A Dense Network for Rapid Measurement of Rainfall Rate*

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We discuss the design and operation of a dense rain gauge system for obtaining statistical data on both the temporal and spatial distribution of heavy rainfall. The data are collected every ten seconds from a network of approximately one hundred rain gauges spaced 1.34 kilometer in a square array which covers an area of 130 square kilometers. The rain gauge is a continuous, flow type with a response time of the order of one second. We describe the system used for recording the data on magnetic tape and give typical computer-generated rain maps for large area storms and for localized showers.

I. INTRODUCTION

Studies of the effects of rain on propagation at centimeter and millimeter wavelength have shown that attenuation by rain becomes more severe as the wavelength decreases.[1–5] The attenuation becomes objectionable at a wavelength of about 5 cm and increases rapidly. Information on the temporal and spatial characteristics of a rainfall at the surface of the earth is scant and further knowledge is needed to permit design of systems for the radio frequency bands above 10 GHz.

An experiment has been designed to obtain statistical data on both the temporal and spatial distribution of heavy rainfall in both time and space. The rainfall data are collected from a network consisting of approximately one hundred gauges about 1.34 km from each other and covering an area of 130 square km, as shown in Fig. 1.[†] The dot within each grid indicates the physical location of a rain gauge mounted at the top of a telephone pole, approximately 7.6 m above

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[*] Part of this material was presented to the Union de Radio Scientifique Internationale Commission 2 in Ottawa, Canada (May 1967).

[†] It has become clear during the course of our experiments that an intergauge spacing of 1.34 km is too large to resolve some of the rain cells.

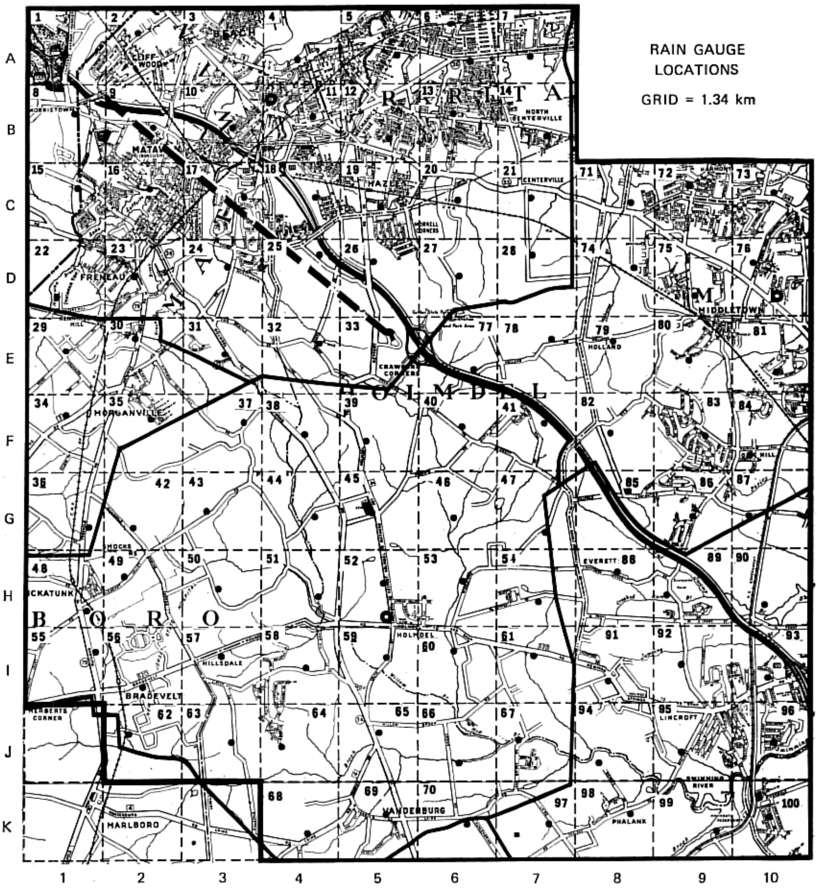

Fig. 1 — Location of rain gauges are shown by small dots in each grid. The heavy lines denote central office boundaries. The dashed line from grid 9 to grid 33 indicates the 18.5 GHz propagation path.

the ground. The heavy lines denote the boundaries of various New Jersey Bell Telephone Company central office areas. The locations of each central office is indicated by a heavy circle; the Red Bank central office serving the lower right hand area is located some distance off the map.* Also shown by the dashed line extending between grids 9 and 33, is the transmission path used in the 18.5 GHz propagation studies which are discussed in a companion paper.[4]

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* To reduce the number of telephone lines which carry information from the rain gauges, the lines are concentrated in each central office and sampling is accomplished there. This is discussed in detail in Section II.

The continuously measuring rainfall rate gauge is discussed fully in Ref. 6; therefore we give only a brief description. The gauge uses the high dielectric constant of water (approximately 80 at low frequencies) to change the frequency of an oscillator. Rain is collected by a funnel in the same manner as that used for other types of gauges; however, the collected water is directed down an inclined plane and flows between the insulated electrodes of a capacitor. Since the capacitance is a function of the amount of water flowing between the electrodes, the frequency of the oscillator is a function of rainfall rate. This capacitor is the variable element in a simple audio frequency resistance-capacitance relaxation oscillator. After the oscillator there is a multivibrator which divides the oscillator frequency by two and provides a square wave output with a fifty percent duty cycle. An emitter follower is used to couple the output to the telephone line; thus a single telephone pair can be used both for supplying dc power and for carrying the signal to the central office. A rain gauge and typical calibration curve are shown in Fig. 2.

In a manner discussed in Section II, the entire network of one hundred gauges is scanned every ten seconds; that is, each gauge is sampled for one-tenth of a second every ten seconds. This choice of scan rate (one scan per ten seconds) was limited in part by economic considerations, but, based on experience with conventional rain gauges, it was also deemed rapid enough to provide sufficient temporal resolution of rain-rate. However, these experiments have shown that one scan per second is needed to resolve some of the intense showers.* Some discussion of the errors introduced by sampling only every ten seconds is given in Ref. 4.

II. DATA ACQUISITION SYSTEM

The apparatus for data acquisition is shown in Fig. 3. The signal conditioning units, one for each line, supply dc power to the gauge from the central office 130 volt battery through a current adjustment and monitor section. The audio frequency signal from the gauge, is separated from the dc and equalized to within about ± $2\text{-}\frac{1}{2}$ dB between one and twelve kHz. All circuits from gauges to counter input transformers are carried and switched on balanced pairs.

The multiplexing is done in two stages. In each of the four central offices, a multiplex samples the lines coming into that office and concentrates them on 15 kHz program quality line, complete with equal-

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* The time constant of the capacitor-type gauge is about one second.

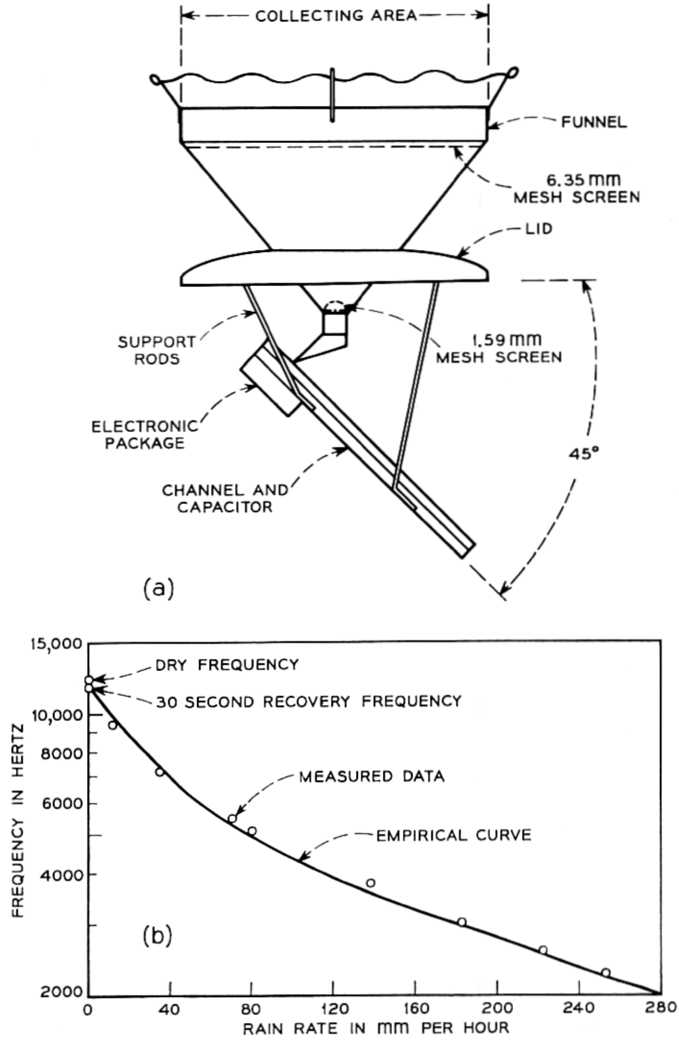

Fig. 2 — (a) Rain gauge removed from container; notice that the electronic unit is fastened to the lid for ease of inspection; (b) Typical calibration data for a rain gauge: the points represent the measured values, and the curve is empirical.

izers and amplifiers, to the master multiplex located at Crawford Hill. The master control synchronizes both the central office and master multiplexes; the latter transfers the incoming samples on the four program lines to the appropriate counter for conversion to digital data. Figure 4 shows the signal flow from a typical gauge to the recorder.

The basic part of the multiplexer is the matrix switch unit; it consists of ten vertical lines by five horizontal lines forming 50 crosspoints each of which consists of a diode in series with a two contact reed relay. Each central office multiple uses only part of its matrix switch since there are less than 50 gauges in any central office area. The master multiplex uses two matrices and each forms the base for a 50 channel multiplex. Thus two gauges can be sampled at the same time. The program for scanning the gauges (an interlaced pattern) is wired into both the central office and master multiplex.

A submultiplex consisting of one horizontal line of ten crosspoints is also synchronized with the master matrix switch and recycles every ten steps; it is used to feed auxiliary data to counter 3. The auxiliary data consists of received level on the microwave propagation path, wind velocity at Crawford Hill, and detailed data from rain gauge 33.

The master control (Fig. 3) receives a pulse every 0.2 seconds from a one hundred kHz time base; this pulse is fed to counters with counts of ten, five, three, and two times. The count-of-ten counter furnishes the vertical information for all matrix switches through a binary coded decimal to ten-line converter. The vertical information is also converted into a "two of five" code and transmitted to each central office multiplex over three pairs where it is reconstructed to ten-line for the matrix vertical lines. The five times counter, through a binary coded decimal to ten-line converter, drives the horizontal matrix lines.

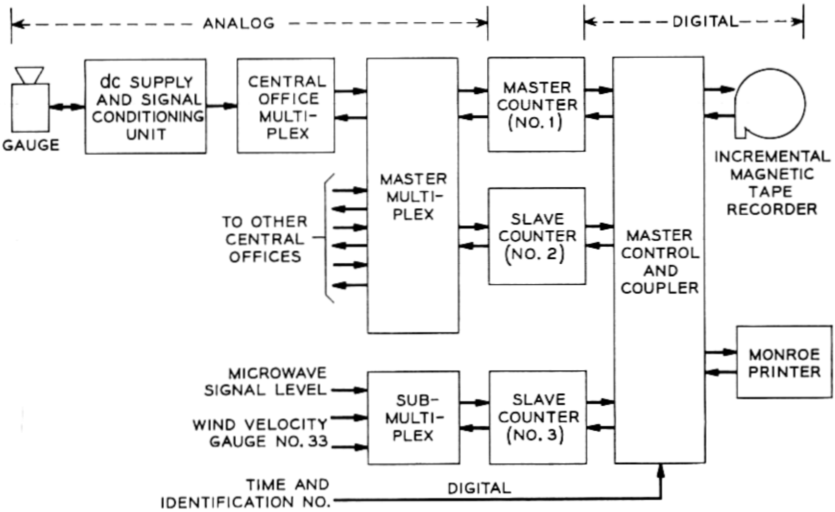

Fig. 3 — Data acquisition system.

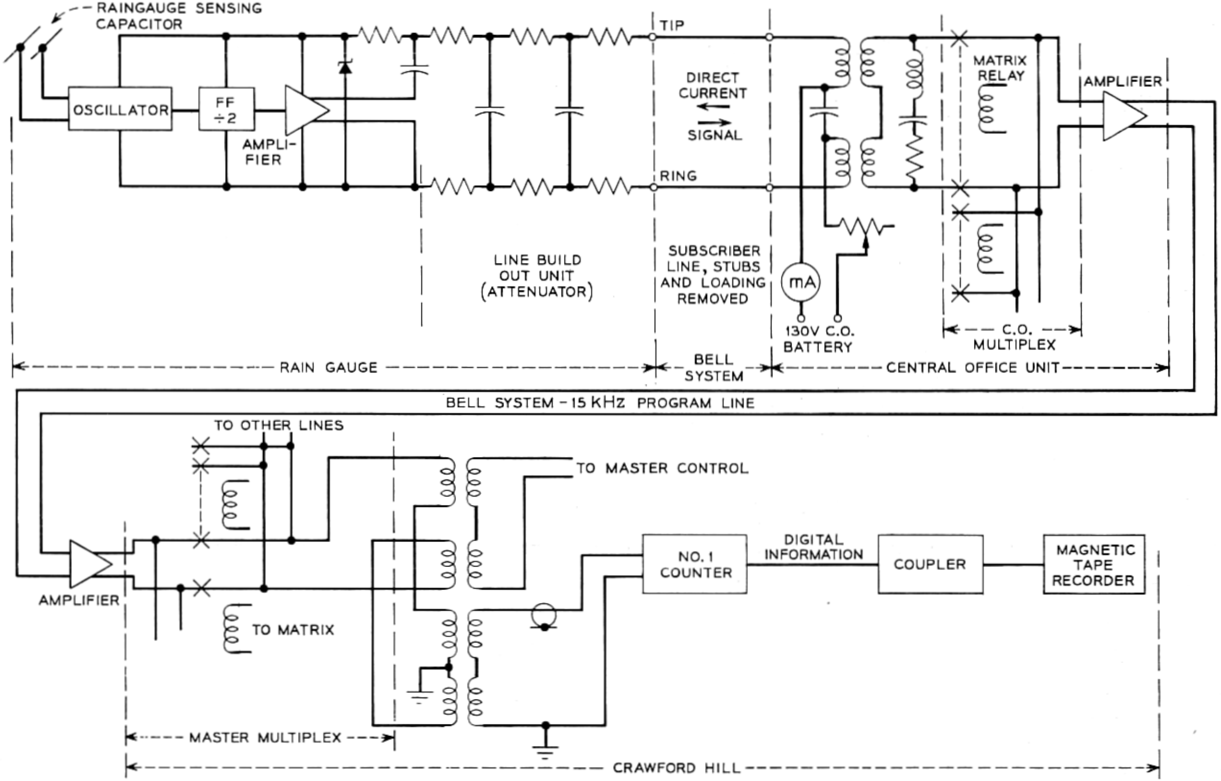

Fig. 4 — Flow diagram showing the direct current feed to a gauge and the signal path from a gauge to the tape recorder.

The count-of-three counter is used to group three scans into a record.

There are two modes of operation, slow and fast scan. In the former, a timing pulse fed to the master control produces a scan every 100 seconds; this is the "rain-watch" mode. When significant rain is indicated on any two gauges, the system switches to fast-scan. Low pass filters with cutoff frequencies of 9.40 kHz* determine the point at which the fast scan begins. When rain is no longer indicated the system returns to slow-scan.

Three frequency counters, used as in Fig. 3, provide the timing pulse for scanner and recorder. In the master control a digital scanner combines, in sequence, the output of counter 3, information from a time clock, and day-of-the-year. The output of each counter is four digits of binary code decimal which is serialized and fed to the tape recorder.

III. DATA PROCESSING

The adjunctive data discussed in Section II are recorded on the A and B tracks of the magnetic tape; both these and the gauge data are expressed as four digit numbers (16 bits). This means that all six of the tracks carry data and that an unpacking routine is necessary.

The raw data on the tape are in the form of frequencies (for example, data from the rain gauges, microwave receiver, and so on). The 200 bits per inch raw data tape is copied to 800 bits per inch. The latter is read into the computer with an unpacking program which sorts the intermixed bits and completes all partial numerical digits. The tape resulting from the unpacking procedure is used for all data reduction. The manner in which the data are analyzed is discussed in companion papers.[4,7]

IV. OPERATIONAL DATA

The system has been operational since late 1966 and data for all rainfalls since then have been recorded,† but because of possible errors in both gauges and recording apparatus, only data taken since May

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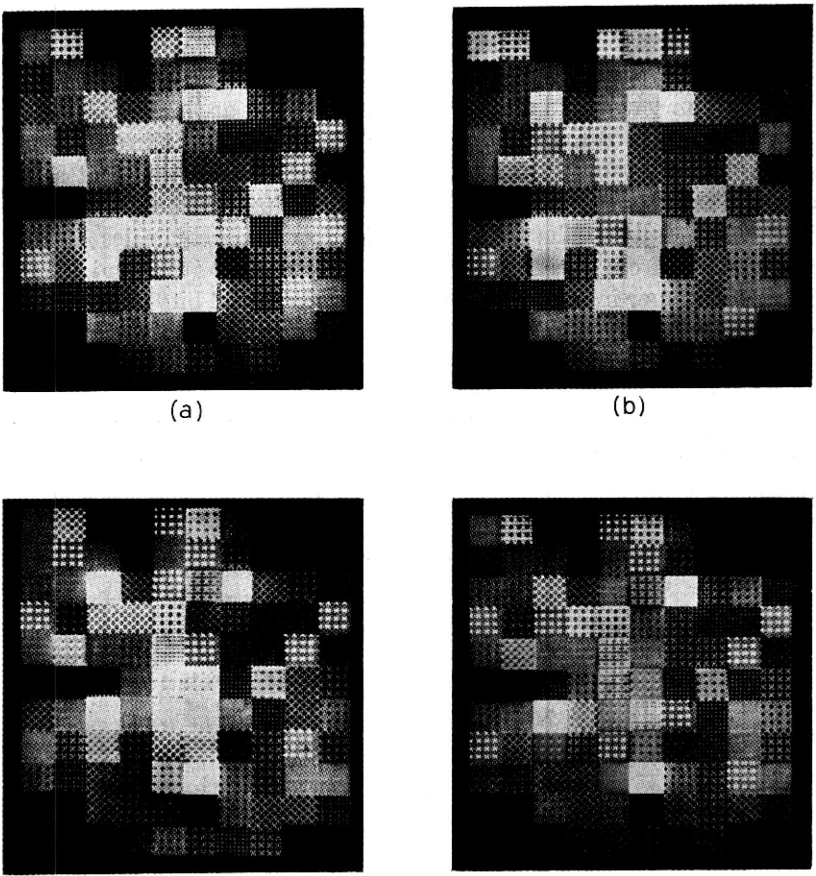
* For the average gauge this frequency corresponds to a rain rate of 15 mm per hour (see Fig. 2b).

† Since the rain gauges in the network are not equipped to handle snow (that is, heaters to melt snow) and in order to avoid any ambiguous data because of freezing rain, it was decided not to operate the system for outside temperatures less than 40°F. However, data obtained from both tipping bucket and weighing gauges indicate that with two exceptions, the rain rate during periods of low temperature was less than 25 mm per hour. The first exception occurred December 3, 1967 when a peak rate of 150 mm per hour was recorded for a period of less than two minutes. The second exception occurred March 12, 1968 with a peak rate of 75 mm per hour.

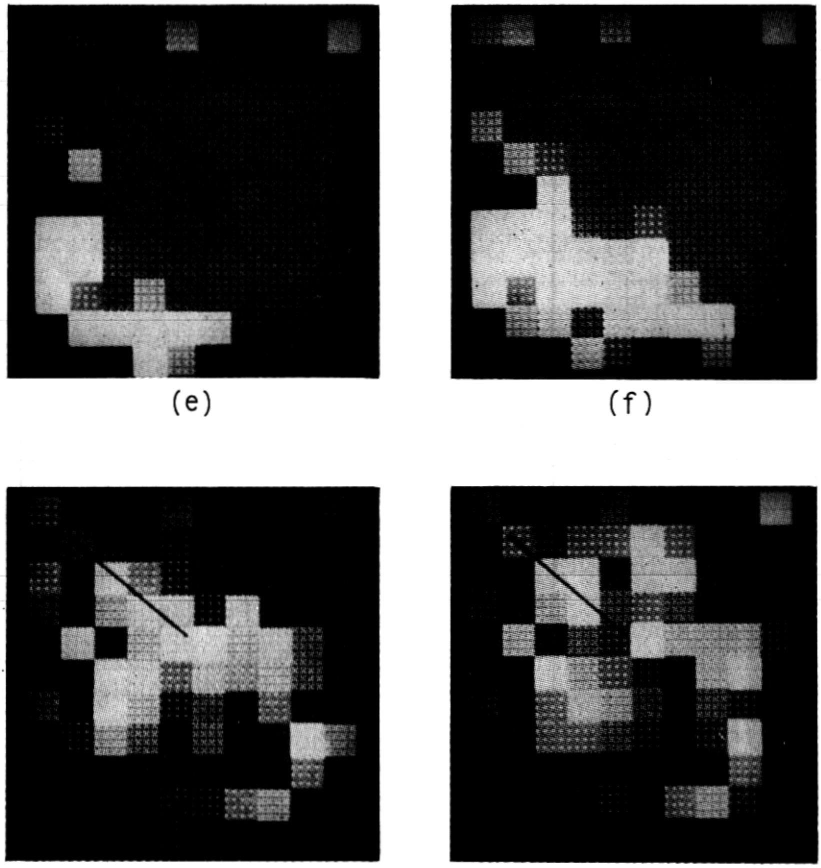
1967 are considered to be a high reliability; numerous heavy rains occurred during the summers of 1967 and 1968. Several examples of the output of the system are given below.

Figure 5 shows eight computer-generated rain intensity photographs. Each photograph shows the instantaneous rain rate as measured on each rain gauge in one scan. The sequence of photos, Fig. 5a thru 5d, occurred in 10 second intevals (the regular scan period). The dark grey areas indicate absence of rain whereas, the brightest areas correspond to 200 mm per hour rainfall. These photos portray a general, large area storm; it is evident that although it was raining over the entire network, cells of considerable intensity occur at various places;



(a) (b)

(c) (d)



(e) (f)

(g) (h)

Fig. 5 — Computer-generated rainfall-rate patterns. Small "patches" correspond to geographic area associated with each gauge. Each patch can have one of 48 intensities: dark for no rain, and gradually brightening for increasing rainfall. Frames (a) through (d) map a general storm over the area at ten-second intervals. The sequence (e) through (h) portrays a localized shower system moving diagonally across the system at 5 minute intervals.

thus "shower" activity is often embedded in a general rain environment. For reasons such as this, spaced-path diversity (discussed in Refs. 5 and 7) provides a considerable advantage in millimeter-wave radio-relay systems.

The sequence of photos, of Figs. 5e thru 5h, have been selected at 5 minute intervals; they show a localized storm, or shower, moving from southwest to northeast through the network; this shower moved about ten miles in 20 minutes (30 mph). In the northwest quadrant of Figs. 5a thru 5d, the 6.4 km propagation path operating at 18.5 GHz (Ref. 4) is shown by a heavy dark line.* The isolated square in the upper right hand corner of the photos of this sequence represents the received 18.5 GHz signal. The magnitude of the signal is indicated by the brightness of this square. In Figs. 5e, f, and h, the square is fairly bright indicating little attenuation, but in Fig. 5g the square is dark, indicating an attenuation of about 30 dB; this coincides with heavy rain on three of the gauges on the path. Entire storms have been processed by computer in this manner to produce moving pictures of the storm activity.

In Fig. 6, data from the rain gauge network has been used to generate contour maps. For this presentation, a linear interpolation is used to produce the contours between adjacent gauges. Elapsed time between the upper and lower maps was 20 minutes. In Fig. 6a, the rain rates are very low, indicating a fairly light and steady rain over the network. However, in Fig. 6b, taken twenty minutes later than 6a, several intense cells have formed within a few miles of each other. The contour interval is 20 mm per hour in Fig. 6b; even with this large an interval, the contours become crowded in some places simply because the rain rate on a given gauge is so much higher than that of its nearest neighbor.

V. MAINTENANCE, TESTING, AND CALIBRATION

A daily record is made of the network performance. Difficulties are caused by malfunction and noise on telephone lines, gauges damaged by inadvertent application of high voltage, clogged capacitors (mainly caused by small spiders), and component failures caused by lightning and undetermined reasons. To date, more than 90 percent of the network has always been operational.

After analysis of preliminary data, the rain gauges were calibrated in the field; this involved taking a source of water to each gauge position and measuring the output frequency of the gauge for three waterflow rates, namely 45, 75, and 254 mm per hour. Due to pollution in the gauge capacitor, some departures from the original calibrations were observed. However, when the gauges were cleaned, they faithfully returned to their original calibration. Thus the present pro-

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* A 1.9 km path at 30 GHz was in operation during 1968. The author plans to discuss these data in a future paper.

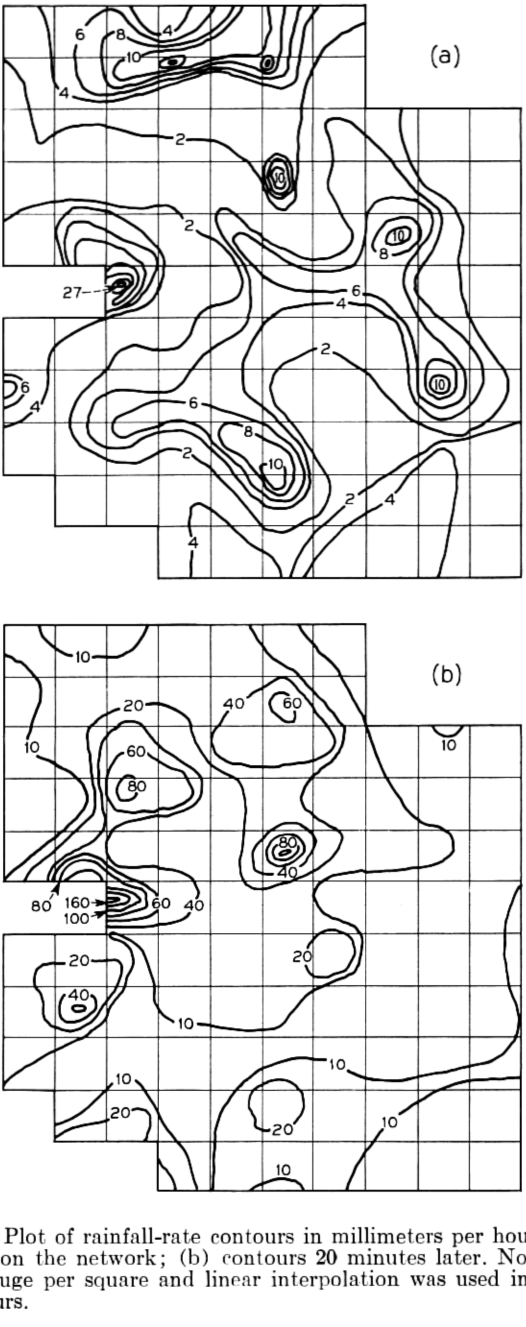

Fig. 6 — (a) Plot of rainfall-rate contours in millimeters per hour showing several rain cells on the network; (b) contours 20 minutes later. Notice that there is only one gauge per square and linear interpolation was used in obtaining the detailed contours.

cedure is to clean the gauges bimonthly and to use the original calibrations in all data reduction.

VI. ACKNOWLEDGMENTS

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