Microprocessor Field Impactometer Calibration: Do We Measure Drops' Momentum or Their Kinetic Energy?

PAWEŁ LICZNAR AND JANUSZ ŁOMOTOWSKI

Department of Building and Infrastructure, Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland

SŁAWOMIR BŁOŃSKI

Department of Mechanics and Physics of Fluids, Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw, Poland

GRZEGORZ J. CIACH

Iowa Institute of Hydraulic Research—Hydroscience and Engineering, The University of Iowa, Iowa City, Iowa

(Manuscript received 17 November 2006, in final form 24 September 2007)

ABSTRACT

This study presents the construction and calibration of a low-cost piezoelectric microprocessor impactometer designed for the field measurements of the rainfall kinetic energy (KE) flux. Its precise calibration was performed in laboratory conditions using waterdrops of different sizes and fall velocities. High-speed photography was applied to measure the velocity of each waterdrop. Although the impactometer constructed for this study is not able to measure the momentum of waterdrops, its accuracy for measuring their KE is excellent. It was found that the processing of the piezoelectric signal might determine which physical quantity is measured by different impactometers. It was also found that the distance between the waterdrop impact position and the impactometer center has a significant effect on the sensor output. A scheme to account for this effect is developed in this study, and the calibration curve for field applications of the impactometer is derived. In addition, an example comparison of the concurrent field measurements of KE flux using the impactometer and rainfall rates using a weighing rain gauge is given.

1. Introduction

The published evaluations of disdrometers of various designs (Kinnell 1976, 1977; Smith et al. 1993; Nešpor et al. 2000; Jameson and Kostinski 2002; Tokay et al. 2003; Salles and Creutin 2003; Krajewski et al. 2006) demonstrate that the currently available techniques for measuring drop size distribution (DSD) in rainfall are still corrupted with substantial errors. These errors propagate to the integral quantities derived from the DSD data, such as rainfall rate, radar reflectivity, and kinetic energy (KE) flux. Some of these quantities can be measured more accurately with specialized instruments (e.g., measuring rainfall with rain gauges of modern design). However, the currently achievable precisions of the KE flux measurements in rainfall are still quite limited (see the brief literature review below). While different techniques for more accurate and more affordable DSD monitoring are under continuous development (e.g., Henson et al. 2004), there is also an increasing demand for an inexpensive specialized instrument to measure the rainfall KE flux accurately. The main topic of the study presented below is the construction, signal processing, and calibration of an inexpensive piezoelectric-based microprocessor impactometer designed specifically for field measurements of this quantity.

The KE flux of surface rainfall has been of growing interest in civil engineering and in hydrologic and agricultural research because of its importance in the soil erosion process and its many practical consequences. The rainfall KE term was introduced to the Universal Soil Loss Equation by Wischmeier and Smith (1978),

Corresponding author address: Paweł Licznar, Dept. of Building and Infrastructure, Wroclaw University of Environmental and Life Sciences, Plac Gruwaldzki 24, 50-363 Wroclaw, Poland.
E-mail: licznarp@ozi.ar.wroc.pl

DOI: 10.1175/2007JTECHA938.1

and it remains one of the key predictors in soil erosion modeling. At present, it is a well-known fact that the KE of raindrops plays a crucial role in the mechanisms of soil splash erosion, seal formation, and soil aggregate breakdown (Nearing et al. 1986). Apart from severe agricultural consequences, these phenomena play an important role in hydrologic modeling by changing topsoil properties that affect the processes of infiltration, evaporation, and surface runoff. Also, rainfall-induced soil erosion strongly affects many aspects of environmental hydraulic design that must take sediment transport into account. Finally, the research of Madden et al. (1998) showed that the KE of raindrops has a strong effect on the magnitude of rain splash dispersal and, consequently, a large influence on the size of epiphytic populations of some plant-pathogenic bacteria. Consequently, the availability of low-cost instruments that can accurately measure the spatiotemporal structure of the KE flux in rainfall can have positive implications in many areas of applied research.

It is possible that rainfall KE and other integral quantities derived from the DSD will be measured reliably sometime in the future by using networks of accurate and inexpensive disdrometers. However, at present, the least expensive direct monitors of the rainfall KE flux can be built using simple force sensors. Piezoelectric transducers have been used quite widely as low-cost sensors of physical properties of rainfall. One instrument for measuring the KE or momentum flux released by rainfall, called the impactometer, was constructed by Battista et al. (1994a,b). It was based on a piezoelectric transducer and included additional electronics for the signal amplification, filtering, and processing. The development of our impactometer discussed herein has benefited greatly from the many years of experience of these authors. Another instrument is the KE sensor based on a thick ceramic piezoelectric crystal plate manufactured by Sensit Company. As far as we know, it is still the only commercially available specialized instrument for field monitoring of rainfall KE. The first generation of these instruments was tested by Foltz et al. (1995). A considerably improved version of the same device was later investigated by Madden et al. (1998). Their calibration of the KE sensor resulted in a highly nonlinear relationship between its pulse-count output and the KE of impacting waterdrops. Several other drawbacks of the Sensit KE sensor, such as the strong signals generated by drops impacting the instrument casing outside the sensing crystal and the quick formation of a thick water film on the flat surface of the crystal plate, considerably limit its accuracy in field applications. Under laboratory conditions, Guzel and Barros (2001) investigated the possible application of the commercial piezoelectric-based devices used routinely in acoustic emission testing (AET) to measure stress waves produced by impacting waterdrops. They found that the KE can be related to the signal peaks caused by the drop impacts. However, no further communications are known concerning possible applications of AET technology to field measurements of rainfall KE.

Several important papers were then published presenting applications of modern piezoelectric ceramics to rainfall sensing. Henson et al. (2004) described the design of low-cost disdrometers based on piezoceramic disks. They proposed applying the networks of such sensors to establish local *Z–R* relationships. However, the field performance of the sensor by Henson et al. (2004) is still poorly known. A new piezoelectric rain gauge system designed to measure rainfall on buoys at oceanic sites was presented by Förster et al. (2004). The main part of their "oceanic rain gauge" was a sphere formed of piezoelectric ceramics used in commercial hydrophones. The authors estimated rain rates indirectly by measuring the momentum of the impacting raindrops (see discussion in the next section). Their device was tested in laboratory conditions and evaluated in a field campaign against a JWD RD 69 disdrometer (Joss and Waldvogel 1967), an FM–CW Doppler radar (e.g., Löffler-Mang et al. 1999), and the ship rain gauge SRM 450 (Eigenbrodt 2007). The field tests reported by Förster et al. (2004) were performed on land, even though their instrument was intended to be installed on buoys and to work in much more challenging conditions. Another low-cost piezoelectric-based disdrometer was also proposed by Kourtellis et al. (2005). Their prototype impact sensor consisted of an array of piezoelectric elements encapsulated in water-resistant material, and an adaptive algorithm was applied to the signal processing. However, its calibration was limited to the comparisons with concurrent rain-rate measurements and no validation of its claimed DSD retrieval capabilities is known to us.

In this study, we describe a low-cost piezoelectric-based instrument designed for the field measurements of rainfall KE. We call it the "DBI impactometer" because it was developed at the Department of Building and Infrastructure (DBI) of the Wroclaw University of Environmental and Life Sciences. We present the construction of the DBI impactometer, describe the processing of the signal from the piezoelectric sensor, and thoroughly discuss the calibration of the instrument. We show that our instrument can accurately measure the KE of waterdrops, whereas its utility for measuring drop momentum is questionable. Finally, the field performance of the DBI impactometer is illustrated on a selected storm event.

2. Basic physics and signal processing in piezoelectric impactometers

The piezoelectric effect used in sensors consists of generating opposite electric charges on the sides of some crystals (e.g., quartz) during their mechanical deformations into specific directions relative to the crystal structure. The magnitude of the charges can be measured as the voltage U that is proportional to the force F, causing the deformation

$$U = \frac{d_p}{C_s} F, \tag{1}$$

where d_p is the piezoelectric constant of the crystal and C_s is the capacitance of the sensor element based on the crystal. The typical value of the piezoelectric constant is on the order of 10^{-12} C N^{-1} for hexagonal quartz crystals cut perpendicularly to their main axes.

For waterdrops impacting a piezoelectric sensor, the force (and voltage) in Eq. (1) is a rapidly changing function of time (e.g., see Förster et al. 2004). It depends on the drop size and its impingement velocity, as well as on the duration of the complex interaction between the sensor and the waterdrop. In the simplest approximation, the impingement duration is often assumed to be close to the time that the waterdrop needs to fall the distance of its diameter. Förster et al. (2004) suggested that the quantity accounting for the entire impingement process is the time integrals of the voltage in Eq. (1):

$$\int U\,dt = \frac{d_p}{C_s}\int F\,dt = \frac{d_p}{C_s} M_0 = \frac{d_p m_0 \upsilon_0}{C_s}, \tag{2}$$

where M_0 is the linear momentum of the waterdrop impacting the piezoelectric sensor, m_0 is the mass of the drop, and υ_0 is its impact velocity. The proportionality of voltage integral to waterdrop linear momentum in Eq. (2) was fundamental for developing the special "momentum transfer functions" in Förster et al. (2004) to estimate the drop diameters.

Equation (2) seems to give a definite answer to the question raised at the title of this study: Do we measure drops' momentum or their kinetic energy? However, this answer becomes less obvious when we try to describe more precisely the complex interaction between the impacting waterdrop and the sensor surface. This issue was given special attention in a much earlier study by Nearing et al. (1986). Their results were based on a series of precise laboratory experiments, including detailed analyses of the signals from the piezoelectric sensor for many waterdrops of different masses and impact velocities. The authors demonstrated that the transfer of the entire momentum of the waterdrop impacting the rigid sensor surface occurs during the impact duration, Δt. This specific interval lasts from the start time t_s, when the drop first touches the sensor, to the time t_e, when the rear end of the drop reaches the sensor surface. In view of these findings, it is necessary to complete Eq. (2) with the integration boundaries

$$\int_{t_s}^{t_e} U\,dt = \frac{d_p}{C_s}\int_{t_s}^{t_e} F(t)\,dt = \frac{d_p}{C_s} M_0 \tag{3}$$

in order to measure correctly the linear momentum M_0 of a waterdrop impacting the piezoelectric sensor. The piezoelectric signal beyond the impact end t_e oscillates and includes negative voltage values. Therefore, it has to be excluded from the integration to measure M_0 accurately. However, the precise real-time determination of the integration boundaries in Eq. (3) for each drop is technically quite a challenging task. It can be solved through skillful signal processing by applying fast analog/digital converters and fast microprocessors. However, the technology of signal processing available to us was much too slow for this task. Therefore, we applied a new approach consisting of the integration of the absolute value of the signal,

$$\int_{t_1}^{t_2} |U|\,dt = X_0, \tag{4}$$

over arbitrarily selected intervals $[t_1, t_2]$. Practical realization of the signal processing based on Eq. (4) does not require high computational power, and it can be achieved using low-cost microprocessors. In the next sections, we provide experimental evidence that the new quantity X_0 is indeed linearly proportional to the interval-averaged KE flux of the waterdrops.

3. Technical realization of the DBI impactometer

The general idea of the DBI impactometer is derived from the works of Battista et al. (1994a,b). The central part of this instrument is the commercially available ICP quartz force sensor model 208C01 manufactured by PCB Piezotronics, Inc. (the schematic cross section of the sensor is shown in Fig. 1). The sensor is characterized by a sensitivity of 110 mV N^{-1}, a resolution of 0.00045 N, and a compression range of 45 N, and it can work in a wide range of temperatures, from −54 to 121°C (PCB Piezotronics 1999). The DBI impactometer, shown in Fig. 2, is based on this force sensor. It is equipped with an additional sensing plate covering the

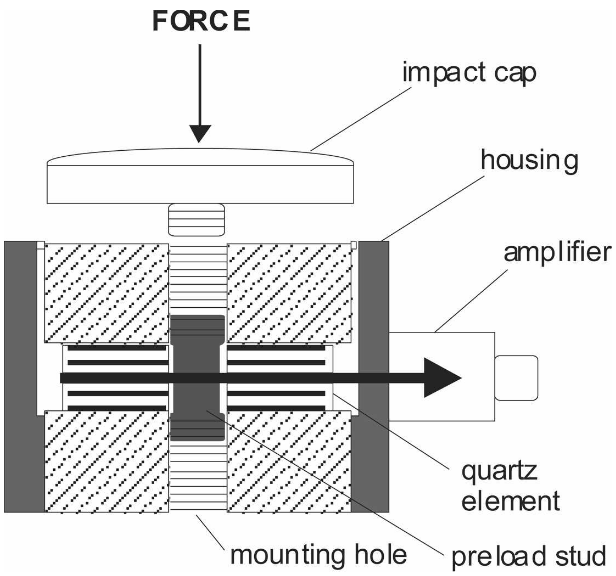

FIG. 1. The cross section of a typical quartz force sensor: General Purpose 208 Series compression/tension model with built-in electronics (PCB Piezotronics 1999).

original small impact cap, the microprocessor, a weatherproof enclosure made of steel, and three adjustable feet for leveling the instrument. The considerable weight of the enclosure assures that the working position of the device is stable in all conditions.

Every ICP force sensor is supplied with its own calibration certificate. The calibration graph approved by the National Institute of Standards and Technology (NIST) shows the exact proportionality of the output voltage to the acting force (PCB Piezotronics 2000). Therefore, the preliminary verification of the piezoelectric effect by applying normal static force on the impact cap, as done in Förster et al. (2004), was omitted. All the tests and calibrations of the complete DBI impactometer were performed by measuring its dynamic response to the impacts of single waterdrops on the instrument cap.

The observed responses of the ICP force sensor installed in the DBI impactometer to the waterdrop impacts agree qualitatively with the plots published in other studies (e.g., Battista et al. 1994a,b; Förster et al. 2004; Henson et al. 2004). The impact duration [$\Delta t = t_e - t_s$ in Eq. (3)] lasts about 250–300 μs, followed by oscillations. The duration and frequency of these oscillations depend on the specific sensor and the construction of the impactometer sensing plate. For a given instrument, their duration also depends on the waterdrop size and impacting velocity. In our case, the oscillations have significant amplitude during 3–5 ms after the impact. The raw signal from the piezoelectric crystal is preprocessed by the built-in electronics of the ICP force sensor. First, it is filtered by an active bandpass filter. Low frequencies are removed as the acoustic noise, and high frequencies are removed as the electronic noise. Second, the filtered signal is amplified and converted to digital form by a 10-bit bipolar A/D converter with a sampling frequency of 10 kHz. The output numbers from the bipolar converter contain a sign bit that allows for coding both positive and negative signals.

Next, the digitized signal of the ICP force sensor is processed by the external microprocessor in the DBI impactometer. We applied the 8-bit microcontroller ATMEL 89C51 which is used in numerous devices, including smoke detectors. The microprocessor modifies the sign bit of the input numbers, converting them into the absolute values of the digitized signal. Then, the time series of the absolute values are integrated nu-

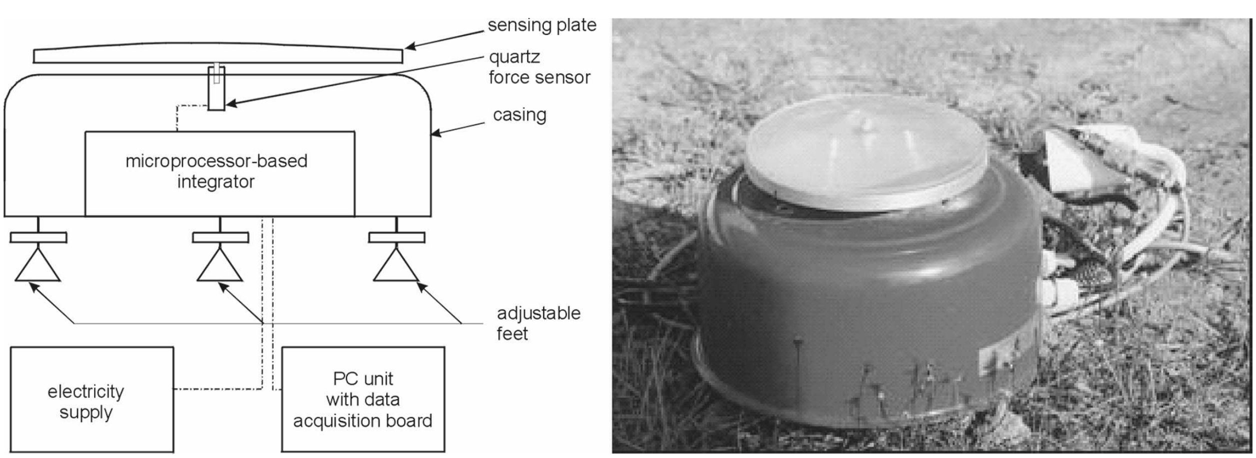

FIG. 2. Technical realization of the DBI impactometer. The quartz force sensor is used to measure the oscillations of the sensing plate originating from waterdrop impacts.

merically over the preset intervals of time. The width of the integration time window can be set by a microswitch to one of the four values: 100 ms, 1 s, 30 s, or 60 s. The integration results are converted back into analog form, which is the final output of the DBI impactometer. The analog output of the impactometer can be transmitted to the data acquisition card of a PC. The 12-bit PCL-818L model manufactured by Advantech Co., Ltd. is the card that we used. The DBI impactometer data are recorded in the PC storage and can be further analyzed during the impactometer calibration or its field operation.

The sensing plate of 13.8-cm diameter is an important part of the DBI impactometer. The cross-section of the upper part of the sensing plate has an oblique shape to eliminate the ponding effect. The area of the sensing plate is 149.6 cm^2, which is comparable with the standard collection area of 200 cm^2 in the typical rain gauges used in our region. A simple theoretical analysis of the device functioning was performed assuming Marshall–Palmer DSD (Marshall and Palmer 1948) and a rain rate of 100 mm h^{-1} (extreme in our region). The intensity of the drop impacts for this rain-rate value is equal to 11 632 drops per second per squared meters and it corresponds to 174 drops per second impacting the sensing plate of the DBI impactometer. Assuming that the raindrops arrive at the sensing plate according to the Poisson process (Uijlenhoet et al. 2006), the distribution of the intervals between the beginning of the impacts is exponential, with an *e*-folding time of 5.75 ms. Under these assumptions, the probability that an impact occurs when the signal oscillations from the preceding waterdrop are still significant is about 20%–30%. Therefore, the effect of "double impacts" in strong rainfall is neither negligible nor devastating. In our opinion, it can be corrected based on thorough field comparisons with accurate measurements of rainfall KE flux. A local cluster of 3–5 good-quality disdrometers can provide such reference data. However, this approach is beyond the scope of this study and will be explored in our future research.

4. Laboratory calibration setup

The DBI impactometer calibration tests were performed using the facilities at the Institute of Fundamental Technological Research of the Polish Academy of Sciences (hereafter IPPT PAN, its Polish acronym). The impactometer output was recorded for a number of single waterdrops with different known volumes and fall velocities. The drops were free-falling in still air conditions after being released at different elevations. Their velocities just before the impacts were measured using a high-speed digital video camera. This technique has already been applied to number of studies of waterdrop impact and splash (Mutchler 1967; Ghadiri and Payne 1981; Fukada and Fujiwara 1989). The IPPT PAN has extensive experience in using this technique in many fluid dynamics studies. In this study, the drop impact velocities were measured at 25 cm directly above the sensing plate of the DBI impactometer. We used the CMOS camera type "1200 hs" manufactured by PCO IMAGING. The interval between the camera frames was set to 0.8 ms, and the exposure time was set to 0.2 ms. In Fig. 3, we show the example of selected frames from the fall and impact of a waterdrop with the diameter of 3.1 mm.

The waterdrops were generated through a thin silicon pipe (adapted from a medical IV kit manufactured by Polfa Lublin, S.A.) ending with the medical needle of selected diameter. The different diameters of the needles controlled the waterdrop size. The Ascor syringe pump type "Ap 12" was used to supply distilled water to the pipe at a constant rate. The regulated outflow rate of the pump controlled the frequency of waterdrop release. The diameter of the falling drops was measured directly from the pictures taken by the abovementioned camera with fixed setting. As a reference, we used a picture of a square-grid paper sheet (with a grid size of 1 mm × 1 mm) placed along the falling route of the waterdrops. The reference-grid picture was taken at the same camera setting as for the rest of the experiment. As an independent verification of the drop diameters, they were also weighted with accurate laboratory scales. The DBI impactometer was tested for single drops falling from three different elevations: 2.34, 11.68, and 26.00 m. Tests for the 2.34-m falling height were conducted in the laboratory room in steady air conditions. The test runs for the two other elevations were performed in the interior staircase of the IPPT PAN building. The air temperature measurements made on different floors showed only small variations from 21.0° to 22.3°C, while the airflow velocities were below 0.08 m s^{-1}.

Preliminary tests of the DBI impactometer revealed that its output depends not only on the waterdrop diameter and impact velocity but also on the distance between the drop landing position and the center of the sensing plate. This aspect of the piezoelectric impactometers has been practically ignored in the published literature. To gain better insight into this dependency, we divided the sensing plate area into three concentric sectors as shown in Fig. 4. For further analysis, we selected only the drops that were impacting approximately in the middle of the three sectors. The positions of the waterdrop impacts were examined visually using the camera pictures recorded before and during the

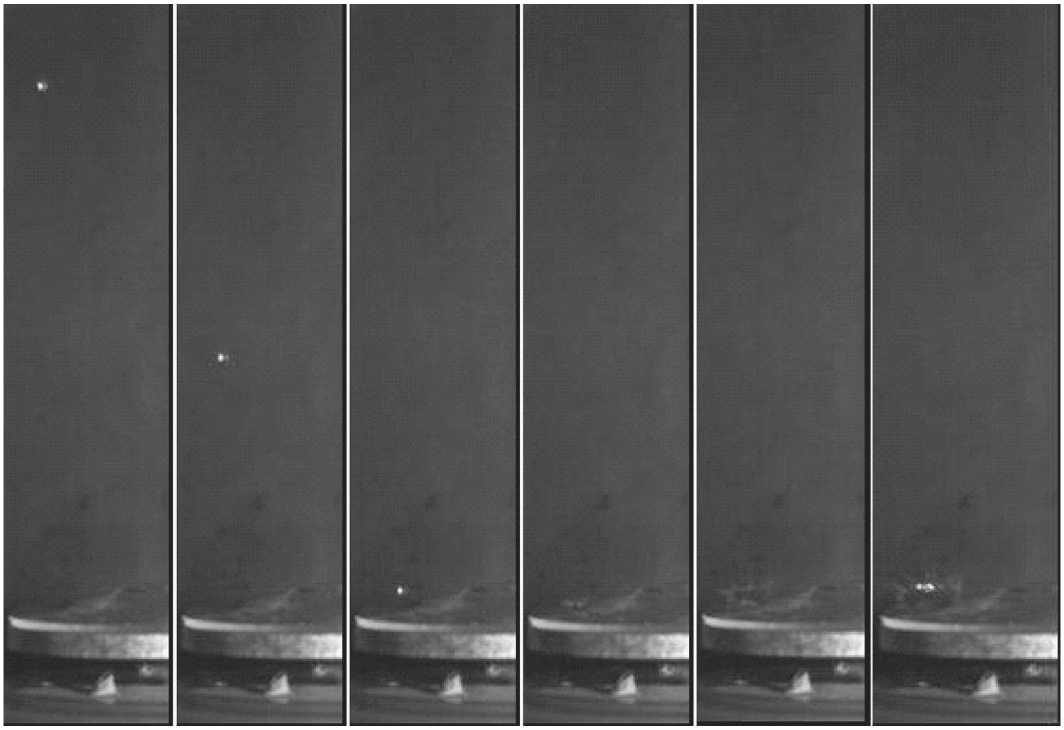

FIG. 3. Different phases of the fall of a 3.1-mm-diameter waterdrop and its impingement on the sensing plate.

impacts (see Fig. 3). A division of the impactometer sensing plate into more sensitivity sectors was impossible in this experiment because of the considerable spread of the waterdrop impact positions. It could be achieved with the help of more precisely controlled laboratory facilities, which are not available to us at present.

During each of the laboratory calibration runs (defined by the combination of fall elevation, drop diameter, and sensitivity sector), the high-speed camera pictures and the impactometer output were recorded for a period of about 2 min. This interval allowed the capture of at least 20 waterdrop impacts that were close to the middle of the sensitivity sectors (see Fig. 4). Both the integration time of the impactometer and the sampling interval of the PC data acquisition card were set to 100 ms. For different calibration runs, the averages and standard deviations of the DBI impactometer output voltage were obtained from the time series recorded by the PC. The camera-based measurements of waterdrop sizes and velocities were then used to compute the values of linear momentum M and KE of each drop.

5. Discussion of the calibration results

In the first stage of our analysis, we compared the camera-measured and the theoretical fall velocities for the waterdrops of different diameters and fall elevations. The theoretical velocities were computed using the approximate method developed by Wang and Pruppacher (1977). The results of these comparisons are presented in Table 1. Good agreement between the theoretical and measured velocities can be seen for the drops in the diameter range of 2.7–3.2 mm, falling from the elevations of 11.68 and 26.00 m. However, for the elevation of 2.34 m, the theoretical velocities are almost 2 times larger than the measured values. A complete mathematical description of this effect is unknown to us. However, the occurrence of complex oscillations in free-falling waterdrops has long been recognized (Pruppacher and Klett 1997, and references therein). We also observed strong oscillations of the waterdrop shapes in the first few meters after their release from the medical needles. As a result of these oscillations, the drag force coefficient also fluctuated strongly, thereby affecting the drop acceleration. Most likely, the free-fall of such oscillating waterdrops is not adequately treated by the method proposed in Wang and Pruppacher (1977). Especially strong and long-lasting shape oscillations were observed for the drops with largest diameters, which can explain the difference of about 40% between the theoretical and measured velocities (seen in Table 1) for the 5.3-mm drops falling from the 11.68-m elevation. The large differences between the measured and

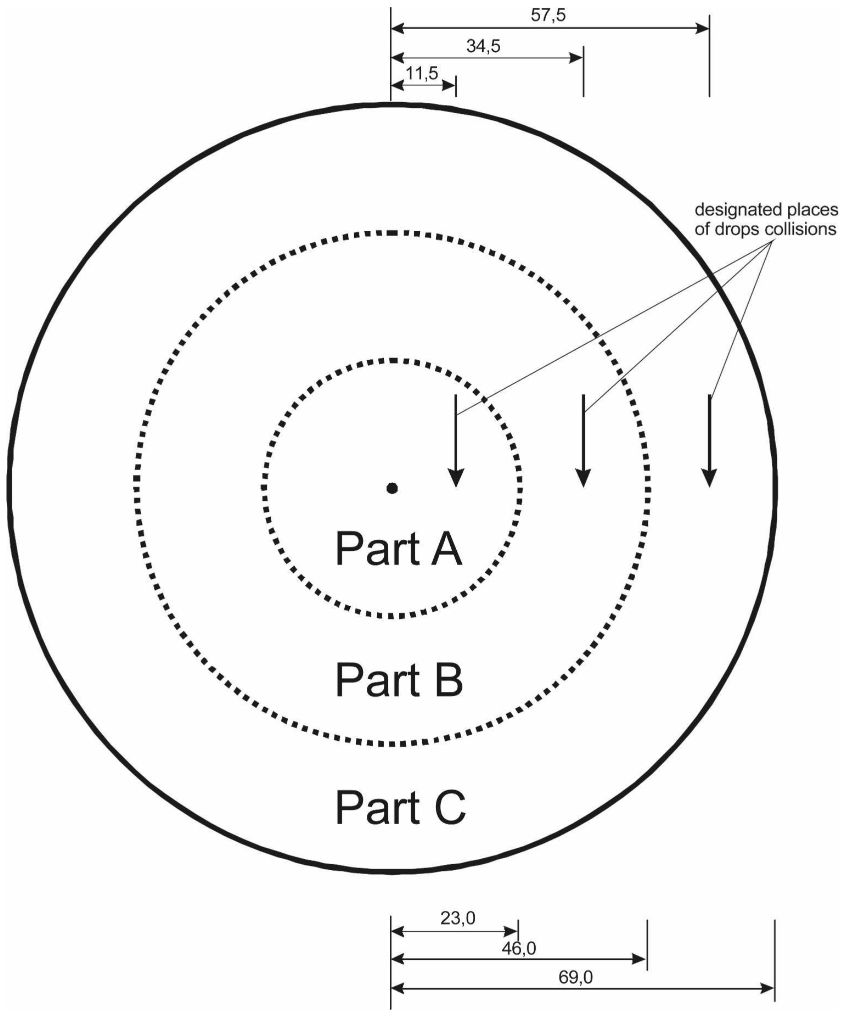

FIG. 4. Division of the impactometer sensing plate into three concentric sensitivity sectors (all dimensions are in millimeters).

TABLE 1. Measured and theoretically computed waterdrop fall velocities for different fall elevations and drop diameters.

Fall height	Drop diameter (mm)	Measured velocity (m s^{-1})	Theoretical velocity (m s^{-1})
2.34 m	5.9	3.4	6.3
	3.0	3.2	5.8
	3.1	3.2	5.9
	2.8	3.2	5.7
	3.2	3.3	6.0
11.68 m	5.3	6.4	8.9
	3.1	8.8	8.2
	3.2	8.9	8.3
26.00 m	4.8	10.5	9.1
	2.7	8	7.7
	2.9	8.7	8.0
	2.3	9.3	7.1

theoretical drop velocities presented above prove the importance of precise waterdrop impact velocity measurements for all reliable calibrations of the impactometers.

An example of the DBI impactometer output recorded during the test run for the drops with a diameter of 5.9 mm, free-falling from a height of 2.34 m and impacting at sector B of the sensing plate, is shown in Fig. 5. The interval between the single drops was close to 0.5 s and the sampling resolution is 100 ms. As stated before, the output values represent the integrals of the absolute values of the piezoelectric sensor voltage integrated over the 100 ms intervals. The total voltage output in Fig. 5 is defined as the sum of the nonzero 100 ms integrals resulting from a single drop. This total voltage was used in our further analysis as the quantity

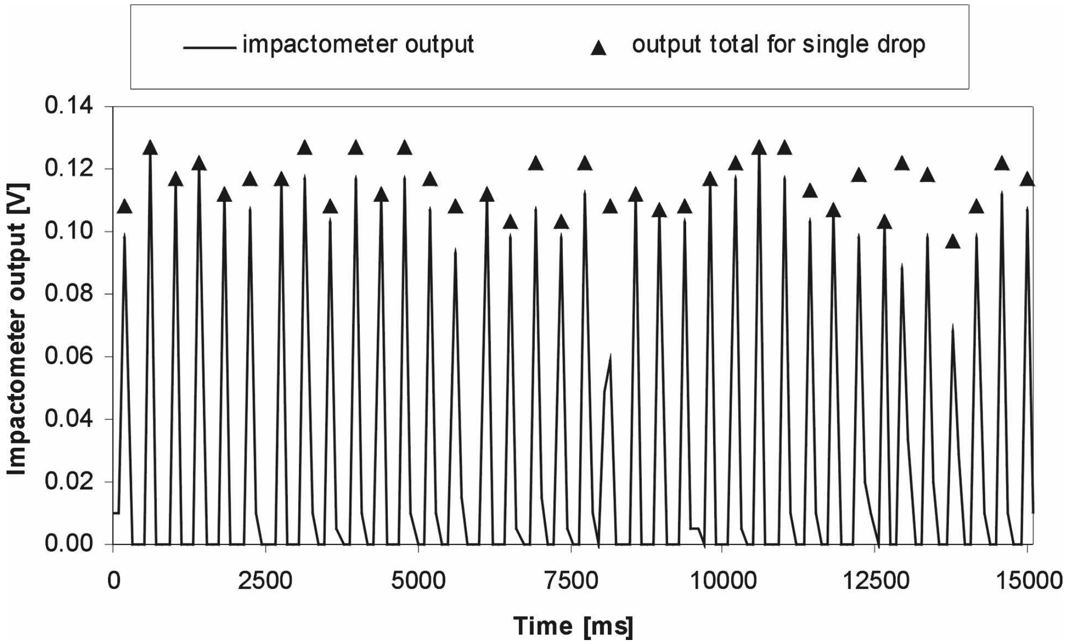

FIG. 5. The output of the DBI impactometer for a series of 5.9-mm diameter single waterdrops free-falling from an elevation of 2.34 m.

representing the impactometer responses to the waterdrop impacts. The response averages and standard deviations were computed for all of the calibration test runs (all shown in Fig. 6). For most of the runs, the response standard deviations did not exceed 10% of the average value. Only in two runs did it slightly exceed the 20% level. The first case was for drops of 2.8-mm diameter falling from a 2.34-m elevation, and the second was for drops of 3.2-mm diameter and an 11.68-m elevation. In both cases, the waterdrops were impacting sector A of the sensing plate. The variations in the impactometer responses are most likely caused by the drop oscillations and by the inevitable scatter of the impact positions, both already discussed above.

The main results of the calibration tests performed in this study are presented in Fig. 6, which shows the scatterplots of waterdrop KE and linear momentum M as functions of output total U of the DBI impactometer. The least square linear approximations of these dependences are also plotted and described in Fig. 6. The results are presented separately for each of the three sectors of the sensing plate. A visual inspection alone is enough to give the answer to the question raised in the title of this study: Do we measure drops' momentum or their kinetic energy? Based on the coefficients of determination R^2, one can state quantitatively that the impactometer output U can explain only about 83% of the variance in the linear momentum, but as much as 99.9% of the KE variance. Thus, the final output of the DBI impactometer is proportional to the KE of the impacting drops, but not to their linear momentum. This finding is in partial opposition to the results published by Battista et al. (1994a,b), although the DBI impactometer is based, in essence, on the same principles. The authors suggested that the output of their impactometer can represent both the KE and the linear momentum of the impacting waterdrops quite accurately. In our opinion, this rather questionable statement resulted from the following four inaccuracies in the Battista et al. (1994a,b) impactometer calibration procedure:

1) lack of direct measurements of the waterdrop impact velocities,
2) inaccuracies in the theoretical computations of the impact velocities,
3) cursory treatment of the effect of drop impact position on the device output, and
4) limitation of the calibration to relatively small values of drop KE and momentum.

The effect of limited output range in the calibrations can also be clearly seen in our results in Fig. 6. It shows fairly linear dependence between each of the two physical quantities and the DBI impactometer output, provided that we limit the considered output voltage to about 0.1 V. Beyond this range, only the values of waterdrop KE remain proportional to the instrument responses.

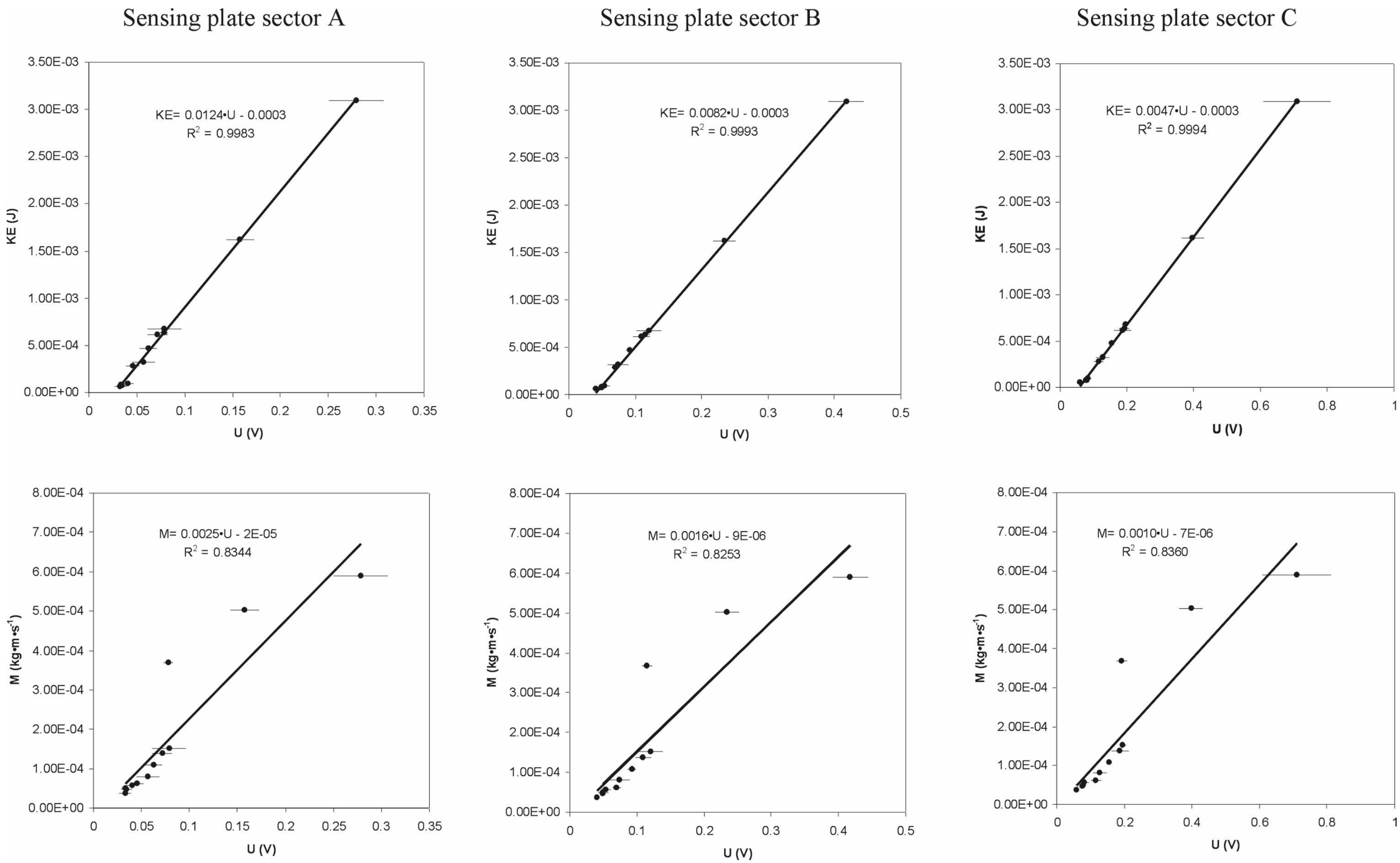

FIG. 6. Scatterplots of the KE and the linear momentum of waterdrops as functions of the impactometer output U for the three sensing plate sectors. The points show the averages of the impactometer voltage and the horizontal bars show its standard deviations. Least squares linear fits are also plotted and described.

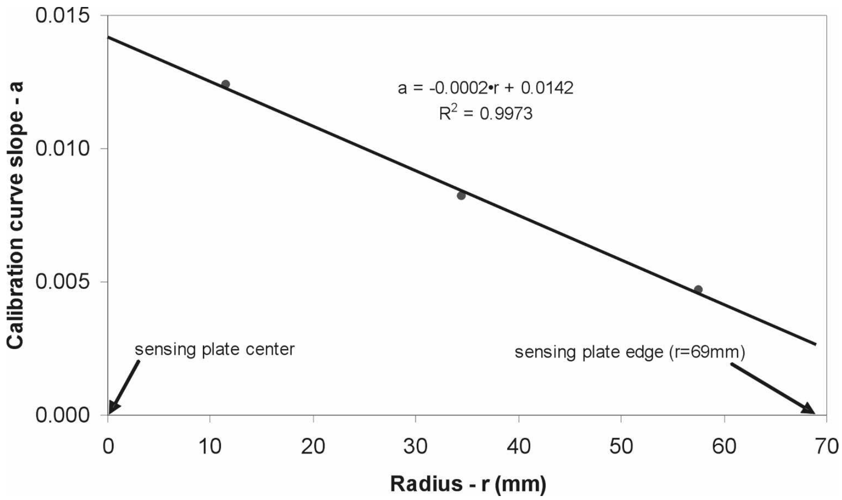

FIG. 7. The slope of the drop KE and impactometer voltage linear relationship as a function of the distance from the sensing plate center.

The effect of the distance between the waterdrop impact position and the center of the sensing plate on the impactometer output is also visible in Fig. 6. The intercepts of the least square lines fitted for the KE versus U relationships are equal to -0.0003 for each sector of the sensing plate. However, their slopes depend strongly on the sector, and are the highest for sector A, and almost 3 times lower for sector C. Figure 7 shows that the slopes of the KE versus U lines depend linearly on the distance between the impact position and the sensing plate center. As a consequence, for waterdrops with fixed KE values, the DBI impactometer output is proportional to this distance. It is in agreement with the intuitive guess that the deformation of the piezoelectric sensor attached to the center of the sensing plate is a linear function of both the force exerted by a drop in the impact spot and the acting arm of the force. Förster et al. (2004) analyzed the related effects of impact position in the much more complicated case of a spherical ceramic sensor.

6. Taking the DBI impactometer into the field

Based on Fig. 7, the slopes a for waterdrop KE of the impactometer sector-specific calibration lines in Fig. 6 can be described as a linear function of the distance r (mm) from the sensing plate center as follows:

$$a(r) = -0.0002r + 0.0142. \tag{5}$$

It can be assumed that in natural rainfall the positions of the impacting raindrops are uniformly distributed over the impactometer sensing plate. Thus, the average slope of the impactometer calibration line for KE, represented as a_{avr}, can be estimated as

$$a_{\text{avr}} = \frac{\int_0^{r_c} a(r)\,dA}{A_{\text{tot}}}, \tag{6}$$

where r_c is the sensing plate radius (69 mm, in our case), dA is the areal contribution at distance r, and A_{tot} is the total area of the sensing plate (14 957 mm^2, in our case). Based on the simple circular geometry of the sensing plate,

$$dA = 2\pi r\,\text{dr}, \tag{7}$$

$$A_{\text{tot}} = \pi r_c^2. \tag{8}$$

After substitution of (5), (7), and (8) into expression (6), one obtains

$$a_{\text{avr}} = \frac{2\pi \int_0^{r_c} (-0.0002r + 0.0142)r\,dr}{\pi r_c^2} = 0.0050. \tag{9}$$

Finally, during field measurements based on the DBI impactometer, the rainfall KE flux can be obtained from the impactometer output using the expression

$$\text{KEF} = 0.0050\,U - 0.0003, \tag{10}$$

where KEF is the KE flux in J m^{-2} s^{-1} and U is the impactometer output in volts.

As mentioned before within this study, we could not validate this expression using side-by-side field comparisons of the DBI impactometer with good-quality optical disdrometers because of their prohibitive cost. However, the general performance of the instrument in field conditions was tested during the campaign in 2004.

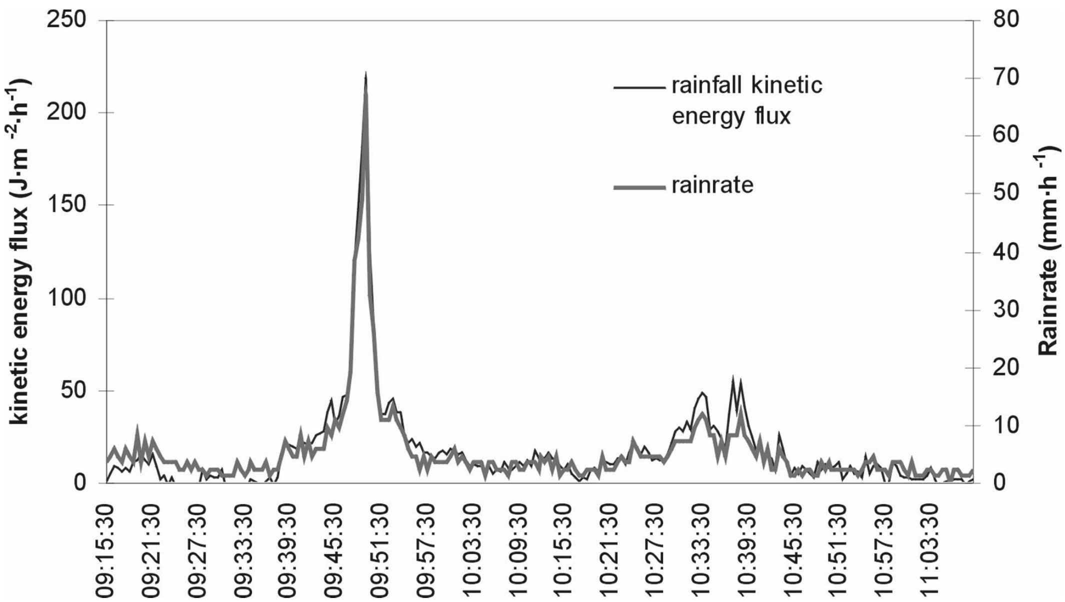

FIG. 8. An example time series of the rainfall KE flux and intensity recorded on 9 Jul 2004.

The DBI impactometer was installed close to an accurate electronic weighing-type rain gauge. Both instruments were connected to the same data acquisition board in a PC in order to have fully synchronized readings. The measurements of KE flux and rainfall intensities were recorded for 30-s averaging intervals. An example of the results obtained for an event including strong rain rates is shown in Fig. 8. Although not exactly equivalent, both time series are obviously closely related to each other. This can be treated as qualitative confirmation that the DBI impactometer performs well in field conditions. Large datasets of such concurrent measurements can be used to develop local relationships between KE flux and intensity of rainfall, as discussed in Salles et al. (2002).

7. Conclusions

The calibration tests of the DBI impactometer described herein demonstrate that the processing of the piezoelectric sensor signal (consisting of integrating its absolute values over fixed time intervals) results in relatively accurate measurements of the KE of impacting waterdrops. After simple accounting for the impact position effect described above, the impactometer can be used as a low-cost instrument for field measurements of the KE flux in rainfall.

Using an accurate waterdrop fall velocity measuring technique, such as the high-speed camera that we used, is of crucial importance for obtaining accurate laboratory calibration results. Theoretical computation of the drop fall velocity has to be based on strong assumptions and is often far from reality. It is especially true for drops falling from low elevations and having velocities much lower than their terminal velocities in still air. Strong oscillations of the waterdrops can have a profound effect on the drop fall in the first few meters. This most likely explains the observed differences between the measured and theoretically computed drop velocities.

The DBI impactometer was not capable of measuring the linear momentum of waterdrops. The simple signal processing of a piezoelectric sensor output consisting of the integration of its absolute value can only provide information about the drop KE. Most likely, accurately measuring drop momentum with a piezoelectric force sensor requires limiting the integration of the signal to the impact duration (about 200–300 μs). Technically, it can only be achieved with much higher signal sampling frequencies and much faster microprocessors. Even using such techniques, the accurate identification of impact beginning and end times is not a trivial problem and demands using advanced algorithms (e.g., Henson et al. 2004).

The DBI impactometer has a sensing plate area of about 150 cm^2, which is approximately 3 times larger than the sensing areas of typical disdrometers (about 50 cm^2). This limits to a degree the undersampling problems arising from the small sensing areas of the instruments (Smith et al. 1993; Jameson and Kostinski 2002). On the other hand, it causes additional problems because of the higher probability of simultaneous waterdrop impacts. These two opposing problems can be overcome by using multiple KE sensors with smaller sensing plate areas in each measurement point. The unique data samples collected this way can advance the systematic studies of the spatiotemporal characteristics of rainfall KE in different locations and precipitation regimes.

Acknowledgments. The major support for this research was provided by the Polish State Committee for Scientific Research (KBN Grant 5P06302324). Dr. Grzegorz Ciach was supported by the NSF Grant EAR-0309644. The authors thank Jacek Kawecki for his technical assistance in the DBI impactometer realization. Encouraging comments of Prof. Szymon Malinowski and Prof. Tomasz Kowalewski are also gratefully appreciated. Finally, Dr. Paweł Licznar wishes to thank the Foundation for Polish Science (FNP) for financial support of his research and scientific development and to recognize the help of the Cessar (Center of Excellence in Small Scale Atmospheric Research) program at the Institute of Geophysics of the Warsaw University.

REFERENCES

Battista, P., F. Benincasa, P. Duce, and A. Materassi, 1994a: Design and construction of a microprocessor impactometer. *Proc. Conf. on Land Use and Soil Degradation: MEDALUS in Sardinia,* Sassari, Italy, University of Sassari, 169–180.

——, ——, and A. Materassi, 1994b: Progetto e realizzazione di un impattometro a microprocessore. *Riv. Ing. Agr.,* **25** (1), 27–33.

Eigenbrodt, 2007: Catalog: Meteorological sensors. 18 pp. [Available from Eigenbrodt GmbH & Co. KG Baurat-Wiese-Str. 68, D-21255, Königsmoor, Germany.]

Foltz, R. B., C. H. Luce, and P. H. Stockton, 1995: The KE field under a rainfall simulator. *Proc. Watershed Management Planning for the 21st Century,* San Antonio, TX, Committee on the Water Resources Engineering Division/ASCE, 388–397.

Förster, J., G. Gust, and S. Stolte, 2004: A piezoelectrical rain gauge for application on buoys. *J. Atmos. Oceanic Technol.,* **21,** 179–193.

Fukada, M., and T. Fujiwara, 1989: Photographic analysis on the impact of raindrop on the water's surface. *Trans. JSIDRE,* **143,** 21–29.

Ghadiri, H., and D. Payne, 1981: Raindrop impact stress. *Eur. J. Soil Sci.,* **32,** 41–49.

Guzel, H., and A. Barros, 2001: Using acoustic emission testing to monitor kinetic energy of raindrop and rainsplash erosion. *Proc. Int. Symp. on Soil Erosion for the 21st Century,* Honolulu, HI, American Society of Agricultural and Biological Engineers, 525–528.

Henson, W., G. Austin, and H. Oudenhoven, 2004: Development of an inexpensive raindrop size spectrometer. *J. Atmos. Oceanic Technol.,* **21,** 1710–1717.

Jameson, A. R., and A. B. Kostinski, 2002: Spurious power-law relations among rainfall and radar parameters. *Quart. J. Roy. Meteor. Soc.,* **128,** 2045–2058.

Joss, J., and A. Waldvogel, 1967: A raindrop spectrograph with automatic analysis. *Pure Appl. Geophys.,* **68,** 240–246.

Kinnell, P. I. A., 1976: Some observations on the Joss–Waldvogel rainfall disdrometer. *J. Appl. Meteor.,* **15,** 499–502.

——, 1977: Reply. *J. Appl. Meteor.,* **16,** 113–114.

Kourtellis, A. G., T. Kasparis, L. Jones, and J. Lane, 2005: Disdrometer calibration using an adaptive signal processing algorithm. *Proc. Oceans 2005,* Washington, DC, MTS/IEEE, 2572–2577.

Krajewski, W. F., and Coauthors, 2006: DEVEX-disdrometer evaluation experiment: Basis results and implications for hydrologic studies. *Adv. Water Res.,* **29,** 311–325.

Löffler-Mang, M., M. Kunz, and W. Schmid, 1999: On the performance of a low-cost K-band Doppler radar for quantitative rain measurements. *J. Atmos. Oceanic Technol.,* **16,** 379–387.

Madden, L. V., L. L. Wilson, and N. Ntahimpera, 1998: Calibration and evaluation of an electronic sensor for rainfall kinetic energy. *Phytopathology,* **88** (9), 950–959.

Marshall, J. S., and W. M. Palmer, 1948: The distribution of raindrops with size. *J. Meteor.,* **5,** 165–166.

Mutchler, C. K., 1967: Parameters for describing raindrop splash. *J. Soil Water Conserv.,* **22** (3), 91–94.

Nearing, M. A., J. M. Bradford, and R. D. Holtz, 1986: Measurement of force vs. time relations for waterdrop impact. *Soil Sci. Soc. Amer. J.,* **50,** 1532–1536.

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

PCB Piezotronics, 1999: Force sensor catalog: Piezoelectric sensors for dynamic force measurements. 78 pp. [Available from PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043-2495.]

——, 2000: General operation manual: Model 208C01 ICP force sensor. 8 pp. [Available from PCB Piezotronics, Inc., 3425 Walden Avenue, Depew, NY 14043-2495.]

Pruppacher, H. R., and J. D. Klett, 1997: *Microphysics of Clouds and Precipitation*. Kluwer Academic, 976 pp.

Salles, C., and J. D. Creutin, 2003: Instrumental uncertainties in *Z–R* relationships and raindrop fall velocities. *J. Appl. Meteor.,* **42,** 279–290.

——, J. Poesen, and D. Sempere-Torres, 2002: Kinetic energy of rain and its functional relationship with intensity. *J. Hydrol.,* **257,** 256–270.

Smith, P. L., Z. Liu, and J. Joss, 1993: A study of sampling-variability effects in raindrop size observations. *J. Appl. Meteor.,* **32,** 1259–1269.

Tokay, A., R. Wolff, P. Bashor, and O. K. Dursun, 2003: On the measurement errors of the Joss–Waldvogel disdrometer. Preprints, *31st Int. Conf. on Radar Meteorology,* Seattle, WA, Amer. Meteor. Soc., P3A.2. [Available online at http://ams.confex.com/ams/pdfpapers/64350.pdf.]

Uijlenhoet, R., J. M. Porrà, D. Sempere-Torres, and J. D. Creutin, 2006: Analytical solutions to sampling effects in drop size distribution measurements during stationary rainfall: Estimation of bulk rainfall variables. *J. Hydrol.,* **328,** 65–82.

Wang, P. K., and H. R. Pruppacher, 1977: Acceleration to terminal velocity of cloud and raindrops. *J. Appl. Meteor.,* **16,** 275–280.

Wischmeier, W. H., and D. D. Smith, 1978: Predicting rainfall erosion losses: A guide to conservation planning. Agricultural Handbook 537, U.S. Dept. of Agriculture, 58 pp.