PIEZOELECTRIC VAISALA RAINCAP® RAIN SENSOR APPLIED TO DROP SIZE DISTRIBUTION MONITORING

Atte Salmi, Lasse Elomaa, Panu Kopsala and Emmi Laukkanen
Vaisala Oyj, Helsinki, Finland
P.O.Box 26, FIN-00421 Helsinki, Finland
Tel. +358 9 8949 2785, Fax. +358 9 8949 2987
e-mail: atte.salmi@vaisala.com

ABSTRACT

Drop size distribution (DSD) is important parameter for adjustment of radar measurement of precipitation. Usually, a network of several disdrometers is needed to fulfil the requirements. Instruments in the market are expensive and need regular maintenance. There is, therefore, a strong need to develop a low cost disdrometer with enough performance for the purpose.

In this paper the potential of a piezoelectric instrument based on the maintenance-free Vaisala RAINCAP® Rain Sensor was inspected for monitoring drop size distribution of rain in a laboratory.

1. INTRODUCTION

Radar-based rainfall rate measurement *R* is the measurement of radar reflectivity *Z* by the well known *Z* - *R* relation. Since, the relationship depends on the drop size distribution (DSD) there has been a growing interest in adjusting radar derived precipitation estimates by measuring DSD at the surface. Due to the phenomena of radar measurement and rainfall spatial distribution, a network of several point measurements would be needed to determine statistically adequate corrections. Very often, the high price and substantial maintenance needs of disdrometers have led to single point measurement instead of several point measurement in radar reflectivity adjustments.

In this paper we present a principle of disdrometer, based on piezoelectric Vaisala RAINCAP® Rain Sensor, presented earlier by Salmi and Ikonen (2005). The instrument is in the technology development phase, and some development versions are already under field test. Recently, Pohjola *et al*. (2008) published radar reflectivities derived from DSD data achieved using the Vaisala instrument and the Joss-Waldvogel disdrometer in various rain events.

Disdrometers based on acoustic or electromechanical detection of individual raindrops have been developed in the past. (Mikhaylovskaya, 1964; Joss and Waldvogel, 1967; Kinnell, 1972). Nystuen *et al*. (1994) have reported on a piezoelectric device, called APL disdrometer and compared it with the Joss-Waldvogel disdrometer. Jayawardena and Rezaur (2000) measured DSD utilizing a piezoelectric force sensor. Lane *et al*. (2006) reported on a piezoelectric transducer designed for hail size distribution measurement in the vicinity of space shuttle launch pads.

2. PIEZOELECTRIC VAISALA RAINCAP® SENSOR

2.1 Construction of the sensor

When Vaisala RAINCAP® rain sensor was developed, in conjunction with a Vaisala Weather multi-sensor, WXT510 Weather Transmitter, the original aim of the design was to make a robust sensor with negligible maintenance needs. These requirements led to a very simple design without any moving parts. The construction of the sensor is shown in Fig 1. The sensor cover made of stainless steel is attached to the sensor frame and a piezoelectric detector has been mounted on its underside. The voltage pulses delivered by the piezoelectric element are filtered, amplified, digitized, and finally analyzed as to their selected parameters in relation to the raindrop size. Final computations are performed by the micro-processor system.

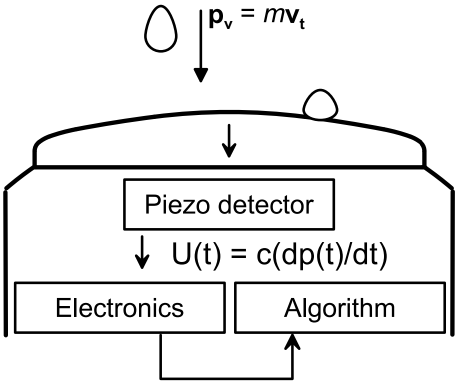

Fig. 1. A schematic drawing of the Vaisala RAINCAP® sensor.

The material and dimensions of the detector cover were selected such that the resonant vibration excited by the impacting raindrop is attenuated rapidly. The sensor surface area was determined by compromising between two opposite specifications:

a) The larger the sensor surface area the smaller the statistical variation in the computed value of cumulative rainfall.

b) On the other hand, the larger the sensor surface area the greater the number of simultaneous raindrop impacts, which leads to inaccuracy in the interpretation of the measured signals.

A good compromise for the diameter of the sensor surface was found to be about 90 mm (Salmi and Ikonen, 2005).

2.2 Measurement principle

The measurement principle of the sensor is based on the acoustic detection of individual raindrop impacts. The drop impact generates elastic waves to the sensor plate, and further on to the piezoelectric sensor. The resulting mechanical stresses in the piezoelectric material causes a voltage between the sensor electrodes. Due to the well known dependence between terminal velocity and mass of the drop, the drop size can be calculated from the relation

$$U(t) = c\frac{dp_v(t)}{d(t)} = cm\frac{dv_t(t)}{d(t)}, \tag{1}$$

where U is the voltage, $dp_v(t)/dt$ is the time varying vertical force component, m is a mass of the drop, c is the constant dependent on the properties of the piezoelectric material, and v_t is the terminal velocity of the drop.

2.3 Sensor calibration

The sensor voltage response was calibrated at Vaisala Rain Laboratory by dropping water drops of known size to the sensor surface. Since, the physical process behind the raindrop impact is a function of drop size, shape and impacting velocity. It was important to verify the functionality of the laboratory before beginning the calibration measurements. The verification included the determination of fall velocity and the shape of falling raindrops in the laboratory. The work was reported by Salmi and Elomaa (2007).

2.4 Sensor output

The instrument divides the measured data into eight drop-size classes and normalizes the drop diameters with a weighted equivalent drop diameter. As an example, all data in the class 1.795-2.244 mm are normalized to 2.0 mm in the number of drops. Therefore, the number of drops in a class can be expressed with a decimal point. The eight drop-size classes are shown in Table 1.

Size class	Weighted diameter [mm]	Range [mm]
1	1.00	- 1.122
2	1.25	1.122 - 1.403
3	1.60	1.403 - 1.795
4	2.00	1.795 - 2.244
5	2.50	2.244 - 2.895
6	3.20	2.896 - 3.591
7	4.00	3.591 - 4.489
8	5.00	4.489 -

Table 1. Eight drop-size classes and their corresponding weighted diameters and size ranges.

3. EXPERIMENTAL ARRANGEMENTS

3.1 Vaisala Rain Laboratory

A schematic diagram of the Vaisala Rain Laboratory is shown in Fig. 2. It is constructed of a cylindrical steel shaft, of diameter of 1m and a height of 14m, which can be accessed at the top and the bottom. The drop generator (Fig. 3) is located at the top of the shaft. The intensity of simulated rain is controlled by the depth of the water in the reservoir. The water drops are produced by syringe needles that pierce the base of the reservoir. A parallel beam linear sensor (Omron Z4LB-V2) measures the drop velocity and shape at the bottom of the shaft . All the drops are also weighed with an accurate scale (Sartorius CP224S) immediately after they pass through the parallel laser beams.

The parallel beam linear sensor consists of two parallel laser beams and a prism, shown in Fig. 4. The beam width is 30mm and wave length 650nm. The received optical signal is amplified and fed to the A/D converter. The converted voltage signal is directly proportional to the area of the laser beam intercepted by the raindrops. Every drop falls through both beams producing two sequential voltage signals. By comparing the resulting signal pairs, we ensure that no acceleration has occurred. From the time difference, Δt, between the peak values of the voltage signals, speed of the drop can be calculated.

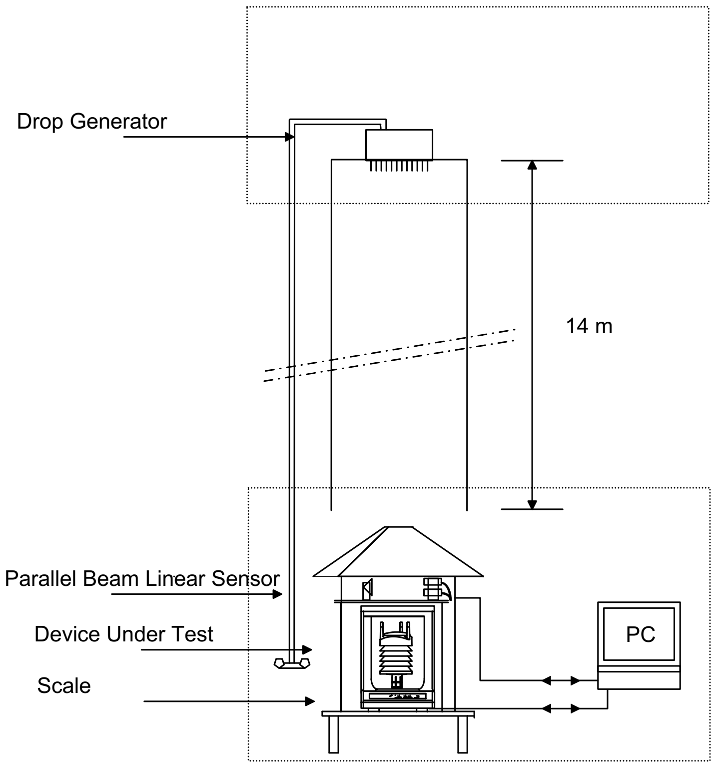

Fig. 2. A schematic diagram of the Vaisala Rain Laboratory

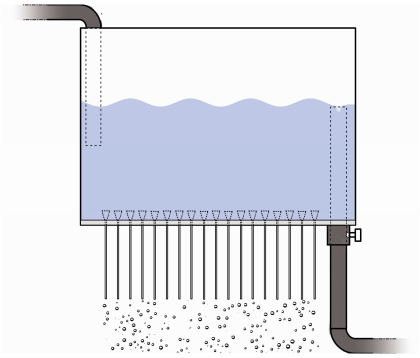

Fig. 3. The water reservoir, at the top of the rain laboratory shaft, with a set of syringe needles as the source of raindrops. The intensity of the rain is relative to the depth of the water in the resrvoir.

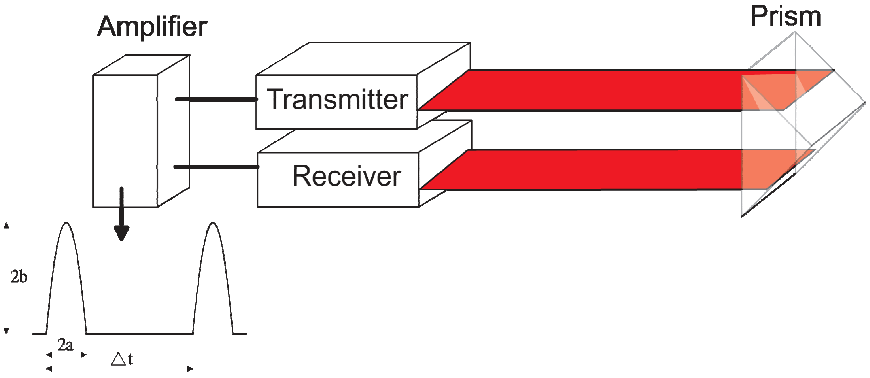

Fig. 4. A schematic diagram of the parallel beam linear sensor.

3.2 Drop size measurement

WXT510 Weather Transmitter was mounted at the bottom of the shaft as shown in Fig. 2. The sizes of the drops hit on the Vaisala RAINCAP® sensor were determined measuring drop terminal velocity with a parallel beam linear sensor, and known correlation between the terminal velocity, v_t [m/s] and the drop size D [mm], determined by Salmi and Elomaa (2007):

$$v_t(D) = 9.4\left[1-\exp\left(-0.556D^{1.13}\right)\right].$$

The experiments presented in this paper included drop sizes 2.1 mm, 3.0 mm and 4.0 mm. The measurement data from the WXT510 were transmitted to and stored on a computer.

4 RESULTS AND DISCUSSION

The Table 2. shows median value of terminal velocity, measured with parallel beam linear sensor and standard deviation of three measurement instances. From which we have calculated drop sizes and compared them against median values of measured drop size. Also standard deviation of measured drop size is shown. All data values contain about 2000 individual measurements.

Velocity measured [m/s]		**Diameter calculated [mm]**		**Diameter measured [mm]**	
v(median)	v(std)	D	D(std)	D(median)	D(std)
6.7808	0.1116	2.09	0.03	2.09	0.3906
8.0406	0.0572	3.01	0.03	2.99	0.8374
8.7417	0.0498	3.99	0.055	3.97	1.2882

Table 2. Calculated drop sizes compared against measured drop sizes.

Good comparability is quite clear between the calculated and measured drop sizes. However, the standard deviation of measured data is significant. This reflects very well the characteristic behavior of the instrument namely: sensitivity variations over the sensor area (due to surface wetness and construction of the sensor itself), and the production of stochastic error (seen particularly in the short integration time). The standard deviation in measured drop size data increases when drop size increases. That can be explained by the less sensitive verges of the sensor. The verges of the sensor become reactive with the increase in drop size, giving 20 % of signal magnitude of that detected on the middle of the sensor.

Fig. 5. illustrates a typical example of a histogram, with drops sizes in the range of 2.98 - 3.04mm. 47.8% of the drops fall in to the size class 6 ranging from 2.896mm to 3.591mm. Anyway, 19.5% of drops are in size class 5 (2.244mm-2.895mm) and 14.2% of drops are in size class 7 (3.591mm-4.489mm). This can be also explained by sensitivity variations of the sensor. The median value of the data is still 2.99mm, even the standard deviation is high.

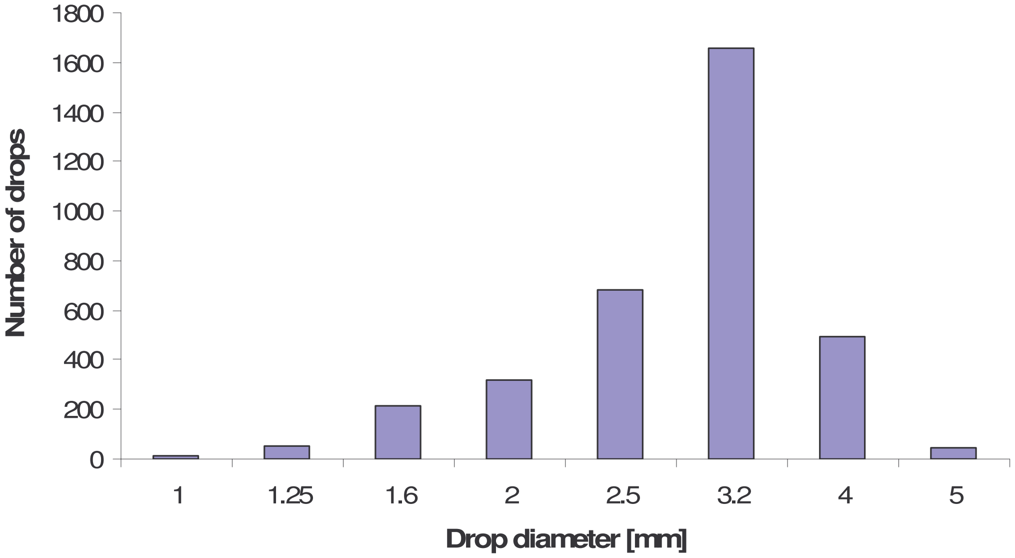

Fig. 5. A typical example of measured DSD with drops ranging from 2.98-3.04mm in size.

5 CONCLUSIONS

The Vaisala RAINCAP® Rain Sensor was developed to measure rain amount and rain intensity. When these parameters are measured, the sensitivity variations characteristic to the sensor are not of great importance since the accumulation is integrated over the sensor area. The integration time is rarely so short that spatial variation in sensitivity has an effect.

In this study, we concentrated on ability to measure drop size with the Vaisala RAINCAP® sensor. Basically, the determination of drop size approaches the rain amount measurement on a very small scale. Therefore, we had possibility to carry out DSD measurements in small software modifications without altering the sensor hardware at all. Since the instrument was calibrated in the laboratory where DSD measurements were done, this paper presents also the quality of calibration.

Applying the technology used in the Vaisala RAINCAP® Rain Sensor, we have a great possibility of developing an affordable disdrometer with negligible maintenance. Further study is still needed to clarify the ability to adjust Z - R relation in radar application.

REFERENCES

Jayawardena, A. W., and R. B. Rezaur, 2000: Measuring drop size distribution and kinetic energy of rainfall using a force transducer. *Hydrol. Process.* **14**, 37-49.

Joss, J., and A. Waldvogel, 1967: Ein spektrograph fuer niederschlagstropfen mit automatischer auswertung. *Pure Appl. Geophys.*, **68**, 240-246.

Joss, J., and A. Waldvogel, 1977: Comments on "Some observations on the Joss-Waldvogel rainfall disdrometer". *J. Appl. Meteor.*, **16**, 112-113.

Kinnell, P. I. A., 1972: The acoustic measurement of water-drop impacts. *J. Appl. Meteor.*, **11**, 691-694.

Lane, J. E., R. C. Youngquist, W. D. Haskell, and R. B. Cox, 2006: A hail size distribution impact transducer. *J. Acoust. Soc. Am.*, **119**, 47-53.

Mikhaylovskaya, V. V., 1964: Theory of measuring the size of raindrops by acoustic method. *Sov. Hydrol. Selected Papers*, No. 1, 85-90.

Nystuen, J. A., J. R. Proni, C. A. Lauter, Jr., J. Bufkin, U. Rivero, M. Borland, and J. Wilkerson, 1994: APL disdrometer evaluation. NOAA Technical Memorandum ERL AOML-83, Atlantic Oceanographic and Meteorological Laboratory, Miami.

Pohjola, H., L. Konkola, M. Hoikkanen, and D. M. Schultz, 2008: Adjusting radar-derived QPE with measured drop-size distributions at the surface. *The Fifth European Conference on Radar in Meteorology and Hydrology*, Helsinki, Finland.

Salmi, A., and L. Elomaa, 2007: Measurements of the Terminal Velocity and Shape of Falling Raindrops at Vaisala Rain Laboratory. *8th European Conference on Application of Meteorology (ECAM)*, San Lorenzo de El Escorial, Spain.

Salmi, A., and J. Ikonen, 2005: New piezoelectric Vaisala RAINCAP® precipitation sensor. *19th Conf. of Hydrology*, San Diego, Amer. Meteor. Soc., P2.6.