PIEZOELECTRIC PRECIPITATION SENSOR FROM VAISALA

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ABSTRACT

The new piezoelectric Vaisala RAINCAP® precipitation sensor and measurement method are presented. Unlike commonly used precipitation instruments the Vaisala RAINCAP® precipitation sensor is virtually maintenance free; without any moving parts or components needing emptying and cleaning.

Empirical results from Finnish Meteorological Institute test field in Finland and Vaisala test fields in Malaysia and Finland are presented and compared to the traditional tipping-bucket and weighing gauges. It is shown that the Vaisala RAINCAP® precipitation sensor performs especially well in moderate to heavy precipitation, and due to the measurement method is free from the typical sources of error in precipitation measurements.

1. INTRODUCTION

The Vaisala RAINCAP® precipitation sensor was developed in conjunction with a Vaisala weather multi-sensor, WXT510 Weather Transmitter. Requirements like robustness and negligible need for maintenance were mandatory. Therefore, the sensor described in this paper provides practically maintenance free precipitation measurement without any moving parts or components needing emptying and cleaning.

Precipitation instruments based on acoustic or electromechanical detection of individual raindrops have been developed in the past. However, most of them have been designed for measuring the drop size and drop size distribution (Mikhaylovskaya, 1964; Joss and Waldvogel, 1967; Kinnell, 1972; Nystuen et al., 1994).

Madden *et al*. (1998) have reported on a piezoelectric device for measuring the kinetic energy of raindrops. Also, a report on the piezoelectric rain gauge for application on buoys has been published lately by Förster *et al*. (2004).

The Vaisala RAINCAP® sensor, presented earlier by Salmi and Ikonen (2005), is based on acoustic detection of individual raindrop impacts. The signals resulting from the impacts are proportional to the volume of the drops and therefore, the signal of each drop can be directly converted to accumulated precipitation. The sensor is also capable of distinguishing hail stones from raindrops.

This paper presents the principle of the sensor and the measurement method. Field test results compared to the traditional precipitation gauges are reported from Finland and Malaysia.

2. PIEZOELECTRIC PRECIPITATION SENSOR

2.1 Construction

A schematic diagram 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 related to the raindrop size. Final computations are performed by the micro-processor system.
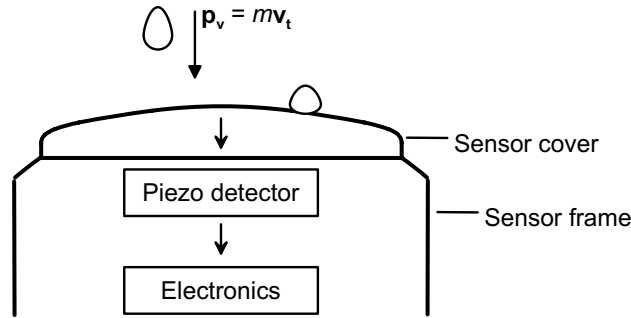
Fig. 1. A schematic drawing of the piezoelectric precipitation sensor.

The material and dimensions of the detector cover are 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.

2.2 Measurement method

A schematic diagram of the acoustic measurement method is shown in Fig. 1. The drop hitting on the sensor surface has a momentum

$$\mathbf{p} = \mathbf{p}_v + \mathbf{p}_h \, , \tag{1}$$

where $\mathbf{p}_v$ and $\mathbf{p}_h$ are vertical and horizontal momentum components. The vertical momentum can be written in the form

$$\mathbf{p}_v = m\mathbf{v}_v = m(\mathbf{v}_t + \mathbf{v}_{wv}) \, , \tag{2}$$

where m is the mass of the drop, $\mathbf{v}_t$ the terminal velocity of the drop and $\mathbf{v}_{wv}$ the vertical wind velocity. However, it has been analyzed earlier by Joss and Waldvogel (1977) that updrafts and downdrafts have negligible effect on vertical velocity and we can approximate the vertical momentum just prior to impact as

$$\mathbf{p}_v = m\mathbf{v}_t \ . \tag{3}$$

The horizontal wind velocity $\mathbf{v}_{wh}$ generates the horizontal momentum

$$\mathbf{p}_h = m\mathbf{v}_{wh} \tag{4}$$

and changes the angle of the drop impact. Due to the fact that the drop impact phenomenon is different between oblique and normal impacts, $\mathbf{v}_{wh}$ has a reducing effect on the vertical momentum component. Although this has only a small influence on the measurement, compensation has been done with the curvature of the sensor cover so that part of the horizontal momentum is also measured during oblique impacts.

The drop impact generates elastic waves to the sensor plate, which are transferred further to the piezoelectric sensor. The resulting mechanical stress in the piezoelectric material causes a voltage $U(t)$ to appear between the sensor electrodes and it can be written in the form

$$U(t) = c\frac{dp(t)}{dt} , \tag{5}$$

where c is a constant dependent on the properties of the piezoelectric material. Hence, the output of the sensor is a measure of the time-varying impact force $dp(t)/dt$, which is a function of the volume of the impacting drop. Since, the sensor surface area is known, the drop signals can be directly converted to accumulated precipitation.

The distinguishing of hailstones from raindrops is based on the fact that the detector signals they produce are very different from each other. The impact of a solid object, such as a hail, on the detector surface is bouncy, whereby firstly the pulse rise time is faster and, secondly, the pulse amplitude is higher than in a pulse generated by a raindrop. The third difference is found in that the hail impact also excites the resonant frequencies of the detector cover, whereupon the cover vibrates after the impact. Typical signal from a rain drop impact at sensor output is shown in Fig. 2. Typical output pulse generated by a hailstone is shown in Fig. 3.
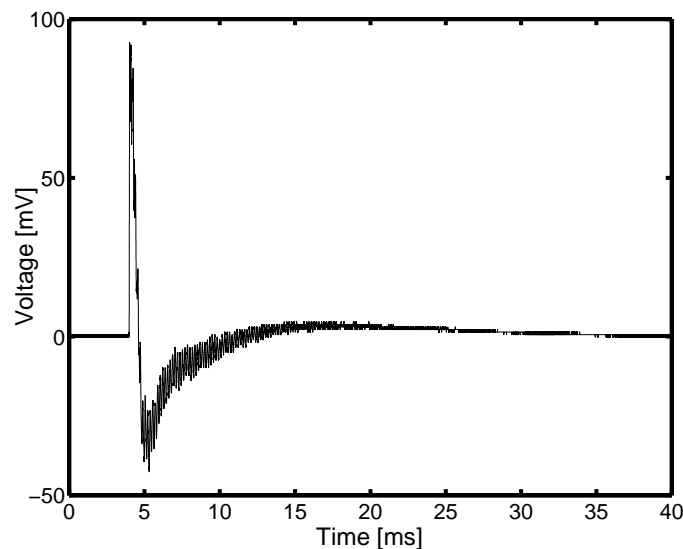

Fig. 2. Typical output signal generated by a rain drop.

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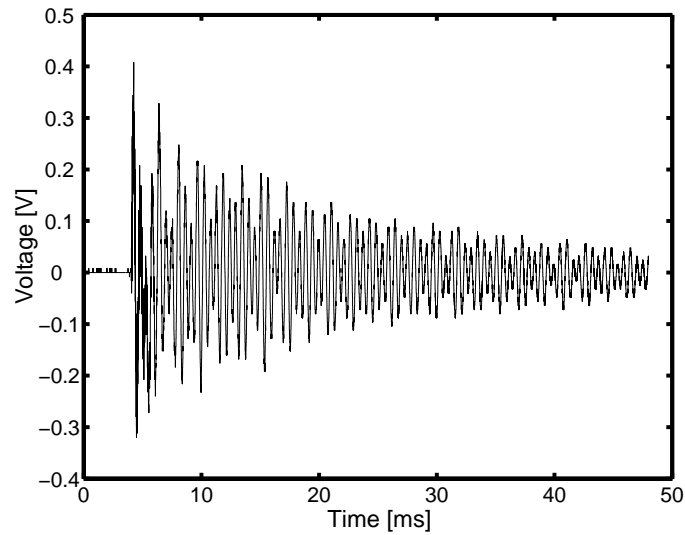
Fig. 3. Typical output signal generated by a hailstone.

2.3 Sensor calibration

The sensor calibration was done by comparing the detector voltage response with precipitation readings from accurate reference instruments under different field conditions. The data consisted large amount of measurements in light and moderate rain in Finland and moderate and heavy rain in Malaysia. The resulting calibration algorithm was verified in the laboratory by using different drop sizes and intensities. A fall distance of 14 m was achieved in the Vaisala rain laboratory. An example of such calibration data from the field is shown in Fig. 4.
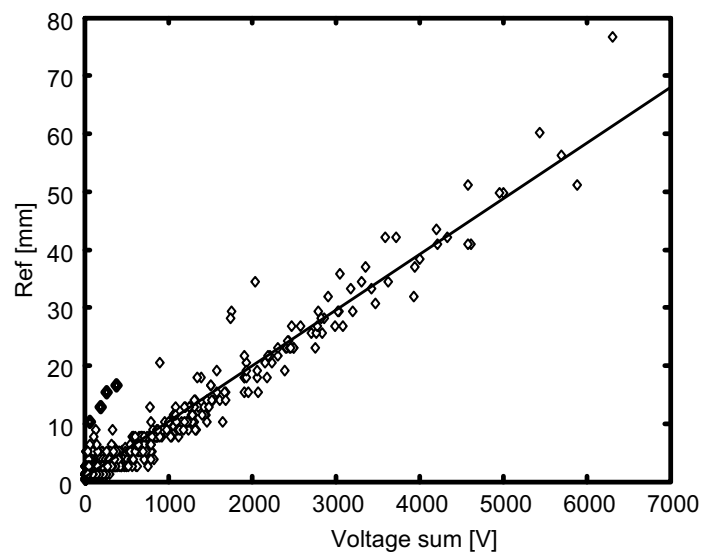
Fig. 4. An example of the field calibration data.

2.4 Errors in measurement method

Commonly used can-type raingauges are subject to significant systematic error (WMO, 1996 and 2000). The amount of liquid precipitation measured can be less than the actual amount reaching the ground by up to 30 per cent or even more. The real amount of precipitation is usually estimated by adjusting the data with a general model:

$$P_k = k(P_g + \Delta P_1 + \Delta P_2 + \Delta P_3 + \Delta P_4) + P_r \,, \tag{6}$$

where P_k is the adjusted amount of precipitation, P_g the recorded precipitation in the gauge, k and ΔP_1 - ΔP_4 the adjustments for different error components listed in Table 1 and P_r random observational and instrumental error.

Term	Description of error component	Magnitude
k	wind-field deformation	2 - 10 %
$\Delta P_1 + \Delta P_2$	wetting on the internal walls of the collector and the container after emptying	2 - 15 %
ΔP_3	evaporation from the container	0 - 4 %
ΔP_4	splashing of water in and out	1 - 2 %

Table 1. Error components in commonly used precipitation gauges listed in order of importance (WMO, 1996 and 2000).

Due to the measurement method, the adjustments ΔP_1 - ΔP_4 are not needed for the sensor described in this paper. Errors related to piezoelectric sensor are more stochastic than systematic. Since the measurement of rain amount is based on momentum of individual drops, variation in the shape and velocity of raindrops caused by air movements is the most important error factor. Sensitivity variations over the sensor area, due to surface wetness and construction of the sensor itself, produce stochastic error seen particularly in short exposure time. The supplementary data needed for factor k in Eq. (6) is easily achieved as the Vaisala Weather Transmitter measures the wind velocity just above the precipitation sensor.

3. FIELD TESTS

The field tests reported in this paper were performed at the Finnish Meteorological Institute observatory at Jokioinen; the Vaisala test site at Vantaa, Finland and at the test site at Kuala Lumpur, Malaysia. The data collected consists of light and moderate precipitation typical for Finland and moderate or heavy precipitation collected in Malaysia.

Also, other weather parameters from different sensors were available for data validation at all test sites.

In the following chapters, reference gauges are compared to the Vaisala Weather Transmitters. The precipitation measurement of Vaisala Weather Transmitter is based on the Vaisala RAINCAP® precipitation sensor.

3.1 Vaisala test site at Vantaa, Finland

A weighing-recording gauge (WGA) and tipping bucket gauges (TBA and TBB) from two different manufacturers were used as comparison instruments for this test. The tip size was 0.2 mm in both tipping buckets. The weighing gauge was installed with the Tretyakov wind shield, the orifice height being 1.5 meters. The both tipping buckets were at ground level and the Vaisala Weather Transmitters (WX1 and WX2) were installed at height of two meters.

3.2 Finnish Meteorological Institute observatory at Jokioinen, Finland

Three different weighing-recording gauges (WG1, WG2 and WG3) from two manufacturers were used for reference measurements at Jokioinen. The WG1 and WG2 weighing type gauges were equipped with the Tretyakov wind shield. The WG3 was surrounded by a standard double fence, consisting of two lath fences of 4 and 12 m diameter. Two Vaisala Weather Transmitters were installed at height of two meters, about 50 meters apart from the WG3. The WG1 and WG2 were mounted to the middle between the WG3 and Weather Transmitters.

3.3 Vaisala test site at Kuala Lumpur, Malaysia

Test site at Kuala Lumpur consisted of two Vaisala Weather Transmitters and two identical tipping buckets with 0.2 mm tip size as comparison instruments. The Vaisala Weather Transmitters and one of the tipping buckets (TB2) were elevated to 1.5 meters above ground. The other tipping bucket (TB1) was at ground level.

4. RESULTS AND DISCUSSION

As an example of heavy rain events, a ten-day measurement period from Malaysia is shown in Fig. 5. The average wind speed during the period was below 2 m/s and therefore has no remarkable effect on measurement, although wind shields were not used at this site.
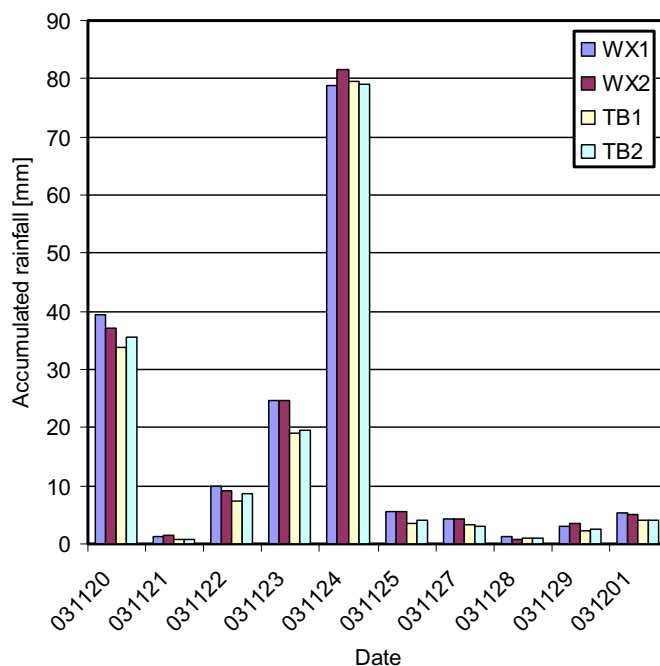

Fig. 5. Moderate and heavy rain events in Malaysia.

The tipping buckets indicated less precipitation than the Vaisala Weather Transmitters. The measurement differences between the tipping buckets and the Vaisala Weather Transmitters were 5 to 10 percent in the long term, the daily differences were occasionally somewhat higher. The readings from the two Weather Transmitters were consistent during the whole test period.

Gauge	WX1	WX2	WG1	WG2	WG3
[mm]	222.7	227.5	205.4	203.9	189.6

Table 2. Total accumulations during a three months test period at Jokioinen observatory.

The results from a three month test period at Jokioinen are shown in Fig. 6 and Table 2. The period included 42 rainy days, mainly with light rain. The collected data demonstrate comparability of the weighing-recording gauges to the Weather Transmitter.
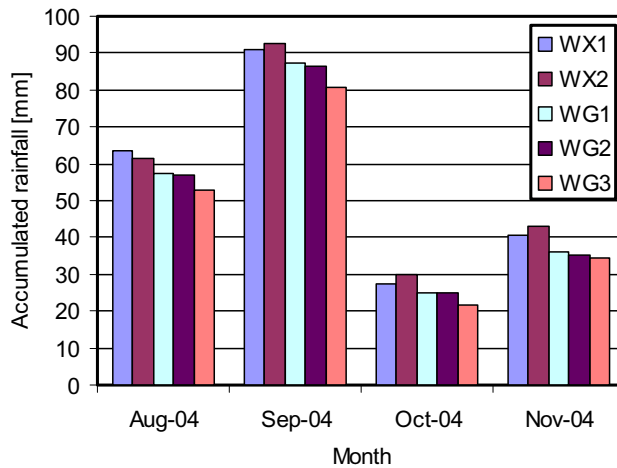
Fig. 6. Monthly accumulations at Jokioinen observatory

The Table 2 shows that there is only a slight difference between the two Weather Transmitters, (4.8 mm) as well as between the WG1 and WG2, (1.6 mm). The difference between the WG1 and WG3 is 15.8 mm and between the WG1 and Weather Transmitters 17.2 and 22.0.

Table 3 shows total accumulations of light and moderate rain measured at Vaisala test site in July-August 2004. The differences are calculated against the weighing-recording gauge (WGA). The difference between the two Weather Transmitters is negligible, but between the two tipping buckets (TBA, TBB) as large as 8.8 mm. The Weather Transmitters have reported slightly lower accumulation than the WGA.

Gauge	WX1	WX2	TBA	TBB	WGA
Total [mm]	102.2	101.2	104.4	113.2	108.0
Diff [mm]	5.74	6.74	3.57	- 5.23	-

Table 3. Total accumulations at Vaisala in July-Aug 2004.

Fig. 7 illustrates a characteristic short-interval data from three types of precipitation recorders at the Vaisala test site. It can be seen from the data that due to the measurement method, the Weather Transmitters do not suffer from evaporation error and their response time is short compared to the tipping bucket type gauges.
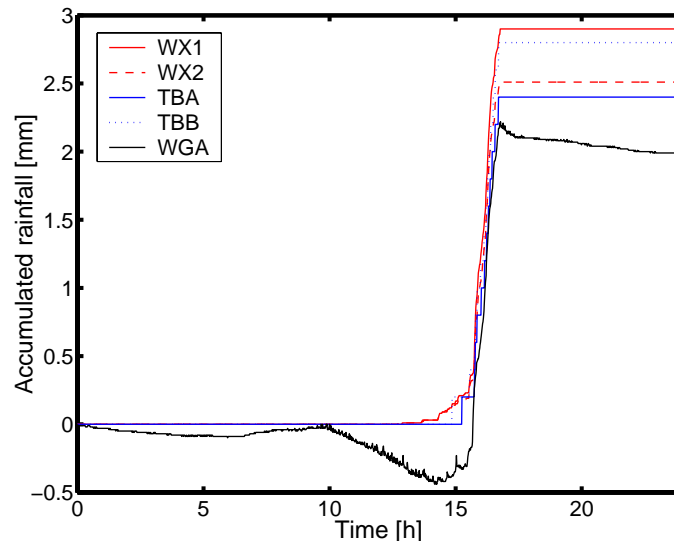
Fig. 7. Hourly data from different types of precipitation recorders.

5. CONCLUSIONS

We have demonstrated a novel piezoelectric precipitation sensor that can be used to measure liquid precipitation and characterize whether the precipitation is rain or hail. The field results show good comparability of the sensor to traditional tipping buckets and weighing-recording gauges.

Due to the measurement method and construction of the sensor, the Vaisala RAINCAP® is virtually maintenance free. The sensor does not suffer from systematic errors due to wetting, evaporation or splashing of raindrops.

When the distance between the precipitation gauges increases, deviations caused by spatial variability of precipitation have more significant effect on instrument readings than the sensor performance. That was seen at Jokioinen where the distance between the gauges were dozens of meters. Because of its robust design with no moving parts the precipitation sensor described in this paper is suitable for dense measurement networks. A network of several gauges would give better estimate of overall precipitation than a single a point measurement with a high-end instrument.

6. ACKNOWLEDGMENT

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