A Device for Measuring the Radii of Raindrops

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ABSTRACT

The sizes of raindrops with radii between 0.025 and 0.2 cm can be measured by amplifying the voltage pulses they make when they hit a high voltage wire. I have made such a device using two wires charged to +2000 V and a differential amplifier. Unwanted radio noise affects each wire in nearly the same way and is thus greatly reduced at the output of the differential amplifier. The device is simple and easy to build, and it works well except in the vicinity of thunderstorm electrical activity.

1. Description

An abrupt change in the capacity between two metal electrodes occurs when a raindrop touches one of the electrodes. Since the magnitude of the capacity change depends on the radius of the drop, this effect can be used to measure the radii of raindrops and to determine the distribution of raindrop radii present in various kinds of rainfall.

The device I wish to describe in this paper is meant to be used on the ground to measure raindrops with radii between 0.025 and 0.2 cm. It consists of three electrodes—two parallel wires, both charged to +2000 V, and a grounded surface (see Fig. 1). The wires are connected to the two inputs of a differential amplifier. When a drop hits one of the wires, the abrupt change in capacity between that wire and the grounded

surface causes a corresponding abrupt change in voltage, which is then amplified. Two wires and a differential amplifier are used to reduce unwanted signals due to radio waves. Radio pickup could also be reduced by using only one wire and shielding it. However, this latter method has the disadvantage that small drops which result from the breakup of larger ones hitting the shielding can cause spurious signals.

The oscillogram of Fig. 2 shows the output signal from the differential amplifier due to a drop of radius 0.17 cm. The signal begins to rise only when the drop comes very close to the wire and *reaches its maximum amplitude when the surface of the drop first touches the surface of the electrode*. The rise time of the signal is limited by the conductivity of the raindrop. Distilled water with a conductivity of about $2\mu\text{mho cm}^{-1}$ was used

FIG. 1. Top view of one end of the two-wire drop-size device. The wires are 0.08 cm diameter tinned copper, 166 cm long. They are both charged to +2000 V. In this photograph the wires are spaced 10 cm apart, but unwanted electrical pickup can be reduced by placing them just 2.5 cm apart. The power supply and signal-output leads enter through the bottom of the chassis.

FIG. 2. Pulse shape at the output of the differential amplifier for a 1.7-mm radius drop. The damped oscillation is an artifact of the amplifier.

to make Fig. 2. Rainwater generally has a higher conductivity and would thus make signals with faster rise times. The fall time of the signal shown in Fig. 2 is due to the RC time constant of the electronic circuit. If the RC time constant is made very long, the signal falls as the drop temporarily coalesces with the electrode and then rises again as the droplets from the fragmenting drop fly away from the electrode. This later part of the signal (that due to the breakup of the drop) is rather long (about 2 msec) and highly variable since it depends on the way in which the drop breaks up.

It might be easier to visualize how this device worked if it consisted of one wire with a concentric cylindrical shielding around it. Then it would be clear that a spherical drop would make the same amplitude signal upon touching the wire whether it hit directly on the top of the wire or made a grazing hit on the side of the wire. In the apparatus I am describing there is no symmetry and it is thus perhaps a little surprising that the signal a drop makes does not depend strongly on where it hits a wire. The reason it does not is that the electric field close to each wire electrode (within one drop diameter) is fairly symmetrical even though there is no large-scale symmetry. The calibration curve given in Fig. 3, in which drops of a known size were produced with vibrating hypodermic needles (Atkinson and Miller, 1965), shows how much the signal can vary for a given size drop. Much of the variability is due to the asymmetry. The rest of it may be due to a number of causes. For example, small blobs of water which cling to the wire decrease the electric field at their location, resulting in lower signals for drops which hit blobs than for drops which hit a bare section of wire. The non-spherical shapes and the vibrations of large drops might also cause some of the observed variation.

The short duration (about 40 μ sec) of the signal has two advantages: First, it means that it is extremely unlikely that two raindrops will ever produce overlapping signals. Second, it makes it possible to eliminate unwanted slow signals with a high-pass filter. There are five sources of slow signals: 1) the break-up of drops

after they collide with the electrode, 2) raindrops which come very close to the wire but miss it, 3) water dripping from the wire, 4) wire vibrations, and 5) 60-cycle electrical pickup which is not completely eliminated by the differential amplifier.

Since only those drops which hit the wire will be counted, the "collection" area for drops falling vertically is

$$A = L(d + 2R), \quad (1)$$

where L is the length of the wire and d its diameter, and R is the radius of the drop. For example, the collection area of this device for 0.2-cm radius drops is 80 cm^2 if only positive signals are used. (One wire will give positive signals and the other negative signals due to the differential amplifier.) Notice that the collection area increases with drop radius. This is a desirable feature since large drops are often more scarce than small ones.

If there is a wind which causes drops of radius R to descend at an angle, then the contribution to the rain-fall rate (number of drops $\text{cm}^{-2} \text{sec}^{-1}$) due to these drops is $[n(R)/A] \cos[\theta(R)]$, where $n(R)$ is the number of electrical pulses per second from drops of radius R , A is defined by Eq. (1), and $\theta(R)$ is the angle between the vertical plane in which the wire lies and the plane determined by the drop trajectory and the wire.

2. A theoretical estimate of the signal amplitude

The amplitude of the signal can be calculated roughly for a wire electrode by the judicious use of a theory presented in an earlier paper (Winn, 1968) for spherical electrodes. The maximum signal amplitude for a conducting sphere coming in contact with a spherical electrode is

$$\Delta V = \frac{AE^2R^3F}{CV} [\text{statvolts}], \quad (2)$$

where A is the amplification of the differential amplifier, E the electric field at the surface of the electrode (statvolts cm^{-1}), R the radius of the drop (cm), C the capacity of the wire plus the input capacity of the differential amplifier (cm), V the voltage on the wire (statvolts), and F a number which depends on the radius of curvature of the spherical electrode where the drop touches it. This equation is true only when $\Delta V \ll V$.

Applying Eq. (2) to cylindrical electrodes requires using a value for F which corresponds to an appropriate radius of curvature. In a previous paper (Winn, 1968) good agreement between this equation and measurements made with a large cylindrical electrode was obtained by using as a radius of curvature twice the radius of the cylinder. Doing the same for the small wire electrode gives $F=1$ (from Winn, 1968) for a drop radius $R=0.022$ cm. The other values to be substituted into Eq. (2) are $A=5$, $E=24.6$ statvolts cm^{-1} , $C=94$ cm, and $V=6.7$ statvolts. The result is $\Delta V = 5.1 \times 10^{-5}$ stat-

volts (0.0153 V), which is to be compared with the measured value of 0.018 V taken from Fig. 3. This agreement is good considering the uncertainties in the values of the parameters. The most questionable values are those for F and E . The electric field was calculated from $E = V/[r \ln(b/r)]$, which assumes a coaxial-cylindrical geometry (r is the radius of the wire and b the radius of the outer coaxial shielding). The value used for b (40 cm) is in question since the grounded surface is not coaxial-cylindrical.

Eq. (2) should not be trusted in making estimates of the signal amplitude for larger drop sizes since then the choice of a suitable value for F becomes even more uncertain than in the given example. The equation does, however, serve as a useful guide for designing drop size devices. For example, it shows that increasing the input capacity—by increasing the length or diameter of the wire—decreases the signal. It also shows that increasing V increases the signal since $E^2/V \propto V$.

Raindrops often carry an electric charge. Whether or not such a charge will alter the signal amplitude as the drop hits the wire can be assessed in the following way: if the charge on the drop before it touches the wire (i.e., its natural charge) is small compared to the charge it acquires upon touching the wire, then the signal amplitude will not be affected appreciably by the natural charge. Thus, it is required to determine how much charge a drop acquires upon touching the wire and how much natural charge raindrops are likely to have.

Spheres of radius R hitting a flat surface where the electric field is E will acquire a charge

$$Q_T = 1.65ER^2 \text{ [statcoulombs]}, \quad (3)$$

(see, for example, Winn, 1968). This equation is a useful approximation for cylindrical electrodes when the radius of the drop is less than the radius of the cylinder. The charge acquired by large drops can be measured in the laboratory by having the drop make a grazing hit on the side of the wire (so it does not break up into many pieces) and catching it in a Faraday cup attached to a charge amplifier. A charge of 0.51 statcoulomb was measured in this way for a 0.168-cm radius drop impinging on one of the 2000-V wire sensors of the two-wire raindrop device. If Eq. (3) is naively applied to the large 0.168-cm radius drop, the result is 1.14 statcoulombs; thus Eq. (3) overestimates the amount of charge which large drops will acquire upon touching the electrode.

Data on the relation between natural charges and radii of raindrops are very meager. Gunn (1949) made some measurements under a thunderstorm whose raindrops were unusually highly charged, more highly charged than any previously reported in the literature. He found that the average charge on a raindrop of radius R (cm) was $Q = 2.8R^2$ [statcoulombs, esu], and that 80% of the drops had charges between $Q = R^2$ and $Q = 10R^2$. The total charge which a drop of radius R would have after hitting one of the wire electrodes

FIG. 3. A calibration curve for the two-wire raindrop device. The wires were 2.5 cm apart and charged to +2000 V.

would be given by substituting $E = 24.6$ statvolts cm^{-1} (the field corresponding to 2000 V) into Eq. (3); i.e., $Q_T = 41R^2$ for small drops. For large drops $Q_T \approx 20R^2$. Thus, the most highly charged drops observed by Gunn would have signal amplitudes which depended on the sign and magnitude of their charge as well as on their radii. If the two-wire raindrop device reduced radio pickup enough to allow it to be used in the vicinity of thunderstorm electrical activity, the signal amplitude variations caused by large drop charges could be reduced by increasing the voltage on the wires, thereby increasing Q_T and decreasing the effect of the drops' natural charges.

When measurements are made with this device in a rainfall where the natural charges are not known, the importance of such charges can be roughly determined by disconnecting the high voltage from the wires. When this is done, the observed signals will be due to charges on the drops. If these signals are much smaller than those produced by the drops hitting the wire when the high voltage is turned on, then the drops' charges will not cause erroneous signals.

3. The differential amplifier

A circuit diagram for the RC filters and the differential amplifier is shown in Fig. 4. The entire circuit was designed with the aim of making the inverting (−) and noninverting (+) channels as nearly identical as possible in order to eliminate electrical pickup. The resistors, capacitors and diodes of the filter circuit were hand-picked to be matched to within less than 1%.

FIG. 4. Differential amplifier circuit. The input impedance is 560 k Ω and the gain is 5.

The variable 10 k Ω resistor is to balance the gain in the inverting and noninverting inputs of the differential amplifier for relatively low frequencies. Once this adjustment has been made, the variable capacitor shunting the noninverting input can be adjusted to reduce the high frequency pickup. The pickup cannot be reduced entirely, partly because the differential amplifier is not perfect, but mainly because the two wires which the drops hit do not receive identical radio signals. If the wires are placed one inch apart, the electrical

pickup at 60 Hz is 14% of what it would be if only one wire were used. At 20 kHz it is 5%.

The circuit draws about 60 mA, most of which goes through the 2N3566 emitter-follower, which allows the circuit to drive a 50 Ω load.

4. Data reduction

Perhaps the greatest advantage in drop-size devices giving an electrical output instead of images or im-

FIG. 5. A simple pulse-height analyzer for recording drop-size distributions.

prints lies in the possibility of reducing the data (the electrical pulses) electronically. Finding the drop size distribution means sorting the pulses into categories (channels) according to amplitude and counting the number of pulses which accumulate in each channel in a given length of time. Ten to thirty channels would probably represent a sufficiently fine sorting for any experiment requiring drop size distributions. Unfortunately, ready-made pulse-height analyzers have many more than 30 channels (and in other ways are much more sophisticated than this application requires), and they are expensive.

The best homemade pulse-height analyzer which I can think of for this drop size device is shown in Fig. 5. The voltages $V_1, V_2, \dots, V_n$ are reference voltages which determine what amplitude pulse will activate each comparator. The binary counters count the number of times each comparator is activated. An analogue signal proportional to the number of counts in each channel can be obtained by using a ladder network with each counter. If a commutator switch is used as shown in the figure, the analogue signals from all the channels can be recorded with one pen on a strip-chart recorder.

Notice that the number of counts in the i th channel gives the total number of pulses with amplitudes *greater* than the reference voltage V_i for that channel. The most desirable quantity to have is the number of pulses with amplitudes *between* V_i and V_{i+1} . The counts in channels i and $i+1$ must be subtracted to get this number. It

would be nice to do all the subtractions electronically, but the additional circuitry may make it prohibitive.

5. Conclusion

This device has many attractive features. Drop radii are correctly measured when there is wind and the rain is coming down at an angle. It is lightweight, inexpensive, simple, and easy to build. It may be adaptable for use on balloons or kites.

It has two main limitations. First, although radio signals are greatly reduced by the differential amplifier, they are not eliminated, and are still a problem in the vicinity of thunderstorm electrical activity. And second, as the error bars in Fig. 3 indicate, drop radii cannot be measured with an accuracy greater than about $\pm 20\%$.

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