A LINEARITY COMPENSATOR FOR THE PAM-FM TELEMETERING SYSTEM

by

JOHN ALBERT GAUTRAUD

S.B., Massachusetts Institute of Technology

1946

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

AT

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1950

Signature Redacted

Signature of Author: ______________________

Certified by: ______________________

Department of Electrical Engineering

Signature Redacted

____

Thesis Supervisor, January 14, 1950

Signature Redacted

____

Chairman, Departmental Committe on Graduate Students

E E
Thesis
1950

January 14, 1950

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Professor Newell:

In accordance with the regulations of the faculty, I hereby submit a thesis entitled "A Linearity Compensator for the PAM-FM Telemetering System," in partial fulfillment of the requirements for the degree of Master of Science.

Very truly yours,

JOHN ALBERT GAUTRAUD

ACKNOWLEDGMENT

The author wishes to express his thanks to Professor W. H. Radford for supervising the thesis and to J. P. Chisholm and G. W. Farnell for valuable help on the switching circuits of Chapter II.

TABLE OF CONTENTS

ABSTRACT

One of the most expensive and time-consuming operations in the general art of telemetering has been the manual reduction of the output data received from the telemeter. Data reduction consists of performing certain mathematical manipulations on the output data and the presentation of the results thus obtained in convient graphical form. Before data reduction is performed, it is necessary that the output signal from any channel of the telemeter be a linear function of the quantity being measured. In practice, this input-output function (the calibration curve) may deviate from linearity by as much as 10%, and it has been necessary, in the past, to linearize this curve by a tedious, point-to-point method. The work of this thesis has been devoted to the design and construction of a device which will automatically and instantaneously linearize this channel input-output function to within 1%. We have termed this device "a linearity compensator."

The Raytheon Manufacturing Company has successfully designed a device to accomplish linearity compensation for telemetering application. To the author's knowledge this is the only other linearity compensator in existence. However, the design evolved in the course of the thesis investigation has several marked advantages over Raytheon's compensator. These advantages are: 1) less complexity by a factor of (approximately) 1:5 in terms of equipment required; 2) greater accuracy by a factor of 2:1.

CHAPTER I

INTRODUCTION TO THE PROBLEM AND STATEMENT OF RESULTS

I. Statement of the Problem

The PAM-FM telemetering system is designed to transmit information from a supersonic aircraft test vehicle to a ground station. The information to be transmitted consists of certain physical quantities such as pressure, temperature, roll and acceleration, all of which are converted to electrical signals by means of appropriate sensing devices. These electrical signals are then suitably commutated in order that they may be transmitted to a ground station via a single radio relay link to be received and recorded.

Reduction of the data thus received to suitable graphical form is a formidable, time-consuming, and uneconomical process when done manually. For these reasons, considerable effort is now being devoted to the construction of electro-mechanical computational systems which will automatically convert telemetered data to the desired form.

Before data reduction is performed, however, it is essential that the electrical output signals from the telemetering system be linear functions of the quantities being measured in the test vehicle. A conservative specification is that the input-output function be linear to within 1%. Unfortunately, the input-output functions (that is, the calibration curves) for existing telemetering systems may deviate from linearity by as much as 10%.

Before data reduction can be performed then, it becomes essential that some device be interposed between the telemetered output and the data reducer, the device to act on the telemetered output in such a manner that the calibration curve nonlinearity be reduced from the maximum of 10% to the required 1%. Development of such a device, hereafer called the "linearity compensator" has been the work of this thesis.

II. General Aspects of Compensation

Heretofore we have been discussing, for simplicity's sake the calibration curve of the telemetering system when, as a matter of fact, the telemetering system consists of many distinct information channels. (As many as 64 channels are envisaged for the PAM-FM system). Each of these channels, in the most unfavorable circumstances, will have nonidentical, nonlinear calibration curves, all of which must undergo linearity compensation. As the following discussion will make clear, this fact complicates the compensation problem only if all the channels must be compensated simultaneously.

First of all, it is obvious that to compensate any channel the compensator must be given information regarding the calibration curve of that channel. If a compensator is to correct the output of one channel at a time, only information regarding the calibration curve of the one channel undergoing correction need be stored within the compensator. After the first channel has been compensated, information regarding the second channel's calibration curve is stored within the compensator and the second channel is compensated. This process is repeated for all the channels.

If, however, all the channels are to be corrected simultaneously, the compensator must be able to store at once the information regarding all the calibration curves. It can be seen that correcting many channels simultaneously requires a compensator of greater complexity than would be necessary if one channel at a time were to be compensated.

The question naturally arises, why not record the channel outputs first and then compensate each of the channels in succession, if by so doing the amount of equipment necessary for compensation can be reduced? The answer is, this is exactly what might be done providing that certain other conditions regarding the telemetering system are such that this method of compensation can be used.

While these "other considerations" are important, it is not necessary, for the purposes of this thesis, to discuss or even to enumerate the factors which will determine whether the channels must be compensated simultaneously or whether they may be compensated one at a time. The important thing to note is that the former method requires more complex equipment --- i.e., a multi-channel compensator --- whereas the latter method permits the use of a single-channel compensator and hence relatively simple equipment.

III. The Thesis Investigation

At the inception of the thesis work, a design for a four-channel compensator was proposed by the author. It was anticipated that this basic four-channel design could later be adapted to 64-channel operation, but that the total equipment necessary for 64-channel operation would only be something like 8 times the equipment necessary for the basic four-channel unit. In designing the four-channel unit, the method of compensation was so chosen that the accuracy requirement of the unit was considerably lower than the accuracy requirement of a linearity compensator* developed by the Raytheon Manufacturing Company of Waltham, Mass., the only other compensator existing to the knowledge of the author.

A serious disadvantage of the originally proposed four-channel unit was that the set-up time required was at least one hour (as compared with a 15-minute set-up time for Raytheon's unit) in that the preparation for operation involved photographing curves on a photo-sensitive glass plate.

The development work on the four-channel compensator was pursued almost to completion when preliminary tests performed on the system made it evident that a considerable amount of additional effort would be necessary to make the system practical. At the same time, cursory work on a single-channel compensator using the same principles of compensation but different circuit design indicated that this new approach was much more feasible from the practical design standpoint. Moreover, the new design eliminated the main disadvantage of the four-channel compensator --- that of a long set-up time. The set-up time for the single-channel compensator is about 15 minutes.

*The reference for this information is classified and therefore not presented in the Bibliography.

Influenced by these considerations, the work on the four-channel compensator was terminated and effort was devoted to completion of the work begun on the single-channel compensator. If it is necessary to compensate all the telemetering channels simultaneously, it will be necessary to construct as many single-channel compensators (all of the same design) as there are telemetering channels.

IV. Results

The essential characteristics of the single-channel compensator are tabulated below:

Input Frequency Range:	0-200 cps
Input Voltage Range:	0-3 to 0-10 volts
Input Impedance:	100,000 ohms
Output Impedance:	25,000 ohms
Compensator Accuracy:	± 2.5%
% Deviation from Linearity of Compensated Output:	.5%
Set-up Time:	15 minutes
Power Consumption:	40 watts
Cost of Materials (estimated):	$75 (without power supplies)

Although no formal results were obtained from the four-channel compensator, the theory, operation and circuit diagrams for the system are presented in Chapter II.

Chapter II also presents the theory of compensation which is essentially common to both the four-channel and single-channel compensators.

Chapter III presents the theory and operation of the single-channel compensator.

CHAPTER II

THE FOUR-CHANNEL COMPENSATOR

I. Theory of Compensation

A. Input to the Compensator. The output information from any channel in the PAM-FM system is carried in an amplitude-modulated voltage wave having a maximum amplitude of approximately 10 volts and a frequency range of 0-200 cycles per second. This then is the input to the compensator.

B. The Error Curve. The philosophy underlying the method of compensation can best be understood by reference to Fig. 1, wherein is shown an hypothetical nonlinear calibration curve (curve A) and the desired linear calibration curve* to be produced by the compensator (curve B). It can be seen that there is a point-to-point correspondence between curve A and curve B. This is the

*It will be noticed that the linear curve B lies everywhere above the calibration curve and is not the best linear approximation to the calibration curve. Curve C is the best linear approximation to curve A. The linear curve B is chosen in this manner because the method of correction for the four-channel compensator, as will be seen, requires that voltage increments always be added to the original calibration curve to obtain a linear curve.

However, the specification of 10% maximum deviation from linearity for any calibration curve is given in terms of the best

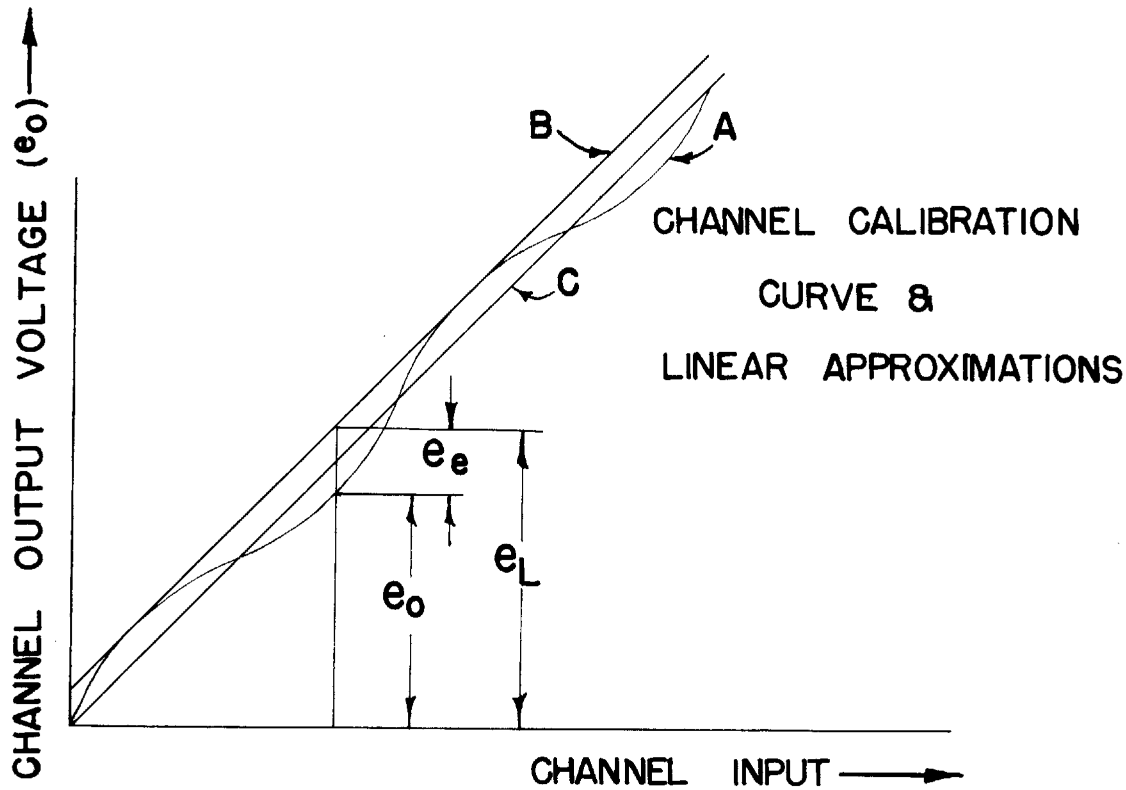

CHANNEL OUTPUT VOLTAGE (e_o)
B
A
C
CHANNEL CALIBRATION
CURVE &
LINEAR APPROXIMATIONS
e_e
e_L
e_o
CHANNEL INPUT

Fig. 1

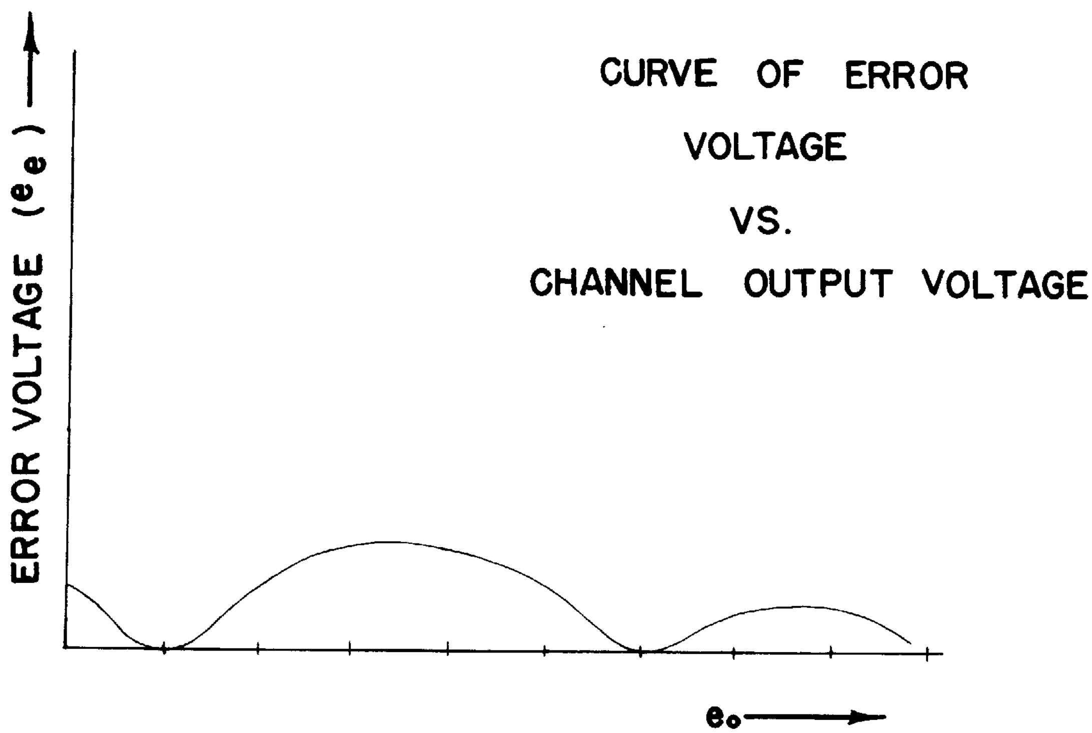

ERROR VOLTAGE (e_e)
CURVE OF ERROR
VOLTAGE
VS.
CHANNEL OUTPUT VOLTAGE
e_o

Fig. 2

case as long as the calibration curve is monotonic. The operation of the compensator is essentially this: When the output from any channel (and hence the compensator input) is, say e_o, the compensator output should be e_L. This can be done if every time the channel output is e_o the compensator generates the error voltage e_e and adds it to e_o, since, from Fig. 1, $e_L = e_o + e_e$. This process can be repeated for every point on the calibration curve, the error voltage e_e being everywhere the vertical distance between the calibration curve and the linear curve. One can plot the error voltage e_e as a function of the channel output voltage e_o, as is done in Fig. 2, to obtain the so-called "error-voltage curve." The shape of the calibration curve is arbitrary, hence the error-voltage curve is also arbitrary. Since for any channel output voltage e_o the compensator must generate the corresponding error voltage e_e (e_e then to be added to e_o), it follows that the basic element of the compensator must be generator which can produce an arbitrary function. It will be noted in Fig. 1 that

---

*linear approximation to the curve. Choosing the linear curve, the way shown has the effect of increasing the deviation (from the linear curve B) to 20%. This means, in effect, that the compensator must be able to compensate for 20% deviations instead of 10% deviations. On the surface this seems to be disadvantageous, but it turns out that the compensator need only have 5% accuracy to produce the linear approximation to the calibration curve to within 1%.

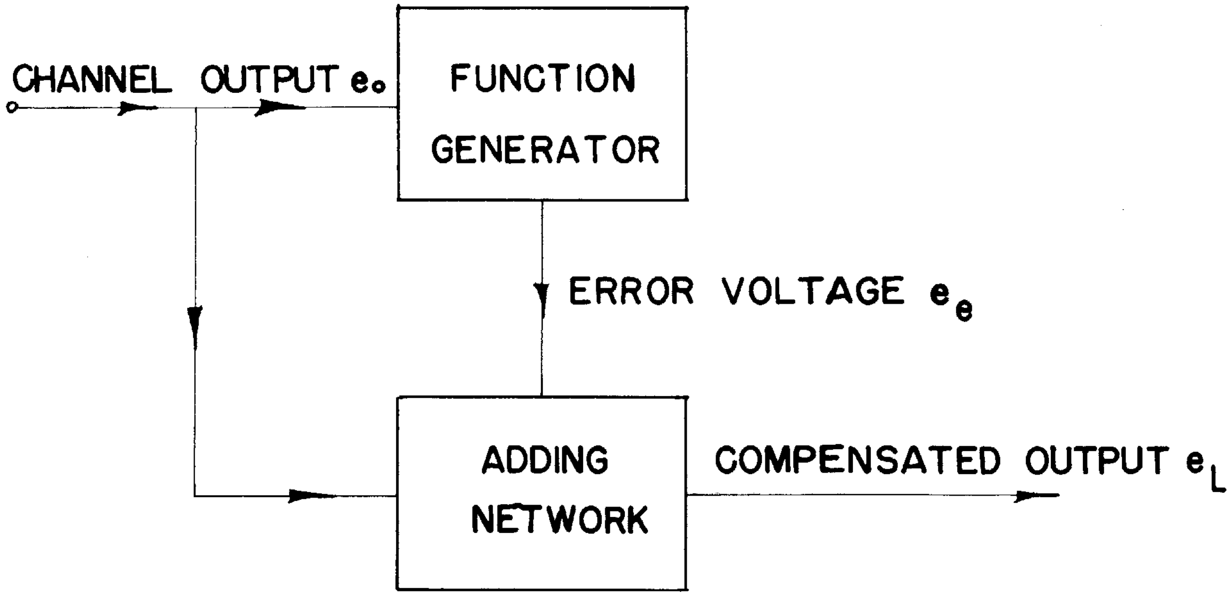
curve B does not pass through the origin as it should. Fortunately this does not complicate the compensation problem since we can shift curve B downward by a "zero setting"control whereever it most convenient to do so in the compensator. (It would be obviously foolish to generate this "zero setting" as part of the error voltage, since the maximum error voltage amplitude would be greater than 20% of the channel output voltage and we would accordingly be required to generate the error voltage with an accuracy greater than the 5% otherwise required, as we shall presently see).

Before the mechanics of the arbitrary function generator are discussed, two very important advantages of compensating in this manner, should be pointed out.

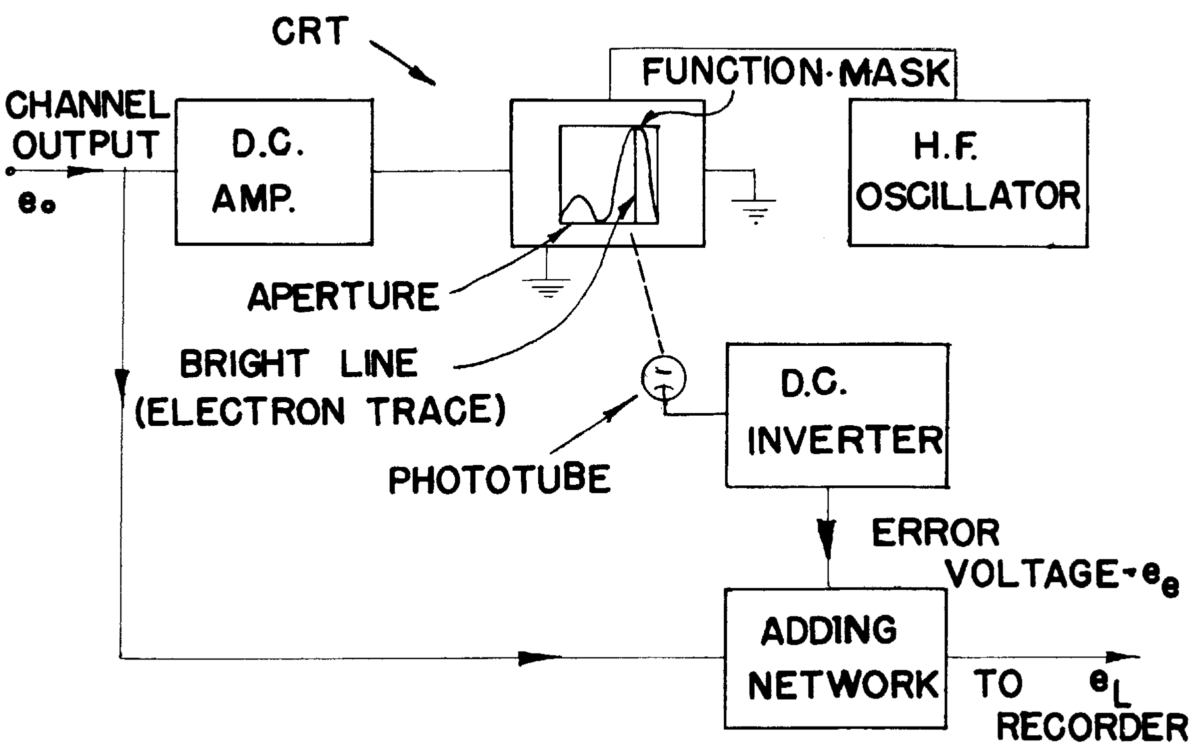
1. Reference to the block diagram of an elementary single-channel compensator*, Fig. 3, shows that the channel output is fed into the error-voltage-function generator and also into an adding network. It can be seen from Fig. 3 that if the function generator fails in operation, the channel output will still be recorded --- although uncorrected.

---

*The term "single-channel compensator" used in this chapter is merely an explanatory device introduced only to make clear the principles of operation of the four-channel compensator. It does not refer to the single-channel compensator which was actually built. The latter is discussed in Chapter III.



SINGLE-CHANNEL COMPENSATOR
Fig. 3



FUNCTION GENERATOR
Fig. 4

2. The error-voltage-function generator need only produce the error curve to within 5% in order for the linear curve to be produced to within 10%. This is so because the error voltage is a correction voltage and represents, at most, 20% of the maximum voltage to be obtained from the channel being compensated. Thus 5% x 20% = 1% maximum deviation.

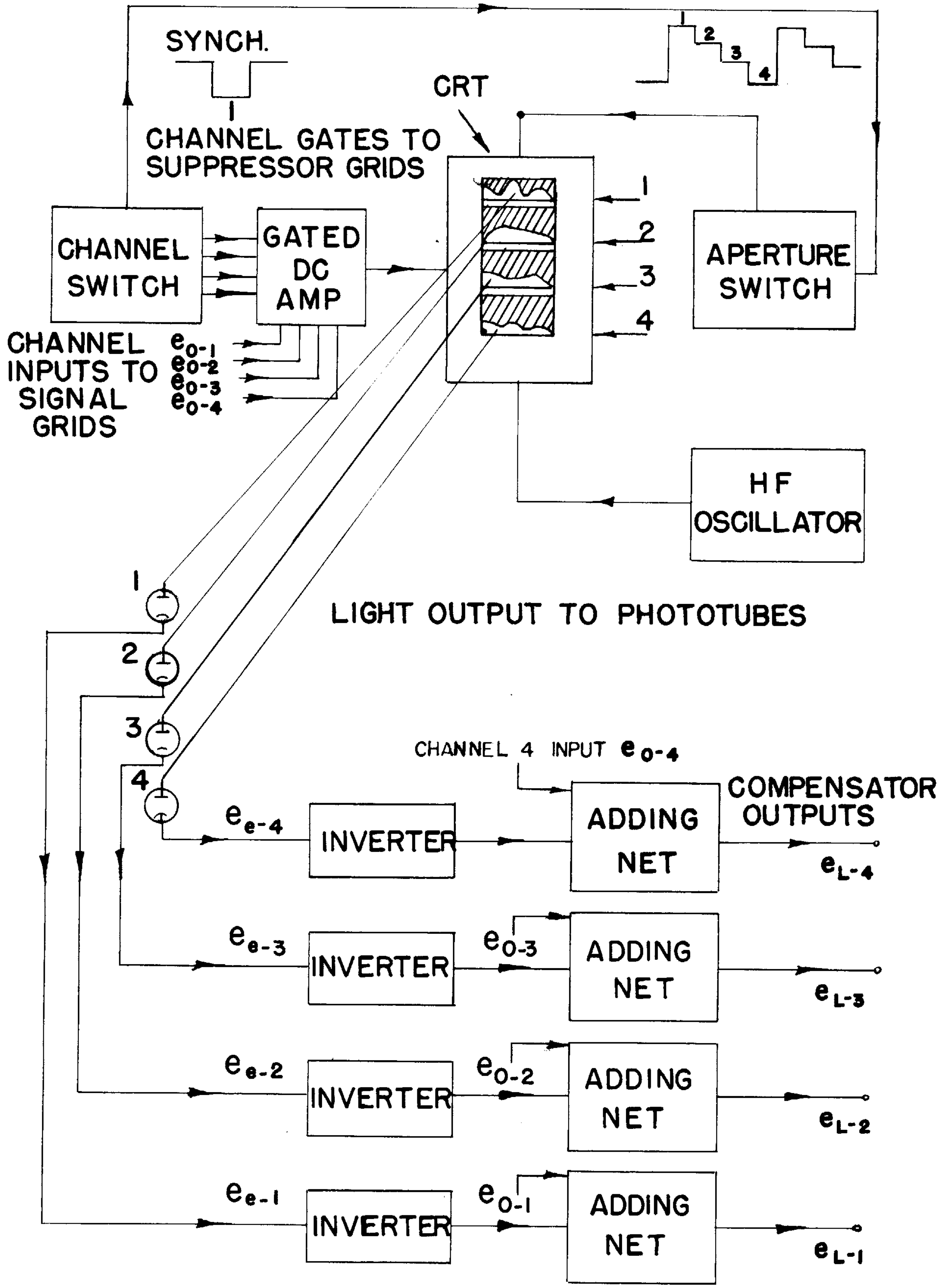
II. General Considerations

A. Function Generator and Single-Channel Compensation. It has already been pointed out that the heart of the compensator must be a generator which can produce an arbitrary function. One method of producing an arbitrary function (the error voltage in our case) employs a cathode-ray tube and a function mask which is placed in front of the cathode-ray tube screen, as is demonstrated in Fig. 4. An aperture in the shape of the error curve is cut in the face of the function mask. The cathode-ray-tube electron beam is swept vertically by a high-frequency oscillator, and the vertical line thus generated is caused to move horizontally across the face of the screen by the input signal (the output signal of the channel being compensated) applied to the horizontal plates. A phototube, suitably housed, is placed in front of the function mask aperture. The light impinging on the phototube, and hence the phototube current, is directly proportional to the length of the electron-beam trace visible through the aperture. The phototube current, in turn, produces a voltage drop across the phototube plate resistor. This is the desired error-voltage output from the function generator.

Because an increase in light causes a decrease in the phototube plate potential, this voltage must be inverted by a d-c amplifier. The output from the d-c amplifier is then fed into the adding network together with the original channel output voltage. The output from the adding network is proportional to the desired corrected output voltage.

B. Four-Channel Compensator. Extension of the single-channel compensator to a four-channel compensator involves placing four function masks, one above the other, on the face of the cathode-ray tube as illustrated in Fig. 5. Each aperture is cut in the form of the error curve for the channel it is to compensate. Four phototubes are placed in front of the respective apertures. Since there is only one electron beam in the cathode-ray tube, only one telemetering channel at a time can be fed into the horizontal deflection plates. It is therefore necessary to switch from one channel output (compensator input) to another in succession. (If there were a cathode-ray tube with 4-beam, this switching would not be necessary). The compensator input-switching process must be accompanied by vertical switching in order that the beam is fed into the appropriate aperture. Thus, as the compensator input is switched to channel 1, the aperture switching circuit must place the beam vertically so that it is fed into aperture 1, etc.

As for the single-channel compensator, the outputs from each of the phototubes are inverted and then added to the respective channel outputs to give compensated outputs for four channels.



MULTI- CHANNEL COMPENSATOR,

FIG. 5

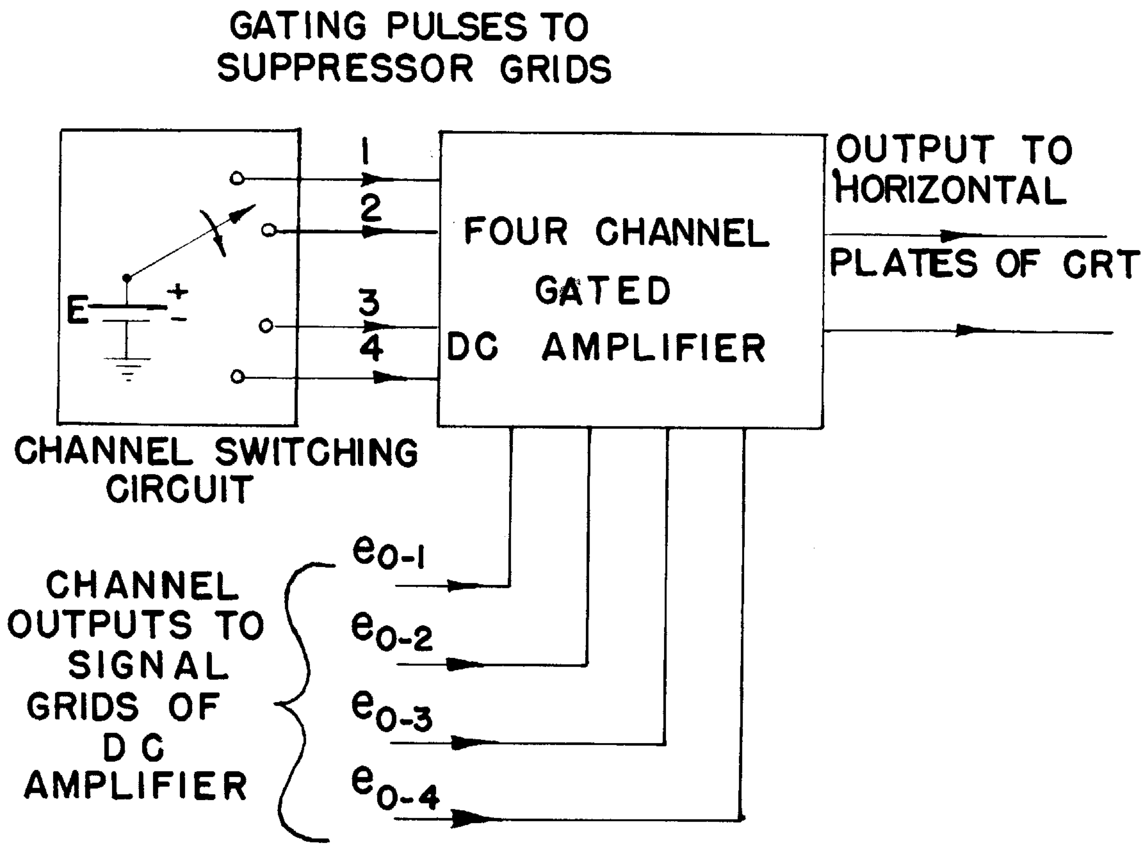
III. Four-Channel Compensator Operation and Circuit Details.

A. Determination of the Switching Rate. Choice of an appropriate switching frequency is of primary importance in the operation of the four-channel compensator. In as much as each channel is active in the compensator only one-fourth of the time, the switching rate (which is synonomous with sampling rate in this instance) must be high enough so that the highest channel output frequency component will be sampled effectively. "Effective sampling" is usually taken to mean a sampling rate which is at least 2.5 times the highest frequency component being sampled. The highest compensator input frequency component is about 200 cps, therefore, the sampling rate must be at least 500 cps.

However, there is another more important factor which governs the choice of an appropriate repetition frequency. By way of explanation, consider for a moment the single-channel compensator discussed earlier in this chapter. The electron-beam is swept vertically by a high-frequency oscillator and is moved horizontally by compensator input voltage. For proper operation the decay time of the cathode-ray tube phosphor should be long compared to the time required for a single vertical sweep, but short compared to the time required for a single horizontal sweep. In this case, the fastest horizontal "sweep" is 1/200 = 5 milliseconds. The P-11 phosphor has the fastest decay time for commonly available cathode-ray tubes. The P-11 decay time is about .15 milliseconds, so that the decay-time, horizontal-sweep time requirement is met. The vertical oscillator frequency can be of the order of 500 kcps.

For the four-channel case, the beam is switched vertically (in addition to being swept vertically), and this vertical switching time should be as short as possible compared with the phosphor decay time so that the light output from any aperture will not come in pulses. In practice this is hard to do as the following simple calculation will demonstrate: A short time compared to .15 millisecond would be about .01 milliseconds, corresponding to a frequency of 100 kcps. To switch 4-channel at a 100-kcps repetition rate means that each channel would be "on" for 2.5 microseconds. However, generation of 2.5 microsecond pulses, while entirely feasible, requires careful and complicated circuitry, and the results that would be obtained would not justify the effort required. Therefore, a compromise repetition frequency of 25 kcps was chosen, giving a frame period of 40 microseconds. Each channel is therefore "on" for 10 microseconds, and generation of 10-microsecond pulses is no hardship. Of course in 40 microseconds the phosphor light output is down to 70% of its maximum value, so there will be a "ripple" on the light output, but this small amount can easily be filtered.

B. Channel Switching Circuit. The channel switching circuit provides the 10 microsecond, 25-kcps gating pulses for the four-channel compensator and hence is the basic timing circuit for the unit. It performs the function of a high speed rotary switch, as shown in Fig. 6, by supplying the 10-microsecond positive gating pulses to the suppressors of 4 amplifiers with a common plate load resistor. Thus only one amplifier conducts at a time, and the



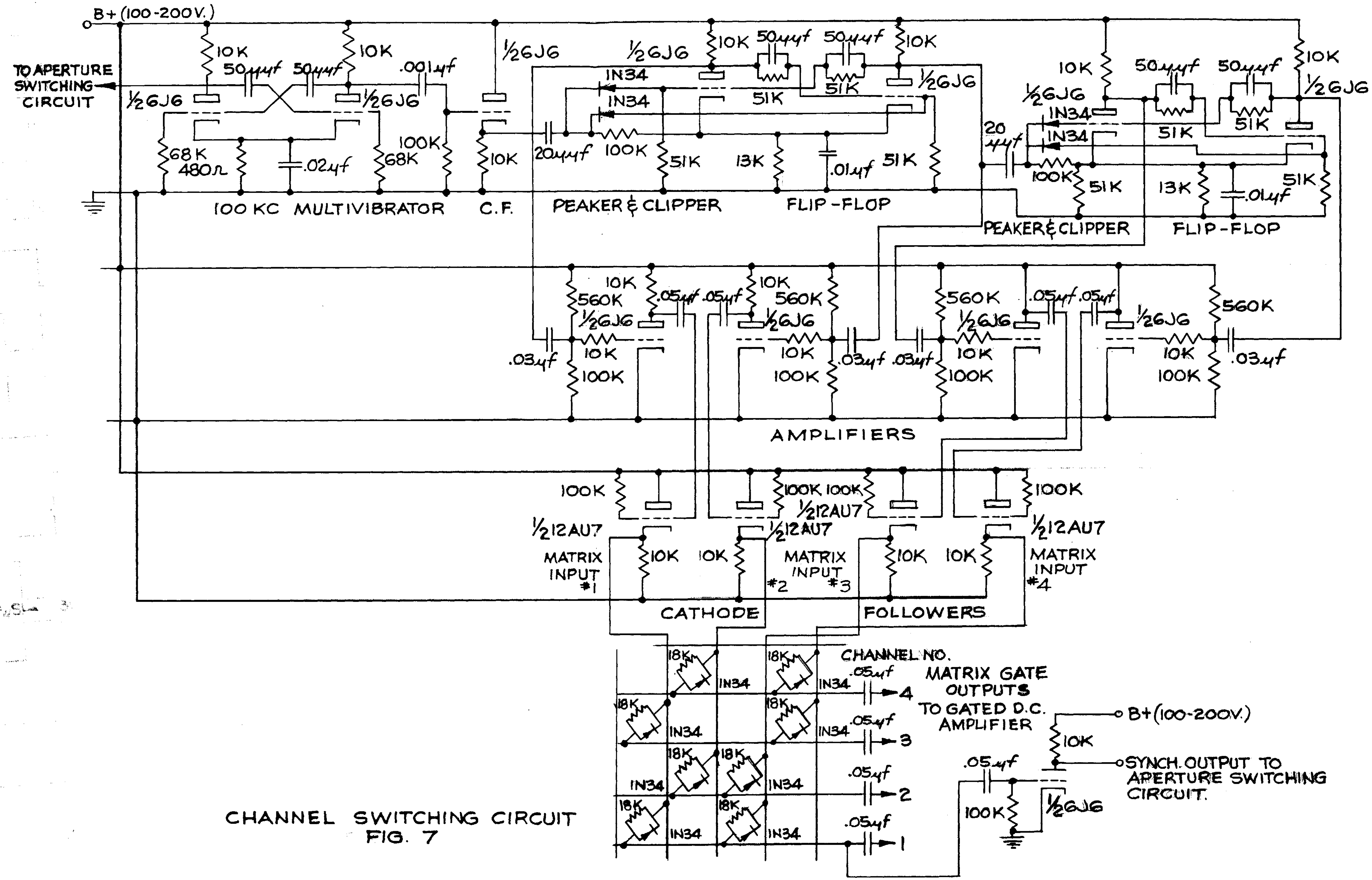
COMPENSATOR INPUT CIRCUITS

FIG. 6

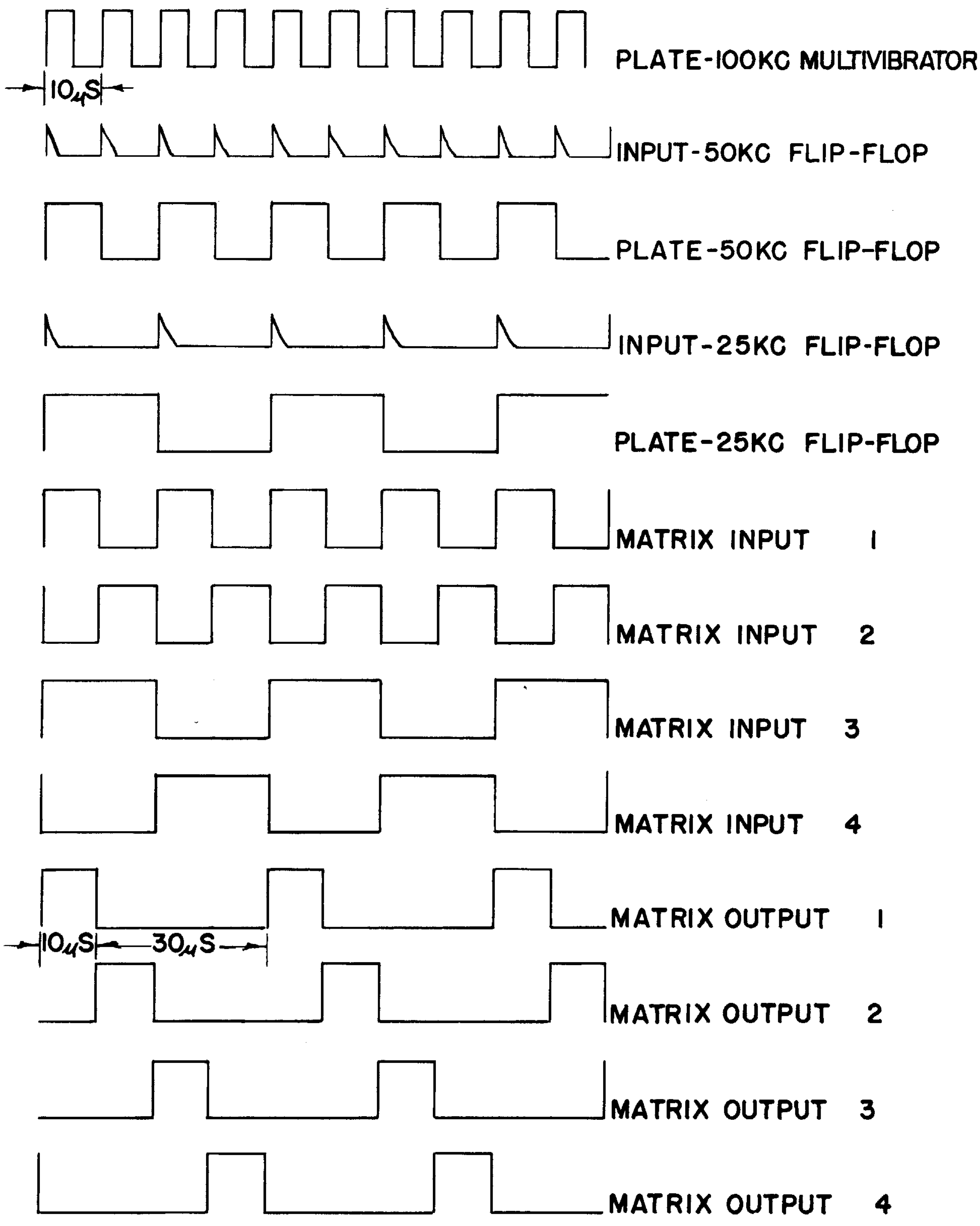
signal on its grid will be reproduced on the plate, while the signals on the grids of the other three amplifiers will be ineffective until their suppressors, in turn, receive the positive gating pulses. The channel switching circuit also provides actuation and synchronization pulses for the aperture switching circuit. The latter's function is discussed in Part D.

The heart of the channel switching circuit is a 100-kcps free-running multivibrator of conventional design (see Fig. 7). The multivibrator output is fed into a cathode follower whose output is peaked and clipped, the resulting 100 kcps pulses driving a flip-flop which therefore runs at 50 kcps. The peaking and clipping action is repeated on the output of the 50 kcps flip-flop to provide pulses at a 50-kcps rate to drive the next flip-flop stage which runs at 25 kcps.

The output from each of the four plates of the two flip-flop stages are amplified and then sent through cathode followers. The cathode follower output waveforms are shown in Fig. 8 together with the important waveforms for the entire channel switching circuit. Thus, referring to Fig. 7 and 8, the outputs from the cathode follower labelled Matrix Input 1 and Matrix Input 2 are each 50-kcps square wave but 180 deg. out of phase. Similarly the outputs from the cathode followers labelled Matrix Input 3 and Matrix Input 4 are each 25-kcps square waves but 180 deg. out of phase. These four wave trains are combined in a crystal-resistor matrix, the outputs from which are shown in Fig. 8. The output from any one



CHANNEL SWITCHING CIRCUIT
FIG. 7



CHANNEL SWITCHING CIRCUIT WAVEFORMS
FIG. 8

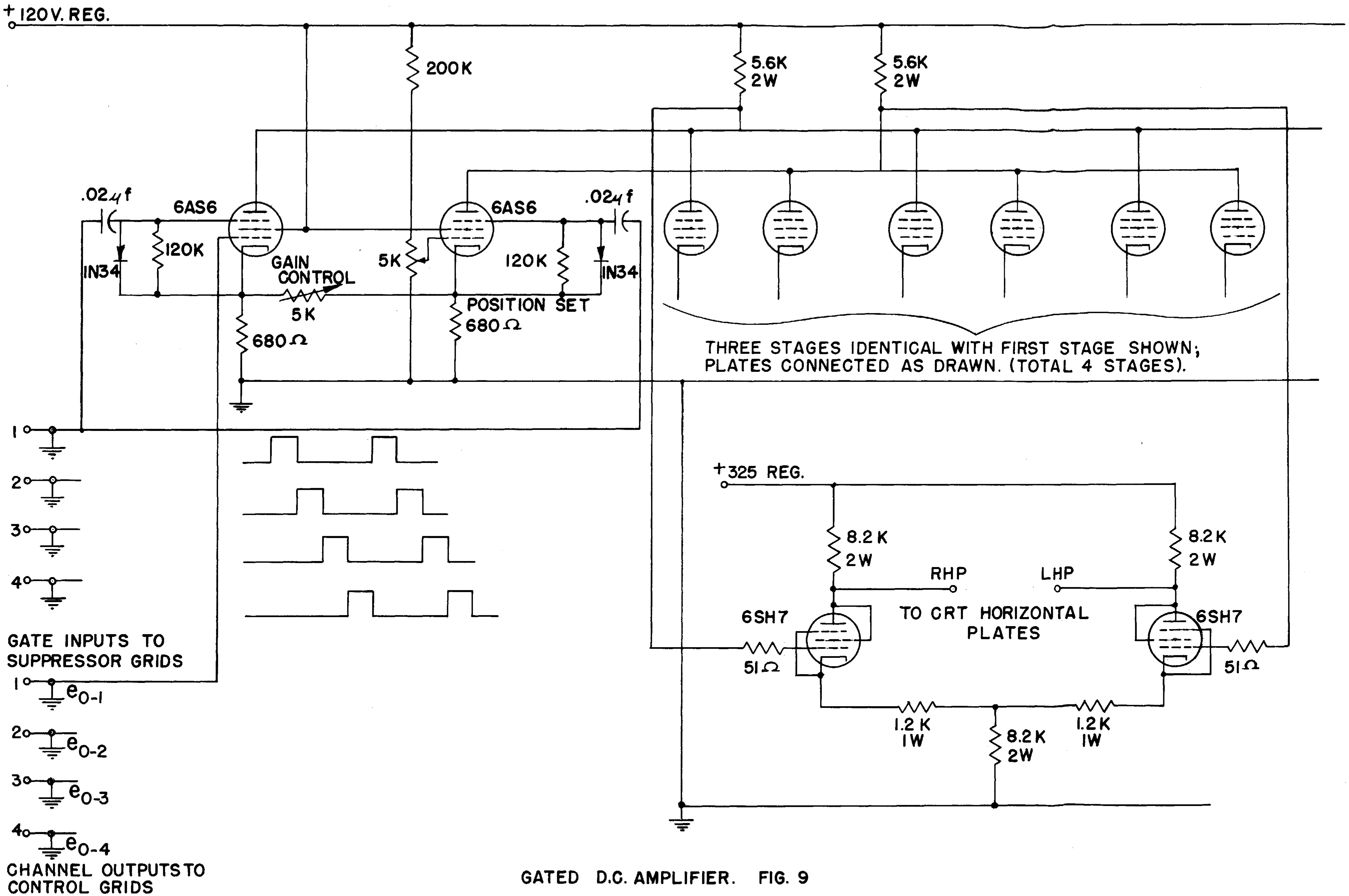
matrix output arm consists of 10 us pulses occurring at a 25-kcps rate, and between successive arms there is a 90 deg. phase shift in the output voltages. These 10-us gating pulses are then applied to the gated d-c amplifier, as previously explained.

C. Gated D-C Amplifier. The d-c amplifier of Fig. 9, is of somewhat unique design, although it is nothing but a variation on an old theme. The idea of gated amplifiers with common plate loads is the very heart of the PAM-FM system[1*], but the use of push-pull gated amplifiers is somewhat different. The push-pull aspect is necessary for application of the commutated signals to the horizontal plates of the cathode-ray tube. The amplifier has a large bandwidth in as much as it must pass 10 us pulses.

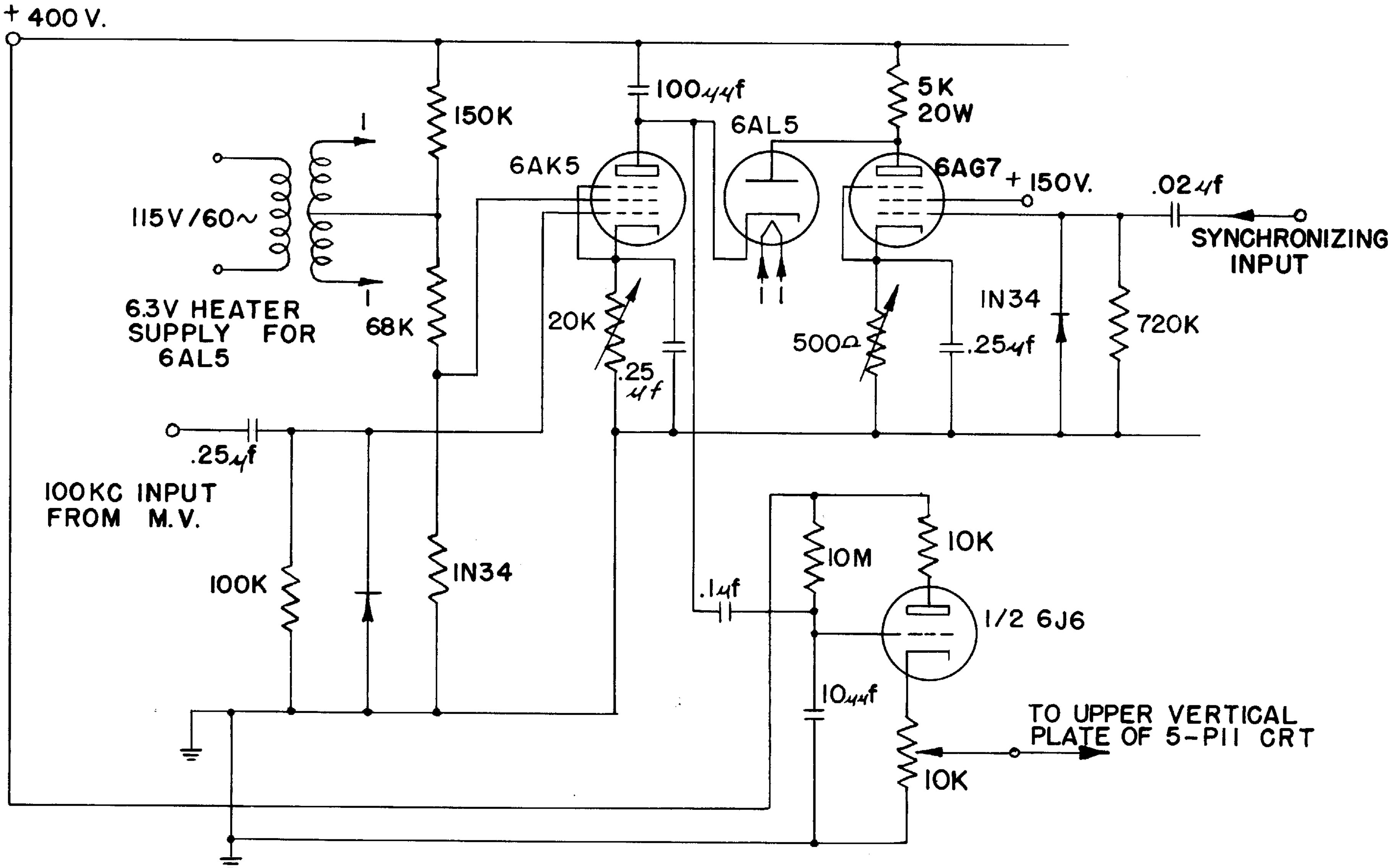
D. Aperture Switching Circuit. The aperture switching circuit, shown in Fig. 10, performs the function of switching the electron trace vertically, so that the trace feeds into a particular aperture at the correct time. Thus, when channel 1 is "connected" to the horizontal plates, the aperture switching circuit places the beam in the channel 1 aperture and so forth. The output voltage waveform, shown in Fig. 11, consists of equal amplitude "steps" which are applied to the upper vertical plate of the cathode-ray tube. The actuating pulses come from the left-hand plate of the 100-kcps multivibrator in the channel switching cirucit are obtained from an inverter which, in turn, is fed from output arm 1 of the crystal-resistor matrix.

---

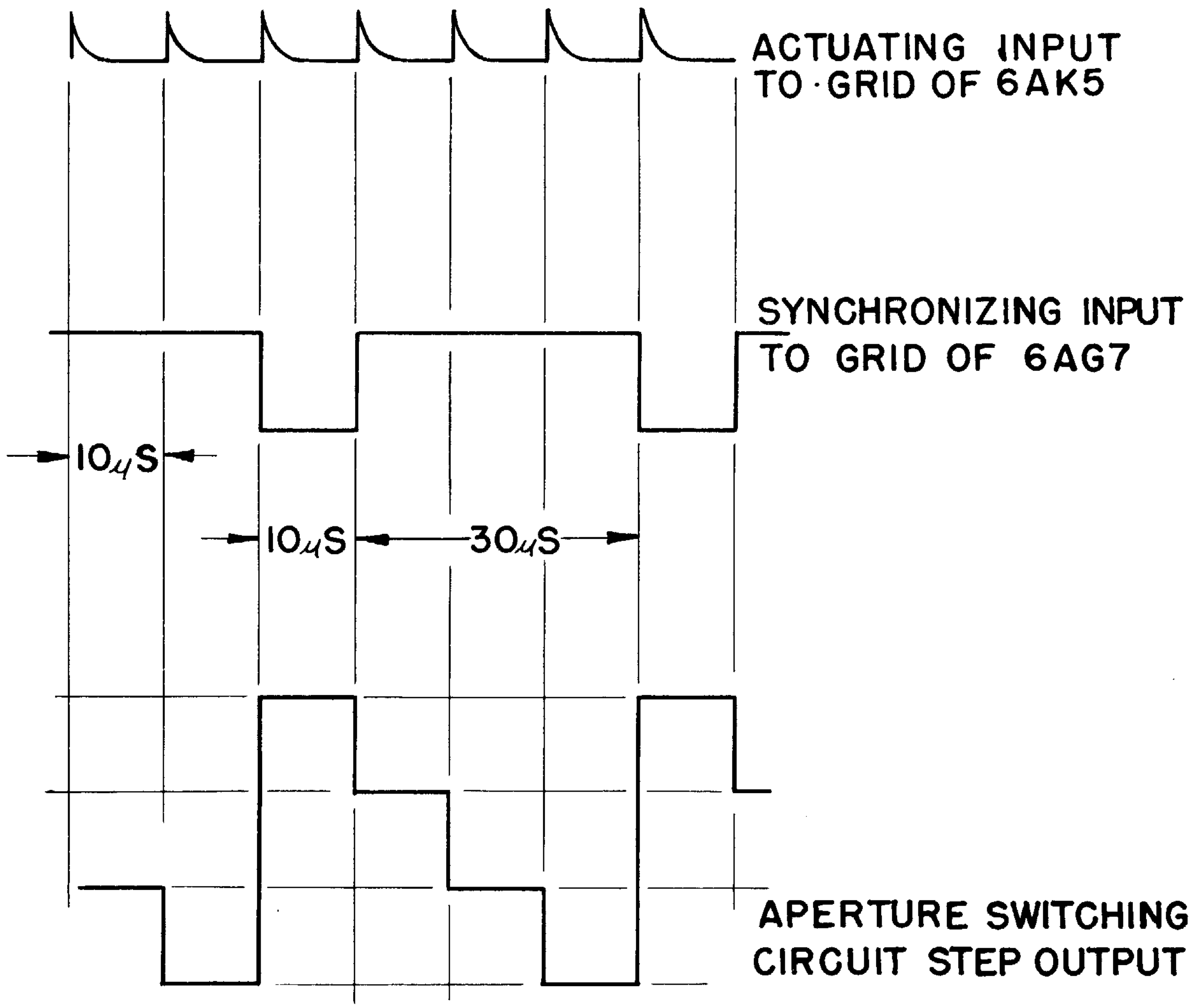
*Superscripts refer to the Bibliography.



GATED D.C. AMPLIFIER. FIG. 9



APERTURE SWITCHING CIRCUIT. FIG. 10



APERTURE SWITCHING CIRCUIT WAVEFORMS

FIG. 11

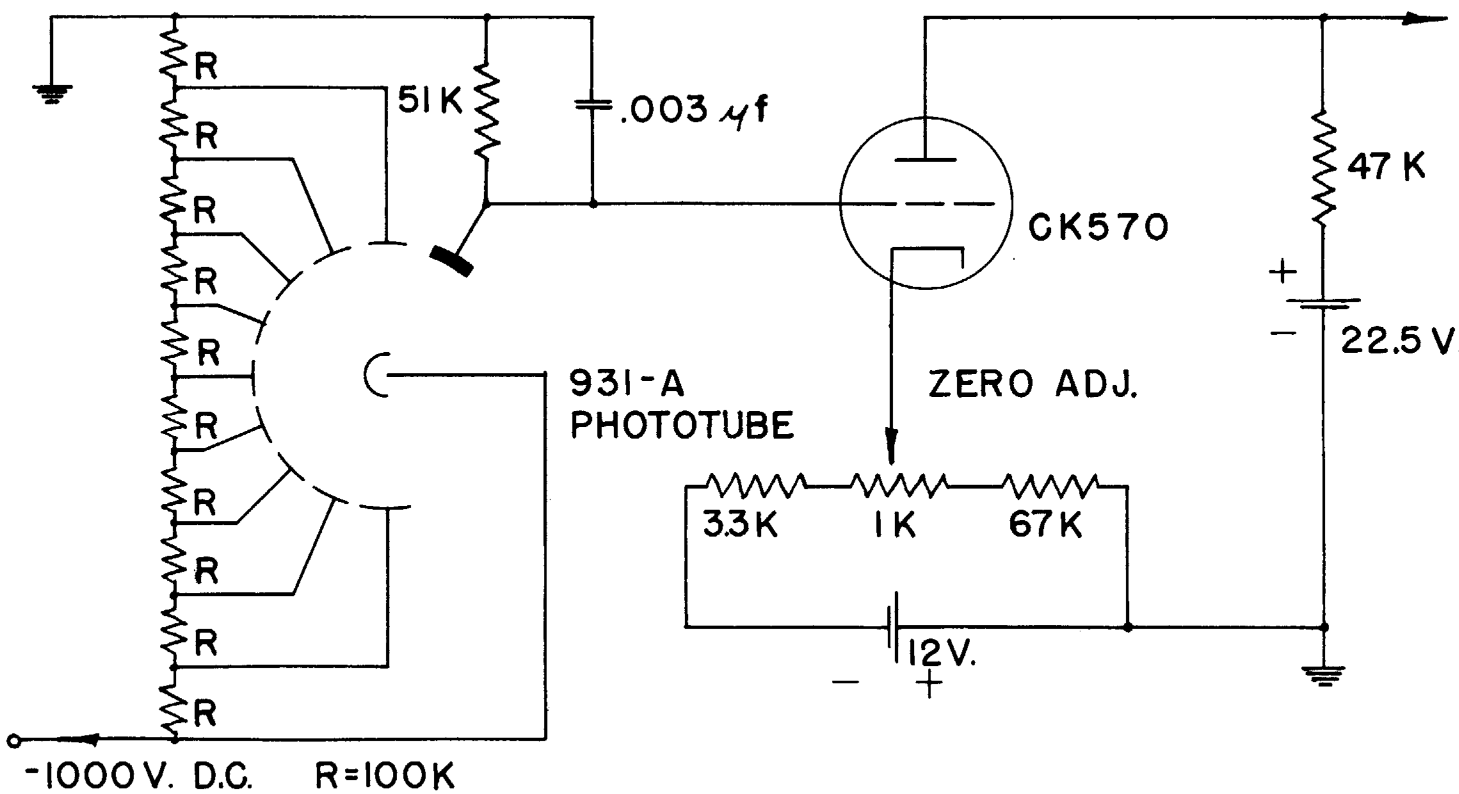
E. Cathode-Ray Tube and Phototube Circuits. A 5-inch cathode-ray tube with a P-11 phosphor was chosen for use in conjunction with four 931-A phototubes. The 5-inch screen allowed the use of four 3/4"x 3" apertures which, while small, was deemed good enough for reproduction of the error cuves to within 5%. As previously discussed, the P-11 phosphor was chosen for its extremely fast decay time.

The phototube circuitry for one channel is shown in Fig. 12. The resistor-condenser combination in the plate circuit of the 931-A phototube is a simple low pass filter to attenuate the 25-kcps ripple in the light intensity. Also shown in Fig. 12 is the circuit of a d-c inverter with a gain of about -1. The variable 1K potentiometer allows the insertion of the "zero setting" discussed earlier.

IV. Test Results on the Four-Channel Compensator

After all the switching circuits and the output circuit for one channel were constructed, preliminary tests were made on the system. The results of these tests gave clear indication that achievement of the 5% accuracy required would be an extremely difficult task, necessitating additional equipment. The results of the tests were as follows:

1. Three different 5-P11 cathode-ray tubes (and their associated power supplies) from three different DuMont oscilloscopes, Type 247A, Type 241 and Type 279, were used. It was found that the beam intensity of all three types tested suffered from excessive ripple. Sudden, erratic jumps in intensity were also noted. The



PHOTOTUBE & D.C. INVERTER CIRCUITS

FIG. 12

ripple varied from a minimum of 5% to a maximum of 15% of quiescent intensity in the tree types. The intensity jumps amounted to as much as 30% in some cases. Furthermore, the light output varied about 3% with change in position of the beam on the face of the cathode-ray tube.

The ripple and intensity jump problems could be obviated by use of line voltage regulators and carefully regulated high-voltage power supplies, but variation of beam intensity with beam position is a matter involving the phosphor coating, something about which nothing can be done.

2. During the switching time from one vertical position to the next, it was found that an undesirable light trace was made, thereby necessitating blanking during the switching time. This was successfully done but careful control of the blanking pulse duration was needed.

3. Another difficulty was encountered when it was realized that when the beam is swept vertically by a high-frequency sine-wave oscillator (see Fig. 5), the light intensity of beam trace varies along its length since the beam spends more time at the extremities of the sweep than at the central portion. This is clearly evidenced when a sine-wave is applied

to the vertical plates of any cathode-ray tube with no signal on the horizontal plates. It can then be observed that there is a bright "dot" on the upper and lower extremities of the trace. This condition being so, the light output from an aperture in a mask will not be linearly related to the vertical height of the opening and is another source of error. This problem can be solved by the use of a high-frequency sawtooth generator instead of a sine-wave generator.

4. Finally, the whole problem was one of careful control of d-c level, again something which can be done but is hard (in terms of equipment) to do.

CHAPTER III

SINGLE-CHANNEL COMPENSATOR

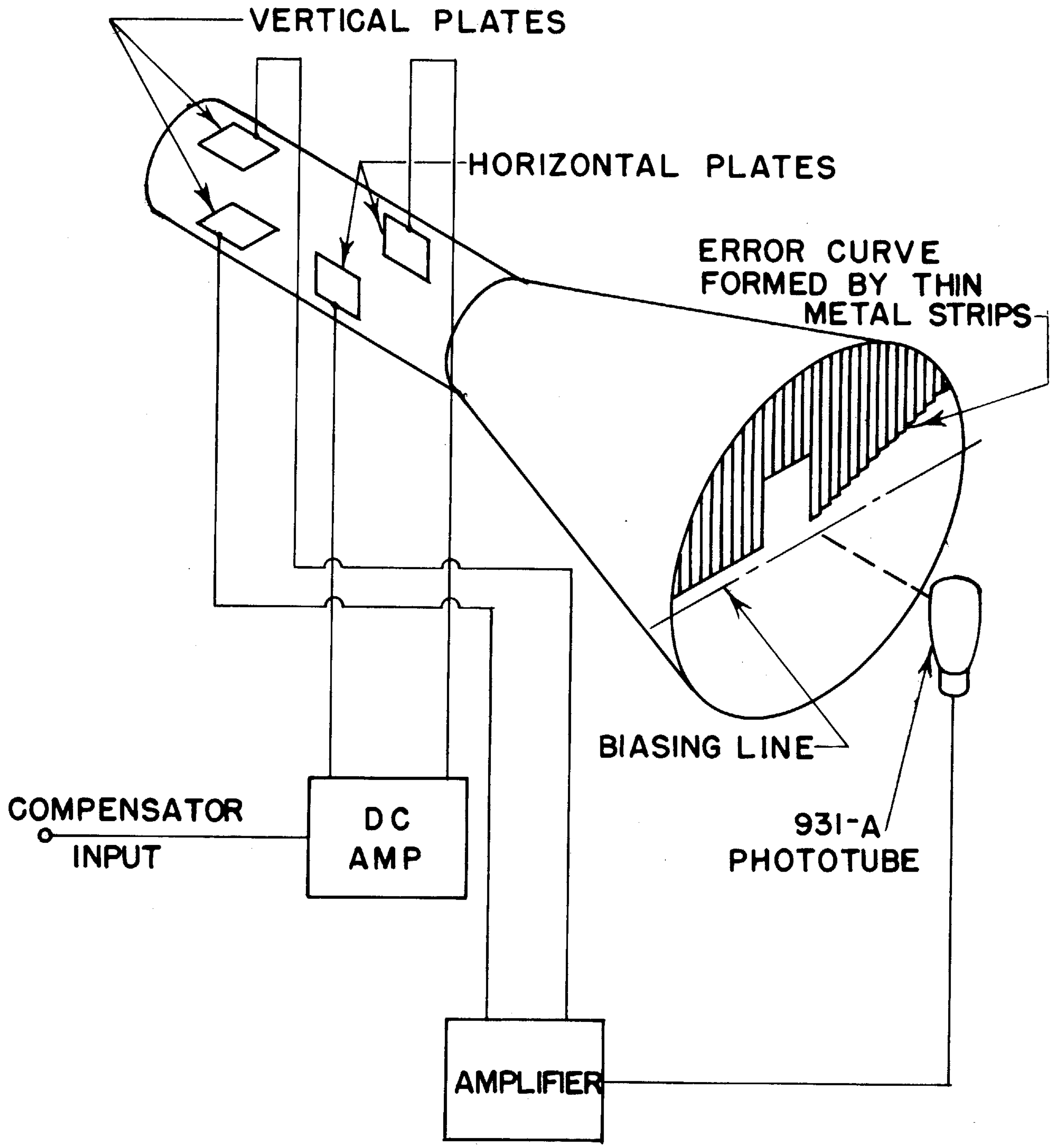
I. General

It will bear repeating that the primary reasons for abandoning the four-channel system were two in number:

1. The instable characteristics of the cathode-ray tube and the careful circuitry required throughout made precise reproduction of a curve very difficult.
2. The error-curve apertures had to be reduced to a small size on a photo-sensitive glass plate, thereby making the set-up time prohibitively high. This was discussed in Chapter I.

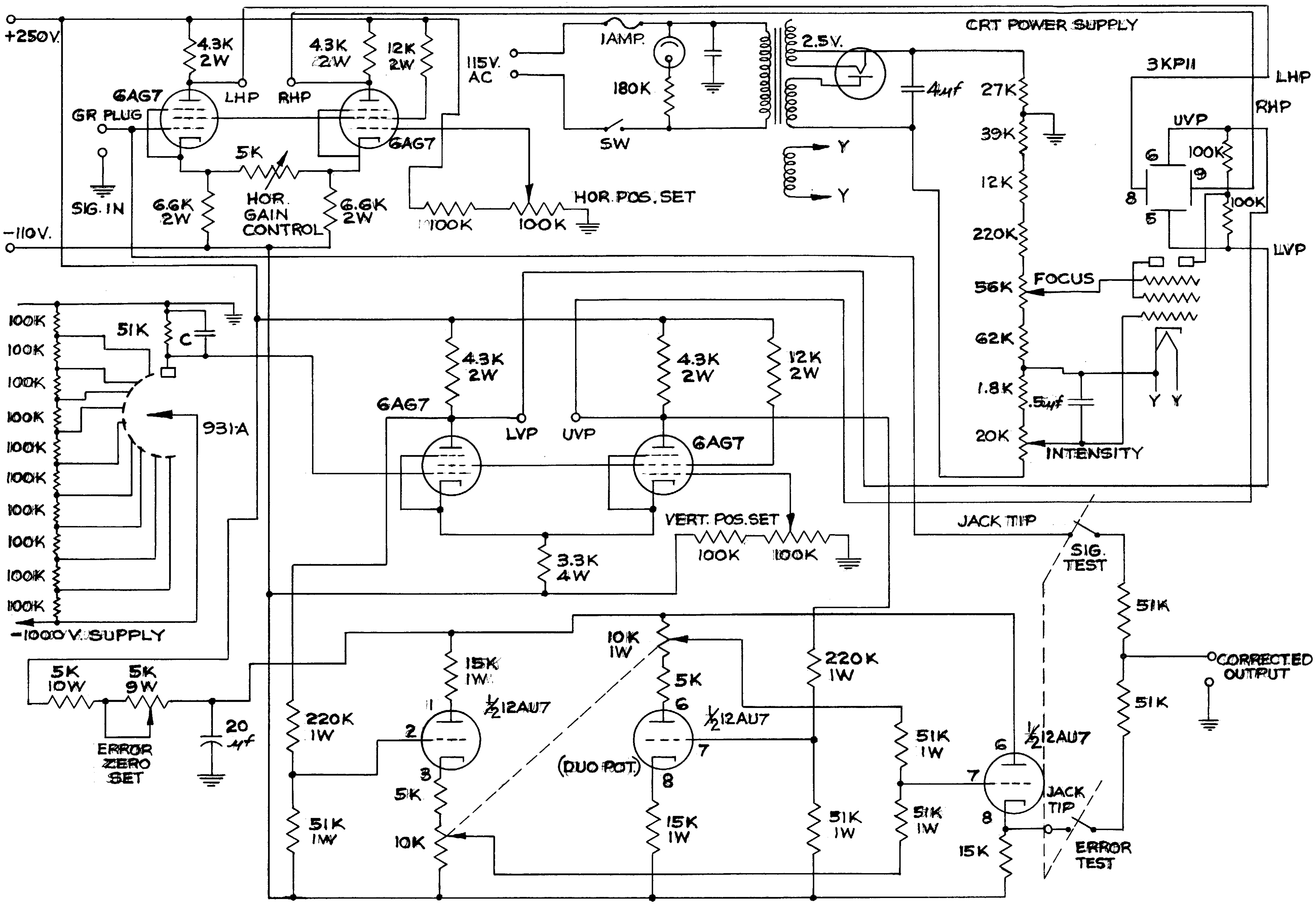
A solution to the first of these problems was found in the use of a feedback-function generator as the primary component of a single-channel compensator. The block diagram of this circuit is shown in Fig. 13 and the practical circuit design in Fig. 14. The use of the feedback circuit, developed by Macnee, reduces the sensitivity of the output to the instable characteristics of the cathode-ray tube and the photocell.[2]

To meet the problem of long set-up time, the author designed a special-type, easily adjustable function mask for use on the face of the cathode-ray tube. As will be shown, an adjustable mask possesses the additional important property of allowing the function generator to compensate for its own nonlinearities.



FEEDBACK FUNCTION GENERATOR

FIG. 13



FEEDBACK FUNCTION GENERATOR
FIG. 14

The four-channel system does not lend itself to the use of either the feedback principle or the special function mask.

II. Compensation Theory.

Introduction of feedback gives the single-channel compensator an additional advantage over the four-channel system, tending to increase the accuracy of error curve generation.

It will be recalled that it was not possible, in the four-channel system, to generate both positive and negative error voltages, and that it therefore became necessary to draw a linear approximation to the calibration curve which lay everywhere above the calibration curve. This meant that the effective deviation from linearity became 20% and the compensator accuracy had then to be 5% to produce an over-all linearity of 1%. The feedback function generator, on the other hand, can produce both positive and negative error voltages; therefore, the best linear approximation to the calibration curve can be drawn, the effective deviation from linearity is 10%, and the compensator accuracy need be merely 10%, a 2:1 improvement over the four-channel compensator.

III. Theoretical Operation of the Feedback Function Generator.

Unlike the four-channel system, where the error curve to be generated is cut in the form of an aperture, the feedback function generator requires that the curve to "cut" in the form of a mask, as illustrated in Fig. 13 and Fig. 26 (see Appendix) and placed across the face of the cathode-ray tube. As before, a phototube is placed in front of the tube face in a light-proof enclosure. The output of the phototube is fed into an amplifier whose output is connected to the vertical plates of the cathode-ray tube. The phase of this amplifier is such that increasing light gives an upward deflection of the beam and decreasing light a downward deflection. The amplifier is so biased that, with no light entering the phototube, the beam always lies below the function mask. Activation of the feedback loop will cause the beam to move upward until it strikes the edge of the mask where it will take up an equilibrium position wuch that the amount of light showing from the partially obscured spot is just sufficient to give enough phototube output to keep the beam at the edge of the mask. If now the channel output voltage is introduced to the horizontal plates of the cathode-ray tube causing the beam to move horizontally, the beam is constrained to follow the edge of the mask, thus producing the error voltage output desired.*

IV. The Function Mask

Examination of Fig. 26 shows that the function mask consists of 32 thin steel strips, 1/16" wide and 6" long. These strips are moved vertically in such a manner that their lower extremities approximate the shape of the error curve to be generated. Obviously then, the curve is not a smooth one but consists of many small discontinuities. The effect of these discontinuties is discussed in Section VI.

---

*For a full discussion of the feedback function generator, see Reference 2.

V. Circuit Features

The compensator employs a basic oscilloscope panel, containing only the necessary power supplies to actuate the cathode-ray tube (3K P-11), built by the James Millen Company of Malden, Mass. and modified for our particular use. The modified circuit diagram for the cathode-ray tube and power supply is shown in Fig. 14. As before, a 931-A phototube is the light detector. A pair of 6AG7 tubes giving push-pull output is used to amplify the compensator input for application to the horizontal plates. The vertical amplifier in the feedback loop also uses 6AG7's. The push-pull output from the 6AG7 plates is sent through a pair of 12AU7's, whose outputs in turn are added through 51K resistors as shown in Fig. 14. This unique arrangement, due to Macnee, gives single-ended output from double-ended input but, more important, the (unwanted) in-phase signals at the grids of the 12AU7's are rejected, but the desired out-of-phase signals are passed through, attenuated only slightly by the gain of one 12AU7 stage. The output from the adding resistors is sent through a cathode follower whose output is the desired error voltage. The magnitude and d-c level of the error voltage are potentiometer controlled as shown in Fig. 14.

VI. Characteristics of the Single-Channel Compensator

The fundamental question which must be answered to describe the performance of the compensator is: How accurately can the error curve be produced? There are four factors which determine the accuracy of the function generator. These factors are:

1) frequency response of the function generator; 2) linearity of the function generator; 3) quantization error introduced by the approximation of the smooth error curve by use of descrete amplitude levels; 4) d-c stability of the function generator. These items are discussed in detail in the following pages.

The frequency response of the compensator is 10 kcps, with optimum intensity and focus settings for the cathode-ray tube. This is determined by inserting a square wave as the function to be generated, sweeping the beam horizontally, and measuring the rise time of the square wave. This rise time has been determined to be 20 microseconds.

Of course, 10 kcps is a much higher frequency component then the compensator will ever be called upon to generate in this application. This better-than-needed performance can be put to good use. In as much as the frequency response of the function generator is so good, the beam follows well the discontinuous outline of the function mask strips. These discontinuities can be partially removed simply by defocussing the electron beam (that is, deliberately lowering the frequency response* of the function generator)! The defocussing causes the beam to smooth out the discontinuities, thus reducing the quantization error; hence a more exact replica of the desired error curve can be reproduced.

The effects of defocussing can be seen by examination of Figs. 15-20. The waveform of Figs. 15 and 16 were obtained by applying a 300 cps sine wave to the compensator input, and a

*Ref. 2, op. cit. page 74

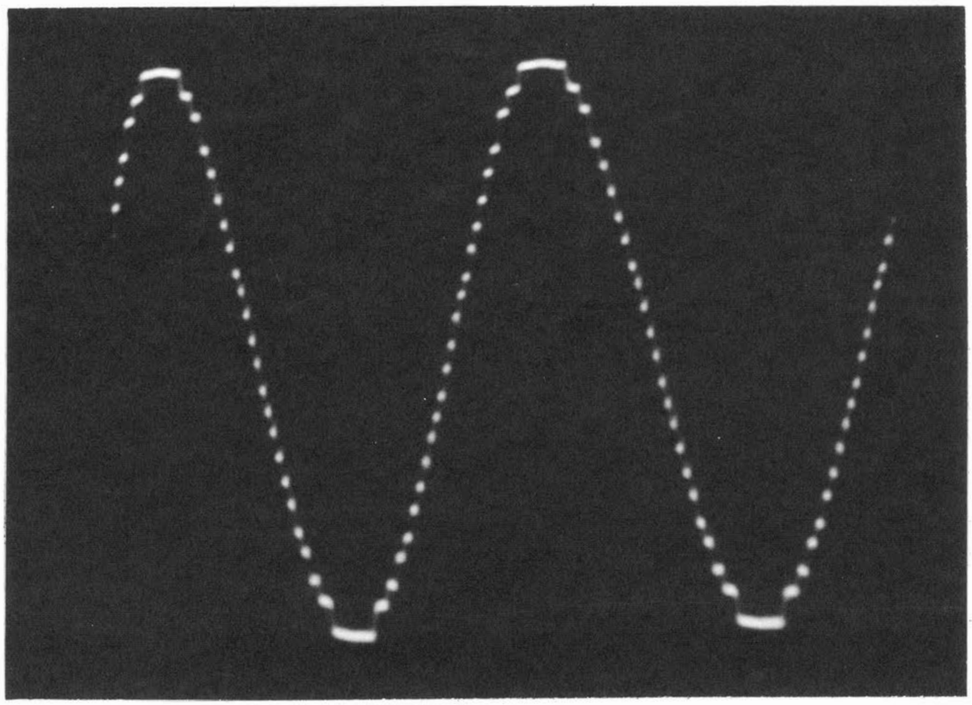


Fig. 15

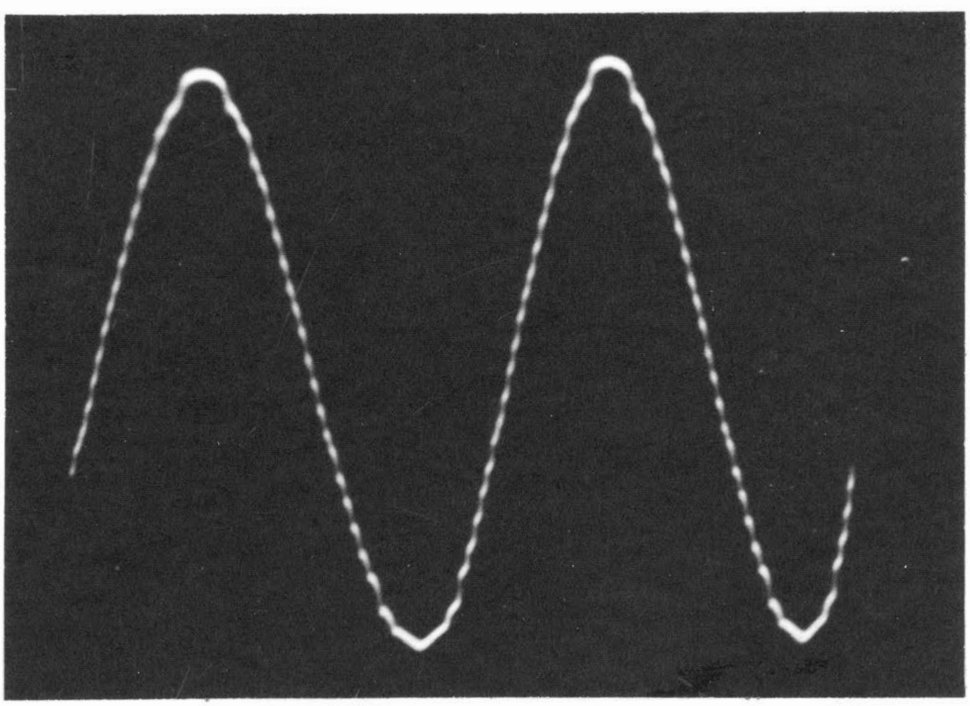


Fig. 16

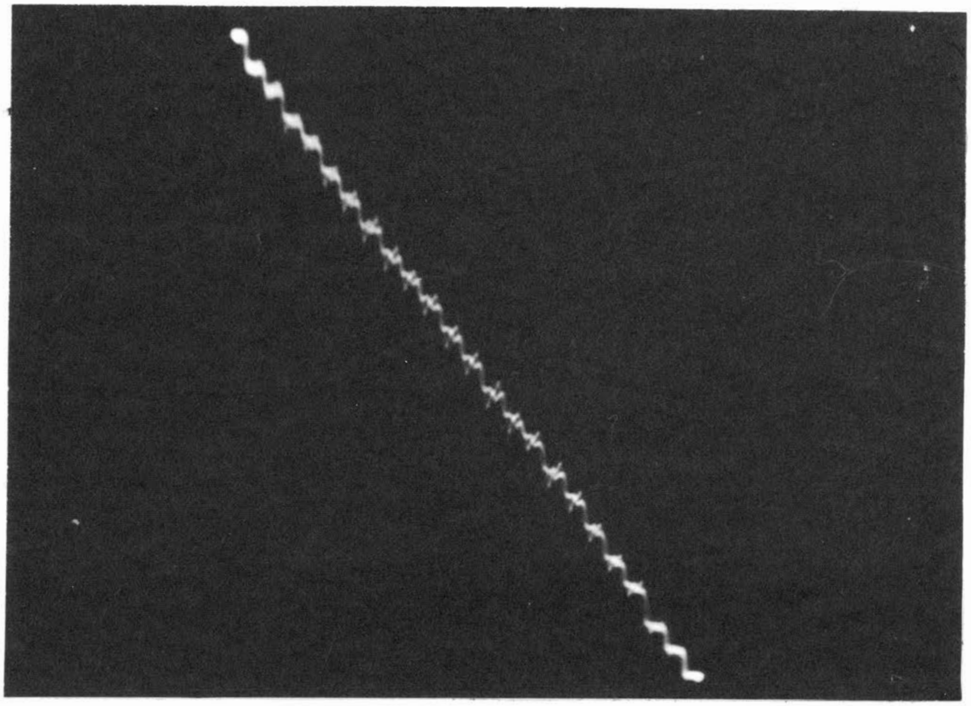


Fig. 17

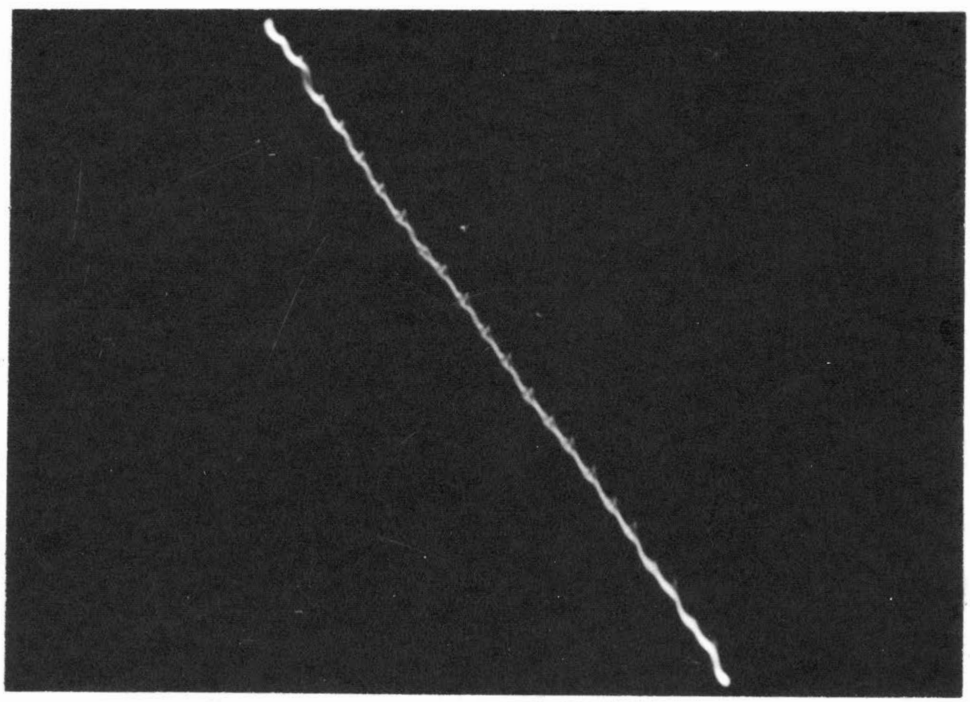


Fig. 18

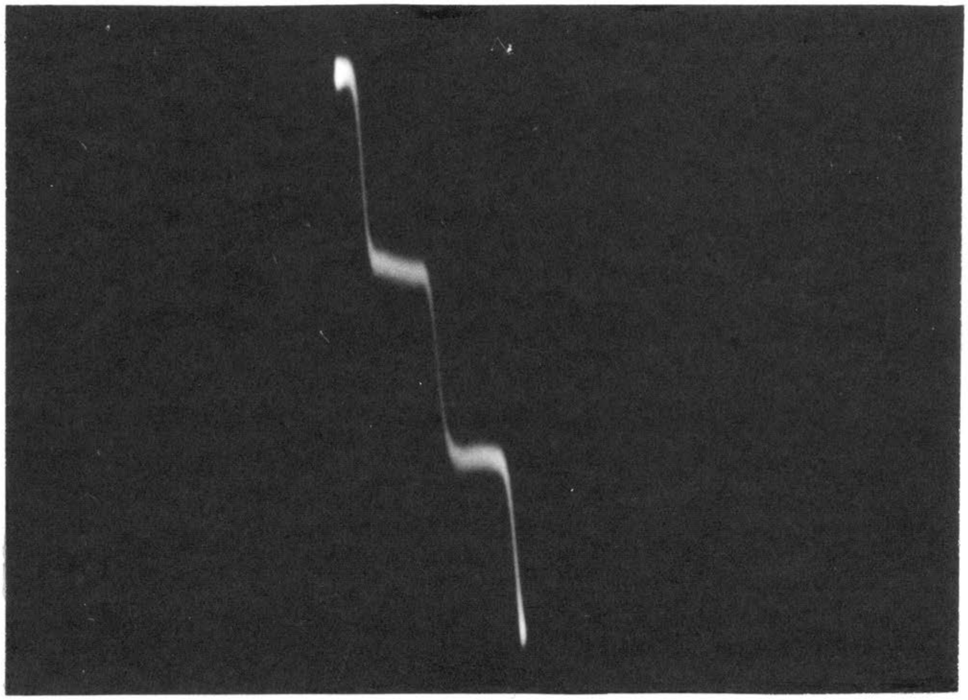


Fig. 19

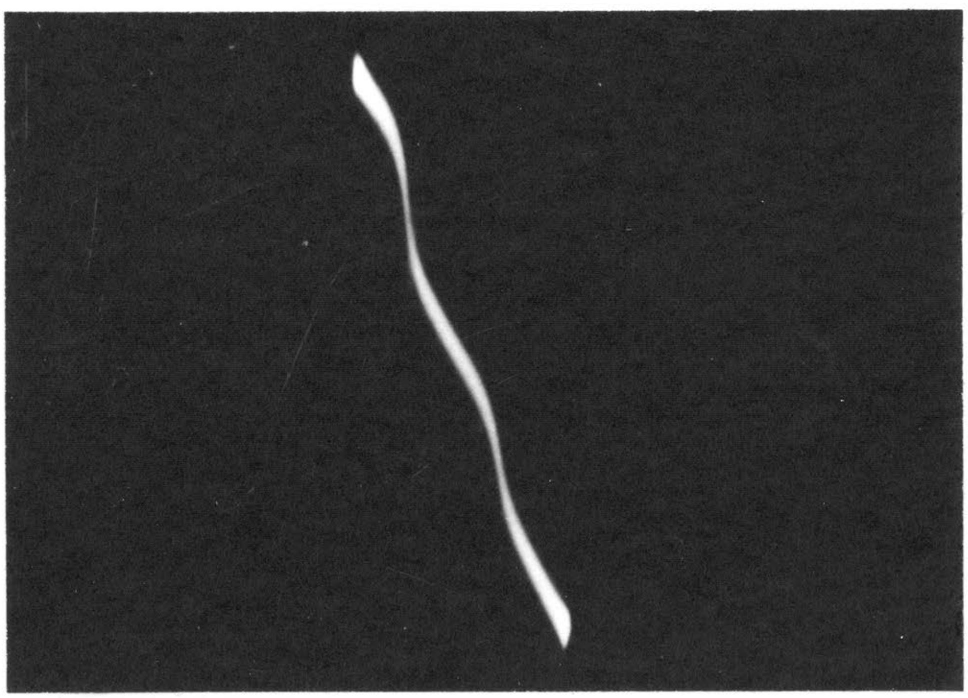
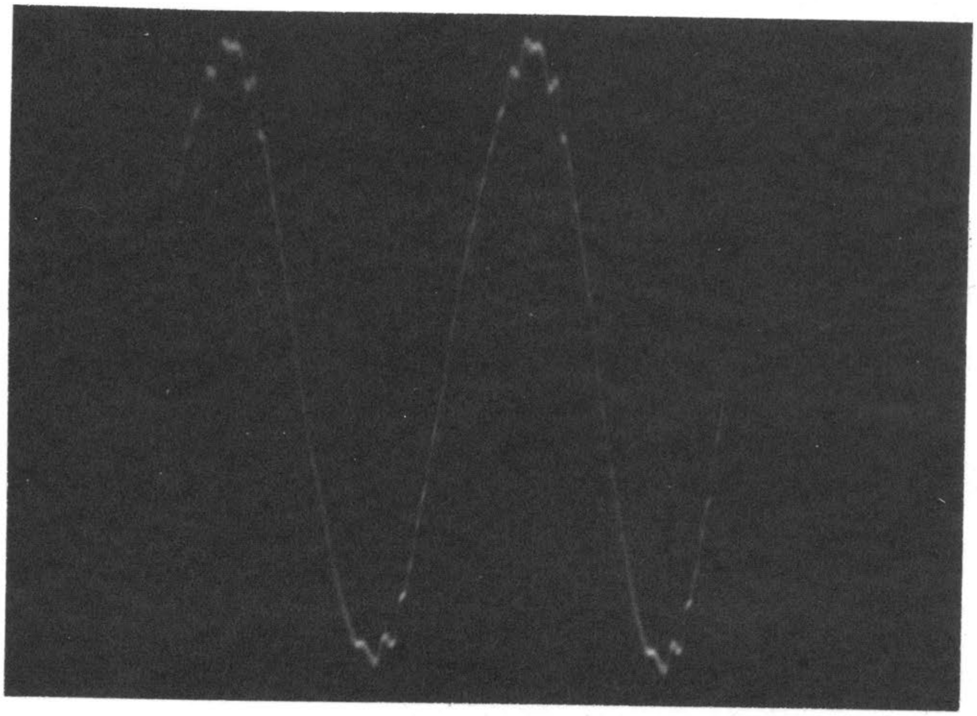
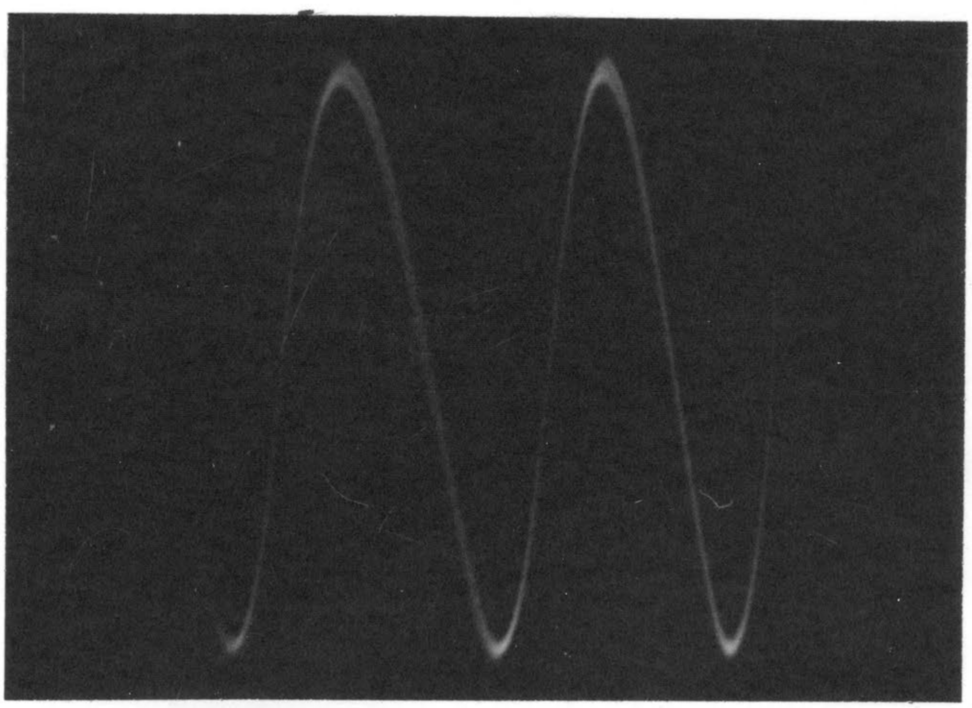


Fig. 20



3 Kcps Sine Wave
Fig. 21



30 Kcps Sine Wave
Fig. 22

linear curve on the function mask. Fig. 15 shows the error voltage output with the beam focussed and Fig. 16 the error voltage output with the beam defocussed. The same effect is demonstrated in a different way in Figs. 17 and 18 wherein are shown Lissajous' figures obtained by applying the sinusoidal input to the compensator to the horizontal plates of an oscilloscope and the error voltage output to the vertical plates of the oscilloscope. The function generator beam is focussed in Fig. 17 and defocussed in Fig. 18. More intimate details of the step-discontinuities with the beam focussed and defocussed are shown in Figs. 19 and 20 respectively. A quantitative measurement of the error introduced through the use of the function strips (instead of a continuious curve) was made by applying the compensator input (the 300 cps sine wave) and the error curve output (the approximated sine wave) through a difference amplifier. The maximum deviation of the error curve from a true sine wave was found to be 5%.

It is well at this point to note that, although a function mask of the type employed introduces the so-called quantization error, the variable feature of the mask can be utilized to remove any nonlinearity existing in the function generator itself. The function generator will reproduce a curve on the face of the cathode-ray tube to within 5%. However, one can remove the nonlinearities of the function generator simply by so adjusting the function mask until the desired output is obtained! This can be done to within the accuracy of the measuring instrument employed to measure the error voltage output.

At this point it will be rightly asked how the 5% function-generator nonlinearity can be removed by use of a function mask that introduces a 5% quantization error. The answer of course is that when one sets up a curve with the function strips the resulting output can be obtained to within 5% and the 5% function-generator nonlinearity does not cause an additional inaccuracy. If there were many more than 32 steel strips, the quantization error could be reduced to say 1%, and the error curve could be reproduced to within 1%, even though the inherent function generator nonlinearity remains 5%.

The last question to be answered regarding the accuracy of the compensator is that of d-c stability of the function generator. This is an important consideration since the error voltage at any instant is simply the d-c voltage appearing at the cathode of the last cathode-follower stage (see Fig. 14). It can be seen that marked changes in the supply voltages will cause (unwanted) changes in the error voltage. Dependency of the error voltage output upon changes in supply voltages have been minimized to a large extent by the use of push-pull amplifier stages, as previously mentioned. Satisfactory operation, with no observable d-c drift in the output, was obtained using Lambda power supplies, manufactured by Lambda Electronics Corporation of Corona, New York. These supplies have less than 10-millivolt ripple at the output and an internal impedance of approximately 10-ohms.

VII. Conclusions and Recommendations.

The single-channel compensator meets the requirements of accuracy, simplicity and ease of operation set forth in Chapter I and hence is entirely suitable for use with the PAM-FM telemetering system.

There are several things that might be done to improve the compensator. Doubling or tripling the number of function mask strips would of course decrease the quantization error. It would also be desirable to provide screw adjustments for adjusting the individual strips in order to facilitate setting up the error curve.

Regarding linearity compensation in general, it cannot be emphasized too strongly that the function to generate is the error curve, as here defined, and not the calibration curve.

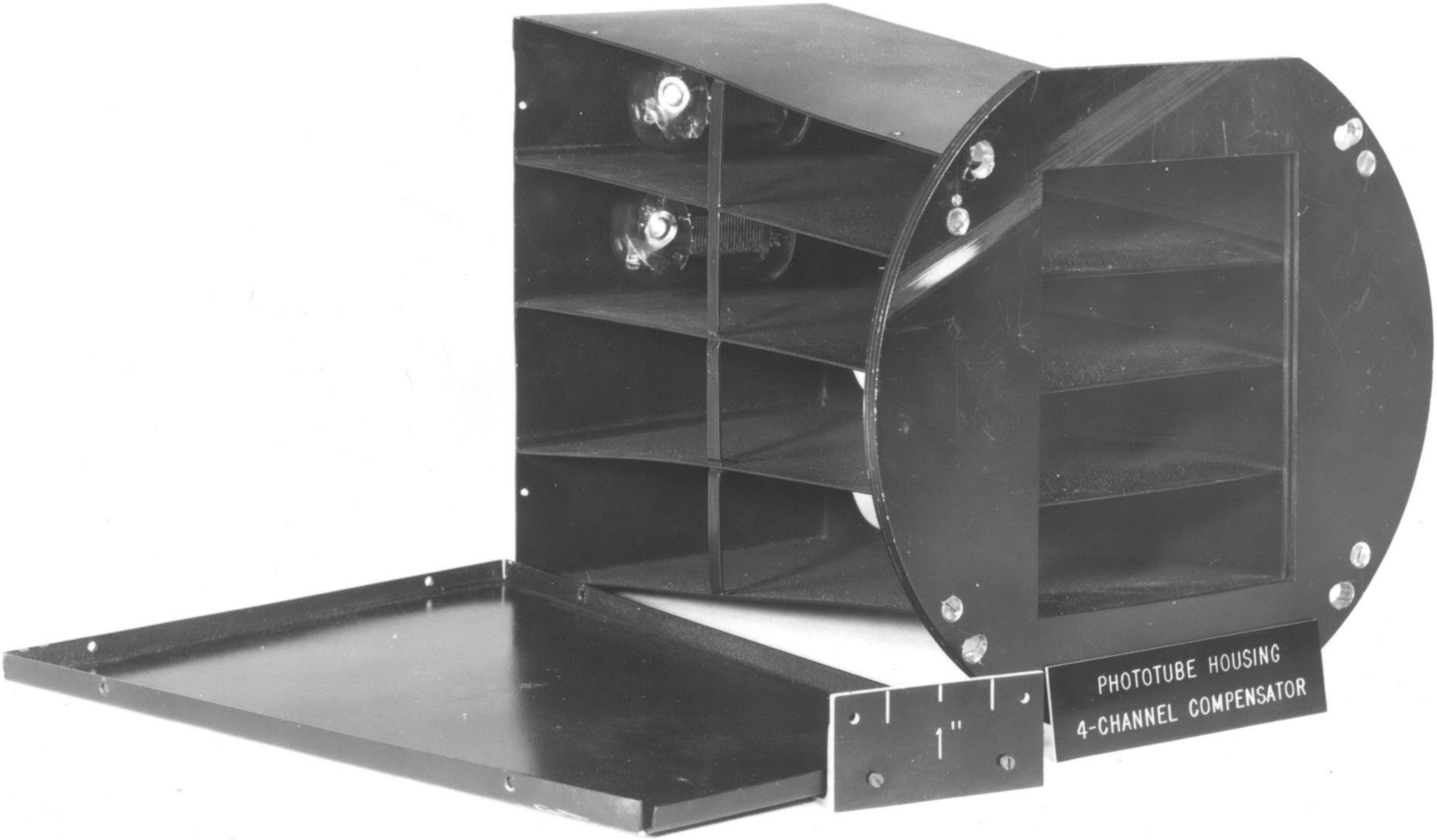
As has been pointed out, this choice relaxes the accuracy requirements for the function generator, and results in simpler, less expensive circuit design and equipment.

APPENDIX

EQUIPMENT PHOTOGRAPHS

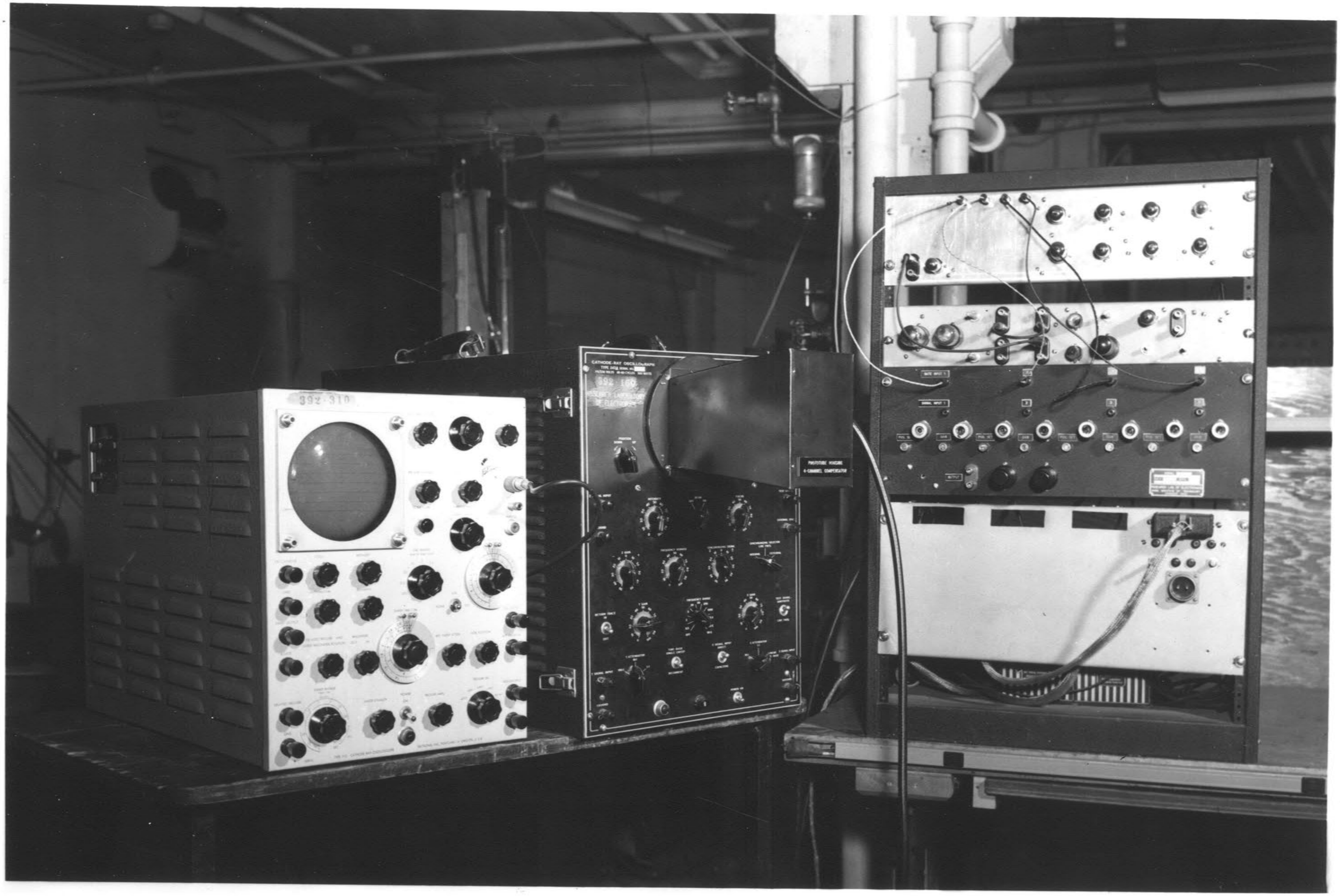
PHOTOTUBE HOUSING, 4-CHANNEL COMPENSATOR

Fig. 24



PHOTOTUBE HOUSING, 4-CHANNEL COMPENSATOR

Fig. 23



4-CHANNEL COMPENSATOR

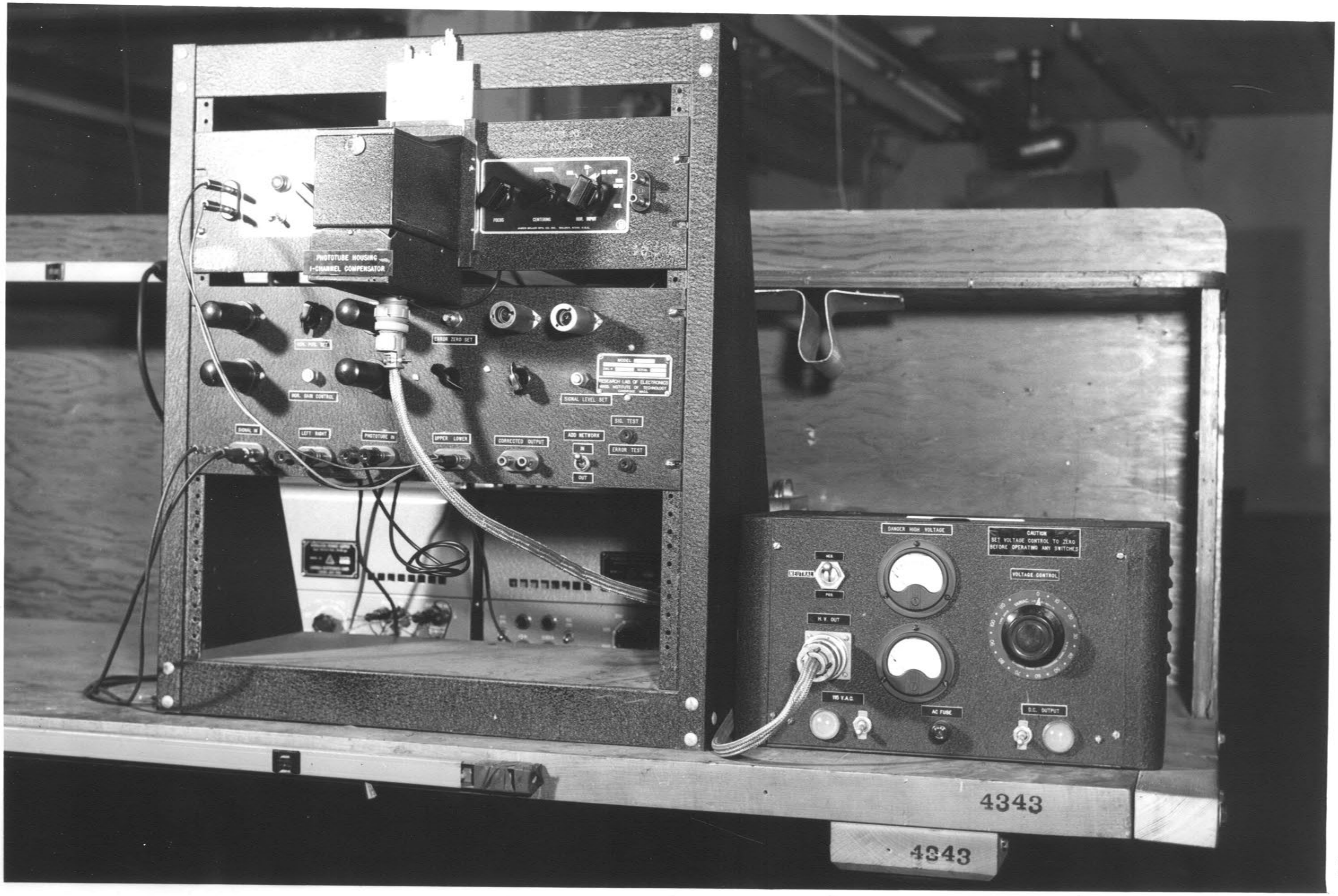
Fig. 25

PHOTOTUBE HOUSING AND FUNCTION MASK
SINGLE-CHANNEL COMPENSATOR

Fig. 26

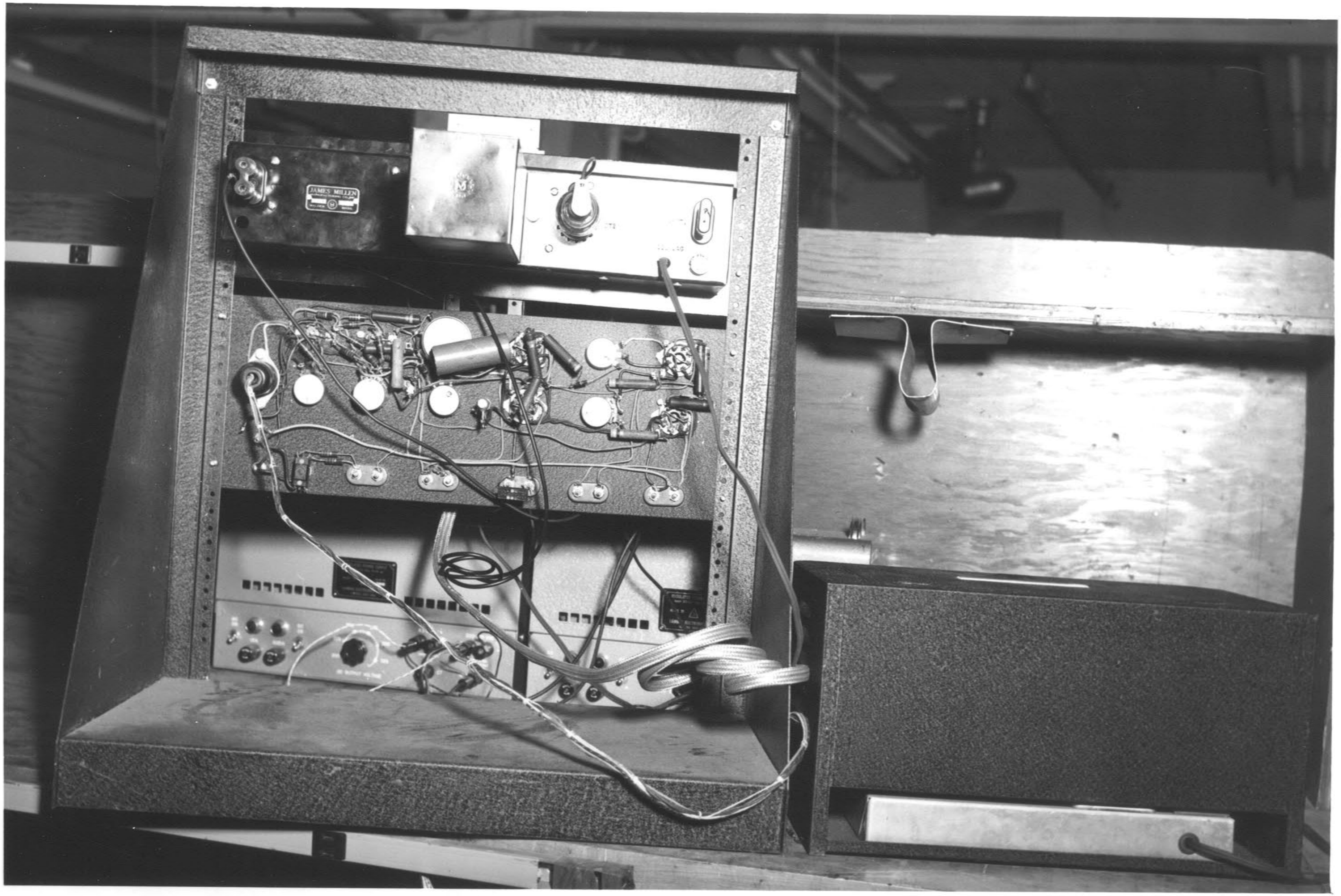
PHOTOTUBE HOUSING AND FUNCTION MASK
SINGLE-CHANNEL COMPENSATOR

Fig. 27



SINGLE-CHANNEL COMPENSATOR

Fig. 28



SINGLE-CHANNEL COMPENSATOR

Fig. 29

BIBLIOGRAPHY

Kilpatrick, Lester L., A High-Capacity Matrix-Commutated Telemetering System. S. M. Thesis, Massachusetts Institute of Technology, September, 1948.

Macnee, Alan B., An Electronic Differential Analyzer, Sc.D. Thesis, Massachusetts Institute of Technology, September, 1948.