Propagation Studies at Microwave Frequencies by Means of Very Short Pulses

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Microwave pulses with a duration of about 0.003 microseconds were transmitted over a 22-mile path from Murray Hill, N. J., to Holmdel, N. J., in order to determine the effects of the transmission medium upon such pulses. During "fading" periods multi-path transmission effects with path differences as great as 7 feet were observed, as well as some other effects. A microwave frequency of 4000 megacycles was employed.

INTRODUCTION

This experiment was set up with two main purposes in view: First, as a means of studying microwave propagation, especially with regard to multi-path transmission effects and second, to determine the effect of a transmission path upon the shapes of very short pulses, particularly to learn what restrictions might be imposed upon minimum pulse length or spacing between pulses by distortions produced in the transmission medium.

In regard to multi-path transmission the pulse method seems to be the most straightforward way of studying such effects. For example, if there is transmission by more than one path, and if the pulses are sufficiently short in comparison to the path length differences involved, then there will be received a separate pulse for each path. Under these conditions the number of paths involved, path length differences and other information become directly evident. If pulse duration is too great with respect to the path differences involved, the pulses received via the various paths will overlap in time and the resultant multi-path effect will be pulse distortion rather than reception of individual pulses. This situation is much more difficult to analyze.

TRANSMISSION PATH

The transmission path is the same as that used by A. B. Crawford for microwave propagation studies by means of the frequency sweep method, i.e., the path from Murray Hill, N. J., to Crawford's Hill (near Holmdel), N. J.[1] The path length is approximately 22 miles, and is partly over water and partly over rough land terrain. The frequency sweep studies had indicated that the path differences involved in multi-path fading were of the order of one or two to about seven feet. In terms of delay times this means differences of about 1 to 7 millimicroseconds. In order to resolve the paths when the path differences were only one or two feet, we should have liked to have pulses of about 1 millimicrosecond duration. Because of the difficulties involved in generating, amplifying

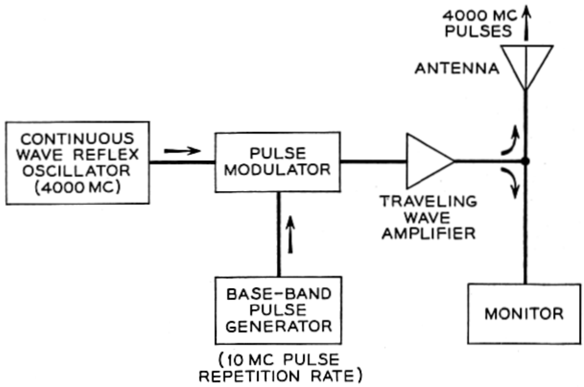

Fig. 1—Transmitting equipment.

and detecting such short pulses, we accepted pulses which, when displayed on our final indicating equipment, had a length of 3 millimicroseconds at half amplitude. (About 6 millimicroseconds at the base.) In free space this pulse would be just about 6 feet long at the base.

TRANSMITTING EQUIPMENT

The transmitter was mounted on top of a 100-foot tower at Murray Hill. As can be seen from Fig. 1, it consisted of a c-w reflex oscillator operating at 4000 megacycles, a baseband pulse generator, a modulator, or gate, for modulating these pulses on the microwave carrier, a single stage traveling-wave amplifier and finally a horn antenna. Approximately one watt of power was obtained from the transmitter at the peaks of the pulses. The antenna area was 25 square feet and its gain 32 db above that of a dipole. A pulse repetition frequency of 10 mc was employed.

[1] A. B. Crawford and W. C. Jakes, Jr., "Selective Fading of Microwaves," *Bell System Tech. J.*, **31**, Jan. 1952, pp. 68–90.

RECEIVING EQUIPMENT

The receiving antenna, a large horn, was mounted between two poles guyed for support. It had an aperture of about 90 square feet and a gain of approximately 38 db over a dipole. The receiver circuit is shown in Fig. 2. About 60 db of gain at 4000 mc was provided by either two or three stages of traveling-wave tube amplifier depending upon the gain of the particular tubes used. It was necessary to provide very good shielding and also careful filtering of all power leads to eliminate the tendency for this amplifier to sing. The amplifier fed two crystal detectors through a hybrid tee junction. Each detector employed a silicon crystal of the IN23B type.

Two indicator circuits are shown in Fig. 2. These circuits are very similar except that one employed a vertical amplifier coupled to a Dumont 5XP2 CRO tube, whereas in the second the baseband output of the crystal was fed directly onto the deflection system of a traveling-wave type of CRO tube. The latter CRO tube, which has been described by J. R. Pierce in the November, 1949, issue of *Electronics*, has a very high deflection sensitivity and is used with a microscope to enlarge its trace; hence, no amplification was required between it and its driving crystal. The deflection system of this tube has a bandwidth of 500 to 1000 mc. The micro-oscilloscope was provided primarily for photographing pulses by means of a 35-mm camera attached to the microscope. (Exposure time was 5 to 15 seconds. The time recorded for each picture corresponds

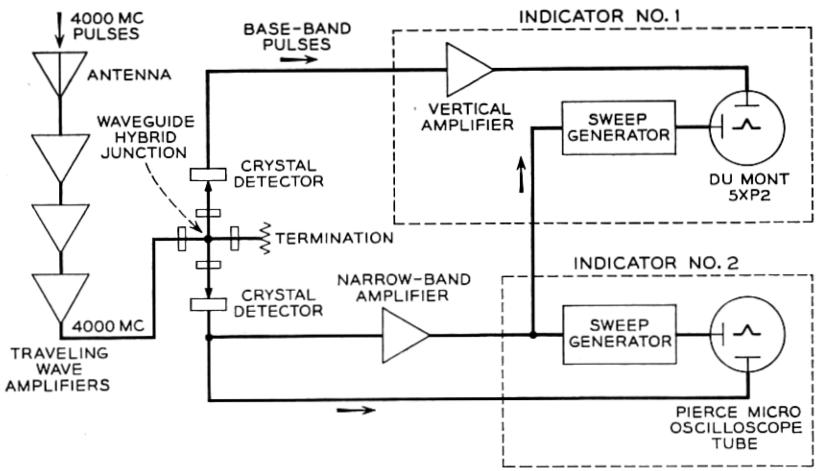

Fig. 2—Receiving equipment.

to that at the end of exposure.) A second microscope made it possible to view and to photograph the screen of the tube simultaneously. The general procedure was to observe continuously during periods of disturbed transmission, taking pictures at regular intervals of 5 to 10 minutes. When conditions were seen to be changing rapidly, pictures were taken much more frequently. The large oscilloscope with its vertical amplifier had a bandwidth of about 150 mc and hence caused some deterioration of the pulse. It, however, was less tiring than the small scope, especially for long periods of observation and was watched to follow the general trend of events. It was capable of resolving the pulses resulting from two-path transmission when the path differences were large.

The sweep circuits for the two indicator oscilloscopes were practically identical. The horizontal sweep voltage for each consisted of the linear portion of a sine wave which was generated by a c-w oscillator operating at one third of the pulse repetition frequency of 10 mc. Each oscillator was synchronized with the incoming pulses by means of a 10-mc voltage derived by amplifying the pulse energy through a narrow band amplifier. This circuit provided very satisfactory synchronization even during the times when signal amplitude was so low as to produce a very poor signal-to-noise ratio. Timing markers were provided on each roll of film by periodically photographing a series of pulses spaced by an interval of 9 millimicroseconds.

RESULTS OF THE EXPERIMENT

The picture at the left of Fig. 3 shows the transmitted pulse. The right-hand picture shows the received pulse under what were considered to be normal transmission conditions. It is seen that, except for the addition of noise and widening of the pulse due to passage through the amplifiers and other equipment, the pulse shape is unaffected. The time calibration on this and the following photographs are in millimicroseconds, each mark representing one millimicrosecond (0.001 μs).

During the summer of 1950, when this experiment was in progress,

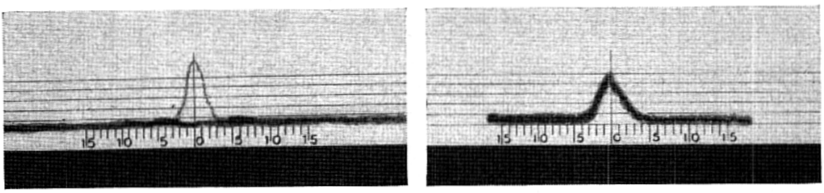

Fig.3—(Left) transmitted pulse (right) received pulse—normal transmission.

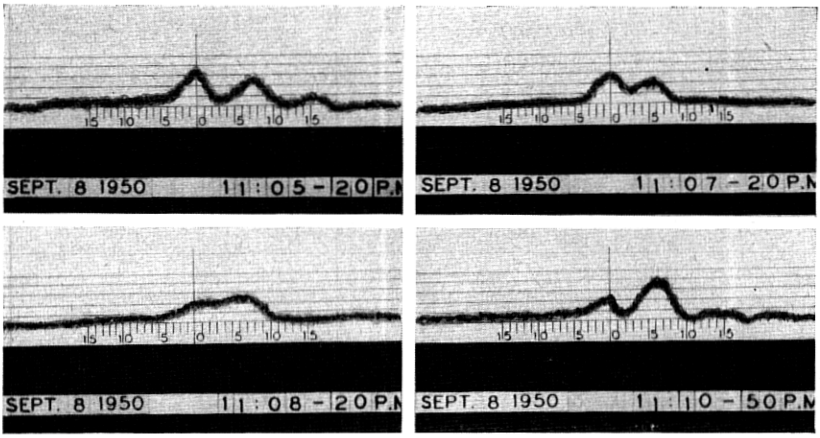

Fig. 4—Received pulses—disturbed transmission.

there was comparatively little fading over the path in question at microwave frequencies. There were, however, a few nights of considerable activity and some interesting results were obtained.

The series of pictures on Fig. 4 show one good example of multi-path transmission where the path length difference was great enough to produce complete resolution of pulses. At 11:05-20 there are two pulses, each 7 millimicroseconds wide at the base and with their peaks just 7 millimicroseconds apart; in other words, the path difference was just sufficient to produce two pulses with no overlap. The pulse at the left is presumably coming by the main path and that at the right from some second path resulting from bending of the rays caused by atmospheric effects. At 11:07-20 the second path appears to have shortened, resulting in a path difference of only about 5 millimicroseconds. This may actually have been due to a change of length of the second path or it may have been due to distortion of the second pulse by energy coming by way of a third path. The pictures taken at 11:08-20 and 11:10-50 show evidence of transmission by a third path. In the first of these, for example, the width of the disturbance at the base line indicates the presence of the two original pulses spaced 7 millimicroseconds apart but the midpoint of the two no longer falls to the base line as was the case in the first picture. This could be accounted for by the presence of a third pulse coming over a path whose length was somewhere between that of the other two. Conditions obtaining at 11:10-50 could also be accounted for by the presence of pulses from three paths, that is, energy coming by way of a third path might cancel part of one pulse and at the same time add to the other. This could account for the fact that the spurious pulse is larger than the

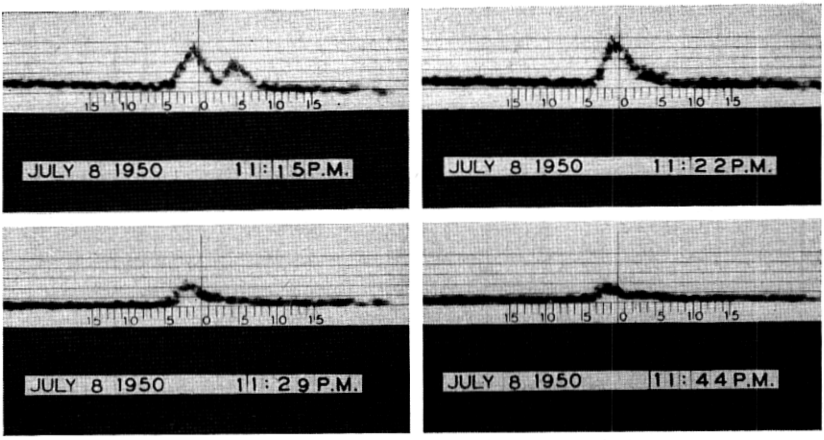

Fig. 5—Received pulses—disturbed transmission.

normal one. It is also possible that more than three paths were involved. On a number of other occasions the pulse coming by way of the second path appeared to be of greater amplitude than the one coming by the main path. This same effect has been observed by Mr. Crawford and his colleagues on the angle of arrival equipment.

Information obtained from the above set of pictures shows that for a time-division multiplex system using the length of pulse used here (7 millimicroseconds at the base) and operating over this path, pulses would have to be spaced a minimum of about 14 millimicroseconds apart if it were desired to avoid distortion at all times. If very much shorter pulses were used the spacing might be reduced to 9 or 10 millimicroseconds. However, the 7-foot path difference indicated by these pictures is about the maximum ever observed and occurs rather infrequently so that if somewhat closer spacings were employed troubles would result only a small percentage of the time.

The next series of pictures, Fig. 5, taken July 8, show an example of a more common type of multi-path transmission. Here the path difference is apparently less than for the last series. At 11:15 there are two distinct pulses with an apparent path difference of about six feet (6 millimicroseconds) if judged from the spacing between the peaks of the pulses. However, from the length of the disturbance at the base line, which we consider a better criterion, the path difference was more nearly four feet At 11:22 distortion of the trailing edge of the pulse was the only indication of a second path. For the pictures taken at 11:29 and 11:44 the path difference is sufficiently small that there is almost complete cancellation of pulses, only the leading portion of each pulse being present.

On the 11:44 picture there is just a trace of a second pulse. The next set of pictures (Fig. 6) were taken a little over an hour later on the same night and show about the same conditions, that is, pulse amplitude and shape change and other evidence of the presence of a second pulse delayed about 2 to 3 millimicroseconds.

On the night of October 2, fading, which was apparently due to transmission by way of two paths with little path difference, was observed. Some of the results are shown on Fig. 7. At 7:49 two distinct pulses are evident, there being 6 millimicroseconds between their peaks. One might conclude from this that there was a second path about 6 feet longer than the main path but the total length of the disturbance along the base line and the shapes of the pulses indicate that the actual path difference was about 2 to 3 feet.

Apparently we had here two pulses of r-f energy overlapping in time and involving a large number of frequencies. These pulses are capable of interfering with each other in a rather complicated manner, it being possible for some frequencies to add and others to cancel at the same time, depending upon their relative phases. Phase relationships of course depend upon frequency and path length differences. As a result pulses may be distorted and have their peaks shifted about by a considerable amount. We must, therefore, realize that the first picture of Fig. 7 does not really represent two distinct pulses as appears to be the case, but actually shows the resultant interference pattern of two overlapping pulses. Since a change of path difference of only about one and one-half inches is enough to produce a 180° change in relative phase at 4000 mc, it is not

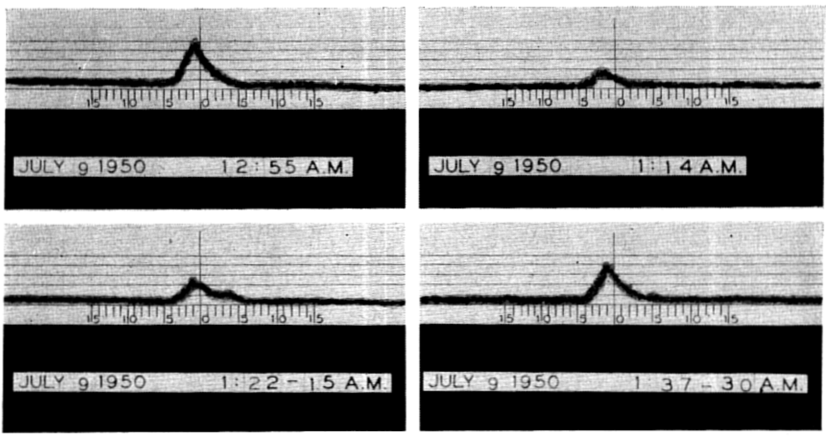

Fig. 6—Received pulses—disturbed transmission.

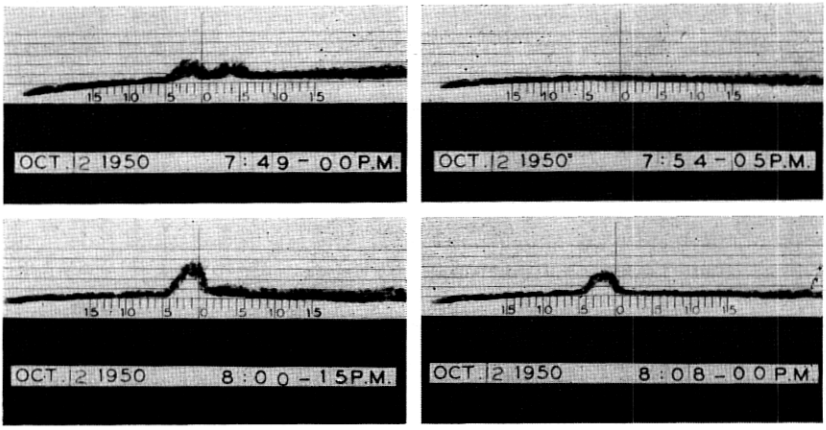

Fig. 7—Received pulses—disturbed transmission.

at all surprising that pulse shapes and amplitudes change very rapidly at times.

Looking again at the photograph, Fig. 7, we see that at 7:54-05 there was a complete fade as far as our system is concerned. To produce this degree of cancellation the path difference must have been very small though still sufficient to give a relative phase angle of 180° at the radio frequencies involved. At 8:00-15 and 8:08-00 pulse distortion is the most noticeable effect of the "fading," the pulses being considerably shorter than their normal value. Pictures, not shown here, taken between 7:54 and 8:08 show definite evidence of two-path transmission with a path difference of 2 to 3 feet; therefore the pulses of 8:00-15 and 8:08-00 are probably also the result of two-path effects.

The first two pictures of Fig. 8 show another form of pulse distortion observed on a number of occasions. Here the pulse is flattened out on top probably due to energy coming in over a second path differing in length by only one or two feet from the main path. Each time this type of pulse was observed a check was made to be sure that the flattening was not due to overload in our equipment. The pictures presented up to now have all shown comparatively slow changes of conditions. Very rapid changes were, however, quite common. In many cases pulse shape or amplitude changed considerably during the 5 to 15 second exposure time ordinarily used. The picture taken at 2:20-45 A.M. on August 27 is one example of such a rapid change, there being two definite sets of conditions shown on the one photograph. The remaining picture on Fig. 8 shows the pulses used for obtaining time calibration of the system. These pulses were spaced 9 millimicroseconds apart and by adjusting sweep expansion so that succeeding pulses fell on proper parts of the scale and by keeping this expansion constant, it was possible to obtain a calibration.

TWO-PATH SIMULATOR

As an aid to interpreting the results obtained from the above experiment, particularly when the two pulses overlap and interfere, a circuit was set up in the laboratory to simulate two-path transmission. The equipment, as shown on Fig. 9, consisted of a wave guide hybrid junction with the r-f pulse energy being fed into the E plane arm. To each side arm was connected a variable attenuator in series with a few feet of wave guide fitted with a short circuiting plunger. Waves reflected from these two plungers recombine in the H plane arm where the detector is located. There are two separate paths through the hybrid as follows: (1) Input, side arm A, reflecting plunger A, side arm A to output. (2) Input, side arm B, reflecting plunger B, side arm B to output. By adjusting the attenuator in either branch the amplitude of the signal transmitted by way of that branch could be adjusted. In the same way by adjusting the position of the reflecting plunger in either branch the distance traveled by a signal in traversing that branch could be varied.

If the path lengths were made the same and the amplitudes adjusted to be equal there would be perfect cancellation due to a phase turn-over in the hybrid junction and hence no output from the detector. If one plunger were now left fixed in the above position and the other moved by a quarter wavelength (to produce a total shift of half wavelength or 180°)

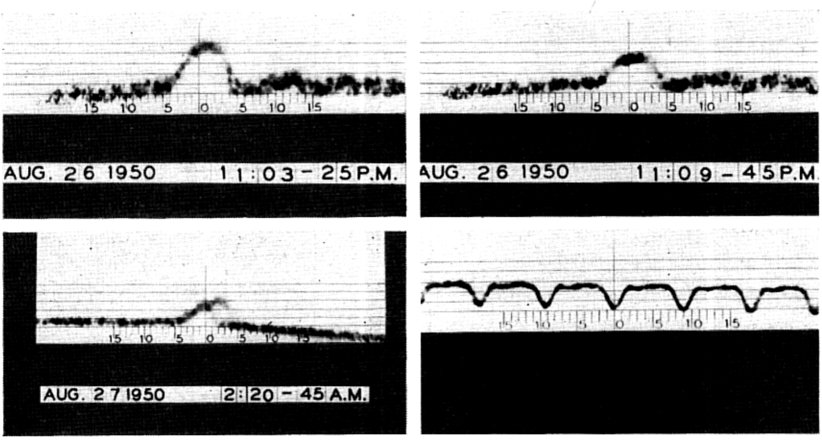

Fig. 8—Received pulses and calibrating pulses.

the output signal would be at maximum amplitude due to addition of energy coming from the two paths. This amplitude is, of course, twice that of the signal from one branch alone. In the experiment the plunger in one branch was left fixed and the attenuator in that branch left set at zero. The path through this branch then represented the normal transmission path for an actual system. The path through the other branch could be made to correspond to spurious paths having different amounts of delay and attenuation simply by adjusting the position of the reflecting plunger and the setting of the attenuator. A series of photographs were taken of pulses resulting from these different amounts of delay and attenuation.

The first three pictures of Fig. 10 were taken with the path lengths exactly equal. When the amplitudes were also equal there was complete cancellation. As the signal in one branch was attenuated the amplitude of the resultant pulse increased until it became equal to that of the original pulse as shown in the third picture. Increasing one path by one-half wavelength brought the signals from the two branches into phase and they added up to double amplitude as seen in the fourth picture. It should be pointed out that although in our experiment we changed delay by 0.36 millimicroseconds in going from the first minimum to the first maximum, in free space a change of delay of only 0.125 millimicroseconds

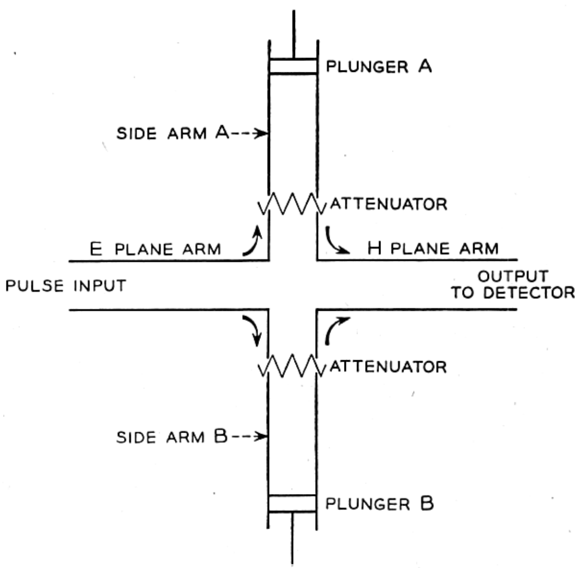

Fig. 9—Apparatus to simulate two-path transmission.

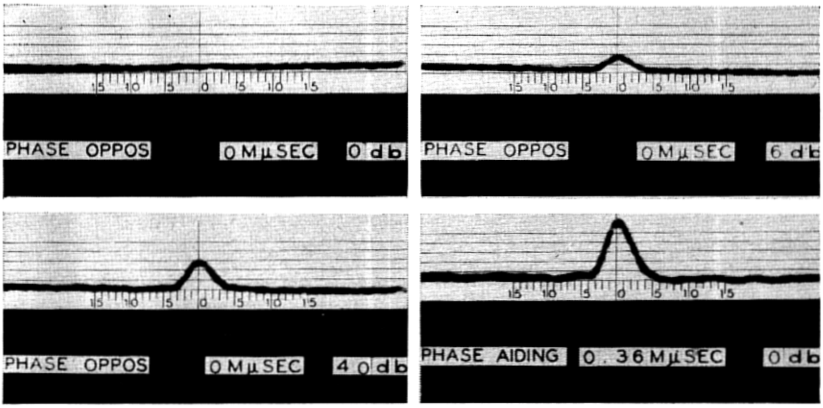

Fig. 10—Simulated two-path transmission.

would be required. The discrepancy lies in the large ratio between the phase velocity and group velocity in the wave guide used whereas in free space this ratio is, of course, equal to unity. In free space the amount of delay required to go from a maximum to a minimum signal corresponds to a change of path difference of only about one and one-half inches. With only this slight shift required to change conditions from those shown by the first picture of Fig. 10 to those shown by the last, it is not at all surprising that the received signal is very unstable during time of multi-path transmission.

Fig. 11 shows the effect of changing relative phases in 90° steps while keeping the amplitudes equal to each other. It is seen that even with the carriers in direct opposition cancellation is far from complete due to the

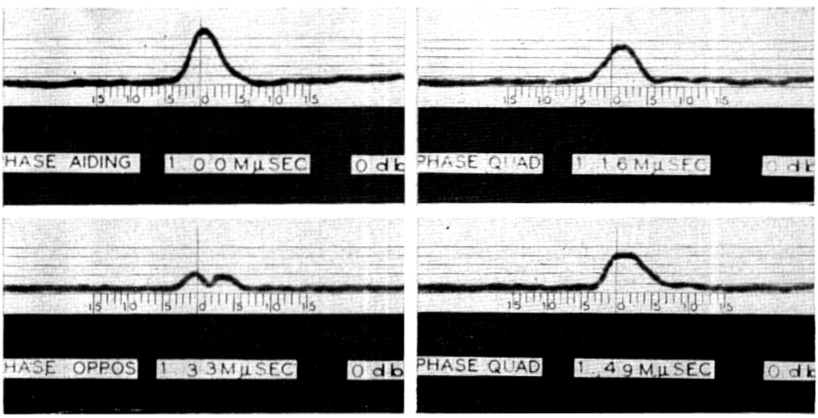

Fig. 11—Simulated two-path transmission.

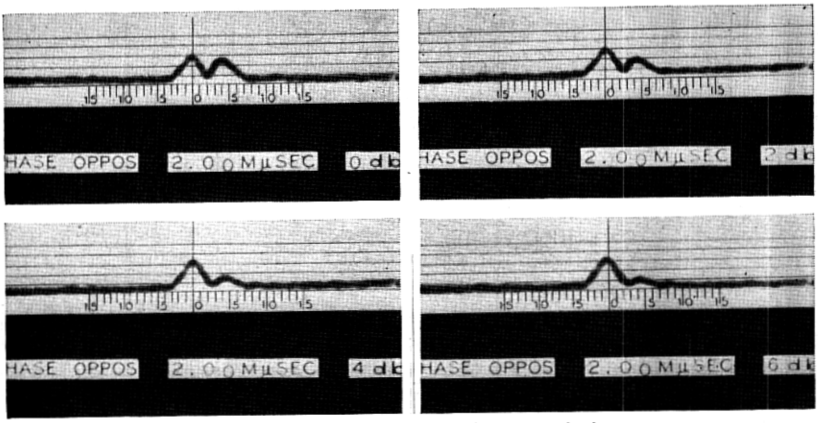

Fig. 12—Simulated two-path transmission.

relative delay between the two component pulses. Flat topped pulses seem to be characteristic of conditions where the two carriers are in phase quadrature and about equal in amplitude.

Fig. 12 shows a set of conditions with a constant delay difference of 2 millimicroseconds (corresponding to a path difference in free space of about 2 feet). For the pulses shown on Fig. 13 there was a constant delay difference of 7.34 millimicroseconds, enough to provide complete separation of the pulses. The carriers were in phase opposition but with this amount of separation there is no overlap of pulses and the results would have been the same if the phase had been aiding. Any increase of delay

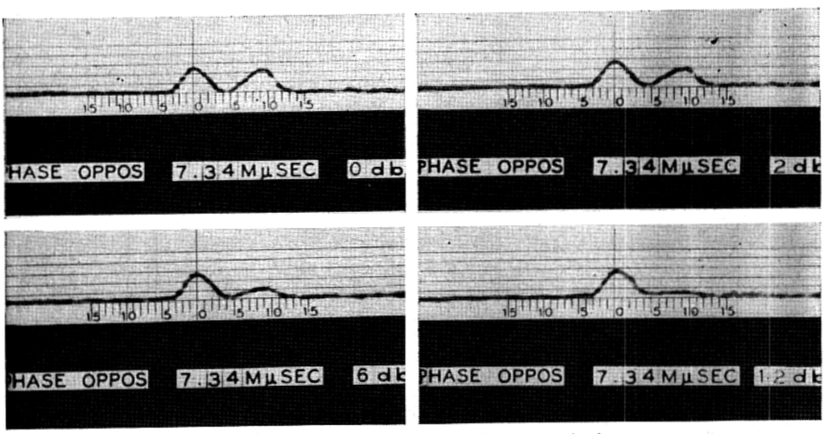

Fig. 13—Simulated two-path transmission.

beyond this point results only in moving the pulses farther apart and has no effect upon pulse shape or amplitude.

The experimental set up just described proved to be somewhat unsatisfactory since it was not possible with it to produce phase opposition between the two carriers without having zero delay difference between the two paths or a difference of at least 0.66 millimicroseconds. For the length of pulse used this latter amount of delay difference is sufficient to prevent anything like complete cancellation of pulses. In fact the amplitudes of the two resultant peaks are only about 12 db below the peak amplitude of the original pulse. From this we know that for the natural path any fade which appeared to be complete must have resulted from path differences of less than 0.66 feet, in fact from differences of less than about one-half foot.

SUMMARY

The pulse experiment results indicate that over one particular path at least there is, at times, transmission of microwaves by at least two, and probably more than two, paths. Path differences involved are from a fraction of a foot up to about seven feet, differences of less than about three feet being the most common. These results agree with those obtained by other methods. These multi-path effects result in bad distortion of very short pulses and even in the presence of entirely separate spurious pulses. These effects put a definite lower limit on pulselength and spacing between pulses in a pulse transmission system. The limit depends upon the amount of distortion which can be tolerated and also upon the percentage of time such distortion can be accepted. No statistical data were recorded.

With the laboratory equipment for simulating transmission over two paths, many of the waveforms obtained over the natural path could be duplicated. There were times, however, when the waveforms received by way of the natural path were too complicated to be explained by transmission by as few at two paths.

ACKNOWLEDGEMENTS

Space does not allow giving credit to all of the many people who contributed to the success of this project. A. F. Dietrich made the mechanical layouts for most of the equipment and supervised its construction as well as assisting in taking data and in many other ways. I also wish to thank J. C. Schelleng and W. M. Goodall for guidance and suggestions. G. M. Eberhardt furnished the traveling-wave-amplifier circuits.