The Optimization and Calibration of a Rain Intensity Gauge

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(Manuscript received 10 October 2000, in final form 2 May 2001)

ABSTRACT

The high temporal variability of rainfall requires that measurements be taken at a high frequency for that variability to be recorded well, but most conventional gauges do not have this capability. The gauge described has a resolution estimated to be about 6 s and its measurements do capture the variability. Furthermore, the large datasets associated with high-frequency measurements can be avoided and the essential information retained by storing the data as breakpoints. These are a series of data pairs, each of which consists of the rain rate itself and the time when that rate commenced.

A gauge in which the collected rain is formed into a series of drips all of approximately the same known size was a practical choice. The design and calibration of this gauge, in which particular attention was paid to producing a robust instrument incorporating standard components wherever possible, is described. Long-term comparison in the field with a collocated tipping bucket gauge was used in a calibration scheme in which equality between the gauges was sought for both the long-term accumulation and the short-term rain rates. Although the gauge depends on the formation of equisized drips, it was found that drip size increased slowly with rain rate, and so two calibration parameters were required to convert the time interval between drips into the mean rain rate between the drips. After an initial aging period with inconsistent drip formation, the calibration was stable and the onset of the lowest rain rates (0.1 mm h$^{-1}$) could be determined to within 1 or 2 min and streaming (i.e., the series of drips merging into a continuous stream) did not occur for rain rates less than 100 mm h$^{-1}$. Some sample applications for the gauges are described: the extraction of breakpoints, the estimation of 1-min rain rates from Dine’s tilting siphon data, and their use in a field experiment.

1. Introduction

The technology for the measurement of rainfall on timescales of hours or longer is well established while for shorter timescales it is still developing. At the longer timescales, to measure rainfall implies just the measurement of its accumulation over a given interval of time at a point in space. However, this totally neglects a fundamental property of rain—its intermittency—and, compared to measuring accumulations, the determination of the ratio of wet to dry time is much more difficult. Measurements at short timescales provide information on rainfall intermittency and consequently on the mean rain rate during periods of continuous rain between dry times. Such measurements are required for the scientific assessment of the phenomenon of rainfall itself and are essential to some users, such as soil conservators and communications engineers.

Two words were emphasized in the paragraph above: point and continuous. Spatially, measurements cannot be made at a point and usually rainfall is collected over an area of a few hundred square centimeters. In an analogous way, temporally, accumulations cannot be made at an instant, but rather over some collecting interval. Thus, simplistically, better assessment of the instantaneous point rainfall rate would be achieved by reducing both the collecting area and interval. Consider also that rain gauge measurements are generally stored as the accumulation (or mean rate) over a fixed period. If the period is too long compared to the scale of the variation of rainfall, then the fixed period representation is a poor approximation to reality. On the other hand, attempts to improve the situation by using shorter periods not only lead to large datasets but are ultimately limited because rainfall is a discrete process.

Rainfall occurs as raindrops and, in the limit, during what could sensibly be recognized as a time of rainfall, there would be large oscillations from no rain (observations between drops) to intense rain (observations during drops). However, Marshall and Palmer (1948), Joss and Waldvogel (1969), and Torres et al. (1994) relate the distribution of raindrop size to a rain rate that can be termed the ambient rate since it is a steady rate applying for an arbitrary period during which—and to an arbitrary volume over which—the distribution of raindrop size is stationary. Thus the fundamental point measurement for rainfall, rather than raindrops, is the temporal variation of the ambient rate. From both plu-
viographs (Sansom and Thomson 1992) and the current gauge (see Fig. 11), this can be well approximated as a series of periods of arbitrary length each with the rate constant throughout and with its end defined by an abrupt change of rate. This type of temporal variation could be stored as fixed period amounts/rates but would result in large datasets as a short fixed period would have to be used to accurately locate in time when a change in ambient rate occurred. Also, the actual time of change would not be accorded any particular importance whereas it is fundamental. Both these objections are overcome by using breakpoints, which, essentially, are the times when the ambient rain rate changed and the breakpoint dataset consists of those times and the associated rates or, equivalently, the durations of steady rates (with dry times having zero rate). Further details regarding breakpoints and their use can be found in Sansom (1992) and Barring (1992).

One motivation for developing the rain intensity gauge (RIG) described in this paper was to enable the efficient collection of breakpoints. Thus, to adequately sample the ambient rate, the RIG could well use a standard collecting area, but needs to be designed to take measurements at a high frequency to accurately locate the breakpoints. Disdrometer data (i.e., limiting case measurements at a high frequency to accurately locate in time when a rate change would not be accorded any particular importance whereas it is fundamental. Both these objections are overcome by using breakpoints, which, essentially, are the times when the ambient rain rate changed and the breakpoint dataset consists of those times and the associated rates or, equivalently, the durations of steady rates (with dry times having zero rate)). Further details regarding breakpoints and their use can be found in Sansom (1992) and Barring (1992).

Fig. 1. An exploded schematic vertical cross section through the RIG. The components are labeled, identified in the accompanying key, and have their functionality described in the text. When assembled, 11 fits snugly into 10 and they both sit right down into 2, which screws onto 3; 1 is held in 2 by 7 and 4 screws onto 2; 6 are inserted into 4 and are soldered onto 5; the outlet of 4 passes through 5 and has 17 pushed onto it, and 18 is inserted into the end of 17.

The RIG design adopted was a simple one with no moving parts or complicated electronics and is based on the gauge of Stow et al. (1998) (hereafter STW gauge), who improved on that of Norbury and White (1971). It forms rain into equal-sized drips that are counted electronically and are small enough for the gauge to follow changes in precipitation rate taking place over short periods of time. Indeed, the precision and accuracy of the gauge depends on the drip size being as small and consistent as possible but these are not entirely compatible and some optimization is required for the drip forming part of the gauge. Another component of the optimization is the relationship between the drip and funnel sizes. For a given drip size, the larger the funnel the smaller the amount of rainfall each drip represents and, as the rain intensity increases, the rate at which drips are formed also increases until eventually individual drips cannot form and a single stream of water results. The rain rate beyond which “streaming” can be tolerated needs to be considered in the design. The general specification was that the onset of the lowest rain rates (0.1 mm h\(^{-1}\)) should be determined to within 1 or 2 min and that streaming should not occur for rain rates under 100 mm h\(^{-1}\). Higher rain rates do occur—300 mm h\(^{-1}\) has been observed—but are extremely rare with all rates over 100 mm h\(^{-1}\) only covering about 0.001% of the time in New Zealand, where the RIGs were deployed. Furthermore, restricting the funnel size to shift streaming to higher rates would result in poorer temporal location of low rates.

The gauge performance, with respect to consistency of drip size, was found to improve with time spent in the field, in a fashion similar to that found by Stow et al. (1998). Indeed, the initial calibrations performed in the laboratory were unstable and no steady calibration figures were achieved until the gauge had spent several weeks in the field. Also, the laboratory calibrations of a new gauge bore little resemblance to its final “aged” calibration factors. Further details concerning the principle of the drip gauge are given in section 2 with a description of the particular implementation. Sections 3, 4, and 5 will describe how the gauge was calibrated, how it performed and compared to the STW, and some initial applications. Section 6 is a summary and will describe what future developments might be considered.

2. Rain intensity gauge

The principle of the rain intensity gauge is that for a sufficiently low flow, the stream of water emitted from the end of a hollow needle breaks up into a series of drips. If all the drips are of equal size, then the flow can be estimated by counting the number of drips. To achieve equisized drips the diameter of the needle must be small enough for each drip to completely fill the cross section of the needle, otherwise drips of arbitrary diameter would form somewhere on the needle’s rim. Given such a needle mounted vertically with a low inflow from above, a drip will form at the exit end and grow until its weight provides sufficient force to overcome the surface tension holding it in place. Drips of water
Fig. 2. Calibration results for the four RIGs. These are log–log plots of the time between drips against the rain rate with fitted regression lines whose intercepts and slopes are shown together with their standard errors in parentheses.

with a diameter of the same order as that of the needle are formed.

An implementation of the RIG is shown in Fig. 1 as an exploded cross section and the numbers quoted in this description are those used in Fig. 1. The collection ring (23) at the top defines a collection area 200 mm in diameter from which the rain is funneled down to the shuttle (10). This with its filter (11) provide a barrier to insects and leaves etc. and a hydraulic decoupling between the funnel and needle (1) where the rain is converted into a series of drips. These fall from the needle through the contact chamber (4), which is fabricated from an electrical insulator and holds two electrodes (6). These are held apart but are close enough so that each drip as it passes will complete an electrical circuit and cause the circuitry on the printed circuit board (PCB) (5) to output a pulse that can be passed to a logger. There is sufficient space within the gauge’s cover (22) to hold a small logger and some batteries. After passing through the contact chamber (4), the rain is drained from the gauge through a rubber outlet tube (17) terminating in a filter (18) that prevents insects entering. This design is similar to that of the STW with the main differences being to the design of the needle and the particular attention that was paid to producing a robust instrument incorporating standard components wherever possible.

Two primary optimizations are required in the design of the RIG: the collection area and the needle’s inner diameter. The former needs to be large enough to gather sufficient water when rain rates are low and so generate enough drips for such rates to be determined. However, it needs to be small enough so that at high rates the amount of water collected is not enough to cause streaming. Also to prevent streaming at all but the highest rain rates, the needle’s inner diameter needs to be large enough to cope with the amount of water collected. However, apart from being small enough to be completely filled by the drips to ensure they are equisized, it also needs to be small enough for drips to form quickly so that the gauge will have high temporal resolution. For example, if a
FIG. 3. The dependence of the rain accumulation/drip on the rain rate. The points are plotted using the gauge number and a robust locally weighted trend line through the points is given.

rain rate of 10 mm h$^{-1}$ gave only one drip in a minute, then the duration of a period of rain at that intensity could only be determined to the nearest minute and typically durations of 10 mm h$^{-1}$ only rarely exceed 10 min (Sansom 1999), so the minimum duration error would be 10%. Furthermore, finding the time at which a change to a smaller rain rate took place would have a larger inaccuracy, since the time between drips would increase, so it would be difficult to follow even the low-frequency fluctuations of the rain rate.

The absolute sizes of and balance between the collection area and needle’s inner diameter were reached through the specification of the gauge and a series of trials. As a starting point, the standard size casing (22 in Fig. 1) as used with many tipping bucket gauges was a convenient choice. This set the collection area, and a suitable inner needle diameter was found, which enabled the RIG to meet its specification, although the casing’s upper orifice could have been choked down if necessary. This choice of needle size was, as noted above, the other main difference from the STW and the size chosen led to a doubling of the number of drips resulting from 1 mm of collected rain despite a near doubling of the drip size, that is, finer quantisation of rainfall amount but not at the cost of drip size.

3. Calibration

a. Laboratory calibration

Four gauges were constructed and calibrated by feeding a steady stream of water into the collection area and counting the pulses generated by the PCB. The inflow was regulated by a needle valve tap and the outflow collected and measured. For a range of drip rates, the total number of drips over a measured time gave the time between drips ($t$, in s) and the collected volume over that time together with the collection area gave the rain rate ($R$, in mm h$^{-1}$). If the drips formed were equi-sized, then $R$ would be inversely proportional to $t$ with the constant of proportionality being the size of each drip in terms of the equivalent rainfall accumulation that each drip represents ($V$, in mm). Thus

$$R = kV/t,$$

where $k$ is 3600 (i.e., the number of seconds in an hour) and a regression of log $R$ against log $t$ would have an intercept of log $kV$ and should yield a straight line of slope $-1$.

Figure 2 shows the calibration plots for the four gauges. All of the slopes are less negative than $-1$, by about two standard errors for gauge 1 with $t = (1 - (-0.943)) / 0.03 = 2$ but about one standard error for the other gauges so individually the slopes are not significantly different at the 5% level from a slope of $-1$. However, the probability that all four would be one or more standard errors less negative than $-1$ is less than 0.001 and much doubt is cast on $V$ being strictly independent of $R$. Any dependence can be determined since for each calibration run $V$ was measured as well as $t$ and $R$. Figure 3 is a plot of $V$ against log $R$ for all the gauges with the gauge number being used as the plotting symbol and a robust locally weighted trend line added. The gauges can be
used together in this figure since there is no strong bias that any gauge has values either consistently above or below the trend line. The figure falls into two distinct regions: for the lower rates the drip size increases slowly with only a small scatter about the trend; for rates higher than about 15 mm h\(^{-1}\) the scatter becomes much greater and the drip size decreases. The low-rate scatter just illustrates the ongoing variability in the drip size, but the scatter at higher rates most likely results from none of the gauges being sufficiently aged.

The aging process is still not well understood, but of interest was the deposition, in sufficiently aged gauges, of a light-brown discoloration on the surface of the needle where the drips form. While it seems unlikely that such a permanent deposit would be highly soluble in water, it is likely that it is hydrophilic and so at least partly soluble in water. Also, unless it is either an oxidation product or an insoluble wind deposit, which are both unlikely, it must arrive in the rain and be left behind during evaporation, so it could be a simple soluble salt. Therefore, samples were extracted from the discolored surface by washing with methanol and water. These were chemically analyzed using an ion chromatography system that, essentially, gives the ionic composition of the extracted samples—the methanol may also have extracted a few organic compounds. The major cation found was sodium with smaller amounts of potassium and calcium also present, and the anions were almost equal amounts of chloride, nitrate, and sulfate, that is, typical of rainwater or seawater. Thus the aging may simply be the time required to accumulate an equilibrium—some is washed away but redeposited each rain event—amount of the substances dissolved in rainwater.

b. Field calibration

The only amelioration for aging is time and/or enough rain through the gauge and so, after exposing them for several weeks until their operation seemed stable, the gauges were deployed at various locations around New Zealand where they could finish aging in situ. They were collocated with 0.2-mm tipping bucket gauges (TBGs) to act as the calibration standard. Data loggers were installed with each RIG–TBG pair and the number of drips or tips were logged every 0.5 s with a record only being written if at least one drip or a tip had occurred; more than one tip would be unlikely as it would imply a rate over 1440 mm h\(^{-1}\). Since the casings of both the RIG and TBG were identical, any undercatchs of rain by the gauges due to the wind would be similar and would not have biased the calibration. The TBG also suffers from some loss during the tipping action but, since this only amounts to a few percent at rates of 100 mm h\(^{-1}\) or more and the catch for those times would typically be under 1 mm, the extra—compared to the TBG—RIG catch would only be that from a few drips and of much less concern than losses due to streaming.

The data gathered during January, February, and March 1999 from the RIG–TBG pair deployed in the far north of New Zealand at Kaitaia (35°8’S, 173°16’E) is shown in Fig. 4. The upper panel is similar to the panels of Fig. 2 except greater ranges are covered for both the time between drips and the rain rate. Indeed, the figure shows that the RIG has met its specification with rates of about 0.1 mm h\(^{-1}\) having a 1–2-min interval between drips and for the high rates up to 100 mm h\(^{-1}\) were measured. The outlying points at high rates result from streaming, that is, drips are not formed, and thus are “missing,” giving fewer drips than expected and, hence, a longer interval between drips.

Each point in the upper panel of Fig. 4 represents a mean rain rate during the interval between one tip and the next of the TBG and the mean time between RIG drips over the same interval. Note that there should always have been about 60 drips between tips since 0.2 mm of rain is measured by each tip and each drip and, as will be shown below, is approximately equivalent to 0.003 mm of rain. As before the slope of the regression, shown as a dashed line, is not −1 as would be expected if V were independent of R, but now the slope is highly significantly more negative than −1 rather than the less negative of Fig. 2. (The slope and intercept shown were derived after discarding the outliers shown as the larger dots in the figure.) The lower panel of Fig. 4 uses the same data as that used in the upper panel and is similar to Fig. 3 with a trend line shown by the thinner solid line. The thicker line is a regression line that has a highly statistically significant slope and is never more than 10\(^{-4}\) mm from the trend line. Thus the dependence between V and log R can be taken to be linear, and if

\[
V = V_o(1 + b \log R),
\]

then, provided \(b \log R\) is less than unity in magnitude and is small enough for the approximation \(\log (1 + x) = x\) to be valid then (1) yields

\[
\log R = (\log kV_o - \log t)/(1 - b). \tag{3}
\]

Thus a regression of \(\log R\) against \(\log t\) now has an intercept of \(\log kV_o/(1 - b)\) and a slope of \(-1/(1 - b)\) that with \(b\) small and positive, is, as was found, slightly more negative than −1. This is consistent with the observations of Stow et al. (1998) who saw a decrease in the number of drips per millimeter of accumulated water as the rain rate increased.

These field calibration parameters (i.e., the intercept and slope shown in the upper panel of Fig. 4) are significantly different than those found in the laboratory calibration (i.e., the intercept and slope shown in Fig. 2 for gauge 1). Also a steadily increasing trend of the drip size with rain rate has been found that differs from that shown in Fig. 3. Thus it seems likely that the RIG had been aged sufficiently and Fig. 5 is a time-ordered plot of the drip size corrected for rate by (2); that is, \(V_o\) has been plotted. The figure shows that the drip size has significant variability but the trend line shows no
FIG. 4. Field calibration results for the RIG deployed at Kaitaia. The upper panel is a log–log plot of the time between drips against the rain rate with a fitted regression line whose intercept and slope are shown together with their standard errors in parentheses. (The points shown by larger dots were not included in the regression.) The lower panel shows the dependence of the rain accumulation/drip on the rain rate and a robust locally weighted trend line through the points is given by the thinner line. The thicker line is a fitted regression line whose intercept and slope are shown together with their standard errors in parentheses.
steady tendency as might be expected if the gauge were still aging.

The largest dots plotted in Fig. 5 (and another two, unplotted as they had drip sizes of over 0.007 mm) are the streaming cases shown by the six larger dots near the top of the upper panel in Fig. 4. Streaming results in fewer drips and so they will seem to have been larger. The next larger dots in Fig. 5 show the occasions when the rain rate was at most 0.1 mm h$^{-1}$. These will include many times when a period of light rain was insufficient to form a drip and dry periods, as well as wet ones, would make up the interval between tips. Such periods, which will still contain the normal 60 or so drips between the tips, may last several days and partially formed drips hanging from the needle might occasionally be induced to fall prematurely through wind vibration or the like. Small drip size caused in this way may happen after rain of any intensity, but is probably more prevalent for the lowest rates since, being associated with the longest times between tips, more occasions will occur when a partially formed drip may prematurely fall.

c. Optimization

Using the calibration parameters—intercept and slope—shown in the upper panel in Fig. 4, the total accumulation of rainfall estimated by the RIG is 306.4 mm during the time that 300 mm was measured by the TBG. A 2% difference between these gauges—one of which is primarily designed to estimate rates at a high temporal resolution rather than total accumulation over a long period—is acceptable. However, even that small discrepancy can be eliminated by a suitable choice of the calibration parameters, that is, the intercept \( a \), and slope \( b \).

In determining this “better” choice it was found that there was not a single point in the \((a, b)\) plane that resulted in the RIG and TBG agreeing exactly regarding the total rainfall accumulation; rather a set of points along a line gave exact agreement. The line was determined by finding, for a grid of values over the \((a, b)\) plane, the percentage difference at each grid point of the accumulation derived from the RIG to that from the TBG and then contouring the result. The exact agreement line is shown in Fig. 6 as the one labeled with 0 indicating that along that line there was 0% difference; the lines labeled 5 and −5 define the limits of 5% difference between the gauges. It can be seen that these lines are more dependent on \(a\) and \(b\), and that most \((a, b)\) pairs defined by this line would lie outside the scatter of the upper panel in Fig. 4. Thus, another method of optimizing \((a, b)\) is required.

Since the RIG is mainly intended for measuring rain rates, this new method should optimize the rate estimated by the RIG against that from the TBG. Applying the regression-derived \((a, b)\) to the RIG drip counts gave RIG-estimated rates, and a regression between those and the TBG rates had a slope of 1.014, rather than the 1 expected if they had agreed perfectly. As with the difference in accumulation, the difference is small but could be eliminated by an suitable choice of \((a, b)\). However, the TBG is a poor estimator of rates, especially low rates, and so only those occasions when the interval between tips was no more than 2 min were considered, that is, the TBG estimated rate was over 6 mm h$^{-1}$. The slope of the regression line between RIG and TBG rates was determined for a grid of values over the \((a, b)\) plane and the result contoured. As with the first optimization, there was not a single point in the \((a, b)\) plane where the RIG and TBG rates most closely agree but again a set of points along a line. The exact agreement line is shown in Fig. 6 as the one labeled with 1 indicating that along that line the slopes of the regres-
sion lines between RIG and TBG rates were 1; the lines labeled 1.1 and 0.9 define the limits of 10% difference with respect to rain rate between the gauges.

As before, most \((a, b)\) pairs defined by this line would lie outside the scatter of the upper panel of Fig. 4, but now these lines are equally dependent on both \(a\) and \(b\) and cross the line showing the \((a, b)\) pairs which resulted in the RIG and TB accumulations being equal at an angle sufficiently large for the intersection to be well defined. Thus, the \((a, b)\) pair where the lines marked 0 and 1 in Fig. 6 intersect (i.e., 1.0519, -1.0638) simultaneously satisfies exact agreement between the accumulations and the rain rates. This pair also represents a line within the scatter. Using these calibration parameters, the RIG accumulation was 299.5 mm, which is 0.2% less than that of the TBG, and the slope of the regression of the RIG rates to the TBG rates was 1.0006.

4. Performance of the RIG

Because the calibration ensures that any differences in a collocated TBG are minimal, the RIG’s performance is acceptable with respect to those aspects of rainfall that the TBG can handle. However, the following questions arise. (a) Is the performance of the RIG acceptable in comparison with the STW? (b) Does the calibration need constant adjustment as time goes on? (c) Is the amount of streaming acceptable? (d) Is the RIG measuring short-term rain-rate fluctuations or just noise in the size of the drips formed?

a. Comparison to STW

Data from a RIG and collocated STW were collected for several weeks and the top panel in Fig. 7 shows the wettest 12-h period during that time, and that the difference between the temporal variations of the rates from the RIG and STW is barely perceptible. Also shown are the accumulation curves in which a small discrepancy (RIG 32.8 mm, STW 32.6 mm; that is, a 0.6% difference) can be seen to have started during the second hour, which is shown on a larger scale in the middle panel of Fig. 7. The discrepancy resulted from the 10 min at about the 1.8-h mark where the STW rates were noticeably lower than those of the RIG; this was the only period during the 12-h record with a significant difference.

The calibration of the RIG in this case was achieved by finding the \((a, b)\) pair that maximized the \(R^2\) of a linear regression between the calibrated RIG and the STW given that the slope should be unity and the intercept zero. The bottom panel in Fig. 7 shows the scatter of the RIG and STW rates and the regression—from which an intercept is excluded as it was not significant—one line has an \(R^2\) of 92.3% and a slope of 0.9964. Thus the RIG performs at least as well as the STW. However, since the number of drips in fixed periods forms the basic dataset, the rate as measured by the STW is discretized as can be easily seen in the bottom panel in Fig. 7. Discretization also affects the rate as measured by the RIG but is finer since more RIG drips are required for each millimeter of accumulated rain. Furthermore, to enable the comparison of Fig. 7 some of the time resolution of the RIG was lost by accumulating the drips into 15-s periods, that is, the time resolution, and logging period, of the STW.

Thus not only is the RIG an improvement with respect to the STW because there are more drips in each mil-
Indeed, even applied to subsets of the actual calibration observations poorer agreements would result since, as illustrated by Fig. 5, to achieve continuous close agreement \((a, b)\) would need continual adjustment. This would be difficult to implement and, in any case, invalid since the TBG is far from being an absolute standard. What is required is a calibration over a sufficiently long period—or throughput of rain—that for all such periods the same \((a, b)\) leads to close agreement between the RIG and TBG.

However, this will only be the case if the calibration is stable. A period during which the TBG measured 300 mm of rain had been used to establish Fig. 6 and to check calibration stability further periods of 300 mm were processed for Kaitaia and for three other localities where RIG–TBG pairs had been deployed. These localities were Motu \((38°17′S, 177°31′E)\), Wallaceville \((41°8′S, 175°3′E)\), and Reefton \((42°7′S, 171°52′E)\) and Fig. 8 summarizes the calibration results with each column of the figure being for a different RIG. The top row panels are each similar to Fig. 6 with a pair of lines, one labeled 0 and the other 1, for each independent TBG throughput of 300 mm. From the open circles, which mark the \((a, b)\) where the lines intersect to define the calibration parameters, it can be seen that, generally, there is little variation in calibration between the 300-mm throughputs of rain. The largest difference appears to be at Wallaceville where the first period of 300 mm gave the \((a, b)\) at the bottom left of the circle grouping; being the first it may be that the gauge was still aging.

For each column in Fig. 8 the calibrations used in the middle and bottom rows are the mean of the \((a, b)\) pairs in the corresponding top row. The middle row shows the scatter of RIG rates against TBG rates for all 300-mm throughputs. A 1:1 line is also shown and, by cutting through the center of the scatter, indicates that the mean of the \((a, b)\) pairs provides appropriate calibration parameters. For Wallaceville the 1:1 line appears less centrally placed than for the others; this may be due to the possibility mentioned above that the gauge was not fully aged when deployed. The bottom row shows the distributions of the difference between the RIG and TBG accumulations for every throughput of 20 mm. A thick vertical line located at the mean difference is also shown and, by being about zero, again indicates that the mean of the \((a, b)\) pairs provides appropriate calibration parameters. Even for Wallaceville the mean difference is close to zero; however, it is the location where the range of differences is greatest.

b. Stability of calibration

The close agreement between the RIG and TBG reached by the optimal calibration scheme is, of course, dependent on the observations so the same \((a, b)\) pair applied to other observations from the same gauges would not necessarily lead to such close agreement. Indeed, even applied to subsets of the actual calibration observations poorer agreements would result since, as illustrated by Fig. 5, to achieve continuous close agreement \((a, b)\) would need continual adjustment. This would be difficult to implement and, in any case, invalid since the TBG is far from being an absolute standard. What is required is a calibration over a sufficiently long period—or throughput of rain—that for all such periods the same \((a, b)\) leads to close agreement between the RIG and TBG.

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The small scatter of the \((a, b)\) pairs would appear to indicate that the calibrations are stable and this is vindicated by the centrally placed 1:1 lines through the rates’ scatter and the near-zero values for mean differences in the accumulations.

c. Streaming

The middle row in Fig. 8 also shows the times when streaming took place, that is, the outliers toward the bottom and right of each panel where a low RIG rate is associated with a much higher TBG rate. There are about 50 such occasions, which is about 0.2% of the total number of tips involved in Fig. 8. Also most of these occurred when the TBG rate was over 100 mm h\(^{-1}\) but there were 10 at Motu when rates were only 40–60 mm h\(^{-1}\). The history of these in terms of the tip times and the individual drip count records is shown in the bottom panel in Fig. 9.

Each panel in Fig. 9 shows such a history. For example, in the top panel the adjacent solid vertical lines to the left indicate that two tips of the bucket occurred in such rapid succession that the TBG experienced a mean rate of 180 mm h\(^{-1}\) between the tips. There is no sign of any drips being formed so the RIG must have been streaming up until the next tip, which is indicated by the vertical dashed line after the rapid double tip. The drips then appear at a rate of 1 or 2 every 0.5 s and this rate increases with up to 9 and 10 every 0.5 s occurring just after the other streaming event when although the TBG experienced 125 mm h\(^{-1}\), fewer drips than might be expected at such a rate were detected in the RIG.

The top two panels in Fig. 9 show the histories of the streaming that occurred during the first 3 months at the Kaitaia gauge, that is, those shown by the large dots at the top of the top panel of Fig. 4. The expected streaming pattern would be more like that shown in the second to the bottom panel in Fig. 9 where an increasing trend in the rate, shown by the upward trend in the number of drips in 0.5-s intervals, stops abruptly and a little later a decreasing trend in drip rate starts. Without the TBG tip times, the continuance of the rain during the time no drips were detected would not be known, but in this case the tip times clearly delineate the streaming. The streaming pattern is not so clear in the top two panels, but there are generally lower total drip counts between the tips; the individual drip counts are lower than those before or after—eight or more drips on either side of the second streaming event in the top panel, but only six or less within, and, the intervals between the logging of drip counts are greater.

Returning to the streaming at Motu (i.e., the bottom panel in Fig. 9), the typical streaming pattern is not apparent: the drip counts are consistently lower than expected but not to the same extent as in the other panels, the counts are larger than before or after, and the logging frequency is as expected. There is no evidence for streaming during this period, but it is not known what caused either a short-term decrease in drip size or increase in tip amount. Thus, the amount of streaming that occurs is generally for rates above 100 mm h\(^{-1}\) and is acceptable.

d. Optimal integration time

The most detailed information that could be gathered from a drip-style gauge such as the RIG is the timing of each drip formed by the needle. However, the frequency of recording drip counts may be limited since the datalogger may well have other measurements to collect and record, and, in the case at hand, records could not be made any more frequently than at 0.5-s intervals.

Also, finding the interval between individual drips to obtain the closest possible estimate of the instantaneous rate may have no valid purpose since the concept of an instantaneous rain rate is flawed (Sansom 1999; Sansom et al. 2001). Rather, the frequency of recording drip counts needs only to be high enough for both the ambient (see section 1; Sansom 1999; Sansom et al. 2001) rain rate and the times when it changes to be closely estimated.

The ambient rate defines a mean level that parameterizes the raindrop size distribution (Marshall and Palmer 1948; Joss and Waldvogel 1969; Torres et al. 2001). A sample from this is taken as raindrops pass through the collection area of the gauge during the integration time being used. Thus, assuming the integration time is less than the duration of a particular ambient rate, the measured rain rates over a series of integration periods each comprise the ambient rain rate with a small-scale fluctuation that, for a larger temporal scale, can be considered as noise. Figure 5 shows that noise also exists in the drip size, but the robustly estimated mean and standard error of the ratio of adjacent drip sizes are 1.005 and 0.12, respectively. Thus, even though the drip size tends to drift about on daily timescales, for shorter timescales the drip sizes are more consistent.

For those occasions from the data displayed in Fig. 9. Some histories of streaming events as a plot of the times of tips shown by the vertical solid and dashed lines and the number of drips logged in 0.5-s intervals shown as points. The time axis is in decimal days for the day of the year indicated in the axis label, e.g., the top panel is for 17 Jan 1999 for nearly 6 min from about 1010 New Zealand standard time (NZST). The solid vertical lines define the periods of streaming and the TBG rate for the period concerned is given at the top.
Fig. 10. RIG rain rates estimated from the mean time between drips after the drip numbers have been grouped into intervals of different length, i.e., for different integration times of 1, 6, 60, and 360 s. The breakpoints that were extracted for this period of rain are repeated in each panel as the solid trace.

When the rain rate was between 3 and 20 mm h\(^{-1}\) the mean drip volume was 97.4 mm\(^3\) with a standard deviation of 9.7 mm\(^3\) compared to about 50 and 2 mm\(^3\) for the STW for the same ranges of rain rates. The STW results are derived from direct laboratory measurements and indicate that even under ideal conditions—well-defined rain rates with sudden changes and a carefully prepared needle—significant variation in drip size occurred. The RIG values derived under less favorable field conditions, and allowing for the larger variation that would be expected for the larger drip volumes, are comparable. Furthermore, since it is under field conditions that the RIGs must operate, little value was seen in making laboratory measurements of a nonexistent “actual” drip volume. Even under ideal conditions the drip size will vary but any variation can be included within the calibration and will not greatly affect the estimate of the rain rate.

A more significant and fundamental contribution to variation in the RIG-estimated rain rate comes through the combined time and amount discretizations, that is, a number of drips is recorded in a fixed interval. For example, a steady collection rate of one drip per 0.5 s implies a rain rate of about 21 mm h\(^{-1}\) and a doubling of the drip rate implies an approximate doubling of the rain rate to 42 mm h\(^{-1}\). However, if the actual rain rate were about 30 mm h\(^{-1}\)? The RIG would alternately count one and two drips, which, simplistically, implies that the rain rate is oscillating at 1 Hz with a square wave between 21 and 42 mm h\(^{-1}\). Essentially, the discretization gives rise to spurious variation in the rain rate that, for a given drip size, can be resolved by increasing the integration time. At low rates when insufficient rain is collected to form a drip every half second, the gap between the rate levels is
much smaller, for example one drip every 5 s represents a rate of 2.2 mm h\(^{-1}\) while one drip every 5.5 s represents 2.0 mm h\(^{-1}\).

Figure 10 shows the first rain event that was recorded by the RIG deployed at Kaitaia as a time series plot of the rain rate. In the top-left panel the rates as estimated from 1-s counts clearly illustrate the spurious variation arising from discretization and the progressive removal of this as the integration time is increased is shown in the other panels. The rates are plotted as points at the ends of the integration periods while the “real” variation is taken to be that captured by the breakpoints, whose extraction from the raw data is described in section 5, and is shown by the same solid line in all the panels in Fig. 10. However, in the bottom-right panel where the drip counts have been integrated into intervals of 6 min, it can be seen that too much of the real variation has been removed.

Thus, the RIG can follow those short-term rain-rate fluctuations that have a timescale an order of magnitude longer than that of the drip counting frequency—or noise in the drip size—and than that of the rate variations about the ambient rate. Since the breakpoints appear to conform with an integration time of 6 s, the temporal resolution of the gauge can be also be taken to be 6 s.

5. Applications

The gauge described has been termed a rain intensity gauge since its intended primary use is for collecting information on the rain intensity rather than on rainfall accumulation. An efficient way of storing intensity data is as breakpoints, which follow the temporal variation of the ambient rain-rate and not just the progression of accumulation at fixed intervals. The breakpoints were found by quantizing the collected rain into small drips and logging the drip counts frequently. The extraction of the breakpoints is described below. Also a comparison between the RIG breakpoints and those from an earlier gauge is described as is a use of the RIG that relied on its high temporal resolution but did not involve breakpoints.

a. Extraction of breakpoints

The major source of breakpoint data has been the paper charts, or pluviographs, from gauges like the Dines tilting siphon (DTS) gauge from which the breakpoints are digitized. More recently the data from STW gauges became available and a method of extracting the breakpoints was developed (Sansom 1997). The principle of the extraction method is that a day’s data could be displayed as an accumulation versus time plot with a point plotted every 15 s (i.e., the temporal resolution of the gauge) but most of the structure of the plot remains if only a small subset of the data is retained. A line between the first and last points of the plot would form the coarsest approximation but within all the other data points there is at least one that is the most important because it is farthest from the first approximation. Retaining that point results in a second better approximation to the full accumulation versus time plot and again there will be a point that is farthest from this new approximation. In this way all the points can be ranked and, through criteria established by Sansom (1997), points below a certain rank can be discarded leaving a subset that forms the breakpoints for that day’s data and an estimate of the variation of the ambient rate through the day.

This method could now be applied to the RIG data except the drip counts were integrated into 6-s periods giving a temporal resolution of 6 s rather than the 15 s of the other gauges. This was done in light of Fig. 10 from which some integration of the raw data was shown to be desirable, and because the manually digitized data had been archived with a temporal resolution of 0.1 min. Figure 11 shows a time series plot of the RIG rates estimated from 0.5-s drip counts with the resulting accumulation scaled to fit, and the breakpoints shown by the steplike solid line. The timings of the breakpoints have been emphasized by vertical dashed lines to show that the breakpoints have generally been selected at times when the rate of accumulation changes. Some of the changes are quite subtle for instance through the period of heaviest rain, nevertheless careful manual checking confirms that the chosen breakpoints are valid through that period. Also some equally subtle changes seemed to have not been picked for instance occasionally in the period when the rates are falling from the peak rates, but no major changes have been omitted. Many other example plots were studied but Figs. 10 and 11 are typical.

b. TRIPS

From the breakpoint dataset held in New Zealand’s National Climate Database (Penney 1999) a software package, called Threshold Rainrate Information for Propagation Systems (TRIPS; Sansom and Thompson 1999), has been developed for engineers designing microwave links. For high enough transmission frequencies, the reliability of such links is mainly dependent on sufficient power being used so that signals avoid complete absorption by any rainfall along the links. Often a reliability of 99.99% is required so the rain rate that is only exceeded for 0.01% of the time is required for determining the level of operational power. The microwave industry standard rain-rate is that from 1-min integration measurements, but the only data suitable for TRIPS were from the manual digitization of pluviographs for which it was thought that the equivalent integration time was 2–3 min. Comparing RIG and collocated DTS data provided a conversion factor so that the threshold rates, which might have been derived from
1-min rain rates, could be estimated from the available data.

Only the Kaitaia and Wallaceville RIGs were collocated with DTSs. The upper panels of Fig. 12 show the upper tail of the “cumulative distribution” of rain rate for RIG data after integration into various intervals and after conversion into breakpoints; the distribution for breakpoints from the collocated DTS is also shown. These curves are not standard depictions of the cumulative distribution, but are modified to illustrate clearly the information required by the microwave link designer. For example, at Kaitaia it can be seen that the rain rate that is only exceeded for 0.01% of the whole time, varies according to the gauge and the integration time and ranges from 50 to 60 mm h⁻¹, so a standard time (i.e., 1 min) is adopted to define a unique value for the threshold rate. The curves also show that the longer integration times smooth out the higher rates and the steplike nature of their distributions at the high rate end arises since the rain rate is not continuously represented after coarse integration. The steplike trend for the 1-s integration results from the discretizations discussed in section 4d.

The tendency for estimates of the 0.01% threshold rate to decrease as integration time increases and how the estimate from the DTS breakpoints relates to the others can be seen from the top row of Fig. 12. The DTS curves down to about 0.01% seem to represent an integration time of no less than 6 min, but by 0.001% the equivalent integration time appears to be about 1 s. This change arises through the manual digitization process used to extract breakpoints from the DTS pluvographs in which a poorly digitized interval can be given a default length of 6 s and consequently a rate far in excess of the actual rate that occurred. In comparison, the RIG breakpoint curves seem well behaved and lie near the 30-s integration curves.

The lower panels in Fig. 12 are a repeat of a portion of the upper panels redrawn to clarify the variation between integration times and gauges. The panels are limited to the threshold rates that cover 1%–0.001% of the time—with the 0.01% level indicated by the vertical dashed line—and show the variation as the ratios of the distributions to that of the 1-min integration rain rate. Only for the breakpoint ratios have individual points been shown, as open circles for DTSs and solid circles for RIGs, and the trends of these ratios and those for the raw RIG data have been smoothed to clarify what differences arise when an integration time other than 1 min is used. Thus, the 1-min trend becomes a horizontal line at a value of unity—as would have been the case, of course, without smoothing—while other integration times, since they are not identical to the 1-min trend, have nonhorizontal trends. For example, it can be seen...
that at Kaitaia the threshold 1-s rain rates applying to about 1% of the time are a little lower than the 1-min ones but they, on the other hand, are about 80% of the threshold 1-s rates applying to about 0.001% of the time.

For both Kaitaia and Wallaceville the results are similar since the distributions vary little at low rates but diverge widely as rain rate increases. Also the two distributions for RIG breakpoints both indicate lower threshold rates for percentages of the time over 0.01% but for lower percentages they approximate the one for 30-s integration. Finally, the distributions for DTS breakpoints both show a trend with a maximum but approximately steady ratio for percentages of the times between 0.1% and 0.01%, which is followed by a drop through that part of the distribution that was noted above as being due to poor manual digitization. Taking means over the 0.1%–0.01% range gave 1.28 and 1.23 for Kaitaia and Wallaceville, respectively, as the factor that the DTS distribution must be multiplied by to give an estimate for the 1-min integration distribution. Thus, a microwave link designer needs to increase the results from TRIPS by 25%.

c. TARPEX

A network of RIGs were deployed in support of the Otaki Precipitation Estimation by Radar (OPERA; Gray and Seed 2000) and the Tararua Precipitation Experiment (TARPEX) (http://katipo.niwa.cri.nz/salpex/TARPEX/index.html) campaigns, which aimed to elucidate the rainfall processes that lead to the orographic enhancement of rainfall; the hills concerned rise to 1500 m. RIGs were chosen specifically for their high time resolution, which made possible, through the analysis of the time series information, the proper derivation of two simple statistics. These were the fraction of time that was spent raining (duration) and the rain rate averaged over those periods when rain was occurring (conditional rate). From a comparison of these statistics for gauges upwind
to those in the hills, the likely rainfall enhancement mechanism was identified.

For periods when duration was nearly 100% at the coast and was 100% in the hills but with a higher conditional rate, it would be likely that the seeder–feeder mechanism was causing the enhancement. In contrast, periods when the duration increased to high levels as the precipitation moved into the hills, but with little change in the conditional rate, were likely to be periods of triggered convection. Thus, in a triggered convection enhancement regime, if only hourly gauge totals had been used, the dry periods between showers would have been unrecorded, and the rain rate near the coast would have been measured as lower than the actual conditional rate. Consequently, the hourly totals would show an increase in rain rate in the hills rather than in duration and triggered convection would not be distinguishable from seeder–feeder conditions. The high temporal resolution of the RIGs enables the discrimination of these two enhancement mechanisms (Gray and Seed 2000).

6. Summary and future developments

After sufficient aging, the RIGs were calibrated against collocated TBGs by choosing calibration parameters that ensured the long-term accumulations from both gauges were essentially equal and that, on average, contemporary short-term mean rain rates were also equal. The calibrations were stable as shown by the top row of Fig. 8 and were such that an increase of the drip size with rain rate was firmly established (see lower panel in Fig. 4). The RIGs performed within specification with the onset of the lowest rain rates (0.1 mm h$^{-1}$) being determined to within 1 or 2 min and streaming not occurring for rates under 100 mm h$^{-1}$. No temporal resolution had been specified and, without guidance from an instrument with a higher temporal resolution, the resolution achieved is hard to assess. However, Fig. 10 does suggest that it is about 6 s.

At a higher temporal resolution, the top-left panel of Fig. 10 would show less discretization with more levels of rain rate accessible and a smoother variation of the rate with time resulting. To achieve this the drip size would need to be smaller, which would assist in more closely defining the onset of rain, but would lead to streaming at lower rates. A conflict exists: smaller drips are necessary to follow rapid changes in rain rate as in determining the fine structure of a period of heavy rain, but smaller drips lead to more streaming and lost information. The drip size depends on the needle size and the particular size of that for the RIG and its catch area were somewhat arbitrary; thus, a more objective optimization of these sizes might increase both their performance and their temporal resolution.

The other main thrust for future development would be to determine what physical or chemical processes take place during the gauge’s period of aging so that they could be performed to artificially age the gauges. These preaged RIGs would still need extensive calibration since, as shown in Fig. 5, the drip size does vary. However, their calibration could start immediately and by doing the calibration in a high rainfall area the elapsed time required could be kept to a minimum.

Acknowledgments. This work was carried out under Foundation for Research, Science and Technology Contract CO1628. The authors would like to thank Dave Humphreys and Steve George for their work in developing the RIG and providing laboratory calibrations, Andrew Harper and Kevin McGill for deploying the RIGs and collecting their data, and Colin Tinker for contributing toward the field calibrations, as well as Jill Cainey for the chemical analysis.

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