A PULSE—TIME MODULATION SYSTEM FOR EXPERIMENTATION IN HIGH QUALITY TRANSMISSION AND DETECTION

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PREFACE

In recent years there has been a decided trend toward the exploration and use of higher frequencies in the radio spectrum. Broadcast allocations are being forced into the microwave region due to crowded conditions at the lower frequencies. Frequency-modulated transmission was developed because of this trend and also because of improved economy. The rapid advancement of radar during World War II, has made possible the development of a much more extensive field of communication wherein pulse circuits are employed. This field of communication is known as "multiplex broadcasting."

In a multiplex broadcasting system, several (one for each modulating signal to be transmitted) "pulse trains" must be generated. Each individual pulse train is then modulated with one of the desired programs and the several channels multiplexed into an interleaved pulse train. This multiplexed signal, which contains the intelligence of the several programs, is then used to modulate a high frequency carrier wave. Several such systems have been developed in recent years for experimental purposes. In these systems, the pulse train repetition rate (not the carrier frequency) was relatively low, and the attainable upper audio frequency response therefore somewhat limited. It is not the purpose of the present study to improve existing methods of multiplex broadcasting, but to test the feasibility of pulse communication by means of cable rather than carrier-frequency transmission. As in multiplex broadcasting, an interleaved pulse train containing the intelligence of the several programs must be generated, but no high-frequency carrier is required.

The present study was begun in February, 1949, by Mr. C. W. Merle and Mr. John A. B. Bower, with the idea of increasing the repetition rate of the pulse train and thus increasing the upper limit of attainable audio frequency response. A 100 kc. repetition rate was decided upon and construction of a three channel transmitter commenced. In September, 1949, Mr. Thomas King joined Mr. Bower, Mr. Merle having left Oklahoma A. & M. College in May, 1949, and construction was continued until January, 1950. At this point in the project development, a complete transmitter had been constructed and basic plans made for the construction of a three channel demodulator.

In February, 1950, Mr. R. D. Kelly and the writer commenced the construction of a three channel demodulator. Upon completion of the first few stages of the demodulator it was decided, in conjunction with the advice of Professor A. L. Betts, that a new transmitter design would have to be made and a model constructed if the proper and desired results were to be obtained. The existing transmitter was found to be far too erratic and proper modulation of the channel pulses could not be obtained.

As a result of the above decision, the writer commenced work on the construction of a new transmitter, while Mr. Kelly continued working on the demodulator construction. The new transmitter was completed in May, 1950. Mr. Kelly continued working on the demodulator through the summer months.

By September, 1950, the demodulator construction had proceeded to the point where channel separation had been achieved. A proposed method of converting the modulated pulses back into an audible form had received preliminary tests. The writer, having decided upon a different method of making this conversion, constructed a working model in order that a comparison might be made.

In this study, a 52 ohm coaxial cable system was used as the transmitting medium. This procedure not only shows the feasibility of cable use in pulse communication, but in no way excludes the use of the transmitter as a source to modulate a carrier wave for radiation, should this be desired.

The writer wishes to take this opportunity to acknowledge the guidance given by those persons whose work preceded this phase of the project development, as well as the assistance of his associate Mr. R. D. Kelly. He also wishes to express his thanks to Professor A. L. Betts and Professor Harold Fristoe, of the Electrical Engineering Department, Oklahoma Institute of Technology, both of whom gave invaluable assistance during the development of the project.

I. Edward Lynch

Oklahoma Agricultural and Mechanical College
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PART I - INTRODUCTION

Recent advancements in radar and its associated pulse circuits have made possible the rapid development of a new and very extensive field of communication wherein "pulse modulation" is employed. Unlike conventional methods of modulation where sound vibrations are converted into a current, the amplitude, frequency, or phase of which is made to vary continuously according to the sound intensity, pulse modulation employs intermittent current flow (current pulses), as a means of intelligence transmission. It is the intermittent current flow property of pulse modulation transmission that makes its use in multichannel communications of particular advantage.

Multichannel communication systems may be divided into two classes:

1. Frequency-division.
2. Time-division.

Frequency-division multiplexing is accomplished by shifting the individual channel frequency bands, by means of modulators and filters, to successive positions in the frequency band. Similar results may be obtained by the modulation of a series of subcarriers so spaced in frequency that each speech signal occupies a separate band of frequencies. The combined signal is then transmitted by a single path to the receiver where the inverse operation is performed. Such a system has been in operation since 1935 in connection with multiplex telephone communication.[1] In recent years, frequency-division multiplexing has been constantly giving ground to time-division multiplexing. This trend has resulted because time-division multiplexing requires only common circuit components, large tolerances are allowable, and economy of

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[1] E. M. Deloraine, "Pulse Modulation," Proceedings of the Institute of Radio Engineers, XXXVII (June, 1949), 702-705.

space results.

Time-division multiplexing is based upon the fact that it is not necessary to transmit the complete modulating waveform. By taking successive "samples" of the signal amplitude, and transmitting these separate samples in the form of short bursts of energy, the speech signal can be reproduced by the demodulator provided the pulse repetition rate is at least twice the highest audio frequency which it is desired to transmit.[2] The cited reference gives a mathematical proof of this pulse repetition requirement, however, intuitive reasoning will lead the reader to the same conclusion. It is impossible to conceive any physical method whereby a voltage wave could be represented by a sampling process which occurs less than once for every half cycle of the wave. In practice, an output audio frequency of one-half that of the pulse repetition rate cannot be obtained due to other limiting factors. These factors will be discussed in connection with the receiver design of PART IV. Since the pulse train which is sampling one particular modulating signal occupies but a fraction of the time of each repetition cycle, several such pulse trains can be interleaved (multiplexed), and the several signals transmitted simultaneously. For proper results, the separate pulse trains must be properly displaced in time in order to prevent superposition or interaction of different channels. The use of time-division multiplexing is especially useful where it is expensive or difficult to attain high quality multichannel transmission by the use of frequency-division multiplexing.

Five methods of pulse modulation are presently available for the purpose of time-division multiplexing. They are:

1. Pulse-Amplitude Modulation.

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[2] C. E. Shannon, "Communication in the Presence of Noise," Proceedings of the Institute of Radio Engineers, XXXVII (January, 1949), 10.

2. Pulse-Width Modulation.
3. Pulse-Time Modulation.
4. Pulse-Frequency Modulation.
5. Pulse-Code Modulation.

Pulse-amplitude modulation is achieved by modulating a given channel pulse train in such a manner that the amplitude of successive pulses follows the amplitude of the signal voltage. This type of modulation can be simply achieved by the use of a pentode tube where the pulse train is fed to the screen grid and the signal voltage to the control grid. Pulse amplitude modulation is efficient in bandwidth utilization, but its relatively low signal-to-noise ratio caused attention to shift to other methods of pulse modulation. At present there is no method available to reduce the noise in a pulse-amplitude modulated system which is operating within a set frequency bandwidth. It should be mentioned as a matter of comparison, that "link" requirements as to nonlinear distortion are less stringent in this type of pulse modulation than in frequency-division systems.[3]

In pulse-width modulation systems, the channel pulse train is modulated in such a manner that the width of successive pulses is proportional to the modulating voltage at the instant of sampling. The low signal-to-noise ratio encountered with the use of pulse-amplitude modulation, is considerably improved by the use of pulse-width modulation, if noise is properly removed. Since intelligence is transmitted in the form of pulse-width variations, limiter circuits may be employed to remove the upper and lower portions of the pulse train without effecting the signal properties. By removing these portions of the pulse wave, all amplitude variations (noise) are removed with the exception of that present on the sloping rise and fall portion of the pulse.

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[3] Deloraine, loc. cit.

This system inherently requires a larger bandwidth than does pulse-amplitude modulation, however, it is the reduced efficiency and economy of operation, not the frequency requirements, that led to extended research in other types of pulse modulation.

In pulse-time modulation, pulses of constant form, amplitude, and duration, are displaced in time with respect to a reference pulse, in accordance with the amplitude and frequency of the signal being sampled. Efficiency is increased over that of pulse-width modulation,[4] however, the number of channels which can be transmitted in a given bandwidth is in no way improved. The major advantage of this system is the fact that the transmitter and demodulator, to the point of audio detection, need not have linear amplitude characteristics.

In pulse-frequency modulation systems, pulses of constant amplitude, form, width, and time position, are used to transmit the intelligence. Modulation is effected by causing the frequency of a carrier (not the repetition rate of the channel pulses) to be changed in each individual pulse by an amount which is proportional to the amplitude of the signal at the instant of sampling. The requirement of a carrier signal makes pulse-frequency modulation slightly different from other types of pulse modulation. Pulse-frequency systems are of particular importance in "multiplex broadcasting" because of this carrier-frequency requirement.[5] Other pulse modulation systems may be used for multiplex broadcasting, but the method of carrier modulation is different. Pulse-frequency systems have a high signal-to-noise ratio, however, as in

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[4] Ibid., p. 703.

[5] Harold Goldberg, Carl C. Bath, "Multiplex Employing Pulse-Time and Pulse-Frequency Modulation," Proceedings of the Institute of Radio Engineers, XXXVII (January, 1949), 22.

pulse-time systems, at the expense of additional bandwidth requirements.

Pulse-code modulation is characterized by the fact that intelligence is transmitted by either the presence of absence of a pulse of a given type and at a definite time position.[6] By proper design, noise can be made negligible, however, this is achieved at the expense of additional bandwidth requirements.

Two other types of pulse modulation, pulse-number and pulse-spacing, have recently received interest.[7] When pulse-spacing modulation is employed, the spacing between a pair of pulses is made to vary according to the modulating voltage. In pulse-number systems, the number of short pulses transmitted is made proportional to the amplitude of the modulating voltage.

From the above description of possible methods of pulse modulation, it is readily seen that each method has both advantages and disadvantages. The selection of the type of modulation to be used in any system is therefore dependent upon these factors and also to a large degree upon available equipment.

In the present project the feasibility of high-quality pulse communication by means of a cable transmission medium is to be studied. A system employing pulse-time modulation, rather than pulse-amplitude or pulse-width modulation, was decided upon because of its higher signal-to-noise ratio, stability, and economy. The possible use of pulse-frequency or pulse-code modulation was discouraged because of the relative complexity of component parts required. It should be remembered that pulse-time modulation, when compared to pulse-amplitude modulation, has a high bandwidth requirement. This disadvantage is offset, however, by the above mentioned advantages.

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[6] Deloraine, op. cit., XXXVII, 704.

[7] R. C. Whitehead, "Morse by Pulse," Wireless World, L (1949), 102.

It should be noted that this increase in bandwidth requirement is a function of the build-up and decay time of the pulses, and essentially independent of the number of channels being transmitted.[8]

As mentioned before, the pulse repetition rate must be at least twice that of the highest audio frequency which it is desired to transmit. Since a high quality system is desired in the present project, a pulse repetition rate of 100 kc. was selected. This value sets the theoretical maximum audio frequency which may be transmitted at 50 kc. This value is approximately 30 kc. greater than the maximum frequency to which the human ear will respond. The 100 kc. value is therefore seen to be more than sufficient for high quality results, provided the maximum theoretical results can be approached. It should be noted that prior to his project, the highest repetition rate used in any system, to the writers knowledge, was 24 kc.[9]

The transmission system for this project consists of 220 feet of 52 ohm RG8/U coaxial cable. The cable is a seven strand copper conductor, with polyethylene dielectric. The dielectric is enclosed in a woven copper shield and the unit then covered by a hard rubber protective layer.

Although the present system has been designed for use with a coaxial cable transmission medium, the possibility of its use in "multiplex broadcasting" has in no way been precluded. Multiplex broadcasting consists of modulating a high-frequency carrier wave with a pulse modulated multiplexed

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[8] E. M. Deloraine, E. Labin, "Pulse Time Modulation," Electrical Communication, XXII (March, 1944), 91.

[9] A. G. Kandoian, A. M. Levine, "Experimental Ultra-High-Frequency Multiplex Broadcasting System, "Proceedings of the Institute of Radio Engineers, XXXVII (June, 1949), 694.

pulse train. The signal is then radiated to the demodulator where the carrier wave is received, the respective channel pulses separated, and the intelligence of the separate pulse trains converted to a replica of the original modulating signal. The present system could very easily be used to modulate such a carrier by employing either amplitude, frequency, or phase modulation. At the present time articles relating to several such multiplex broadcasting systems, have been published.[10,11, 12, 13]

Before proceeding to the actual channel transmitter and receiver units, a discussion of the theory of operation of the basic circuits employed will be given.

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[10] F. Altman, J. H. Dyer, "Pulse Time Modulation and Its Application to Radiobroadcasting," Electrical Engineering, LXVI (April, 1947), 372.

[11] Kandoian, Levine, loc. cit.

[12] A. G. Cavier, G. Phelizon, "Paris-Montmorency 3,000 Megacycle Frequency Modulation Radio Link," Electrical Communication, XXIV (June, 1947), 159.

[13] Goldberg, Bath, loc. cit.

PART II - CIRCUIT DESIGNS USED IN THE SYSTEM CONSTRUCTION

1. THE OSCILLATOR-BUFFER AMPLIFIER CIRCUIT

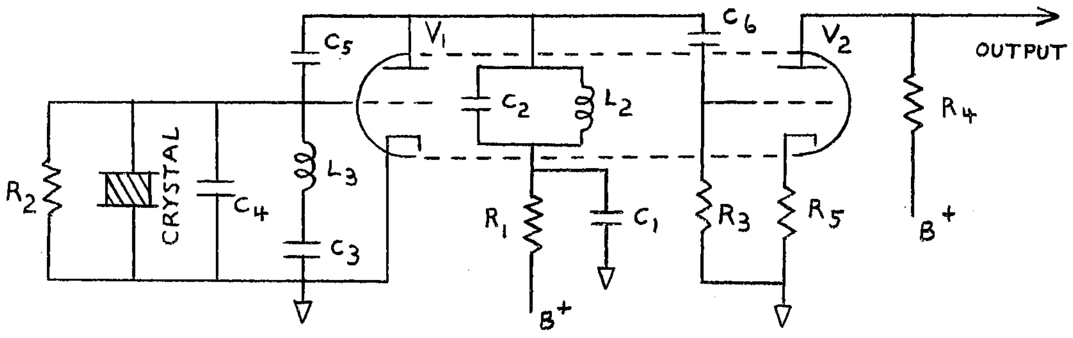

FIG. 1

Fig. 1 shows the crystal oscillator-buffer amplifier type of circuit employed in this project. The purpose of the circuit is to supply a basic timing source for the transmitter unit. The circuit components have been denoted by letters rather than actual circuit values in order that circuit operation might be more easily explained. Circuit values are given on the transmitter circuit diagram (Fig. 18-a) of PART III.

In the circuit, V_1 denotes the oscillator tube while V_2 denotes the buffer amplifier tube. The R_1 C_1 combination operates as a decoupling filter. The operation of this part of the circuit is explained in paragraph 2. The oscillator circuit is essentially that of a tuned-grid, tuned-plate oscillator. C_2 and L_2 form the elements of the plate tank circuit while the crystal has the equivalent effect of a high Q tank in the grid circuit. The advantage of the use of a crystal in the grid circuit is the fact that its high equivalent Q (the circuit thus containing a large energy storage) reduces the effect of any reactance changes upon the frequency of oscillation. The circuit will oscillate only when sufficient energy is fed from the plate to the grid circuit to supply the grid circuit losses. If the circuit is to oscillate, C_2 must be set at a value sufficient to make the L_2 C_2 combination resonant at a frequency slightly above that of the crystal. This results in a high inductive reactance in the plate circuit, a comdition which must be fulfilled if oscillation is to result. The capacitor C_5 along with the grid-to-plate capacitance of V_1, serves as the means of coupling the power from the plate to the grid circuit. R_2 serves as a grid biasing resistor while the C_4 C_3 L_3 combination offers a means of frequency correction to the desired 100 kc.

The oscillator output is coupled to the buffer amplifier by means of the C_6 R_3 coupling arrangement. The purpose of the buffer amplifier is to isolate any change in load conditions from the oscillator circuit. This isolation stage is a necessity since any change in load conditions will, by a change in reflected impedance, alter the oscillator frequency. The buffer amplifier has a slight amplification and provides a constant load on the oscillator circuit.

2. THE DECOUPLING FILTER

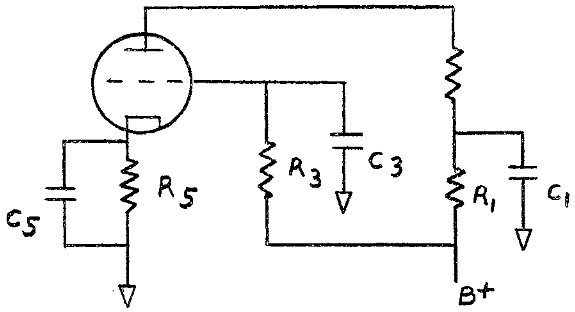

FIG. 2

R_1 and C_1 of Fig. 2 constitute the elements of a decoupling circuit. The condenser C_1 serves two functions which are distinct although related.

One of its functions is to return the alternating component of the plate current to ground through a direct path. To do this the only requirement is that the impedance of C_1 be low compared with that of the B-supply. If C_1 is not properly chosen, alternating currents will flow through the B-supply and in so doing disturb the operation of associated circuits.

The second function of C_1 is that of a decoupling elements. R_1 and C_1 in effect serve as a kind of low-pass filter to prevent coupling between stages due to the common impedance in the B-supply. Under operating conditions the terminal voltage of the B-supply varies with the current drain due to its internal impedance. The addition of the decoupling circuit reduces the possibility of feedback by acting as an additional filter to the output of the B-supply. The effects of the voltage drop caused by the alternating component of the plate current is thus minimized.[1]

The same type of circuit is also utilized in the screen-grid circuit as indicated by R_3 and C_3 of Fig. 2. R_3 is of such value as to place proper voltage on the screen grid.

Although grid bias can be obtained from a voltage souce separate from the B-supply or from the B-supply with the use of a voltage divider, it is more easily obtained by the use of a cathode resistor. The bias thus produced is equal to the product of this resistance and the sum of the plate and screen currents, and is of such polarity as to make the grid negative with respect to the cathode. Since the signal voltage across this resistance is applied to the grid in opposite phase to the input, it is seen that this may also be a source of feedback unless the resistance is

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[1] H. J. Reich, Theory and Applications of Electron Tubes, p. 132.

by-passed with a condenser whose reactance at the signal frequency is small in comparison with the resistance. This circuit, shown by R_5 and C_5 in Fig. 2, is not a decoupling circuit, but has been included here because of its similar action and undesired effects if not properly designed.

3. THE DIFFERENTIATING CIRCUIT

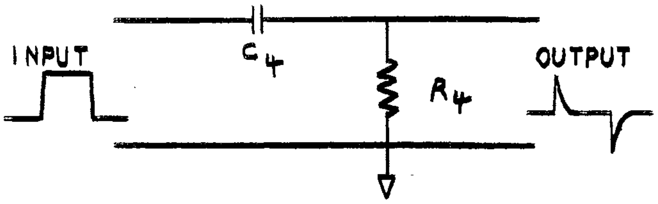

FIG. 3

RC circuits having different time constants are of extreme usefulness in connection with electronic pulse equipment. In connection with the action of these circuits, their response to near rectangular input waves is of importance since this is the condition prevailing in pulse circuits.

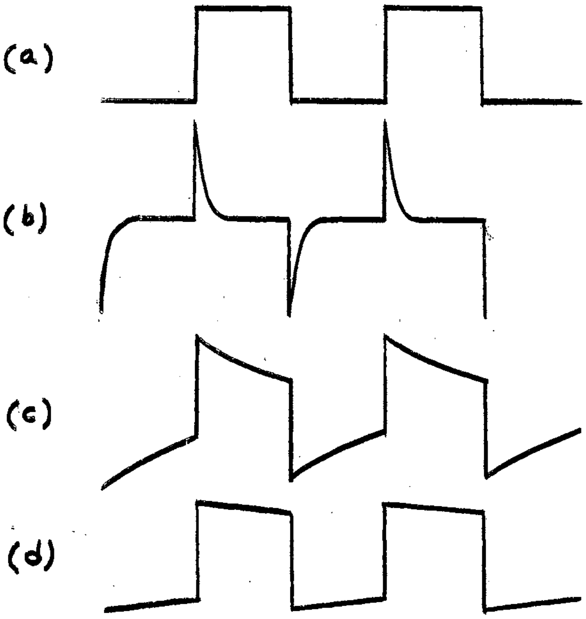

FIG. 4

The curve of Fig. 4(a) shows a form of the voltage wave that may be applied to the differentiating circuit of Fig. 3. When such a voltage wave containing abrupt changes is impressed upon the circuit, expotential charging and discharging of the condenser C_4 takes place. By taking the voltage produced across R_4, pulses are obtained whose width is controlled by the values chosen for R_4 and C_4, since these values control the RC time constant.[2] Curve (b) shows the output wave for a time constant which is shorter than one-half the period of the square wave. Curve (c) is the output wave for a time constant equal to one-half, while curve (d) is for a time constant greater than one-half the period of the input wave. When the RC time constant is small, curve (b), the circuit is called a differentiator circuit. When the RC time constant is large and the output is taken as the drop across C_4, the circuit is known as in integrator circuit. The action of this circuit will be described in paragraph 4. When the RC time constant is large and the output is taken as the voltage drop across R_4, Fig. 4(d), the circuit can and often is used as a means of coupling between the stages of amplifiers. The output wave is seen to approach that of the input wave as the RC time constant is made very large. The above examples indicate several examples where RC circuits may be put to great use.[3]

In connection with pulse circuits, the input wave does not have to be a square wave. If the positive and negative parts of the wave are of unequal time duration, the circuit will function as before, but the output pulses will be shifted. The output pulses must occur at the same

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[2] Ibid., p. 357.

[3] Electronics Training Staff of the Cruft Laboratory, Harvard University, Electronic Circuits and Tubes, pp. 145-148.

instant that an abrupt change in the input voltage takes place. Thus if the duration of one of the rectangular pulses is delayed, so will the time at which the output pulse occurs be delayed. If the input is a periodic wave containing discontinuities, output pulses will be produced at each discontinuity. Because of this action, the differentiating circuit is useful in locating the edges of rectangular pulses.

In connection with the location of pulse edges, waveform (b) of Fig. 4 is the most useful as its action on following circuits to be triggered is more positive. Here the duration of the pulse is made very short by making the RC time constant very small. Pulse edge location is not the only function the differentiator circuit can perform. It can also be used to indicate the time required for the rectangular pulse input to make an abrupt change. For the waves shown in Fig. 4, the discontinuities in the input wave were assumed to take place in zero time, and this entire voltage change assumed to appear across the resistor R_4. This assumption is true in that the sum of the applied voltage and the impedance drops around the complete circuit must at all times equal zero and no sudden change in the condenser voltage can take place.[4] Thus under the above assumption the

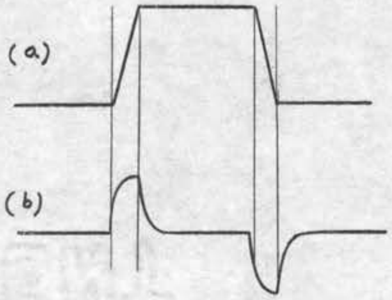

FIG. 5

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[4] Ernest A. Guillemin, Communication Networks, p. 37.

amplitude of the pulses of Fig. 4(b) will be exactly equal to the amplitude of the input wave discontinuities. If now the input wave is taken as that shown in Fig. 5(a), a condition which more nearly exists under practical conditions, the output waveform is that given by curve (b). The amplitude of the output wave is no longer as large as the discontinuity of the input wave since the condenser now has time in which to develop a voltage before the discontinuity is completed. This developed voltage subtracts from the drop across R_4 and thus reduces the amplitude of the output. Under these conditions the smaller RC is made, the smaller the output voltage is made since the departure from true "squareness" of the input is accentuated.

In applying the differentiator circuit to pulse circuits, it should be remembered that the output pulse depends upon the shape, polarity, spacing, and magnitude of discontinuity, of the input wave. Its duration on the other hand depends on the RC time constant. The resistance R_4 can be used as the grid resistor and C_4 as the coupling capacitor between tube circuit stages, however, load impedance should be high or its value included in R_4. If pulses of only one polarity are desired, limiter circuits may be used in conjunction with the differentiating circuit.

4. THE INTEGRATING CIRCUIT

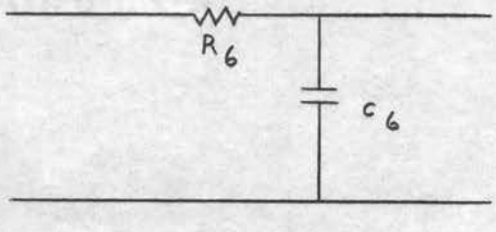

FIG. 6

The RC circuit of Fig. 6 is that of an integrating circuit. Its response to rectangular voltages makes it of extreme usefulness in connection with pulse circuits. The action of the circuit is explained by use of the curves given in Fig. 7.

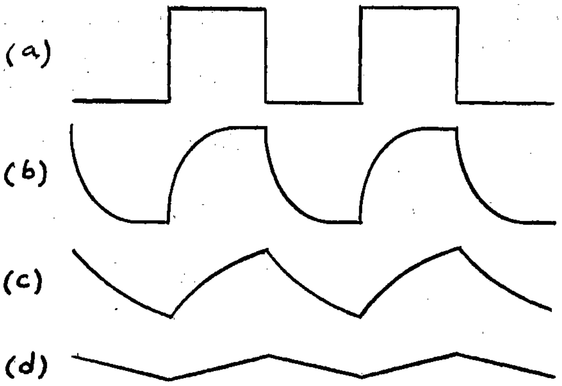

FIG. 7

The curve of Fig. 7(a) is that of the assumed voltage input. With the application of this voltage to the integrator circuit, the condenser C_6 charges or discharges exponentially depending on the polarity of the abrupt change in input voltage at the time under consideration. The voltage waveform developed across the condenser is shown by the curves (b), (c), and (d), of Fig. 7. Curve (b) is the type wave that will be produced if the RC time constant is smaller than one-half the period of the input voltage. Curve (c) is the output waveform for a time constant equal to one-half, while curve (d) is for a time constant larger than one-half the period of the input wave. As stated in paragraph 3., if the RC time constant is made large, curve (d), the voltage developed across C_6 is proportional to the time integral of the input voltage.[5] In order for this

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[5] L. B. Arguimbau, Vacuum-Tube Circuits, pp. 139-141.

condition to prevail, the equation

$$\frac{X_c}{R} \ll 1$$

must be true at the frequency under consideration. This condition is easily satisfied by making the RC time constant of the circuit large. Fig. 7 clearly shows, however, that the amplitude of the output voltage is made smaller as the RC product is increased. If a band of frequencies are to be passed by the integrator, other factors must be taken into consideration. These factors are discussed in PART IV.

As in the case of the differentiator circuit, the positive and negative portions of the cyclic input voltage may be on unequal duration. Under these conditions, the integrator circuit is useful in the determination of pulse length, the integrator output being proportional to the area of the rectangular voltage input. The integrator when followed by a clipper circuit, can be used as a delay mechanism. No output from the clipper will result until the integrator output voltage has risen above the threshold of the clipper.

5. THE PULSE AMPLIFIER-NEGATIVE PULSE INPUT

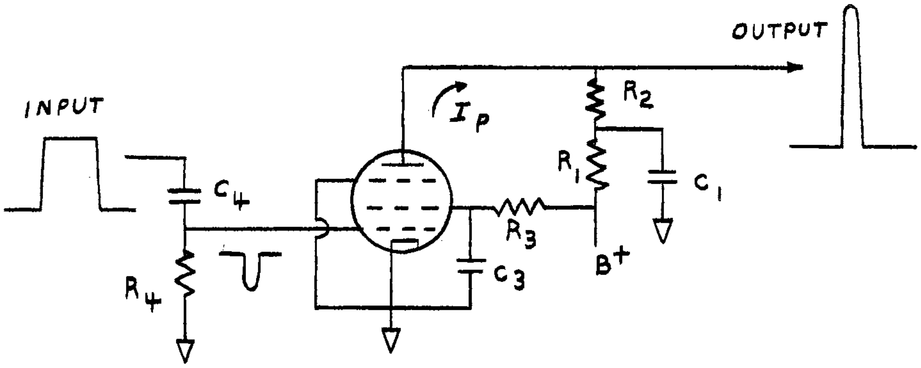

FIG. 8

The pulse amplifier shown in Fig. 8 is a circuit designed to amplify sharp negative pulses. R_1 and C_1 compose the elements of a decoupling circuit, the action of which was explained in paragraph 2. R_2 is the plate load resistance while R_3 functions to produce proper screen voltage. R_4 and C_4, the components of a differentiating circuit, have been included to show the source of the negative pulses and also to explain tube bias conditions. The explanation of the differentiating circuit is given in paragraph 3. For the production of sharp negative pulses, the R_4C_4 time constant is made very short. C_4 therefore charges and discharges very rapidly, with the application of the square wave, thus producing very sharp negative pulses of short time duration. In order to amplify this pulse, it is applied to the grid of the pulse amplifier. Since this applied voltage is of very short time duration, negligible bias is produced and the grid is essentially at ground potential. No cathode bias is provided and the tube thus operates under saturation conditions when there is no input voltage. If now a negative pulse is applied, the tube will be biased to near or beyond cutoff. The tube plate current I_p will cease its flow for a time equal to the pulse duration. The plate voltage will rise sharply due to the decreased I_pR_2 drop. The output voltage will therefore be a positive pulse of much larger amplitude than the input pulse, but of equal time duration. Since the input waveform is shown to be that of a square wave, both positive and negative pulses will be applied, due to differentiating action, to the grid of the tube. Positive input pulses, however, will have no effect since the tube is already operating under saturation conditions. The circuit therefore has amplifying characteristics for a negative pulse input and limiting characteristics for a positive pulse input.

6. THE PULSE AMPLIFIER-POSITIVE PULSE INPUT

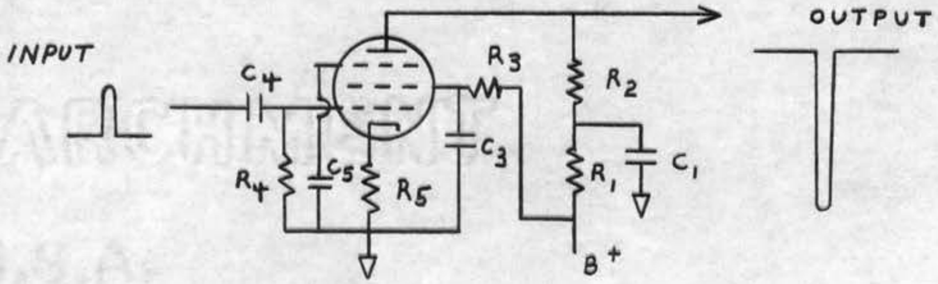

FIG. 9

The pulse amplifier shown in Fig. 9 is a circuit designed to amplify sharp positive pulses. R_1, C_1, R_2, and R_3 of this amplifier perform identical functions to those of the negative pulse input amplifier discussed in paragraph 5. C_3 as in the preceding circuit functions as a screen grid decoupling circuit in connection with R_3. In order to amplify positive pulses of very short time duration, R_5 is chosen to bias the tube near cutoff. The grid will be essentially at ground potential since the bias produced across R_4, by the very sharp pulse, will be of a negligible value. The tube bias is purposely set at a value near cutoff in order to eliminate the effects of any applied negative pulses and also the broad lower portion of the positive pulses. With the application of a positive pulse through the coupling capacitor C_4, the grid of the amplifier is driven very positive with respect to the cathode. This causes a large plate current to flow for a time equal to the duration of the applied pulse. This large plate current produces a large but sudden drop in plate voltage due to the increased voltage drop across R_2. The output voltage is thus a negative pulse of large amplitude.

7. THE RECTANGULAR-PULSE GENERATOR

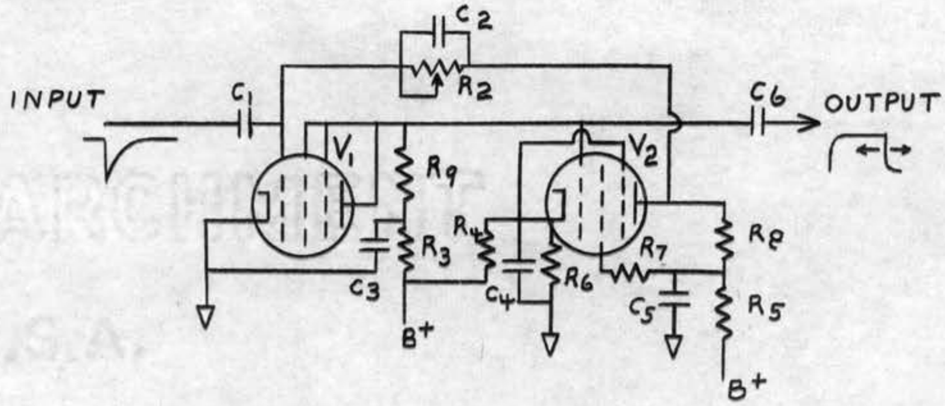

FIG. 10

The circuit of Fig. 10, a form of delay or asymmetrical multivibrator circuit, is for the production of rectangular voltage pulses of controllable time duration. The circuit is designed for a negative triggering impulse applied to the grid of V_1.

The circuit operates as follows.[6,7] Before the negative pulse is applied to V_1, normal conditions prevail throughout the circuit. V_1 is conducting under bias conditions such that the circuit can be triggered, while V_2 is cut off by the bias provided by the voltage divider arrangement of R_4 and R_6. The grid of V_1, being connected to the plate of V_2, tends to be positive, but the charge on C_2 resulting from the flow of grid current, keeps the grid of V_1 at near ground potential. This is done rather than connecting the grid of V_1 to ground for reasons that will be discussed later. R_2 and R_8, in addition to performing other functions,

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[6] W. D. Cochrell, Industrial Electronic Control, pp. 161-164.

[7] Reich, op. cit., pp. 359-365.

limit the grid current of V_1 to a value within the tube limits. With the application of a negative pulse through the coupling condenser C_1, to the grid of V_1, V_1 stops conducting since the tube is now cut off. V_2 on the other hand starts conducting since the grid of V_2 is now at a more positive potential than during rest conditions. This increased positive potential is caused by the reduced IR drop of the plate current of V_1 through the resister R_9. The cathode potential of V_2 is held at a relatively constant value by the condenser C_4. At this point, the plate current of V_2 flows through R_8, reducing both the plate voltage of V_2 and the charging potential of C_2. This causes C_2 to discharge through the resister R_2. As a result of this discharge, the grid of V_1 approaches the plate voltage of V_2 in an exponential manner which is controlled by the constants R_2 and C_2 and to a lesser extent by R_8 and the supply voltage. When the grid potential of V_1 reaches the cutoff value, V_1 will again conduct, V_2 will be cut off as explained above, and C_2 will quickly charge to its normal value as the result of grid current flow from V_1. The current again under rest conditions where it will remain until another negative pulse is applied.

The reason for connecting the grid of V_1 to the plate of V_2 rather than to ground is now explained by the fact that such a practice causes the grid potential curve of V_1 to have a steeper slope at the point of intersection with the cutoff line. This results is more accurate control and under conditions of cyclic input, an output waveform where each recurring pulse will be of the same time duration.

The output of this circuit, the voltage developed across R_9, is a nearly rectangular positive pulse. This voltage is not truly rectangular in form due to the exponential rise and decay of the grid voltage of V_1, the result of the charging and discharging of C_2. This causes the plate current of V_1 and therefore the IR drop across R_9 to have an exponential component.

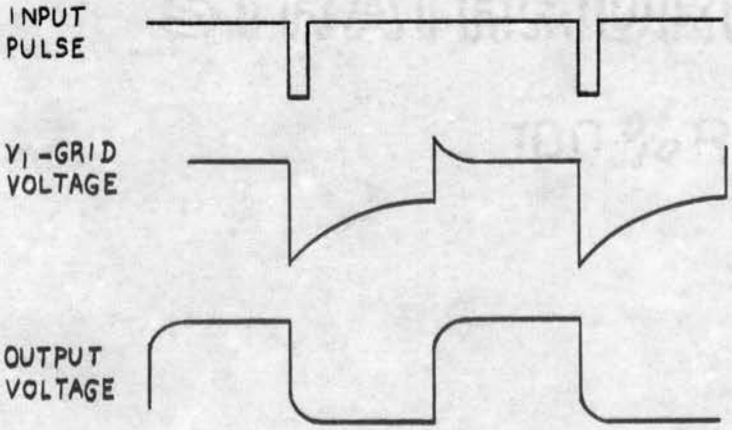

FIG. 11

The output pulse starts with the input trigger pulse and the duration is controlled by variation of R_2. Curves showing the circuit operation are shown in Fig. 11, where for convenience, a square wave output has been assumed. The circuit components R_3, C_3, R_5, and C_5 form decoupling circuits, the action of which was explained in paragraph 2.

6. THE CATHODE-FOLLOWER

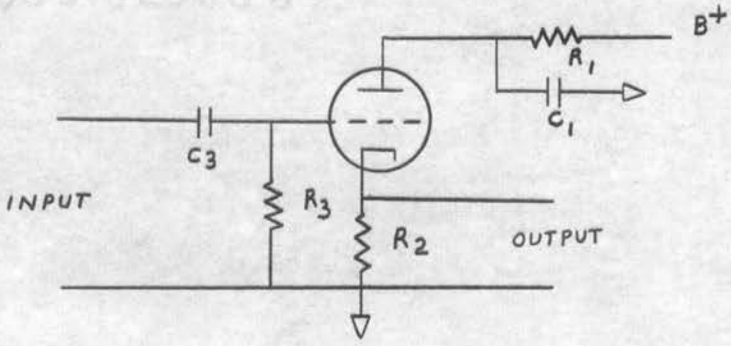

FIG. 12

The circuit of Fig. 12 is that of the conventional cathode-follower. In this circuit the plate load resistance R_2 is placed adjacent to the cathode, thus forming a portion of the grid circuit. R_1 and C_1, as in the preceeding circuits, form the elements of a decoupling circuit. C_3 is the coupling condenser from the preceding stage while R_3 performs the function of a grid coupling resistor.

From the circuit it can easily be seen that the grid voltage is equal to the difference between the input voltage and the alternating voltage developed across R_2. Since the output of the amplifier is taken as the voltage developed across R_2, the amplification of the amplifier is always less than one. Under typical operating conditions, amplifications of 0.9 or better may be achieved. The advantages of such an amplifier are numerous even though it has an amplification less than one. It has low effective input capacitance, high input impedance, low output impedance, and low nonlinear distortion.[8] The amplifier also has the advantage of being able to handle large input voltages without overloading since the grid voltage is equal to the input voltage minus that developed across R_2. The fact that the output voltage is in phase and not phase opposition with the input may prove useful.

The above factors make the cathode-follower useful as an impedance matching device. This is true since the high input impedance can be reduced to any desired value by means of impedance shunting of the input terminals, while the output impedance can be set at a desired value by the proper choice of tubes and tube transconductance, a factor which is controlled by the grid bias. In connection with a pulse input, the circuit

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[8] *Ibid.*, pp. 164-174.

must be designed in such a manner as to limit the plate current to within tube limits. With a positive pulse input, the condition existing in both the transmitter and receiver designs, R_3 in connection with R_2 must be of the proper values to limit the current to the desired value. If R_2 had been used without the aid of R_3, its value would have to be large and the output impedance would therefore be large. In connection with broad band amplfication, R_3 must again be used in order to limit the current flow through R_2 due to its grid biasing action. If this current is of too large a value, amplitude distortion will result.

The cathode-follower when used under conditions of broad band amplification, a condition which exists in the latter stages of the pulse receiver, is useful for reasons other than impedance matching. In resistance capacitance coupled amplifiers, high frequency response begins to fall off at the point where the reactance of the input capacitance of the following stage is no longer negligible in comparison with the effective output impedance of the given stage. In order to obtain uniform amplification, the output impedance of each stage must be low and the effective input capacitance of the next stage small. Pentode tubes have the small input capacitance required, but in order to obtain the low output inpedance required, the stage amplification must be of such a relatively low value that excessive distortion will result. By placing a cathode-follower between two pentode stages, considerable improvement results. The low input capacitance of the cathode-follower prevents falling off of the output of the preceding stage at high frequencies, while the low effective output impedance of the cathode-follower prevents the input capacitance of the following amplifier from causing high frequency loss of amplification in the amplifier following the cathode-follower.

9. THE PULSE MIXER CIRCUIT

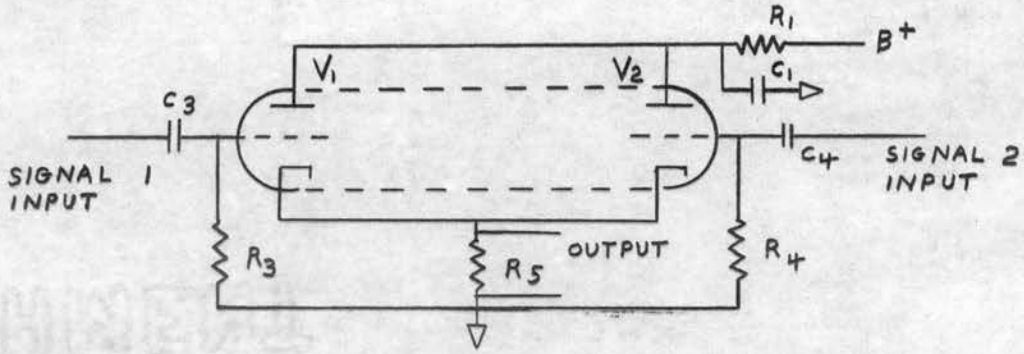

FIG. 13

The pulse mixer circuit of Fig. 13 is in effect a modification of the cathode-follower amplifier discussed in paragraph 8. In this circuit, two triode tubes operate with a common cathode resistor R_5, and with both plates at the same positive potential. R_1 and C_1, as in the previous paragraphs, form the elements of a decoupling circuit. C_3 and R_3 serve to couple signal one to the circuit, while C_4 and R_4 perform the same function for the second signal. With the application of a positive pulse signal to the grid of V_1, an increased voltage drop across R_5 will be produced, the result of the corresponding increase in plate current flow. The same action will take place with the application of a positive pulse signal to the grid of V_2. If both signals are now applied, the voltage developed across R_5 will be the resultant of the instantaneous sum of the voltage developed due to the action of each of the input signals. By taking the output voltage as that developed across R_5, the two input voltages have been mixed or in effect superimposed. The output voltage pulses will be reduced in amplitude, but of the same polarity as the input pulses. The same factors that apply to the design of a cathode-follower amplifier must be considered in the design of this circuit. A 6SN7 tube is convenient in the construction of this circuit since two triode units are contained in the same envelope.

PART III - THE TRANSMITTER UNIT

In any pulse-time modulation system, the principal operations which must be performed are:

1. Generation of a "marker" or reference pulse train.
2. Generation of the channel pulse trains properly spaced in time with respect to the marker pulse.
3. Modulation of the separate channel pulse trains with the desired audio signal.
4. Mixing of the marker and channel pulses into an interleaved pulse train.

Fig. 14 may be used to represent one "frame" of the transmitter output waveform which will result when the above operations are performed. The frame represents that of a three channel negative pulse transmission system. These conditions were selected because of their correspondence to the operating conditions of the present unit. Each frame is seen to contain one marker pulse, the amplitude and width of which has been made greater than that of the channel pulses. This increased marker pulse size serves as a means to distinguish it from the channel pulses and also affords a method by which it may be separated from the channel pulses. This separation process is a necessary operation which must be performed in the present receiver unit of PART IV.

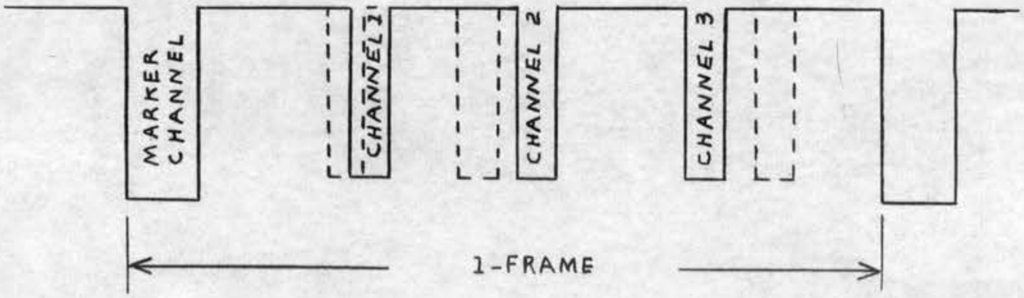

FIG. 14

In Fig. 14, the mean position of each of the three channel pulses, of constant amplitude and duration, is represented by the solid line pulses. Such a pulse train would represent the resultant multiplexed waveform should no modulation be present on any of the channels. If one of the channels should now be modulated, the respective channel pulse will be either advanced or retarded, with respect to the marker pulse, depending upon the polarity of the modulating voltage at the instant under consideration. These advanced or retarded pulses are represented by the dashed line pulses of Fig. 14. At the particular instant represented, the modulation voltage of channel 1 is seen to be of such polarity and magnitude as to advance the pulse by a small amount. The modulation voltage of channel 2 is of the same polarity but of a larger amplitude, while that of channel 3 is seen to be of opposite polarity. Since the frame repetition rate is the same as the pulse repetition rate, 100 kc. for the present project, the pulses representing deviation from the mean position will quickly change to new positions (the rate of which is dependent upon the frequency of the audio signal being sampled) with the passage of time, i. e., the viewing of successive frames. Since the eye cannot follow a process taking as short a time as one microsecond, recourse was made to the synchronization of these repeated pulses in such a way as to give a steady plot of voltage versus time on a cathode-ray oscilloscope. In this manner the actual frame characteristics were made accessible for observation and study.

The present system is one in which as many quantities have been made variable as practicability would allow. The channel pulses have been made continuously variable in both amplitude and time position with respect to the marker pulse. Other quantities such as channel pulse width, marker pulse width, and marker pulse amplitude can be controlled by changing the value of a few critical circuit components. Such a system of many variables was desired in order to test the effect of these circuit parameters upon the degree of results obtained. A continuously variable pulse repetition rate was discouraged because of the difficulty which would have been encountered in obtaining stability, and also because of the filtering difficulties which would have been encountered in the receiver design. A continuously variable repetition rate is in reality unnecessary since it has already been shown that the selected value of 100 kc. is more than sufficient for the results desired. It should be noted that a disadvantage of such a high quality system is the fact that the number of transmittable channels is reduced due to the required increased repetition frequency, i.e., decreased time between marker pulses.

It has already been stated that in order to produce the above desired pulse train, the transmitter must perform the operations of marker pulse generation, channel pulse generation, modulation of the separate channel pulse trains, and mixing of the marker and channel pulses into an interleaved pulse train. Many ways of producing the above pulse trains are presently available, however, they may all be classified under one of the following general groups:

1. The marker pulse train is generated and the channel pulse trains obtained from it by the use of delay circuits.
2. The marker pulse and channel pulse trains are controlled by a common source, proper time position of the pulses being obtained by the use of delay circuit.
3. The marker pulse and channel pulse trains are generated independently.

The second of these three methods has been employed in the present system because of its believed simplicity in the prevention of objectionable interaction between channels. With the advancement of the system, familiarization with pulse modulation and its circuit requirements, led the writer to see the possible merits of the first above mentioned method. If such a method were employed, the necessary sharp negative triggering pulses for the channel rectangular-pulse generators could all be obtained from the output of V_{p-3} (Fig. 18-a) after having been differentiated (trace (23) of Fig. 19). Three cathode followers for isolation purposes would be required, but the three wave shaping circuits and the three amplifiers $V_{1,2,3-3}$ would no longer be necessary. One and one-half 6SN7 tubes could be used to replace the present six 6AC7 units.

The basic timing source for the present system is that of a 100 kc. quartz crystal controlled oscillator. The theory of operation of this circuit has been given in paragraph 1. of PART II. Actual circuit component values have been included in the complete transmitter circuit diagram of Fig. 18-a, found immediately following the present discussion. In addition to Fig. 18 (parts a, b, and c), a block diagram of the system (Fig. 16), a diagram of the physical layout (Fig. 17), and a series of oscilloscope traces (Fig. 19), have been included. The number associated with each of the oscilloscope traces corresponds to a particular point (marked by the same number in parenthesis), on the circuit diagram of Fig. 18. Oscilloscope settings in db. have been included in order that a comparison of relative amplitudes might be made. In Fig. 18, the tubes have been labeled by the notation V_{2-3}, V_{3-7}, etc. The first number of this notation refers to the channel number while the second refers to the position of the tube circuit in its respective channel. The same tube notation has also been used on both the block diagram and the physical layout diagram. Such a notation will facilitate easy cross reference. The timing source, the circuit presently under consideration, has been identified by a V_1 notation. The output of this 100 kc. oscillator is seen by waveform (2) to be that of an undistorted sine wave. This signal is fed to the grid of the buffer amplifier, the output of which is shown by trace (5). The primary purpose of the buffer amplifier is to isolate the crystal oscillator from the remainder of the circuit. This isolation process is a necessity since any change in the loading effect of the existing channels, or that which might be caused by the later addition of supplementary channels, would cause a shift in the oscillator frequency.

It was mentioned above that the present system is to have the marker and channel pulse trains controlled by a common source, time positioning being attained by suitable delay circuits. The requirement of a common synchronizing source is satisfied by the 100 kc. crystal oscillator. For suitable delay, the rectangular-pulse generator circuit described in paragraph 7. of PART II, was decided upon. In the circuit description given there, it was stated that for proper circuit operation, a sharp negative synchronizing pulse must be supplied to the circuit. The problem of producing several (one for each channel and one for the marker pulse) such negative triggering pulse trains, will now be considered. The repetition rate of these pulses must be the same as that of the common driving source. This operation will be achieved by a series of wave shaping circuits. These circuits are denoted in the diagrams following this discussion, by a $V_{1,2,3-2}$ and V_{p-2} notation. In all such notations, the subscript "p" denotes the marker pulse channel. These wave shaping circuits operate in such a manner that an abrupt change in the circuit output voltage is produced. By differentiating this waveform, trace (10), a sharp pulse will be produced (trace (15)). These pulses are then amplified by the positive pulse amplifiers V_{p-3} and $V_{1,2,3-3}$. The operation of these positive pulse amplifiers has previously been given in paragraph 6. of PART II. A sharp negative pulse of synchronous frequency is thus produced for each of the three channels and a fourth for the marker pulse channel. It should be noted that the above mentioned abrupt change in the output voltage wave, was attained in two steps. Waveform (5) shows that the buffer amplifier is so biased that cutoff conditions prevail when the negative portion of the sine wave from the crystal oscillator is being applied. The wave shaping circuits by employing saturation limiting in conjunction with cutoff limiting, increases the squareness of the wave. Since the sides of this wave have abrupt changes, a differentiating process will give the desired sharp triggering pulses. The RC time constant of the differentiatior must be small (one microsecond for the present system). As mentioned in PART I, a complete transmitter design was effected by the combined efforts of those who preceded the writer and Mr. Kelly in the system development. The operation of this transmitter, however, proved unsatisfactory and a new transmitter design was effected. Since the new transmitter required the same negative triggering pulses, the preceding circuits were employed from the originally constructed transmitter. The remainder of the transmitter design is new, however, and a comparison of methods employed and results attained, will be given.

With the production of these triggering pulses, the synchronization requirement of the pulse modulator, has been fulfilled. In connection with time delay, no delay circuit is required for the marker pulse channel since the channel pulse trains are to be delayed with respect to the instant of marker pulse occurrence. The negative pulse of V_{p-3} is merely fed to a negative pulse amplifier, V_{p-4}(Fig. 18-b), in order to obtain both amplification and proper pulse polarity. The output of V_{p-4} is seen by waveform (27) to be a positive pulse of large amplitude. At this point the marker pulse channel is ready to be multiplexed with the properly delayed channel pulses. Proper delay for each of the three channels is effected by the use of the rectangular-pulse generator described in paragraph 7. of PART II. The circuit component values are identical for all three channels. In Fig. 18-b, the delay circuits are denoted by V_{1-4} and V_{1-5} for channel 1, V_{2-4} and V_{2-5} for channel 2, and V_{3-4} and V_{3-5} for channel 3. Waveforms (28), (29), and (30), are the resultant delay circuit traces for approximately equal spacing of the trailing edges of the rectangular pulses. It should be noted that the position of this trailing edge is continuously variable throughout the interval between successive leading edges of the pulse. This variation is effected by controlling the RC time constant of the tank between the grid of the first and the plate of the second tube of the rectangular-pulse generator. By now differentiating this controllable width pulse, sharp positive and negative pulses will be produced. The positive pulses, of smaller amplitude than the negative pulses due to a large rise than decay time of the rectangular pulse, are of no use. At a later point in the circuit these positive pulses will be removed since only the negative pulses, of controllable time position, satisfy the requirement of a pulse train which may be properly delayed with respect to the marker pulse. The first two principal operations of the transmitter have now been performed. The third principal, that of modulating the channel pulse trains, will also be performed in the rectangular pulse generator circuit.

Fig. 18-b shows, by the notation X_1, X_2, and X_3, for channels 1, 2, and 3, respectively, the point at which the audio modulating voltages are introduced into the transmitter. As explained in paragraph 10. of PART II,

the duration of the output pulse of the rectangular-pulse generator is controlled by the RC time constant of the resistor and condenser between the grid of the first and plate of the second tube. This readily suggests the use of a reactance tube circuit[1] which would replace the RC combination. The audio signal fed to the grid of the reactance tube would cause the RC time constant presented to the multivibrator circuit, to vary in accordance with the audio signal. This variation in time constant in turn would cause the duration of the rectangular multivibrator ouput to change, in accordance with the audio signal, and modulation would thus be achieved. Use of such a reactance tube circuit for modulation has been tested and found satisfactory.[2] The present system, however, has proven more satisfactory with a circuit requiring fewer components. In passing, it should be mentioned that the use of a "delay line" was considered, but its use was discouraged because of the resulting discontinuous delay. A change in the number of delay sections would cause an abrupt change in the delay unless precision variable capacitors and inductors were employed. A second undesirable feature would have been the large number of inductors and condensers required for proper delay. In paragraph 7, of PART II, it was stated that under quiescent conditions, V_1 is conducting while V_2 is biased beyond cutoff. The grid of V_1 being connected to the plate of V_2 tends to be positive, but the charge on C_2 resulting from the flow of grid current, keeps the grid of V_1 at near ground potential. With the application of a negative pulse to the grid of V_1, V_1 stops conducting as it is now cut off.

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[1] Reich, op. cit., pp. 211-216.

[2] John A. B. Bower, A Transmitter for Experimentation with Modulated Pulse Communication, pp. 28-31,

V_2 on the other hand starts conducting since the grid bias of this tube is now at a more positive potential than during rest conditions. This increased positive potential is the result of the reduced IR drop of the plate current of V_1 through the resistor R_9. At this point the plate current of V_2 flowing through R_8, reduces both the plate voltage of V_2 and the charging potential of C_2. This causes C_2 to discharge through R_2, the RC time constant of which controlls the length of time before the grid voltage of V_1 reaches the cutoff value, and the circuit, due to the flow of plate current through V_1, returns to rest conditions. Thus it is seen that not only the R_2C_2 time constant but the value of the charging potential for C_2, can be a controlling factor in the time required for circuit rest conditions to return. With these operating conditions in mind, modulation was attained by introducing the audio signal to the multivibrator between the plate of V_2 and the R_2C_2 combination. The audio voltage is thus superimposed upon the voltage at the plate of V_2 (equal to either the power supply voltage or the supply voltage minus the IR drop caused by the flow of the plate current of V_2 through R_8 and R_5 , depending upon the circuit operating condition at the instant under consideration). The charging potential of C_2 now changes at an audio rate, and as a result the instant at which the R_2 C_2 combination has discharged sufficiently for V_1 to resume rest conditions, changes in accordance with the audio voltage. The output pulse of the multivibrator is therefore a rectangular pulse with the trailing edge time modulated in accordance with the amplitude and frequency of the audio signal. Thus it is seen that pulse-width modulation has been attained. Pulse-time modulation is easily obtained by differentiating this rectangular pulse. The results of this differentiating operation are shown by waveforms (32), (33), and (34). By Fig. 18-b, it is seen that the differentiating circuit also serves as a coupling network to the next stage. Its time constant has been made very small in order to produce very narrow channel pulses. Wider pulses may easily be produced by increasing this time constant.

In the original transmitter design,[3] delay and modulation was attained in two separate stages. The principles employed were also different from those employed in the present system. Delay was obtained by the use of a tank circuit in the grid of a "delay-cathode-follower."

> The high amplitude negative pulse from the peaker-amplifier circuit drives the delay tube into cutoff instantaneously, since there is no resistance in the charge path of the capacitor between grid and ground. The discharge time of the parallel RC network between grid and ground determines the amount of the delay by fixing the time the tube is held cut off. The output is a positive going square wave with variable trailing edge as determined by the setting of the potentiometer in the RC network.[4]

This positive square wave was then fed to a multivibrator, by way of a cathode-follower, to prevent loading back of the following circuits. Modulation was then obtained in this circuit by the use of a reactance tube circuit, the operating principal of which has previously been given. This reactance tube circuit replaced the RC tank circuit which controls the operating characteristics of a conventional multivibrator. Later modifications of the system resulted in a modulation method similar to that presently employed. The process of delay, however, was attained in the previously mentioned manner with the exclusion of the cathode-follower circuit. It is believed by the writer that this exclusion was a partial source of the erratic results obtained when the original transmitter was under test.

Fig. 15 shows the circuit diagram of the two types of modulators which were employed in the present system. The signal source is shown to be that

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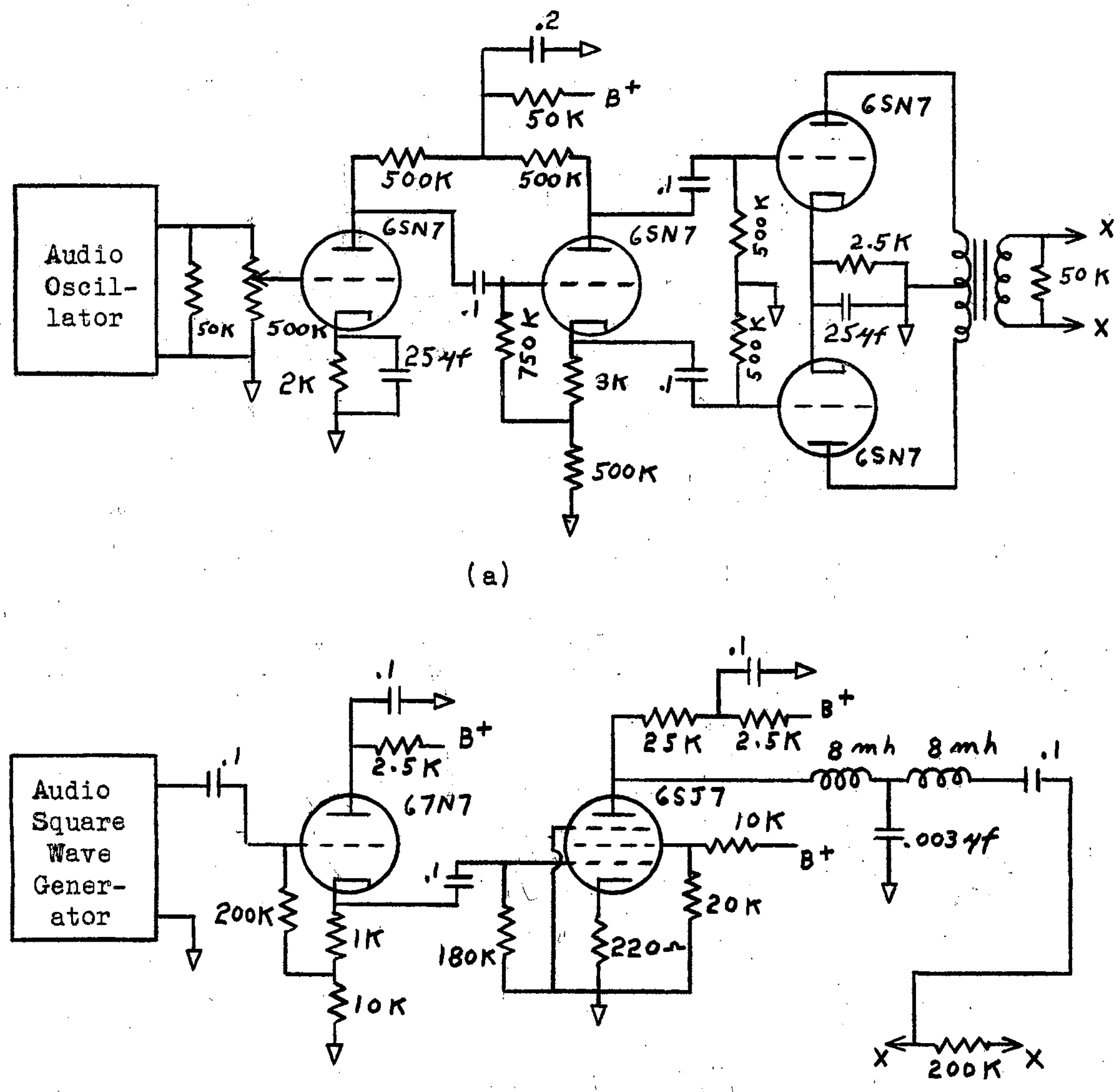
[3] Ibid., pp. 26-27.

[4] Ibid., p. 27.

of an audio oscillator. Circuit (a) was employed in tests of both speech and audio oscillator input. The functions of this modulator are:

1. Amplification of the audio signal.
2. Provision of a precisely adjustable volume control.
3. Isolation of the rectangular-pulse generator from the signal source.
4. Isolation of any D.C. voltages.

In addition to these functions, modulator (b) is provided with a cathode-follower at the input, to prevent loading of the signal source should it have a high impedance output. No cathode-follower is required with the use of circuit (a) since the oscillator employed had a low output impedance. Precise audio amplitude adjustments are easily made by adjustment of the 500,000 ohm potentiometer in the grid circuit of the first audio amplifier. The second tube circuit of Fig. 15(a) is that of a cathode-follower phase-inverter. This circuit then feeds the amplified audio signal to a push-pull amplifier, provided with an audio transformer output. The output voltage is developed across the 50,000 ohm load resistor in the transformer secondary. This voltage is then introduced into the pulse generator circuit by connecting the points X-X, at either X_1, X_2, or X_3, of Fig. 18-b, depending upon the channel which it is desired to modulate. Should it be desired to modulate all three channels at the same time, three such modulators are required. The third and fourth requirements of the modulator are provided by the audio transformer. No D.C. interaction can be present since there is no conductive path between this and the pulse generator circuit. Since an audio transformer will not pass high frequencies, it in effect acts as a low-pass filter, thus preventing the higher frequencies of the 100kc. square wave from interacting with the signal source.



(a)

(b)

X-X Connected to X_1, X_2, or X_3, of Fig. 18-b, for Transmitter Modulation

Fig. 15
AUDIO MODULATOR CIRCUIT DIAGRAM

The modulator of circuit (b) was designed for use in square wave testing of the system. Since the transformer of the preceding circuit will not pass the higher frequency components of such a square wave, a new modulator design was required. The modulator has a cathode-follower at the input in order to prevent loading of the square-wave generator. The second circuit of this modulator is that of a pentode audio amplifier, the output of which is fed to a low-pass filter. The filter was designed in an attempt to allow the passage of the high frequency components of the audio signal, and still prevent interaction of the 100 kc. square wave with the audio source. These desired results are impossible of achievement, and of necessity, a compromise was effected. The results of the square wave tests will be discussed in PART V.

At this point, several statements concerning the audio frequency response of the modulator, should be made. In any pulse-time modulation system, the reference or degree of modulation is always based on the channel pulse deviation from its mean position. Since such factors as cross talk and harmonic distortion are related to this degree of channel pulse deviation, it must of necessity be a constant value for all audio frequencies supplied by the modulator. Should the amplitude of the pulse deviation be a function of the audio frequency, cross talk and distortion would also be a function of frequency. For this reason, the modulator and any components in the rectangular-pulse generator, which might effect the frequency response, must be proportioned in such a manner that pulse deviation is a function of the audio amplitude, but not the audio frequency. All of the amplifier circuits of the modulators were designed with a flat frequency response extending well above 30 kc. However, as mentioned above, the audio transformer will not pass these high frequencies. With a constant audio oscillator output, the voltage supplied to the rectangular-pulse generator begins to fall off at a frequency near 10 kc. If no compensation were provided, such a modulator would be useless in a high quality system. However, such a means of compensation is inherently present in the rectangular-pulse generator circuit. Experimentation, in an attempt to find the location of this compensation, proved that the tank circuit of the pulse generator, was in effect acting as an integrating circuit to the audio signal. Since an integrating circuit is in effect a high-pass filter (response increases with frequency), proper compensation resulted to an audio frequency of approximately 30 kc. Above this frequency, the pulse deviation decreased with the application of a constant modulator amplification setting. In pulse-time modulation systems for practical use, the modulator would also contain an amplitude limiter circuit. Such amplitude limiting would be required in order to prevent objectionable cross talk between channels. Since the present unit is one for testing only, such limiters were not provided. In this way quantities which effect cross talk may be studied.

At this point in the transmitter development, the first three requirements of a pulse-time modulation system have been satisfied. The fourth and last requirement, that of mixing the marker and channel pulses into an interleaved pulse train, must now be performed. Immediately preceding this operation, a stage of pulse amplification has been provided. These amplifiers are denoted in Fig. 18-b by V_{1-6}, V_{2-6}, and V_{3-6}. The modulated square wave output of the preceding stage has been differentiated by the grid coupling network to this stage. Since the amplifiers are designed for a negative pulse input (saturation limiting existing with no grid signal input), the positive pulses from the integrator will have no effect. The circuit in addition to functioning as an amplifier, also acts as a positive pulse limiter. Since these positive pulses contain no intelligence, this action is a desirable one. The plate load resistor of the amplifier has been made variable in order that the amplitude of the channel pulses might be set at any desired fractional amplitude of the marker pulse. The circuit denoted by V_{p-4} has the same amplification properties for the marker pulse channel. At this point (marked by E, F, G, and H, of Fig. 18-b) in the transmitter, a pulse marker train and three properly delayed and modulated channel pulse trains, have been generated. The process of multiplexing these pulse trains into a single interleaved pulse train is performed by the circuits denoted as V_7, V_8, and V_9 in Fig. 18-c. The operation of these circuits has previously been given, in paragraph 9. of PART II. Multiplexing is attained in three steps. V_7 is used for the mixing of channel 1 and 2, while V_8 is used for the mixing of channel 3 and the marker pulse channel. The output of these two circuits is then fed to a third mixer V_9, where complete multiplexing of the channels is obtained. Such an elaborate method of multiplexing (with a circuit which is a modification of a conventional cathode-follower), gives results with a minimum of interaction between channels. In the original transmitter design, no such method or its equivalent was attempted. The output of each of the several channels was merely fed to a conventional cathode-follower. The cathode-follower was used to match impedance to the coaxial cable. This cathode-follower was eliminated in the later system modifications. Such a transmitter design was very economical in the use of circuit components, but the results obtained were far too erratic for a high-fidelity system. Severe interaction between channels was present, and although proper delay was attainable, the interaction present was a function of this delay. Amplitude more than time modulation was also found to be present. Since the sides of the channel pulses were sloping, a limiter circuit would have eliminated the amplitude modulation without effect the time modulation present. Had such a method been employed, the efficiency of audio input transfer to pulse-time deviation, would have been small.

The remainder of the present system design consists of a cathode-follower V_{10}, a positive pulse amplifier V_{11}, and two cathode-followers in parallel V_{12}. These circuits were designed for impedance matching and pulse amplification. The variable bias resistors in the cathode of V_{10} and V_{11} serve as an adjustment whereby maximum power transfer to the cable may be realized. It should be noted that the cathode-follower V_{12} has for its cathode resistor the 52 ohm impedance matching resistor at the far end of the cable. Such a practice gives excellent results for only relatively short cable lengths. Should transmission be over a long cable, extreme care is required in the impedance matching process. If proper matching is not achieved, cross talk will result due to reflections. The purpose of the two cathode-followers in parallel (V_{12}), is to increase current capacity. In this way a large voltage can be developed across the 52 ohm resistor.

The transmitter output waveform is shown by trace (53) of Fig. 19. Transmission is seen to be by means of negative pulses. The marker pulse has a time duration of 1.28 μs. (1.28×10^{-6} seconds) or one-tenth of the frame duration, while that of the channel pulses is 0.6 μs.

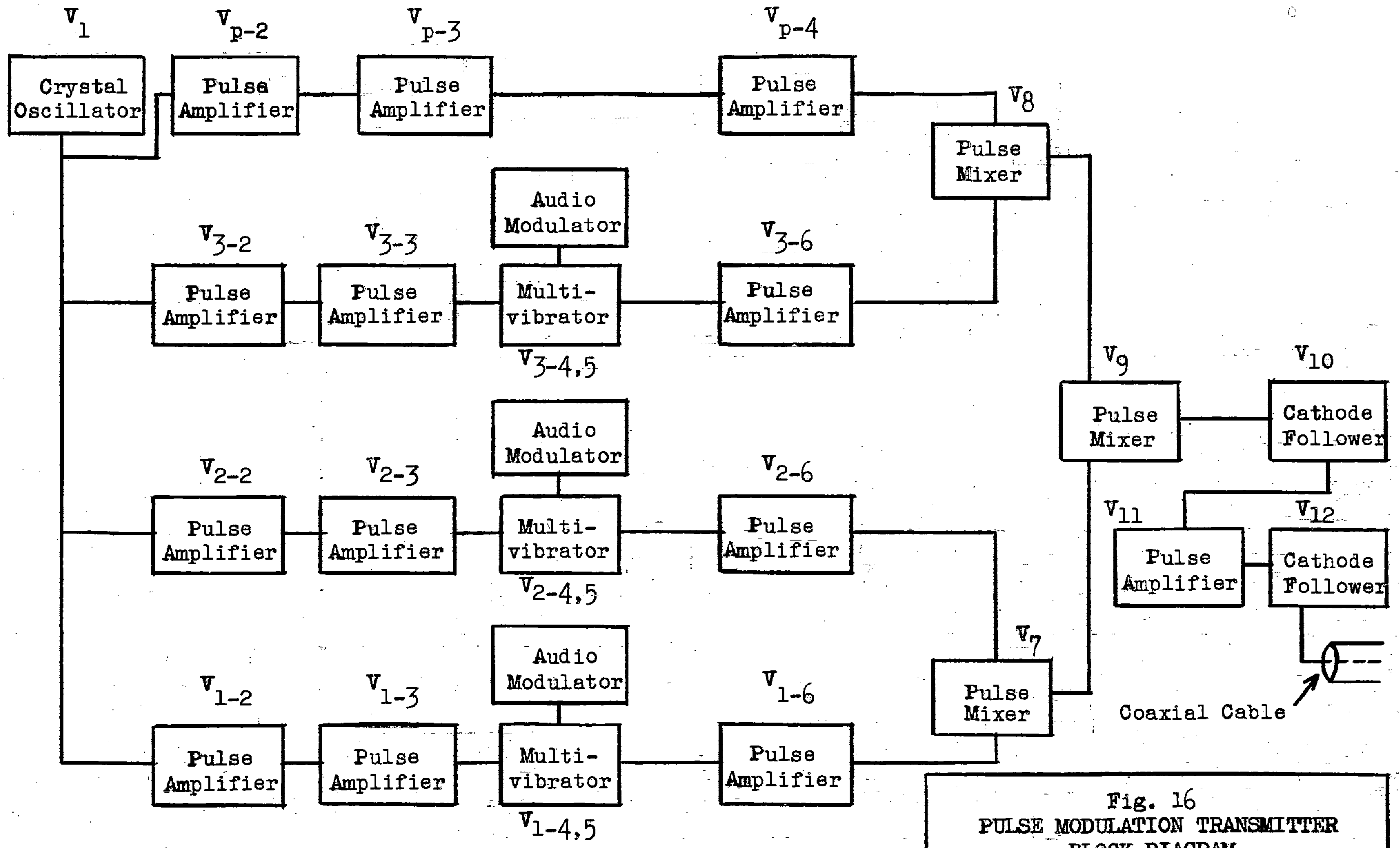
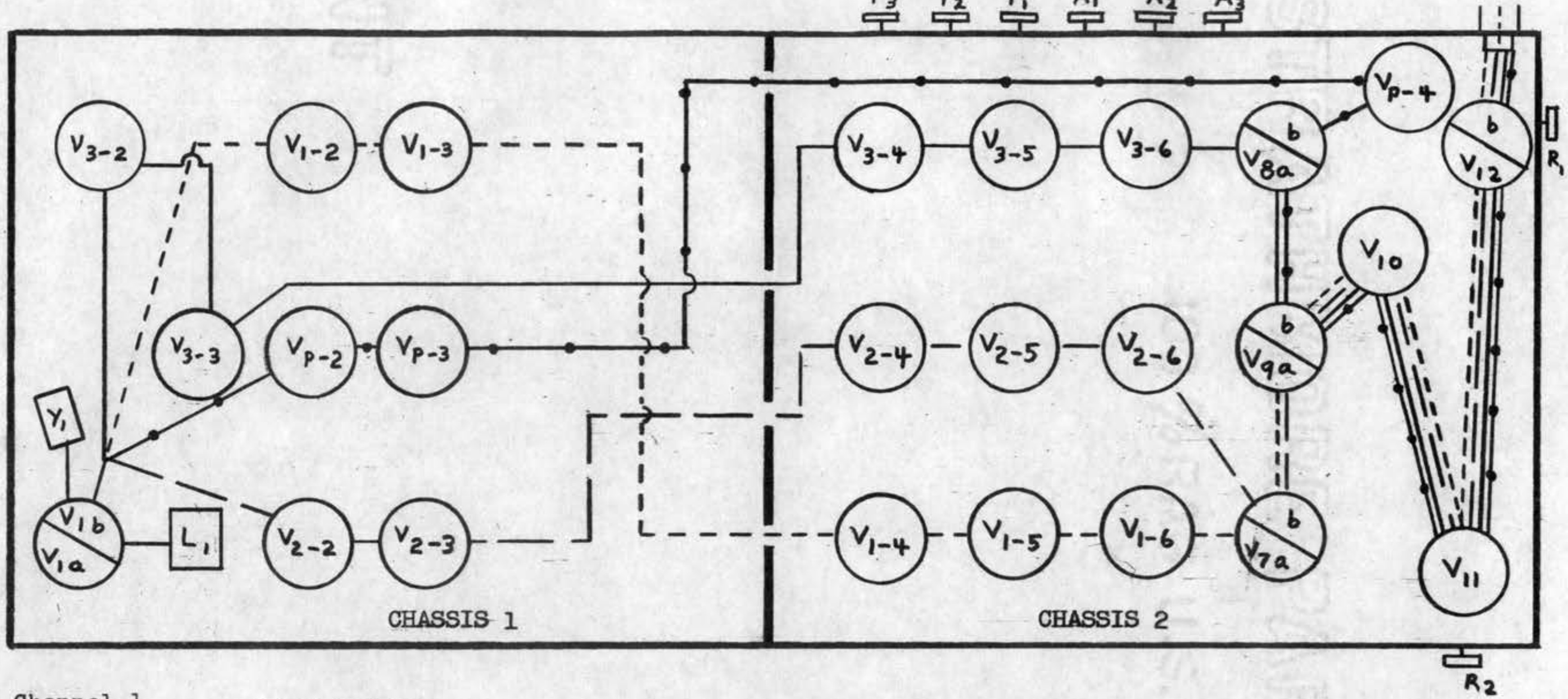


Fig. 16
PULSE MODULATION TRANSMITTER
BLOCK DIAGRAM



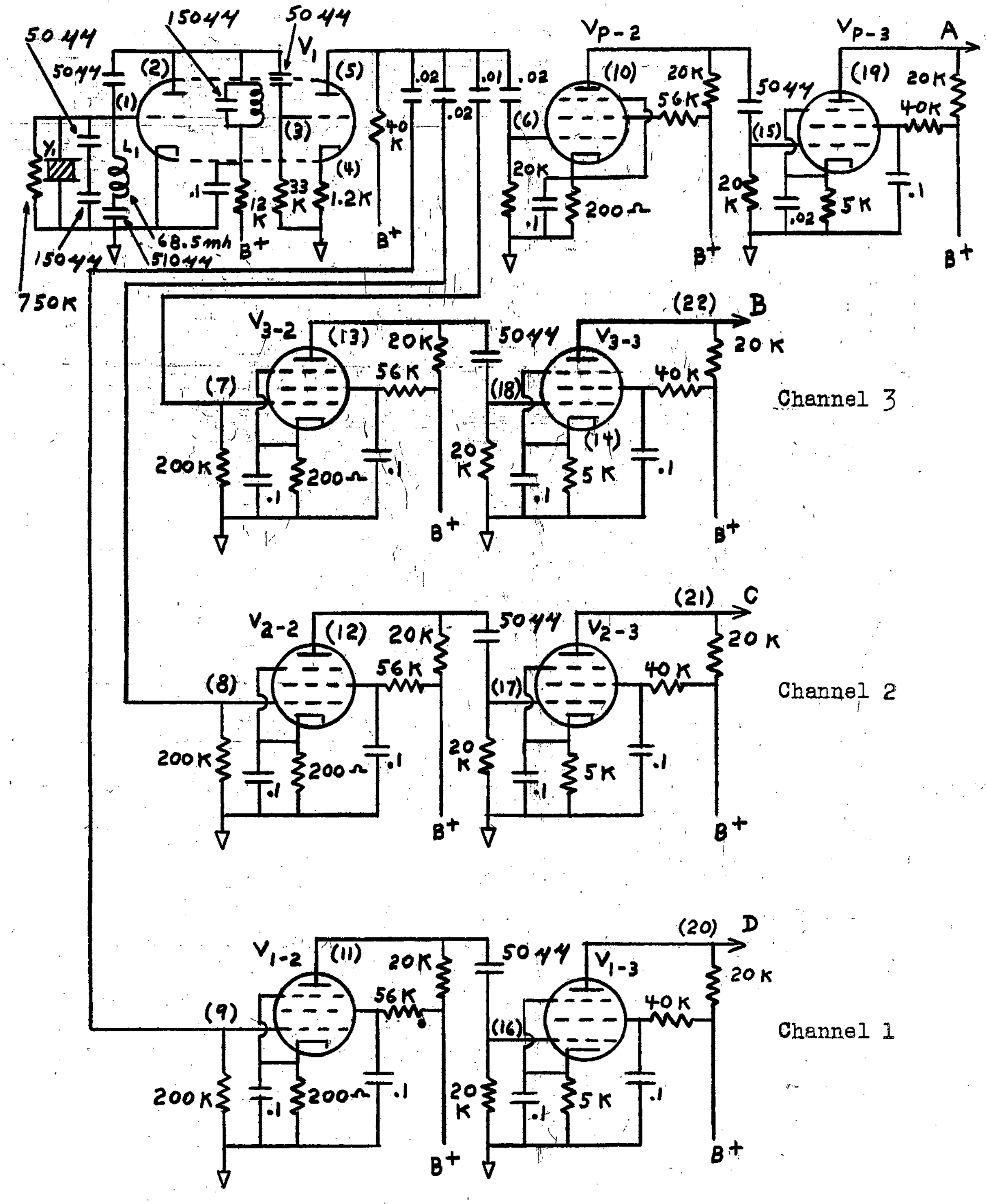
Channel 1 - - - - - -
Channel 2 — — —
Channel 3 ————
Master Pulse —•—•—

V_{p}-2, V_{p}-3, V_{p}-4, V_{1}-2, V_{1}-3, V_{1}-4, V_{1}-5, V_{1}-6, V_{2}-2, V_{2}-3, V_{2}-4, V_{2}-5, V_{2}-6, V_{3}-2, V_{3}-3, V_{3}-4, V_{3}-5, V_{3}-6, V_{10}, V_{11}, . . 6AC7

V_1, V_7, V_8, V_9, V_{12}, ... 6SN7

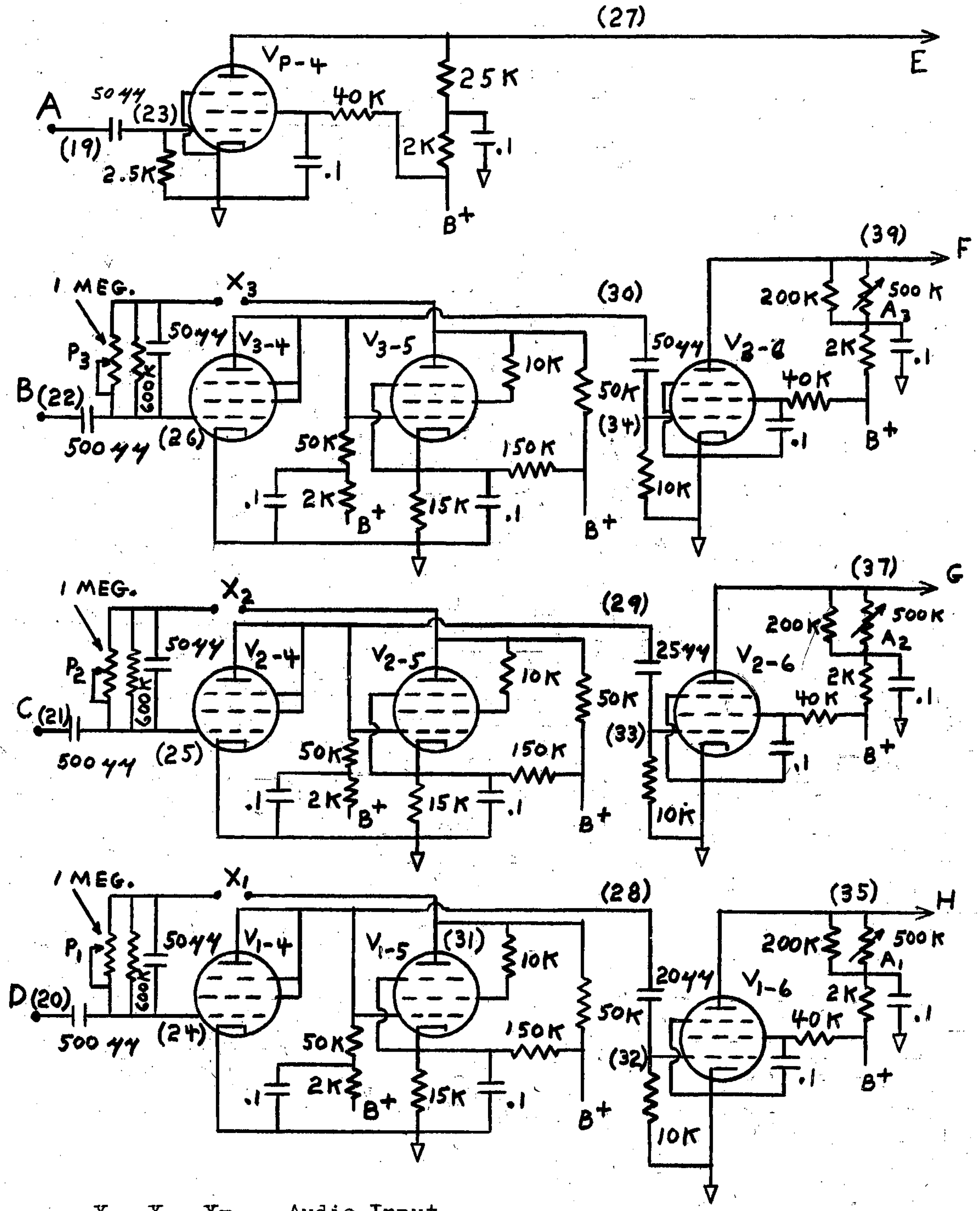
P_1, P_2, P_3, .	1 Meg.	Potentiometers for Pulse Position Control
A_1, A_2, A_3, .	500 K	Potentiometers for Pulse Amplitude Control
R_1.	10 K	Cathode Bias Potentiometer for V_{10}
R_2.	3 K	Cathode Bias Potentiometer for V_{11}
Y_1.	100 kc	Model VC-5-KS, Sr. 3442-A, Radio Corporation of America, Crystal.

Fig. 17
PULSE MODULATION TRANSMITTER
PHYSICAL LAYOUT



A, B, C, D, Connected
to A, B, C, D, of
Fig. 18-b.

Fig. 18-a
PULSE MODULATION TRANSMITTER
CIRCUIT DIAGRAM (CHASSIS 1)

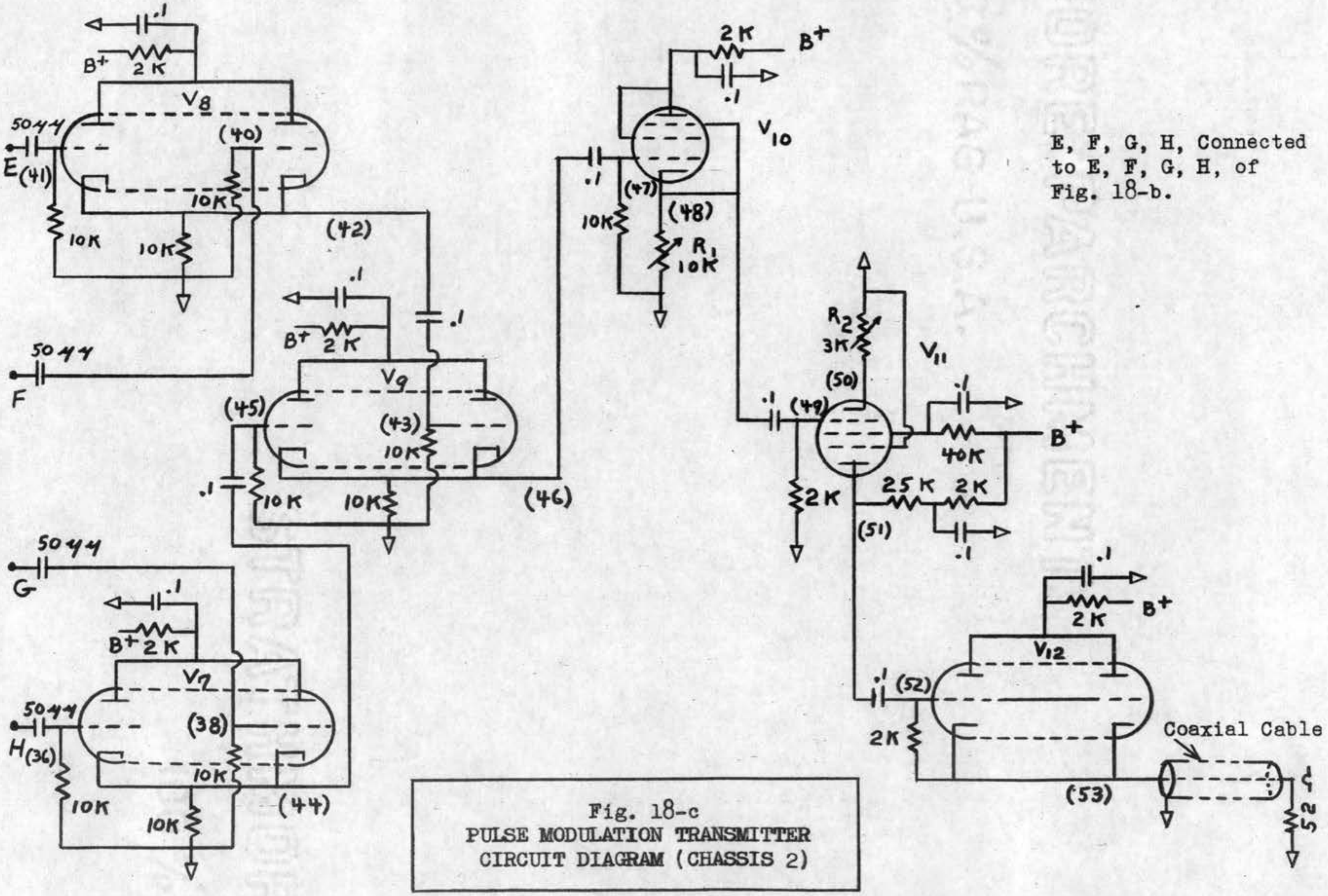


X_1, X_2, X_3, - Audio Input

A, B, C, D, Connected
to A, B, C, D, of Fig. 18-a.

E, F, G, H, Connected
to E, F, G, H, of Fig. 18-c.

Fig. 18-b
PULSE MODULATION TRANSMITTER
CIRCUIT DIAGRAM (CHASSIS 2)



E, F, G, H, Connected
to E, F, G, H, of
Fig. 18-b.

Fig. 18-c
PULSE MODULATION TRANSMITTER
CIRCUIT DIAGRAM (CHASSIS 2)

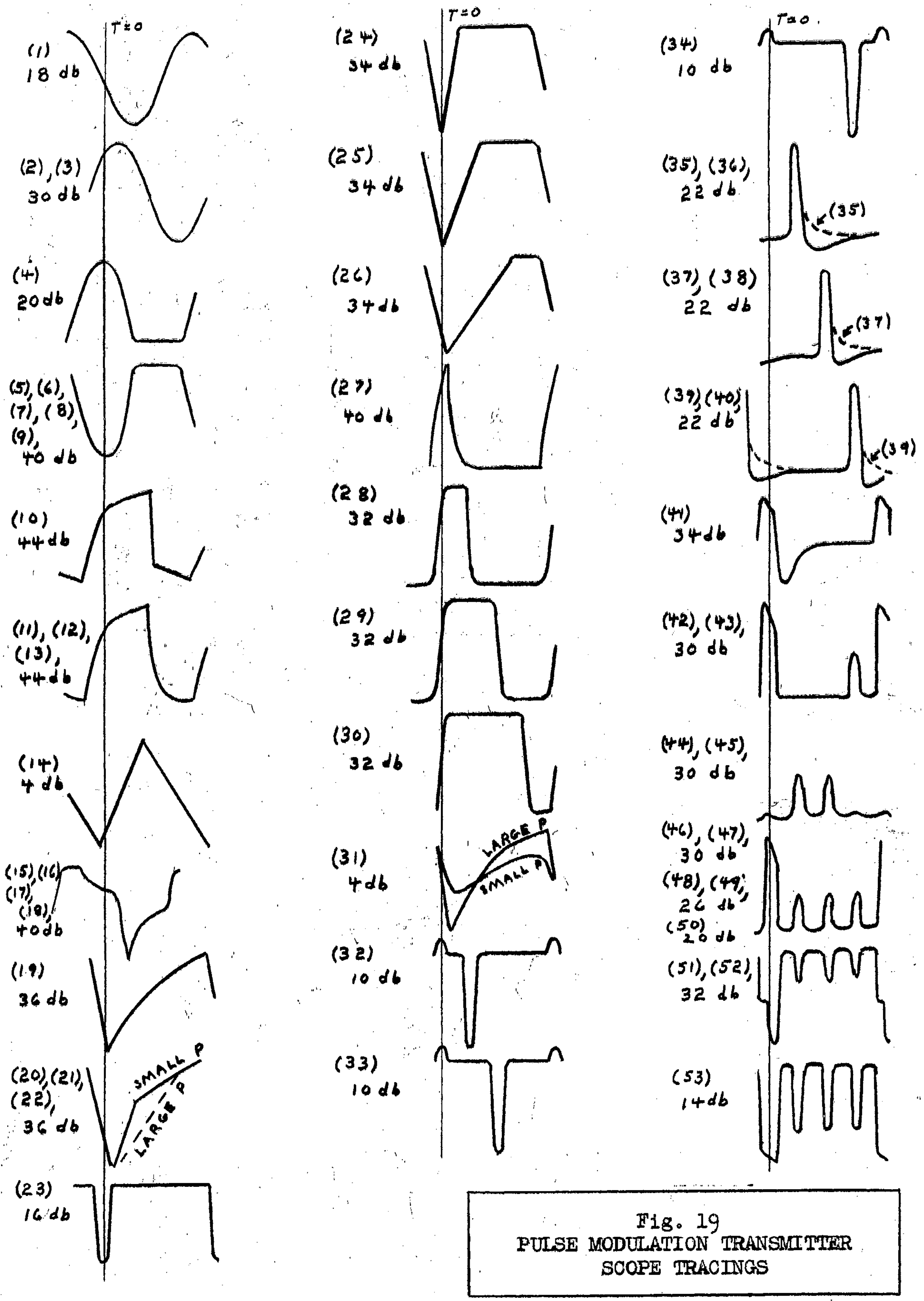


Fig. 19
PULSE MODULATION TRANSMITTER
SCOPE TRACINGS

PART IV - THE RECEIVER UNIT (GENERALIZED)

The principal operations which must be performed in a pulse-time receiver are:

1. Separation of the several channel pulse trains from the received interleaved pulse train.
2. Conversion of these separate pulse trains into a replica of the original modulating signal.

These operations are termed "demodulation." For demodulation to be properly attained, some method of synchronization must be provided in order to insure continuous detection of a given transmitted channel by a given receiver channel. In the present system, the marker pulse channel, of larger amplitutde and width than the channel pulses, is employed for synchronization. Upon reception of the interleaved pulse train from the transmitter, the marker pulse train is separated from the complete signal. This pulse train is then used to control a separating pulse generator circuit. By superimposing the interleaved pulse train input upon the output of this separating pulse generating circuit, channel separation is attained. For additional channels, this process is repeated by employing a separating pulse generator circuit for each desired receiver channel. If the output of the separating pulse generator circuit is continuously variable in time position, each of the receiver channels may be used to detect any one of the transmitted channels. The present system consists of a three channel receiver. It should be noted that this number is in no way related to the number of transmitted channels. The number of receiver channels depends upon the application to which the system is to be subjected. In certain applications only one receiving channel may be desired, while in other instances several, one for each location at which it is desired to have selectivity of the available signals, may be desired.

In the low pulse repetition rate systems previously mentioned in connection with the transmitter design, several methods of channel separation were employed in the receiver designs. The method employed in the present system will be mentioned here only in brief since this subject is to be presented in its completeness by Mr. R. D. Kelly.[1] A short discussion is necessary, however, in order to tie the writer's work on the latter stages of the receiver, into the system.

Immediately following this discussion are to be found several diagrams of the system, including a complete block diagram of the system (Fig. 20, parts a and b), a diagram of the system physical layout (Fig. 21, parts a and b), a complete circuit diagram (Fig. 22, parts a, b, c, and d), and a series of oscilloscope traces (Fig. 23). In these diagrams, the tubes has been denoted by V_{1-3}, V_{2-5}, V_{3-1}, etc. In this notation, the first number refers to the channel number while the latter refers to the position of the tube circuit in its respective channel. It should be mentioned that these numbers are in no way related to the numbers associated with the transmitter channel, since any one of the receiver channels may be used to detect any one of the transmitter channels. The receiver channel numbers are used only as a means of circuit tracing. The same tube notation has been employed in all of the diagrams in order to facilitate easy cross reference. Since the three receiver channel designs are alike in their entirety, a discussion of only one of the channels will be given. The oscillascope traces of Fig. 23, represent the results attained by use of channel 3, with proper time phase positioning for detection of the second transmitted pulse channel. Oscilloscope settings (in db.)

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[1] R. D. Kelly, <u>A Receiver for Time Modulation Pulses</u>, 1951.

have been included in order that a comparison of relative amplitudes might be made. The number associated with each of the oscilloscope traces of Fig. 23, corresponds to a particular point (marked by the same number in parenthesis) on the circuit diagram of Fig. 22. Reference should be made to these figures in connection with the following discussion.

In the present system, pulse channel separation is attained in the following manner:

1. Pulse amplification of the incoming pulse train by V_2 (waveform (3)).
2. Marker pulse separation for synchronization purposes by V_{3b} (waveform (5)).
3. Marker pulse amplification by V_{3a} (waveform (7)), in order to produce a sharp negative triggering pulse for the following delay circuits.
4. Time delay by the use of the rectangular-pulse generator, circuit $V_{3-1,2}$ (waveform (8)).
5. Differentiation of this rectangular wave in order to obtain a sharp negative pulse of controllable time position (waveform (9)).
6. Time delay from this negative pulse by use of a second rectangular-pulse generator, $V_{3-3,4}$ (waveform (11)), in order that a pedestal pulse of controllable time position and width might be produced.
7. Superposition of the amplified interleaved pulse train (the output of V_{p-1}, waveform (12)) upon this pedestal pulse by the use of V_{3-5}.
8. Separation of the desired channel pulse train by the proper time positioning of the pedestal pulse (waveform (13)).

The circuit of tube V_{3-5} is so designed that the interleaved pulse train when applied to the control grid of the tube, will produce no output voltage. This is achieved by placing a large bias upon the tube. By applying one of the pedestal pulses, of controllable position and width, to the screen grid of the pentode tube, the effect of the large bias can be overcome during a fractional portion of each frame. The duration of this time is controlled by the arbitrary width at which the pedestal pulse is set. If now the time position of the pedestal pulse is made exactly equal to that of the desired channel pulse, and the time duration of the pedestal made only slightly larger than the channel pulse width (sufficient to cover the time deviation of the pulse when modulated), proper channel separation will result. The bias placed on the tube must be large enough to prevent any output voltage due to tube current flow which might otherwise result, due to the pedestal pulse occurrence. In this manner only the desired positive channel pulse (the pulse which has been superimposed upon the pedestal pulse) will cause plate current to flow, and an output voltage to be developed. Clipping of the undesired channels and the pedestal pulse is thus produced. The output voltage of V_{3-5} (waveform (13)), is a time modulated negative pulse containing all of the intelligence of the desired channel.

At this point in the system design, channel separation has been attained. The second function of the receiver (conversion of this separated pulse train into a replica of the original modulating signal) must now be performed. In the receiver design, the circuits V_{3-6}, V_{3-7}, and V_{3-8}, are in no way employed in this process, but are used for amplification purposes following channel separation. The actual conversion process takes place in the multivibrator circuit $V_{3-9,10}$ and those circuits which follow it.

In the transmitter design of PART III, modulation was achieved by causing the trailing edge of a rectangular-pulse generator output wave, to vary in accordance with the modulating signal. In the present detection process, the inverse of this is performed. The desired time-modulated channel pulse train is converted into a train of rectangular pulses, one edge of which is time modulated in accordance with the intelligence of the channel. Since the area of succeeding pulses in such a train, changes in accordance with the desired signal, integration of the wave train will give the desired audio signal. The rectangular pulse train is produced by a circuit modification of the rectangular-pulse generator of paragraph 7., PART II. The circuit is denoted by V_{3-9} and V_{3-10} in Fig. 22-c. For this circuit, the required negative triggering pulse train is that of the desired time modulated channel pulse (the output of V_{3-5} after amplification by V_{3-6} and V_{3-8}). This triggering pulse is shown by waveform (18) in Fig. 23. If no other provisions were made, a rectangular pulse would result with both the leading and trailing edges time modulated. This would be caused by the fact that the discharge time of the RC circuit in the grid of V_{3-9}, is constant regardless of the instant of circuit triggering. Thus, if the triggering pulse is time modulated, the occurrence of the trailing edge of the rectangular pulse (the time at which rest conditions return to the circuit) will also be time modulated. If these conditions were to prevail, the area of succeeding pulses would be equal, and integration would result in no audio output voltage. If proper results are to be attained, it will be necessary to cause one of the rectangular pulse edges to remain constant in time position. This is accomplished by feeding a large negative pulse of constant time position to the grid of V_{3-10}. Such a pulse causes V_{3-10} to cease conduction, V_{3-9} to again conduct, and rest conditions to return to the circuit. However, rest conditions now return to the circuit at the same time position in succeeding frames, provided the controlling pulse applied to the grid of V_{3-10} occurs at a constant time position. Care must be taken to insure circuit action which is the result of this negative controlling pulse, and not that which would result from the discharge of the RC tank in the grid of V_{3-9}. This is easily accomplished by making this RC time constant sufficiently large to hold the circuit in its unstable condition for a considerable portion of each frame. The occurrence of the controlling pulse will then precede the instant at which the RC tank would cause rest conditions to return to the circuit. The controlling pulse train of constant time position is produced by:

1. Separation of the marker pulse train from the interleaved pulse train input, by use of the limiter V_{p-2}.
2. Amplification by V_{p-3} and V_{p-5} to produce a large amplitude negative pulse.

The pulse train thus produced is of necessity constant in time position since it has been derived from the equally time spaced marker pulses. The resulting output wave of the multivibrator is shown by waveform (19) of Fig. 23. The leading edge of the rectangular wave is time modulated while the trailing edge is constant in time position. Integration of this waveform will give a replica of the audio modulating signal.

The integrating circuit selected for the present system consists of the 150,000 ohm 50 $\mu\mu f$. resistance-capacitance combination shown in Fig. 22-c, immediately follwoing V_{3-10}. As explained in paragraph 4. of PART II, the RC time constant of this circuit must be made large if the voltage developed across the capacitor is to approach the time integral of the input voltage to a good degree. In opposition to this requirement of the time constant, is the fact that the attainable high frequency response of such a circuit, decreases with an increase in the RC time constant. This is caused by the reduced reactance of the capacitor at the higher frequencies. In the present system, a relatively large RC time constant was employed. The audio voltage thus developed across the capacitor thus approaches the time integral of the input wave to a good degree. However, some type of compensating circuit is required if the higher frequencies of the audio signal are to have an amplitude equal to that of the lower frequencies. Compensation is provided by the voltage divider circuit which immediately follows the integrator circuit. This circuit is composed of a 500,000 ohm resistor in parallel with a 150 $\mu\mu f$. capacitor and a 500,000 ohm resistor to ground. At very low frequencies the capacitor has little effect upon the circuit due to its large reactance. At the higher frequencies, the reduced reactance of this capacitor will cause the series impedance of the circuit to be reduced. In so doing, a larger portion of the input voltage will be developed across the 500,000 ohm resistor to ground. Since this circuit has a frequency response which increases with frequency, proper circuit design will cause a compensation of the intergrators frequency response.

In the signal conversation system designed by Mr. R. D. Kelley, [2] a "flip-flop" type of multivibrator circuit was employed to produce the desired time modulated rectangular pulse train. This type of multivibrator proves slightly more economical in circuit requirements since two less tubes and circuits are required. Only three tubes are required for the multivibrators (in terms of the present three channel system), and the circuits of V_{p-4} and V_{p-5} (required for pulse amplification and inversion), are no longer necessary. However, three diode circuits are required to isolate the multivibrators from the channel selector (pedestal generator) circuits. Thus a saving of two tubes is achieved. If

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[2] Ibid.

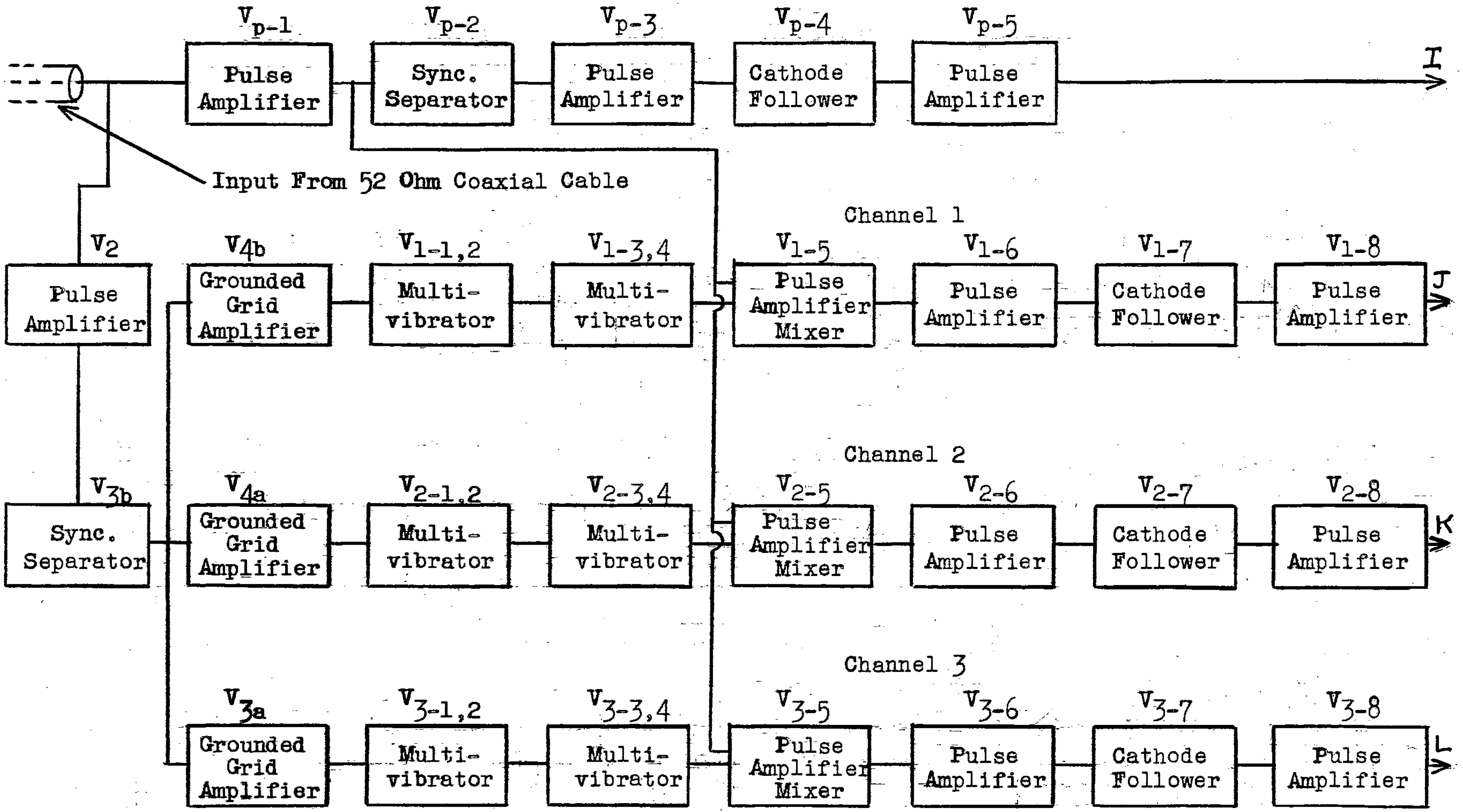
additional channels were later to be desired, the same number of tubes would be required for each additional channel, regardless of the system design employed. The chief advantage of the present system is that no circuit adjustments are required when a change in channel selection is made. The time position of the pedestal pulse selector can be properly set for detection of any of the transmitted channels without any multivibrator adjustments being required. With the use of the flip-flop type multivibrator circuit, adjustments are required with a change in channel pulse selection. Other characteristics of the two circuits are approximately the same. The operating characteristics of the flip-flop multivibrator circuit will be found in the reference cited above.

The remainder of the present system design consists of circuits for audio amplification and removal of the undesired high frequency components of the rectangular-pulse generator output. This rectangular pulse is composed of a 100 kc. sine wave (the pulse repetition rate being 100 kc.) and many harmonics of this frequency. Attenuation of these frequencies is produced by a low-pass "pi" type filter and two "bridge" type filters. These filters are found immediately following the cathode-follower V_{3-11}. The cathode-follower is employed to allow the filters to work from a low impedance source. It must be mentioned at this point in the system development, that the basic timing frequency of the system changed due to an overloading condition on the transmitter oscillator circuit. This overload condition caused the crystal to lose control of the circuit and the oscillator frequency to shift to 78 kc. Without knowledge of this shift in the pulse recurrence rate, the above mentioned filters were designed, and data taken on the system operation. It was during this testing of the system that the shift in oscillator frequency was detected.

However, no correction was at that time attempted. If the 100 kc. pulse repetition rate had been resumed, a complete redesign of the filters would have been necessitated, and a rerun of the system operating conditions made. Rather than make these changes, the 78 kc. pulse repetition rate was employed throughout the remainder of the system testing since such a value proves more than satisfactory for a high-fidelity system. This change in the system base frequency should be remembered in connection with the system results given in PART V. The circuit components of the oscillator shown in Fig. 18-a (circuit V_1), are for a 100 kc. output. The overload comdition was produced by the use of a 250 μμf. rather than the 50 μμf. coupling capacitor shown in the grid current of the buffer amplifier.

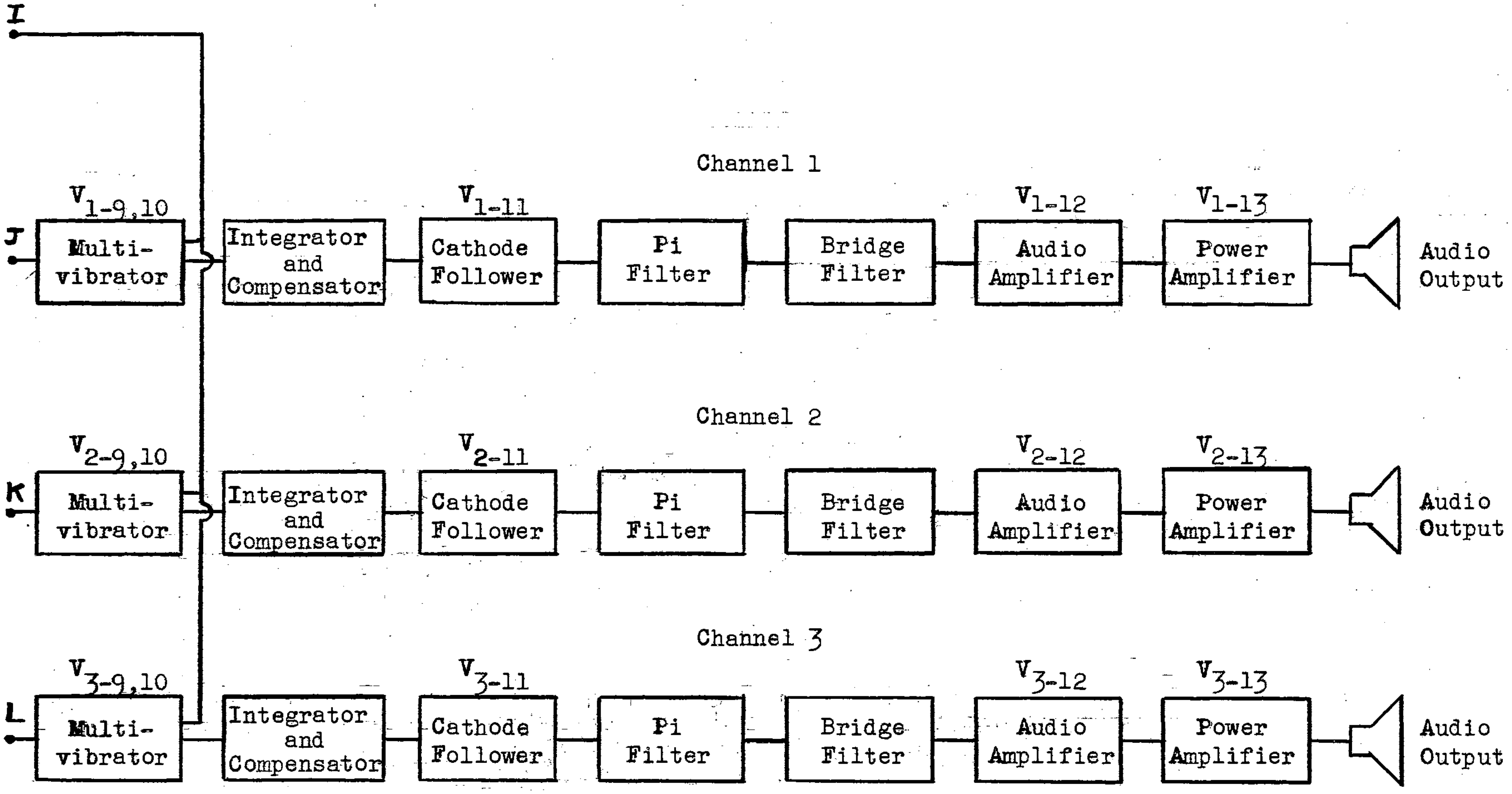
In the present design, the "pi" filter has a cutoff frequency of 78 kc. The following bridge filters have been designed for attenuation of the pulse repetition frequency (78 kc.), and the third harmonic of this frequency (234 kc.). These bridge type filters proved quite satisfactory since they have an attenuation of approximately 60 db. Attenuation is attained by resonance of a parallel capacitor and inductor arrangement (Fig. 22-d). The degree of attenuation as well as the band width of frequency which is attenuated, is controlled by the variable resistor arrangement from the center of the capacitive branch to ground.

Upon the attainment of proper filtering, audio amplification must be provided. This is provided by the voltage amplifier V_{3-12} and the power amplifier V_{3-13} (Fig. 22-d). Volume control is attained by variation of the potentiometer arrangement in the grid circuit of the voltage amplifier. The 500,000 ohm resistor immediately above the potentiometer is necessary in order to prevent overloading of the filter circuits. The audio output of V_{3-13} is fed by way of an audio transformer to the loud-speaker. This system of audio amplification and high frequency elimination represents only one of many designs which might have been employed. Although it proves quite satisfactory, there are undoubtedly many improvements which might be made in the audio section of the receiver in order to achieve more failthful signal reproductions. These requirements were not considered necessary in this experimental receiver.



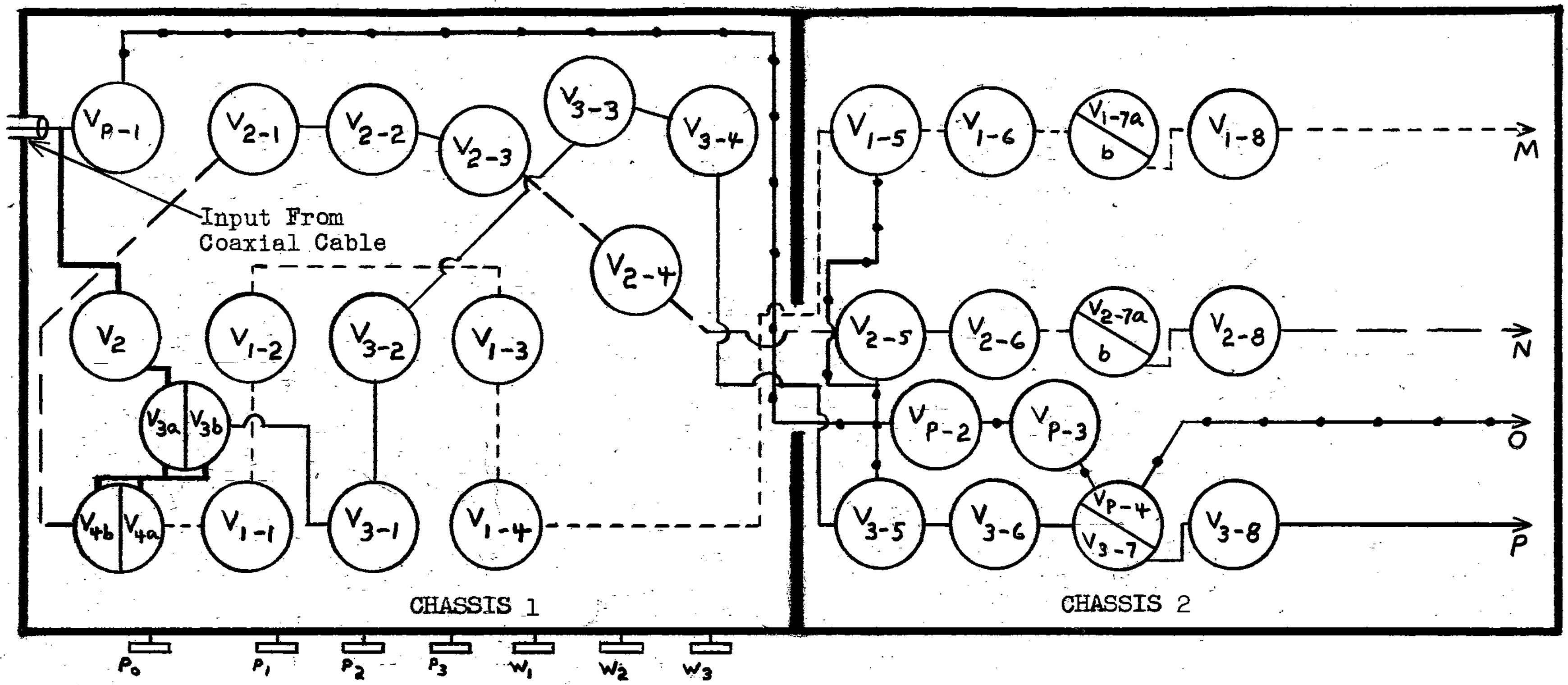
I, J, K, L, Connected
to I, J, K, L, of Fig. 20-b.

Fig. 20-a
PULSE MODULATION RECEIVER
BLOCK DIAGRAM



I, J, K, L, Connected
to I, J, K, L, of Fig. 20-a.

Fig. 20-b
PULSE MODULATION RECEIVER
BLOCK DIAGRAM



Channel 1 - - - - - - - -
Channel 2 —— —— ——
Channel 3 ————————
Master Pulse —●——●——●—

P_0. . . . . . 3 K Potentiometer for Sync. Control
P_1, P_2, P_3, . 1 Meg. Potentiometers for Pedestal Position Control
W_1, W_2, W_3, . 500 K Potentiometers for Pedestal Width Control

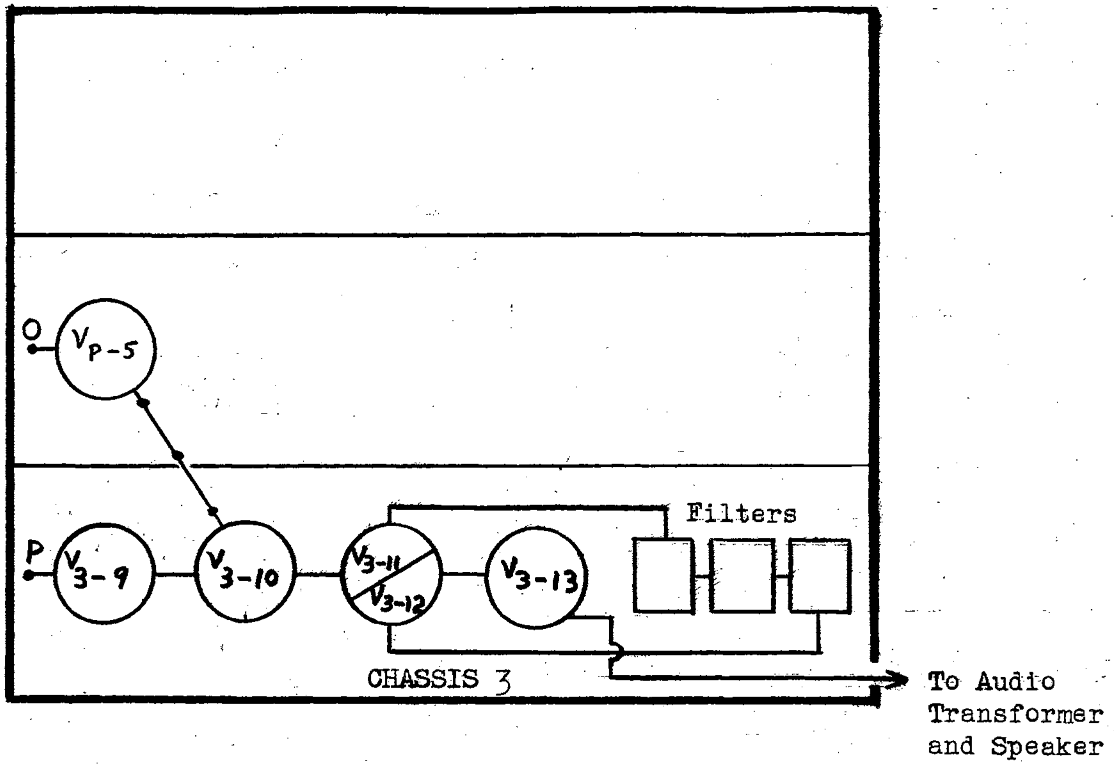
O, P, Connected to O, P, of Fig. 21-b.

V_{p-1}, V_{p-3}, V_2 , V_{1-1}, V_{1-2}, V_{1-3},
V_{1-4}, V_{1-5}, V_{1-6}, V_{1-8}, V_{2-1}, V_{2-2},
V_{2-3}, V_{2-4}, V_{2-5}, V_{2-6}, V_{2-8}, V_{3-1},
V_{3-2}, V_{3-3}, V_{3-4}, V_{3-5}, V_{3-6}, V_{3-8}, . . 6AC7

V_3 , V_4 , V_{1-7}, V_{2-7}, V_{3-7}, V_{p-4}, . . 6SN7

V_{p-2}, ... 6J5

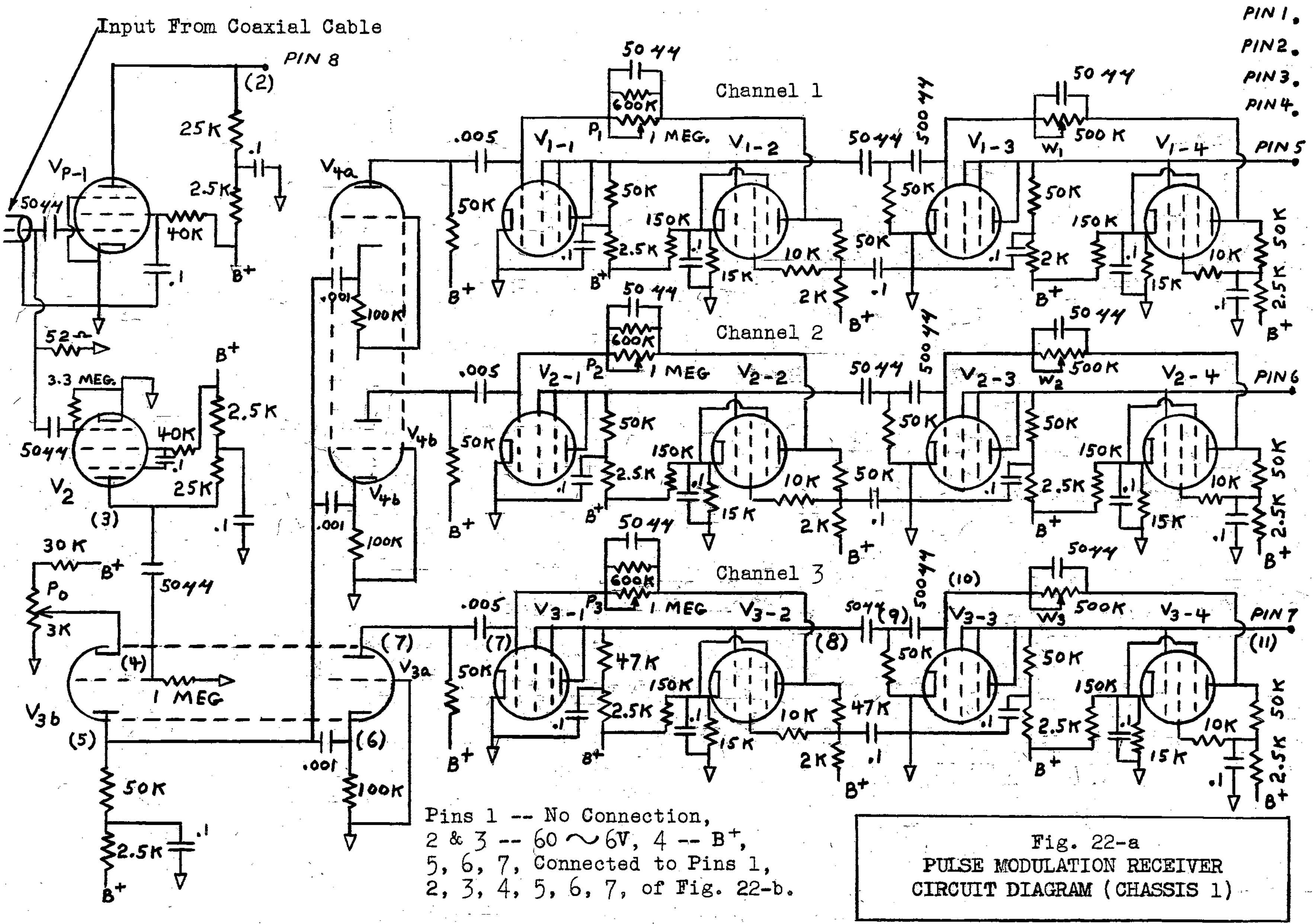
Fig. 21-a
PULSE MODULATION RECEIVER
PHYSICAL LAYOUT (CHASSIS 1 & 2)



O, P, Connected to O, P, of Fig. 21-a.

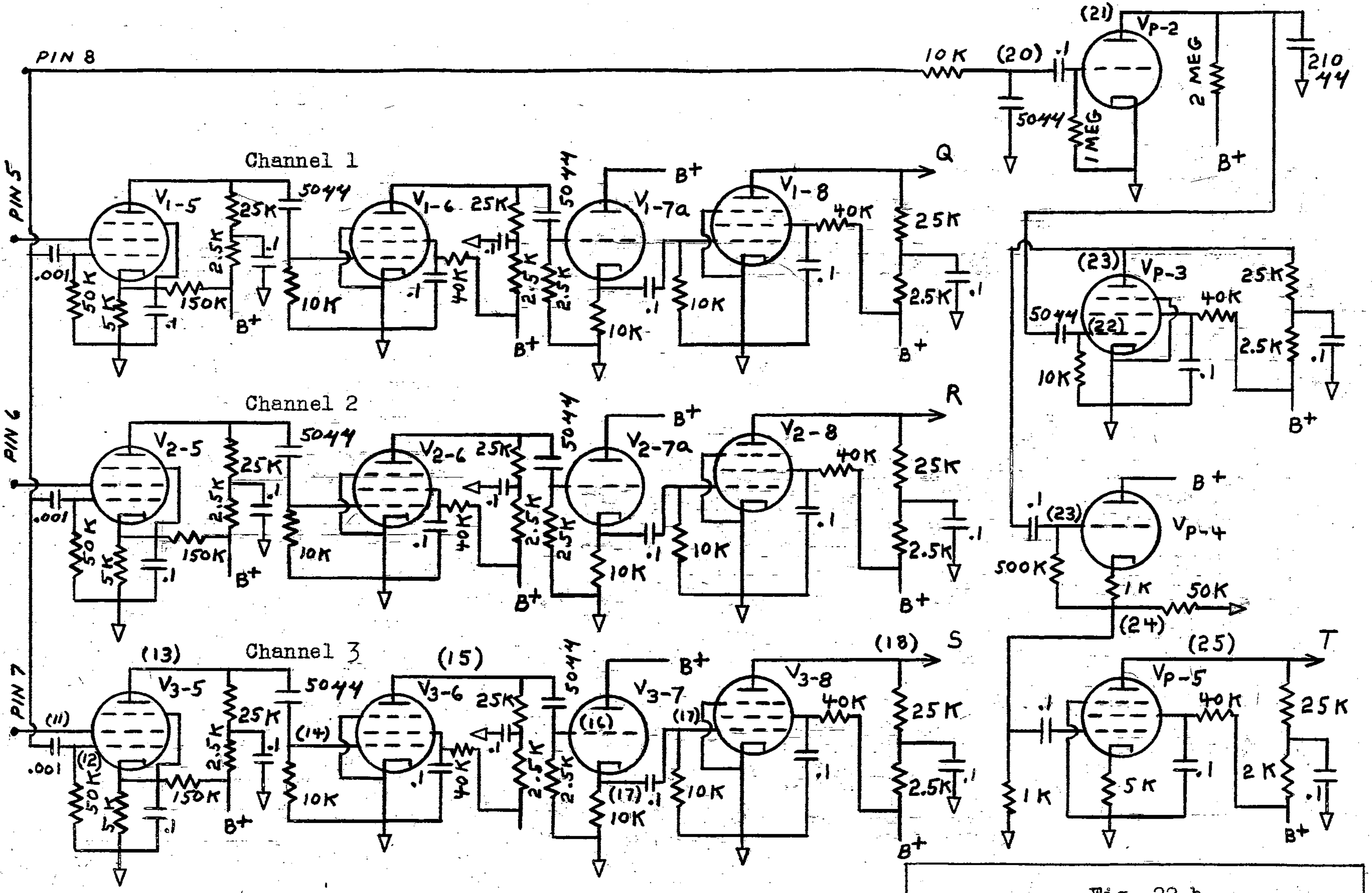
V3-9, V3-10, Vp-5, . . 6AC7
V3-11, V3-12, ... 6SN7
V3-13, ... 6V6

Fig. 21-b
PULSE MODULATION RECEIVER
PHYSICAL LAYOUT (CHASSIS 3)



Pins 1 -- No Connection,
2 & 3 -- 60 ~ 6V, 4 -- B+,
5, 6, 7, Connected to Pins 1,
2, 3, 4, 5, 6, 7, of Fig. 22-b.

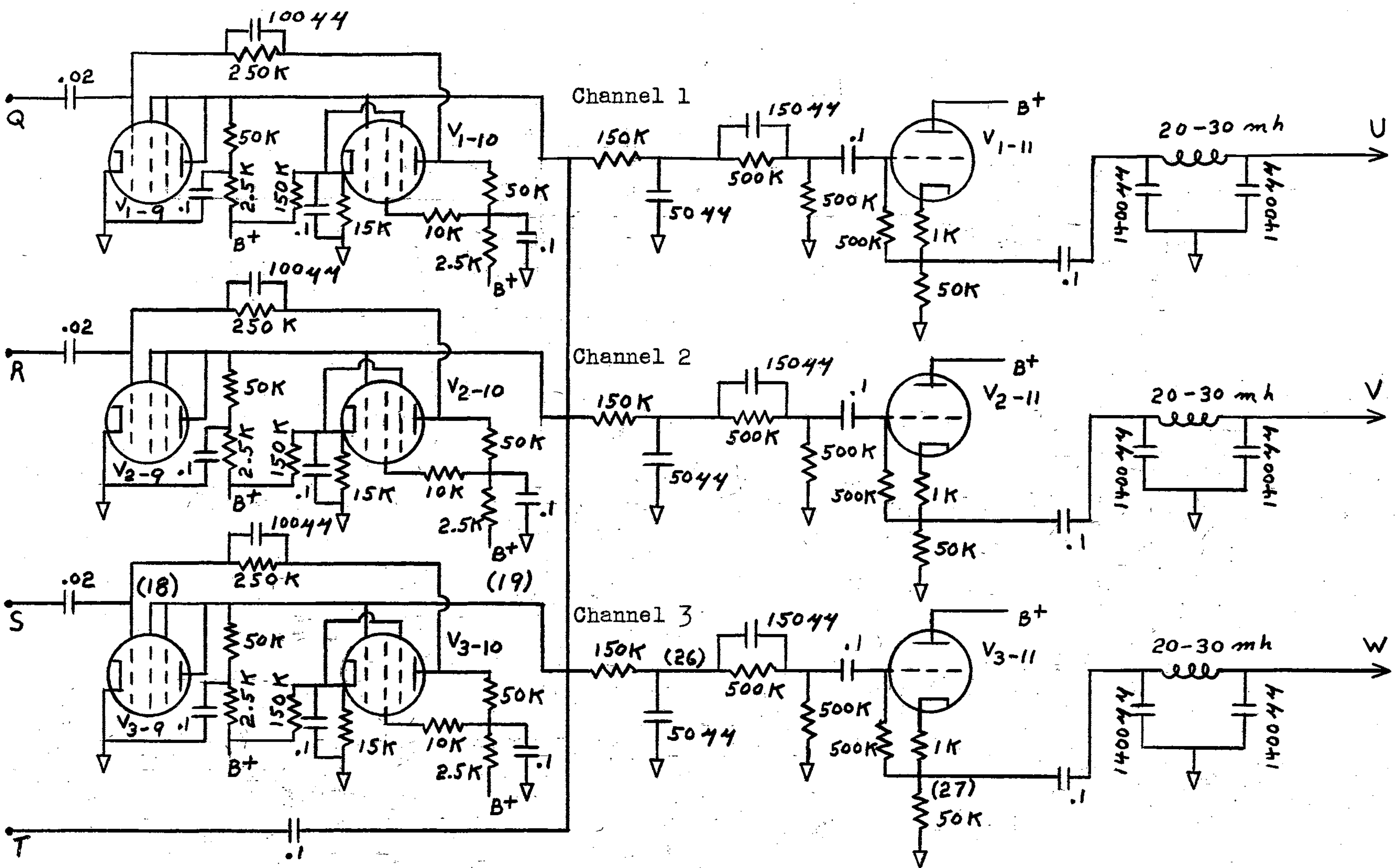
Fig. 22-a
PULSE MODULATION RECEIVER
CIRCUIT DIAGRAM (CHASSIS 1)



Pins 1, 2, 3, 4, 5, 6, 7, 8, Connected to Pins 1, 2, 3, 4, 5, 6, 7, 8, of Fig. 22-a.

Q, R, S, T, Connected to Q, R, S, T, of Fig. 22-c.

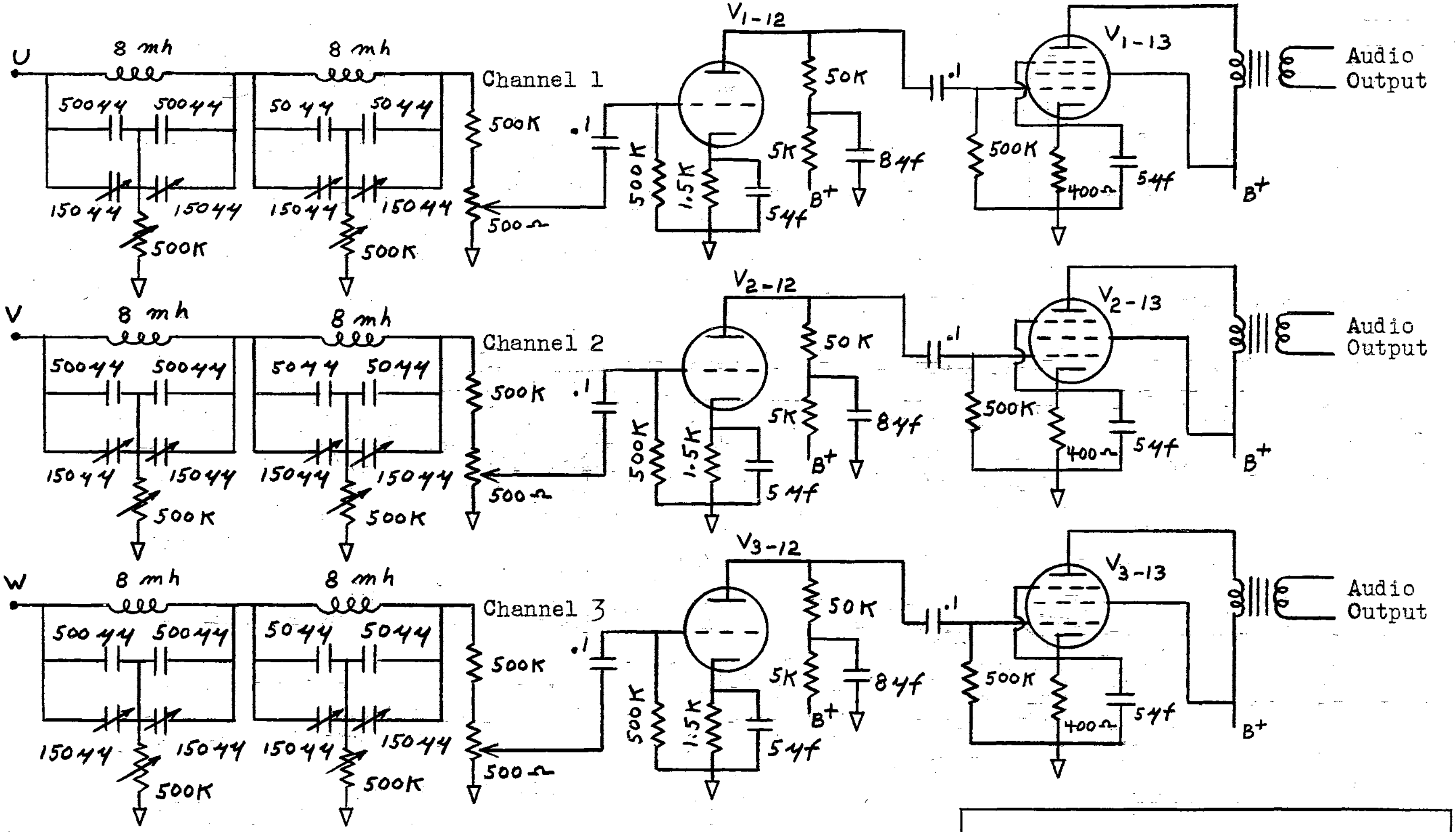
Fig. 22-b
PULSE MODULATION RECEIVER
CIRCUIT DIAGRAM (CHASSIS 2)



Q, R, S, T, Connected to Q, R, S, T, of Fig. 22-b.

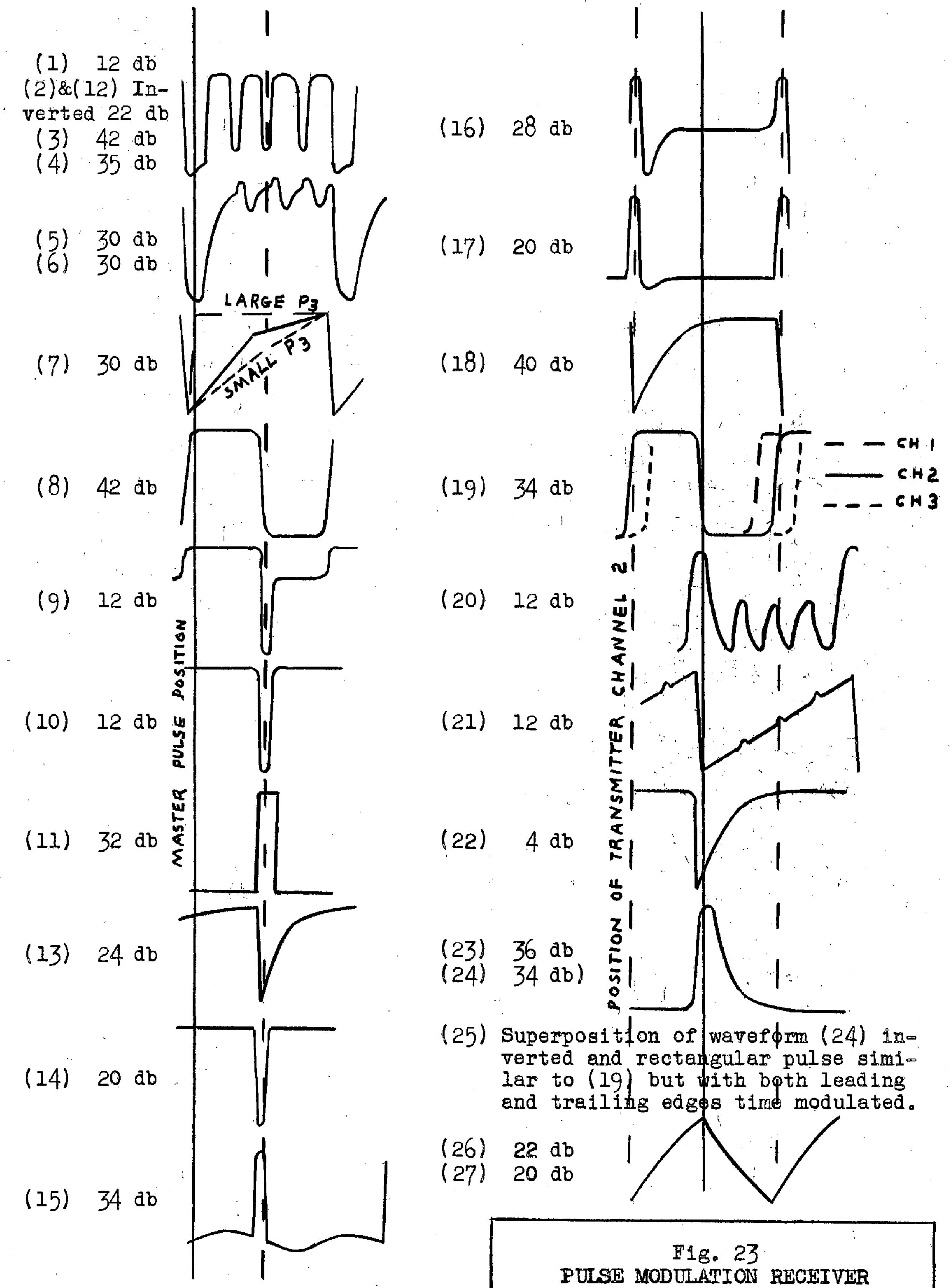
U, V, W, Connected to U, V, W, of Fig. 22-d.

Fig. 22-c
PULSE MODULATION RECEIVER
CIRCUIT DIAGRAM (CHASSIS 3)



U, V, W, Connected to U, V, W, of Fig. 22-c.

Fig. 22-d
PULSE MODULATION RECEIVER
CIRCUIT DIAGRAM (CHASSIS 3)



(25) Superposition of waveform (24) inverted and rectangular pulse similar to (19) but with both leading and trailing edges time modulated.

Fig. 23
PULSE MODULATION RECEIVER
SCOPE TRACINGS

PART V - RESULTS AND PROPOSED INPROVEMENTS OF THE PRESENT SYSTEM

The purpose of the present study has been the construction and testing of a high-fidelity pulse-time modulation system employing a co-axial transmitting medium. The system was constructed with as many parameters variable as practicability would allow. Such a system readily lends itself to the study of factors effecting fidelity, signal-to-noise ratio, cross talk, and other pertinent operating characteristics. A high pulse repetition rate was selected in order that a frequency response greatly improved over the results attained in previous studies of this type, might be realized.

In any time-division multiplexing system, such as the present, the number of transmittible channels decreases with an increase in the pulse repetition rate, i.e., a decrease in time between successive marker pulses. The number of allowable channels (for a given cross talk ratio) is also decreased with an increase in build-up or decay time of the channel pulses. Since the pulse repetition rate of the present system was set for the attainment of a desired system frequency response, it is no longer a controlling factor in the number of transmittible channels which may be realized. However, the build-up and decay time of each channel pulse is a controlling factor and must, therefore, be made as short as possible (if the number of channels is to be large). By so doing, the signal-to-noise ratio will also be improved since it is the sloping portion of the pulse which contains the noise (the pulse amplitude variations or noise having been removed or clipped from the upper and lower (horizontal) portions of the pulse). If an infinite slope could be realized, no noise would be present on this portion of the wave. In opposition to this desired effect is the fact that frequency bandwidth requirements increase with a decrease in the pulse build-up and decay time. Since increased bandwidth requirements impose no problems in the present system, the transient time of rise and decay of the pulses was made as short as possible. Transient rises and decays of the order of 0.1 μs. were attained. In so doing, channel pulse widths of approximately 0.6 μs. resulted. The marker pulse width was arbitrarily set at one-tenth the time duration of each frame or 1.28 μs. (the pulse repetition rate being 78 kc. gives a frame duration of 12.8 μs.).

The system channel pulses have been made continuously variable in time position. They may also be set at any fractional amplitude of the marker pulse amplitude. It is estimated by the writer, that five additional channels (eight channels in all) might be added to the transmitter, if desired. In making this estimate experimental results were used, attained by crowding the three existing channel pulses into a small time portion of the frame. The estimate is made on the basis of a 0.2 μs. guard time between modulated channel pulses. This is to prevent objectionable across talk between channels. A total pulse time deviation of 0.6 μs. or 0.3 μs. to either side of the mean channel pulse position was considered as one-hundred percent modulation. This modulation index proves satisfactory in that no overloading of the audio modulator circuit resulted (the transfer of audio energy from the source through the modulator and into the transmitter was found to be flat in frequency response to well above 30 kc). Such an index is also quite easily visualized with the aid of an oscilloscope since the total apparent pulse width will be exactly twice (1.2 μs. in this particular case) that of the pulse with no modulation present. A larger channel pulse-time deviation would have proven more desirable in connection with the overall system signal-to-noise ratio, but would have resulted in a decrease in the number of transmittible channels. If the number of transmitted channels were to be held constant, an increase in the degree of modulation would cause a decided increase in the cross talk ratio. It is the purpose of guard time between channels to prevent cross talk, should a modulating signal slightly greater than one-hundred percent be applied.

Although the present transmitter system proves satisfactory, there are undoubtedly many modifications which might improve both its operating characteristics and economy of construction. In PART III, a method was proposed whereby the negative triggering pulses, for the marker pulse channel and the several channel pulse delay circuits, might all be generated by the same wave-shaping unit. Such a practice would eliminate the first two tubes ($V_{1-2,3}$, $V_{2-2,3}$, and $V_{3-2,3}$ of Fig. 18-a) of each channel. A thorough study of pulse-time modulation systems will suggest other possible methods of improvement.

The present pulse-time receiver consists of three independently selective channel demodulators. It is the purpose of each of these demodulators to have complete selectivity of the several transmitted channels and in so doing, maintain a large signal-to-noise ratio, small signal distortion, and small cross talk ratio. The degree with which these requirements are satisfied is indirectly dependent upon the build-up and decay time of the selector pedestal pulses. The actual transient time of the pedestal pulses does not effect the selectivity of the system since the pedestal is clipped (one of the operations of V_{3-5} of Fig. 22-b) from the desired signal. However, it is directly related to the selectivity in that it controls the sharpness of the pedestal pulse corners. Sharp corners are required if amplitude variations of the selected time modulated pulse are to be prevented. The upper portion of the pedestal pulse must be entirely horizontal if amplitude variations are to be prevented. Should they result, an additional circuit would be required for amplitude clipping of the selected channel pulse. Sharp pedestal pulse corners also prevent elevation of adjacent channel pulses to a point where clipping will no longer entirely eliminate them (cross talk will result). The circuits employed resulted in transient build-up and decay times of less than 0.1 μs. Experimental results (achieved by crowding the existing channels into a small portion of the total time duration of each frame) indicate that the present demodulator design proves entirely adequate for proper separation of the maximum number of properly transmittible channels. This would indicate that the present system is entirely capable of transmission and proper demodulation of eight interleaved and time modulated channels. Conditions existing during the receiver tests were the same as mentioned in connection with the transmitter testing. They are:

1.	Channel pulse duration	0.60 μs.
2.	Marker pulse duration	1.28 μs.
3.	Total time deviation of channel pulse for 100 % modulation	0.60 μs.
4.	Guard time between channel pulses	0.20 μs.

The results attained were:

1.	Signal-to-noise ratio	45 db.
2.	Signal-to-cross talk ratio	38 to 42 db.
3.	Harmonic distortion	2.0 %

In these tests, the demodulator output voltage was taken as the output of the voltage amplifier V_{3-12}. The power amplifier V_{3-13} was not included in the tests. In connection with "square wave" testing of the system, a 2,000 cps. audio square wave was found to be transmitted and faithfully reproduced by the receiver. At frequencies above this value rounding of the square wave corners resulted. The above signal-to-noise ratio can be directly increased by increasing the modulation index but this would of necessity result in a decrease in the number of transmittible channels if the same cross talk ratio is to be maintained. Additional clipping of the time modulated channel pulses would also improve this ratio. The signal-to-cross talk ratio can be improved by the allowance of a large guard time between channels. However, such a provision will again necessitate a reduction in the number of channels tranmitted. Harmonic distortion can be decreased by increasing the ratio of the pedestal pulse width to the total time deviation of the modulated channel pulse (additional insurance that the total time deviation of the channel pulse is less than the pedestal pulse width). Such a practice will, however, increase the cross talk ratio unless the number of transmitted channels is reduced. Thus it is seen that channel pulse spacing for fewer transmitted channels will result in an improvement of all the above stated system operating characteristics.

As previously mentioned in connection with the demodulation process (PART IV), there are undoubtedly many improvements which might be made in connection with the conversion of the channel pulse intelligence into a replica of the modulating signal. The use of electronic integrator circuits in the rectangular pulse integration process, might prove desirable. Improvements in the filters and audio amplifiers might improve frequency response, noise characteristics, and system economy. Experimental results, however, proved that the over-all frequency response of the present system is flat within 3 db. (a level within which the human ear can essentially detect no intensity difference) from 30 cps. to 25 kc. The actual frequency response was found to extend above 25 kc. (within 3 db.), but the noise content of the signal becomes prohibitively large in this region. At the lower audio frequencies, pulse sampling in the transmitter is so rapid that no appreciable change in the audio signal occurs between two successive sampling pulses. The audio signal is thus transmitted with full fidelity and the integrator or storage action inherent to the "low-pass" frequency characteristics of the receiver, is capable of good signal reproduction. In connection with the higher audio frequencies, however, the number of samples per audio cycle is of necessity reduced (an inherent operating characteristic of a pulse sampling system). Full intelligence is no longer transmitted and the demodulator has difficulty in proper reproduction of the modulating signal. It is this fact which produces the undesirable results at audio frequencies above 25 kc. The system operating characteristics would no doubt be improved should additional filters be designed and placed in the system, to remove all frequency components above 25 kc. Such a practice would decrease the noise inherent to the system.

It should be mentioned in conclusion, that many system modifications and additions might be made. The possibility of system conversion to pulse-width or pulse-amplitude modulation has in no way been tested. Such a conversion could in all probability be very easily made. System tests could be made employing the originally selected 100 kc. pulse repetition rate instead of the present 78 kc. value. A comparison of the improvement in over-all frequency response could be made. The degree of change of the other system operating conditions would also be on interest.

The audio section of the demodulator could also be greatly improved. Although these several improvements might be made, the present system has proven its applicability to high fidelity pulse communication by means of a coaxial cable transmission medium.

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