

#### IV COMMUNICATIONS AND RELATED PROJECTS

This project was begun in November 1945 in an attempt to determine the system or systems of modulation that give most efficient utilization of spectrum and power. Although it might be thought that the age of this general problem would mean that all of its complexities had been unraveled, such is not the case by any means. War-time developments in circuits and war-nurtured viewpoints have caused many changes in those communication techniques accepted as standard and, it is believed, can cause even more. The use of microwaves for the relaying of television or of many voice circuits or of meter readings has brought with it many new problems as well as a distinct reluctance to accept the old answers as the final ones. Further, there has been a distinct feeling that some communication systems have grown by the compounding of a series of hasty development projects, each aimed at solving a particular problem in the most expeditious way rather than by planned fundamental research. Accordingly, it was planned to combine a general fundamental study of the communication process with several detailed studies of problems which it was believed, were worthy of detailed fundamental analysis. The detailed problems first selected for study were those associated with the Pound stabilized microwave oscillator. This study resulted in a program which, as will be seen, has continued ever since. As the general analysis proceeded, specific problems accumulated in connection with it and these problems have been studied to the limit of available man power.

The general communication problem may be readily resolved into a study of the effects of various types of noise and interference on communications system. Types of noise and interference considered are thermal or "white" noise, impulse noise, adjacent channel interference, common channel interference and that special type of common channel interference known as multipath interference. The effects of these types of noise and interference on amplitude-modulated signals are moderately well known but theory and experiment are rather inconclusive in the realms of frequency and pulse modulation, where exact theories have rarely been published and experiments have rarely been duplicated. Accordingly, prime consideration has been given to the various types of pulse and frequency modulation. Detailed problems considered have been analyses of the modulation and demodulation process, studies of the fundamental characteristics of thermal and impulse noise, and the response of ideal and actual receivers to the latter. Experimental and theoretical studies of the FM receiver discriminator and limiter system, studies of pulse modulation components and the analogue analysis of multipath transmission. In addition to these problems, all concerned basically with the interaction of signal and noise or interference, the Pound oscillator has been analysed in detail, its modulation problems considered and its improvement attained. Detailed discussions of all of these projects follow.

##### A MODULATION STUDIES SPECTRUM UTILIZATION EFFICIENCY OF POWER UTILIZATION SIGNAL-TO-NOISE RATIOS

###### 1 General Analysis of the Transmission of Information

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Analyses made in the past have arrived at the conclusion that the quantity of information that may be transmitted over a given bandwidth in a given period of time

is limited<sup>1,2</sup> These analyses have been studied here in some detail, and it has been shown that they apply to conventional systems of modulation. It has also been shown however that coding systems may be devised which have the property of apparently compressing the information so that in the limit an infinite amount of information may be transmitted in zero time and zero bandwidth. To show this it need only be shown that one point, determined to infinite accuracy conveys an infinite amount of information, and that a point may be determined to infinite accuracy in zero time if the transmission characteristics of the system are exactly known and no noise is present. A theoretical limit is reached in that the point may be determined only to within a quantity  $h$  where  $h$  is Planck's constant but this fact is of negligible importance and has no bearing on the "unit of information" defined by Gabor.

The clue to the practical resolution of the situation described above lies in the statement that no noise is present. Once thermal noise or other interference, is allowed, a limit does exist and an expression may be written relating the power bandwidth, noise, and time of transmission of a system. This expression is

$$BT \log_e(1 + S/N) = \text{constant}$$

where  $B$  is bandwidth,  $T$  time during which the system is available,  $S$  signal strength, and  $N$  noise strength<sup>3</sup>. The full implications of this expression are now being studied.

In the course of this general work much specific theoretical work has been done on the analysis of various systems of modulation. Some of the details of this work have been published in a technical report<sup>4</sup>. Others will be published in technical reports now being written. These include analyses of the signal versus noise behavior of coded transmission systems and of pulse time modulation systems.

## 2 Pulse Modulation Studies

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As was mentioned above, the recently announced systems of pulse modulation still have many unsolved problems worthy of considerable research. In an effort to consider some of these problems as well as to gain better insight into the fundamentals of operation of pulse modulation systems modulators and demodulators have been constructed for pulse amplitude modulation, pulse duration modulation and pulse position modulation. These units have not been constructed in any attempt to develop commercial or near-commercial equipment, but to make available laboratory apparatus with which to investigate system and component problems. The pulse amplitude and pulse duration systems have been considered in previous progress reports and will not be gone into in detail here since

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- 1 R V L Hartley, "Transmission of Information", B S T J , 7, 535, (1928)
  - 2 D Gabor, "Theory of Communication", IRE (London), 93 Pt III, No 26 429 (1946)
  - 3 Similar expressions, it has recently been publicly announced, have been derived independently by Professor N Wiener of the MIT Mathematics Department and Dr C Shannon of the Bell Telephone Laboratories
  - 4 W G Tuller, "Distortion in FM Discriminators", RLE Technical Report No 1, March 8 1946

little work has been done on them recently. Considerable time, however, has been put into the pulse position modulation system, as the most efficient of the pulse modulation family. A description of this apparatus and some of the theoretical work done follows.

a Practical System Study

Description of System This study is concerned with the problems and performance of a multi-channel pulse position (PPM) modulation system. The system, in its present state, consists of the following major components as shown in Fig 1.

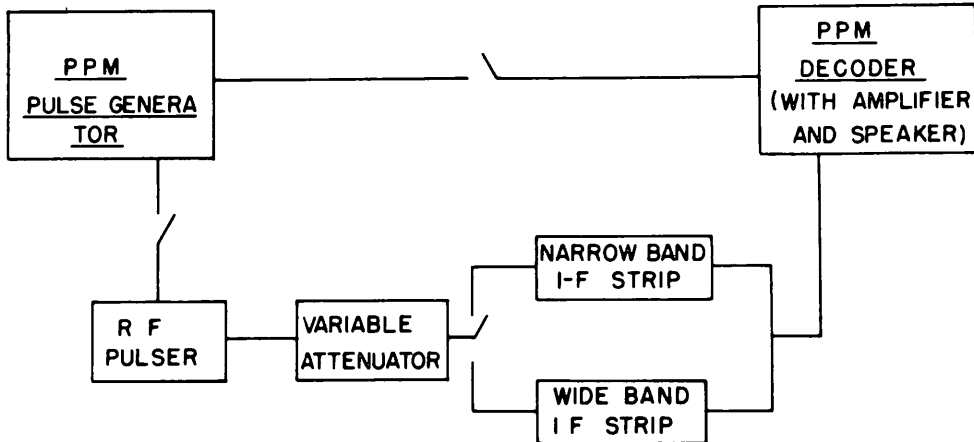


Figure 1 Over-all diagram of system

(1) 10-Kc pulse-position modulation pulse generator designed to produce a train of channel pulses, all of which can be independently position-modulated by different audio signals (Fig 2). In the actual generator however pulse-forming equipment was built for only one time channel which can be switched to any one of the ten channel positions. One of these can be moved continuously through the entire time range of the repetition period. This offers a possibility of measuring interchannel crosstalk under various conditions.

Each synchronizing signal consists of three pulses separated by certain fixed time intervals. This method of coding the synchronizing information affords a means of

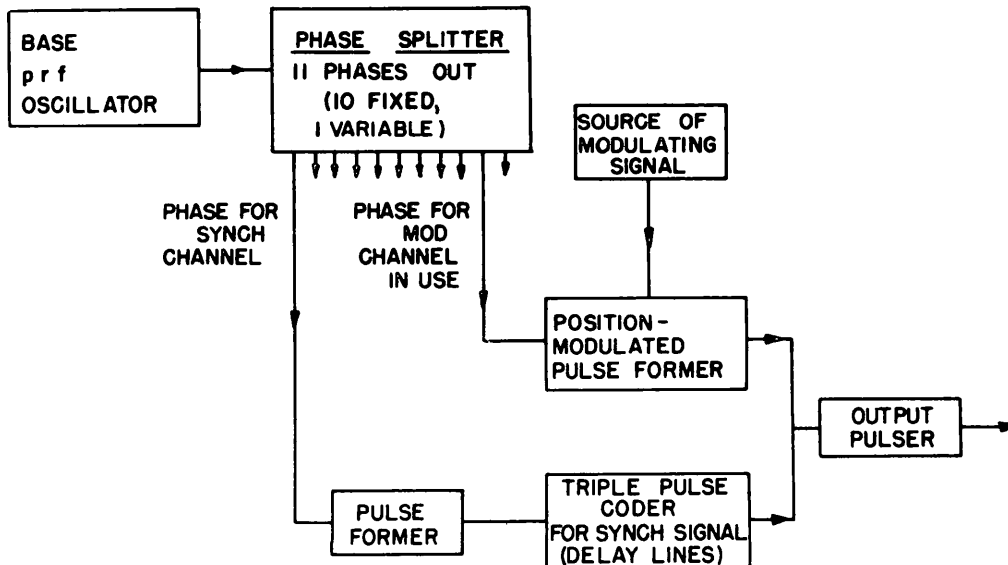


Figure 2 Block diagram for pulse-position modulation generator

distinguishing between it and the channel pulses as well as noise pulses

The component of principal interest in the generator is the position modulator, which was investigated in considerable detail in order to arrive at a simple circuit with good linearity (An audio oscillator or the output of a broadcast receiver serves as a source of modulation)

The output stage of the unit is a biased blocking oscillator-type pulser, which puts out all pulses at a low voltage low-impedance level and with a duration of exactly one microsecond as determined by a delay line

(2) A pulse-position modulation decoder similarly designed for ten channels but with detecting equipment built for only one (any one) of the ten channels (See Fig 3) This unit first limits the incoming pulses so as to minimize the effect of noise and then recovers the audio signal by either of two schemes In the first scheme a trigger

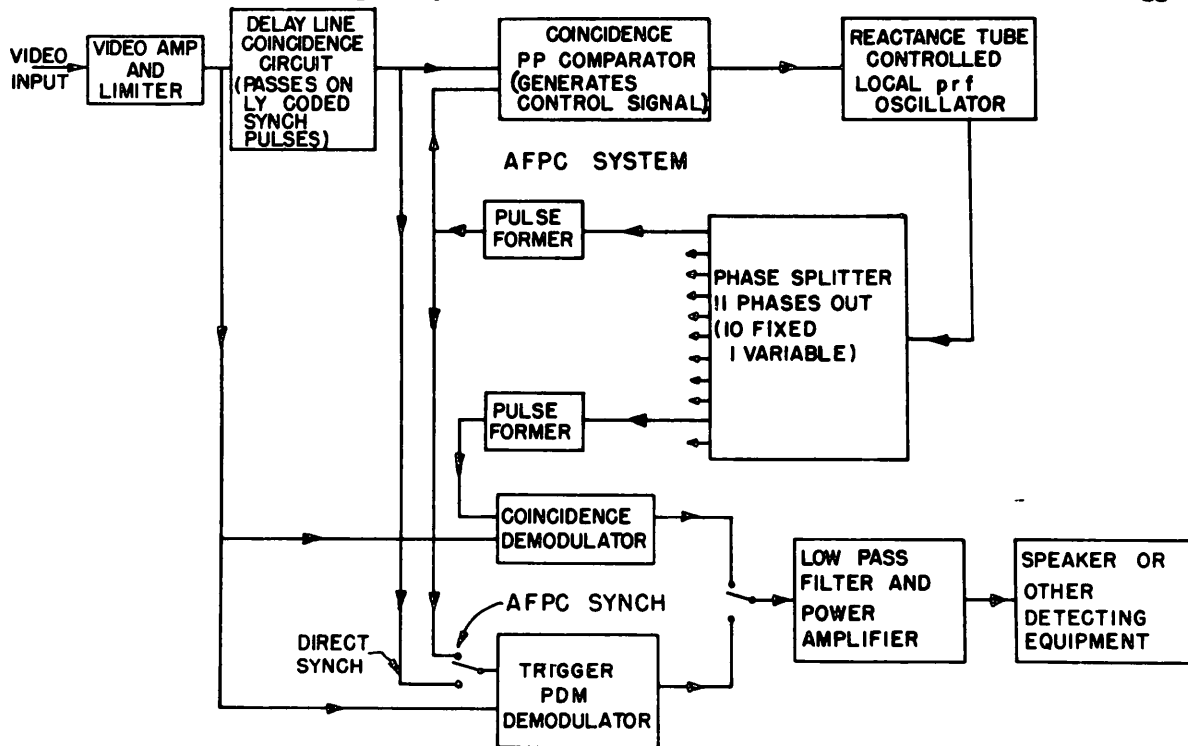


Figure 3 Block diagram for pulse-position modulation decoder

circuit is used to produce duration-modulated pulses, the two edges of which are formed by synchronizing and channel pulses respectively Since duration-modulated pulses contain the signal directly, it is necessary only to remove the pulse frequency components The second scheme uses a coincidence method of detection which yields the signal together with a relatively small component in the pulse repetition frequency

A novel method of synchronization is used with the coincidence scheme of decoding, while the other scheme can make use of either this or the conventional method of synchronization In the case of the conventional method, the time reference in the receiver is established directly by incoming synchronizing pulses The more novel method

which has been successfully used in television receivers<sup>1</sup>, makes use of an automatic frequency-phase control (AFPC) system. The wave used for synchronization is derived only indirectly from the synchronizing pulses and has a certain amount of "flywheel momentum", which tends to make the all-important receiver synchronization more reliable in the presence of noise.

The unit can easily be switched back and forth between the various demodulation and synchronization schemes for direct comparison through the output loud-speaker or other detecting devices.

The input video pulses to the unit may be obtained either directly from the generator described above (1), or by way of r-f pulses with the equipment described in the following paragraphs:

(3) A radio-frequency oscillator to be pulsed by the generator described under (1). This is simply a MK-3 test pulser modified for present purposes to be pulsed by externally supplied pulses at either around 30 or around 60 Mc.

(4) An adjustable coaxial attenuator, which although usually used in microwave work is suitable for insertion between the output of the pulsed oscillator (3) and the i-f amplifier strips (5).

(5) Two i-f amplifier strips, designed for 30 and 60 Mc respectively, with respective bandwidths of about 2 and 10 Mc. Either one of these is fed with r-f pulses (see (4)) which after amplification, are enveloped-detected in the last stage and may then be supplied to the decoder (2).

General Attack The purpose of this equipment is to investigate the problems and characteristics of the system and compare the latter with the expected results. The problems are mostly those encountered in connection with the operation of circuit components, while the characteristics include susceptibility to noise, crosstalk interference, and so forth.

The method of attack has been to set up the system trace through it systematically from the input of the transmitter to the output of the receiver and optimize the performance of each stage or component in its turn.

System Components and Problems Encountered Certain crucial system components which required closer investigation will be briefly discussed. The position modulator mentioned under (1) must be reasonably linear over the modulation range, produce pulses of low "jitter" and rise time to minimize noise, have uniform frequency response, and the quiescent or average pulse position should have little dependence on supply voltages. The circuit used is essentially a regenerative overdriven amplifier operating on the linear slope of the input sine wave and avoiding the use of RC coupling. The output pulser of (1) must supply pulses of duration independent of the characteristics of the driving pulses and furthermore it must be capable of supplying pulses in rapid succession. The

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1 A. Wright "Automatic Frequency-Phase Control in TV Receivers" Tele-Tech 6 74, Feb 1947

biased blocking oscillator using a delay line to cut the pulses short of their natural duration was found to perform well, provided a relatively high-impedance pulse transformer is used

The limiter originally devised for the video portion of the receiving equipment (2) made use of two type IN-34 crystals but it now consists merely of two suitably biased amplifying pentodes. The problem is that of taking a thin slice out of the middle of a pulse. Crystals are admirably suited for this purpose when the slicing level coincides with the average value of the wave, e g in the case of an FM carrier. In the pulse application troubles due to d-c components have been encountered and the optimum limiter design is still open to question.

The first demodulation scheme (2) uses a conventional trigger circuit followed by a low-pass filter which must be nearly flat up to 3.5 kc and have at least 80 db attenuation at the pulse repetition frequency of 10 kc. A constant-k two-section  $\pi$  filter in cascade with a bridge-T rejection network was found satisfactory.

The second demodulation scheme (2) uses two coincidence tubes in a balanced circuit one having more coincidence and hence more output for "forward" modulation and the other likewise for "backward" modulation. Careful adjustments of pulse durations, spacings, and shaves were found necessary to reduce distortion to near the level encountered in the first demodulation scheme. Advantage can be taken of the balanced output from the coincidence tubes by having it drive a pushpull amplifier so that the p r f component is largely balanced out. Unbalance resulting from relative drift between the pulses compared in the coincidence tubes results in a d-c component which is indicated on a meter for easy balancing adjustment. Apart from these advantages the "double coincidence" method is expected to show a 3-db signal-to-noise improvement over other methods while the signal level is raised 6 db the noise voltage should rise only 3 db if the noise components riding on the two edges of the channel pulse are independent.

Synchronization has undoubtedly presented the biggest single circuit problem. The conventional method of synchronization (2) presents no problem in the absence of noise but this is not true of the automatic control synchronization system mentioned under (2). While it was possible to obtain apparently satisfactory performance at the expense of much time the desired flywheel effect is apparently not attained, and the behavior of the system under certain conditions is not thoroughly understood. While there is little doubt that an automatic frequency and phase control system of synchronization offers definite advantages it is now believed that the particular method of control used is impractical and should be replaced by one of the methods used in television<sup>1</sup>. The latter method is analogous to a pulsed servo<sup>2</sup> receiving its error signal at regularly spaced intervals, while in the automatic system used here the error pulses are irregularly spaced with a certain degree of randomness. Like the coincidence demodulation scheme, the method is based on coincidence between received and locally generated

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1 A Wright, loc cit

2 W Hurewicz "On Servos with Pulsed Error Data", RL Report 721 (April 26 1945)

pulses an error signal being produced each time a partial coincidence occurs. An investigation of the new methods used in television receivers is now under way.

The radio-frequency portion of the system consisting of pulsed-oscillator attenuator and i-f amplifier strip serves to make the system more realistic for the purpose of measurements. In particular it affords a simple method of introducing random noise into the transmission path since the pulses fed to the i-f strip can be made comparable in amplitude to the thermal noise generated in the first stage. While the 30-Mc narrow-band i-f strip performed satisfactorily the 60-Mc wide-band i-f strip has not yet given satisfactory results because of equipment difficulties.

Qualitative Measurements Only rough qualitative appraisals of over-all performance have been made. These will be briefly discussed.

(1) Distortion With speech or music for modulation, average "broadcast receiver quality" was obtained with both methods of demodulation. Fidelity with the trigger method of decoding is particularly good, since it depends only on the linearity of the modulator and the spurious components inherently associated with duration-modulated pulses [see Sec. b, Theoretical Work]. While the coincidence method of decoding has unnoticeably higher distortion with optimum adjustments the non-linear distortion becomes noticeable when the pulses reaching the coincidence circuit depart from the optimum shape and duration. (This condition could possibly be remedied by insertion of a triggered pulser of the type used in the generator output.) Furthermore, with the coincidence scheme used here the maximum total time swing in pulse position is limited to one pulse duration. No such limitation exists with the other method where linearity in the modulator is the limiting factor. Disregarding distortion a limit to the degree of modulation is obviously set by the channel spacing. From the preceding it may be concluded that the trigger scheme of demodulation is superior to the basic coincidence scheme where high fidelity is a requirement.

(2) Noise With the pulse generator (1) feeding the decoder (2) directly (by-passing the r-f portion of the system) output noise/signal is negligible with normal degree of modulation. Initially considerable trouble was had with 60-cycle noise which was subsequently sufficiently reduced.

When the r-f system is inserted with narrow or wide-band i-f strip virtually identical results can be obtained when the pulses supplied are large compared to thermal noise generated. Thermal noise quickly becomes perceptible when the pulses are reduced in amplitude relative to the noise. As expected the effect is worse with the narrow-band amplifier since the pulse edges are less steep and thus more susceptible to time modulation by noise. The point where the signal is almost completely masked by noise is reached when the average noise level appears to be somewhat below one-half the pulse peaks at the output of the i-f strip. (The corresponding observation for the wide-band i-f strip has not as yet been made.) It was found that at about the same point, the automatic synchronization fails. The trigger system of demodulation fails at a considerably lower noise level. On the other hand a comparison in the working range shows considerably more hiss noise with either demodulation scheme combined with

automatic synchronization than in the trigger scheme with direct synchronization. This must therefore be attributed to poor performance of the automatic control synchronization. This is born out by the fact that the hiss noise has a peak at one frequency. This noise is further found to depend on adjustments of limiter and other components. The trigger scheme is subject to a characteristic objectional popping noise, as the breaking point is approached.

Evidently a better synchronization circuit should be of primary concern both to improve the system performance and to make quantitative noise measurements possible.

#### b Theoretical Work - Harmonic Analyses

A paper entitled "Distortion in Pulse-Duration Modulation" previously mentioned in the Progress Report of October 15, 1946, has since been accepted for publication in the IRE Proceedings. The distortion inherent in pulse duration modulation is found as a function of modulation index and maximum signal-to-pulse frequency ratio. The results are also applicable to pulse position modulation if one uses the trigger scheme of converting position modulation to duration modulation in the receiver (see above). For this and most other applications inherent distortion is found to be at most a few per cent provided the pulse repetition frequency is at least twice the highest modulation frequency.

An analysis of a step-approximated wave (sampling at regular intervals) has been made and presented in Technical Report No. 12. It is found that a good approximation to the actual wave is contained in the stepped wave so long as the sampling frequency is at least twice the signal frequency. Besides having direct application to pulse amplitude modulation and certain other systems where sampling is used, the results are useful in certain general theoretical analyses.

### 3 Properties of Random Noise

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The purpose of research being done under this program is to determine theoretically and experimentally the effects of transit time on shot noise in tubes used in communication networks. Experimental work, according to present plans, will be done using "scale models" having relatively large transit times. This will allow the work to be done at low frequencies, so that the complicating effects of lead inductance and stray capacity will be minimized. It is hoped that the information obtained in the process of these investigations will give a better insight into the significance and the effects of transit time in tube operations of all kinds and that it will aid in the design and development of lower noise tubes for high frequency operation.

In the execution of these plans a large scale diode has been constructed and preparations are under way to measure the noise generated by this diode under various operating conditions.

The spectrum of the noise from a temperature-limited parallel-plane diode has been calculated and is shown in Fig. 4. The shape of the current pulse in the anode of the diode due to an electron traveling from cathode to anode is shown in Fig. 5. It is probable that these results appear elsewhere but since they have not been found in a random perusal of the literature it seems worthwhile reproducing them here.



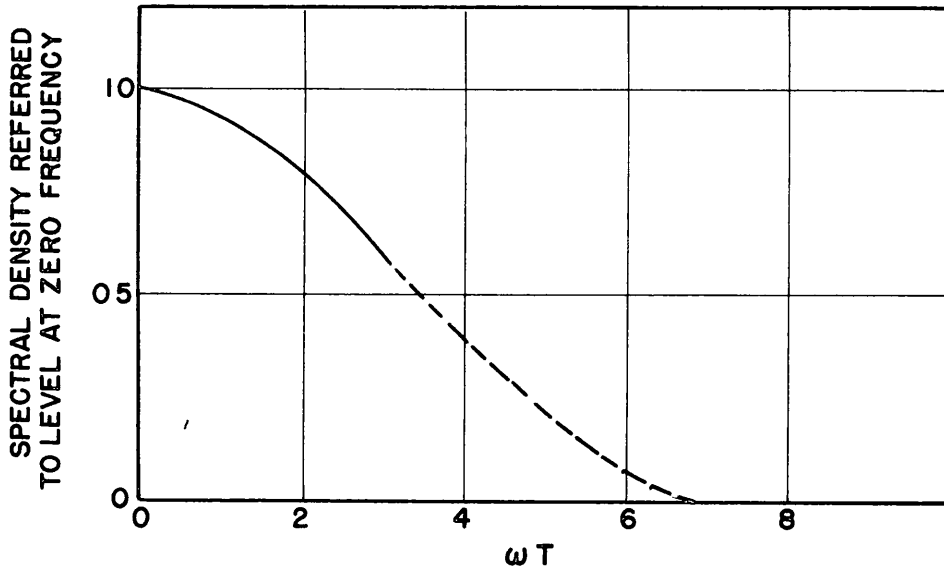


Figure 4 Power spectrum produced by pulses of Fig 5 added randomly

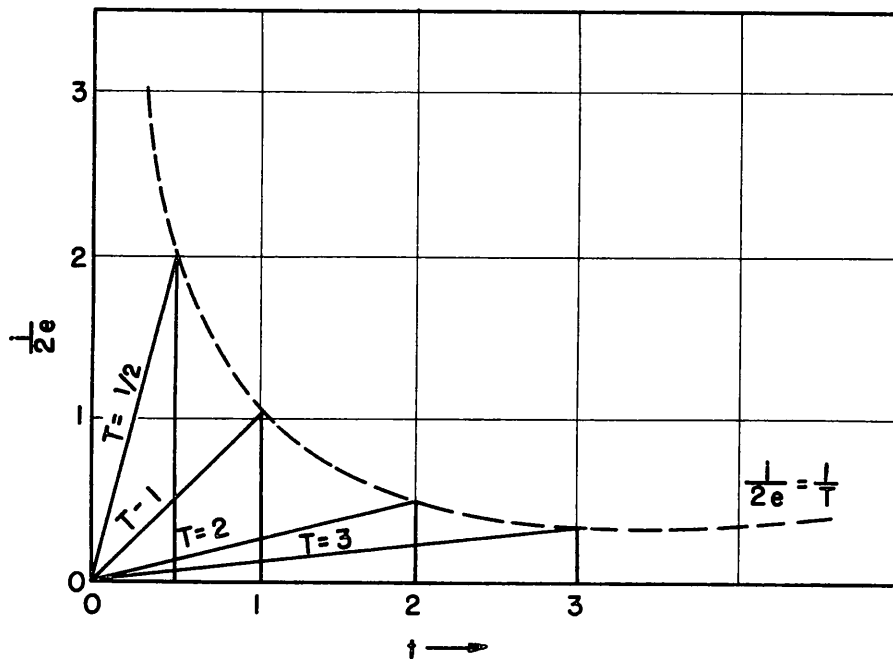


Figure 5 Pulses produced in the anode circuit of a plane-parallel diode by an electron traveling from cathode to anode with transit time  $T$   
 $i$  = instantaneous current  $e$  = electronic charge  $t$  = time measured from instant electron leaves cathode

IV A 4 The Action of Limiters and Discriminators in FM Receivers in the Presence of Noise

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Description of Project One of the most serious limitations of the present FM system of communications is the lack of an FM receiver which will closely realize the theoretical expectations of the system. In this respect the correlation between the theoretical response of an ideal FM receiver to impulse noise and the response of the average good FM commercial receiver today is quite bad. It is the main purpose of this study to determine through analysis and experiment the reasons why theory and practice differ and if possible to resolve this difference. It is obvious that this difference if resolved, may point the way to improved communications with frequency modulation.

Status As previously reported, a theoretical analysis of impulse noise in an FM receiver has been completed. This analysis has covered the following points:

(1) A determination of the response of a Foster-Seeley discriminator to a square-wave modulated carrier and to the transient resulting from the injection of a d-c pulse of short time duration at the input of the receiver has been made. Expressions have been derived for both the envelope of the resulting transient and the instantaneous phase of the resultant signal vector for the case of the square-wave modulated carrier input.

(2) An expression for the fractional deviation of the instantaneous frequency of the resultant transient signal vector has been derived from the expression for the instantaneous phase.

(3) A mathematical check has been made of the material presented by Messrs Bradley and Smith of the Philco Research Laboratories in their paper on "The Theory of Impulse Noise in Ideal FM Receivers"<sup>1</sup>. Where applicable this theory has been extended and correlated with results previously derived above.

(4) Experimental work, using oscillographic methods, has been carried out concurrently with the theoretical work outlined above. The experimental setup used will be described later in this report.

On the basis of the above analysis and certain experimental data the following conclusions have been reached:

(1) The output of a Foster-Seeley discriminator is very nearly zero in both its transient and steady-state components for any type of amplitude-modulated wave provided the carrier frequency of the input wave is the same as the center frequency of the discriminator.

(2) The transient at the output of a discriminator mathematically equivalent to a Foster-Seeley that has been adjusted for optimum coupling is proportional to the bandwidth of the discriminator and inversely proportional to the damping coefficient.

(3) The time constants of the output filters of the detector of a Foster-Seeley discriminator must be balanced to within about 6 per cent if impulse noise is to be

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1 Proc IRE 34 743 (1946)

reduced to 50 db below maximum signal This balance is far less critical if a cathode-driven discriminator<sup>1</sup> is used in place of the conventional Foster-Seeley discriminator

(4) We agree with the Bradley and Smith division of impulse noise into two basic types called "pops" and "clicks" and with their general conclusions

(5) The probability of the occurrence of a "click" or "pop" has been computed for the following types of impulse noise

- (a) Periodic impulse noise of constant amplitude
- (b) Random impulse noise having a distribution approximated by the Gaussian error curve
- (c) Random impulse noise with sinusoidal amplitude distribution

(6) On the basis of the expressions and graph derived from (5) and with the additional provision that the capture time of the transient be small compared to the time constant of the de-emphasis network it can be said that while the amplitude of a "click" is largely and that of a "pop" essentially independent of the original noise impulse, the probability of the occurrence of a "pop" or "click" is however dependent upon the original noise impulse and in particular is a function of the following parameters

- (a) Peak noise-to-signal ratio
- (b) Number of stages in receiver filter
- (c) Over-all receiver half-bandwidth
- (d) Instantaneous frequency deviation of the desired signal at the time of the impulse
- (e)  $P(s)ds$  (the probability that a noise impulse peak amplitude will lie between  $s$  and  $s+\Delta s$ )

(7) The receiver must be accurately tuned and aligned if the inherent advantages of frequency modulation in discrimination against noise are to be realized The detuning of the receiver under the action of the transient signal must be minimized or eliminated

(8) The theoretical effect of impulse noise of even the "pop" variety on a program signal should be negligible

Since the theory indicates that the effect of impulse noise should be negligible within very broad limits of amplitude and duration attention has been shifted to a detailed study and analysis of limiters their functions and their effects on FM receiver performance This study has reached the point where it has been possible to classify limiters into four general types

- (1) "Slicer" limiters
  - (a) Center reference sub-type
  - (b) Peak reference sub-type
- (2) Instantaneous amplitude control limiter

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1 W G Tuller, T P Cheatham Jr "An Adjustable Band-Width FM Discriminator", RLE Technical Report No 6 June 30, 1946

(3) Zero crossing indicator limiters

(4) Limiters utilizing the properties of negative feedback of frequency-modulated signals

The sub-division of the "slicer" type of limiter has been made because a Fourier analysis shows distinct differences in the operation of the two sub-types

Experimental progress has been made on the design construction, and testing of several specific limiter types. The designs are governed by the theoretical results obtained in the study of the characteristics of impulse noise. Particular attention has been paid to amplitude variations (rise time of the transient envelope) capture time and instantaneous frequency variations.

The experimental setup used in the work described above is shown in Fig 6. Its principal components are an A/R range scope and a MK3 test pulser. The A/R range scope supplies both A sweeps and R sweeps. An A sweep is a trace of the cathode ray tube which starts simultaneously with a radio-frequency pulse from the radar transmitter. Distance or time is measured from the left edge of the trace increasing with increased distance from the left edge. An R sweep is defined as an expanded portion of an A sweep. The MK-3 test pulser was also designed during the war as a special piece of test equipment. In its original form it accepts a positive input pulse which triggers two separate multivibrator circuits. The outputs of the multivibrator circuits are used to produce a positive or negative short and long d-c pulse and a short and long pulse carrier at about 30 Mc. For the purpose of this study it was necessary to modify the MK-3 pulser for double triggering and for a carrier frequency of 4 to 5 Mc. The output of the modified MK-3 test pulser is now a short d-c pulse (about 1 microsecond) and a square-wave modulated carrier each of which is initiated by a separate trigger. These triggers are supplied for the A/R scope. The pulsed carrier always begins with the same r-f phase so individual cycles may be examined on the screen of the scope. The phase of the d-c pulse with respect to the carrier may be varied by a control on the A/R scope making possible a study of the effect of relative phase.

This method of transient study is extremely flexible in its application to other noise and interference studies since the d-c pulse can be used to trigger other interfering sources and the pulsed carrier can be amplitude or frequency-modulated as desired. Figure 7 is a block diagram of the equipment layout.

In the course of the work described above it was early discovered that any study of limiters must be preceded by a study of discriminators since the discriminator is in general, the device used to measure the output of the limiter. The mathematical analysis of a typical discriminator circuit showed the possibility of constructing a discriminator whose bandwidth would be readily adjustable, but whose output versus frequency characteristics would have a shape independent (in normalized coordinates) of discriminator bandwidth. This possibility was successfully investigated experimentally with the detailed results given in RLE Technical Report No 6.

This discriminator has proved to be an extremely useful laboratory tool and it has been recently discovered during the current study of impulse noise that it is less susceptible to impulse noise than the Foster-Seeley discriminator and that the

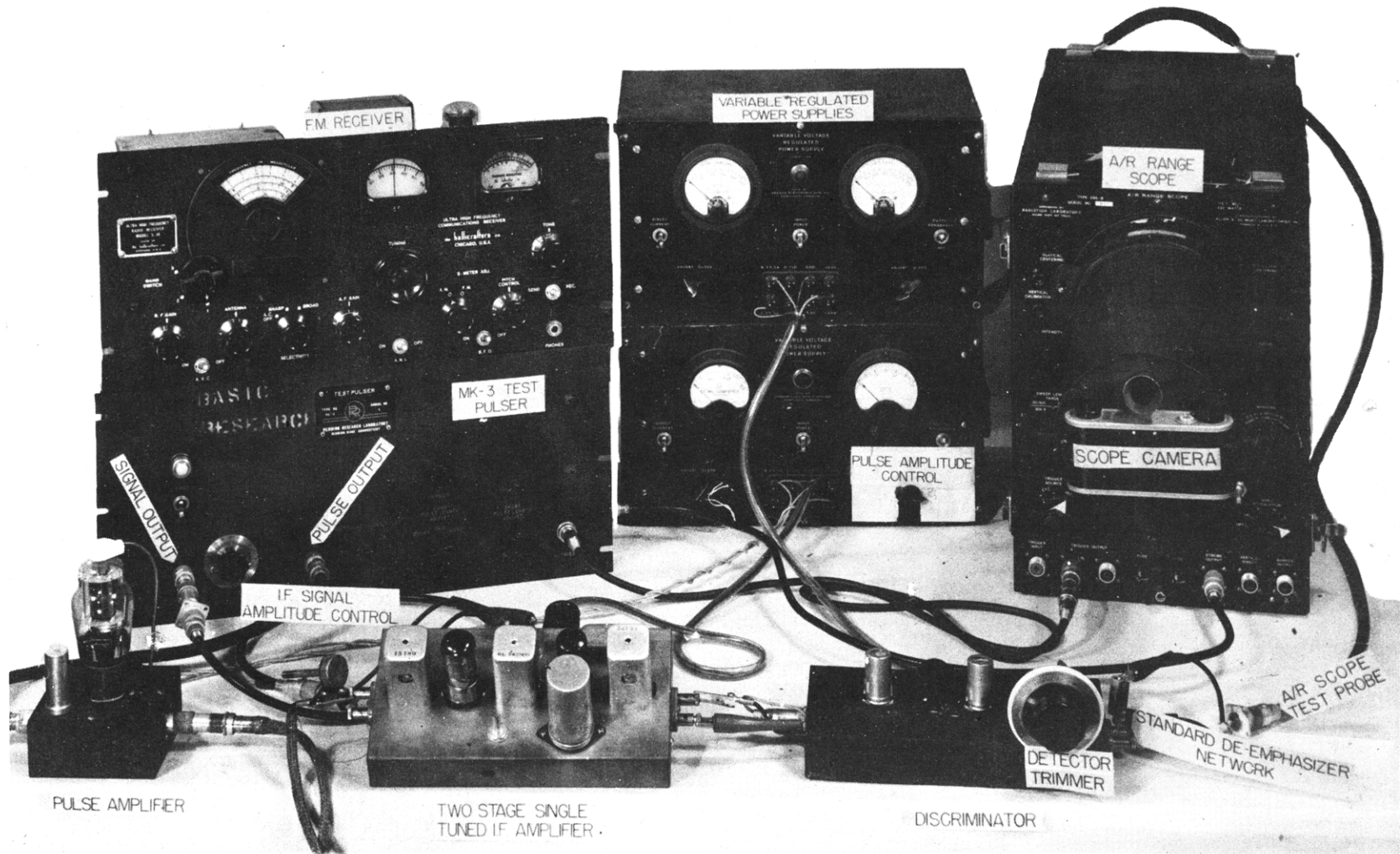


Figure 6. Experimental equipment used in the study of limiters and discriminators.

balancing of its output filter time constants is less critical than in the usual case

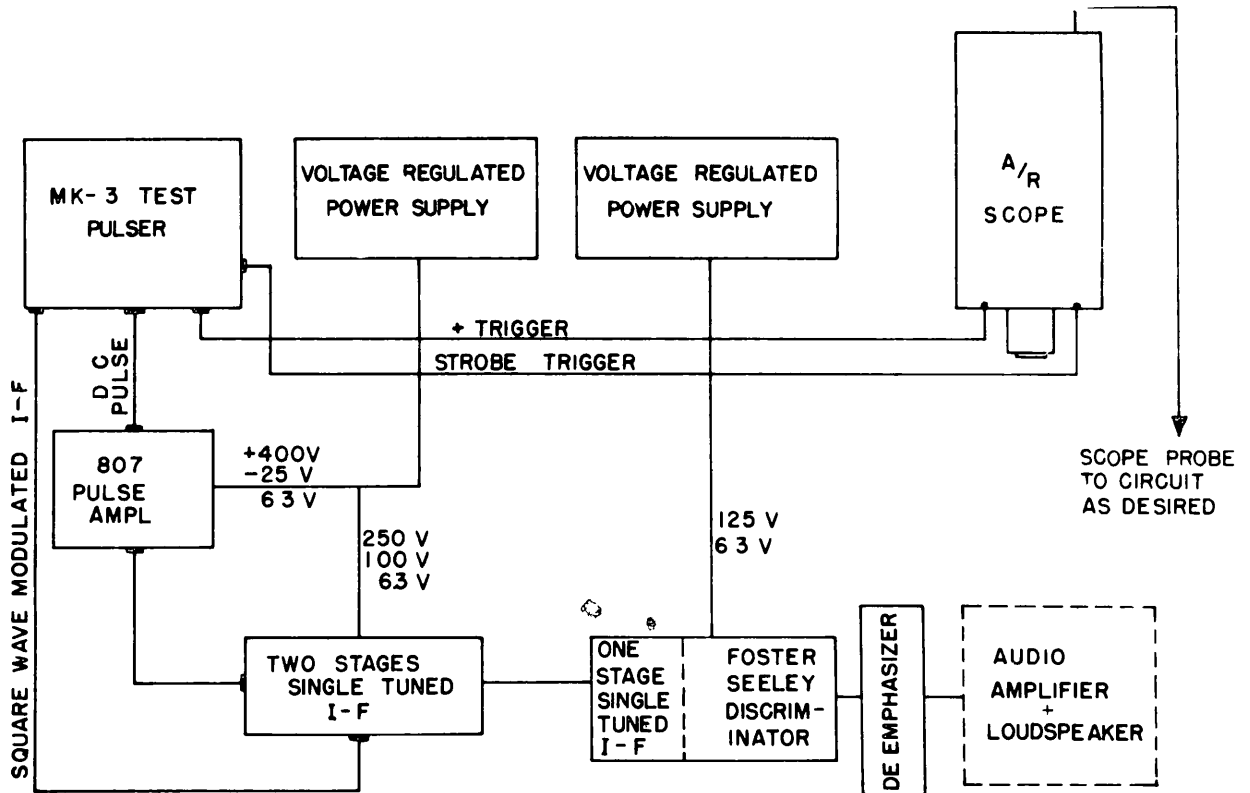


Figure 7 Block diagram of equipment

#### B STABILIZED OSCILLATOR PROBLEMS

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This project was originally launched to investigate the problems arising in the use of stabilized microwave sources with the eventual aim of frequency modulating these sources

Each of the stabilizing systems adapted by R V Pound to the microwave frequency discriminators he developed has its advantages and disadvantages<sup>1 2 3</sup> A preliminary investigation consisted of constructing models of both the direct-current and the intermediate-frequency stabilizer for comparison purposes. As expected the intermediate-frequency system proved to be much more flexible, have a higher loop gain and lower background noise than its predecessor. Surprisingly the more complex system also required fewer readjustments for optimum operation at various frequencies. The main disadvantage seemed to be the decrease in the range of frequencies over which one set of adjustments produced satisfactory operation. This problem and a possible method of overcoming it will be discussed later in this report. All further study was therefore

- 1 R. V Pound "An Improved Frequency Stabilization System for Microwave Oscillators" RL MIT Report 837 October 26 1945
- 2 R. V Pound, "An Electronic Frequency Stabilization System for CW Microwave Oscillators" RL MIT Report 815 October 1 1945
- 3 R. V Pound "Electronic Frequency Stabilization of Microwave Oscillators" RSI 17 November 1946

limited to the more promising intermediate-frequency type of system.

Two complete systems were constructed; one, a rack and panel arrangement (Fig. 8) to serve as a laboratory source, the other, a bench setup flexible enough to serve a variety of purposes.

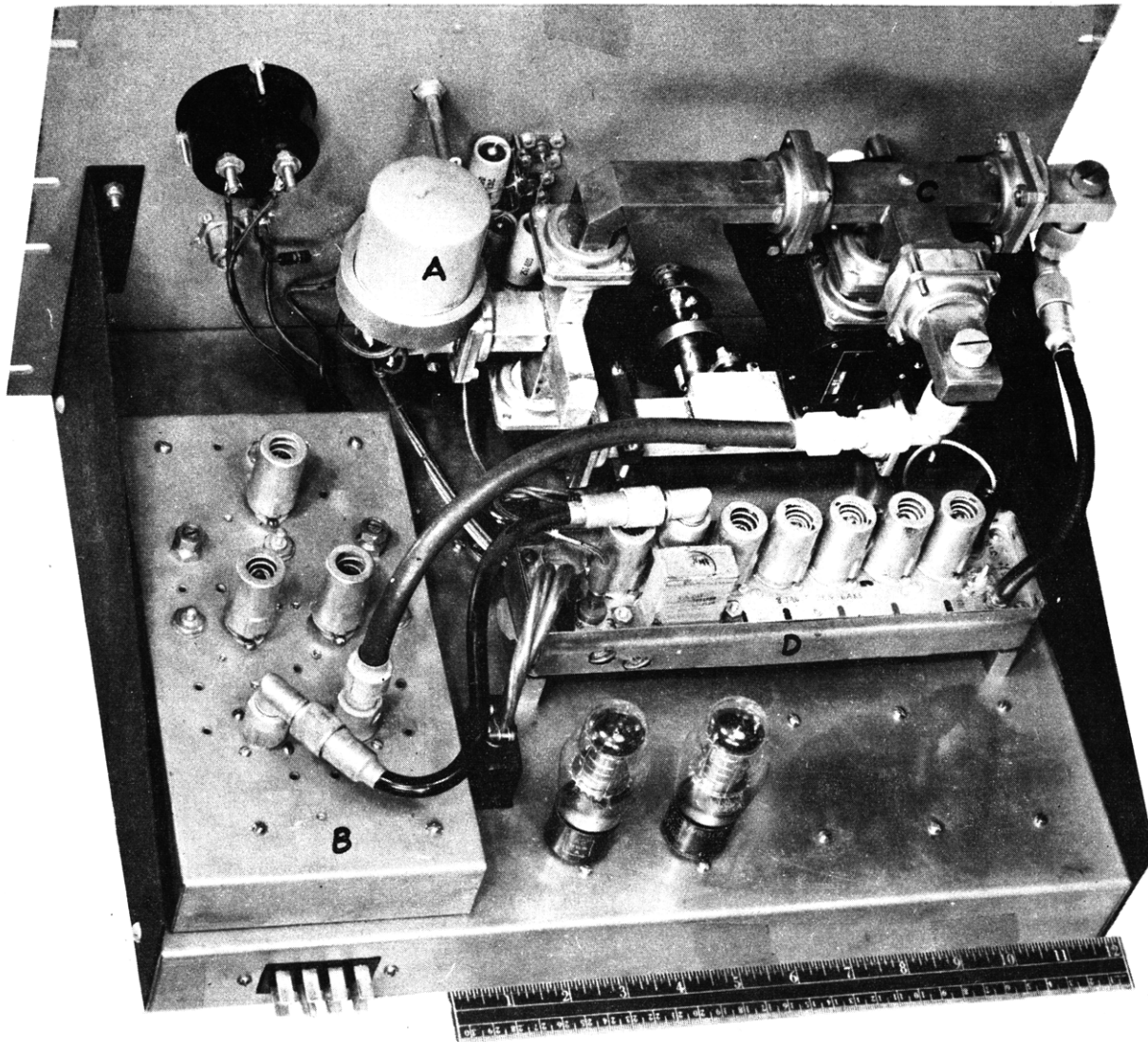


Figure 8. Rack and panel arrangement of stabilizer. (A) Microwave source (723A/B), (B) reference signal source and buffer amplifiers, (C) "equal-arm" discriminator, (D) IF amplifier and phase-sensitive detector.

A sweep-frequency system of viewing the oscillator correction voltage supplied by the stabilizer versus frequency on an oscilloscope has been in use since the inception of this work. With this method of measurement discriminator curves similar to Fig. 9a were obtained. Most of the deviations from the ideal discriminator curve were traced to the detector crystal. As the frequency sweeps to the edges of the mode, the power level decreases and a mismatch of the detector crystal results. This mismatch will cause

secondary signals to be generated which disturb the phase relations within the waveguide circuit.

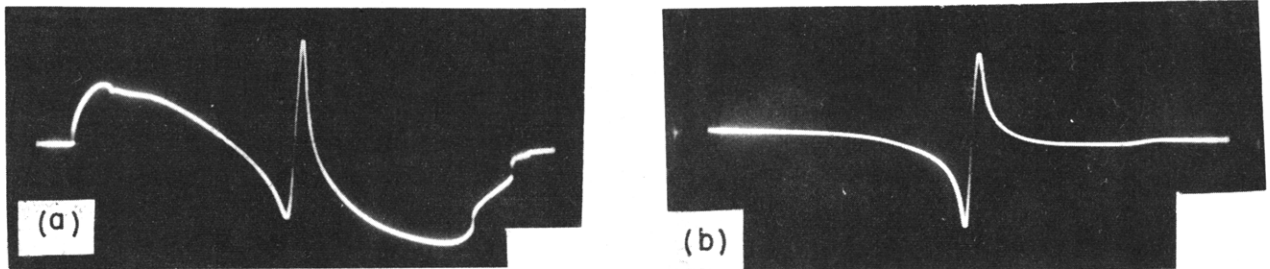


Figure 9. Discriminator curves: correction voltage as a function of frequency. (a) Without bias, (b) with bias.

The level-sensitivity characteristic for a number of 1N23B crystals was measured. It was found that a negative voltage applied to the tip of the crystal could be used to reduce the mismatch at the edges of the mode. A negative voltage of one-fourth volt was found to be optimum since this voltage made the crystal much less sensitive to energy-level changes and yet did not reduce the conversion efficiency appreciably. Greater voltages decreased the conversion efficiency without improving the level sensitivity. A fixed-tuned crystal mount was designed to match the crystals with the one-fourth volt bias applied. Figure 9b shows the improvements that can be realized in the discriminator curve of Fig 9a by using the bias. Both curves were taken with a fixed-tuned crystal termination.

The conversion efficiency of the modulator crystal was investigated for a 1N23B crystal. For a number of crystals the ratio of total energy generated in the two first sidebands to the total incident energy averaged 32 per cent. This measurement was made with less than 50  $\mu$ w r-f power incident on the crystal and with 10 ma current flowing in the crystal d-c circuit. The 10-ma current gives maximum conversion efficiency and no further increase can be gained with these low levels of r-f power by increasing the i-f power. The spread in conversion efficiency for the crystals was found to be from 10 per cent to 44 per cent. An attempt to measure the modulation efficiency of the modulator crystal from d-c characteristics did not prove successful. It would seem that further investigation of crystals as modulators is warranted.

The effect of the i-f amplifier and phase detector on the over-all stability of the system has also been investigated. The phase and amplitude characteristics of the two circuits as a function of frequency have been measured and found to correlate with experimental measurements of system stability. A two-stage amplifier was designed to check further the characteristics of the over-all system. An attempt was made to design the i-f strip by reducing phase shifts in it so that the range of modulation frequencies over which the stabilizing system would work could be extended. The method of design was to make the amplifier as broadband as possible and then reduce the amplitude with a single R-C network on the output circuit of the phase detector. An alternative procedure of controlling the amplitude and phase characteristics in the



i-f amplifier above has not as yet been considered in detail. As in most feedback networks the criterion for stability is that the amplitude of the over-all open-circuit gain be reduced to less than unity at the frequency at which the phase shift in the i-f strip is 90 degrees.

The phase-sensitive detector was examined to see if any improvement could be realized by using a full-wave detector rather than the half-wave type of circuit being used at the present. All of the full-wave detectors tried had at least one of the following disadvantages:

- (1) No improvement in conversion efficiency
- (2) Poor phase characteristics due to increased interelectrode and wiring capacitances
- (3) Added circuit complexity
- (4) Balanced output to ground rather than the desired unbalanced output
- (5) Impractical because of interelectrode capacitances

The only realizable advantage appeared to be independence of the amplitude of the reference signal. This advantage is to a large extent unimportant because the half-wave detector is fairly insensitive to reference signal variations if the injection grid is driven from the grid limiting condition to cutoff. Since the ripple frequency of the detector has not been the limiting factor in the output filter design up to the present time the increase in ripple frequency in the full-wave detector by a factor of two was of diminished importance.

The main factor which prevents the Pound discriminator from working over a wide range without readjustments other than changing the reference cavity may be seen by reference to Fig 10. Energy is divided into two components at the magic T. One component goes directly to the detector crystal, the other reaches the detector crystal by a path which differs in length from the direct path by twice the combined length of the cavity and modulator crystal arms. The phase relations of the two signals at the detector crystal must be such as to produce amplitude modulation for proper operation. Because of the difference in path length this phase relation is a function of frequency. Calculations show that even when the arm lengths of the Pound discriminator circuit are reduced to the smallest practical values in  $1" \times \frac{1}{2}"$  waveguide and used in the vicinity of 900 Mc/sec the expected frequency range of the discriminator is less than 150 Mc/sec. This figure correlates quite well with the measured frequency range of a Pound discriminator (Frequency range is taken as that range causing the required phase relationship to vary over a range of 180 degrees.) There are secondary phase shift effects which occur in the portion of the waveguide carrying r-f sidebands. The magnitude of these effects has been calculated and shown to be negligible in this circuit (The major effect is almost 2000 times greater.)

Considerable improvement in frequency range may be obtained by using what may be called an "equal arm" discriminator. The simplest configuration of this type is obtained if the crystal detector and modulator crystal of Fig 10 are interchanged. Energy reflected from the reference cavity into the detector arm may be made to travel

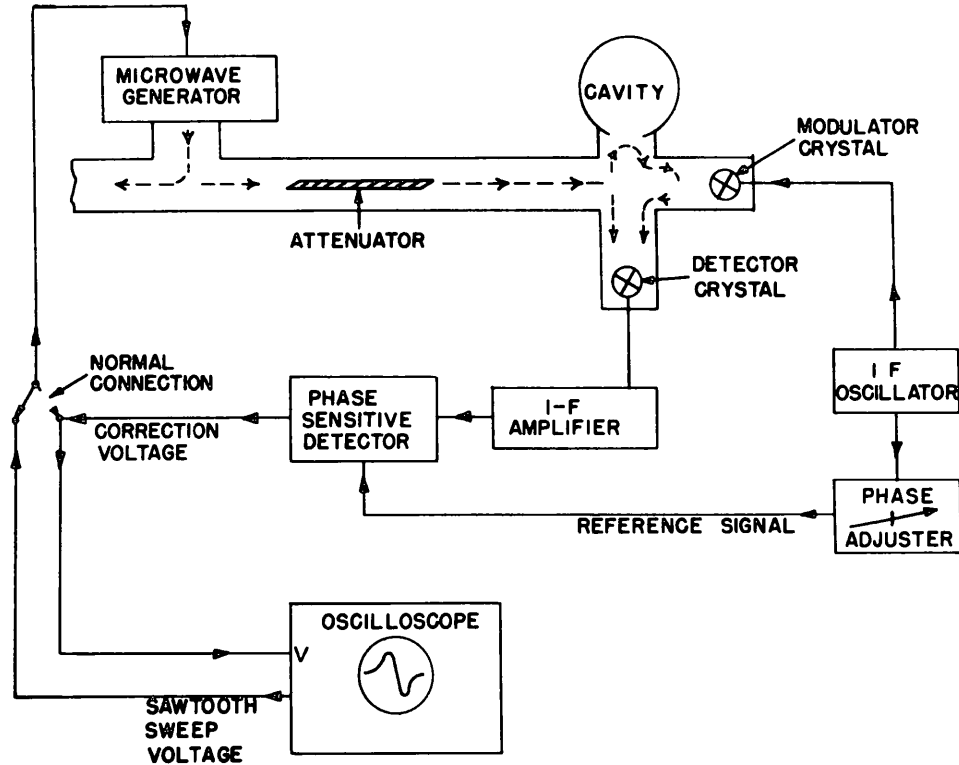


Figure 10 Block diagram of stabilizer with provision for continuous plotting of discriminator characteristic

the same length of path as energy reflected as i-f sidebands from the modulator crystal. With this discriminator frequency ranges of the order of 1000 Mc with no adjustment other than cavity tuning have been obtained. An analysis of the operation of the equal-arm discriminator is now in progress. An important dissimilarity between Pound's and this discriminator is noted. In the equal-arm circuit, the detector crystal operates normally on a signal composed of a constant sideband level and varying carrier amplitude. This is analogous to overmodulation since the carrier is normally nearly zero. Large amounts of second harmonic power are generated at the crystal and must be rejected by the i-f amplifier. There is reason to believe that increased sensitivity may result from this mode of operation.

Studies have been initiated on the operation of the stabilizer circuit when the oscillator is frequency modulated. The problem will be attacked by

- (1) Determining the manner in which the discriminator characteristic as determined by the reference cavity only controls distortion in the modulated output
- (2) Determining the manner in which the i-f amplifier and phase-sensitive detector affect the distortion in the modulated output

All studies will be done with the i-f system. W. G. Tuller<sup>1</sup> has analyzed distortion in the output of a discriminator for a pure frequency-modulated input.

1 W. G. Tuller "Distortion in FM Discriminators" RLE Tech Report No. 1 March 8 1946

A recently completed report entitled "Notes on the Pound Microwave Frequency Stabilizer" is now being prepared for publication (RLE Technical Report No 31)

#### IV C MULTIPATH TRANSMISSION

Staff Professor L B Arguimbau  
John Granlund

It has been long recognized that the fading interference caused by transmission over two or more paths is one of the chief limitations to long distance transmission of speech and music. This project has been set up to study such effects under controlled laboratory conditions with various types of modulation.

The arrangement of apparatus is indicated by Figs 11 and 12. The delay line in the two-path amplifier is of the supersonic mercury variety used in radar equipment. It is terminated in 30-mc crystals which are very heavily damped by contact with the mercury. The delay is mechanically adjustable within narrow limits. The total delay is somewhat more than a half millisecond, which corresponds to a transmission path difference of slightly more than one hundred miles. The reciprocal of the time delay is equal to the period of a 1600-cycle note. If a sinusoidal modulating signal of this frequency or integral multiples of this frequency are used, no distortion results because there is an envelope phase shift of a whole number of revolutions. It is of importance that the

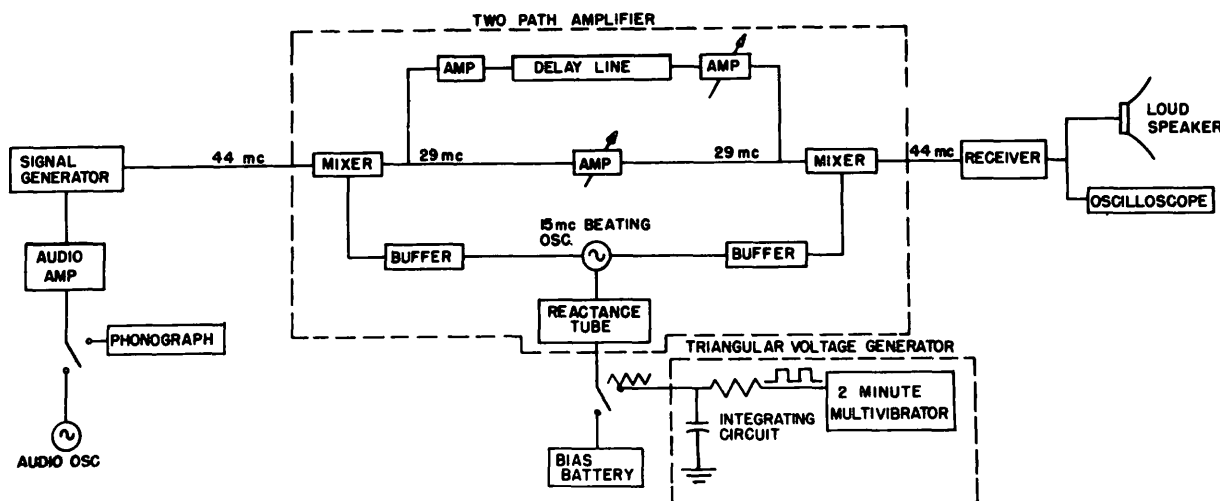


Figure 11 Block diagram of equipment for simulating fading in long distance radio transmission

delay is so large that in general it causes a phase shift of the envelope as well as the carrier.

The equipment is capable of simulating the type of fading commonly experienced over long distance radio transmission links. The pass band of the two-path amplifier is wide enough to pass a standard frequency signal so that the desired comparison between frequency modulation and amplitude modulation may be made with the use of this box. As can be seen from Fig 11, oscillographic studies of the distortion produced by fading can be obtained with sinusoidal modulation or speech and music may be used in listening tests.

In amplitude-modulation fading serious distortion is noticed only during periods when the delayed and undelayed carriers are within about 30 degrees of phase opposition. Under such conditions the carriers very nearly cancel and bad envelope distortion results.

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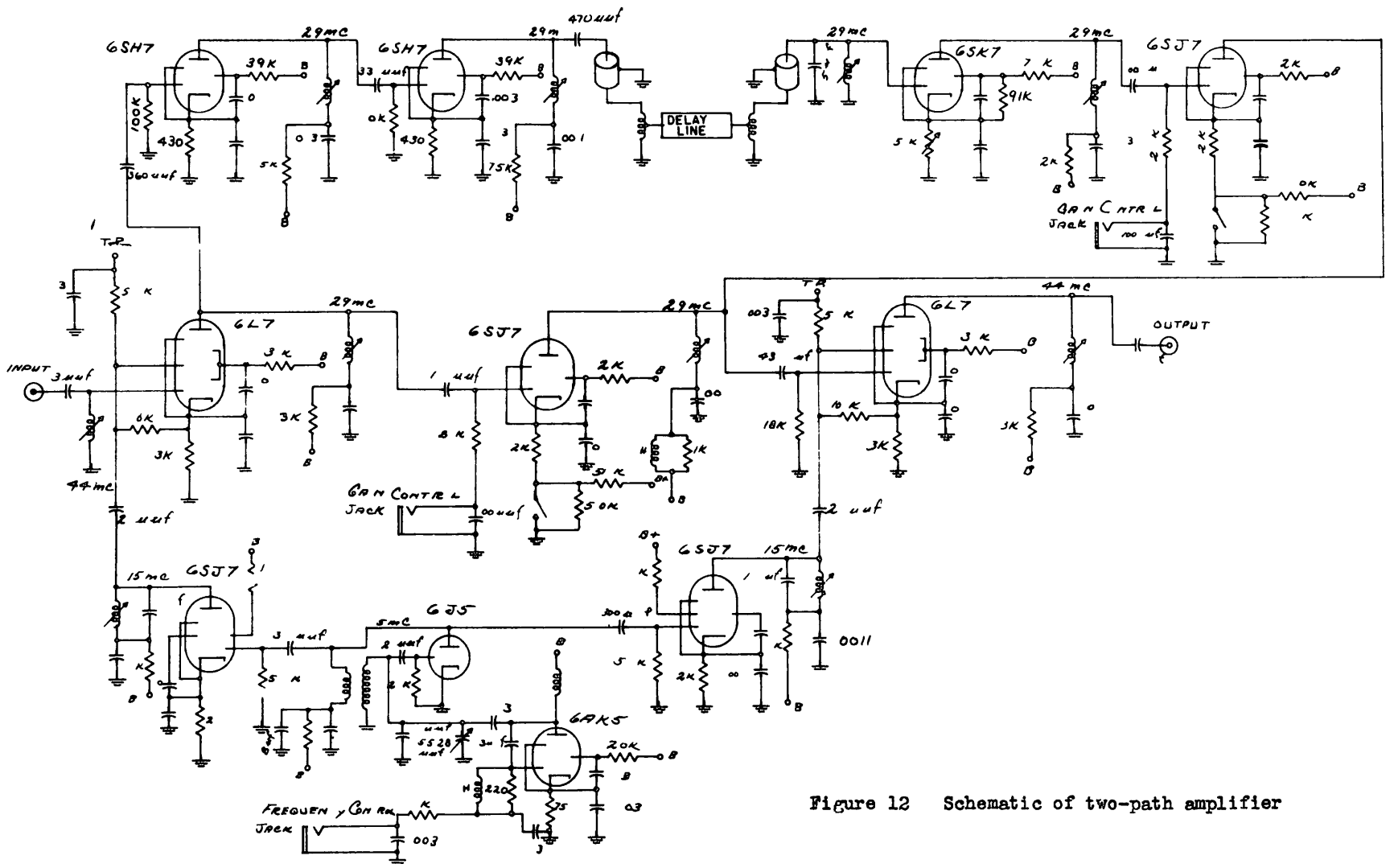


Figure 12 Schematic of two-path amplifier

To make the listening tests representative, it was decided to change the phase relation of the combining carriers continuously. With the system so arranged, the out-of-phase condition recurs at about one-second intervals.

The circuits for producing this phase variation are the triangular voltage generator and reactance tube shown in Fig 11. The phase difference between the delayed and undelayed carriers upon recombination is given by the product of the angular frequency of transmission through the delay line and the time delay of the line. In a physical transmission link, this phase difference is changed naturally by a change in the relative transmission time of the two paths. In the laboratory model, however, it is simpler to change the frequency. This change is made by changing the frequency of the beating oscillator, so that it is not necessary to change the tuning of the signal generator and receiver simultaneously.

In frequency modulation the signal phase goes through wild gyrations in the course of being modulated. Hence one might suspect that the phase difference between the unmodulated carriers upon recombination is of little consequence. This has been observed to be true with the laboratory setup. For this reason, the equipment for producing continuously variable phase is made inoperative in frequency-modulation tests.

The results on amplitude modulation are in agreement with the early studies concerning fading<sup>1</sup>. The waveforms so far obtained on frequency modulation are similar



Figure 13. Characteristic waveform of multipath interference in frequency modulation.  
Modulation frequency = 200 cycles.  
Frequency deviation =  $\pm$  3000 cycles.  
De-emphasis time constant = 100  $\mu$ sec.  
Time delay = 625  $\mu$ sec.

Amplitude of delayed path is slightly greater than amplitude of undelayed path.

in appearance to those obtained by others<sup>2,3,4,5</sup>. A characteristic waveform is shown in

1. R. Bown, D. K. Martin, R. K. Potter, "Some Studies in Radio Broadcast Transmission", Proc. IRE, 14, 57, (Feb. 1926)
2. M. G. Crosby, "Frequency Modulation Propagation Characteristics", Proc. IRE, 24, 898, (June 1936)
3. M. G. Crosby, "Observation of Frequency-Modulation Propagation on 26 Megacycles", Proc. IRE, 29, 398, (July 1941).
4. E. Hölzler VDE, F. H. Gecks, G. Kamphausen, "Übertragung amplituden- und frequenzmodulierten Schwingungen auf kurzen Wellen", Elektrotechnische Zeitschrift, 65, 133, (April 1944).
5. M. D. Corrington, "Frequency-Modulation Distortion Caused by Multipath Transmission", Proc. IRE, 38, 878, (Dec. 1945).

Fig 13 It is not difficult to compute the positions and magnitudes of the small disturbances in most cases. Some waveforms are less easily handled and depend upon receiver characteristics. In spite of the agreement with earlier results there are indications that frequency modulation has certain advantages over amplitude modulation under proper conditions.

Incidental to the study of multipath transmission with amplitude modulation and frequency modulation it is found that

(1) An amplitude-modulation link having a transmitter subject to incidental frequency modulation may have very much more distortion than a similar link having a transmitter that is stabilized in frequency.

(2) A frequency-modulation link which is subject to incidental amplitude modulation is more distorted than one which does not have amplitude variations introduced at some point.

#### IV D WIDEBAND AMPLIFIER STUDIES

Staff W G Tuller  
 H. H Montgomery Jr  
 M W Whitaker Jr

The introduction of the various wideband systems of pulse modulation such as pulse code modulation, has brought about a great need for amplifiers capable of reasonable gains over extremely wide bands. In the microwave region these requirements are met by the travelling-wave amplifier tube but no equivalent to this device exists at low frequencies. At the suggestion of Professor H Wallman an amplifier circuit has been built and tested which may be considered as a low frequency analogue of the travelling-wave tube. The circuit constructed is shown in simplified schematic form in Fig 14. As can be seen from this figure the amplifier consists of three

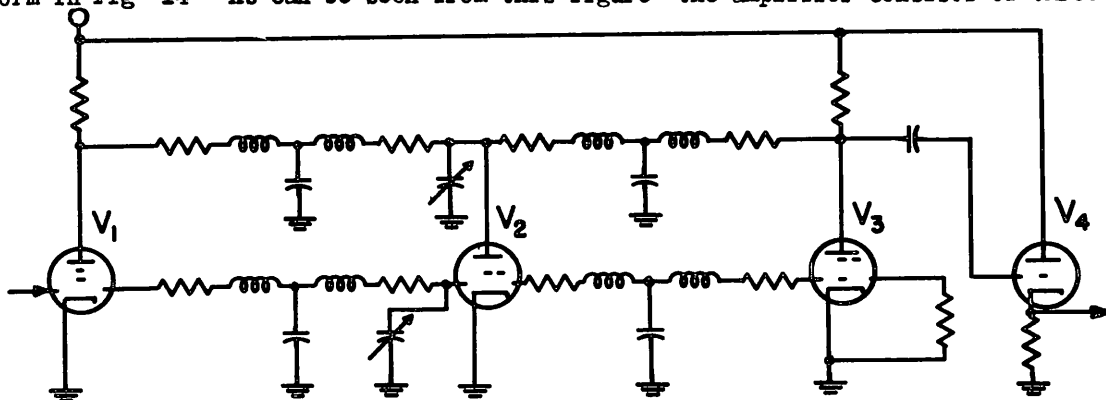


Figure 14 Wideband video amplifier

amplifying tubes all 6AC7's, and an output cathode follower. The tubes are effectively connected in parallel by delay lines between grids of adjacent tubes and similar delay lines between plates of adjacent tubes. The signal may be considered as propagating along the amplifier from left to right in the figure. Suppose a negative pulse excites the grid of  $V_1$ . The plate of  $V_1$  will be driven positive correspondingly. The negative grid pulse will then pass down the delay line to the grid of  $V_2$ . Simultaneous with its arrival at the grid of  $V_2$  the positive pulse generated at the plate of  $V_1$

arrives at the plate of  $V_2$ , where it is reinforced by an additional positive pulse of equal magnitude generated by the amplifying action of  $V_2$ . A similar action takes place at  $V_3$  so that at the plate of  $V_3$  a pulse exists with approximately three times the amplitude of the pulse at the plate of  $V_1$ . The gain-bandwidth factor of an amplifier of this type with  $n$  tubes is therefore  $ng_m/C$ , where  $g_m$  is the transconductance of each tube of the chain, and  $C$  the sum of its input and output capacitances. The amplifier built in this manner has been found to operate substantially in accordance with theory. A similar device has been patented in England but, just as was true in the early travelling-wave tubes, the reflections from the ends or junction points of the delay lines caused oscillations and had to be suppressed by extremely careful matching. Professor Wallman suggested that these delay lines be made dissipative as has been done in the most recent and most successful travelling-wave tubes. This procedure has been followed and has resulted in an amplifier that may be quite readily adjusted so as to give no sign of oscillation. The experimental model was not built with any idea of exploiting the possibilities of this design to the limit and therefore has a pass band of only about 5 Mc. Plans are now under way to build a second unit to cover a somewhat wider frequency range.

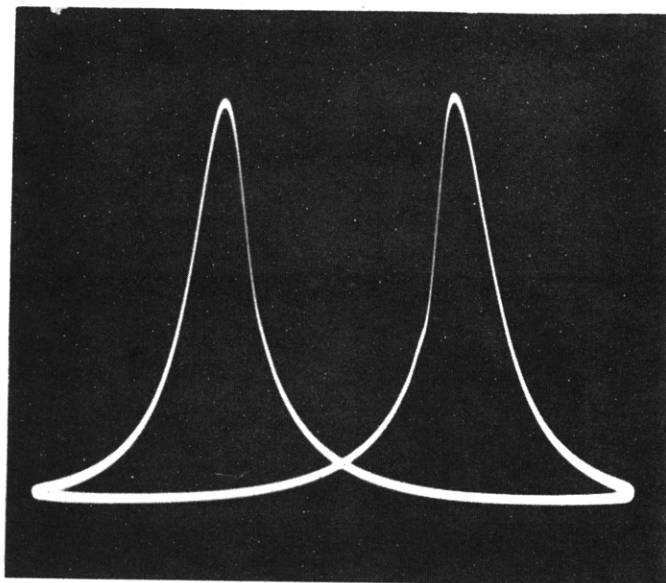
#### IV E RESPONSE OF NETWORKS TO FREQUENCY TRANSIENTS

Staff Professor E A Guillemin  
D M Powers

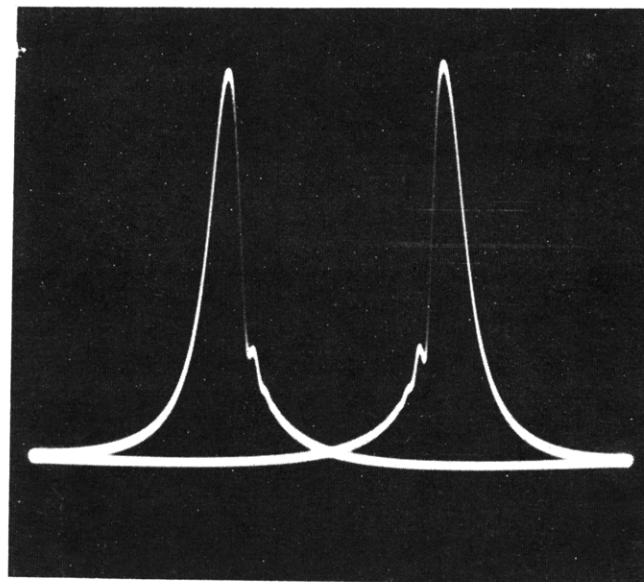
Introduction The response of networks to a carrier with amplitude changes of many different kinds but with constant frequency is a subject that has been handled numerous times and is generally well understood. However, the response of networks to frequency changes of a carrier with either a constant or a changing amplitude is not well known and solutions have been attempted only for certain special cases. Since there are a number of systems in particular communications and broadcasting by frequency modulation, that are vitally concerned with the response of networks to frequency changes, it has been thought important to develop theory or procedures for handling the problem. If possible, these means should be simple in order that they be conveniently applied wherever necessary.

The program being followed has been to carry out a number of experiments in parallel with theoretical work. Then at appropriate points comparisons between theory and experiment are made.

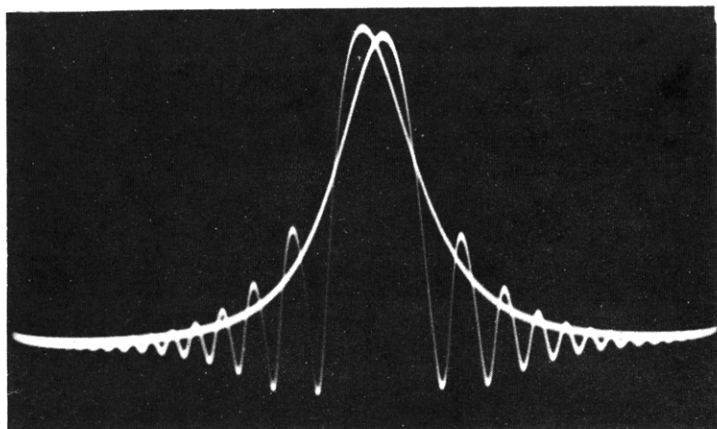
Theoretical Approach In the case of the problem of amplitude transients, a transformation from the time domain to the frequency domain is usually made since in the latter domain the response is simply the product of the excitation function and the response function of the networks under consideration. A second transformation is then made to gain the derived time function of the response. If transients of frequency are considered, it is found that in many cases that of a frequency-modulated wave for example, the transformation to the frequency domain leads to a spectrum having an infinite number of components or at least a large number of important components. This difficulty could be avoided if the excitation and response as functions of time were related



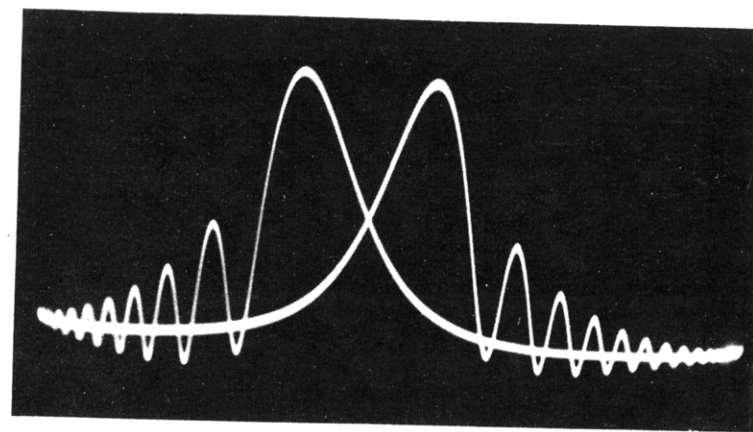
(a) Average sweep velocity 20 Mc/sec<sup>2</sup>.



(b) Average sweep velocity 50 Mc/sec<sup>2</sup>.



(c) Average sweep velocity 250 Mc/sec<sup>2</sup>.



(d) Average sweep velocity 500 Mc/sec<sup>2</sup>.

Figure 15. Response of a single-tuned circuit.



in closed form They are so related by the superposition integral in terms of the impulse response of the network

If  $e_1(t)$  = applied time function  
 $e_2(t)$  = response time function  
 $A_0(t - \xi)$  = response of the network to a unit impulse applied at  $t = \xi$   
 $h(\omega)$  = system function of the network

then 
$$e_2(t) = \int_{-\infty}^{\infty} e_1(\xi) A_0(t - \xi) d\xi$$

where 
$$A_0(t - \xi) = \frac{1}{2\pi} \int_{-\infty}^{\infty} h(\omega) d\omega e^{j\omega(t - \xi)}$$

The applied time function is regarded as a succession of elementary rectangular pulses of duration  $d\xi$  The response of the network to this impulse is found and the integral is evaluated by summing all of the small responses and taking the limit as the pulse duration approaches zero Another useful way of looking at the convolution of the functions  $e_1(t)$  and  $A_0(t)$  is to regard  $A_0(t - \xi)$  as an aperture through which the  $e_1(\xi)$  curve is scanned

This is the method being used at present Other attacks some of which are found in the literature, are also used where applicable

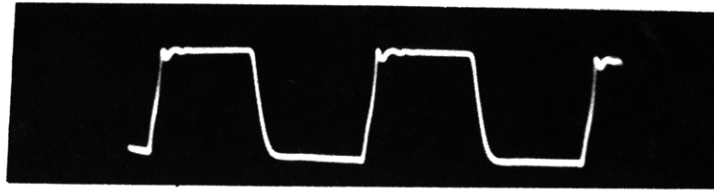
Experimental Work To date two experiments have been made The object of the experiments was to show the existence of the problem to provide data with which to compare the theory and to determine the best results obtainable with latest circuits and techniques

The first experiment was to apply the output of a frequency-modulated signal generator at a center frequency of one Mc/sec to a one-stage single-tuned amplifier having a 3-db bandwidth of 9 kc/sec or a Q of 111 at its center frequency of one Mc/sec<sup>1</sup> By varying the sweep frequency or the total frequency or both the average sweep velocity was varied from 20 to 2600 Mc/sec<sup>2</sup> Figures 15a-d show the response, and hence indicate the existence of the problem at hand as well as provide one case to be checked with the theory Both upsweep and downsweep are pictured, but in the cases shown, no adjustment was made of the phase

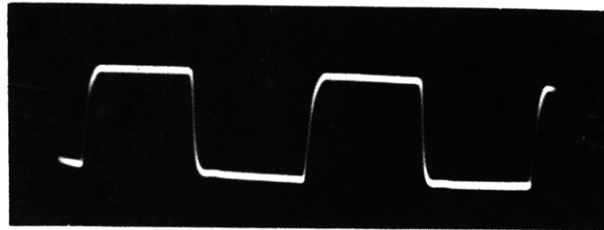
The second experiment was undertaken to discover what effects would arise and how good a system could be made when a square-wave frequency variation was applied to a FM receiver A d-c square wave was applied to the grid of a reactance tube that varied the frequency of a 30-Mc/sec oscillator The modulated signal was received either by a standard FM receiver or by a laboratory receiver having two wideband limiters and a cathode-follower type discriminator Figures 16a b c show the various outputs from the receivers The sweep velocity in all cases was 1000 Mc/sec<sup>2</sup>

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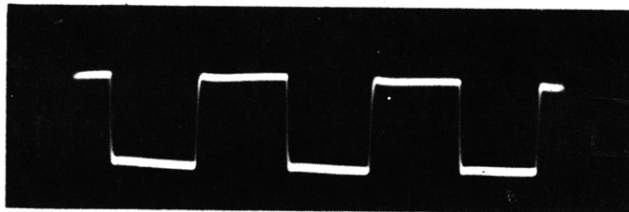
1 W J Frantz "The Transmission of a Frequency-Modulated Wave Through a Network" Proc IRE 34 114 March 1946



(a) Over-all receiver bandwidth 70 kc/sec.  
standard communications receiver.



(b) Over-all receiver bandwidth 230 kc/sec,  
standard communications receiver.



(c) Wideband limiter and detector, laboratory model.

Figure 16. Response of a square wave of frequency.

Status. Calculations are in progress to check the present experimental results. Further experiments and calculations, and possibly other theoretical approaches are to be made next. Types of excitation for which answers are desired are:

- (a) Sudden change of frequency from one value to another.
- (b) Linear change of frequency from one value to another.
- (c) Sinusoidal frequency modulation.

These excitations may be applied to any of several networks and they may begin either inside or outside of the network pass band and end either inside or outside of the pass band.

Networks of interest are:

- (a) The ideal bandpass filter.
- (b) Synchronous single-tuned circuits.

Following work on these networks, more general cases will be considered.