# Radio Attenuation at 11 kmc and Some Implications Affecting Relay System Engineering

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*Radio waves at 11 kmc are attenuated by rain. In order to derive rules for engineering radio relay systems at 11 kmc, a one-year experiment was conducted in a region of frequent heavy rainfall. The attenuation of paths 27 and 12 miles long was measured, together with rainfall at two-mile intervals along the paths. The instrumentation and the test results are described, and some implications related to systems engineering are pointed out.*

## I. INTRODUCTION

Increasing use of the common-carrier microwave frequency bands at 4 and 6 kmc has directed attention to the next higher band at 11 kmc. All three bands are subject to atmospheric fading, but propagation at 11 kmc differs from that at the lower frequency bands chiefly in its vulnerability to rain. Knowledge of the statistics of the excess path loss caused by rain is a necessary prerequisite to 11-kmc system design, and therefore an experiment was undertaken to extend the modest body of available knowledge.

The effects of rain on microwave radio propagation have been calculated by Ryde and Ryde.[1,2] The radio energy is absorbed and scattered by the rain drops, and these effects become more pronounced at the higher microwave frequencies where the wavelength and the raindrop diameter become more nearly comparable.

The excess attenuation caused by rainfall depends on the number of drops per unit volume in the radio path, the square of the drop diameter and a complex factor representing the ratio of the total energy absorbed and scattered by a single drop to the energy in that area of the wavefront equal to the projected area of the drop.

Laws and Parsons[3] observed the distributions of drop sizes for various

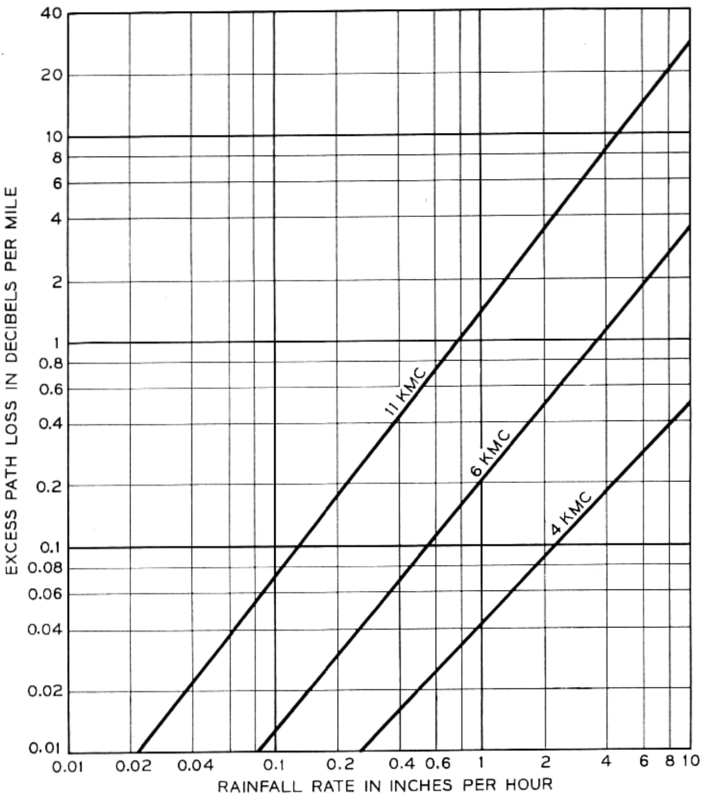


Fig. 1 — Rain attenuation vs. rainfall rate (theoretical, after Ryde and Ryde[1]).

rates of fall on a horizontal surface, using the method of Bentley.[4]* The higher the rainfall rate, the larger the drops, and also the greater the spread in size of drops. Ryde computes the number of drops per unit volume from the data of Laws and Parsons by applying the terminal velocity appropriate to the drop mass.

The excess path loss per mile according to Ryde for the three common-carrier frequency bands — 4, 6 and 11 kmc — is shown on Fig. 1 for various rates of rainfall.†

* The Bentley method involves exposing trays of sifted flour to the rainfall, baking the flour to solidify the pellets formed by impinging raindrops and then sorting the pellets by size. The flour has been calibrated by generating drops of known size, so that drop size can be determined from the pellet size.

† It is interesting to note that, from his computations, Ryde concludes that the excess attenuation caused by hail is in the order of one-hundredth that caused by rain, that ice crystal clouds cause no sensible excess attenuation, and that snow produces very small attenuation, even at the excessive rate of fall of five inches per hour.

Much rainfall data is available for point locations, but very little is known about the relationship between the rate of fall at a single rain-gauging point and the profile of rate of rainfall along a radio path. Furthermore, most rainfall data are in terms of fairly long discrete intervals, such as 30 minutes or one hour, and the relationship between hourly and instantaneous rates of fall is not perfectly known.

Bussey[5] has analyzed rainfall data for one year from the Muskingum River watershed in Ohio,[6] and finds that the annual distribution of one-hour point rates is approximately the same as an annual distribution of instantaneous 50-km path rates. He further suggests that 10-minute point data may apply to an 8-km path, 30-minute data to a 25-km path, etc.

It was the purpose of the experiment described here to seek confirmation of Ryde's relationship between excess path attenuation and instantaneous rate of rainfall, and to measure the profile of rate of rainfall along a radio path in hopes of finding correlation with rainfall measured at a single point. It was expected that this information would be useful in determining design parameters for 11-kmc radio relay systems and for suggesting the conditions under which they be used.

The experiment consisted of operating a radio path of a length typical of short-haul radio relay systems in a heavy rain area for a year. Instrumentation included devices for measuring excess radio path loss and rain gauges along the path at intervals short enough to define the rainfall profile.

## II. RADIO PATH

The requirements that determined the choice of the radio path were:

(a) Heavy rainfall, both in rate and depth.

(b) Length of about 25 miles, which is considered typical of possible 11-kmc application, with the possibility of a second receiver midway in the path so that some feel of interpolation versus length would result.

(c) All-weather highway parallel to and very near the path, to permit access to rain gauges.

(d) Existing structures and buildings for antennas and radio equipment.

(e) Preferably a path equipped with an operating 4-kmc radio relay system, so that some comparison could be made between 4- and 11-kmc propagation.

Literally hundreds of possible paths were examined. The choice narrowed quickly to the Gulf Coast region because of the high incidence of heavy rainfall and the great total rainfall, which is in the order of 60 in. per year.* Finally, a path was selected between Mobile and Mount Vernon, Alabama, 27.7 miles long, approximately north and south, and parallel to a good highway, as shown in Fig. 2.

Arrangements were made to locate the transmitter at the Mount Vernon TD-2 4-kmc radio relay station, and an 8- by 12-ft plane reflector, specially made to be flat to $\frac{1}{16}$ in., was mounted at the 300-ft level of the TD-2 antenna tower. The reflector was illuminated by a 5-ft parabolic antenna mounted on top of the transmitter equipment housing, using a button-hook feed constructed of commercially available waveguide pieces. The gain of the antenna system at Mount Vernon was 44.2 db, 1.2 db greater than the gain of the parabolic antenna alone.

At Mobile, a similar antenna system for the receiver was placed on the TD-2 tower atop the telephone building, but, because this tower was only 85 ft tall, a 6- by 8-ft plane reflector was used with the 5-ft parabolic antenna. The gain of the antenna system at Mobile was 42.8 db, 0.2 db less than that of the parabolic antenna alone because of the small spacing between the antenna and the reflector.

At a point 12.6 miles south of the transmitter at Mount Vernon, near Axis, Alabama, a second receiving station was constructed. It used a 104-ft path-loss testing tower,[7] with a 3-ft parabolic antenna having a gain of 37.1 db, mounted directly on the receiver front-end, which could be run up and down the tower on a carriage. The tower was located directly in the path from Mount Vernon to Mobile.

The antenna sizes were chosen to produce roughly equal received signal levels at Mobile and Axis, and to produce as large a received signal as was consistent with physical stability of the towers and the flatness of commercially available reflectors.

The path loss (between isotropic antennas) from Mount Vernon to Mobile is 146.3 db, and from Mount Vernon to Axis 139.4 db. When the antenna gains are included, the net loss is 59.4 db from the Mount Vernon transmitter to the Mobile receiver and 58.1 db to the Axis receiver, in the absence of rain and atmospheric fading.

The terrain near Mount Vernon is gently rolling, and south of Axis the path traverses the broad swampy valley of the Mobile River, the southernmost three miles being partly over water. The Mobile-Mount Vernon path had been tested previously[8] at 4 kmc and was found to be free of strong ground reflections, so it was considered unnecessary to retest at 11 kmc. A profile of the path is shown in Fig. 3. The path was engineered at 4 kmc to have one-third first Fresnel zone clearance over

* Annual depths of about 150 in. occur in the North Pacific Coast rain forests, but, surprisingly, the rate of fall is quite low.

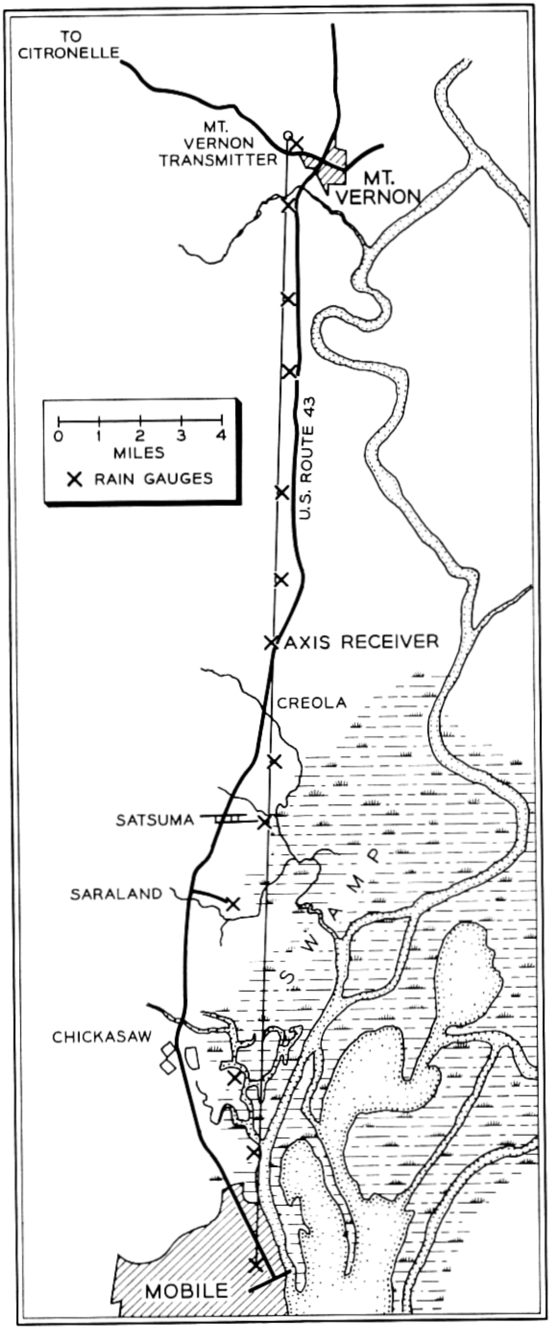


Fig. 2 — Map of Mobile-Axis-Mount Vernon radio path.

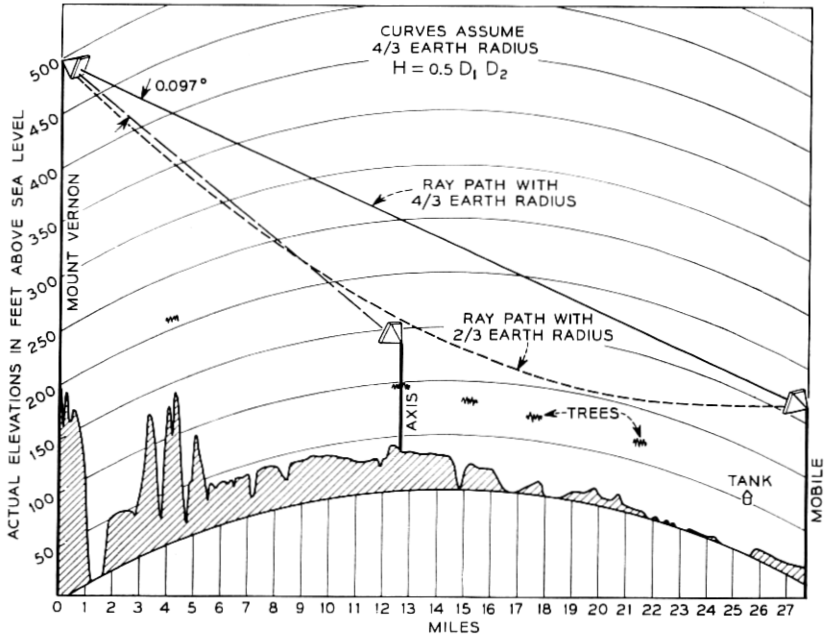


Fig. 3 — Profile of Mobile-Axis-Mount Vernon radio path.

an apparent earth radius equal to two-thirds of its true value. The passive reflectors for the 11-kmc tests had to be mounted below the existing TD-2 system antennas for physical reasons. Because of the lower antenna heights, the path clearance was 15 ft less than at 4 kmc. The limiting point in the path was 18 miles from the Mount Vernon end and, with 60-ft trees, the clearance was 36 ft when the effective earth radius was two-thirds of the true earth radius. At 11 kmc this was approximately 0.7 first Fresnel zone, which is considered adequate even for this area. The shorter path, Axis-Mount Vernon, had clearance in the order of four Fresnel zones, which was far more than sufficient.

## III. RESULTS

### 3.1 *Fading*

Fig. 4 shows the signal level distributions of both paths due to multipath fading for a four-month period, omitting the effects of rain. The long path distribution exceeds Rayleigh for fades greater than 20 db. This would seem to indicate a strong stable reflection condition due either to ground reflections or to layer stratifications in the atmosphere.

Since no path-loss tests were made at 11 kmc, ground reflections cannot be ruled out. However, the path for the most part traverses land covered with low vegetation and pine forests, usually thought to be nonreflective. The TD-2 system suffered similar fading, and it had been established that at 4 kmc the path was essentially nonreflective. Unfortunately, only a slow-speed strip recorder was monitoring the 4-kmc system and comparative distribution data are not available.

Figs. 5 and 6 show typical 4-kmc and 11-kmc signal strengths during periods of multipath activity. In general, multipath fading on 4 kmc

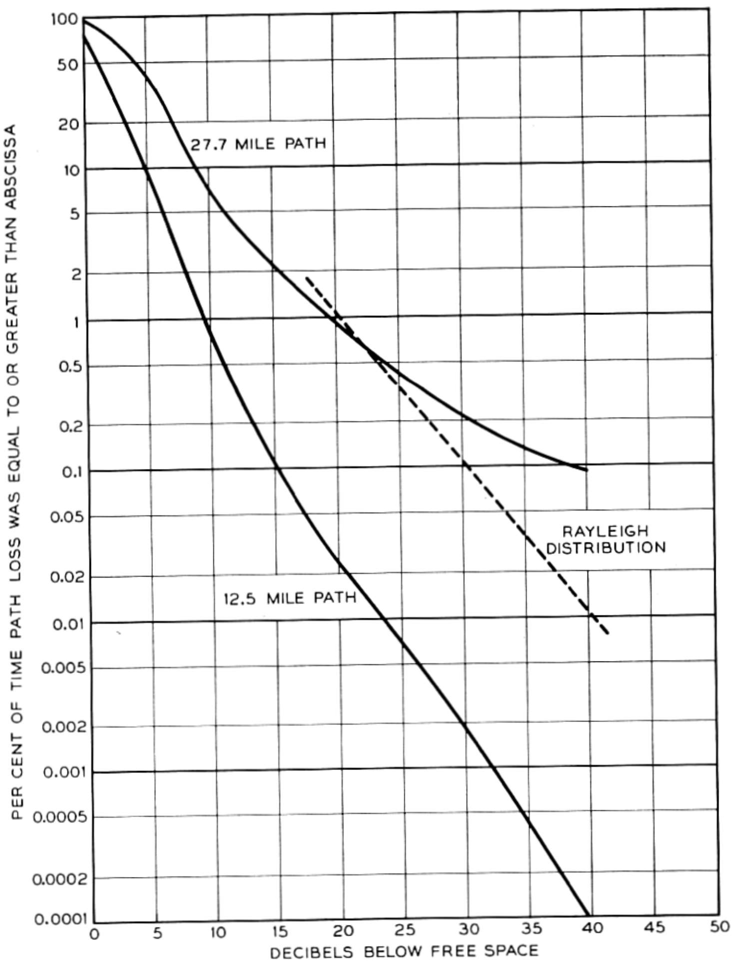


Fig. 4 — Distribution of selective fading, March 1 through July 31, 1956.

and 11 kmc began and ended at approximately the same time and followed the same over-all pattern. However, the number of fades was greater at 11 kmc than at 4 kmc. The necessity of having diversity protection for such systems is apparent if they are to meet long distance telephone circuit standards.

In addition to selective fading there were several long periods of depressed fields caused by earth bulge or obstructive-type fading. Atmospheric conditions in the Gulf region are favorable for fading of this type because high humidity and stable conditions exist at night and

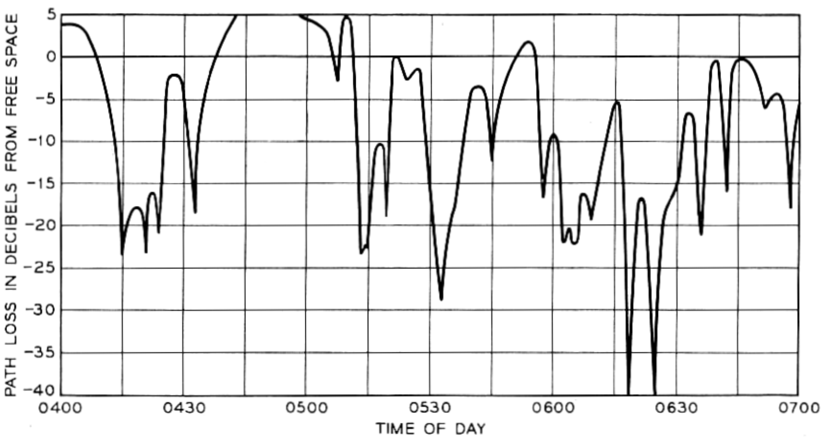


Fig. 5 — Typical selective fading at 4 kmc.

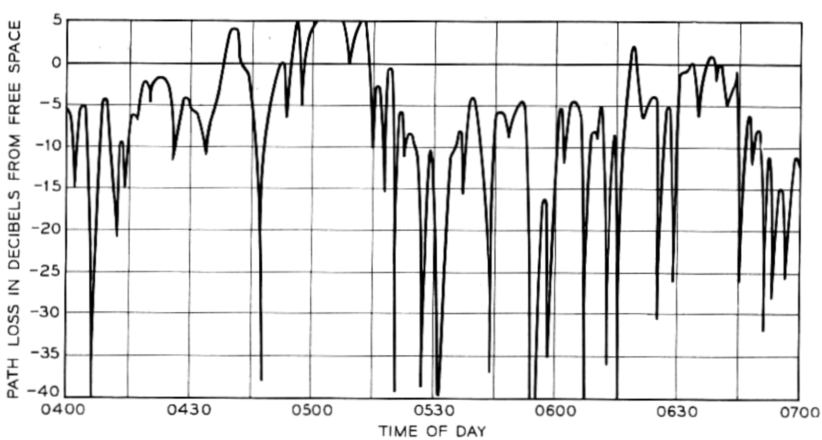


Fig. 6 — Typical selective fading at 11 kmc.

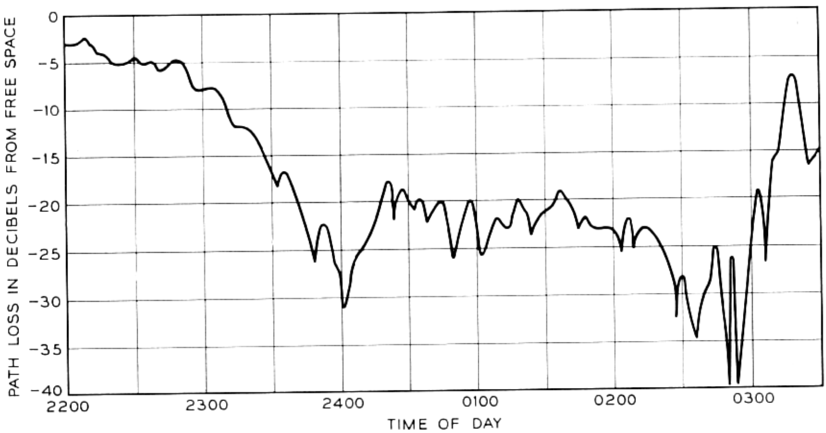


Fig. 7 — Earth bulge fading at 4 kmc.

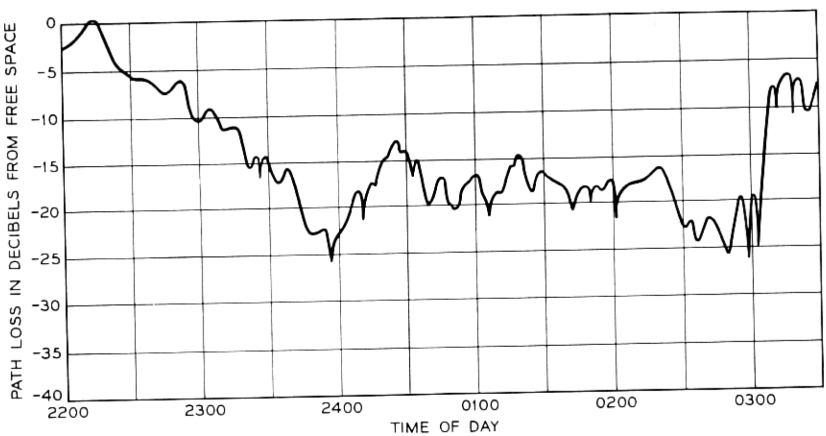


Fig. 8 — Earth bulge fading at 11 kmc.

during the early morning hours. Figs. 7 and 8 show depressed fields that occurred on November 18 and 19. Since fades of this type are insensitive to frequency, protection can be accomplished only by providing adequate clearance and restricting the lengths of the radio paths. The received signal strength at 11 kmc on the Mobile-Mount Vernon path was 40 db or more below the normal received level during less than 0.03 per cent of the year, due to obstructive-type fading. The shorter path was unaffected.

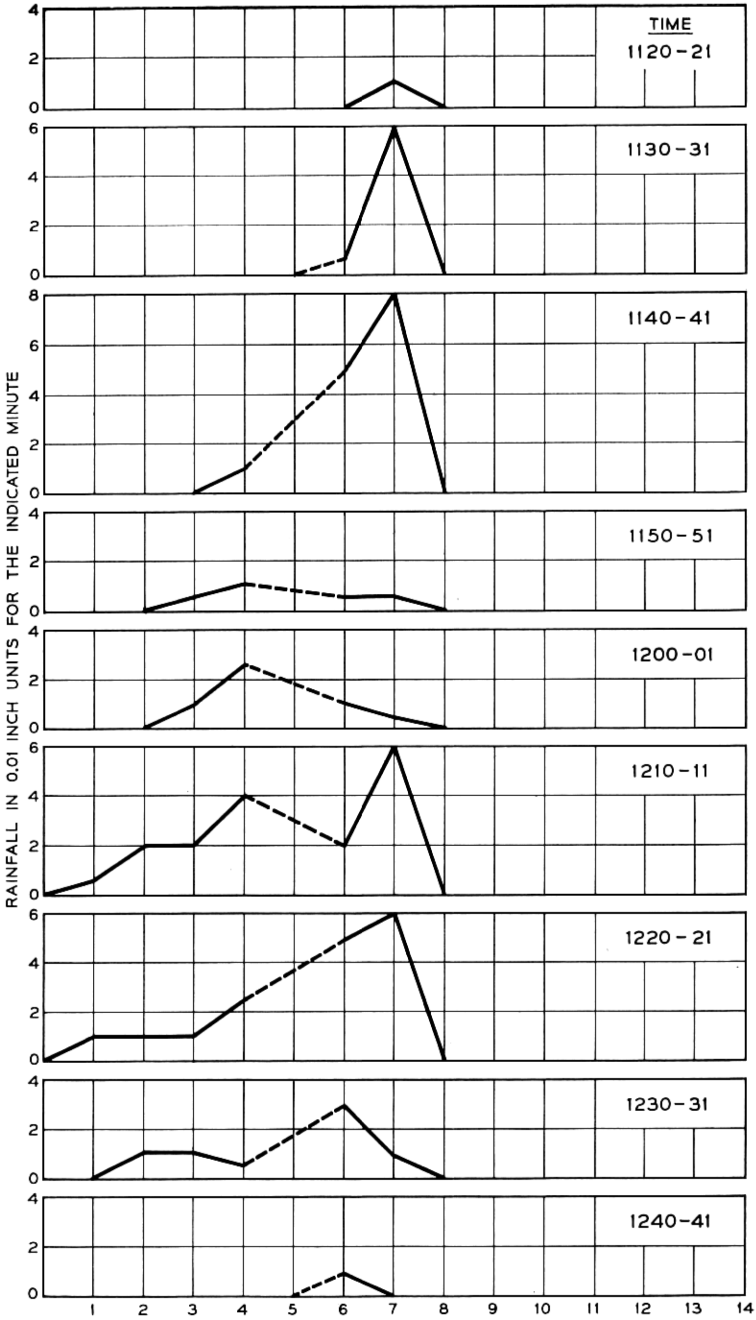


Fig. 9 — Rainfall distribution over Axis-Mount Vernon path, March 15, 1956.

3.2 *Rain Attenuation*

Frontal storms of short duration and high rates of rainfall are common in the Delta area of the United States. In general, these storms originate in the Gulf of Mexico and travel landward in a northeasterly direction. A typical storm arrived in Mobile on March 15, 1956, and passed diagonally across the radio test path between the small towns of Creola and Mount Vernon, Alabama. Rain fell over this area of the test path from about 11:15 A.M. to 12:45 P.M. Fig. 9 shows the rainfall rate distribution at ten-minute intervals as the storm progressed across the path. In analyzing the data, such profiles were constructed for each minute of each significant rain event.

Fig. 10 shows the correlation between the measured and calculated signal levels during the progress of the March 15 storm. The calculated signal level is based on the effective two-mile rainfall rate measured along the path during the storm. Ryde[2] has indicated that the attenuation due to rainfall can be approximated by

$$\text{db} = k \int_0^r R^\alpha \, dr,$$

where

$$R = \text{rainfall rate},$$

$$r = \text{length of propagation path}.$$

Hitschfeld, Gunn and East of McGill University, Montreal, Canada,[9]

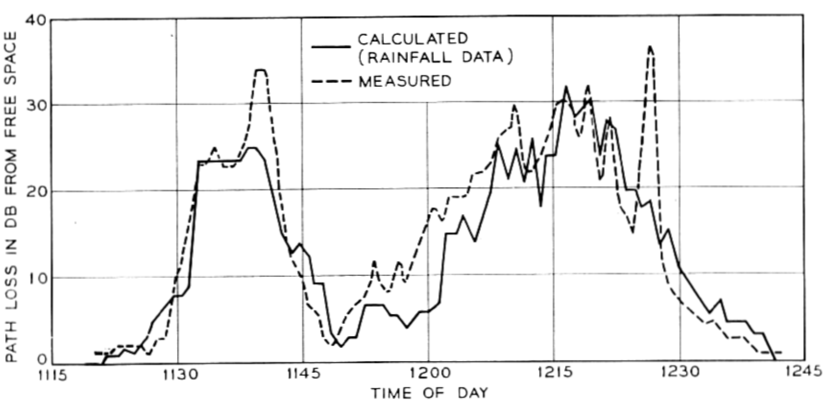


Fig. 10 — Correlation between rainfall and path loss, March 15, 1956.

have made computations of $k$ and $\alpha$ for various wavelengths at 18°C. Extrapolation of their work yields for 11 kmc:

$$k = 1.395 \text{ db/mile/in./hr},$$

$$\alpha = 1.3.$$

The rain gauges on the Mobile-Mount Vernon path were placed at approximately two-mile intervals. The rainfall rate within one mile either side of a rain gauge has been assumed uniform. Then, over any two-mile path the attenuation due to rainfall is approximated by

$$\text{db} = 2kR^\alpha.$$

The attenuation over the entire path is then the sum of the attenuations due to the two-mile segments of the path:

$$\text{db} = 2k(R_1^\alpha + R_2^\alpha + \cdots + R_n^\alpha).$$

The assumption of uniform rainfall within one mile either side of a rain gauge is most surely inaccurate. However, it permits an approximate solution to the problem of attenuation due to rainfall that is not inconsistent with the measured values. Certainly a better correlation would have been obtained if the rain gauges had been spaced closer together.

A number of rain events were analyzed and the data reduced to the equivalent two-mile rate assuming uniform rainfall over the two-mile spans. Fig. 11 is a scatter diagram showing transmission loss in db per mile due to precipitation versus precipitation in inches per hour. For comparison, Ryde's equation is plotted using the constant values suggested earlier.

The recording equipment at Mobile and Axis was arranged to record receiver input levels from 0 to 40 db below the normal input level (approximately $-32$ dbm). The received signal strength was 40 db or more below the normal received level due to rainfall for 0.106 per cent of the year on the Mobile-Mount Vernon path and 0.020 per cent of the year on the Axis-Mount Vernon path. These figures indicate the expected order of outage time due to rainfall for single-hop 11-kmc radio systems having a 40 db fading margin and operating over similar paths in the Gulf Coast region. Fading margin is taken to mean the number of db the receiver input level can be reduced before the noise exceeds the system objective; outage time is defined as the time the noise does exceed the objective. Any predictions based on the above figures for outage time would be pessimistic for most other areas of the United

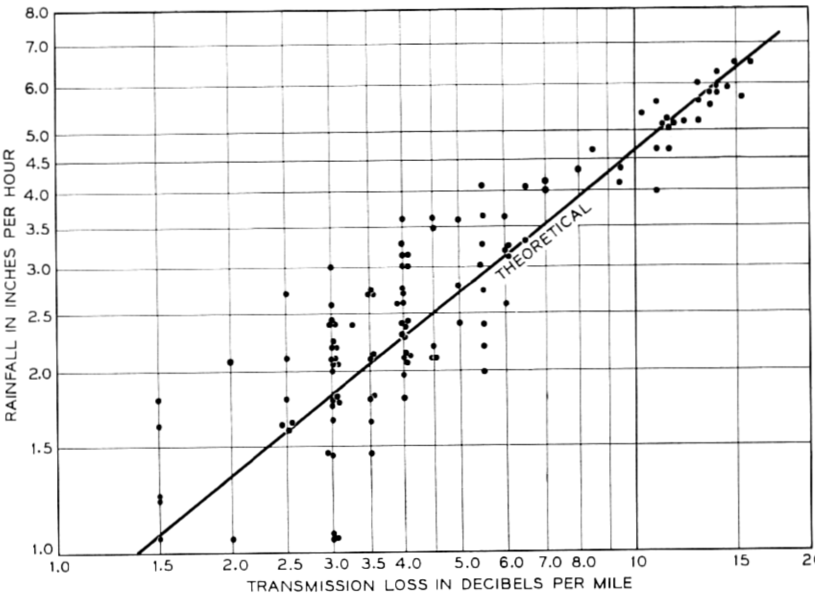


Fig. 11 — Scatter plot — transmission loss vs. rainfall rate.

States since they reflect the attenuations due to severe rainfall found along the Gulf.

## IV. IMPLICATIONS AFFECTING SYSTEM ENGINEERING

Rain attenuation is obviously a large factor in determining system reliability, and hence it reacts strongly on both the design and the application of the system. Since rainfall varies greatly in frequency and intensity from one region to another, it is important to be able to predict performance in any region, so that the system as designed will have the widest possible application consistent with cost, and so that the applications engineer will know how to tailor those system parameters at his command to produce the degree of reliability desired.

It is not feasible, for reasons of cost, to measure rain attenuation in all parts of the country, so it is necessary to use what rainfall data are available, and to couple the data, through what are thought to be reasonable assumptions, to the relationships between rainfall and attenuation. The validity of the predictions rests clearly on the validity of the assumptions, and it is to be expected that further refinements in predicting rainfall outage will result from observing the performance of early 11-kmc systems.

As an approach to the problem of predicting outage time due to rainfall for all areas of the country, it has been assumed that the annual distribution of one-hour point rates is indicative of the annual distribution of instantaneous 30-mile path rates, along the lines suggested by Bussey.[5] This is equivalent to assuming a fixed storm pattern moving at 30 miles per hour in the direction of the path. Furthermore, it has been assumed that the frequency of occurrence of severe rainfall of the type measured in the Mobile area will be reduced in other parts of the country in proportion to the distribution of annual point rates of one inch or more per hour. Fig. 12, based on these assumptions and the work of Dych and Mattice,[10] illustrates contours of constant path lengths for fixed outage times for different areas of the United States. Fig. 13 shows the expected outage time due to rainfall for various path lengths in different rain areas of the United States. Curves A through H of Fig. 13 correspond to the general areas described by the contours in Fig. 12. The longer paths have been weighted somewhat to take account of less severe rainfall covering larger areas than do storms typical of the Gulf region.

In engineering a complete 11-kmc radio relay system, the rain outages of the individual hops must be added to obtain the performance for the system. Also, it is desirable to lay out the system in such a manner that

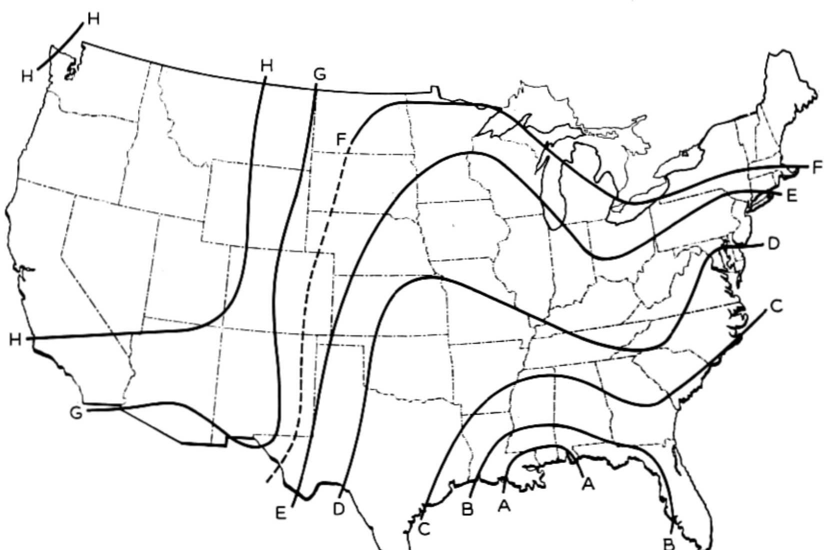


Fig. 12 — Contours of constant path length for fixed outage time.

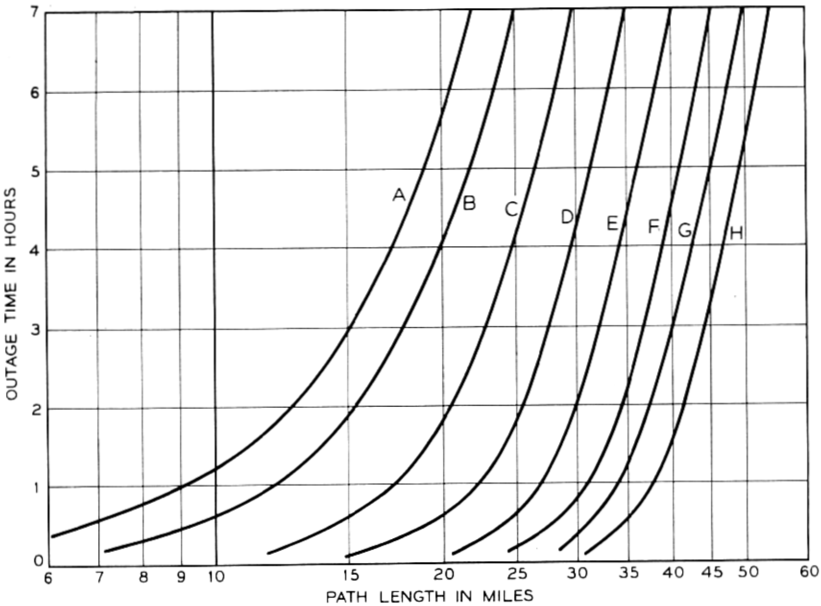


Fig. 13 — Expected outage time in hours per year vs. path length in miles for various areas of the United States.

the individual hops meet the same objective. From a practical standpoint, this will not always be possible. Sometimes it is necessary to have one or more hops of a system electrically long; they will have insufficient fading margin and hence contribute more than their share of outage time. From the over-all system viewpoint, this "excess" must be made up by imposing tighter requirements on the remaining hops.

To meet the over-all system objective, it becomes necessary to know the contributions of the long hops—those having a fading margin less than 40 db. Fig. 14 shows excess path loss due to rain versus hours per year for the Mobile-Mount Vernon path. The shape of this curve is nearly identical with Bussey's curve of cumulative distribution for point rates at Washington, D. C. If we assume the shape of this curve to be representative for other areas of the country, then the additional outage time for path lengths given by Fig. 13 can be estimated for hops having a fading margin less than 40 db. The data shown in Fig. 14 have been rationalized and are shown in Fig. 15 as an estimate of additional outage time.

Sometimes it is practical to shorten a proposed path to bring the fading margin up to 40 db. An approximation of the necessary reduction

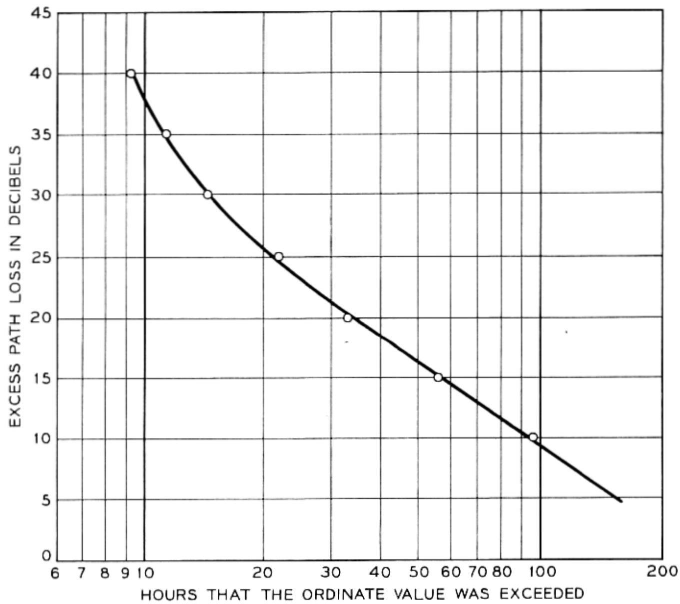


Fig. 14 — Excess path loss due to rainfall vs. hours per year (at Mobile).

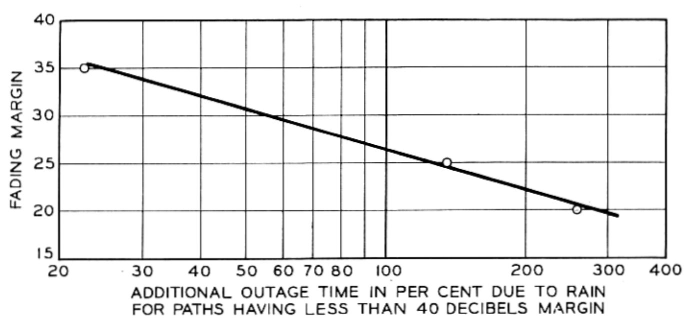


Fig. 15 — Additional outage time expected for 11-kmc systems having a fading margin less than 40 db.

in path length can be made if uniform rainfall rate is assumed over the path. Under this condition, Ryde shows the attenuation due to rainfall to be directly proportional to the path length. Thus the path length given in Fig. 13 can be shortened to correct for insufficient fading margin.

Rainfall in the extreme southeastern region of the United States will limit 11-kmc radio systems having a 40-db fading margin to path lengths of approximately 10 to 15 miles, depending on the number of hops, if normal reliability objectives are to be met. Path lengths of 20 to 30 miles should be acceptable in the central area and paths as long as 35 miles should be acceptable in the northwestern part of the country. However, in existing short-haul radio systems, the paths average 22 to 24 miles, due to considerations other than those of propagation. It would then appear that 11-kmc systems will not be penalized unduly except in the extreme southeastern part of the United States.

## V. INSTRUMENTATION

### 5.1 *Transmitter*

The transmitter employed a small commercially available klystron whose output was 0.5 watt. A variable probe was used to match the klystron to the waveguide to the antenna, and a 20-db directional coupler sampled the output so that frequency could be measured and the output power monitored. The frequency stability was such that it was not necessary to use automatic frequency control. Since the ac line was subject to frequent failure (a natural result of the thunderstorms whose rainfall provided the reason for the experiment), a strip-chart recorder with a mechanical clock drive was used to monitor the transmitter output.

The transmitter with its power supply was mounted in a weather resistant cabinet, as shown in Fig. 16.

### 5.2 *Receiver*

The receiver was adapted from equipment designed to record path loss at 4 kmc,* which was, in turn, adapted from equipment designed to measure path reflections.[8] It is shown in block schematic form in Fig. 17. The normal received signal level was −32.2 dbm at Mobile and −31.1 dbm at Axis. The receiver was arranged to record signals from 0 to −40 db relative to the normal signal.

A balanced converter supplied by a local klystron oscillator modulated the incoming 11.4-kmc signal to a 60-mc intermediate frequency. In the preamplifier the 60-mc signal was amplitude modulated with 1000-cps. The output of the preamplifier was divided between an IF amplifier feeding a frequency discriminator, which provided automatic frequency

* An extensive path loss measuring program was carried out in 1947–1950 at 4 kmc prior to commercial use of those frequencies by the Bell System. This 4-kmc equipment was designed by H. C. Franke and was converted to 11 kmc by S. D. Hathaway.

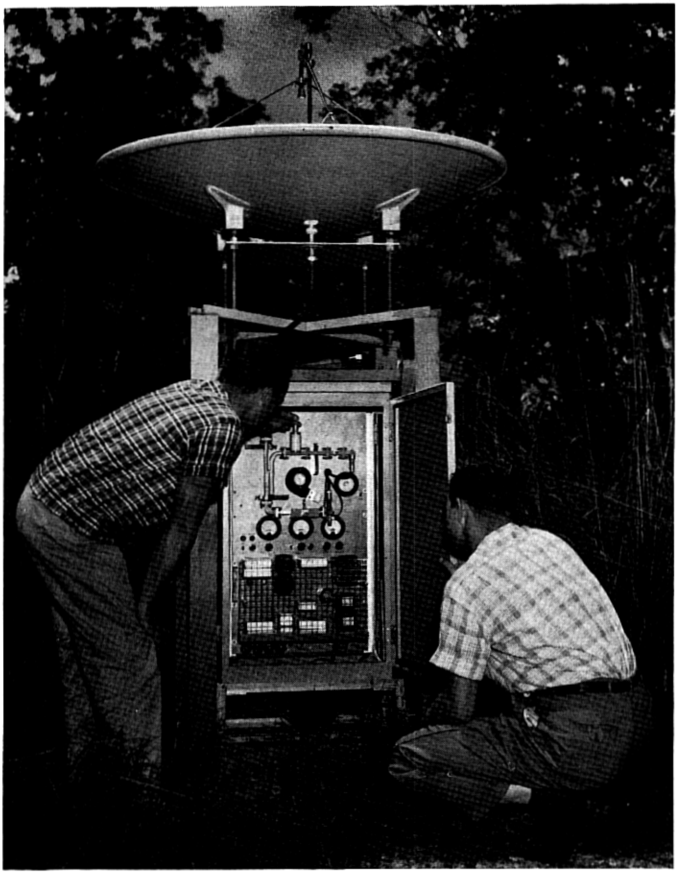

Fig. 16 — 11-kmc transmitter, power supply and antenna, Mount Vernon, Alabama.

control to the local klystron oscillator, and an amplitude detector, where a 1000-cps signal reasonably proportional to the microwave input signal over a 50-db range was recovered. The 1000-cps signal was amplified and rectified at a level suitable to operate the display equipment. The receiver at Axis (except for the converter, which was tower-mounted) and the display equipment are shown in Fig. 18.

### 5.3 *Display Equipment*

Two types of display equipment were used:

(a) A level distribution recorder with a range of 40 db, which operated

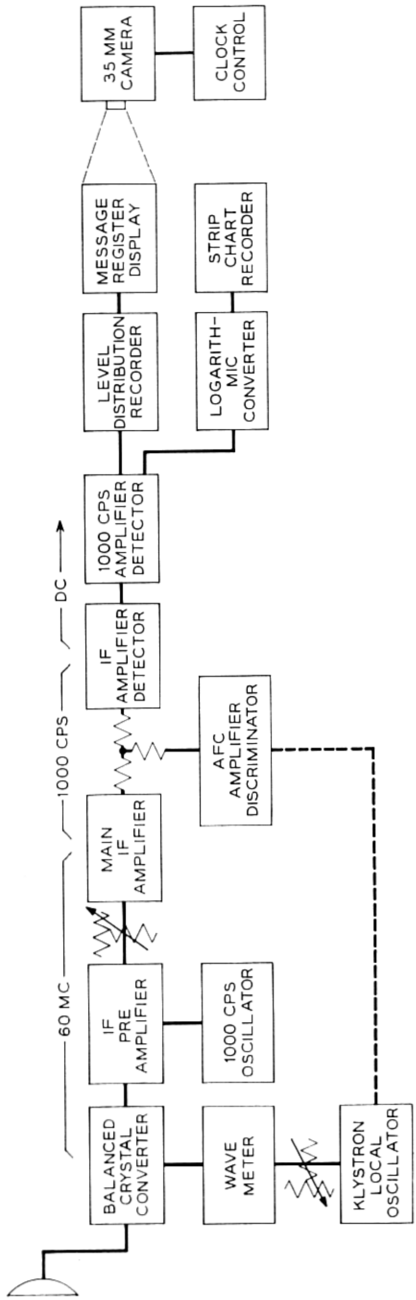


Fig. 17 — Block schematic of radio receiver and recording equipment.

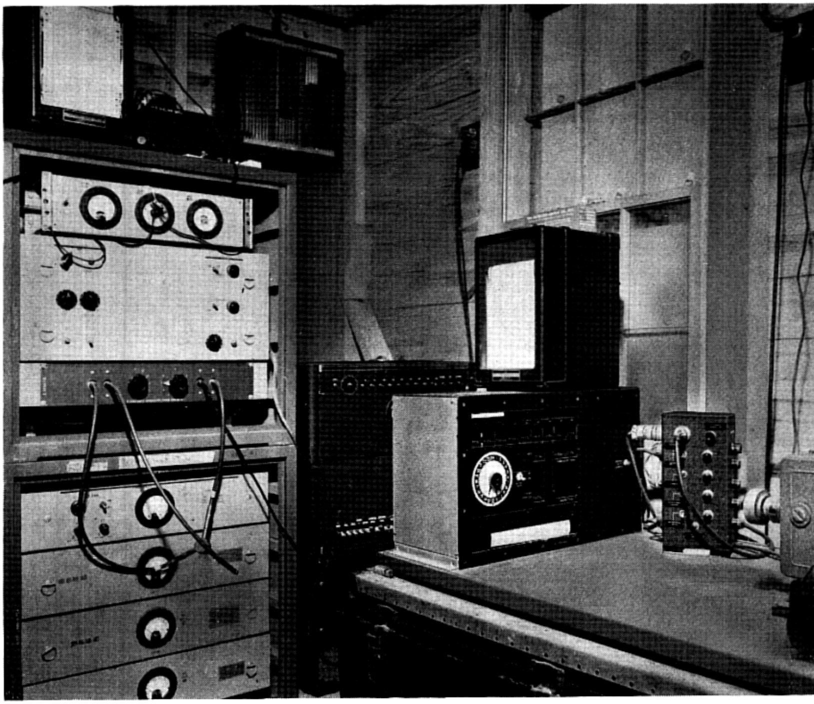

Fig. 18 — Axis station — IF portion of radio receiver, display equipment.

message registers which were photographed automatically on 35-mm film every 0.1 hour.

(b) A strip-chart recorder with a logarithmic converter to produce a scale linear in db over a 50-db range.

### 5.4 *Level Distribution Recorder**

A series of nine dc slicer circuits, each arranged to operate at an input of one volt, was connected to a voltage divider at 5-db intervals, thus covering a range of 40 db, as shown in Fig. 19.

A 2-mf capacitor was connected by a relay actuated by a synchronous timer to a cathode follower output of the 1000-cps rectifier for 0.85 sec-

* This electronic level-distribution recorder was developed in 1946 to replace a relay device that had been used for many years to study distributions of talker volume and telephone circuit noise. This circuit was conceived by L. Y. Lacy and developed by C. R. Eckberg for mobile use in connection with investigations of VHF transmission to vehicles, and later modified by H. C. Franke for use in microwave propagation measurements.

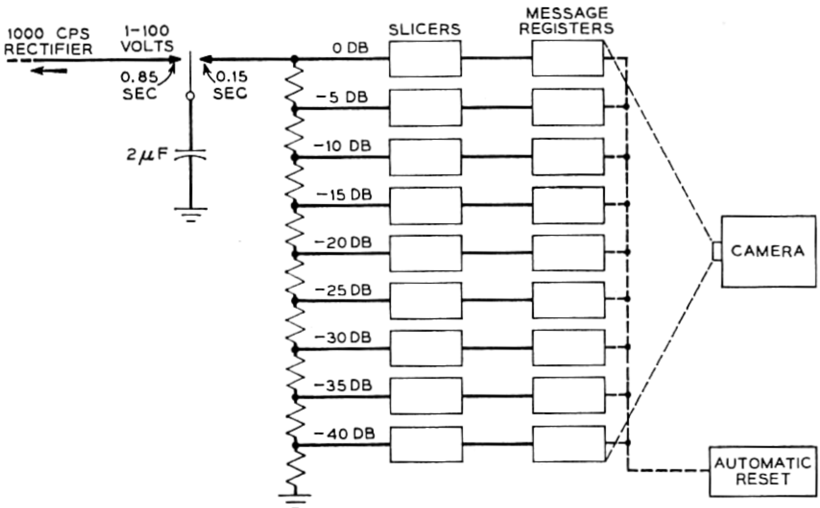


Fig. 19 — Block schematic of level distribution recorder.

ond. Then, for 0.15 second, the capacitor was connected to the voltage-divider slicer circuit. The slicer circuits were arranged to drive message registers (counters) with the polarity such that, if the slicer threshold was exceeded, the message register would not count; if the slicer threshold was not exceeded, the message register counted. Thus, an input of 100 volts (normal signal) caused no counts. An input of 0.9 volt (41-db fade) caused all message registers to count.*

Standard 14-type telephone message registers were used, and a neon tube was connected across each message register for easy observation of individual counts.†

Means were provided to calibrate the level distribution recorder in a preliminary way from an accurate dc source, but final calibration was always made from an accurate signal generator connected to the radio receiver input, so as to reduce the effects of nonlinearity in the radio receiver.

* Other level distribution recorders have been built with crossgating between the slicers, so that only the message register corresponding to the level just exceeded will operate. This type yields a histogram data presentation, whereas radio fading data are usually presented as a cumulative distribution.

† Some message register units were arranged with an automatic reset mechanism that reduced all message register readings to zero hourly. This simplified reducing the data, since smaller numbers had to be dealt with, but the delicate mechanism of the resettable registers available at the time the equipment was designed led to maintenance problems in the field, so these units were rebuilt to use the simpler registers.

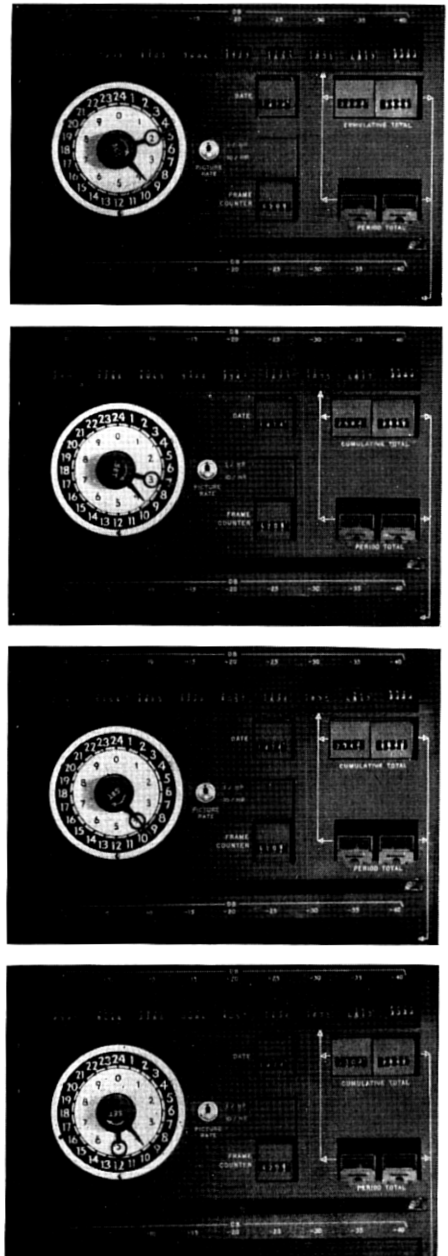

Fig. 20 — Level distribution recorder camera film (enlarged two times).

### 5.5 *Camera Equipment*

Pictures of the message registers were taken every 0.1 hour by a 35-mm camera adapted from a movie camera, under the control of a 24-hour electric clock which was included in the message register panel so that the time of each picture was recorded. A series of pictures is shown in Fig. 20. Auxiliary message registers recorded the total number of measurements and the date, the latter register being actuated by the 24-hour clock. The message register units and cameras were enclosed in a trunk to reduce spurious illumination. A projection film reader was used to transfer the data to a data book for analysis.

### 5.6 *Logarithmic Converter*

The logarithmic converter accepted a dc input voltage in the range $-0.3$ to $-100$ volts (as developed by the 1000-cps detector) and changed it to a direct current proportional to the logarithm of the input voltage, with a range of 0–1 ma for the operation of a strip-chart recorder.

The dc input voltage was chopped at a 60-cps rate and applied to a differentiating circuit followed by a dc slicer circuit. The time that the differentiated wave exceeded the threshold of the slicer was proportional to the logarithm of the input voltage, so that the output of the slicer was a 60-cps wave with pulse length modulation proportional to the input voltage in decibels. This output was filtered* and applied to a strip-chart recorder to provide a linear 0–50 db recording.

This display was limited by the slow response of the strip-chart recorder, whose time constant was about 0.5 second, so that the strip-charts were used chiefly for monitoring and quick scanning of data.

### 5.7 *Rain Gauges*

Automatic recording tilt-bucket rain gauges† were placed approximately every two miles along the radio path, as shown in Fig. 2. The exact locations were determined by considerations of accessibility, since many of the roads across the radio path were little more than swamp traces. Also, an effort was made to minimize the effect of nearby objects such as trees and buildings.

The rain gauge mechanisms, shown in Fig. 21, were proportioned so that the bucket tilted after each 0.01 in. of rain fell. A magnet attached

* It was found that imperfect filtering was desirable, in that a small amount of the 60-cps component improved the response of the strip-chart recorder to small changes in input.

† The rain gauges were designed by L. E. Hunt.

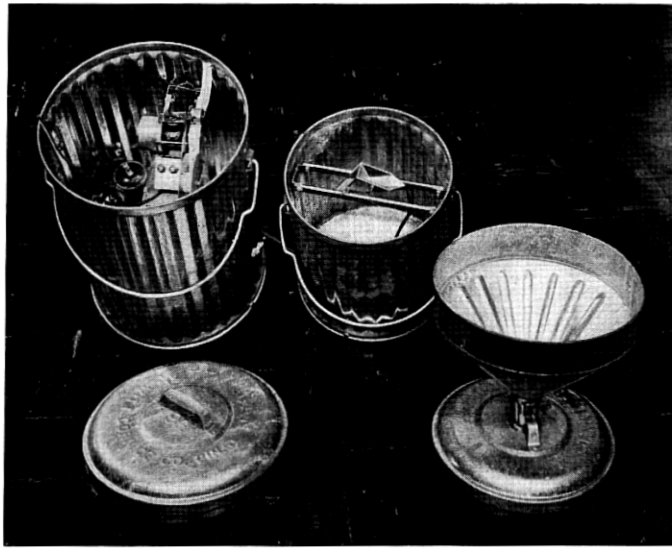

Fig. 21 — Rain gauge assembly: (a) recorder; (b) tilt bucket; (c) funnel.

to the tilt bucket closed the contacts of a glass-sealed switch* during the instant of tilting.

### 5.8 *Rain Gauge Recorders*

Because of sparse wire facilities along the path, it was impossible to bring each rain gauge circuit to a central recorder, so individual strip-chart recorders were used at each rain gauge. These used teletypewriter tape driven† by a clock‡ at the speed of 0.1 in. per minute (a little over 11 ft per day), and a stylus driven by an electromagnet punched a tiny hole in the tape each time the rain gauge bucket tilted. Thus at the cloudburst rate of fall of eight inches per minute, the punch marks were just over 0.01 in. apart, so that careful examination under a strong glass was required.

* Earlier models used open contacts which worked well in the laboratory but proved unsatisfactory under field conditions.

† The usual trouble of changes of paper dimension caused much experimentation with chart drive. Pins in the drive drum were superseded by a neoprene band friction drive.

‡ Several types of clocks were tried — automobile electric clocks, precision automobile electric clocks, large spring-wound clocks and, finally, governor-controlled dc motors. None yielded the precision of timing desired, so that it was necessary to interpolate to avoid errors in correlating the individual rain gauge records for particular rain events. The improvements in the recorders were made by K. J. Frolund.

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