A Rain Gauge for the Measurement of Finescale Temporal Variations

C. DAVID STOW, STUART G. BRADLEY, KEITH E. FARRINGTON, KIM N. DIRKS, AND WARREN R. GRAY*

University of Auckland, Auckland, New Zealand

(Manuscript received 7 August 1996, in final form 1 May 1997)

ABSTRACT

A rain gauge is described that quantizes rainwater collected by a funnel into equal-sized drops. Using a funnel of 150-mm diameter, the quantization corresponds to 1/160 mm of rainfall, enabling the measurement of low rainfall rates and the attainment of a fine temporal resolution on the order of 15 s without unduly large sampling errors. Two drop-producing units are compared and an operational rain gauge design is presented. Field comparisons with conventional rain gauges are made, showing excellent correlations for daily rain totals, and intercomparisons between clusters of dropper gauges are also given. Examples of highly resolved rainfall events are shown demonstrating the ability to measure low rainfall accumulations and also coherent high intensity events of short duration, which are not detectable with conventional rain gauges.

1. Introduction

For some applications in meteorology and hydrology, temporal and spatial resolutions of rainfall on the order of 10 s and 100 m, respectively, are desirable, possibly from an array of sampling locations. The interests of the authors in meso-α-scale rain generation and redistribution processes have led them to seek a design for an inexpensive instrument that could be used to achieve such resolutions. This paper is not concerned with the problems of external shape, collection efficiency, and aerodynamics, such as are treated, for example, by Folland (1988), but with the measurement of the collected rainwater mass.

Since very few short-period high-resolution rainfall intensity data have been obtained by any workers, it is difficult to design for the possible upper limit to, say, 10-s rainfall intensities. Semplak (1966), for example, cites intensities in excess of 260 mm h^{-1}, and Seibel (1972) catered for possible intensities of up to 800 mm h^{-1}. From long-term data collected by the National Oceanic and Atmospheric Administration (NOAA), Lin (1976) produced 5-min rain-rate distributions for many locations in the eastern United States. Typically, these show that the distribution of high rainfall rates may be approximated by the ''tail'' of a lognormal distribution based on the local yearly extreme value statistics. This suggests, for instance, that for this broad geographical region a 5-min average rainfall rate of about 240 mm h^{-1} may be expected about once every 7–25 years. It is therefore reasonable that the sensing element should be capable of handling rainfall rates of up to about 300 mm h^{-1}. From guidelines produced by the World Meteorological Organization WMO (WMO 1983), the typical accuracy requirement for intensity measurements is $\pm 2\%$ for rates above 10 mm h^{-1} (with estimates above this threshold frequently being required as 1-min averages). At lower intensities, requirements differ markedly, but a reasonable basis for design would seem to be ± 0.02 mm h^{-1} for 10-min rate averages below 2 mm h^{-1}, and ± 0.2 mm h^{-1} for rates between 2 and 10 mm h^{-1}.

Lin (1975), from photographic measurements of rain, determined that for heavy rain the finescale vertical structure was on the order of 1 m, and that between 50 and 100 drops m^{-3} were present at an intensity of about 1 mm h^{-1}. These data imply a lower limit for the time of integration of measurements, using conventional gauge collector diameters of about 15 s since, at this low rainfall rate, the sampling error is of the order of 25%. Using 1-s data from Semplak and Turrin (1969), Gertzman and Atlas (1977) found that after estimating the variance due to sampling effects there was a significant residual, probably due to real rainfall-rate fluctuations. Duncan (1993) examined the power spectrum of the sound caused by impacts of raindrops on a metal sheet. He determined that ''nontrivial'' structure existed in the measured rainfall up to a frequency of 0.1 Hz. Assuming that this frequency is not determined by the size of the metal sheet, a suitable lower limit for rain gauge sampling is on the order of 10 s. It should be noted that, even at long sample times, rainfall intensity

* Current affiliation: National Institute of Water and Atmospheric Research, Wellington, New Zealand.

Corresponding author address: C. D. Stow, Dept. of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand.
E-mail: d.stow@auckland.ac.nz

exhibits a large degree of temporal variability, as shown by Lin (1978). These records reveal that there was a definite correlation between the short-term (60 min) mean rainfall rate and deviations from this short-term mean within each period. Thus, it is necessary to cope with both a wide range of rainfall intensities and with high variability over short time intervals.

One approach to obtain very fine temporal resolution is to use a large collection funnel so that a sufficient volume of water is channeled to the sensing element, especially during low intensity rain. However, the time taken for the rainwater to flow down the funnel to the sensor may be appreciable in some cases and, if this response time involves the wetting of the funnel surface, then it will almost certainly be intensity dependent (Mellanby 1976; Kirkham 1980). Any fluctuating lag error must be considered if high-resolution rainfall data are to be compared with other highly resolved measurements such as radar. Norbury and White (1971, 1972) describe an alternative approach in the rain gauge developed for their studies of the attenuation of microwaves in rain. Their device converted raindrops landing on a funnel into nearly constant-size drops formed at the funnel exit. Counting the output drops over a fixed time interval gives the rainfall intensity. The technique is attractive because the unit of measurement is one drop volume. Hosking and Stow (1987), who measured rainfall events using an optical disdrometer, found that 40% of the rain periods they registered had total falls of less than 0.1 mm, which is generally below the resolution limit of standard recording rain gauges. Breuer and Kreuels (1977), in Germany, made observations that suggest a slightly higher percentage. A Gaussian fit to a distribution of rainfall totals, made by Hosking and Stow, suggested further that 10% of rain periods comprise rainfall totals of less than 0.01 mm. Statistics on low rainfall events should not be ignored since their combined and individual contributions may be important, for example, in sustaining components of our biosphere. Water volume resolution equivalent to not more than 0.01 mm rainfall is desirable on this account. Hosking et al. (1986) discuss the selection of a dropper rain gauge and treatment of associated sampling errors. Using the optical disdrometer of Stow and Jones (1981), they examined the spectra of drop sizes produced by the Norbury and White gauge. They found that at certain flow rates the size spectra were broad, exhibiting two or more modes (see Fig. 1a), which they attributed to resonances in the water pathway and reservoir. At very low rainfall rates, drops were released singly, but at moderate or high rates drops were released in pairs or in threes.

Hosking et al. (1986) improved the design by the near elimination of the reservoir and pathway through their incorporation into a small torpedo-shaped labyrinth at the base of the collecting funnel together with the smoothing of water flow. These new rain gauges were used successfully to examine rainfall enhancement over

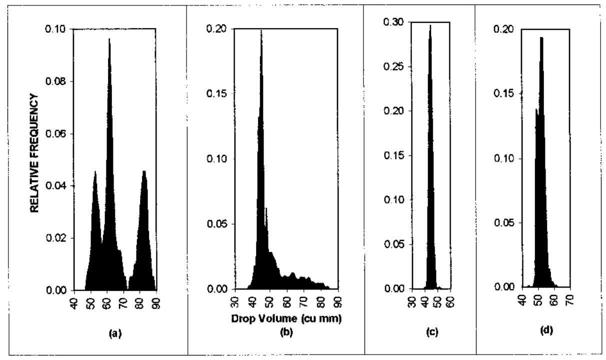

FIG. 1. (a) Multimodal behavior of the rain gauge of Norbury and White (1971) as determined by Hosking et al. (1986). (b) The output drop-volume distribution obtained by simulating rain input to a smooth plastic funnel connected to a high-performance dropper unit. (c) The output drop-volume distribution obtained using the simplified decoupler-type unit in conjunction with a well-weathered galvanized iron funnel that suppressed beading. (d) The accumulated output drop-size spectrum obtained from a series of sudden changes in intensity over the range 3–20 mm h^{-1} using a simplified dropper unit.

low hills (Stow et al. 1991); to evaluate the extraction of intensity data from the chart records of cumulative rainfall gauges (Bradley et al. 1991); and to measure simultaneously the rainfall intensity, rain drop-size distribution, and the attenuation of visible light (Stow et al. 1991a, b). The gauge described by Hosking et al. (1986) however, produced an excessively broad drop volume spectrum (standard deviation 18 mm^3), thereby denying accurate measurement of low rainfall intensities over short periods. An improved design capable of producing a very narrow output drop-size distribution is described below, from which a simplified version with only a slightly inferior performance was evolved. Particular attention has been given to the examination of the water flow on the funnel surface, flow smoothing, and output-drop production. Field performance data and examples of events detectable using the gauge are presented below.

2. The design of a high-resolution dropper gauge

a. Funnel performance and flow control

Flow into the dropper tube is governed by the Poisson-like arrival of individual raindrops and the subsequent wetting behavior of the funnel surface. Nonwetting leads to drop retention or ''beading'' on the funnel surface, and the random release of such drops leads to surges in the flow of water at the funnel base. The amount of spreading of a liquid drop on a solid surface is determined by the relative magnitude of the surface free energies of the solid–vapor interface γ_{sv}, the solid–liquid interface γ_{sl}, and the liquid–vapor interface γ_{lv}. Since spreading decreases the area of the solid–vapor interface and increases the area of the other two interfaces, if the net change in free energy is negative, the total Gibbs free energy of the system decreases and the

TABLE 1. A summary of the observed flow characteristics for different funnel materials.

Material	Treatment	Initial wettability	Flow behavior
Aluminum	Polished	Adhesional wetting (irregular beads with volume ≅ 20 mm^3)	Sudden beaded runoff (nonwetting)
	Uniformly roughened	Spreading wetting (irregularly shaped patches)	Irregular runoff with retention of considerable surface film
	Anodized and Electroless zinc	Adhesional or spreading wetting depending on grade of anodizing	Initial runoff will establish a laminar flow path. Good drainage except for heavy coats
Galvanized iron	Hot dip	Adhesional wetting (uniform beads with volume ≅ 30 mm^3)	Sudden beaded runoff (nonwetting)
	Electroless zinc	Adhesional wetting (irregular beads with volume ≅ 20 mm^3)	Irregular runoff, good drainage
	Uniformly roughened*	Spreading wetting (moderate regularly shaped patches)	Irregular runoff with retention of surface film
PVC plastic and acrylics	None	Adhesional wetting (irregular beads with volume ≅ 30 mm^3)	Sudden beaded runoff (nonwetting)
	Uniformly roughened*	Spreading wetting (moderate regularly shaped patches)	Irregular runoff with retention of surface film

* Surfaces air blasted with 5–90-μm glass beads.

liquid tends to spread; otherwise, the liquid will tend to cover a minimum area of the solid. At equilibrium, the contact angle θ assumed by a sessile drop is given by Young's equation: $\cos\theta = (\gamma_{sv} - \gamma_{sl})/\gamma_{lv}$. Wetting is signified by a contact angle of less than 90° and is "total" at 0°. Even for funnel surfaces with a slope of 45°, if the wettability is poor, gravitational effects will be dominated by surface factors as long as the liquid volume remains small. In the case of PVC plastic funnels with polished surfaces, the maximum "bead" size that the surface can retain is on the order of 100 mm^3, which is quite large when compared with raindrop volumes (typically less than 15 mm^3). Consequently, the beads of water that run down the funnel, largely maintaining their shape and often coalescing with other various sized beads that lie in their path, suddenly swamp the dropper unit and overpower the desired decoupling process of flow smoothing. This behavior not only leads to a broadening of the output drop-volume spectra but also causes the sensor response to steady rain to become irregular, thus adding a significant noise component to any finescale intensity data.

To test the performance of other materials suitable for funnel construction, various samples of aluminium plate, galvanized iron, and plastic were first degreased with either trichloroethylene or acetone and then sprayed with water to simulate rainfall. The surfaces were all inclined at an angle of 45° and were initially dry. Table 1 gives a summary of the observed flow characteristics for each sample. It was observed that, particularly for well-wetting materials, the flow appeared to spread and become more smooth as the surface roughness was increased. This is consistent with the finding of Wenzel (1936) that there is an effective angle of contact, θ^*, given by $\cos\theta^* = r\cos\theta$, where r is the ratio of the true (rough) area of surface to the projected (smooth) area. Thus, roughening of a substrate should decrease the angle of contact for wetting surfaces and vice versa for nonwetting surfaces (where $\theta > 90°$). Indeed, new roughened PVC surfaces still showed a tendency to cause beading.

Observations of the effects of weathering showed that the stability of all types of gauges improved, possibly because of the effects on the surface diffusion of polar water drops of dry deposition and oxidation of the funnel. It was also observed that the upper limit of the measurable rainfall intensity increased. This limit occurs when discrete drops are no longer formed. The existence of sea salt deposits or bird excreta was not found to alter gauge calibration significantly. Regular cleaning, which will remove natural deposits and leave traces of organic or inorganic cleaning agent, was found to be undesirable and to cause erratic calibration drifts for several weeks.

b. *Water flow and drop production*

1) A HIGH-PERFORMANCE DROPPER UNIT

Initially, consideration was given to the discharge outlet of the dropper tube since it is there that the local balance of gravitational force and surface tension ultimately controls the output drop size. In attempts to decouple the pendant drop from the water column at the instant that it detaches and to suppress secondary forces such as water column oscillations, a suspended spheroid was placed below the orifice of the siphon outlet tube. Under laminar flow input, the drop volumes produced by units using this new control element were found to be remarkably stable; the standard deviation is on the order of 13 mm^3. Furthermore, the centralization and vertical positioning of the decoupler with respect to the outlet rim were not critical. Figure 1b shows the output drop-volume distribution obtained by simulating rain input to a smooth plastic funnel (on which beading will occur). The standard deviation in output drop volume

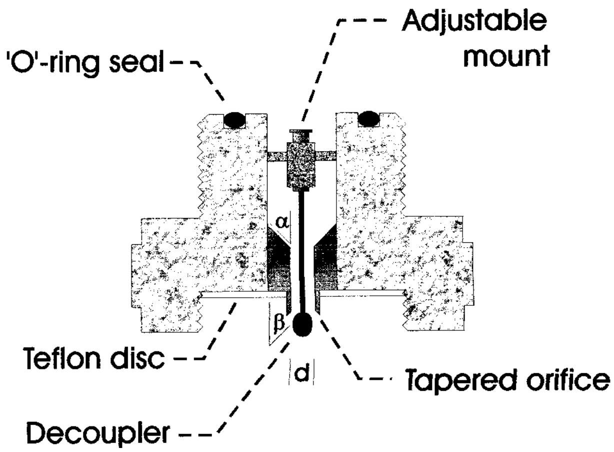

FIG. 2. Schematic of a simplified decoupler-type dropper unit from which the torpedo-shaped labyrinth has been removed.

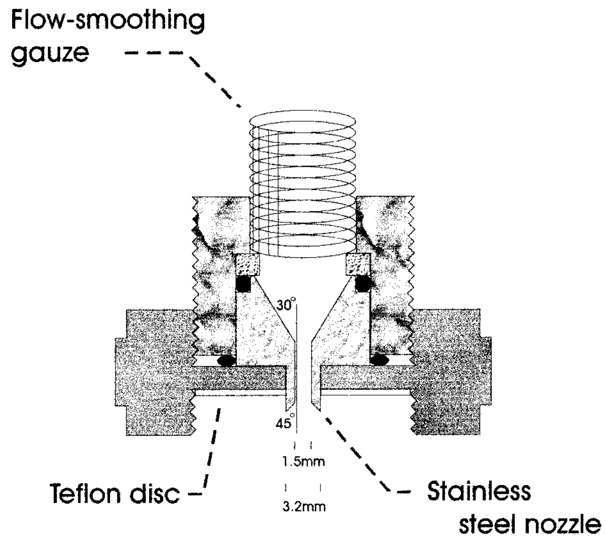

FIG. 3. A much simplified dropper gauge.

was 11.7 mm^3, of which the greater contribution can be attributed to the ''tail'' caused by the flow surges when water beads are released from the funnel sides. Roughening of the funnel wall reduced this tail substantially and allowed a very simple mechanical design, as shown in Fig. 2.

Since early experimentation had shown that the best improvements in drop-volume distribution were obtained with a stainless steel elongated-ellipsoid decoupler having a cylindrical width similar in size to the internal diameter of the outlet tube, the decoupler was designed to slide inside the dropper tube. It was also advantageous to form a bevelled orifice at the base of the tube, as this smoothed the discharge flow and presented more surface area for the water bridge spanning from the tube wall to the decoupler.

A number of different dropper tubes were manufactured from both acrylic rod and type 304 stainless steel to test various bevel angles α and β, bore internal diameters d, changes in orifice surface area, and material response (see Fig. 2). Screw adjusters were also provided to enable the decoupler to be positioned.

Figure 1c shows the output drop-volume distribution obtained using the simplified decoupler-type unit in conjunction with a well-weathered galvanized iron funnel that suppressed beading. Here, the standard deviation in output drop volume is 1.3 mm^3.

Finally, it was determined that the most critical aspect of the dimensions of the dropper tubes investigated was the amount of surface area A at the lower orifice. Values of A at the lower end of the range (7.5–30 mm^2) were found to provide the greatest stability. An acceptable value for the bevel angle β was found to be 45°.

2) A SIMPLIFIED DROPPER UNIT

There were two important features that permitted the use of the simplified dropper unit illustrated in Fig. 3. First, a well-roughened funnel surface and gauze filter/smoother at the entrance to the nozzle generate laminar-like water flow were used; these components should be thought of as part of the dropper unit since, without them, the rain gauge operation will be unsatisfactory. Second, the roughening of the 30° upper bevelled surface of the stainless steel tube to improve its wettability, together with the polishing of the lower bevel, resulted in visibly smoother growth and detachment of drops over a wide range of rainfall intensities. Figure 1d shows the accumulated output drop-size spectrum obtained from a series of sudden changes in intensity over the range 3–20 mm h^{-1} that can be obtained from a carefully prepared simplified dropper gauge with these characteristics. Here, the output drop volume distribution shows no pronounced tail but has a standard deviation of 2.1 mm^3.

The primary disadvantage of the simplified dropper units is that, unlike the pendant decoupled units, the output drop size increases monotonically with the input flow rate. This is part of the reason for the broadened distribution in Fig. 1d as compared with Fig. 1c. A mean value for this nonlinearity, obtained from tests on nine units with a funnel diameter of 150 mm, was on the order of -0.18 drops mm^{-1} rainfall per mm h^{-1} rainfall rate. Thus, for a typical unit whose calibration at 1 mm h^{-1} is 170 drops per millimeter of rainfall, the calibration at 100 mm h^{-1} would be about 152 drops per millimeter rainfall. Where high rainfall intensities must be measured accurately, it is therefore essential to calibrate the simplified rain gauge at a series of rainfall rates so that the appropriate coefficient of nonlinearity can be found.

3. An operational version of the dropper rain gauge

a. Water collection

Figure 4 shows the details of the catcher/funnel, drop-forming nozzle, and drop detector. The funnel cone of

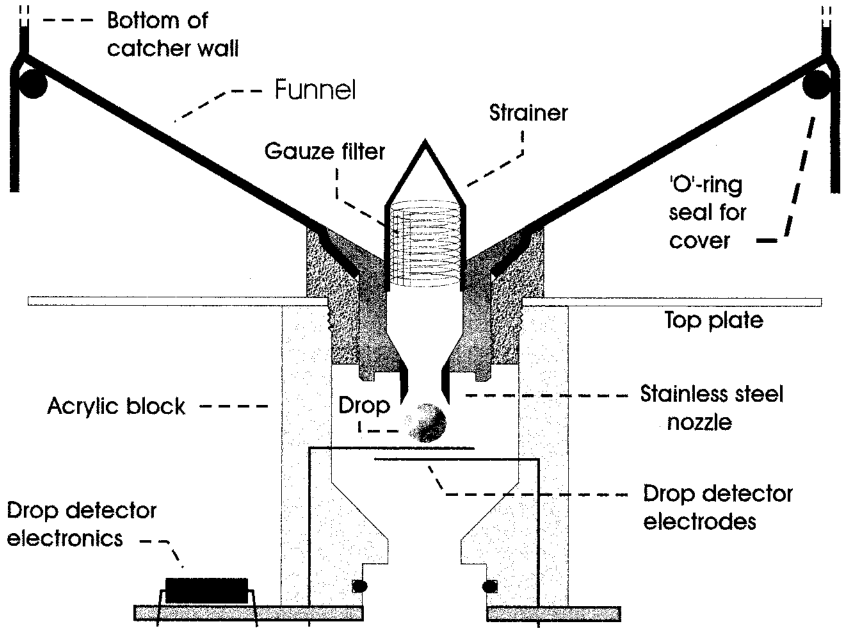

FIG. 4. Details of the catcher/funnel, drop-forming nozzle, and drop detector of an operational rain gauge.

145-mm diameter is made from spun aluminium and has a slope angle of 30° to minimize surging. The exposed surface of the funnel is roughened to discourage beading of collected rainwater. The upper rim of the funnel is welded to a cylinder bevelled at its top rim to provide a catcher diameter of 150 mm. An upper and lower aluminium bush at the base of the funnel provides support for mounting on the gauge body and provides recesses for insertion of a filter and gauze (for the smoothing of water flow and exclusion of insects and other extraneous material) and for insertion of a stainless steel nozzle (for drop production). The assembly screws into an acrylic block machined to hold the stainless steel electrodes (by which drops are detected through electrical conduction) and retain an O-ring for the connection of the water exit pipe. The inside surface of the block must be polished smooth to minimize leakage conduction between the opposed electrodes. All metal components are electroless nickel treated to provide anticorrosion, electrically conducting surfaces. The latter is required to effect good earthing of the gauge frame.

b. Drop detection

To conserve power, drop detection is passive. After release from the dropper unit, drops fall between two stainless steel electrodes, causing temporary bridging; a derived 20-ms pulse activates a CMOS Schmitt trigger/buffer. In Auckland, the rainwater resistivity was about 0.2 MΩ cm or higher and it was necessary to use an impedance at the electrodes of 22 MΩ; such a high value requires that the buffer unit be located immediately next to the drop detector to minimize capacitative links and prevent false triggering. Leads from the buffer unit were fitted with ferrite bead isolators to exclude backchatter from the microprocessor.

After drop detection, water is vented via a closed tube through the base for either discharge or collection. If the latter course is chosen, it is important that there is adequate breathing to prevent the creation of back pressures, or other flow impedances, as this will affect calibration and proper operation of the dropper unit.

c. Data acquisition

While the output from the detector buffer unit can be directed to any available data logger, the least expensive option was found to be a custom-built logger located onboard; an infinity of options exist for its design. The requirements set by the present authors were simplicity, low power consumption, data retention on power failure, choice of sampling intervals, and serial output of status.

A double-sided printed circuit board holds all components except the detector buffer and batteries. Central to the logger system was an HD637B01VOP microprocessor used in "single chip" mode and normally in a "sleep" configuration to conserve power. Its ROM could be loaded with an operating code, ID number, and user label, as required. Identification and data are loaded to a 27C256 EPROM mounted in a zero-insertion-force socket. The sample interval is determined by DIP switch settings that allow seven possible values between 15 s and 30 min. Because an EPROM should not be removed with power on, a hinged cover conceals the circuit board. Opening or closing the cover operates microswitches that control power input to the circuit board.

Nonzero drop counts are recorded on the EPROM for every sample interval. If no drops are detected, then a count of the number of nonraining intervals is initiated and written to the EPROM (a ''dry write'') the next time that rain occurs. Again, if no rain occurs within 30 min, a dry write will be enforced. All dry writes are followed by a data checksum. On power-up, during wet-weather conditions, at the end of the first sample period a header containing ID number, user label, and sample period information is written to the EPROM, together with the drop count for the first period; in dry weather, a header will not be written to the EPROM until there is an enforced dry write at the end of the first 30 min. Each data item written is also read back and an error code is written if there is a difference. Successive power-ups generate a series of records on an EPROM, each with its own header. No data are overwritten.

Simultaneously, there is a continuous serial transmission of a status data frame in ASCII format via a connector in the base of the rain gauge body; the same connector enables the use of an external power supply, as required. The data frame, which repeats approximately every second, contains an ID number, EPROM memory used, estimated total rainfall since last power-up (to the nearest 0.1 mm), and drop count since last power-up. These serial data are readable using a suitable pocket calculator, can be transmitted via a radio or telephone link, or can be used in conjunction with a personal computer to create data files and show real-time displays of rainfall intensity and accumulations.

Using standard dry cells for power, a highly conservative lifetime of 3 months can be expected. Although tests have shown that the rain gauge will continue to operate for several hours at $-20°C$, alkaline cells are preferred where cold overnight temperatures are not rare. In the Auckland region, where a marine temperate climate prevails, with about 1300-mm annual rainfall, 1 month of data recorded at a 15-s sampling interval occupies about 20% of the EPROM capacity. In the west coast alpine region of the South Island of New Zealand, during a nor'wester event and using the same sampling period, an EPROM would sometimes ''fill'' within 2 days! Unattended use in the latter situation requires the setting of longer sampling periods.

EPROMs are read using a custom-built reader employing the same microprocessor type as is used in the dropper gauge. Extensive personal computer-based software enables detailed evaluation of both data from individual gauges and gauge arrays, on-line monitoring of gauges, and importation of data into commercial database packages.

d. The gauge body and its encapsulation

In a field environment, robustness is of the essence. The main framework, constructed entirely of electroless nickel-treated aluminium, consists of an upper and lower circular plate separated by pillars. The top plate acts as a mount for the funnel, dropper unit, and detector assemblies. The frame is supported by a boss, fitted centrally under the lower plate, which mounts on standard aluminium scaffolding tubing. Mounted in the boss is an electrical connector for dc supply input and ASCII serial output. The main circuit board and its associated hinged metal cover (or door) are mounted between two of the pillars. Batteries are inserted in holders attached to a frame extending between the top and bottom plates and are positioned to allow for the water exit pipe attached to the drop detector unit to pass down through the bottom plate. The entire space not already enclosed by the circuit board door is surrounded by a part-cylindrical metal screen, creating a Faraday cage enclosure between the top and bottom plates.

The entire rain gauge frame is further enclosed by a thick-walled aluminium cylinder that fits under the outer rim of the catcher/funnel where the former is joined to the funnel cone. Here, O-ring seals in the funnel unit and bottom plate rims complete the encapsulation. It is not possible to position this cover without having first closed the cover door of the data logger; thus power-up is ensured. The cover is retained by a substantial security bolt that also passes through the gauge mounting boss and the post to which the latter is secured. The ''underhang'' of the outer cover provides a degree of shelter for any security lock and for the electrical connector mounted in the boss.

4. Calibration of the operational gauge

The response of gauges to varying rainfall rates is nonlinear because the dropper units produce larger drops as water flow increases. To a close approximation, the number of drops produced per millimeter of rainfall decreases linearly with rainfall intensity. Regression analysis for laboratory calibrations of a number of brand new gauges (unused in the field) produced mean and standard deviations of 160/10 drops mm^{-1}, $-0.17/0.09$ drops mm^{-1} mm h^{-1}, and 180/50 mm h^{-1} for the intercept (zero intensity), slope, and maximum measurable intensity, respectively. As discussed in section 6, the latter quantity improves (increases) significantly with aging in the field. It is feasible to perform calibrations in the field, subject to the following considerations.

For low rainfall intensities, the overall effect of gauge nonlinearity is small or negligible; similarly, differences in nonlinearity between gauges do not become noticeable until rainfall rates are on the order of 50 mm h^{-1}. Calibration in the field is thus made feasible if some mean value is adopted for the slope and only the low-flow rate calibration determined. Using data from an operational gauge running continuously over a period of 1 year, the difference in yearly recorded total rainfall was calculated assuming slope values of -0.10 h mm^{-1} and -0.26 h mm^{-1} (one standard deviation either side of the mean slope of -0.18 h mm^{-1}); the difference was found to be 0.9%. This is a consequence of the

TABLE 2. The overall specification of the operational dropper rain gauge.

(a) Rain collection	
Catcher	145-mm diameter, 50 mm high, anodized aluminum integral with funnel
Funnel	145-mm diameter, anodized aluminum with 30° slope angle
Catch	16.51 milliliters per millimeter rainfall
Filter	1-mm nylon square mesh gauze inside aluminum strainer
Drop size	3.0 mm (nominal)
Size error drops	3% drop radius (10% drop volume), random variation in individual
Drop rate	10-Hz maximum (equivalent to approximately 300 mm h^{-1} rainfall rate)
Calibration	165 drops per millimeter rainfall (nominal) at zero rainfall rate; range: 155 to 170
Nonlinearity	−0.18 drops per millimeter rainfall per rainfall rate (mm h^{-1}); range: −0.05 to −0.25
(b) Data processing	
Processor	Hitachi HD637B01VOP
Xtal freq	2.4576 MHz
Max drop rate	20 Hz (exceeds maximum dropper unit rate possible)
EPROM	27C256 (CMOS)
Power supply	9 V (via ''D'' cells) plus 9 V (low current)
Battery life	Greater than 150 days without serial output; greater than 75 days with serial output enabled

preponderance of low-intensity events in the annual rainfall record. If the interest is in peak rainfall rates at high resolution (e.g., 15 s), it is essential to perform a full calibration in the laboratory since the effects of nonlinearity are large at rainfall rates above about 100 mm h^{-1}.

5. The assessment of gauge performance in the field

The current version of the dropper gauge (see Table 2 for specification) has been in continuous use in the field since 1989, notably for high-resolution (15 s) studies of rainfall on Norfolk Island in the South Pacific Ocean (29°S, 168°E), investigations of orographic enhancement and redistribution of rainfall in low hills near Auckland and, most recently, studies of the ''nor'wester'' and its interaction with the Southern Alps of New Zealand (SALPEX). In addition, some experiments were performed in which the dropper gauge was compared with some so-called standard gauges.

For a period of about 1 year in 1991, comparisons were made at two sites on Norfolk Island of daily rainfall totals in excess of 2 mm. At one site (Duvall), the comparison was with an 8-in. simple collector gauge, which was read manually. The separation of the gauges was on the order of 4 m. Both gauge rims were at a height of about 1.2 m above closely clipped grass. At the other site (airport), the reference gauge was a 6-in. tipping-bucket type having a rim height of about 1 m; this reference gauge was operated by the Australian Meteorological Bureau. Both reference gauges nominally resolved accumulations to ±0.1 mm. Water collected after passage through the dropper gauges was similarly resolved. The following rainfall totals were compared at each site: 1) dropper physical/dropper electronic, 2) reference/dropper physical, and 3) reference/dropper electronic. No actual collection of water from the reference gauge was possible at the airport site.

TABLE 3. The *R*-squared value and standard error of residuals for four types of comparison between standard and dropper gauges at two Norfolk Island sites: 1) dropper physical/dropper electronic, 2) reference/dropper physical, and 3) reference/dropper electronic. No actual collection of water from the standard gauge was possible at the airport site.

Test	Site(s)	*R*-squared	Std error
1)	Airport and Duvall	0.992	1.54 mm
2)	Airport only	0.964	4.11 mm
2)	Duvall only	0.997	0.65 mm
3)	Airport only	0.976	3.47 mm
3)	Duvall only	0.987	1.22 mm

The *R*-squared value and standard error of residuals for the three types of comparison are given in Table 3. Despite the difference in collection efficiency of the Duvall gauge on account of its larger diameter, its agreement with the dropper gauge was better than for the airport gauge. The reason for this is not clear and may be due to a combination of a slight height difference (0.2 m) and the absence of water collection at the reference gauge at the latter site. According to Woodley et al. (1975), daily accumulations recorded by identical gauges separated by only 2–3 m may differ by as much as 10%, so that the Norfolk Island data, obtained under a variety of wind conditions, would appear acceptable. As mentioned in section 2a, it has been found that individual gauges stabilize with exposure in the field, typically within about 2 months. The calibration performance of the Norfolk Island gauges *before* installation in the field was as described in section 4. However, in the field, no gauges showed evidence of failure to produce drops at very high rainfall intensities. All 13 of the gauges have shown the ability to record rainfall intensities well in excess of 300 mm h^{-1} and in some cases more than 500 mm h^{-1}.

In a separate series of comparisons over several months, four dropper gauges were collocated with a standard Dynes gauge at the Kelburn site of the New Zealand Meteorological Service. A total of 84 daily

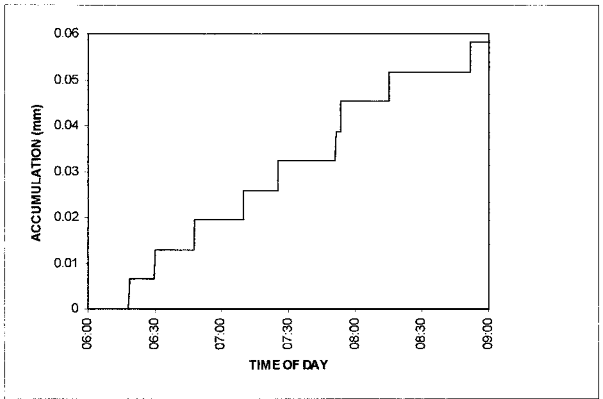

FIG. 5. A field record showing the ability of the gauge to detect early morning condensation in the collector/funnel; the minimum resolved input is equivalent to 1/155 mm of rainfall.

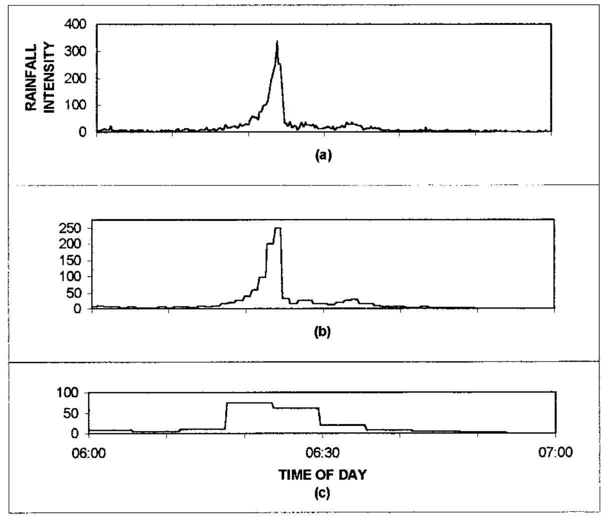

FIG. 6. An event of high rainfall intensity and short duration with time resolutions of (a) 15, (b) 60, and (c) 360 s.

rainfall values were obtained over the range 0.05 mm to about 30 mm from the combined dropper gauges. An *R*-squared value of 0.994 was obtained with an intercept of −0.13 mm. The latter quantity indicates the ability of the dropper gauge to detect small totals missed by the reference gauge. An analysis of residuals showed a standard error of 0.61 mm per day. The use of the dropper gauge for the estimation of daily rainfall totals is thus justified.

6. Examples of dropper gauge records

The performance of the dropper gauge in resolving detail in rainfall is first illustrated in Fig. 5. Here, the record shows the ability of the gauge to detect early morning condensation in the collector/funnel. The gauge was situated in a semisheltered position at the mouth of a small valley during a period of residence of a strong anticyclone, with clear night skies and strong radiative cooling. The record, for which the sampling period was 15 s, shows early morning accumulations of dew from the cold funnel surface resolved to 0.0063 mm. Notwithstanding the lack of meteorological significance of this record, it shows the ability of the dropper gauge to detect water masses well below the threshold of standard gauges.

Figure 6a shows an event of high rainfall intensity and short duration, again with a time resolution of 15 s. There is good self-coherence, so that the peak rainfall rate measured is not an artifact of unstructured noise. Also shown is the same record integrated over 60 s (b) and over 360 s (c); the latter is a common standard in New Zealand for the archiving of time-dependent data. It should be noted that a preliminary analysis suggests that the extrapolation of data resolved at long sample times appears to underestimate the duration and frequency of high intensity events, so that there is a need to establish an archive of highly resolved rainfall records. The application of such datasets to fields such as soil erosion or microwave communications is clearly desirable.

7. Conclusions

Detailed experimentation with a range of configurations of the dropper gauge has shown that it is possible to construct a high-performance instrument whose calibration is independent of rainfall intensity. Consideration of the factors involved in the control of flow through a dropper gauge showed that a simpler, more robust version could be constructed that can provide acceptable performance provided that calibration is performed over a range of rainfall intensities. Using the simpler dropper unit, a rain gauge with an onboard data logger has been described for operational use in the field and capable of resolving rainfall to 1/160 mm and of coping with rainfall intensities up to about 250 mm h^{-1}. In moderate or heavy rain, events can be temporally resolved to 15 s, which is close to the expected natural limit of coherence. Instrumental uncertainties are less than those associated with the natural differences to be found between adjacent, identical standard gauges, and maintenance is minimal owing to the lack of moving parts. Experience with the dropper gauge has shown that coherent rainfall structures often have a duration that is not resolvable with conventional instruments and that these structures may be of very high intensity. The low cost of the dropper gauge, together with its robustness, provides an opportunity for the installation of extensive arrays not otherwise feasible. Through telemetering, real-time rainfall fields could be examined at full resolution and the status of the array determined. As well as having application to a wide range of practical problems, data obtained with the dropper gauge can provide information on rainfall extremes that have implications in the modeling of rain-bearing systems and the modification of rain by orographical influences.

Acknowledgments. The authors wish to thank Gordon Duvall and Steele Saunders for obtaining the Norfolk Island calibration data; the Australian Meteorological Bureau for use of their enclosure and rainfall data at the airport site on Norfolk Island; and the New Zealand Meteorological Service for use of their enclosure and rainfall data at the Kelburn site in Wellington, New Zealand. Two of us (CDS and SGB) wish to thank the Research Committee of the University of Auckland for grants awarded for high-resolution rainfall research, and another (WRG) wishes to acknowledge the receipt of a Foundation Grant CO1521. The authors also appreciate the ongoing contributions to gauge development of workshop personnel in the Department of Physics, in particular Frank Blair, Kevin George, Danny Ghent, Murray Hollis, Noel O'Brien, Harry Oudenhoven, Eric Strickett, and Steve Warrington. Comments by the two anonymous referees are acknowledged with thanks.

REFERENCES

Bradley, S. G., C. D. Stow, and W. R. Gray, 1991: Extraction of rainfall intensity data from the chart records of cumulative rainfall gages. *N.Z. J. Geol. Geophys.,* **34,** 559–561.

Breuer, L. J., and R. K. Kreuels, 1977: Rainfall drop spectra intensities and fine structures on different time bases. *Ann. Telecom.,* **32,** 430–436.

Duncan, M. R., 1993: The universal multifractal nature of radar return echo fluctuations. Ph.D. dissertation, McGill University, Montréal, PQ, Canada, 203 pp.

Folland, C. K., 1988: Numerical models of the raingauge exposure problem, field experiments and improved collector design. *Quart. J. Roy. Meteor. Soc.,* **114,** 1485–1516.

Gertzman, H. S., and D. Atlas, 1977: Sampling errors in the measurement of rain and hail parameters. *J. Geophys. Res.,* **82,** 4955–4966.

Hosking, J. G., and C. D. Stow, 1987: Ground-based high-resolution measurements of the spatial and temporal distribution of rainfall. *J. Climate Appl. Meteor.,* **26,** 1503–1539.

——, ——, and S. G. Bradley, 1986: An improved high-resolution rainfall-intensity gage. *J. Atmos. Oceanic Technol.,* **3,** 536–541.

Kirkham, H., 1980: Instantaneous rainfall rate: Its measurement and its influence on high-voltage transmission lines. *J. Appl. Meteor.,* **19,** 35–40.

Lin, S. H., 1975: A method for calculating rain attenuation distributions on microwave paths. *Bell Syst. Tech. J.,* **54,** 1051–1086.

——, 1976: Rain-rate distributions and extreme-value statistics. *Bell Syst. Tech. J.,* **55,** 1111–1124.

——, 1978: More on rain rate distributions and extreme value statistics. *Bell Syst. Tech. J.,* **57,** 1545–1568.

Mellanby, K., 1976: Inaccuracy in rainfall measurements. *Nature,* **264,** 167.

Norbury, J. R., and W. J. White, 1971: A rapid-response rain gage. *J. Phys. E.,* **4,** 601–602.

——, and ——, 1972: Microwave attenuation at 35.8 Ghz due to rainfall. *Electron. Lett.,* **8,** 91–92.

Seibel, R. R., 1972: A capacitor-type raingage with dc output and improved flow characteristics. *Rev. Sci. Instrum.,* **43,** 1081–1085.

Semplak, R. A., 1966: Gage for continuously measuring rate of rainfall. *Rev. Sci. Instrum.,* **37,** 1554–1558.

——, and R. H. Turrin, 1969: Some measurements of attenuation by rainfall at 18.5 Ghz. *Bell Syst. Tech. J.,* **48,** 1767–1787.

Stow, C. D., and K. Jones, 1981: A self-evaluating disdrometer for the measurement of raindrop size and charge at the ground. *J. Appl. Meteor.,* **20,** 1160–1176.

——, S. G. Bradley, and W. R. Gray, 1991a: A preliminary investigation of orographic rainfall enhancement over low hills near Auckland, New Zealand. *J. Meteor. Soc. Japan,* **69,** 489–495.

——, ——, K. Paulson, and L. Couper, 1991b: The simultaneous measurement of rainfall intensity, drop-size distribution, and the scattering of visible light. *J. Appl. Meteor.,* **30,** 1422–1435.

Wenzel, R. N., 1936: Resistance of solid surfaces to wetting by water. *Ind. Eng. Chem.,* **28,** 988–994.

WMO, 1983: Guide to meteorological instruments and methods of observation. WMO 8, 5th ed. [Available from World Meteorological Organization, Case Postale 2300, 1211 Geneva, Switzerland.]

Woodley, W. L., A. R. Olsen, A. Herndon, and V. Wiggert, 1975: Comparison of gage and radar methods of convective rain measurement. *J. Appl. Meteor.,* **14,** 909–928.