW disdrometer and a recent device, called the Pludix (in Ferrara), and Pludix and the two-dimensional video disdrometer (2DVD) (in The Netherlands). The performances of the two pairs of disdrometers were analysed by comparing their rain amounts with the nearby TB-RGs, and by subsequently comparing their DSDs. The most important rainfall integral parameters (like R and Z) and DSD parameters were analysed and compared.

Regarding the rainfall rate comparison in Ferrara, it was found that both types of disdrometers underestimate the total rain, but, for the light/moderate rain events analysed here, the agreement is better between the JW and the TB-RG. The Z values of the two instruments are quite close, with the Pludix reflectivity always somewhat less that the JW reflectivity. The Z–R relationships were also derived: the A and b values of the two instruments are quite close, with the Pludix A and b values generally lower than the JW values. Such results are probably due to the fact that the light/moderate rain events analysed here were characterized by many small drops (between 0.3 and 0.8 mm), which the Pludix does not consider, its minimum detected diameter being 0.8 mm. The Pludix truncation effect at diameters less than 0.8 mm will be qualitatively evaluated through simulations using, for example a MP DSD model in a future work.

Comparing the DSDs in Ferrara, it was found that for the same diameter classes the two instruments have similar DSDs. The long-time-period averaged DSDs were parameterised by an exponential and a gamma DSD. It was found that the Pludix DSD is better parameterised by an exponential DSD, the JW DSD by a gamma DSD. Such behaviour also reflects on the average exponential and gamma DSD parameters, which are nearly always greater in Pludix than in the JW. To better compare the two instruments, the coincident measurements of DSDs performed by the two instruments were averaged for three rain classes.
Good agreement was found between the two measurements at all three scales, especially for $R<2$ mm h$^{-1}$. Good agreement was also found when all the coincident DSD measurements of the JW and Pludix were averaged, with a smaller concentration of medium size drops in Pludix.

The comparison between the Pludix and a 2DVD installed at the Cabauw site, also showed that for the less intense events the Pludix generally tends to underestimate the rainfall rate with respect to the 2DVD. Otherwise, for the heavy events ($R>10$ mm h$^{-1}$), the Pludix tends generally to overestimate the rainfall rate. Such behaviour is attributable to the different size classes of the two instruments and to the minimum detected diameter (0.8 mm for the Pludix and 0.2 mm for the 2DVD). The maximum Pludix detected diameter of 7.0 mm may also influence the final result for the heavy rain events. Moreover, the presence of substantial splash effects in the Pludix, especially significant during heavy and very heavy rain events, may influence the rain comparisons, adding many drops in the first Pludix diameter class (1 mm mean diameter). An algorithm to remove these effects is under analysis.

Comparing the DSDs in Cabauw, it was found that for the same diameter classes the two instruments had similar DSDs, with the Pludix DSD better parameterised by an exponential DSD, and the 2DVD DSD by a gamma DSD. Good agreement was also found when all the coincident DSD measurements of the 2DVD and Pludix were averaged, with a smaller concentration of medium size drops in the Pludix. It is important to note that no correction for the wind effect was carried out on the 2DVD; this will be the subject of future work.

Considering the different natures of the instruments and the fact that the Pludix is still in a calibration and testing phase, the results found here were encouraging. The analysis also demonstrated the good capability of the Pludix in measuring the rainfall rate and the drop size distribution with high accuracy. In the future, a new signal inversion algorithm will be tested, which will remove these effects is under analysis.

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References


