An Automatic Recording Raingage Network for a Cloud-Seeding Experiment

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ABSTRACT

The CSIRO Division of Cloud Physics has designed and built 103 automatic recording raingages, at a cost of about $US600 each, for use in a cloud-seeding experiment. Each unit consists of a siphoned tipping bucket interfaced to a monophonic cassette tape recorder. The raingages have a resolution of 0.2 mm, and this can be recorded to an accuracy of ~2 s. Each tape can store 3000 tip events, and with a battery drain of 500 μA the units can be left unattended in the field for many months. Experience with the network has shown that ~6% of the units have failed when left unattended for 4½ months. Some examples of the type and quality of the data that can be obtained from such a network are presented.

1. Introduction

The experimental unit used in many cloud-seeding projects has been a period of one or more days. The Israeli (Gabriel, 1967) and Climax (Grant and Mielke, 1967) experiments used one day as their unit, and for the Tasmanian experiment (Smith *et al.*, 1979) the range was from 10 to 18 days. The use of long periods has been due to some extent to a desire to average over significant weather patterns, but the use of one day or a multiple of it almost certainly reflects a dependence on the daily-read raingage networks operated by most national weather services. Recent advances in the understanding of cloud processes suggest that seeding opportunities are probably not only fewer than previously recognized but also last for much less than one day (see Cooper and Marwitz, 1980). To date, however, a cheap automatic raingage with adequate time resolution has not been available, and hence the experimenter has been unable to select data from only those periods in which he believes seeding to have been effective. An associated problem for the experimenter has been the lack of raingages in sparsely populated areas. This problem could also be overcome with the use of cheap automatic raingages; control areas for the estimation of target area rainfall could thus be located wherever they were needed.

In the course of planning the CSIRO experiment in western Victoria (King *et al.*, 1979) the conclusion was reached that a recording raingage suitable for the experiment should meet the following requirements.

(i) The time resolution should be better than 5 min. This figure assumes that the network is required for an experiment in which fields of clouds are to be seeded, and where the duration of a typical seeding episode will be of the order of hours. For an experiment based on single clouds this requirement would be more stringent.

(ii) The rainfall resolution at each site should be of the order of 0.2 mm, and this unit should be measured with an accuracy of better than 2%. This latter figure assumes that the experimenter may wish to look at rainfall events producing as little as 2 or 3 mm, and that the overall accuracy when averaging over, say, 10 gages, should be better than 5%. If this requirement is not met, the gages themselves may contribute appreciably to the apparent variability in rainfall relationships.

(iii) Reliability, inter-service time, power consumption and data storage capacity must be such that the units can be left unattended in the field for a minimum of three months.

(iv) Processing of the data stored should be a straightforward exercise using existing computer facilities and a minimal labor component.

(v) The unit price should be less than about $US600, since it was expected that 50–100 would be required.

The digital recording system for tipping bucket gages described by Thomas and Merceret (1979) was considered because it met some of these requirements, but it was not adopted, mostly because of uncertainties about its long-term unattended reli-

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ability (most of their units were serviced weekly). In particular, the basic principle of recording the data in a volatile form for later transfer to a non-volatile medium did not appear appropriate for our units which were to be left in the field for 3–6 months. Consequently the system finally adopted consisted of a combination of a commercially available tipping bucket raingage, a recording system centered on a low-cost domestic monophonic cassette tape recorder, and an interface designed and built by the Division of Cloud Physics. This paper describes each of these components in detail and discusses the performance of, and some preliminary results from, the network as a whole.

2. The tipping bucket raingage

The basic elements of any tipping bucket raingage are a conical collector with its outlet above one of two buckets supported in a beam-balance arrangement. The bucket initially under the collector remains there until it has accumulated a mass of water sufficient to tip the balance. That bucket is then emptied and the other bucket positioned under the collector outlet, and the cycle is repeated. At each tip of the bucket, an electrical switch, to which recorders can be connected, is closed momentarily.

The device therefore measures quanta of rainfall determined by the details of the masses of the empty and full buckets. The accuracy and reproducibility of this quantum are determined not only by friction in bearings, etc., but also by the rate of fill of the buckets. At high rainfall rates the bucket may start to tip when the necessary volume has been accumulated, but in the non-negligible time it takes to move away from the collector outlet an extra amount of rain will have been collected. Thus, in the simplest form of tipping bucket raingage there is a degradation of accuracy of the order of 4% at rainfall rates of 25 mm h^{-1} and 8% at 133 mm h^{-1}. The Rimco tipping bucket raingage[1] (Model TBR-8) used by the Division of Cloud Physics avoids this problem by interposing a siphon device between the collector outlet and the buckets. The siphon is such that it collects a volume of water $V_b(1 + e)$, where V_b is the volume required for a bucket tip and e is (ideally) small (an examination of 25 raingages gave values of e from 0.05 to 0.36 with $\bar{e} = 0.29 \pm 0.09$). This amount is then delivered to the buckets at a fixed rate, and the precise point of tipping adjusted for this constant delivery rate. The bucket fill rate is thus independent of rainfall rate, and this enables the inherent accuracy of the device to be maintained at high rainfall rates.

While a simple tipping bucket raingage measures the quantities of rainfall quite accurately the rainfall rate is less well determined, since we obtain only a sequence of times at which bucket tips occur. If t_i is the time of the ith tip, then rainfall rate and bucket volume are related through

$$V_b = \int_{t_{i-1}}^{t_i} R(u)du, \tag{1}$$

where $R(u)$ is the rainfall rate as a function of time. In other words, the rainfall rate information is "smeared out" over the time it takes to accumulate a bucketful. When a siphon is included, the indeterminacy is increased. V_b is replaced by $V_b(1 + e)$ in (1). At first this indeterminacy would appear to cause problems at low rainfall rates, but in practice it does not. Synoptic situations with low rainfall rates, if they produce rainfall of significance (e.g., more than 2 or 3 mm), must of necessity rain for long periods, so that timing uncertainties are less critical. Conversely, the rain from a cumulus cloud may only last for 10 or 20 min, but the rainfall rates will be sufficiently high for the timing uncertainties to be of the order of minutes.

A siphoned tipping bucket, however, does generate a tip record with what seem to be anomalous rainfall rates. Because the siphon holds an amount of rain $V_b(1 + e)$, it will always deliver an amount V_be to the next bucket immediately after a tip occurs. This carryover accumulates, and causes the e^{-1}th and $(e^{-1} + 1)$th tips to occur almost coincidentally in time. This process is illustrated in Fig. 1. If one estimates rainfall rate by the simplistic technique of dividing the equivalent bucket volume by the interval between tips, spuriously high rainfall rates will quite obviously arise. The seriousness of this problem decreases as the rainfall rate is averaged over several tip events. The appendix presents two methods for obtaining, from a gage with a siphon, realistic estimates of rainfall rate with maximum time resolution.

When the principal measurement of interest is rainfall over a period of some hours, as is the case in the experiment in western Victoria, then the effect of incorporation of a siphon in the tipping bucket is minimal. At worst, the error in the total rainfall amount over the period can be two bucket tips or 0.4 mm of rain [made up of $(1 + e)V_b$ in the siphon and $(1 - e)V_b$ in a bucket], an error which is double that which could have occurred had there been no siphon. On average, the error is less than this, and is equal to $V_b/2$ (from bucket) + $V_b(1 + e)/2$ (from siphon). In any case, the errors are small when dealing with rainfall events which cause more than 10 mm of rain.

3. The cassette recorder and data storage

The data are stored on conventional audio compact cassettes used in conjunction with ordinary low-priced commercial monophonic recorders. This type

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[1] Rimco raingages are supplied by Selbys Scientific, North Ryde, Sydney, Australia. Model TBR-8 has a 203 mm collector and stands 300 mm above the surface. It has a rainfall resolution of 0.2 mm which is accurate to ±1% at rainfall rates up to 375 mm h^{-1}.

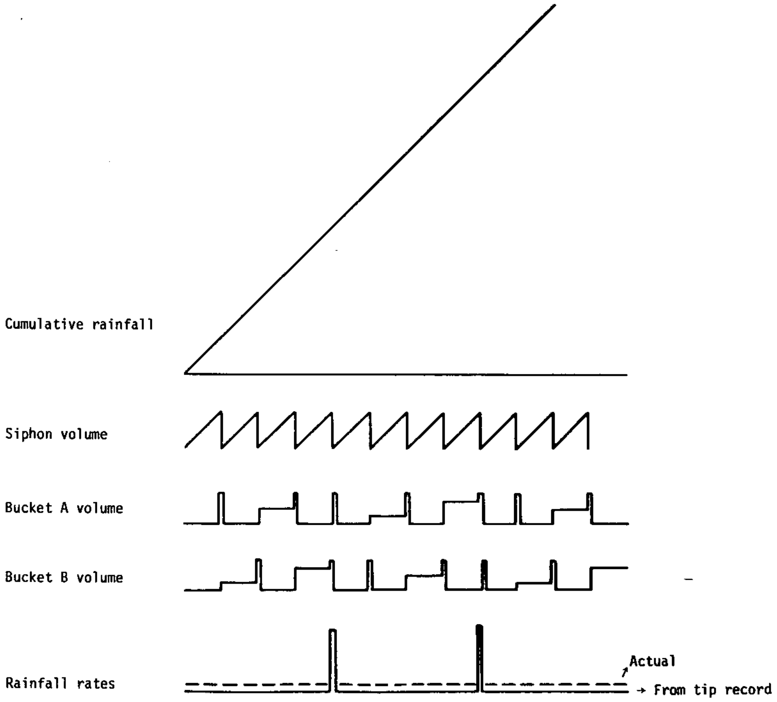

FIG. 1. A diagram showing how apparently high rainfall rates can be obtained from a simple interpretation of the tip record from a tipping bucket with siphon.

of recording device and storage medium was chosen for the following reasons:

(i) The unit price of the data recording system is low, approximately $US30. The monophonic recorder provides cheap cassette mounting hardware, i.e., cassette support and clamp, tape motor drives, record/playback and erase heads, and on/off control of battery power.

(ii) The compact cassette is robust and an ideal package for field use. As a data storage medium, it is non-volatile under normal handling and operating conditions.

(iii) Data storage density is more than adequate (see Section 4).

(iv) Battery life can be as high as 12 months if the recorder is only turned on when an event occurs.

There are two principal approaches for recording data on cassette tapes:

(a) Run the cassette tape continuously at very slow speed with timing marks imposed at fixed time intervals and a separate mark for the event. Usually a stereo system is required, with one track for the regular timing information and the other for event information (e.g., Ross, 1974).

(b) Operate the recorder in the incremental mode in which it is switched on only for that time necessary to record an event.

The advantages of the latter approach are that the data storage capabilities of the cassette tape are maximized (only event data are stored), the overall power consumption is low (power to the recorder is only turned on for a short period of time after an event has occurred), and a standard monophonic cassette recorder can be used with very little modification.

The principle of one event per record seems a desirable one to adhere to when using low-quality recorders and cassette tapes, despite the disadvantages that there is a probable decrease in reliability because of the larger number of start/stop cycles that the unit undergoes and that the data only occupy ~15% of the tape. (The balance of the tape consists of inter-record gaps that occur during the time that the recorder takes to reach stable playing speed after switch-on, and a similar period after switch-off.) Even when using such a conservative technique, there is sufficient tape on a C90 cassette tape to record 3000 events using the interface described later. With a 0.2 mm tipping bucket, the total amount of rainfall that can be recorded is more than adequate for most needs.

Investigations by Smith and Shaw (1976) suggested that, for the western Victoria experiment, a network of 50 gages would be just adequate. Accordingly, a decision was made to use 50 of each of two different recorders and to spread them uniformly throughout the experimental area.

Extensive preliminary tests were carried out on seven different monophonic cassette recorders in the price range $US25 to $US44. Any of these would have been adequate for our purposes, with the exception of one in which problems were encountered with the clutch coupling between the motor and cassette drive.

The final choice was made on the basis of mechanical drive capabilities, minimum time to stabilize supply voltage after switch on, accessibility of main power wiring, record playback head wiring, size, general power requirements, and ease of performing the necessary modification.

The recorders chosen were the National model RQ2106 and Sanyo model M2541. The main difference between these two recorders was in the time taken to reach voltage stabilization and correct tape speed. This time was 60 ms for the Sanyo and 250 ms for the National. In the interface described later the data are transferred to both types of recorder 380 ms after switch on. There were other small differences between the models, such as different head bias currents, battery voltages etc., but these were not significant.

Power for the recorder (as distinct from the interface) was supplied using C size cells (four for the National, five for the Sanyo). These were housed in the internal battery compartment. Voltage drop on these batteries during one field season of about four months was negligible.

4. The interface

This section describes the electronics which link the tipping bucket raingage to the recorder.

The major functions of the interface are to:

(i) Provide a 24 h crystal-controlled time base, together with a day counter, both of which need to be easily preset.

(ii) On closure of the raingage switch, load the day number and time of the event into a series of shift registers and start the cassette recorder.

(iii) After a delay of 380 ms, transfer this information from the shift registers to the data encoder and thence to the cassette record head.

(iv) Increment a counter for the total number of events.

(v) Switch off the recorder after the data have been transferred.

(vi) Simulate an event internally at 2400 local solar time (LST) each day so that the tape recorder is activated at this time. The main purpose of this action is to prevent the tape sticking during prolonged hot dry periods, but it also has certain advantages in assessing data integrity since it allows one to be certain that the unit is functioning even when there was no rain falling.

A block diagram of the circuit is shown in Fig. 2. A detailed circuit diagram and description can be supplied on request.

Some details of the interface include:

(a) The crystal used for the oscillator was a HyQ type K03E with a nominal frequency tolerance of ±20 ppm and calibration tolerance of ±20 ppm in the temperature range −10 to +60°C. Histograms of the clock drifts actually experienced by the units are shown in Fig. 3. For the first service period the average drift was equivalent to a slowdown of 1.5 ± 5 s per week. During the second period the drift was a slowdown of 2.1 ± 2.5 s per week. For most meteorological purposes these drifts are negligible, and no corrections were made in the time records.

(b) Each interface card does not have its own display, since this would increase cost and battery drain, but BCD[2] outputs of the day number, time and total tip counter are wired to edge connectors so that these can be easily connected to a hand-held display unit used by servicing personnel.

(c) The day number and time of a tip event are recorded in a record consisting of 32 BCD bits. The 32 bits are split into 10 bits for the day (up to 399 days), 20 bits for the time (with 1 s resolution), and two spare bits which are held high.

(d) The pulse encoder converts the 32 BCD data bits into groups of two or four pulses—two pulses for a "0" and four pulses for a "1"—by gating a 2048 or 1024 Hz square wave with a 256 Hz signal. The resulting signal is shown in Fig. 4.

This type of encoding was used to overcome any problems associated with tape speed variations that may have occurred with the cheap cassette recorders. No timing or start/stop bits are required because there are 32 individual groups of pulses which are easily detected. During playback, a period of 3 ms is allowed for each of the groups of pulses to occur. Since this is 50% longer than the 2 ms taken to record the pulses, it means that tape speed variations (even between groups of pulses) of this magnitude can be accommodated.

(e) The electrical power to the interface was supplied by one 6 V Eveready lantern battery type 409. The interface uses CMOS integrated circuits and the current drain was ~500 μA on standby. Battery life is greater than six months with this drain, with the average battery voltage falling from 6.2 to 5.6 V during that period.

5. Check and service procedures

As mentioned in Section 4, the total number of tips (including the self-generated ones at 2400 LST) is stored in a buffer on the interface board. Service personnel can interrogate this buffer and use it as a guide to the functioning of the device. The tip total should be comparable to that recorded by neighboring gages, and the amount of tape used should be in proportion to the number of tips recorded. Gages

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[2] Binary Coded Decimal.

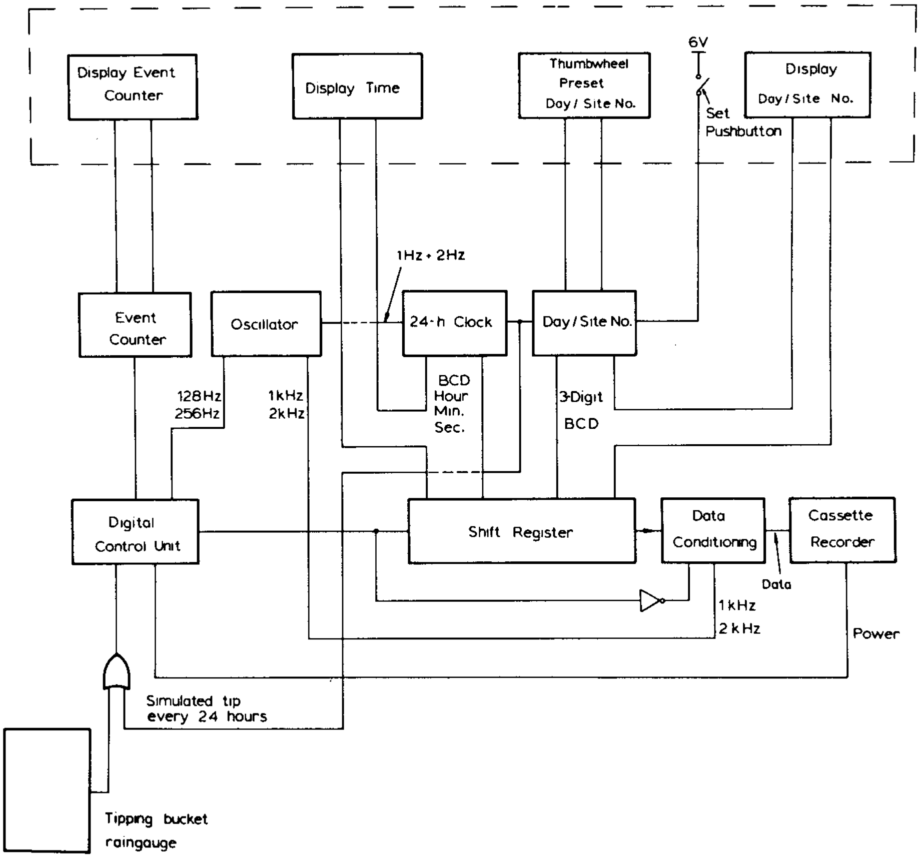

FIG. 2. A block diagram of the interface between the tipping bucket and recorder. Detailed circuits can be supplied upon request.

not satisfying these conditions can be removed for checking.

During the experiment the first and last three records on any cassette were generated (by manually tipping the bucket) with the site identification number recorded in the tape format location usually reserved for the day number. Each tape thus contained all the information necessary for data retrieval.

The servicing procedure also included a step in which the tape just recorded was played back through a conventional recorder. Each record can be heard as a characteristic low-frequency "burp", and experience showed that service personnel could readily tell whether it was of the correct frequency, duration, loudness, etc.

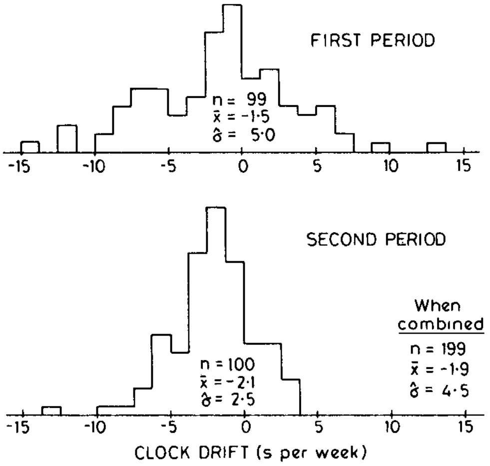

FIG. 3. Histograms of the clock drifts over the first two half-seasons. Note the decrease in spread of the drifts, presumably due to the "burn-in", during the second period.

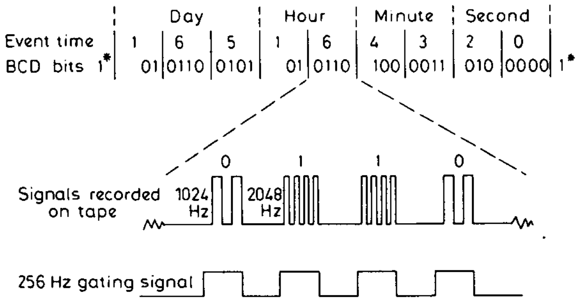

FIG. 4. Details of the manner in which the time information is encoded on the tape. The asterisk indicates bits permanently held high.

TABLE 1. Site failures during 1979 and 1980 field operations.

Cause of failure	Number of failures 1979	1980
Tipping bucket	2	2
Interface	5	5
Recorder	5	0
Cassette tape	14	6
Physical damage to site	2	2
Other	1	1
Total:	29	16

Current drain and battery voltages were also measured during installation and servicing. Units with abnormally high drain (>1 *mA*) were removed.

6. Data retrieval

As mentioned in the Introduction, some form of computerized data retrieval is necessary if the full potential of automatic raingages is to be realized. For the data tapes discussed here, which obviously do not conform to any standard computing format, a custom-designed interface is required to input the data to the computer. For our purposes, we chose to decode each group of two or four pulses into its respective 0 or 1 bit form before transmitting to the computer (an Apple II microcomputer), although the decoding could obviously be performed by the computer itself. Each tape was played back through a standard recorder, and the pulses decoded and input through two I/O ports, one line for the data, the other as a data ready line. As mentioned in Section 4, the gating time for the completion of each group of two or four pulses is 50% longer than used when recording at standard speed, thus allowing for fairly wide variations in tape speed during recording or playback. Each group of pulses is decoded and transmitted to the Apple in serial form on a bit-by-bit basis, and the 32 bits buffered in the computer to constitute a full tip record. If 32 bits are not received by the Apple in a second gated time (which is twice the time required to record them at standard speed), all of the 32 bits are set to zero. In this manner, incomplete tip records show up as a null record (all zeros), but no rainfall amount information is sacrificed.

The time taken to transfer the data from a cassette depends on the total amount of rainfall recorded, but retrieval times for our cassettes, which had recorded average rainfalls of 120 mm, were ~10 min. This time can be reduced by increasing the playback speed in conjunction with a good-quality cassette transport, but the tolerances on the gating times are consequently reduced, and in most cases it is probably not worth the extra effort unless a large number of tapes is involved.

7. Experience from the 1979, 1980 field seasons

A network of 103 gages has been deployed in western Victoria for two experimental seasons, each lasting from about mid-July to late November, and this constitutes the bulk of our experience with the units (i.e., a total of about eight months for each of 103 units). Although the experiment was conducted in western Victoria in spring, when the seasonal rainfall is ~150 mm, occurring in many light rainfall episodes, we also have some limited experience with two other units in higher rainfall climates. One of these has been stationed at Sydney for 12 months (average annual rainfall 1000 mm), and the other in a semitropical area. In the latter, over 200 mm fell in the four-week trial period, and hourly averaged rainfall rates as high as 50 mm h^{-1} were recorded. Both units performed without fault.

The Rimco tipping buckets utilize a 2 cm long by 1 cm diameter stainless steel mesh filter at the base of the collector to prevent insects, leaves, etc., from entering the siphons and buckets, and these have performed well. All of the units have been sited in grassy areas so that we have no experience of the problems that might be encountered when dust accumulates in the collector.

In western Victoria the temperatures to which the units were subjected ranged from −3 to 40°C. Laboratory cold room tests on three sets of interfaces and recorders have shown that both performed without fault when cycled from 20°C to −5°C on a daily basis for six consecutive days. During the cycling the clock frequency increased by six parts in 10^6 when cooled, but these are within the specifications for the crystals, and can account for most of the clock drifts noted in Section 4.

During the 1979 season in Victoria the units were serviced and tapes and batteries changed after 6–10 weeks, but this mid-season inspection was dispensed with in 1980 after it was found that the units had performed satisfactorily, and the units therefore were unattended for 4½ months in 1980. Clearly our experience does not cover a full year's operation, but we feel it is sufficient to give confidence that the design concepts were well founded. We present some information below relating to field operations in 1979 and 1980.

An analysis of the failures of sites is presented in Table 1. (The failures are ascribed to that part of the system which apparently contributed most to the failure.) Recall that in 1979 a complete servicing was carried out at each site mid-season, so that each site could potentially contribute two entries in the 1979 table. In 1979 there were 10 sites with non-perfect records for the first half of the season and 19 for the last half. The degradation in performance in the latter half of the season is even more accentuated when site-days lost are considered—239 for the first half

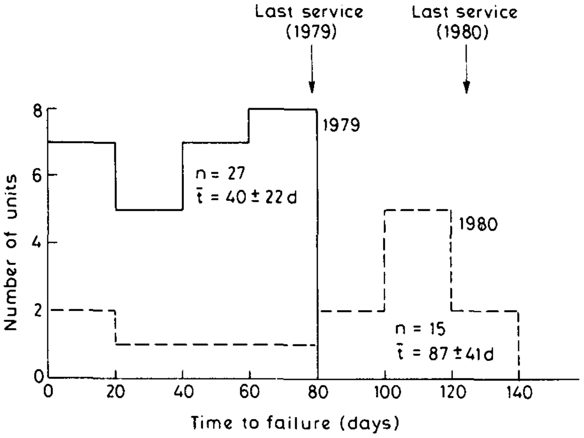

FIG. 5. Useful field life for units in the 1979 and 1980 seasons. Note that these statistics apply only to the units which failed; they cannot be used to infer a mean time to failure.

and 660 for the second half. This increase was due almost entirely to the increased number of failures due to the cassette tape jamming in its housing. The incidence of jamming, which was partly due to warmer weather, was increased by a change in the brand of cassette tape used.[2] In fact, part of the overall improved serviceability obtained in 1980 is undoubtedly due to the fact that all cassettes to be used were first run through a cassette recorder at fast-forward speeds. Eight of the 115 cassettes tested jammed or broke under this simple test, and eight potential problems were thus eliminated. In 1979, the number of lost days constituted 6% of the total site days, although 2.5% of these were outside the control of the Division of Cloud Physics (e.g., one gage was burnt by fire, another trampled by a horse, etc.). In the 1980 season 11% of site days were lost, with 4.5% of these outside our control. More site days were lost during the 1980 season, but we believe this was almost certainly due to the absence of the mid-season service. The units actually performed more reliably in 1980, as can be seen from Fig. 5. Here we have plotted the duration of the field life before failure for the faulty units of the 1979, 1980 seasons (site failures have not been included). It is apparent from Fig. 5 that many units were replaced shortly after failure occurred in 1979, and this helped to reduce the number of lost days. It is expected that, as more experience of the types of failures is obtained, the percentage of lost days will be better than ~3% for a 4–6 month period in the field.

In addition to the loss of a complete or partial record due to instrument failure, there were incidences of faulty data on the tapes. Such data can be caused by low signal strength, tape defects, incorrect tensioning of tape, etc. A preliminary investigation suggests that less than 0.004% of the total number of tips had misrecorded bits. Such tips are not necessarily discarded; since they invariably occur between apparently valid tip records, they can still be used for calculation of rainfall totals. In any case, their occurrence is rare.

These analyses show that failure of the units was invariably complete: most of the units performed well and produced high-quality data, but if there was a failure, the data were either non-existent or so obviously corrupt that there was no possibility of including faulty measurements in the complete data set.

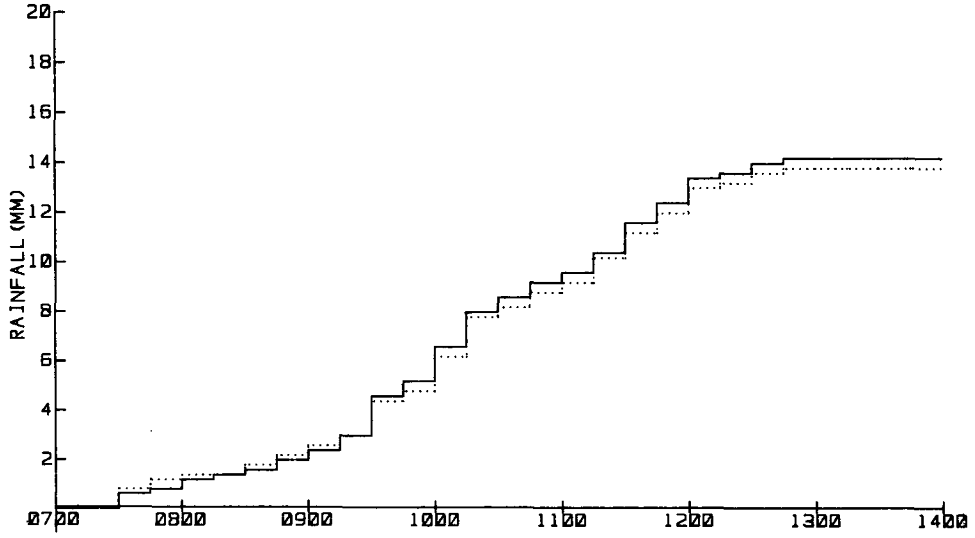

FIG. 6. Cumulative rainfall records for two gages about 10 km apart on a day of widespread uniform rain.

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[2] Information on the brands of cassette tapes used and the problems encountered can be supplied on request.

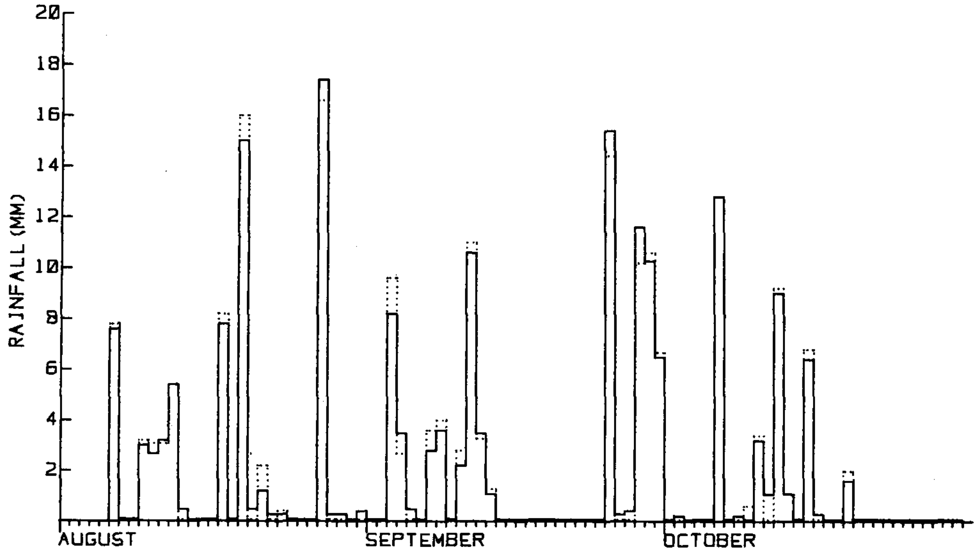

FIG. 7. Comparison between a network gage (solid lines) and adjacent daily-read Bureau of Meteorology gage (dotted lines).

8. Examples of rainfall data from the network

Some examples of the types of data that can be obtained from the network are shown in Figs. 6–8. In Fig. 6 we show plots of cumulative rainfall against time for two gages (distinguished by dotted and solid lines) separated by 10 km. The rainfall has been accumulated for 15 min intervals (no time or siphon corrections have been applied) for a period during 27 September 1979 in which there was widespread rain at a rate of about 2 mm h^{-1}. The agreement between the two records provides a good example of the relative stability of the measurements of rainfall and time. Plots of this type, and scatter plots of daily or shorter period rainfall for a particular gage against the same period rainfall for a neighboring gage or the average of several neighboring gages, are of considerable diagnostic value in assessing performance of gages.

Fig. 7 shows a comparison between a network gage and a daily-read Bureau of Meteorology gage which was cosited. The rainfall for each gage is accumulated for the 0900 to 0900 period, and the record is from 1 August to 31 October, 1979. Again, the agreement is excellent.

Fig. 8 presents cumulative rainfall records for three gages for the period 0600–1400 on 27 September 1979. The three gages are located, about 70 km

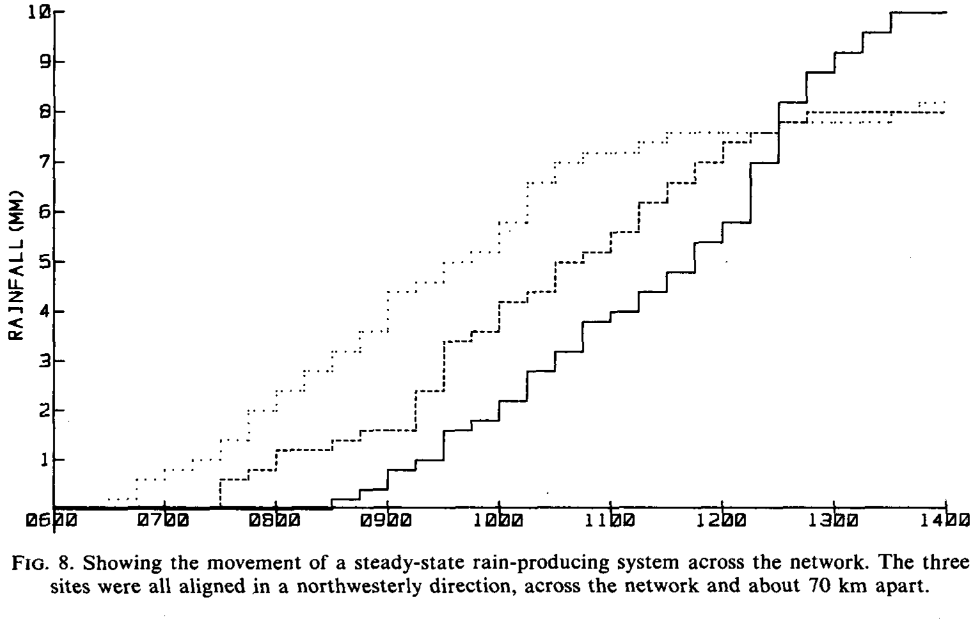

FIG. 8. Showing the movement of a steady-state rain-producing system across the network. The three sites were all aligned in a northwesterly direction, across the network and about 70 km apart.

apart, on a line which was coincident with the wind direction on that day. The synoptic analysis for the day showed the area to be under the influence of a closed low with its center situated 400 km to the northwest. The time delays between the onset of rainfall at each gage are apparent, and the steady-state nature of the synoptic situation is reflected in the constant rainfall rate. The time delays between the onset of rainfall at the three gages are consistent with movement of the system at $\sim$70 km h^{-1}. A research aircraft flying during the period established that the precipitation was originating as large ice crystals in the colder levels of the system (-15 to -25°C), and that the winds at these levels were in the range 60–80 km h^{-1}. There is thus agreement between the aircraft and raingage network observations. It is in systems such as these, with high spatial and temporal coherence, that an automatic raingage network can provide detailed information for use in seeding experiments.

These examples demonstrate only some of the information that can be obtained from the network of recording raingages we have designed and installed. This network, on the basis of our experience with it, appears to meet the requirements imposed by the cloud-seeding experiment for an inexpensive, reliable network with high time and rainfall resolution.

Acknowledgments. The authors wish to acknowledge the assistance of many people who made contributions to various parts of the work described in this paper: Mr. Ray Hobbs, who assessed the suitability of various tipping bucket raingages and recorders; Mr. Peter Ross, of the CSIRO Division of Soils, for advice on the type of recording technique that could be used; Mrs. Annabelle Craighead and Miss Alison Goulder, for help in fabricating the interfaces; Mr. Frank McClelland, of the Victorian Department of Agriculture, for assistance in site selection; Mr. Richard Phillips for maintaining and servicing the network; and Mrs. Enid Turton, Ms. Laurel Arthur and Mr. John Meadows for processing the data.

APPENDIX

Estimation of Rainfall Rates from Tipping Bucket Raingages

In discussing means of retrieving estimates of rainfall rate from the tip records of a tipping-bucket raingage incorporating a siphon, we will assume that the rainfall rate is constant between tips. This assumption cannot of course be tested with the data from the raingage itself, but to consider variations in rainfall rate within time periods in which only 0.2 mm

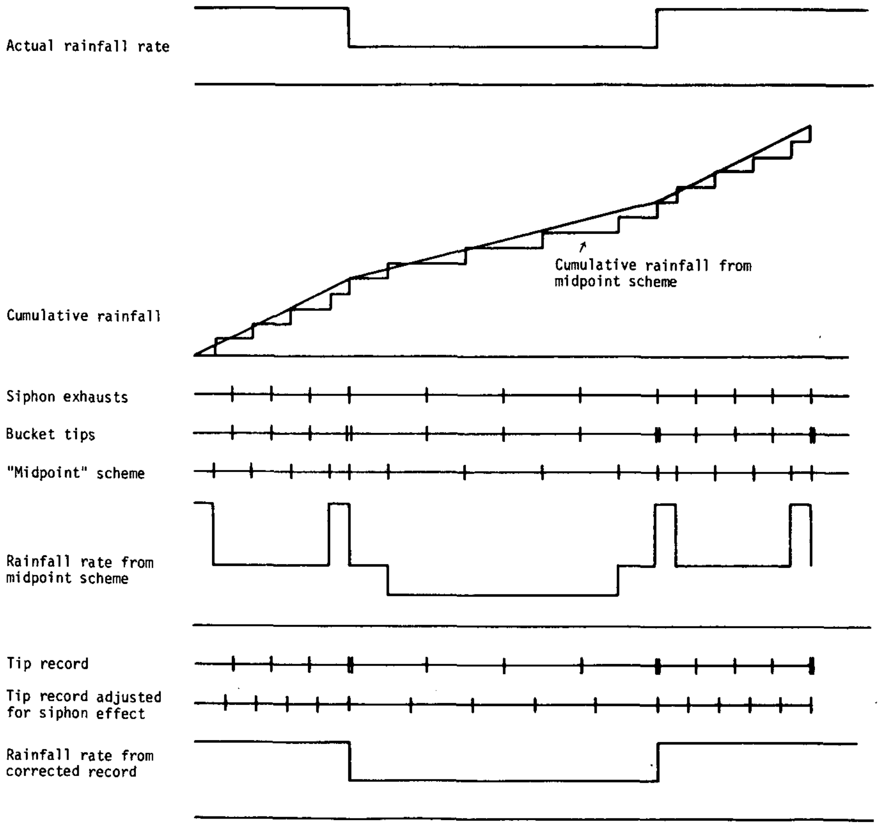

FIG. A1. A diagram showing how the midpoint and siphon correction schemes can be applied to yield realistic rainfall rates.

of rainfall accumulated is, in our context, rather academic.

Note first that the cumulative output from a tipping bucket raingage without a siphon is a series of, say, 0.2 mm steps, and that the mean-square deviation between this record and the actual cumulative rainfall can be reduced by assigning the steps to occur at time points midway between the times at which tips were recorded (see Fig. A1 for an example). The difficulty that arises at the start of the record can be overcome by arbitrarily taking the time origin to be at time $(t_2 - t_1)$ before t_1, where t_i is the recorded time of the ith tip. This is equivalent to assuming that rainfall rate is constant for the first two tips.

If the "midpoint" scheme described above is applied to a gage with a siphon, it goes some way toward removing the difficulty of anomalously high apparent rainfall rates associated with the double tips. Fig. A1 displays a record of siphon exhausts, bucket tips, etc., for the rainfall rates shown and for $e = 0.25$. The cumulative record reconstituted using the "midpoint" scheme is a reasonable representation of the actual cumulative rainfall. However, the rainfall rates are only a fair approximation, being too high by up to 60% on some occasions. It can be shown that, if the rainfall rate is assumed constant between double tip events, the "midpoint" scheme will result in overestimation of rainfall rate by a factor $2/(1 + e)$ for two of the e^{-1} tips between double tips, and underestimation by $(1 + e)$ for the remainder.

If a more precise measure of rainfall rate on the time scale of tips is required (e.g. for calibrating radars, distrometers, etc.) then the following scheme, which removes the effects of the siphon by estimating e from the number of tips occurring between double tips, could be used. Once an estimate of e is available, then the corrected time position for each tip is obtained by reducing the interval between tips by a factor $(1 + e)^{-1}$, beginning with the first tip after each double tip. This approach is illustrated in Fig. A1, where it is apparent that for a constant rainfall rate between double tips the siphon effect is removed completely. The disadvantage of this latter scheme is that it requires two passes through the data—one to estimate e and another to adjust the recorded times of the tips.

For the more usual case in which the rainfall rate is not constant between double tips, it can be shown that the errors in determining spot rainfall rates using the scheme outlined above are less than $\pm 100\, e\%$ of the rates that would have been determined had there been no siphon. It should be noted that even when using siphonless tipping-bucket raingages to determine rainfall rates, it is usual to average over several bucket tips to get meaningful rainfall rates. In this context, then, the requirement that the averaging for siphoned tipping buckets should take place between double-tip events (which are usually only 4–5 tips apart) is not a severe one.

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