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High Resolution Pulse Measurements of Meteor-Burst Propagation at 41 Mc/s Over a 1,295-km Path

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Studies of multipath radio signals have been made over a 1,295-km path from Long Branch, Illinois to Boulder, Colorado. Three microsecond pulses with a peak power of 800 kilowatts were employed. Signals propagated via ionized meteor trails, ionospheric scatter, sporadic E and aurora were observed. Most single meteor trails show no detectable multipath. However, spreading of the received pulse over a 10 microsecond range with several components was visible occasionally. The simultaneous occurrence of several meteor signals resulted in multiple paths differing in time by as much as 500 microseconds, although shorter delays were more probable. Continuous scatter signals cover a 40 microsecond delay range. Strong E_s signals usually show no detectable pulse distortion. When weak, however, they may cover a 40 microsecond delay range.

Terms Used in This Paper

Multipath interference occurs when multiple propagation paths of similar loss exist between a transmitter and receiver. Multipath is taken to be significant when the signals present are separated by less than 6 db in amplitude and one is above a chosen threshold.

Threshold is the received signal intensity (voltage) above which all signals are used for the test in question. In a communication system this would be the minimum signal strength considered suitable for system operation.

Duty cycle is the fractional portion of time that the received signal is above the threshold.

Interpath delay is the time difference between signals arriving over multiple transmission paths which exist simultaneously.

Intermeteor delay same as above, applied to meteor burst signals.

Scatter always refers to the continuously observable component of signal considered to be scattered from turbulent irregularities in the upper part of the D region.

Single trail multipath is multipath interference which is caused by the existence of two or more widely separated reflecting points on a single long meteor trail.

Multitrail multipath results from the simultaneous presence of more than one properly oriented meteor trail.

1. Introduction

When radio signals are propagated from one place to another they often travel by more than one path. If these paths are sufficiently different in length and similar in attenuation, portions of the message sent at different times may arrive at the receiver simultaneously and cause an unintelligible result. This effect generally becomes significant when the propagation time difference becomes as large as a small fraction of the duration of the most brief element of

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the message. Smaller time differences result in destructive cancellation of the radio signal which may often be combated with diversity reception techniques. Such brief path differences could not be directly measured in the present experiment. The effect of a given multipath situation on a communication system is strongly dependent on the configuration of system. The data present here has generally been reduced with a view toward its application to digital transmission.

In the case of meteor-burst communication [Forsyth et al., 1957; Vincent et al., 1957; Montgomery and Sugar, 1957; Carpenter and Ochs, 1959; Hannum et al., 1960] one may wish to transmit messages very rapidly while signals are strong. This is usually accomplished by using brief message elements. The present experiment was performed to investigate multiple transmission paths in meteor-burst communication and to estimate the probable minimum limit on message element duration set by this multipath. In this experiment a 3 μsec transmitted pulse was generally used. In addition to the intended meteor-bursts, sporadic *E* layer, ionospheric-scatter, and auroral-reflected signals were observed on certain occasions.

The data reported has all been obtained at 40.920 Mc/s over the 1,295-km East-West path from Long Branch, Ill., to Table Mesa near Boulder, Colo. The details of the system are contained in table 1. In almost all cases 3 μsec duration pulses with peak power of about 800 kw were delivered to the transmitting antenna. The antennas were located at such a height as to offer maximum illumination at 100 km altitude at the path midpoint. Received signals were oscilloscopically displayed and photographically recorded. Both the transmitter and the receiving oscilloscope were triggered by highly stable pulse-repetition-frequency generators. This allowed continuous recordings to be made for periods of many hours without timing adjustment.

TABLE 1. *System Characteristics*

Path great circle length	1,295 km.
Frequency	40.920 Mc/s.
Transmitter peak power output	0.80×10^6 watts.
Pulse width	3 to 12 μsec.
Pulse repetition rate transmission	125 to 500 pps.
Stability of transmitted prf	1 in 10^8 day.
Transmitted prf jitter	<1 μsec.
Transmitting antenna [a]	Dipole with corner reflector.
Transmitting antenna gain over half wave dipole.	10 db (approximate).
Receiver bandwidth	330 kc/s.
Receiver sensitivity	External noise limited.
Receiving antenna [a]	5-element Yagi.
Receiving antenna gain over half wave dipole	9 db (approximate).
Receiver prf generator stability	5 in 10^8 day.
Receiver prf jitter	<1 μsec.
Pulse repetition rate of display	15.625 to 500 pps.
Duration of oscilloscope sweeps	20 μsec to 1 msec.
Relative drift of time bases	<1 msec/day.

[a] The transmitting and receiving antennas were designed to have similar major lobe characteristics, i.e.—azimuthal beamwidth about 60° and free-space vertical beamwidth of about 80°.

2. Delay Distributions

A one-day run was made with recording taken in the form of figure 1. The minimum signal level displayed was about 20 μv. This record was scaled to determine the *number* of meteor signals *versus* delay from the ionospheric scatter signal for each half hour. Since the scatter signal was not continuously detectable, the time delay data for many periods was purely relative. In the figures the location of the scatter signal was assumed to be a fixed time before the first delay period containing 10 percent of the number of meteors in the most populated delay period. By examining half hour periods in which both meteor and scatter signals were observed, it was found that this method was nearly equivalent (within ±10 microseconds) to relating meteor path delay by means of the shortest scatter path delay. The relatively high stability of

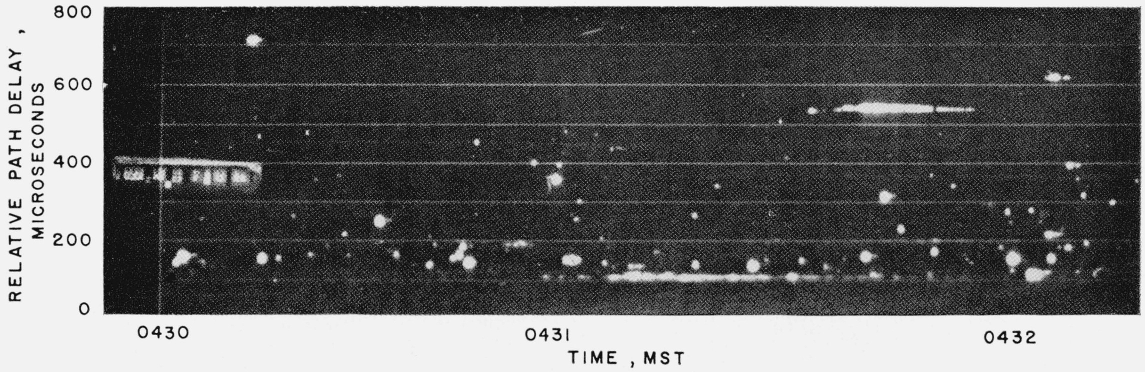

FIGURE 1. *Sample of record used to obtain histogram of meteor signal path delays.*

the time bases adds further confidence in the reliability of this form of presentation. The distribution of meteor signal transmission delay times for the full 24-hr period is presented as figure 2 and the individual parts of the day are contained in figure 3.

Additional data has been taken with higher display sensitivity to allow continuous detection of the ionospheric scatter signal. Figure 4 illustrates a portion of this record, and figure 5 contains data for 3 morning periods. At this time of day, 0830 to 1030, the scatter signal appears to be about 40 μsec in width, with the meteoric signal peaking about 60 to 80 μsec after the start of the scatter.

Calculations have been made of the number of meteors observed versus angle away from the great circle connecting the two stations. If one assumes that the reflection point is most likely to occur in the plane equidistant from the two stations, the angle of departure from the normal propagation path taken by the scatter signal is approximately directly proportional to the delay from the scatter-propagated signal. Thus a given delay would correspond to approximately a fixed angular deviation from the scatter-mode path, but of course it does not indicate the direction. The height of meteoric radio reflections has been well established to be in the region of 90 to 120 km above the Earth's surface. This assumption is used in the location of reflections from the delay data. The two stations are the foci of ellipses of revolution which describe the location of all points of reflection with the same path delay. Since most meteoric reflection takes place in the neighborhood of the *E* region, the problem is one of determining the intersection of the various constant delay ellipses with the chosen height of about 100 km. If reflection were to take place at a point ¼ the way from one station to the other the angular error would be about 50 percent. The theories of meteor reflection put forth by Eshleman and Manning [1954] indicate that the probability of reflection from this point is only about ½ to ⅔ that on the equidistant plane. If true, this would mean that the error in the location of the peak would not be greater than about 30 percent. This error estimation is based on a strong bias toward one end of the path. If the reflection points are more nearly randomly distributed, the result will be a broadening of the peak and little error in its position. Thus it appears that the angle from the great circle path is the first order contributor to the delay and that height and longitudinal position of the reflection point can be expected to have a secondary effect on the data. This angle is computed from observed time delays on the assumption that all reflections take place equidistant from the stations and that average meteor reflection heights are about 6 km higher than the scatter level. A correction has also been made for the change in antenna gain with angle off path. This correction is based on the assumption that the number of meteors detectable at a given angle is proportional to the product of the receiving and transmitting antenna gains at that angle. The results are plotted in figure 6.

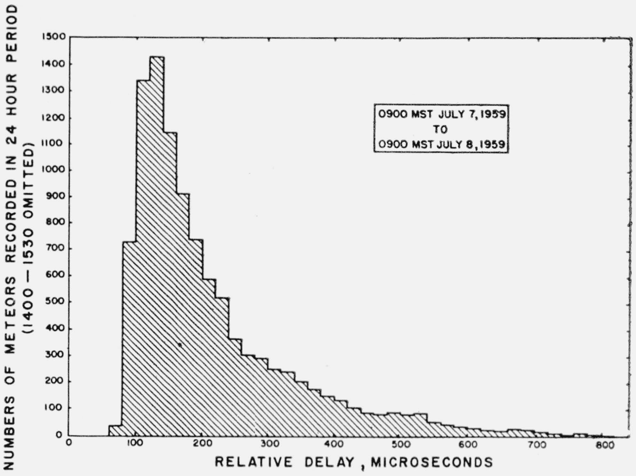

FIGURE 2. *Histogram of relative meteor signal path delays.*

3. Multitrail Multipath

The simultaneous occurrence of two or more suitably oriented meteor trails results in multiple propagation paths. This is illustrated in figure 7. Data of this sort were taken for 1 min each half-hour for a 24-hr period and were examined for multipath interference. The results are presented in figures 8 and 9.

The incidence of multipath appears to increase with decrease in interpath delay to the limit of the resolution of this experiment. This leads to the assumption that there is still much multipath not observable in the experimental data. Extremely short delay multipath will not produce serious message element distortion in a communication system; however, all multipath will be included in the following prediction. The exact effect on any particular communication system is beyond the scope of this discussion.

If one assumes that meteor trails are random in time and have a known signal amplitude distribution, one may predict the portion of time that two meteors will simultaneously produce signals within a particular amplitude range. Using the method of Sugar, Carpenter, and Ochs [1960], a prediction of expected multipath interference has been made based on the data of figures 8 and 9. The relation between duty cycle and threshold level is

$$D=KV^{-a}$$

where D=duty cycle
V=Threshold voltage
a=1.74 for the data of figures 8 and 9.

Table 2 contains the experimental data and the predicted value for multipath interference. For comparison, predictions are included based on

$$a=1.2,$$

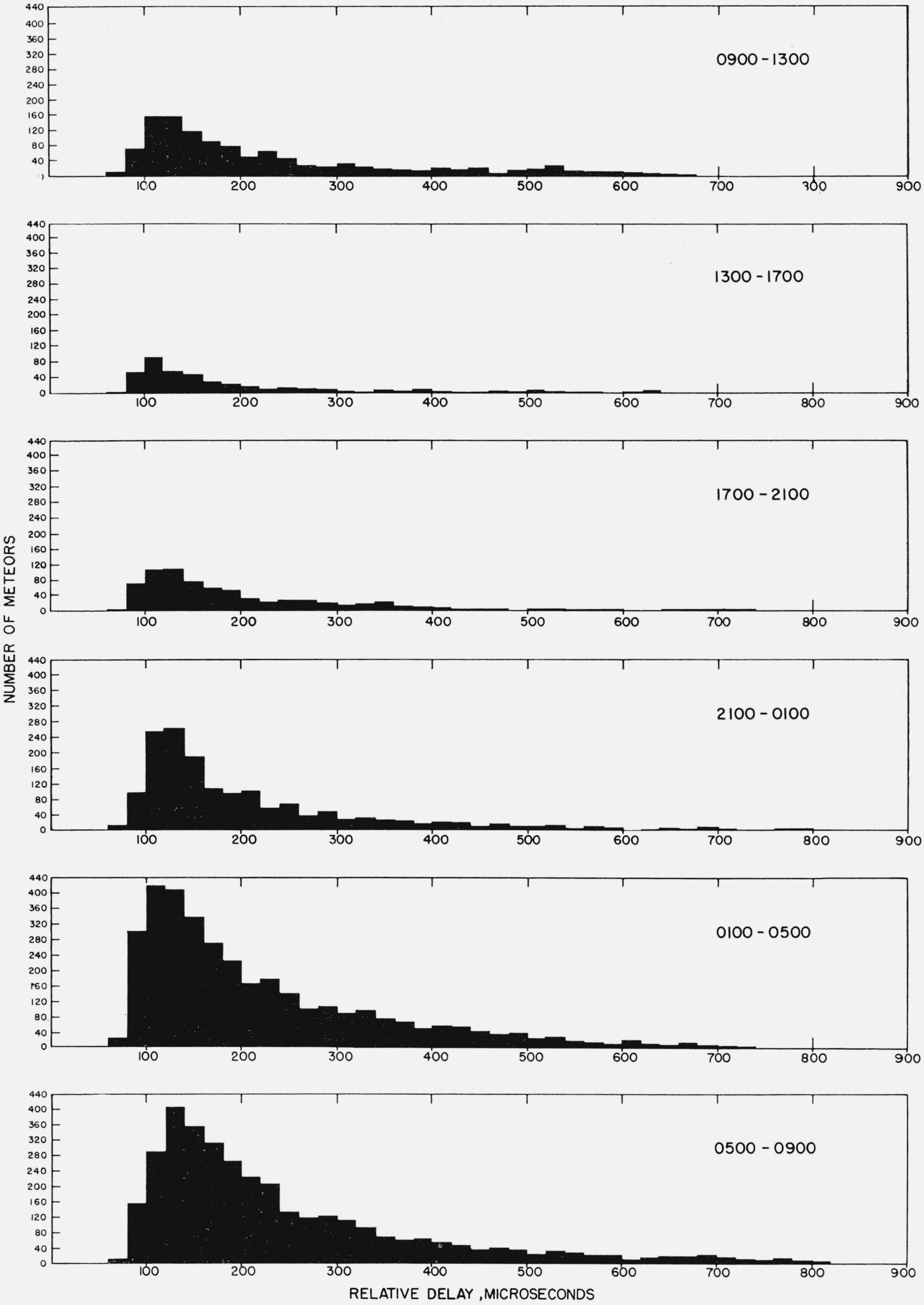

FIGURE 3. *Distribution of meteor path delays.*

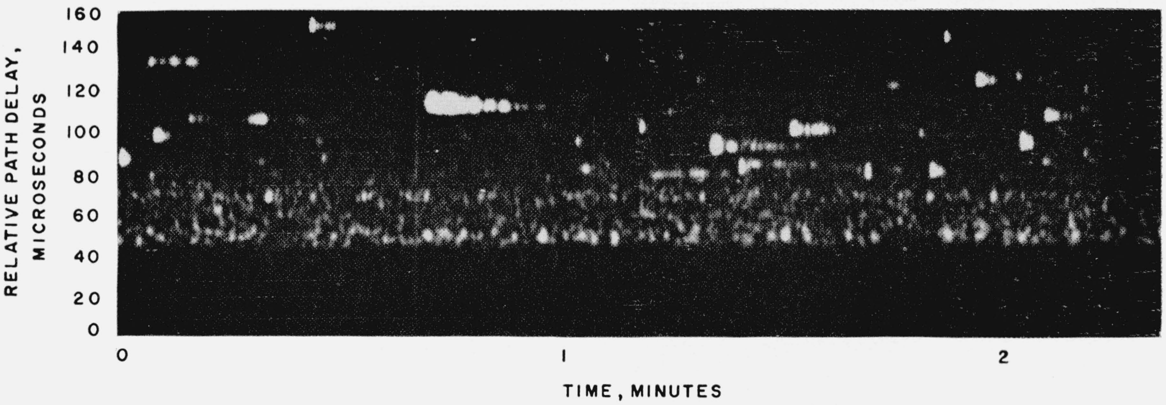

FIGURE 4. *Sample of record showing ionospheric scatter signal.*

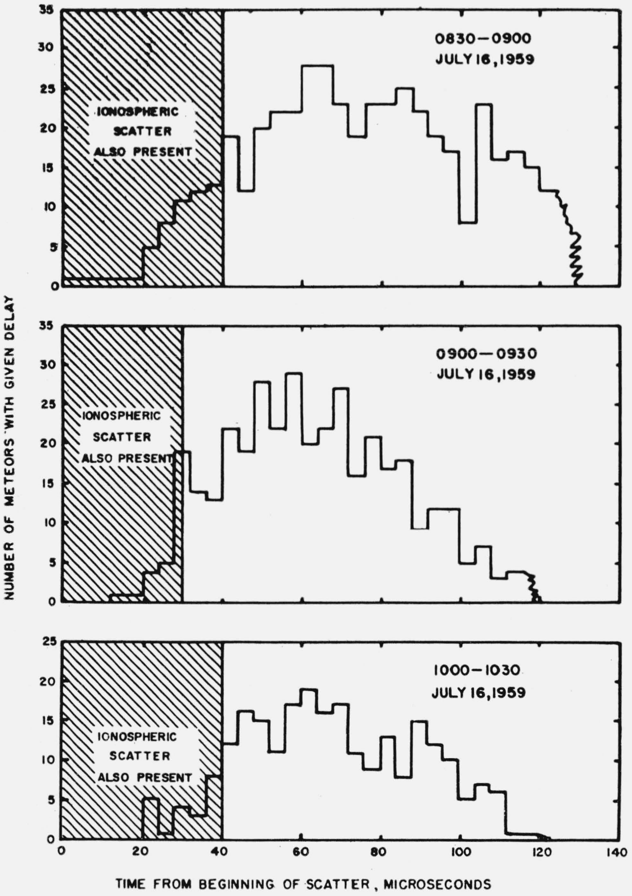

FIGURE 5. *Meteor path delay relative to scatter signal.*

a value which has been obtained in much of the earlier work at NBS [Montgomery and Sugar, 1957]. Very little multipath interference was observed at the 50 μv threshold so that the associated experimental point must be considered very approximate.

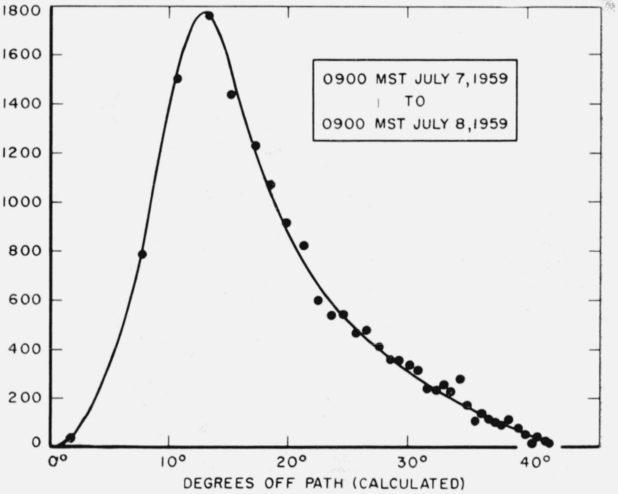

FIGURE 6. *Calculated off-path meteor signals.*

As previously indicated, multipath transmission will not be serious in many types of communication systems unless the two path lengths differ considerably. From distributions of interpath delay, as shown in figures 8 and 10, one may predict the portion of multipath signals that will result in system performance degradation. These figures give the portion of time that two signals were within 6 db of being the same amplitude, while at the same time at least one of them was stronger than an amplitude threshold. Data are plotted for intermeteor delays up to 500 μsec. Figures 9 and 11 contain the same data but are plotted in a cumulative fashion. These can be used to estimate the error rate that would be obtained with a communication system operating with the same duty cycle as observed at a number of different message element durations. As an example, in a system with a 20

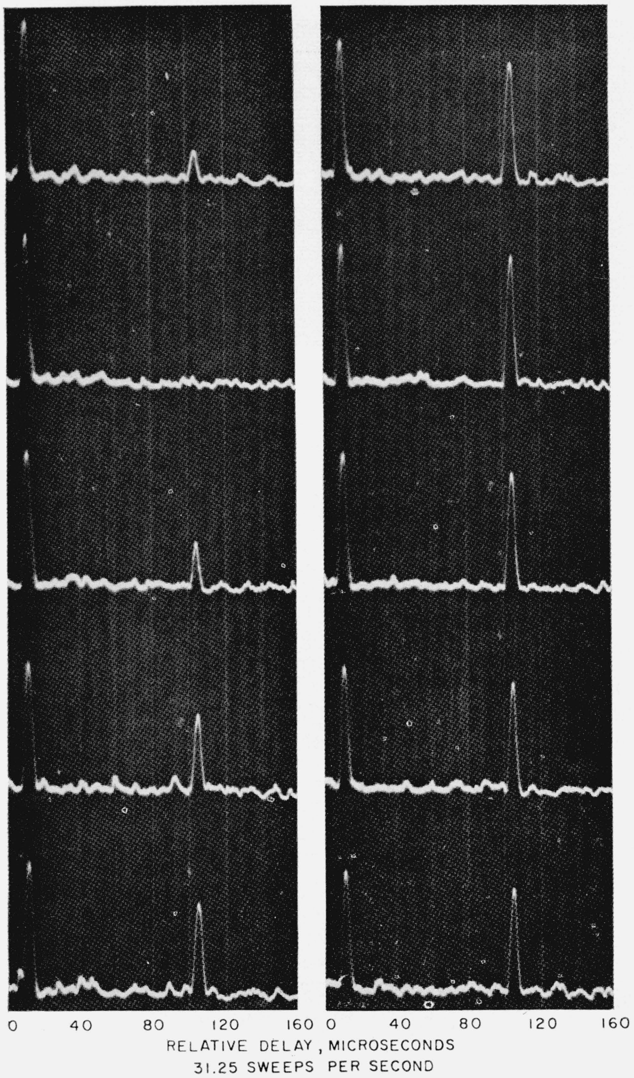

FIGURE 7. *Two trail multipath.*

Time progresses from upper left to lower right.

percent duty cycle (the 25 μv data of fig. 9), one might expect a binary error rate of about 6 percent with 200 μsec message elements and about 1 percent with 1,000 μsec message elements.

Since the average rate of occurrence of meteoric signals with short overall path delay is high, a meteor shower resulting in a significant peak of activity at longer path delay (demonstrated in fig. 10) can result in an unusual increase in multipath with a considerable intermeteor delay. This could result in unusually poor communication system performance for the duration of the shower.

4. Single-Trail Multipath

When a signal continues to be reflected by a meteor trail for periods in excess of about 0.4 sec, a cyclical fading of the signal is generally observed. This fading has been attributed to the appearance and subsequent interference of signals from multiple reflection points along the trail (Greenhow, 1952; Manning, 1959).

TABLE 2. *Experimental Data on Multitrail Multipath*

Data taken for 1 min each half hour from 1100, 15 June 1959, to 1001, 16 June 1959, with a few missed periods.

Threshold level [a]	50 μv	25 μv
Duration of experiment	2, 500 sec	2, 500 sec
Time above threshold	148. 4 sec	492 sec
Duty Cycle	0. 0594	0. 197
Time during which the main signal was above threshold and the interfering signal was less than 6 db below the main signal	9. 75 sec	63. 8 sec
Fraction of time above threshold lost to interference	0. 0657	0. 130
Same—Predicted (a=1.7)	0. 0344	0. 114
(a=1.2)	. 0192	. 064

[a] Open circuit 50 ohm antenna voltage.

Our experimental minimum pulse width of about 3 μsec gave a path difference resolving power of the order of 1 km. The path delay differences responsible for the observed fading were not, in the majority of cases, resolved. We conclude therefore, that the majority of the existing single trail multipath is of very short delay, less than 1 μsec. Figures 12 and 13, showing resolved multipath in long-enduring meteoric signals are believed to illustrate single trail multipath. In a number of other cases however, it seemed quite likely that two signals appearing in close time proximity actually were separate meteor trails which happened to provide radio paths of similar length. For instance, on the A-scope trace, small pulses would at times appear and fade near a longer enduring pulse. Since the amplitude versus time characteristics of these small pulses were like those of underdense meteor bursts, it is assumed they were not part of the longer burst. However, two long enduring trails of nearly the same path delay could present the appearance of a single trail signal and be difficult to interpret.

With the above limitations in interpretation in mind, the widths of the received pulses were examined at the half-voltage points. The receiving equipment widened the received pulse to about 4 μsec at this point and the majority of received pulses were of this width. The maximum width recorded was 10 μsec and was observed in less than 1 percent of the meteor signals.

5. Sporadic *E* Signals

The gathering of data on sporadic *E* layer transmission was not an original objective of this program. However, considerable data were taken on this mode of propagation since it was present on our path for a considerable portion of the test period.

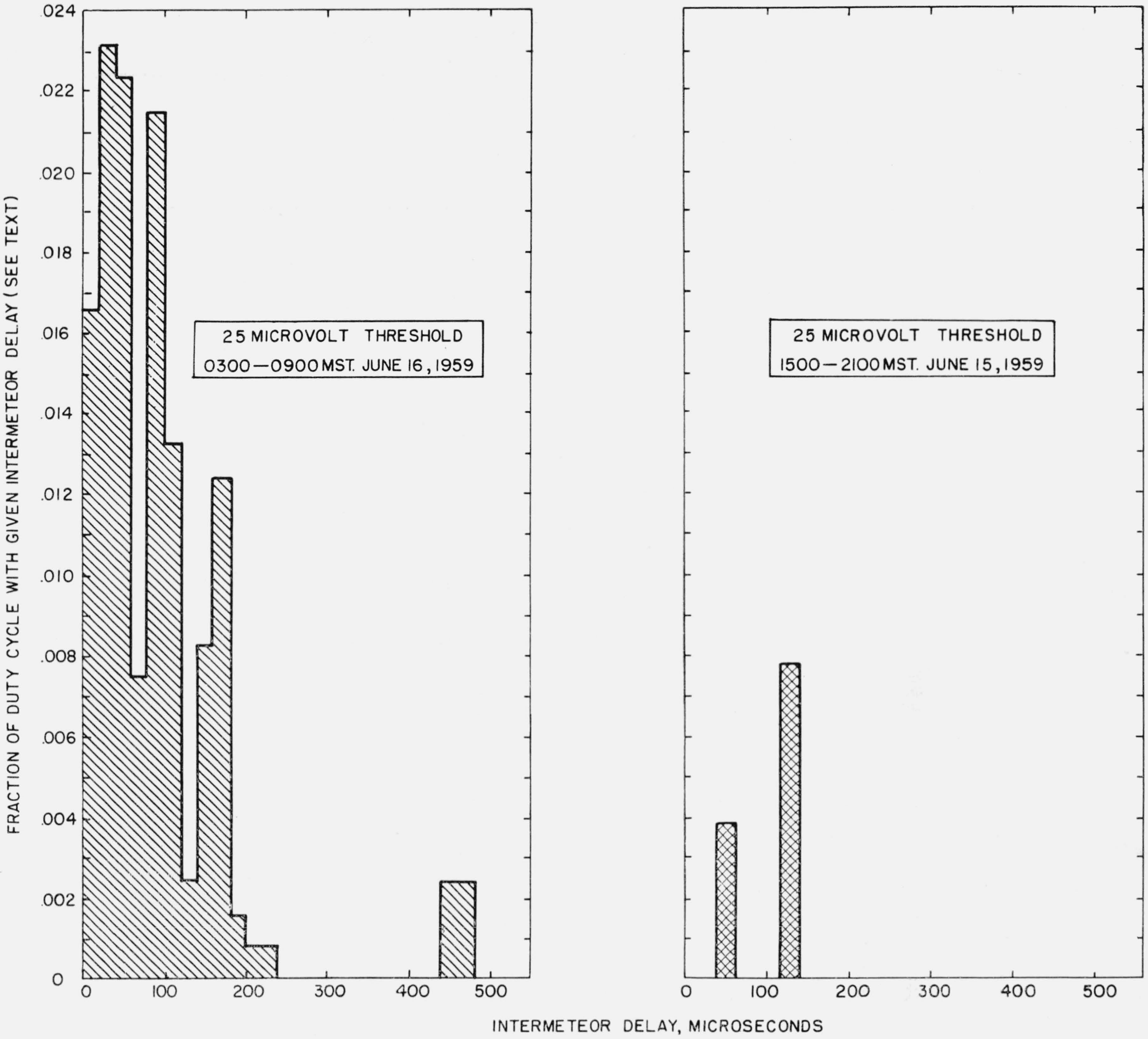

Figure 8. *Occurrence of intermeteor delay, morning and evening.*

Signal intensities from E_s were often very high; much greater that most meteoric signals. When an E_s signal enhancement was first observed it often consisted of modes which differed in delay by 20 μsec or more; figure 14 illustrates an E_s signal enhancement forming as two paths and combining. Figure 15 illustrates the amplitude-time characteristics during severe multipath. The components of the received signal are spread over about 40 μsec. Later in an E_s enhancement signals were often strongly received. At these times they were very "clean" and no multipath could be detected. At almost all times there was fairly deep fading of the signal, which could be accounted for by two slightly differing paths whose relative phases were continuously changing, as drawn in figure 16, and possibly illustrated by the longest delayed pulse in figure 15.

6. Auroral Reflected Signals

In the early morning hours of June 11, 1959, the recordings showed a great many signal components with large delays. Analysis of CW records over the same path at 40.88 Mc/s shows a large signal enhancement. Disturbed magnetic conditions were observed that morning, so it is assumed that these signals are the results of auroral reflection. The transmitter prf at this time was 125 pps, which leads to concern as to which transmitted pulse produced a given received pulse, due to the unusual distance involved in the auroral signal. It is assumed that the many components in figure 17 are auroral-reflected signals from one transmitted pulse. These returns are spread out over a few hundred microseconds, and certainly

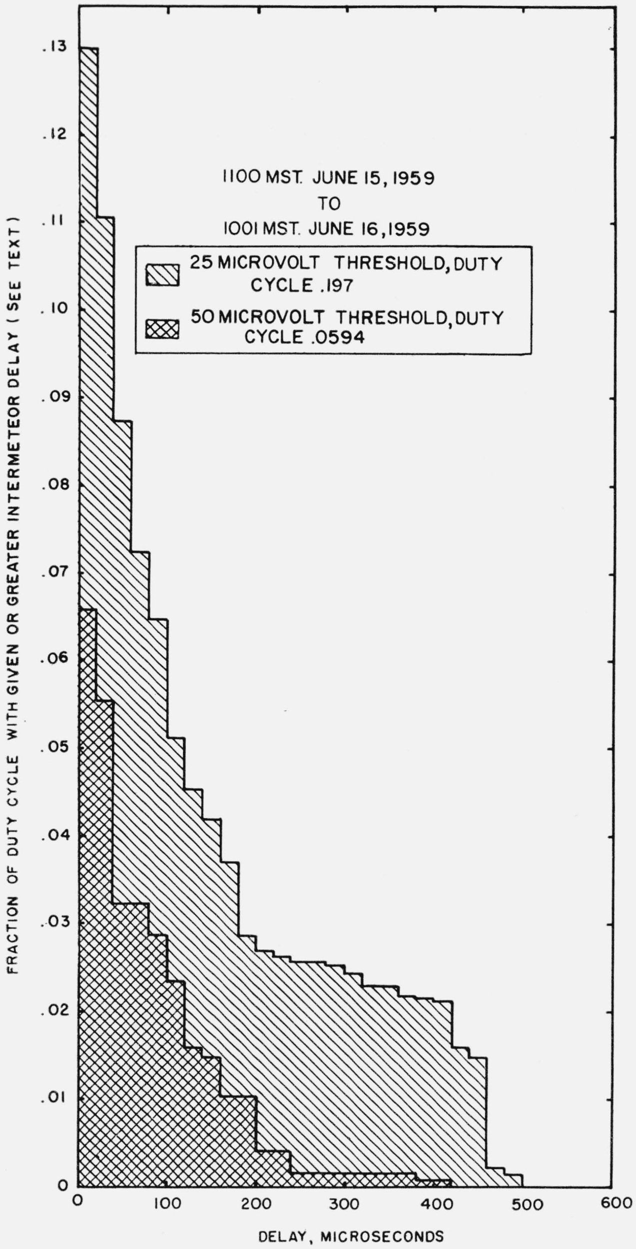

FIGURE 9. *Fraction of duty cycle with multipath of given or greater delay at two thresholds.*

indicate that severe message distortion would occur with message elements of even moderate duration. This figure also contains the Boulder ionograms taken at the times in question.

7. Conclusions

We conclude that modulation elements as brief as 4 µsec duration can be successfully transmitted on the majority of meteor bursts. In fact, no multipath distortion of the 3 µsec pulses was observed on most bursts. The modulation bandwidth of meteor-burst communication systems is therefore likely to be limited primarily by other allocations considerations. The incidence of simultaneous meteor signals of similar amplitude was found to be roughly proportional to the fractional time the received signal was above the threshold level. No meteor signals were observed with path delay less than the ionospheric scatter signal. Meteors with a path delay slightly longer than the scatter path were most common, with more than half of the meteoric signals commonly being contained in a 100 µsec region. In order to control message errors from multiple meteor trails, the transmission duty cycle must be small and/or message elements must be relatively long. The compromise of channel capacity, error rate, and equipment complexity for a communication system must take these conditions into account.

Sporadic E layer signals often exhibited extremely small time distortion. Message elements of 4 µsec or less duration should be practical during periods of strong signals.[2] At other times, particularly at the commencement (and possibly the end) of E_s signal enhancements, message elements should have a duration of perhaps 100 µsec to ensure satisfactory reception.

Examination of the fading of single long enduring meteor signals has led to the conclusion that this type of multipath is of little consequence with message elements of 10 µsec or longer. Little insight into the causes of this fading was obtained since it was conclusively observed only twice. This phase of the experiment was sorely hampered by the duration of the transmitted pulse. On an oblique path, 1 µsec pulses would prove very useful in the examination of single trail fading.

Auroral reflections were observed to spread over hundreds of microseconds on the one occasion that they were observed.

A portion of the preparation for these experiments was performed under the direction of Dr. K. L. Bowles. He also made numerous useful suggestions. Fruitful conversations were also had with G. R. Sugar and R. C. Kirby. A. C. Wilson aided in the selection and design of the transmitting antenna. Glen F. Miller built all of the special electronic apparatus required and designed some of it. Special thanks are due John L. Green and his group at the NBS Long Branch Transmitting Station for their heroic efforts in keeping the transmitter operating. Airmen Raymond F. Miller and Clifford Gardner were extremely helpful during the erection of the transmitting antenna. A number of our other colleagues at NBS furnished valuable assistance in this project.

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[2] This could be inferred from the many reports of distant television reception.

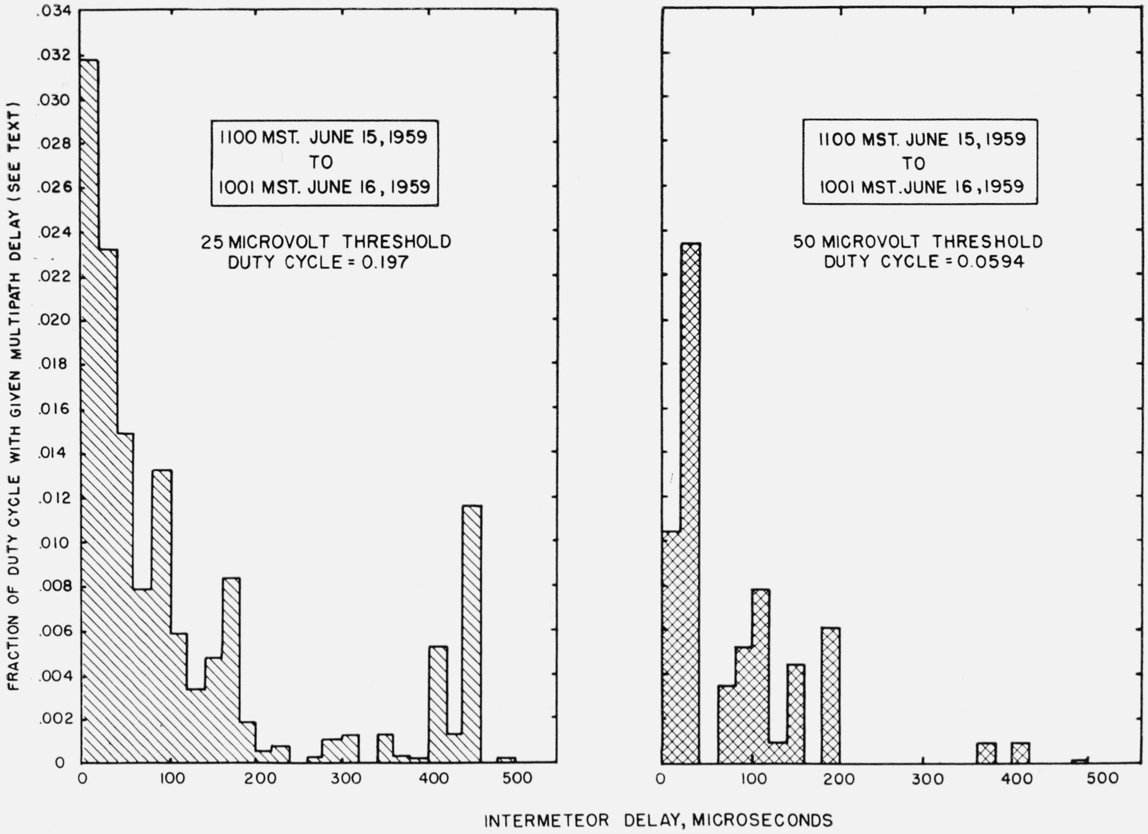

FIGURE 10. *Occurrence of intermeteor delay at two thresholds.*

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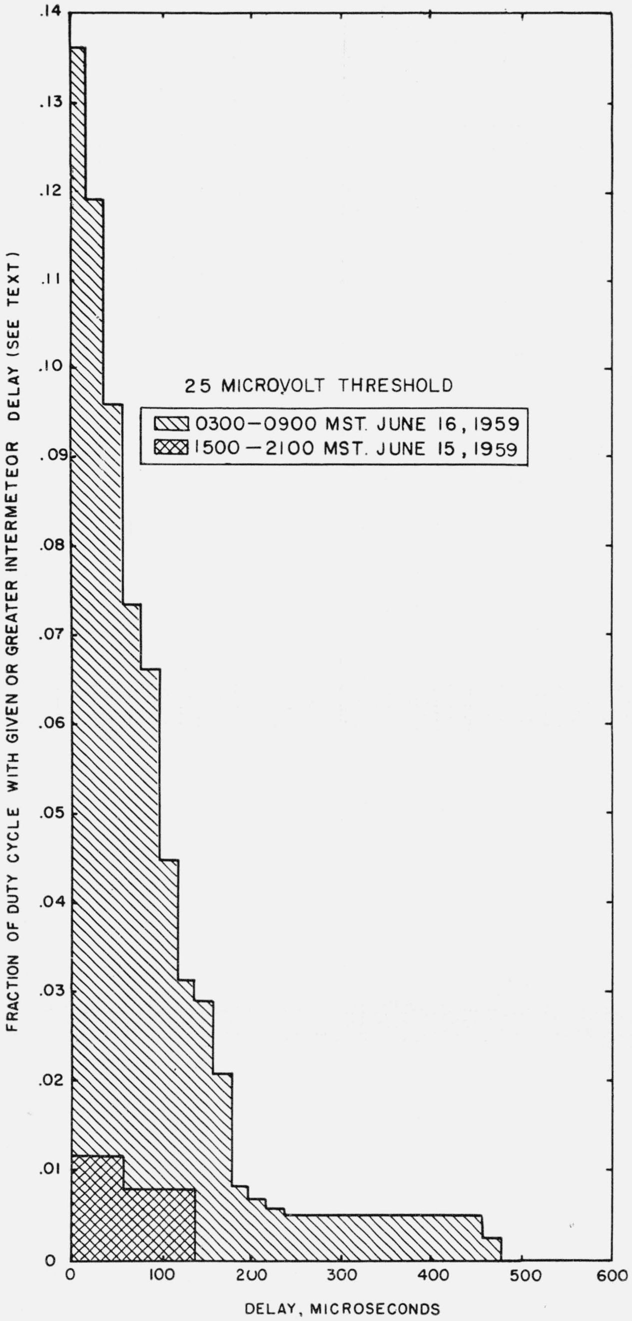

Figure 11. *Fraction of duty cycle with given or greater intermeteor delay, morning and evening.*

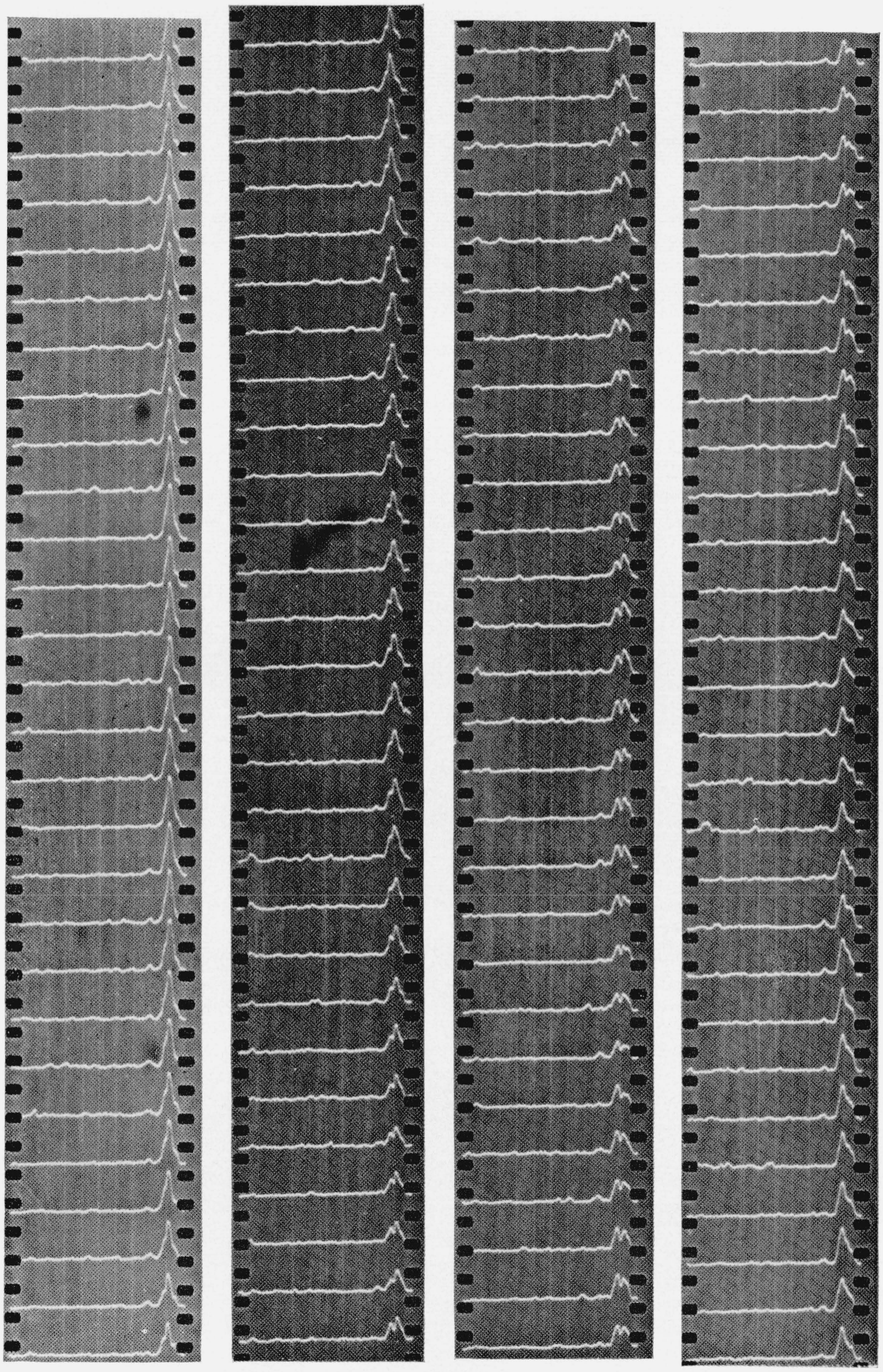

FIGURE 12. *Single-trail multipath.*

Time progresses from upper left to lower right. There are 62.5 sweeps per second and each sweep is 100 μsec in duration. This record begins 4.7 seconds after the signal was first detected. The entire meteor lasted 13.2 seconds. Record was taken 0900, 1 July 1959.

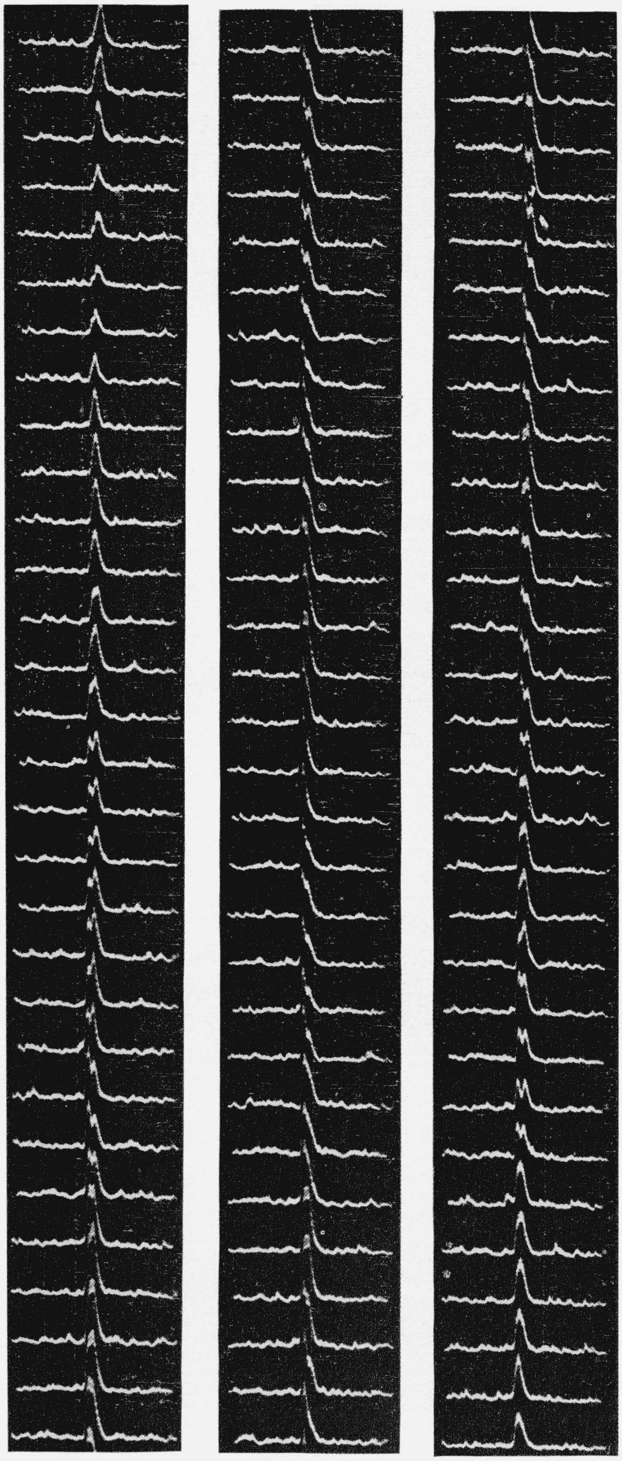

FIGURE 13. *Single-trail multipath.*

Time progresses from upper left to lower right. There are 31.25 sweeps per second and each sweep is 100 μsec in duration. This record is taken approximately in the middle of an overdense burst at noon, 14 May 1959.

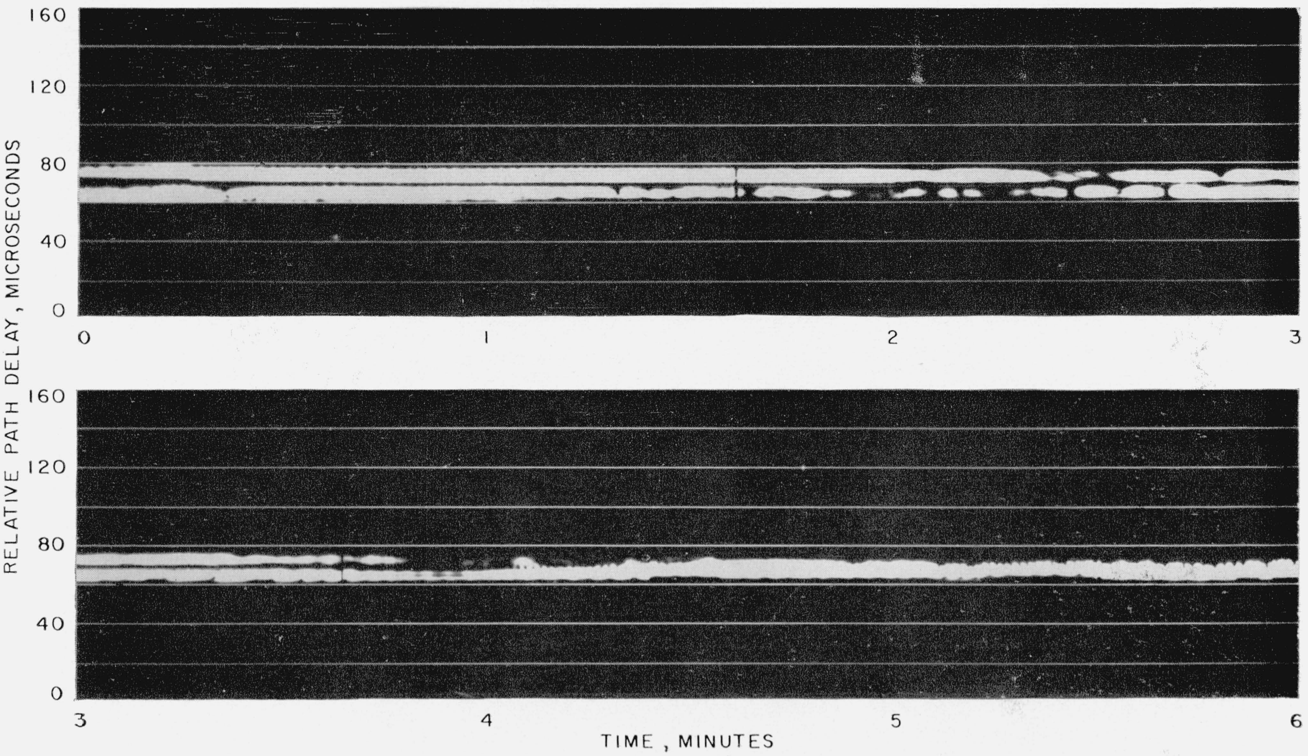

FIGURE 14. *Beginning of sporadic E, 23 June 1959.*

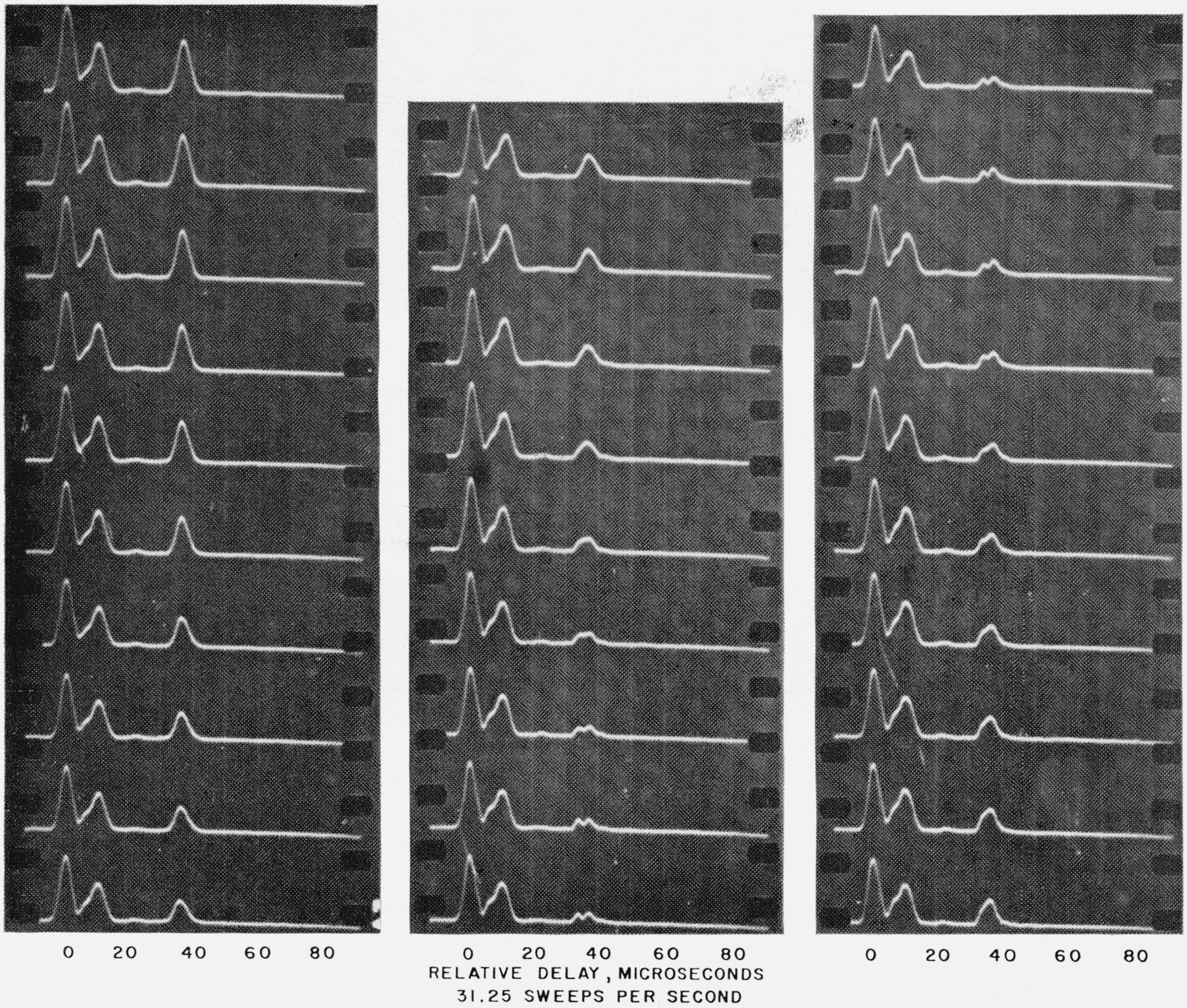

Figure 15. *Multipath from sporadic E.*

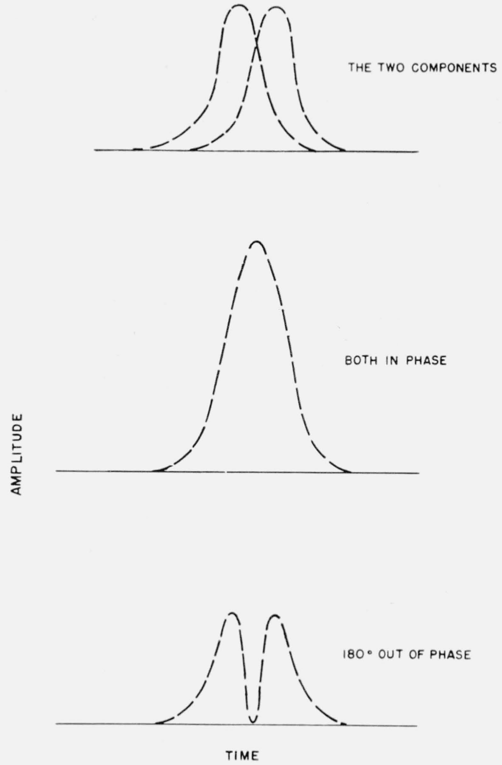

FIGURE 16. *Drawing of two-component signal.*

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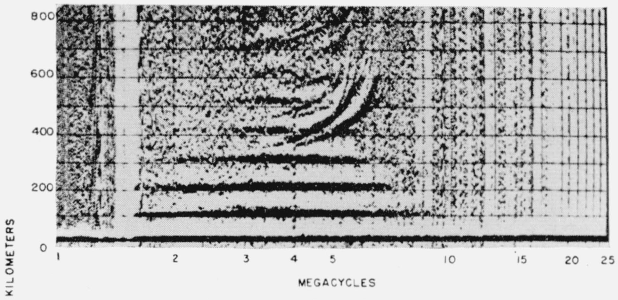
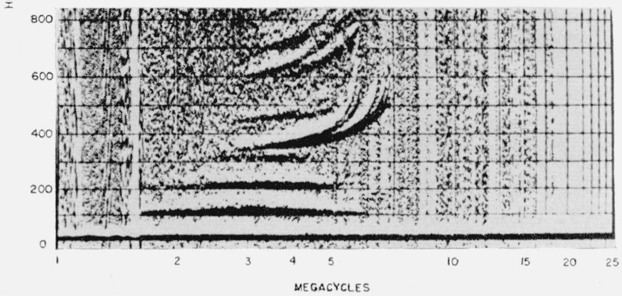
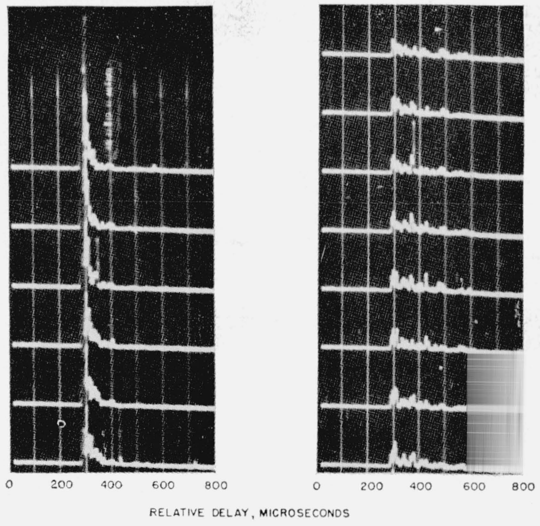


BOULDER IONOGRAM AT 12:30 AM.



BOULDER IONOGRAM AT 01:30 AM.



12:30 AM.

01:30 AM.

FIGURE 17. *Auroral reflection signals received 11 June, 1959. The Boulder ionosphere recordings are included for comparison.*