ELECTRONIC APPARATUS FOR
THE STUDY OF SFERIC WAVEFORMS

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By

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PREFACE

Sferic studies have been made by a great number of investigators for the past thirty-three years. With the exception of the studies made at the Oklahoma Institute of Technology, none of the previous investigations have been made for the express purpose of investigating the sferics due to tornadoes, or to the sferics which are produced during their formation.

Preliminary research has indicated that tornado sferics have distinctive characteristics by which they may be identified. It is hoped that by a further study of tornado sferics these findings will be verified. Once this is accomplished a system can be divised whereby advance tornado warnings can be given in an effort to reduce the number of lives lost and property damaged. In the past communities seldom received sufficient warning because communications facilities were usually disabled by the tornados, thus preventing immediate warning from communities in the wake of the tornado.

It is therefore the purpose of this thesis to design, build and test an improved system for the recording of sferic waveforms to be used for more extensive tornado research.

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Doctor H. L. Jones for his many helpful suggestions and assistance in the preparation of this material. Thanks are also due to Professor A. Naeter and other members of the school for their co-operation in obtaining the required components for the construction of the equipment.

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I INTRODUCTION

A number of different methods have been devised for the study of sferic waveforms. Most methods that have been used have characteristics which either completely prevent or seriously limit their use for a general study of sferic disturbances, while others require ponderous and elaborate antenna systems and receiving equipment.[1,2]

In reviewing the literature regarding the nature of sferic waveforms it is difficult to determine the exact design requirements for a system to be used for further sferic investigations. Appleton, Watt, and Herd came to the conclusion that the duration of sferics in general were less than 2000 microseconds. The antenna used in their experiments had a length of 500 meters and an effective height of 15 meters. The capacitance of the antenna to ground was 2770 micro-microfarads and the input resistance of the measuring equipment was kept at 10 megohms. In order to maintain the desired time constant of the antenna circuit special sulphur insulators were necessary.[3] Experiments performed in Australia indicated that the duration of sferics may be as great as one-half second. The sferic waveforms, however, were recorded with a string galvanometer. Other observers concluded that the duration of sferics may be as long as one-fourth second.[4]

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[1] G. H. Munro and L. G. H. Husley, "Shipboard Observations With a Cathode-Ray Direction Finder Between England and Australia." J.I.E.E. Vol. 71, p. 488.

[2] E. V. Appleton, R. A. Watson Watt and J. F. Herd, "On The Nature of Atmospherics - II", Proceedings of the Royal Society of London. Ser. A. Vol. III, pp. 615-676.

[3] Ibid.

[4] H. Hubert and H. Barberon, "Preliminary Study of Atmospherics by Cathode-Ray Oscillographs." Comptes Rendus, Vol. 207, pp. 400-402, (1938).

The frequency range containing the greatest amount of energy was found to be between 1 and 20 kilocycles per second. Therefore it is believed that a system having uniform response from less than 20 cycles per second to more than 200 kilocycles per second will be satisfactory for a general study of sferics except those which occur very close to the receiving antenna.[5,6]

In some cases local sferic disturbances cause a change in the average potential gradient above the earth immediately following their transition. This condition does not exist however, when the disturbance occurs at considerable distances from the antenna.

The general design of the equipment which is to handle the signal to be observed or recorded, is based on the assumption that it is desired to obtain a plot of voltage at some point in space relative to the ground. Such a requirement could be met if the input terminals of an amplifier having an infinite input impedance were connected to an isolated antenna and to ground.

The equivalent circuit of an antenna connected to a receiver may be represented as a voltage source, the internal impedance of which is equal to the antenna impedance connected to the receiver input.[7] Thus, it can be seen that if the antenna impedance is very small in comparison to the receiver input impedance, the voltage across the receiver input would be essentially equal to that of the voltage source.

The impedance of a grounded antenna which is shorter than one-quarter of a wavelength, can be represented as a capacitive reactance.[8]

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[5] R. A. Watson Watt, J. F. Herd and F. E. Lutkin, "On The Nature of Atmospherics", Proceedings of the Royal Society of London, Ser. A, Vol. 162, pp. 267-291, (1937).

[6] Appleton, Watson Watt and Herd, Loc. cit.

[7] F. E. Terman, Radio Engineers' Handbook, pp. 785-786.

[8] Ibid. p. 776.

Since the shortest wavelength to be considered is approximately 5000 feet, no resonant effects should exist in the antenna circuit providing the receiver input is not inductive and the antenna is relatively short. Therefore if an amplifier having a purely resistive input impedance is connected to a short antenna, the voltage E_{rec}, delivered to the input of the amplifier will be

$$E_{rec} = \frac{E_I R_{rec}}{R_{rec} - j \dfrac{1}{\omega C_{ant}}}$$

where E_I is the voltage induced in the antenna. From figure 1, it can be seen that both the magnitude and phase of the receiver input voltage, E_{rec}, is not independent of the frequency of E_I.

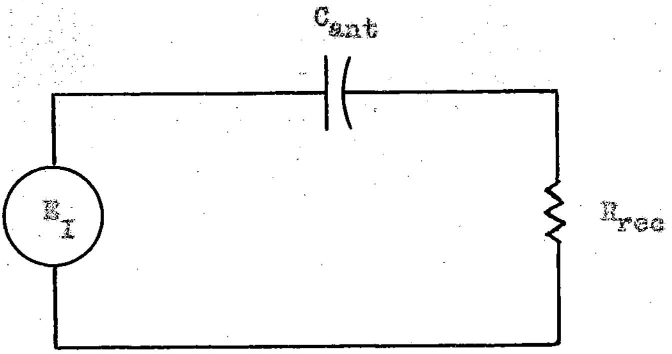

Figure I

Theoretically, uniform response down to approximately 240 cycles per second could be attained by the use of a 10 foot vertical antenna which is 0.6 inches in diameter, the lower end of which is 2.4 inches from the ground, and is connected to a receiver with an input resistance of 200 megohms.[9]

The circuit shown in figure 1 may be a simple differentiating circuit pro-

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[9] Appendix A

vided that the RC time constant is made small in comparison to the period of the highest frequency component of the voltage E_I, in which case E_{rec} is much less than E_I.[10] Such an arrangement could be used to obtain E_I providing the voltage across R_{rec} would later be integrated. This method is not considered desirable from the practical viewpoint because of the low receiver input voltage which results from the necessarily low value of receiver input resistance.

In order to simplify the photographic recording of the waveforms and to conserve film, it was considered desirable to provide a scheme whereby film would not be used unless a signal of sufficient amplitude is received. After the waveform is recorded, the film in the camera is to be advanced and made ready for the next sferic disturbance. Past experience has demonstrated that it is likewise necessary to record other pertinent data on the film in addition to the waveform.

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[10] F. E. Terman, Radio Engineering, p. 599.

II DESIGN CONSIDERATIONS

From the viewpoint of installation and maintainance, it was decided that a whip antenna would be the most satisfactory for this application. This would eliminate the use of the high towers or poles necessary for the support of a long antenna, as well as reducing the number of required insulators to a minimum. It must be kept in mind that the nondirectional pattern of a vertical wire is also a decided advantage. However it must also be noted that the impedance of a short antenna is high, thereby requiring the receiver to have a very high input impedance if relatively low frequencies are to be received without the attendant phase and frequency distortion. When such an antenna is used, the receiver input impedance must be at least 2000 megohms if negligible phase and frequency distortion is to be had at frequencies down to 20 cycles per second. It was not deemed wise to try to maintain such a large input impedance because an electrometer tube requires special precautions in order to keep both the tube and the associated circuits clean and dry. These factors would be in addition to the much higher cost. Therefore it was decided that the most practical method of obtaining a high input impedance and reasonable stability was by the use of a cathode follower at the base of the antenna. The high input impedance can thus be obtained by using conventional components. A cathode follower at the base of the antenna would also make it possible to place the antenna some distance from any region of power line interference. It was decided that a cathode follower input impedance of the order of 500 megohms would be satisfactory so far as stability is concerned, providing a few simple precautions are taken. Since this input impedance is not adequate to give uniform response down to a 20 cycles per second some form of correcting network or amplifier is also required. A simple RC or RL network can not be used alone to obtain an overall uniform response. The use of inverse feedback with the correct characteristics on an amplifier appeared to offer the easiest means of accomplishing the desired correction.

The gain of an amplifier employing feedback is given by the equation

$$A' = \frac{A}{1 - A\beta}$$

where A' equals the gain of the amplifier with feedback, A equals the gain without feedback, and β equals the portion of the output voltage that is fed back to the input of the amplifier. It can be seen that if $A\beta$ is much greater than 1, A' is essentially equal to $\frac{1}{\beta}$.[11] In the equation β is negative when the feedback voltage opposes the input voltage or in inverse feedback circuits. Therefore by making β in an inverse feedback amplifier proportional to

$$\frac{R_{rec}}{R_{rec} - j\,\frac{1}{\omega\ C_{ant}}}$$

the frequency and phase distortion may be corrected for in all cases in which $A\beta$ is much greater than unity.

It is not easy to determine the signal strength of sferics from the published literature. It was originally the opinion of the author that some voltage gain would be required in addition to that of the amplifiers employed in the DuMont Type 250 cathode-ray oscillograph. It was later learned that a voltage of the order of 10 to 20 millivolts is induced in a 15 foot vertical wire from sferics located 2000 miles from the receiver. Nevertheless, it was decided that

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[11] *Ibid.* pp. 311-312.

that a two stage amplifier would be desirable to supplement the gain of the frequency and phase correcting amplifier.

Since it is necessary to conserve photographic film, it was decided to construct a trigger circuit that would prevent the exposure of the film unless a signal with an amplitude above a predetermined value was received.

The camera to be used to record the waveforms and other pertinent data is a modified 35 millimeter theodolite camera. In order for the camera to be used as desired it was necessary to make a number of major modification. The modifications required were; provisions for single frame exposure; 110 volt alternating current operation instead of a 24 volt direct current; the removal of a shield which produced an approximate square field of coverage; lens mount modification for proper focusing; and an arrangement to hold the shutter open when desired. It was considered more feasible to leave the shutter open and to trigger the sweep circuit rather than to have the beam on continously while the shutter is being operated. The main reason for this decision is that the inertia of the shutter is too great to permit rapid transition. The possibility of burning the screen is also greatly reduced by this method of operation. The modifications of the camera were carried out by Mr. J. A. Woods of the Engineering and Research and Experiment Station.

The design as outlined makes it possible to record any information that may be helpful in the analysis of the waveforms. For example, it may be necessary to have a record of the direction of the received signal, the date, the time of day, gain control settings of the amplifiers, and the period of the sweep circuit.

The direction indication of the received signal will appear on a two inch cathode-ray tube located near the waveform oscillograph. The direction finding equipment is now being developed by Mr. Thomas H. Thomason. The date and control settings can be placed on a small card and photographed along with the waveform and direction indication. The time can be recorded from a small clock placed in the field of the camera. The card bearing the control settings and the clock may be illuminated by a small strobotron tube when the signal is received.

III DESIGN

A block diagram indicating the arrangement of equipment for use in sferic waveform research is shown in figure 2.

A Antenna Cathode Follower

The schematic diagram of the antenna cathode follower is shown in figure 3. A 6AK5 pentode tube was chosen for the cathode follower because of its relatively high transconductance, special grid construction, its small physical size, and its low input capacitance. Since it was considered best to keep 60 cycle interference as far from the antenna as possible, direct current was chosen for the heater supply. Plate voltage could be supplied from batteries at the cathode follower or through a conductor in a shielded pair from the amplifier. The grid leak resistance used is as large as could be readily obtained. The screen grid is heavily by-passed to the cathode in order to provide uniform gain down to very low frequencies. By-passing the screen to the cathode offers the advantage of reducing the input capacitance by a factor of (1-A), where A is the amplification of the cathode follower.[12] The capacitance from the antenna input lead to case is also reduced by the same factor in comparison to what it would be, had the case been grounded. This is due to the fact that the metal case used to house the cathode follower is connected to the cathode of the 6AK5. It is estimated that the input capacitance would be of the order of 1 micromicrofarad if A were made equal to 0.9.

Similarly the input resistance would be equal to the grid to cathode resistance divided by (1-A) or would be in the order of 220 megohms. Thus it can

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[12] G. E. Valley and H. Wallman, Vacuum Tube Amplifiers, M.I.T. Radiation Laboratory Series, Vol. 18, pp. 107-108.

be seen that an amplification close to unity is desirable if a very high input impedance is to be obtained.

The approximate amplification may be calculated by the relation,

$$A = \frac{Gm\ R}{1 + Gm\ R}$$

where R equals the value of the resistor between cathode and ground and Gm is the transconductance of the tube.[13] If Gm equals 4000 micromhos and R $=$ 10,000 ohms, A is approximately equal to 0.97. Theoretically, a 10% variation in Gm will produce a variation in A of 0.246%. Any appreciable variation in the input impedance of the cathode follower would probably be due to temperature variations of the grid leak resistor, assuming that the supply voltages are constant.[14] In order to reduce the effects of variations in humidity the housing of the unit can easily be made waterproof, with the exception of the 6 prong Jones plug used for supplying power. The voltage divider used to provide the correct bias was preferable to the usual method of self-biasing because of the slightly higher input impedance that could be obtained.

The output resistance calculated from the relationship

$$R_o' = R(1-A)$$

is found to be 300 ohms.[15]

B <u>Voltage Amplifier</u>

As shown in figure 4 the voltage amplifier consists of two stages of amplification with inverse feedback.

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[13] *Ibid.*

[14] J. F. Blackburn, *Compontents Handbook*, M.I.T. *Radiation Laboratory Series*, Vol. 17, pp. 47-63.

[15] Valley and Wallman, *loc. cit.*

6AG5 pentodes were used because of their relatively high ratio of transconductance to the sum of the input and output capacitances. The gain of a pentode amplifier stage with a cathode resistor which is not by-passed is approximately

$$G \doteq \frac{Gm\, R_l}{1 + Gm\, R_k}$$

where Gm, R_l and R_k are the tube transconductance, plate load resistance and cathode to ground resistance, respectively. The maximum amplification of the first stage is calculated to be 25, and that of the second stage, 42.4. Therefore the overall midband amplification of the two stages should be in the order of the product of these two values, or 1100.

The half power point of the coupling circuit is approximately 1.6 cycles per second. The cathode resistor of VT3 was not by-passed because it was not thought that the additional gain that could be obtained was necessary.

It was decided that inverse feedback could be used to a greater advantage than any other method of gain control. By applying inverse feedback to the first two stages, distortion and circuit noise is reduced. Also this design provides a means of low frequency compensation for the coupling network to the following circuits. This is due to the characteristics of the feedback circuit. By the proper choice of the feedback blocking capacitor with respect to the resistance of the feedback circuit the gain of the amplifier can be made to compensate for the characteristic decrease of voltage applied to the grid of the next tube for the lower frequencies. This can be shown from the relationship,

$$E_{14} \doteq \frac{E_{O3}\, R_{g1}}{R_{g1} - j\,\dfrac{1}{\omega C_c}}$$

where E_{14} is the signal voltage on the grid of VT4, E_{O3} is the signal voltage on the plate of tube VT3, R_{gl} is the grid leak resistance for VT4 and C_c is the capacitance of the coupling condenser.

The feedback factor, β, is determined by the relationship,

$$\beta = K \frac{R_{fb}}{R_{fb} - j \dfrac{1}{\omega C_{fb}}}$$

where R_{fb} is the total resistance in the feedback circuit including the effective resistance from the cathode of VT2 to ground under operating conditions. C_{fb} is the feedback blocking capacitor and K is the ratio of the effective resistance from the cathode of VT2 to ground to the total effective resistance in the feedback circuit. It can be seen that if the amplification of VT2 and VT3 is equal to $\frac{1}{\beta}$, then the voltage applied to the grid of VT4 will be proportional to

$$A = \frac{1}{\beta} \cdot \frac{R_{gl}}{R_{gl} - j \dfrac{1}{\omega C_{fb}}}$$

or

$$A = \frac{R_{gl}\left(R_{fb} - j \dfrac{1}{\omega C_{fb}}\right)}{K R_{fb}\left(R_{gl} - j \dfrac{1}{\omega C_c}\right)}$$

It is evident from these equations that if the impedance of the feedback circuit is made proportional to that of the coupling circuit, compensation for the coupling circuit can be effected to very low values of frequency.

C Compensating Amplifier for Antenna Circuit

The antenna circuit compensating amplifier was designed for the sole purpose of correcting the frequency and phase distortion originating in the antenna circuit. Since it was desired to compensate to very low values of frequency the circuit was designed to obtain maximum possible feedback.

Feedback over an odd number of stages was not considered practical due to the very low input-circuit impedance that would result when feedback was applied to the control grid. This consideration was supported by the fact that the input impedance would also be frequency sensitive. However feedback over an odd number of stages without the above disadvantages could be accomplished by feeding the signal back to the screen grid of the first tube of the circuit. This method however, would result in a feedback factor that would be determined largely by the ratio of the screen grid transconductance to the transconductance of the control grid. This ratio is very small. Therefore it was concluded that the most practical solution would be to institute feedback from two amplifier stages to the cathode of the first stage.

In order to compensate for the differences in the antenna circuit constants, the frequency characteristics of the feedback circuit were made variable. Since the antenna capacitance would probably be of the order of 20 to 30 micromicrofarads if the antenna is located very close to the ground, and the antenna cathode follower input resistance would be several hundred megohms, good design would necessitate the use of a cathode follower in the feedback circuit in order that a variable capacitor could be employed to vary the feedback characteristics.

It was found necessary to employ two cathode followers in cascade in order to obtain the required input impedance so that a 50 micromicrofarad variable capcaitor could be used to vary the compensation as shown in figure 4. With a single cathode follower in the feedback circuit the gain of the cathode follower was of the order of 0.4. This was primarily due to its low effective load impedance. The second cathode follower was designed to have an output impedance of the order of 100 ohms.[16] This was effected by the use of the two sections of a 6J6 connected in parallel. Direct coupling was used between the cathode followers and between the last cathode follower and the cathode of the tube VT4.

Bias for VT4 is obtained from a tap on the load resistor of the second cathode follower. It was found necessary in square wave testing to decouple the biasing return. The dc. cathode-to-ground voltage of both cathode followers was purposely made high so that the output voltage of the amplifier would not be limited to a low value by cutoff of the cathode followers.

Due to the fact that the cathode current of VT4 is small in comparison to the current drawn by the second cathode follower, VT4 is operated essentially with fixed bias. For this reason the grid leak resistor or VT4 was limited to .3 megohms and compensation provided in the feedback circuit of the voltage amplifier.

D Output Stage

A cathode follower was used in the output stage principally because of its inherent low output impedance. This characteristic is necessary if it is desired to place the waveform oscillograph and triggering circuit some distance from the amplifier.

E Trigger Circuit

The circuit used to trigger the sweep of the DuMont Type 250 cathode-ray oscillograph obtains its signal from the output of the voltage and antenna circuit compensation amplifiers as shown in figure 5. Since it is desired to obtain records of sferics which start either in a positive or negative direction,

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[16] D. L. Shapiro, The Graphical Design of Cathode-Output Amplifiers, *Proc. IRE*, Vol. 32, May 1944, pp. 263-267.

a phase inverter and rectifier are used as shown in figure 5, so as to produce voltage of one polarity regardless of the polarity of the sferic. The output of the 6J6 phase inverter, is applied to phase inverter, is applied to the plates of a 6AL5 dual diode. The rectified output of the 6AL5 is coupled to the input of a 6AG5 voltage amplifier. The output of the voltage amplifier is than applied to the control grid of a 6AU6 blocking amplifier. The blocking amplifier serves to prevent the passing of the signal during the time the sferic waveform is being photographed and the period of time required to advance the film in the camera.

As seen in figure 5, the cathode of the blocking amplifier tube VT12 has a cathode resistor in common with the normally non-conducting tube, VT13, of the monostable multivibrator. Due to the bias applied to the grid of VT13, the common cathode resistor normally conducts only the current of the blocking amplifier. However if the blocking amplifier has sufficient output to cause the monostable multivibrator to operate, VT12 will be cut off because of the high current being passed by VT13. The suppressor grid of the 6AU6 is connected to ground instead of the cathode so as to further increase the blocking action of the circuit.

As shown in figure 5, the monostable multivabrator employs two 6AG5's, VT13, and VT14. With VT14 conducting and VT13 cut off by the bias voltage obtained from P_1, VT12 will operate as a voltage amplifier. When a signal is received the control grid of VT13 is driven in the positive direction. If the signal is of sufficient amplitude, VT13 will begin to conduct and the control grid of VT14 will be driven negative. The negative voltage applied to the grid of VT14 will in turn tend to drive the control grid of VT13 further in the positive direction. When this occurs, the voltage on the cathode of VT13 is increased, and as a result the plate current of VT12 will be cut off. This action tends to further increase the voltage applied to the control grid of VT13. As the charging current of C_{25} and C_{26} decreases, the control grid of VT13 will tend to become more negative. When the plate current in VT13 begins to decrease the control grid of VT14 is driven in the positive direction, thus causing a more negative voltage to be applied to the control grid of VT13 through C_{25} and C_{26}.

F Trigger Mechanism for the Sweep of the Cathode-Ray Oscillograph

The driven sweep circuit of the DuMont Type 250 cathode-ray oscillograph is constructed in such a manner that the sweep may be initiated by either a positive or negative voltage applied to the external synchronization input terminals. Consequently a triggering pulse may be derived from either the plate or cathode of VT13 or VT14. This pulse is employed to trigger the strobotron tube and the direction indicator cathode-ray tube in addition to the triggering of the driven sweep of the waveform oscillograph.

G Camera Circuit

A 6J6, VT15 is used to energize the coil of a relay that in turn applies 110 volts, 60 cycle, to a solenoid in the camera for moving the film up one frame each time it is energized. As indicated in figure 5, the cathode of VT15 is connected to the cathode of VT14 and the grid of VT15 is connected to the cathode of VT13. Normally VT15 is cut off due to the negative voltage on its grid with respect to its cathode. When the monostable multivibrator operates, VT15 will begin to energize the relay coil and operate the solenoid that moves the film. Due to the inductance of the relay coil and inertia of the armature it is believed that sufficient time for the sweep to be completed will elapse before the film is actually moved. If this is not the case, a greater delay can be obtained by simply inserting a capacitor between the grid and cathode of VT15. In this case the additional time would be due to the time required for the capacitor to charge to such a value as to permit VT15 to conduct. The time required to denergize the relay in this case would also be increased. Should this additional time be undesirable, it can be greatly reduced by placing a diode or other rectifier across the resistor R58 as shown dotted in figure 5.

H Strobotron Circuit

The light source for illuminating the clock and data card for the recording of the time and other pertinent information is a type 631P1 strobotron located near the cathode-ray oscillograph. The power is supplied from the unregulated side of the power supply as shown in figure 7. The 60,000 ohm resistor between the power supply and the strobotron circuit is for the purpose of isolating the two circuits and limiting the voltage across the strobotron to approximately 300 volts. The circuit arrangement for the strobotron is similar to that used in stroboscope circuits.[17]

I Power Supplies

Two regulated power supplies are used so as to reduce interaction between the circuits. As shown in figure 6, the regulating circuits employ a VR150, a 6AC7 and a 6Y6. The circuit is the common type which uses the VR150 to provide a reference voltage, the 6AC7 as a direct coupled amplifier and the 6Y6 as the series current-limiting tube.[18] The capacitor placed between the ungrounded output terminal and the control grid of 6AC7 is for the purpose of effectively applying the full alternating voltage component of the power supply output to the input of the voltage amplifier. It has the effect of decreasing the output impedance of the regulator, particularly at higher frequencies. The resistor between the voltage divider across the regulated output and the control grid of 6AC7 increases this effect to a lower frequency. The heater circuit for all of the tubes in the two regulators are powered from the 6.3 volt winding of one of the transformers. The center tap of the winding is connected to the anode of

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[17] R. C. Hilliard, "Gaseous Tubes and Applications", Electronics, Vol. 19, (March 1946), pp. 122-127.

[18] H. J. Reich, Theory and Applications of Electron Tubes, pp. 592-594.

one of the VR150 tubes, thereby allowing the heater-to-cathode voltage of the 6Y6's to be only 150 volts when the regulated output voltage is 300 volts. This arrangement allows the heater-to-cathode voltage of the 6Y6's to remain under the maximum rating of 180 volts.

IV CONSTRUCTION

A Antenna Cathode Follower

The antenna cathode follower was constructed in the housing of a war surplus M-299 microphone adapter. A 3/4 inch diameter polystyrene rod was used to insulate the antenna leading from the cathode follower housing. A six prong Jones plug is used to supply the required power to the unit.

B Voltage Amplifier and Compensating Amplifier for the Antenna Circuit

The voltage amplifier and antenna circuit compensating amplifier was constructed in a 7x14x8 inch cabinet. All power to the unit is supplied through a multiconductor cable from the trigger and power supply chassis.

C Trigger Circuit and Power Supply

A 9x18x12 inch metal cabinet was used to house the trigger circuit and power supply. A 10 prong Jones plug was mounted on the rear of the chassis for supplying the required power to the voltage amplifier and antenna-circuit compensating amplifier. A conventional 110 volt recessed male plug and an octal socket were also mounted on the rear of the chassis for the power input and trigger circuit output connections respectively.

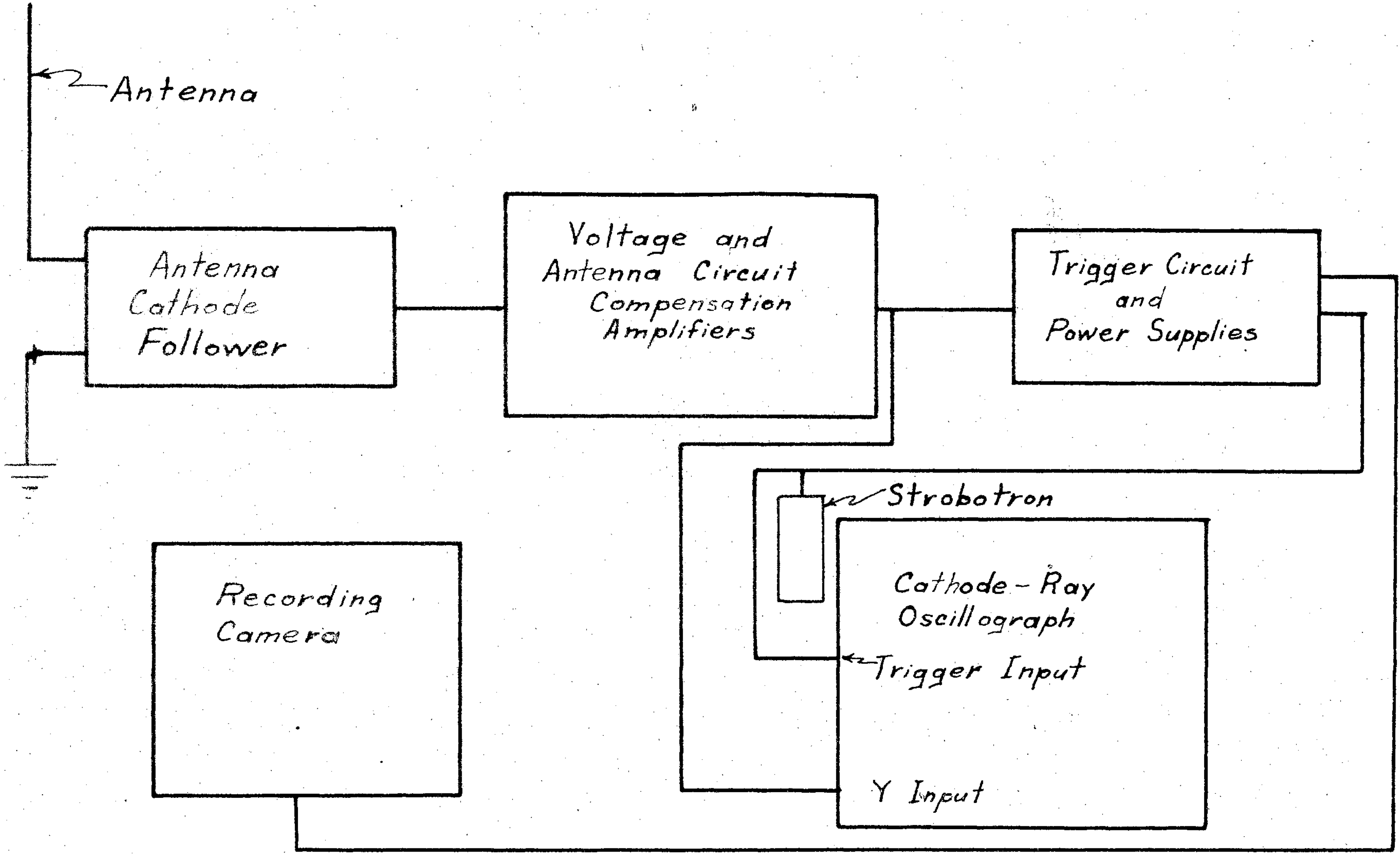

Antenna
Antenna Cathode Follower
Voltage and Antenna Circuit Compensation Amplifiers
Trigger Circuit and Power Supplies
Strobotron
Cathode-Ray Oscillograph
Trigger Input
Y Input
Recording Camera

Figure 2

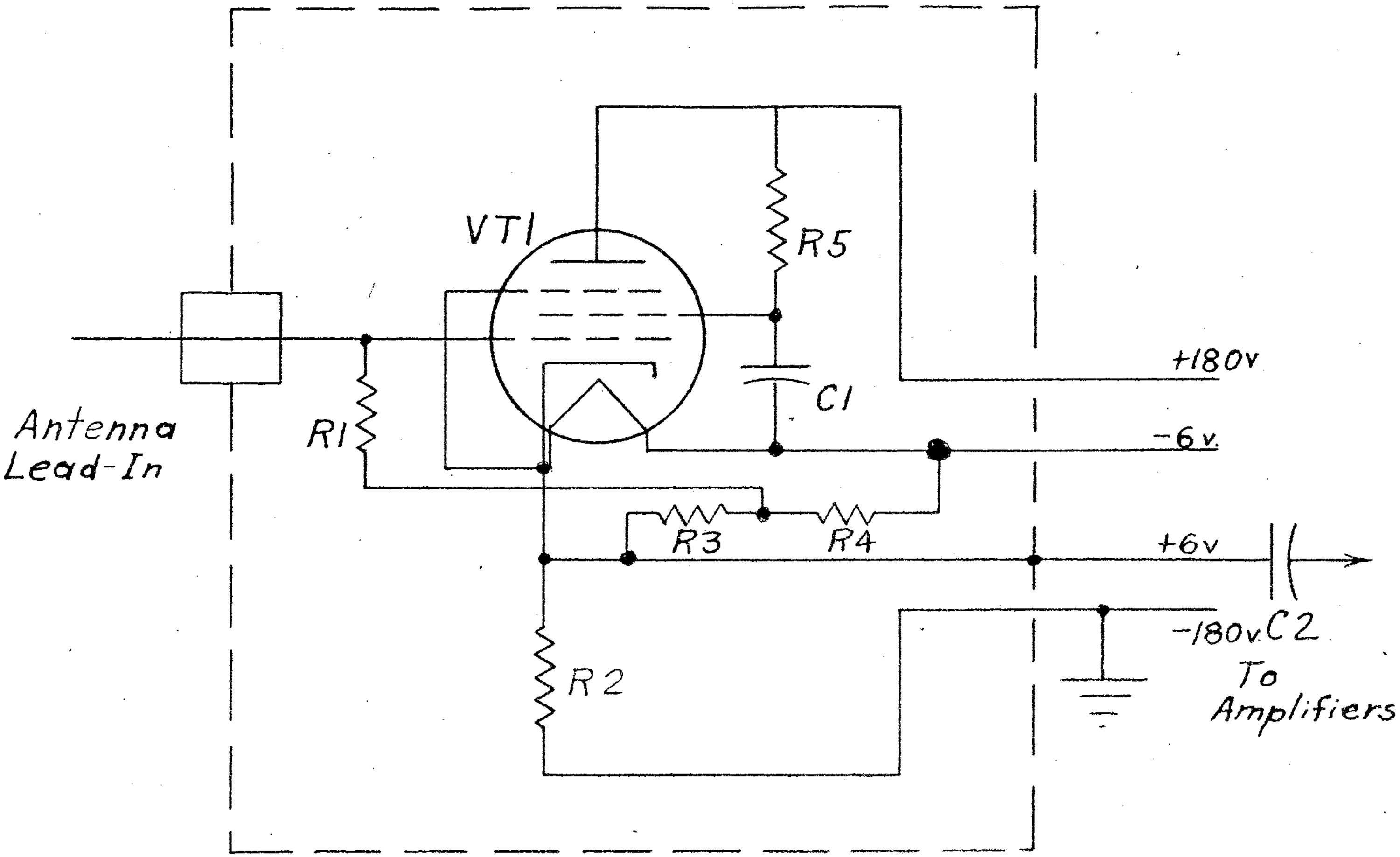
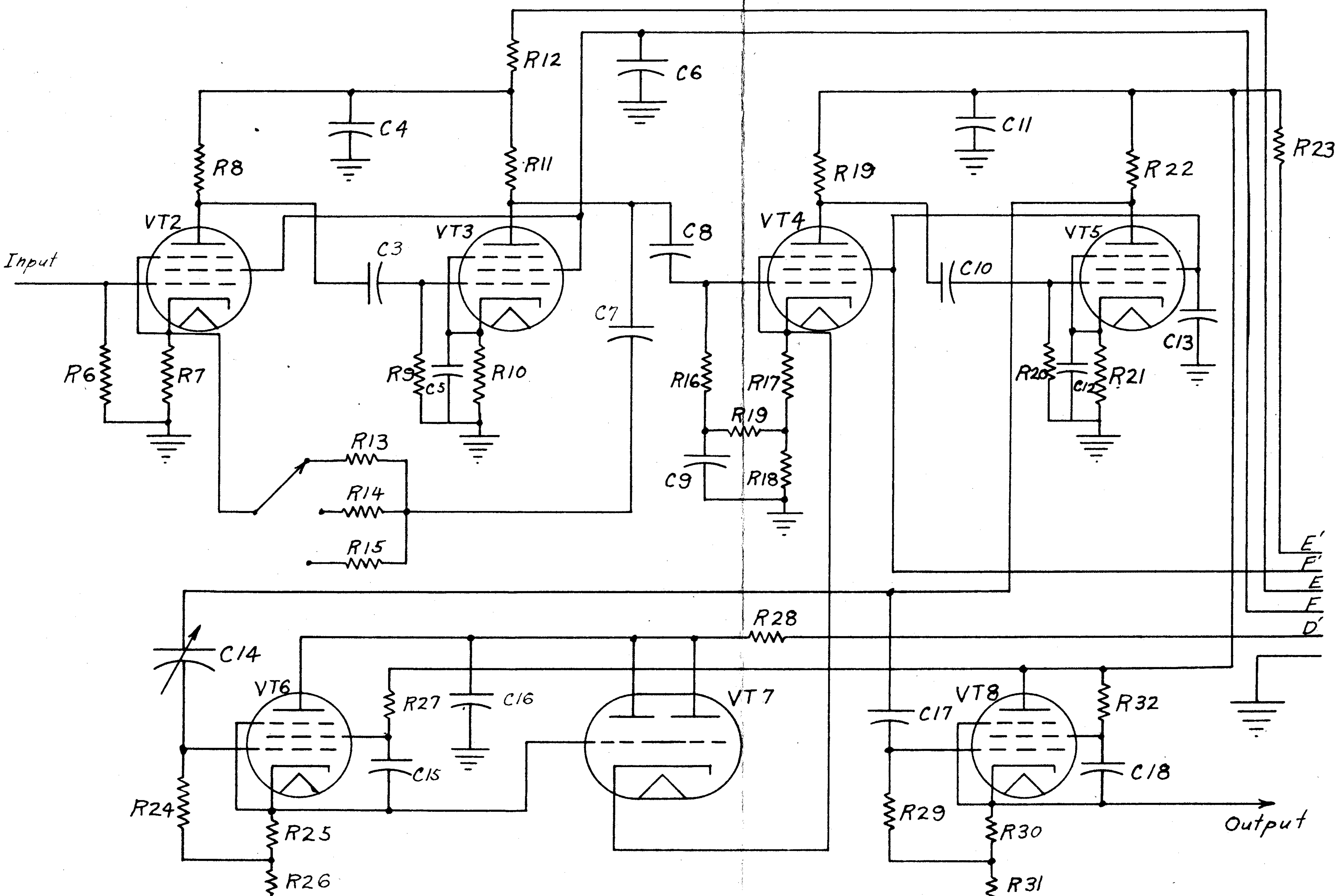

VT1
R5
+180v
C1
Antenna
Lead-In
R1
-6v.
R3
R4
+6v
R2
-180v.
C2
To
Amplifiers

Figure 3


R12
C6
C4
R8
R11
R19
C11
R22
R23
VT2
VT3
C8
VT4
VT5
Input
C3
C10
C7
C13
R6
R7
R9
C5
R10
R16
R17
R20
C12
R21
R19
R13
C9
R18
R14
R15
E'
F'
E
F
R28
D'
C14
VT6
R27
C16
VT7
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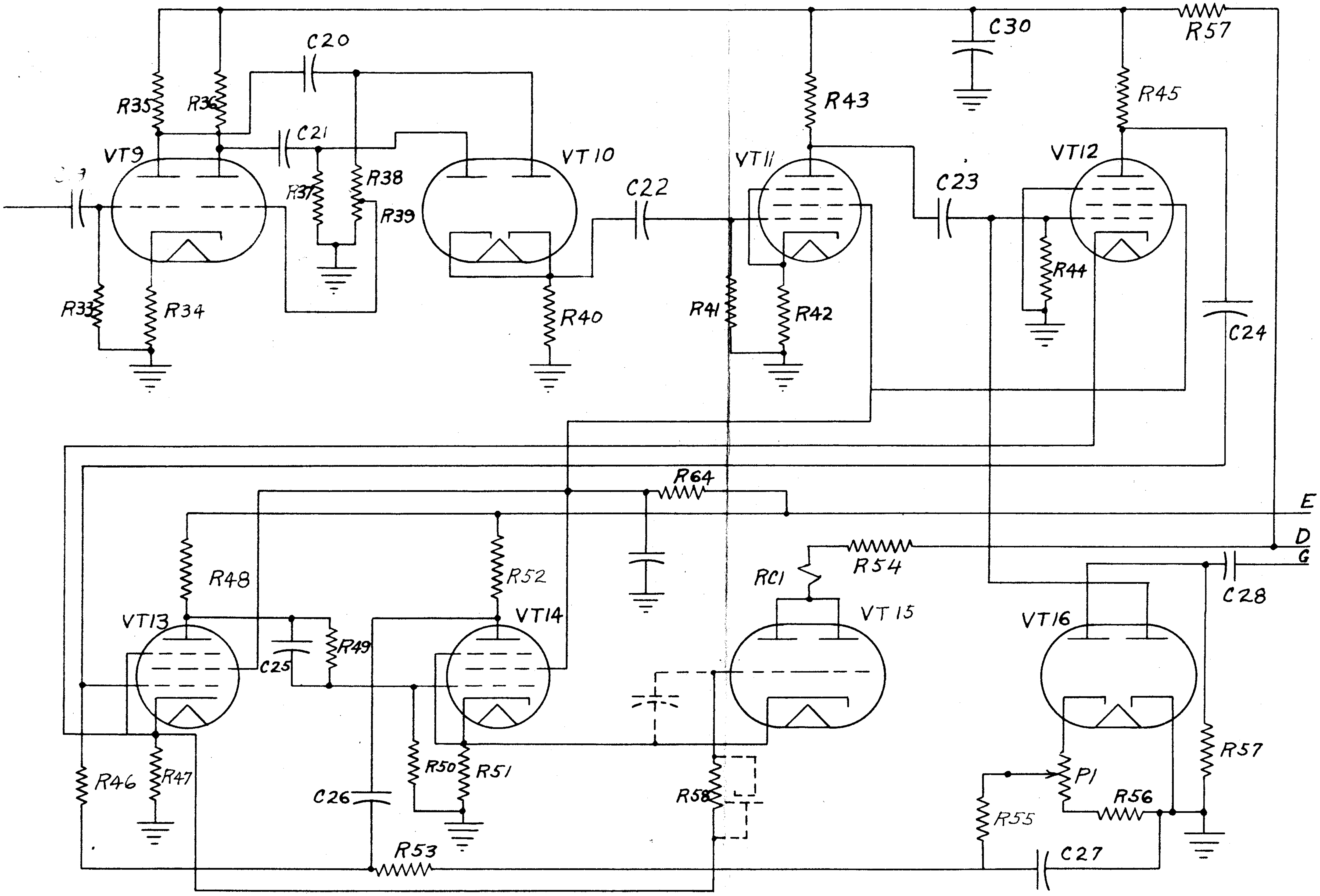
VT8
R32
C15
C18
R24
R25
R29
R30
Output
R26
R31

Figure 4


C20
R35
R36
C21
VT9
R37
R38
R39
VT10
C22
VT11
R43
C30
R57
R45
VT12
C23
R44
C24
R33
R34
R40
R41
R42
R64
E
D
G
R54
RC1
R48
R52
C28
VT13
VT14
VT15
VT16
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R50
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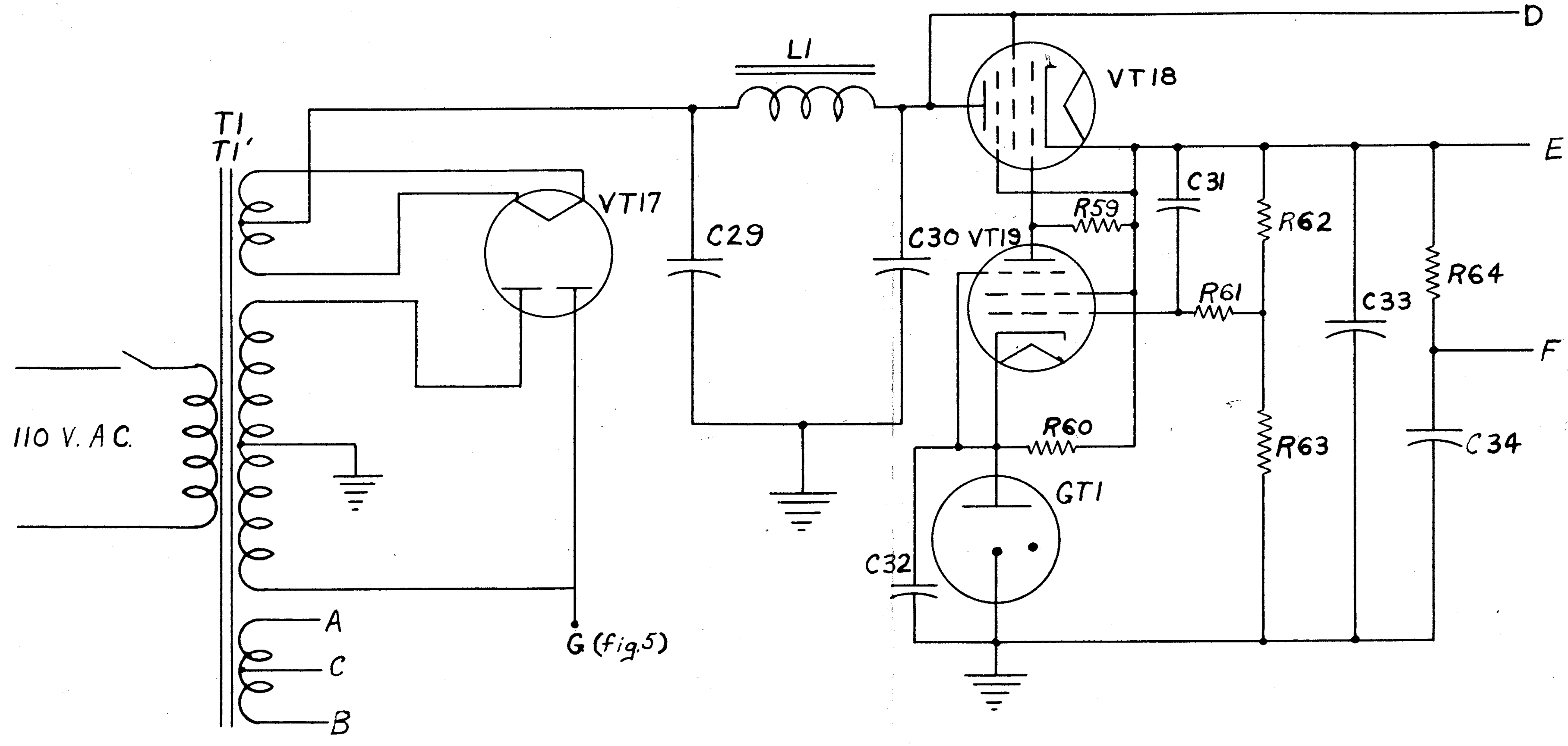
C26
R53
R58
R55
P1
R56
C27
R57

Figure 5



A&B From T1′ to All Heater Circuits Except the Regulators
A&B–From T1 to All Heater Circuits of Regulators

Figure 6

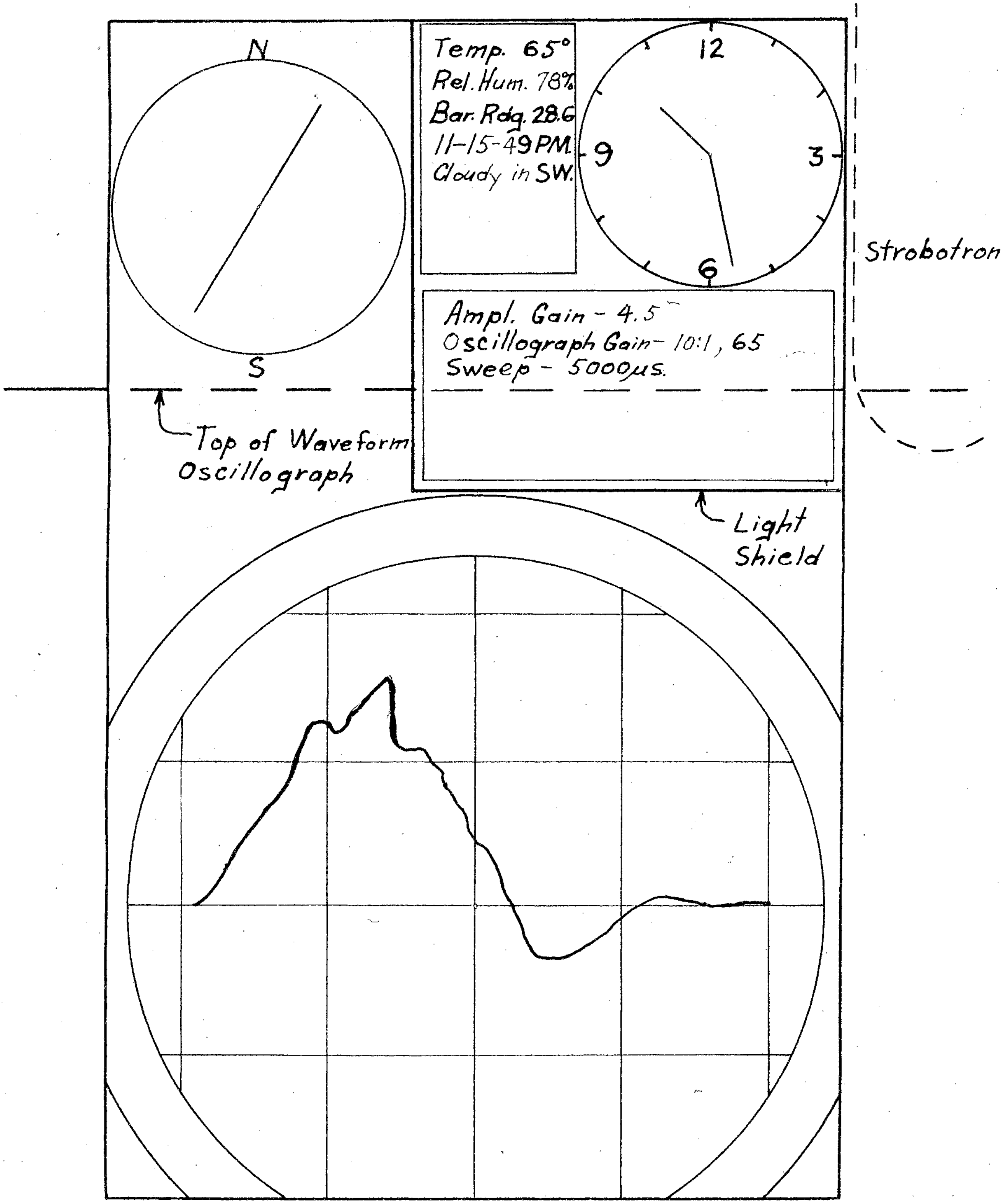

N
S
Temp. 65°
Rel. Hum. 78%
Bar. Rdg. 28.6
11-15-49 PM.
Cloudy in SW.
12
3
6
9
Strobotron
Ampl. Gain - 4.5
Oscillograph Gain - 10:1, 65
Sweep - 5000μs.
Top of Waveform
Oscillograph
Light
Shield

Figure 7

LIST OF EQUIPMENT DIAGRAMS

V TESTS

The frequency response measurements were made with the aid of a Hewlett Packard Model 400A vacuum tube voltmeter and a Wein bridge oscillator, the output of which can be varied from twenty cycles per second to two megacycles per second.

A Antenna Cathode Follower

The frequency response of the antenna cathode follower was found to be constant over the entire range of the oscillator. The amplification was measured to be 0.96 when a heater supply voltage of 6.1 volts and a plate supply voltage of 184 volts were employed. A reduction in heater voltage to 5.7 volts did not change the amplification to any measurable degree. By changing the plate supply voltage from 172 to 196 volts the amplification changed from approximately 0.957 to 0.964. The input and output impedances of the antenna cathode follower are therefore calculated to be approximately 550 megohms and 400 ohms, respectively.[19]

No distortion from the cathode follower could be detected on the DuMont cathode-ray oscillograph as the input voltage was increased to approximately 15 volts root mean square. This was the maximum output voltage for the oscillator employed.

B Voltage Amplifier

With maximum feedback, the frequency response of the voltage amplifier was found to be uniform over the entire frequency range. The voltage gain of the amplifier measured to the grid of VT4, was found to be 4.60. The maximum input voltage without noticeable distortion was 0.78 volts.

With the intermediate value of feedback, the maximum voltage gain was found to be 38.0. The relative frequency response is shown in figure 13. Overloading

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[19] Valley and Wallman, loc. cit.

effects began to appear when the input voltage was increased to .68 volts.

The maximum amplification of the voltage amplifier with minimum feedback and without feedback were measured to be 240 and 615 respectively.

In checking the overload characteristics of the amplifier with feedback, the point at which distortion began to appear was very definitely defined.

In order to obtain more accurate frequency response measurements it was found necessary to apply a known input voltage, connect the cathode-ray oscillograph to the control grid of VT4, and observe the deflection produced. The vacuum tube voltmeter was then removed from the input and placed on the control grid of VT4, along with the oscillograph probe. The oscillator was then adjusted to produce the same oscillograph deflection as observed previously. The results of this method are conservative because of the input capacitance of the probe which is 10 micromicrofarads.

C Antenna Circuit Compensating Amplifier

No frequency-response data was obtained for the compensating amplifier for the antenna circuit alone. Square wave tests were made however, of the complete signal system. These tests included measurements for frequencies as low as twenty cycles per second. Due to the large amount of 60 cycle interference pick-up on the input of the antenna cathode follower, and this was particularly true whenever a considerable correction was necessary, the majority of the square wave tests were simulated by applying a square wave to the input of the voltage amplifier through a small capacitor. Waveforms of the input voltage and the compensated output voltage, are shown in figures 14 to 21, inclusive. All waveforms shown have a fundamental frequency of twenty cycles per second.

Figure 14 is a photograph of the output of the square wave generator as it is produced on the oscillograph.

Figure 15 is the input to the voltage amplifier that is produced when the waveform of figure 14 is applied to the amplifier through a 0.037 microfarad capacitor. The time constant of the input circuit is 0.00924 seconds.

Figure 16 is the compensated output for the input voltage of figure 15.

Figures 17 and 18 demonstrate the effect of over and under compensation. The time constant of the input circuit was adjusted so as to produce the best compensation with C8 one-half closed. Figures 17 and 18 were obtained with C8 three-fourths and one-fourth closed respectively.

Figure 19 is the voltage amplifier input as obtained by applying the twenty cycle square wave through a .01 microfarad capacitor.

Figure 20 is the compensated output obtained with C8 approximately one-eighth closed with the input voltage of figure 19. By further decreasing C8, the leading edges of the pulses are distorted as indicated to a slight degree in figure 20. This is due to the input capacitance of the cathode follower Vt6.

Figure 21 was obtained by applying a square wave to the input of the voltage amplifier with C8 adjusted for the same compensation required for an input as shown in figure 19.

It was found possible to compensate for any time constant from 0.00924 to 0.0022 seconds by means of the 50 micromicrofarad variable capacitor. Tests were also made by applying a 20 cycle square wave to the antenna cathode follower input through a 14.8 micromicrofarad capacitor. The output waveforms were checked to be the same as those obtained by applying the square wave to the voltage amplifier input through a .037 microfarad capacitor.

For any given degree of required compensation of the input circuit the output voltage was found to be independent of the frequency of the square wave input. All square wave tests were performed with the feedback control of the voltage amplifier set for minimum voltage gain.

D Trigger Circuit

In testing the trigger circuit a twenty cycle square wave was applied to the trigger circuit input through a .01 microfarad capacitor. The input of the vertical amplifier of the oscillograph was connected to the grid of VT9. With the oscillograph adjusted to trigger the driven sweep internally, the transient was observed. The same transient waveform was then observed when the sweep was triggered from the plate of VT14 with a sweep duration of approximately 50 microseconds. Eratic operation of the driven sweep circuit was observed. This prevented the determination of the exact time required for the trigger circuit to operate. In some instances the beam of the cathode-ray tube was turned on before the voltage on the grid of tube V110B of the cathode-ray oscillograph reached its minimum value.[20] Such operation is not desirable because the first portion of the waveform will be reversed. Also the writing rate during the return sweep is much greater than during the normal sweep.

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[20] Allen B. DuMont Laboratories, Inc., Operating and Maintainance Manual, Type 250, Type 250H Cathode-Ray Oscillograph.

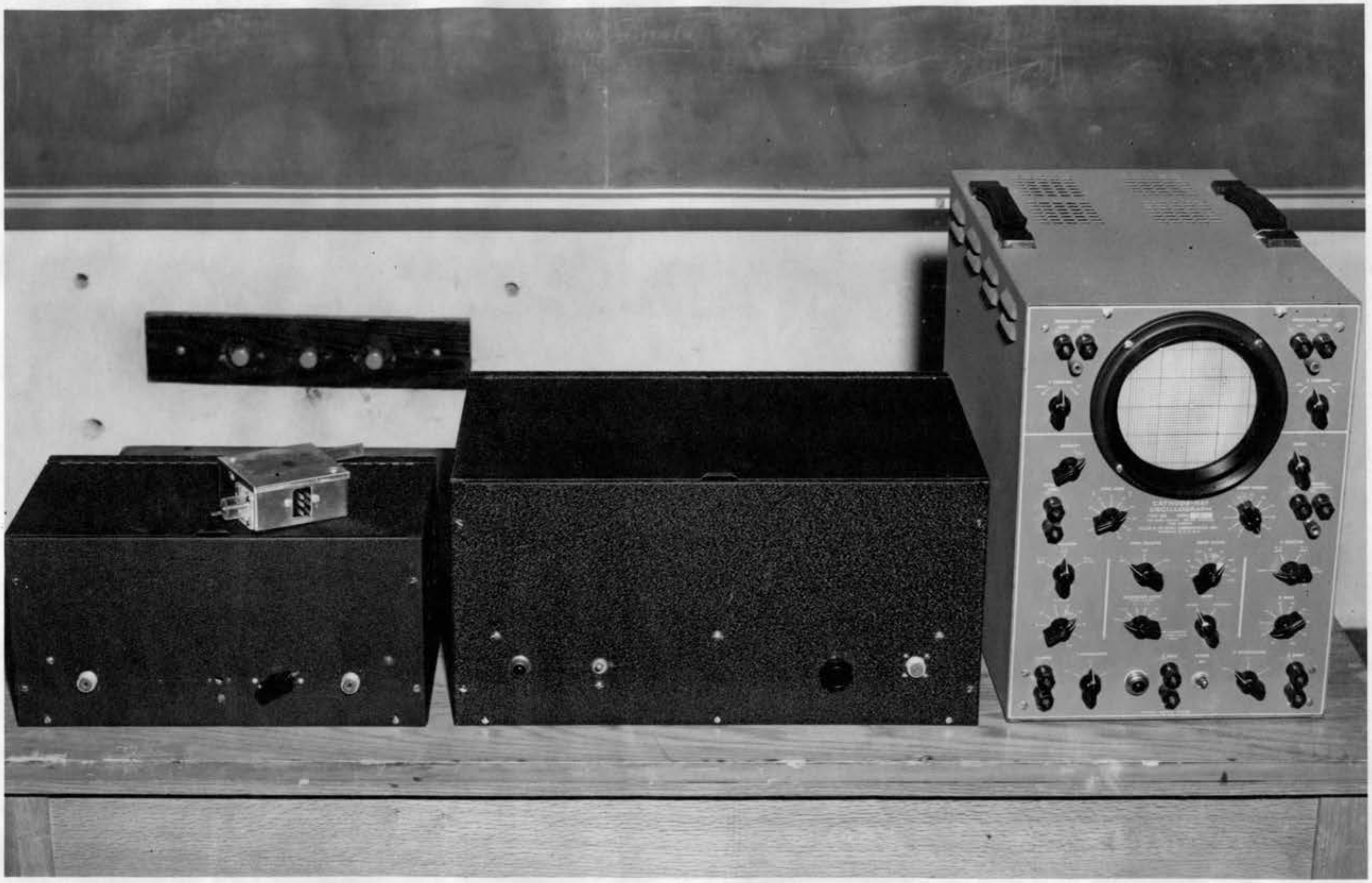

Figure 8 Complete Electronic Apparatus for the Study of Sferic Waveforms.

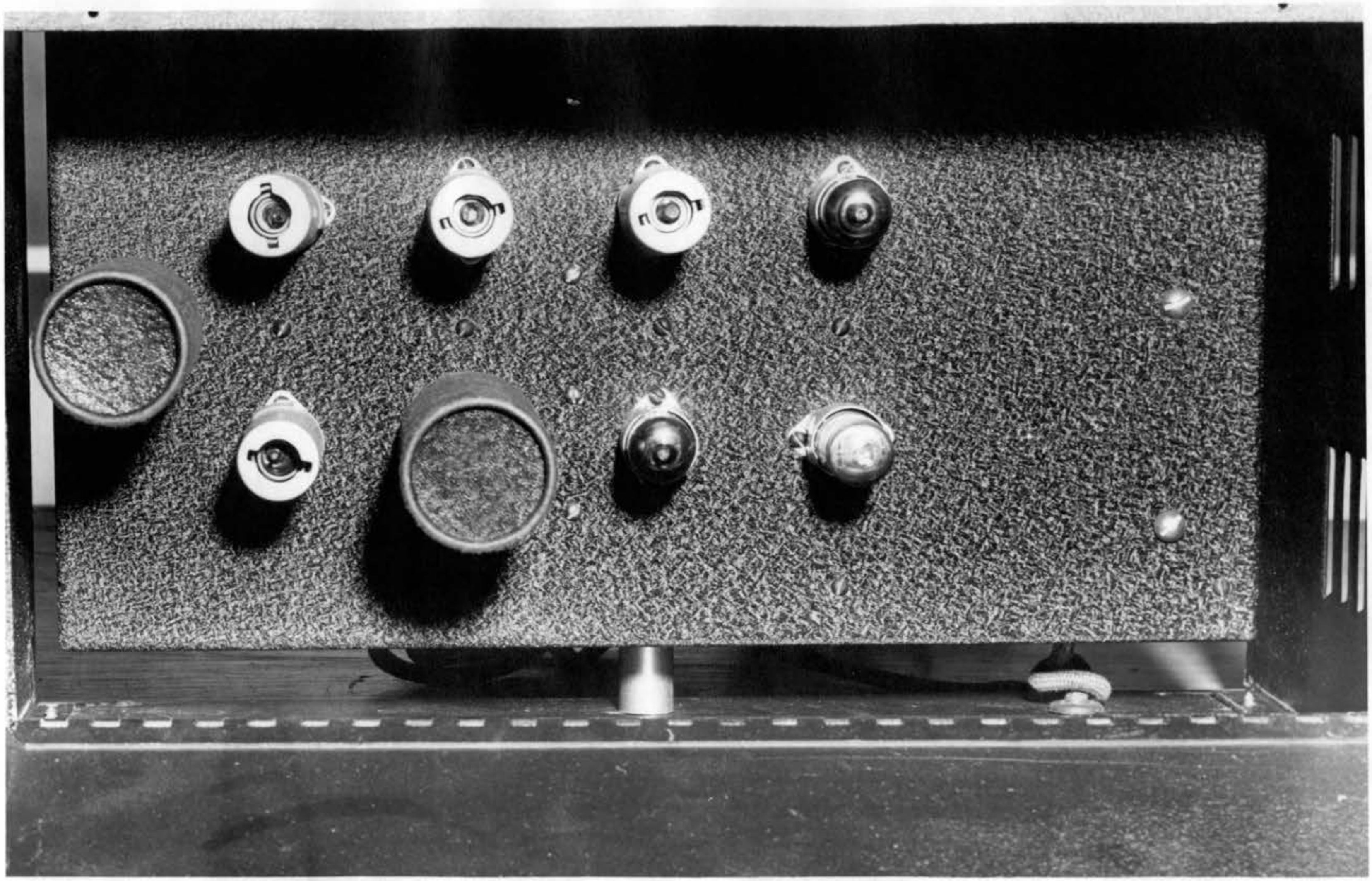

Figure 9 Top View of Voltage Amplifier and Antenna Circuit Compensating Amplifier Chassis.

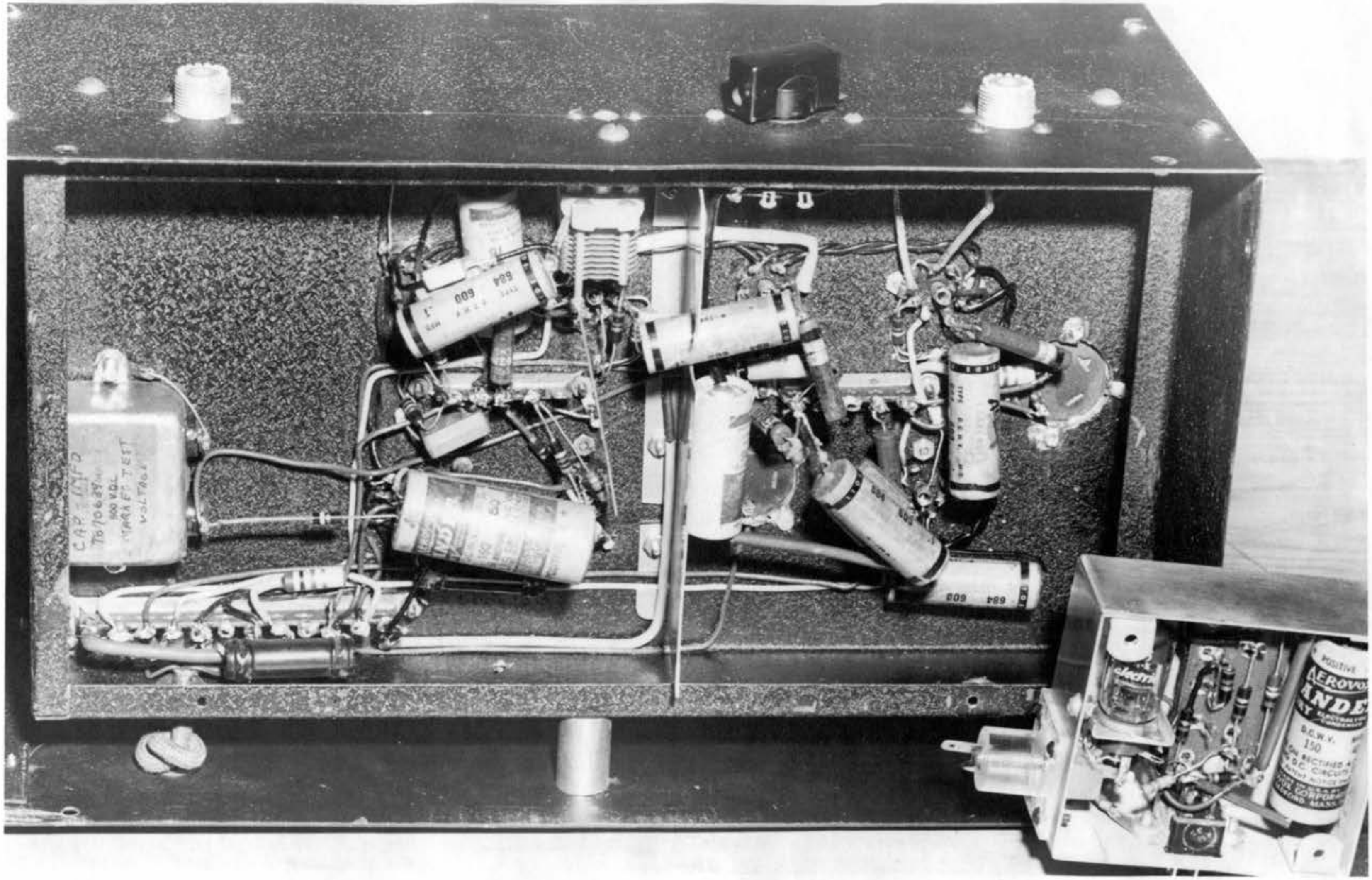

Figure 10 Bottom View of Voltage Amplifier, Antenna Circuit Compensating Amplifier and the Antenna Cathode Follower.

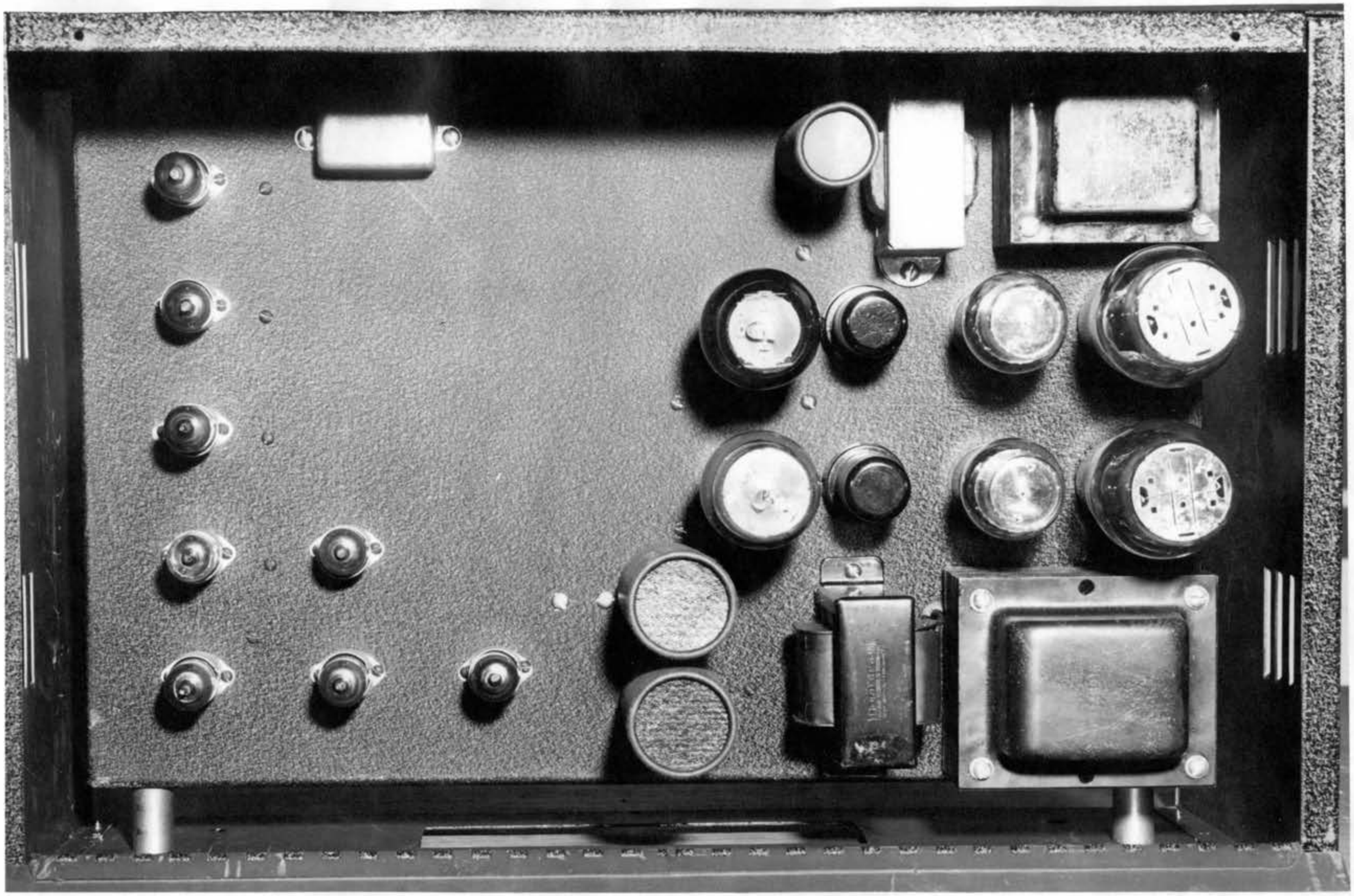

Figure 11 Top View of Trigger Circuit and Power Supply Chassis.

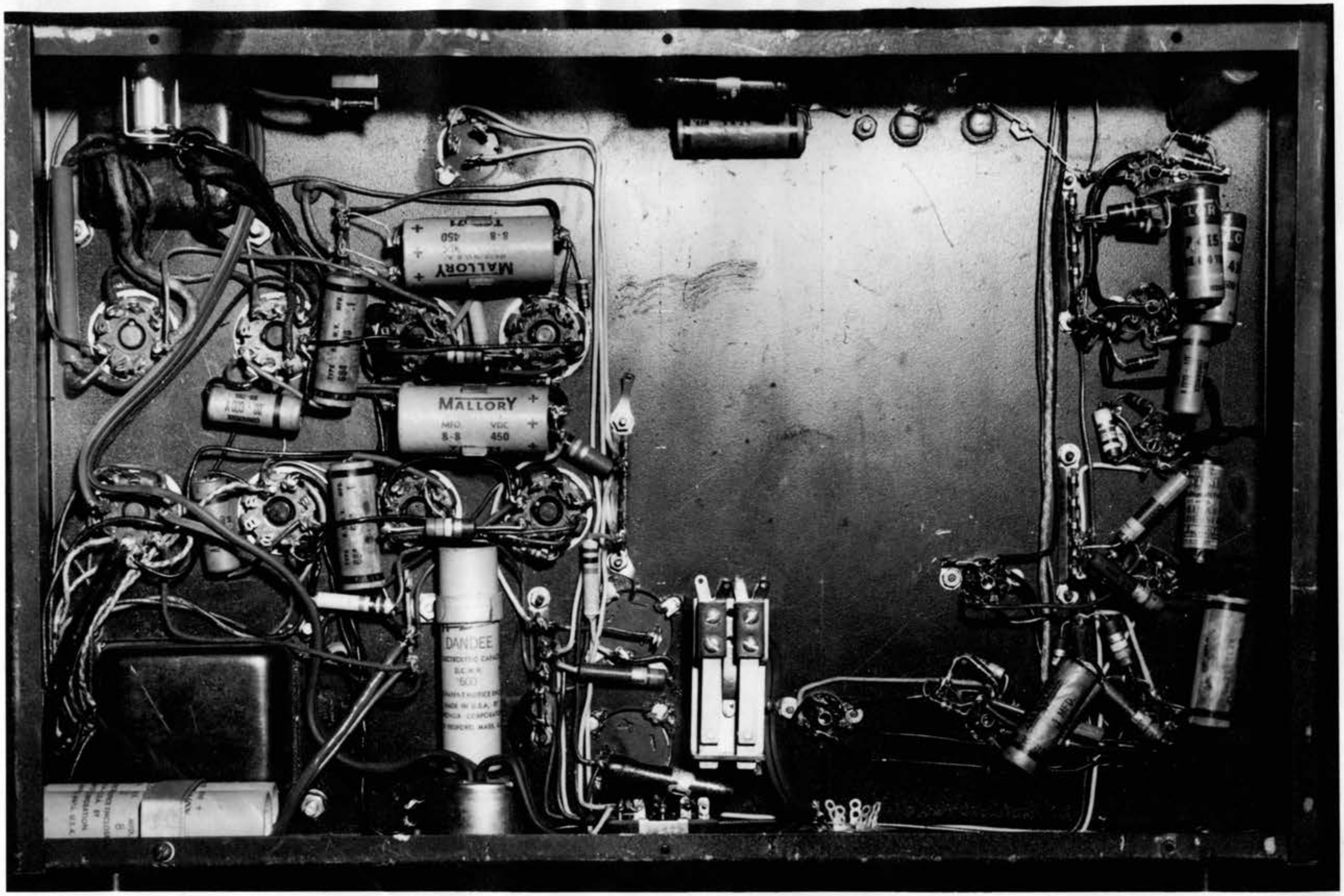

Figure 12 Bottom View of Trigger Circuit and Power Supply Chassis.

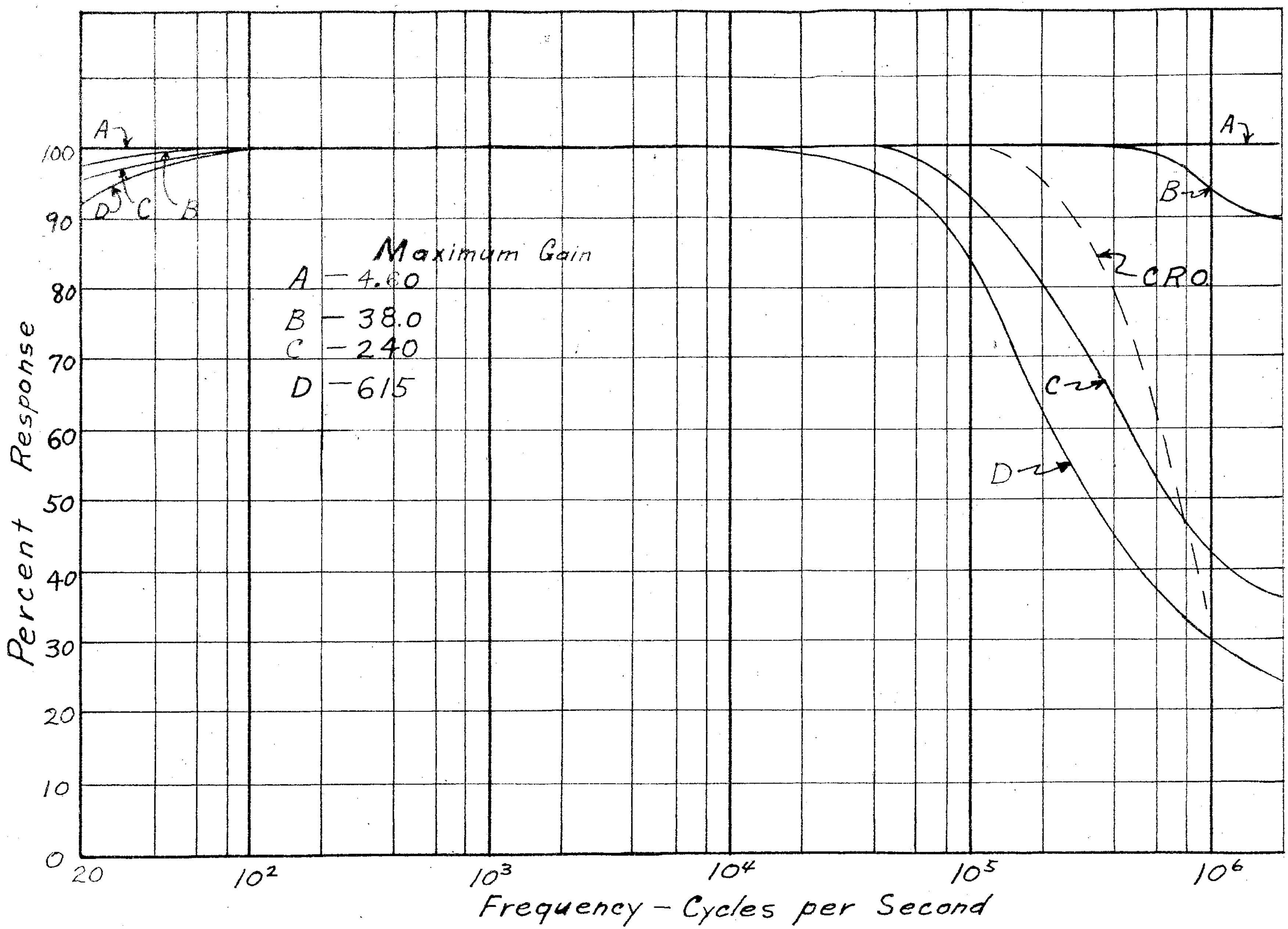
Maximum Gain
A — 4.60
B — 38.0
C — 240
D — 615
A
B
C
D
CRO
Percent Response
100
90
80
70
60
50
40
30
20
10
0
20
10^2
10^3
10^4
10^5
10^6
Frequency – Cycles per Second

Figure 13

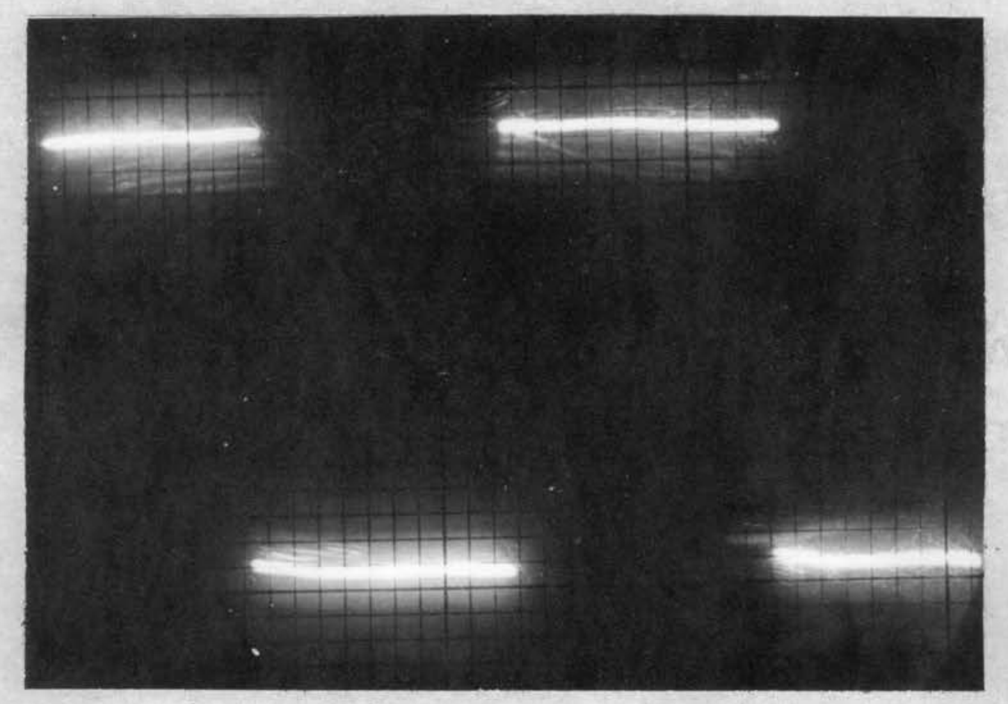

Figure 14

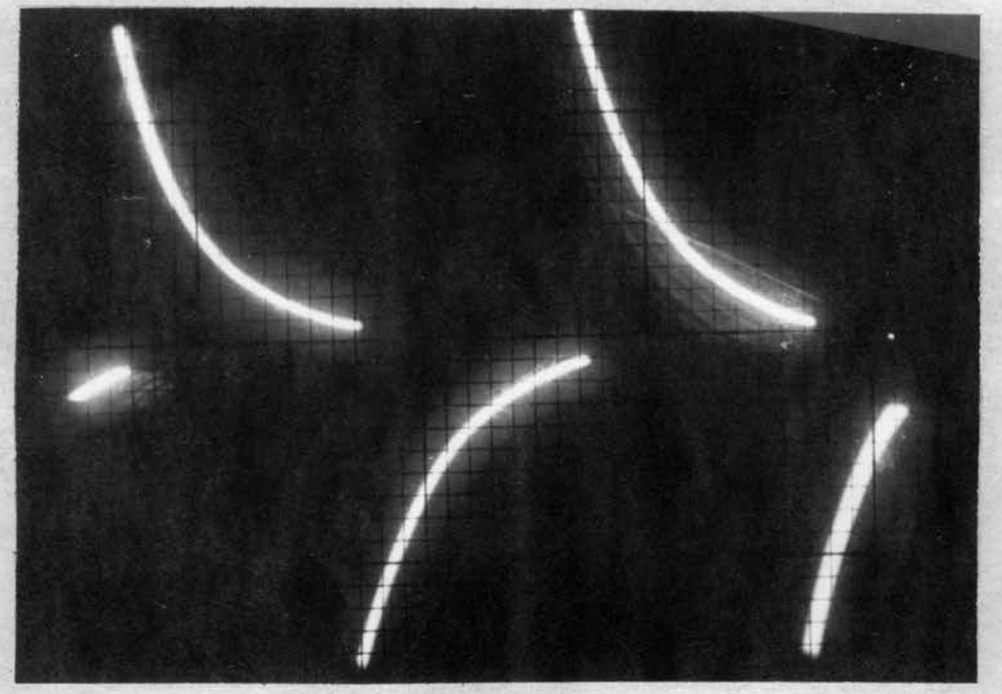

Figure 15

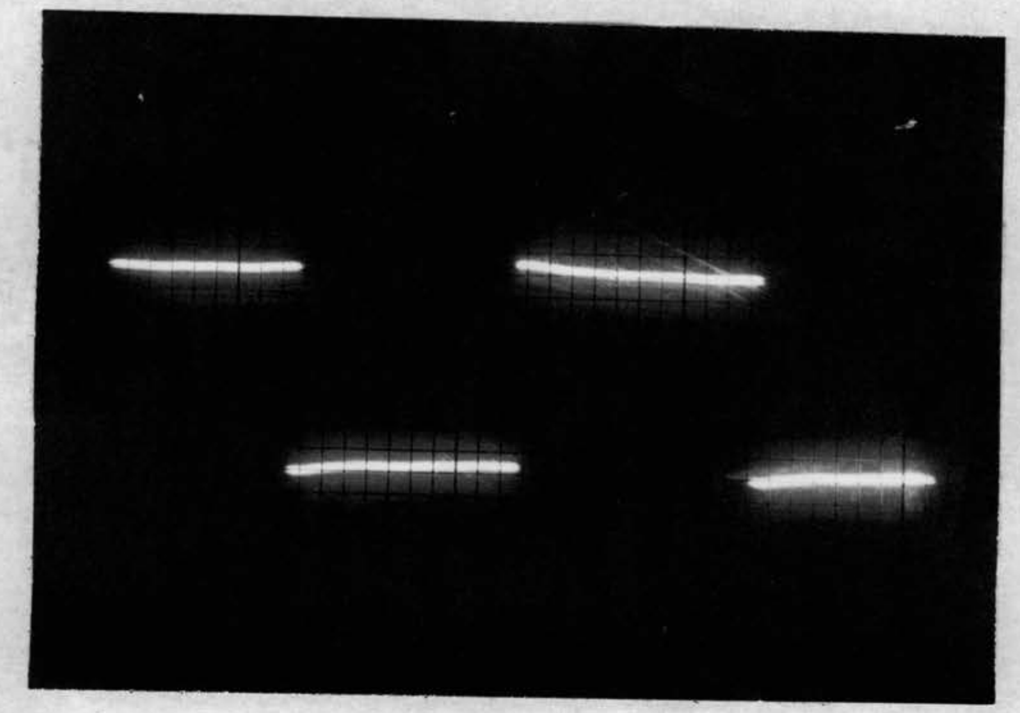

Figure 16

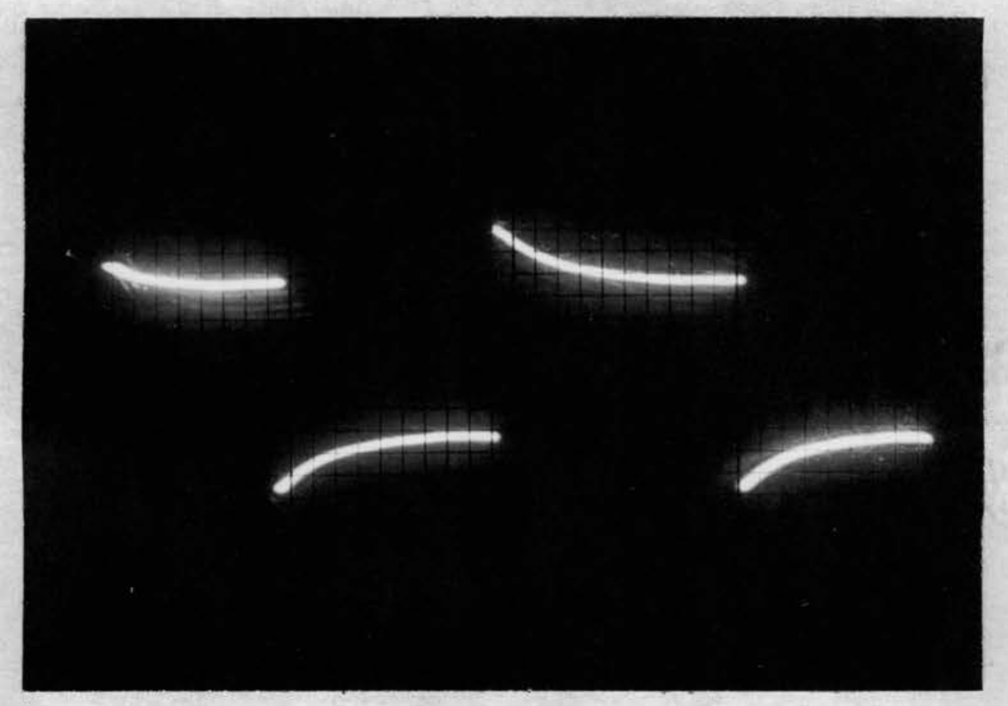

Figure 17

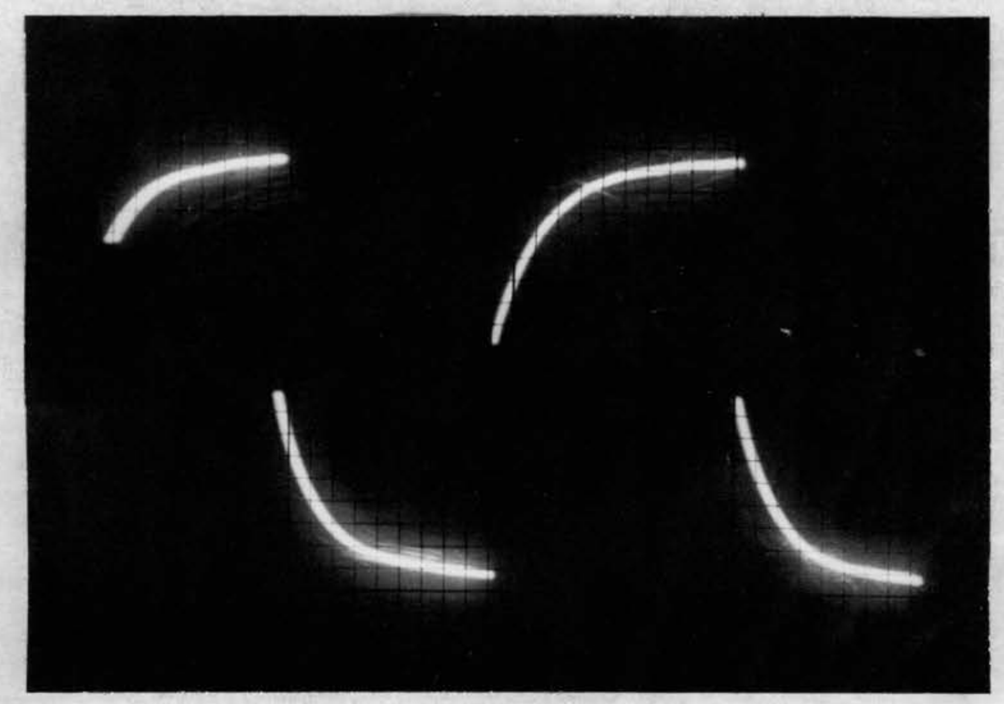

Figure 18

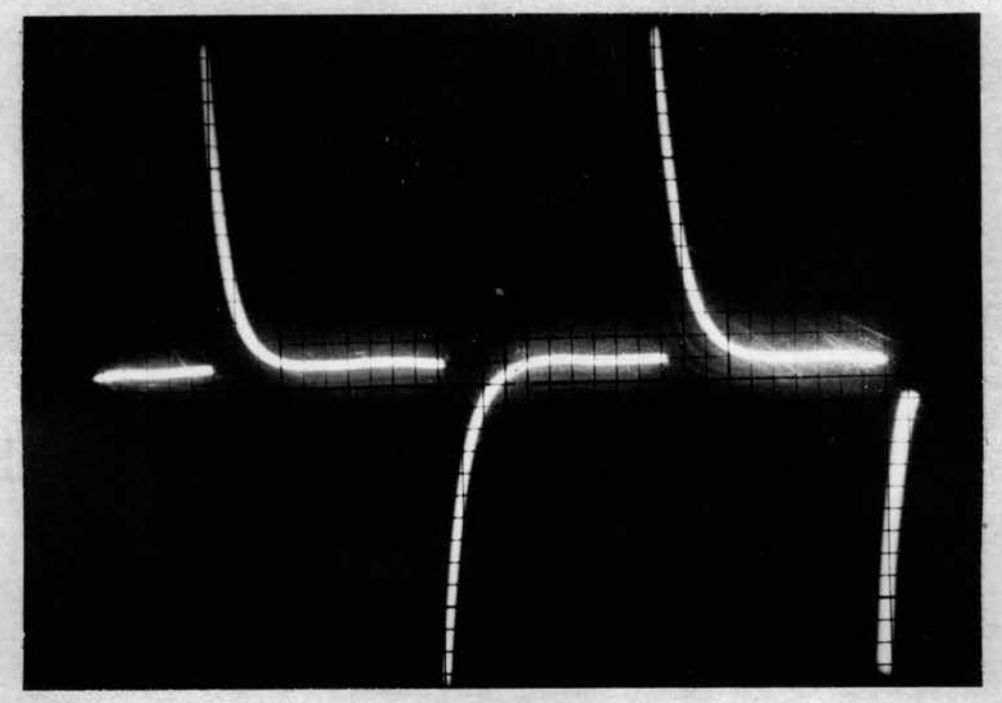

Figure 19

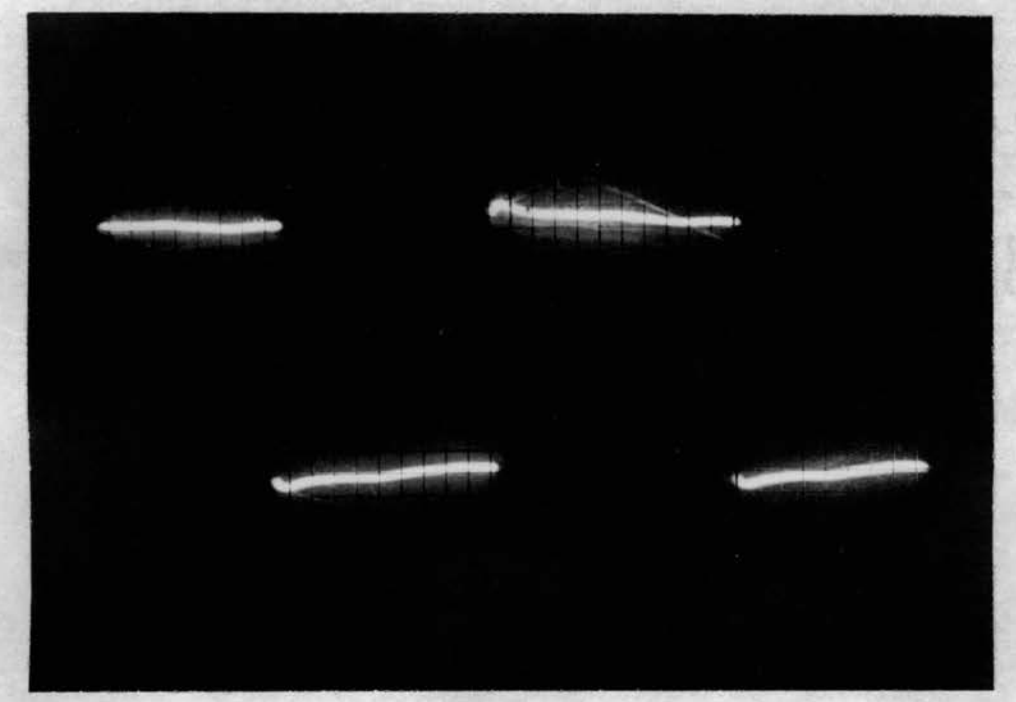

Figure 20

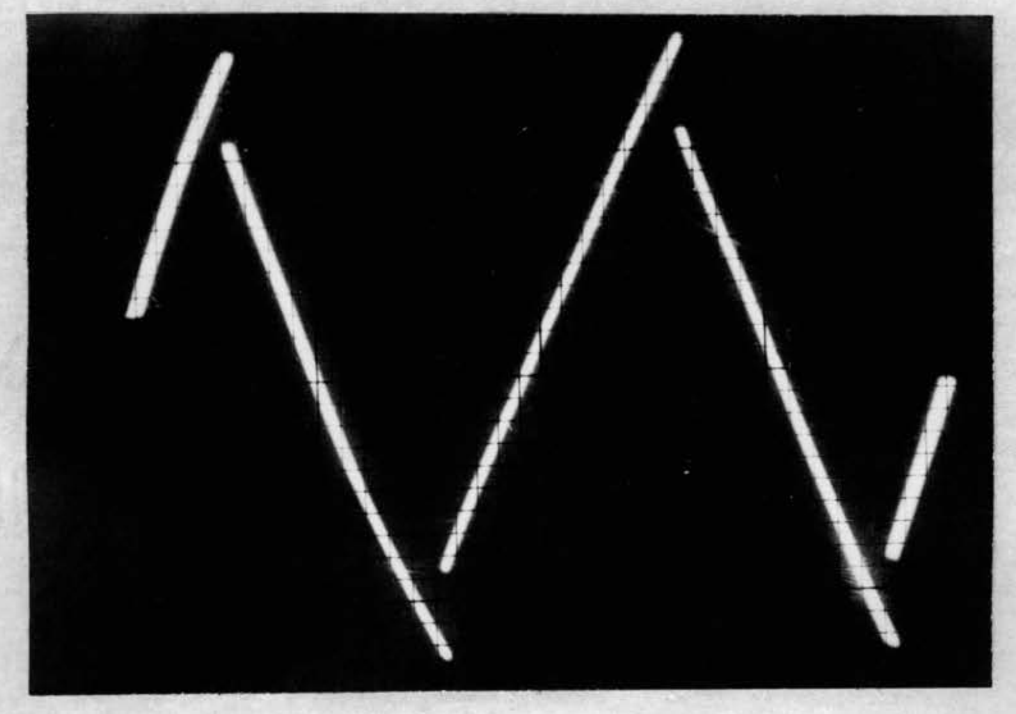

Figure 21

VI OPERATING RECOMMENDATIONS

A Equipment Location

Due to the fact that the completed equipment will amplify all received signals from less than twenty cycles to radio frequency range, it is believed that power distribution systems and local broadcast stations may cause a considerable amount of interference. This is particularly true for cases in which sferics occur at considerable distances from the antenna. It is recommended that the site for the location of the equipment be chosen with this limitation in mind.

Should 60 cycle interference be too great for proper operation, it is recommended that a 60 cycle balancing system be tried. A 60 cycle filter is not recommended because it would destroy the uniform overall frequency response of the system. Broadcast interference would probably be best removed by the incorporation of a parallel-T or bridged-T network in the amplifier. It is not believed that this would impair the quality of the recorded waveforms because frequency components in this range will not be amplified appreciably by the waveform oscillograph amplifier. Also it is to be noted that the high frequency components will appear as a fuzzy trace on the oscillograph unless a very fast sweep is employed.

B Antenna Insulator Mounting

Since the grid-to-cathode resistance of the antenna cathode follower multiplied by the factor (1-A) determines the cathode follower input resistance, the effective resistance of the antenna insulator may also be increased by the same factor if the insulator mounting is connected to the output of the cathode follower. This may be easily done since the cathode follower housing is at cathode potential. A large blocking condenser is required between the cathode follower and the input of the voltage amplifier because of the voltage on the output of the cathode follower. In order to keep precipitation from the antenna insulator, the use of a small umbrella over the antenna insulator is recommended. Occasional cleaning of the insulator will probably be necessary.

C Determination and Compensation for Antenna Circuit Constants

Inasmuch as the uniform response of the system depends upon the correct compensation of the antenna circuit, some simple method of making the correct adjustment should be provided. The antenna capacitance maybe measured by a bridge or calculated by measuring the frequency shift of an oscillator when connected to the antenna.[21] The compensating amplifier can then be adjusted by applying a low frequency square wave to the input of the cathode follower through a capacator which is equal to the antenna capacitance. The compensating circuit can then be adjusted to produce a square wave on the oscillograph.

Another method for accomplishing the same result would be to measure the input resistance of the cathode follower and than apply a square wave to the voltage amplifier through a capacitor the value of which is given by the equation

$$C = \frac{C_{ant} \, R_{ant}}{R_{amp}}$$

where R_{ant} is the effective resistance to which the antenna is connected, and R'_{amp} is the input resistance of the voltage amplifier. The effective resistance to which the antenna is connected includes the effect of the antenna insulator. The measurement of R_{ant} may be determined indirectly by measuring the resistance between the input and output terminals of the cathode follower when the antenna is connected and may be determined from the equation

$$R_{ant} = R'_{ant}(1-A)$$

where R'_{ant} is equal to the resistance between the input and output connections of the cathode follower and A is the amplification of the antenna cathode follower.

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[21] F. E. Terman, *Measurements in Radio Engineering*, pp. 69-70.

D Overall Frequency Response Improvement With Higher Voltage Amplifier Gain Settings

It may be found necessary to improve the low frequency response of the voltage amplifier on the higher gain settings of the feedback control. This can be accomplished most easily by the use of the proper size capacitors in the feedback circuit, as previously indicated in the section on design.

E Arrangement of Information to be Recorded

In the photographic recording of any subject, it is necessary to focus the camera on the subject as closely as possible. In order to obtain the greatest amount of detail or resolution it is also necessary to have the field of the camera cover the entire subject. To accomplish this objective the various units must be arranged in a special manner. The direction indicating cathode-ray tube should be placed on top of the waveform oscillograph and to one side of the vertical centerline. A metal plate should be made to fit flush with the front of the oscillograph. This metal plate should be designed so as to permit the mounting of a small clock or watch on the front side. In addition to this feature, space should be provided to permit the mounting of a pair of small brackets for holding a card on which written information pertaining to the adjustments of the equipment and any other pertinent data can be recorded. The camera should be rotated so that the field will cover all information to be recorded. The arrangement described above is shown in figure 7.

Since the shutter will always be open during operation, a shield should be constructed to protect the lens of the camera from external light sources. The shield should also protect the camera lens from the strobotron that is used to illuminate the clock and the information card.

F Use of a Delay Line

In order to obtain the complete waveform, a delay line placed between the antenna circuit compensating amplifier and the waveform oscillograph is necessary.

The value of time delay required depends on the exact time required for the trigger circuit and the driven sweep of the cathode-ray oscillograph to operate. Delay lines designed for a delay of 0.6 microseconds per foot is manufactured by several companies at a cost of approximately $1.00 per foot.[22]

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[22] Blackburn, op.cit. pp. 192-199.

VII SUGGESTED EQUIPMENT FOR FURTHER SFERIC STUDIES

At the present time it is contemplated to investigate all sferics with the hope of verifying the results of previous tornado research. If this is accomplished, a tornado warning system may be devised to give sufficient warnings to save many lives each year.

The direction indicator now being developed by Mr. Thomas H. Thomason will be a great aid in sferic research in that it makes possible the determination of the direction of the received signal with an ambiguity of 180 degrees. When this type of direction indicator is used, it is necessary to employ at least two separate direction finders located at stations which are far enough apart to permit the determination of the direction and distance of any particualr received signal by triangulation. The information obtained at these stations may then be correlated to determine the location of the sferic. With such a system considerable time would be required to obtain the information desired. It is also obvious that the direction indications would have to be very accurately timed if sferics from any other directions are present. If the direction indications are not accurately correlated, false indications will result. When the location of a sferic due to a tornado can be accurately located, radar can then be used to follow it as it proceeds along its path. However it is obvious that the entire location and correlation process must be accomplished in a very short time if the results are to be of any real value.

A device for determining the direction without the present 180 degree ambiguity, and another device for the determination of the distance to the tornado would be very helpful for the rapid determination of the location and subsequent path.

In the opinion of the author it is believed that the 180 degree ambiguity of a crossed loop direction indicator may be obviated by employing an instantaneous direction finder whose receiving pattern is of the cardioid type. This may be accomplished by rotating the antenna of the second direction finder so as to place the null of the received pattern first in one direction indicated and then the other. By denoting the direction from which the received signal is maximum, when a tornado sferic is received, the 180 degree ambiguity is removed. However this process will also consume valuable time.

Another method would be to apply the signal from one loop to the input of two direction finders. If the phase of the loop voltage applied to the two direction finders is opposite, one direction finder will give maximum output when the other is a minimum, provided that the plane of the loop is in the direction of the received signal. It would also be desirable to trigger the outputs of the direction finder at the same time the sferic waveform oscillograph is triggered.

The problem involved in the determination of the distance to a sferic is an important one and should be the subject of extensive research. A satisfactory solution to this problem will also constitute the solution to the problem of tornado tracking.

F. E. Terman states, "In case of a doublet antenna, the electrostatic induction field becomes proportionally stronger than the magnetic induction field as one comes closer to the antenna. With the loop, the reverse is the case."[23] From this observation, one would be led to believe that the ratio of the voltage induced into a doublet antenna to the voltage induced into a loop antenna a given source would depend upon the distance the source is from the antennae. If this is true, it should be possible to develop a receiver that would indicate this ratio, and the result interpreted as the distance to the sferic disturbances.

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[23] F. E. Terman, Radio Engineering, p. 664.

VIII CONCLUSIONS

The amplification of the antenna cathode follower was found to be lower than the calculated value by approximately 1.6%. The difference is evidently due to a lower value of Gm that exists under actual operating conditions. This did not influence the measured frequency response which was as expected.

The overall amplification of the voltage amplifier is considerably less than the calculated value. Again this is due to the relatively low value of Gm for the tubes used. The tubes for the amplifier circuit were carefully selected so as to reduce 60 cycle interference from the heater circuit to as low a value as possible. As a result it is believed that the Gm for the tubes is considerably lower than the rated value. The use of feedback for controlling the gain of the amplifiers makes it possible to accurately control the voltage gain from the antenna to the oscillograph input. The sensitivity of the oscillograph can be determined by the voltage calibrator that is built into the unit. It is therefore relatively easy to determine the overall sensitivity of the equipment under all types of operating conditions.

The antenna circuit compensating amplifier performs as well as can be expected over the frequency range tested. It is believed that the overall uniform steady-state response will extend down to less than 5 cycles per second when minimum compensation is required. The minimum required compensation can be attained for an antenna, the input capacitance of which is approximately 15 micromicrofarads.

When the trigger circuit is properly adjusted, it will trigger the driven sweep of the oscillograph and block any subsequent signal from triggering the sweep for approximately one-half second.

All tests indicate that any voltage variations relative to the ground that are within the frequency limits of the equipment will be displayed on the cathode-ray tube provided that the capacitance to ground of the vertical antenna is between the values of 3.8 and 15 micromicrofarads.

Appendix A

Antenna Capacitance Calculations[24]

The capicatance of a vertical antenna is given by the relation,

$$C = \frac{7.36m}{\log_{10}(2m/d)-k} \quad \text{Micromicrofarads}$$

where, for the application under discussion,

m = length of antenna = 10 feet

h' = height of lower end above ground = .2 feet = 2.4 inches

d = diameter of antenna = .6 inches = .05 feet

k = constant determined by $\frac{h'}{m}$

Since

$$\frac{h'}{m} = \frac{.2}{10} = .02,$$

it follows from Table 30 that k = .403,

and so

$$C = \frac{7.36 \times 10}{\log_{10}(20/.05)-.403} = \frac{73.6}{2.602-.403}$$

$$= \frac{73.6}{2.199} = 33.45 \text{ micromicrofarads.}$$

Uniform Response of Input Circuit

Assuming $R_{input} =$ 200 megohms

and $\frac{1}{\omega C} = \frac{1}{10}$ R_{input} for uniform response above the frequency f.

$$\frac{1}{2\pi 33.45 \times 10^{-12} f} = \frac{1}{10} \times 200 \times 10^{6} = 2 \times 10^{7}$$

Therefore,

$$f = \frac{1}{2 \times 10^{7} \times 2 \times 33.45\pi \times 10^{-12}} = 238 \text{ cycles per second.}$$

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[24] F. E. Terman, Radio Engineers's Handbook, p. 116.

Appendix B

PARTS LIST

Component Part	Value of Component
C1, 35, 36.	40 mfd, 150 V.D.C. electrolytic.
C2.	16 mfd, 600 V.D.C. oil filled.
C3, 6, 8, 10, 13, 17, 19, 24, 26, 28, 31, 38.	0.1 mfd, 600 V.D.C. paper.
C4, 11, 30, 33, 34.	40 mfd, 450 V.D.C. electrolytic.
C5.	30 mmfd, ceramicon.
C7, 18.	16 mfd, 150 V.D.C. electrolytic.
C9.	1 mfd, 300 V.D.C. oil filled.
C12.	50 mmfd, ceramicon.
C14.	0-50 mmfd, variable.
C15.	50 mfd, 150 V.D.C. electrolytic.
C16.	80 mfd, 450 V.D.C. electrolytic.
C20, 21.	0.05 mfd, 600 V.D.C. paper.
C22.	0.01 mfd, 600 V.D.C. paper.
C23.	0.005 mfd, 600 V.D.C. paper.
C25.	200 mmfd, mica.
C27.	5 mfd, 50 V.D.C. electrolytic.
C29.	8 mfd, 450 V.D.C. electrolytic.
C32.	0.02 mfd, 600 V.D.C. paper.
C37.	4 mfd, 600 V.D.C. oil filled.
L1.	30 henry, 70 ma., filter choke.
L1'.	8 henry, 150 ma., filter choke.

P1.	5,000 potentiometer.
R1.	22 meg., $\frac{1}{2}$ watt.
R2, 14, 50.	10 K, $\frac{1}{2}$ watt.
R3.	100 ohm, $\frac{1}{2}$ watt.
R4, 7.	200 ohms, $\frac{1}{2}$ watt.
R5, 15, 27, 32, 44.	100 K, $\frac{1}{2}$ watt.
R6, 49.	220 K, $\frac{1}{2}$ watt.
R8, 19, 35, 36, 48, 52.	10 K, 1 watt.
R9, 20, 29, 61.	1 meg., $\frac{1}{2}$ watt.
R10, 30.	390 ohms, $\frac{1}{2}$ watt.
R11, 22, 43, 45, 65.	25 K, 1 watt.
R12, 23.	5 K, 1 watt.
R13, 39, 47.	1 K, $\frac{1}{2}$ watt.
R16.	300 K, $\frac{1}{2}$ watt.
R17.	68 ohms, $\frac{1}{2}$ watt.
R18.	5 K, 5 watt.
R21, 25.	620 ohms, $\frac{1}{2}$ watt.
R24.	10 meg.,$\frac{1}{2}$ watt.
R26, 37, 38, 41, 58.	20 K, $\frac{1}{2}$ watt.
R28.	6 K, 5 watt.
R31, 33.	51 K, $\frac{1}{2}$ watt.
R34, 40.	1.5 K, $\frac{1}{2}$ watt.
R42.	600 ohm, 1 watt.
R46, 53, 59.	560 K, $\frac{1}{2}$ watt.
R51.	3 K, 1 watt.
R54.	7.5 K, 5 watt.

R55, 56.	5K, ½ watt.
R57.	50K, 5 watt.
R60.	50K, 1 watt.
R62, 63.	91K, ½ watt.
R64.	50K, 1 watt.
R66.	60K, 1 watt.
T1.	650 V.C.T., 70 ma., 6.3V.4a.,5V.2a.
T1'.	750 V.C.T., 150 ma., 6.3V.5a.,5V.3a.
VT1.	6AK5.
VT2, 3, 4, 5, 6, 8, 11, 13, 14.	6AG5.
VT7, 9, 15.	6J6.
VT10, 16.	6AL5.
VT17.	5R4.
VT18.	6AG7.
VT19.	6Y6.
GT1.	VR150.
GT2.	631-P1.
RG1.	110 V.D.C. DPDT.

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