A STUDY OF TORNADO TRACKING EQUIPMENT

By

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A word of thanks should be given to Mr. Vernon D. Wade who built much of the equipment discussed in this thesis. He willingly supplied circuit diagrams and much other information in order that this thesis may be more complete.

The author also wishes to express his heartfelt thanks to his wife, Deanne, for her untiring work in the preparation of the original manuscript.

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CHAPTER I

INTRODUCTION

In the way of introduction it would be necessary to mention that the general purpose of the Oklahoma A. and M. College tornado project is to locate tornadoes before they become active, and to give accurate warnings to the public so that they may be able to seek shelter. Since weather stations cannot give accurate predictions on the erratic tornado cloud some other means is required to locate this cloud, plot its course and predict when and if it will ever produce an active tornado.

Observers in the past have mentioned that the lightning around a tornado appeared to have a different color from that of ordinary thunder clouds. This led to the belief that possibly this lightning produced a different type of electromagnetic field than that from other clouds. Although audibly the "static" heard on the household radio is quite similar for both types of storms, the oscillograph pattern of "field versus time" shows that for tornadoes the time rate of change of the field is much greater and has many more reversals per second. To put it in engineering terms a waveform shows higher frequency components when its wave originated from a tornado cell burst of lightning.[1] Throughout this paper a lightning burst will be called a sferic. This is a shortened term for "atmoshperic discharge.

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[1] Hess, Philip N., Installation and Operation of Electronic Sferic Detection Equipment, Master of Science Thesis, Oklahoma A. and M. College, 1950. p. 49.

At present Oklahoma A. and M. College has some very elaborate equipment for detecting and recording the presence of tornadoes within a 200 mile range by means of sferic detection. The recording equipment consists of a camera which photographs the sferic waveform, the time, and the date simultaneously. The operation of this apparatus is entirely automatic. A complete description may be found in the thesis submitted by Philip N. Hess.[2]

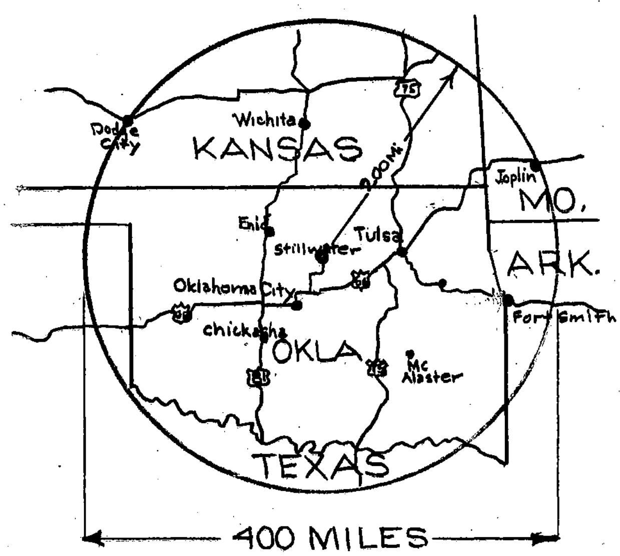

Figure 1. Theoretical Range of Tornado Detector

Once a tornado sferic has been discovered on the oscillograph screen it is obvious that we should try to locate it. The location of tornadoes is the problem to which this thesis is devoted.

Several methods have been proposed. The first and most simple would be to issue a warning when a tornado sferic wave is

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2 Ibid., pp. 12-25

discovered and have visual observers to tell if there is anything in sight. This is feasible but not very practical because tornadoes occur along a squall line[3] which is constantly moving and may be quite long and erratic. This means that it would be necessary to remain in contact with a large number of observers in order to cover the entire danger area.

The second method of location would be to apply the use of "static" direction finders to the problem. This would be more practical. With three tornado stations, one of which would also serve as a central plotting station, the tornado cloud or cell could be located by triangulation. This appears to be a very quick and accurate method of pinpointing the tornado cell, but still it entails the use of several operators on duty at several different stations. An effective communication system between all three stations would be a necessity.

The third method would be to use radar to pick up the tornado. This would be more effective because one tornado station could cover an entire area without dependence upon a communication system which might become ineffective at the crucial moment. The radar system has two disadvantages along with its many outstanding features. For cloud formations the range on ordinary radar is not very great, the maximum range being a possible one hundred miles or less. This disadvantage may be overcome by the use of more powerful transmitter systems. The second disad-

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[3] Tepper, M., "A Proposed Mechanism of Squall Lines: The Pressure Jump Line", Journal of Meteorology, Vol. 7, Number 1, (February, 1950), pp. 21-29.

vantage is that there is a masking effect of ground echoes over the cloud echoes which are inherantly of a weaker nature. This limitation may be overcome by special antenna design and careful adjustment. The use of the antijam circuits employed on military radar may be of considerable aid. It is the opinion of the author that the use of radar is the most practical of either system so long as it is used in conjuction with other equipment to indicate the presence and general direction of the tornado.

The triangulation method requires the use of three stations. In order for them to be very accurate they would need to be separated from each other by around twenty miles. They should also be located at the verticies of an equilateral triangle. These are not rigid requirements and need to be only approximated. As the sferics come in the operators in each station would read and record the bearing of each sferic. This information would then be transmitted to the plotting center where all of the information would be plotted as shown in Figure 2.

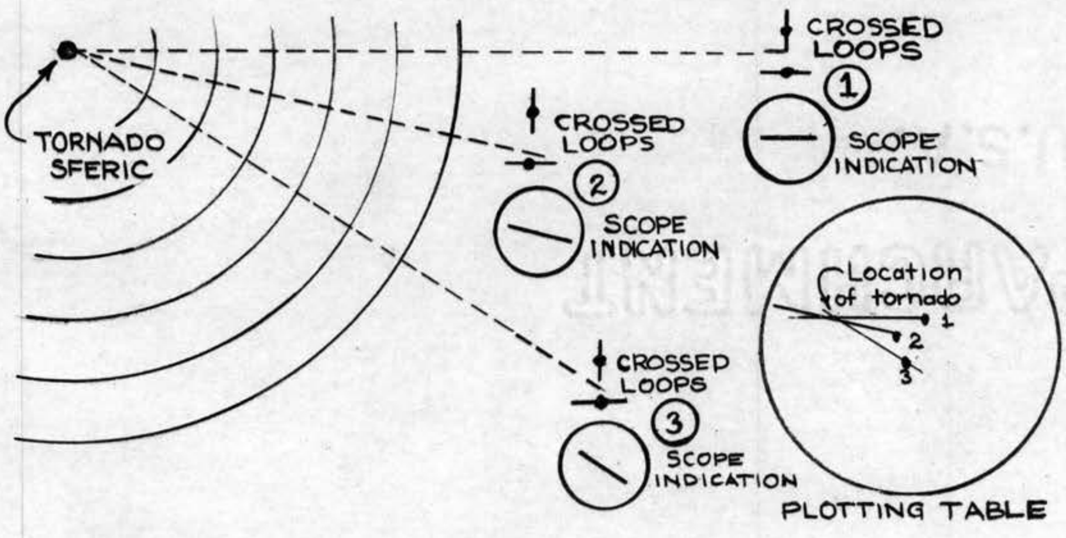


Figure 2.

The plotting table may have a map of the area printed upon it. By using a round table top all points would be easily accessable. The Federal Communication Commission has employed a similar system for finding static or unauthorized transmitters. In this system each monitoring station is indicated by a hole in the table-top map. Up through each hole extends a thread which has a weight tied to it. This weight will hold the thread in place when it is moved about on this table-top type of plotting board. The lower end of the thread which hangs beneath the table has a weight on it to hold the thread tight, as shown in Figure 3.

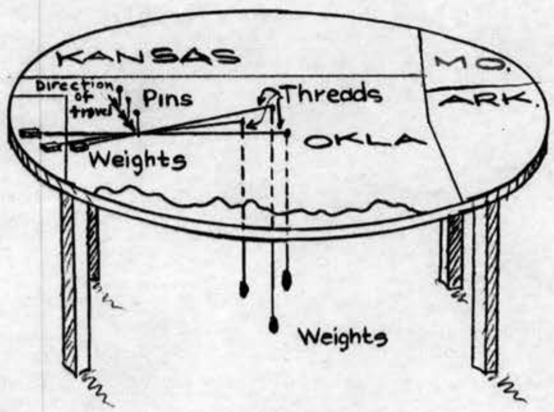


Figure 3.

When a signal is received the thread from station number one is stretched out in the direction from which the signal arrived. The information is indicated in the same way for each of the other stations as the plotter receives it at the plotting board. The undesirable signal is located at the point where the threads cross. In the event that all three threads do not cross at the same point the small triangle so formed is the area in which the unlicensed transmitter is located. In the case of a tornado this area would be small enough so that the people in the danger zone could be put on the alert quite easily.

A pin could be placed in each location as it is plotted.

The row of pins would then indicate the general direction of travel of the tornado. From this information advance warning could be given to those in the path of its travel.

The advantage of this type of direction indicator is that it has a very good range. The direction indicator now in use is able to indicate directions on signals not strong enough to set the detecting device into operation. The accuracy suffers, however, on long range operation. This error is not a characteristic of the radar system designed to pick up these distant clouds.

It is conceivable to have a large television projection tube with three electron guns mounted in it to do the plotting automaticaly. Each gun would be focused on the point corres-

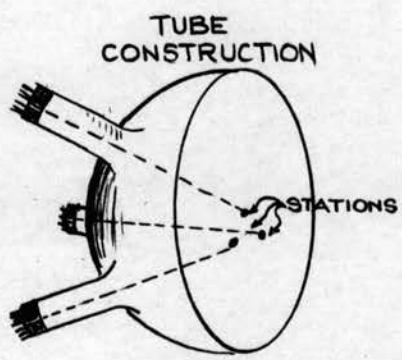


Figure 4a.

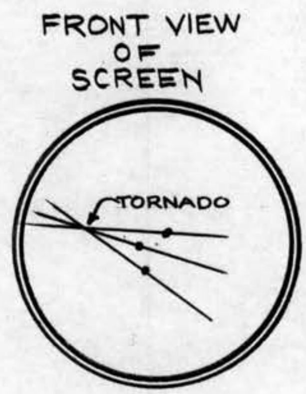


Figure 4b.

ponding to the station it represented and each set of deflection systems would be oriented so that true north was indicated by each in its exact direction. This would result in a perfectly oriented system which would require no plotting except that of the path of travel for the tornado cloud. By using a long persistance screen this plotting could thus be made much easier. The time of an actual sferic pulse is much too short to be plotted by hand.

At first this seems to be the logical solution but when one considers that coaxial cable must be laid between each station, and the plotting house, and that there is the problem of balancing not just two but six amplifiers and antenna systems and together with the problem of finding locations which would not give incorrect bearings due to reflection phasing of the signal, the engineering problem becomes involved. The projection tube would also need to be custom made and so this is far from a practical solution.

One other important possibility is that of the radar as a tornado spotting device. Radar, which operates on the pulse echo principal, is inherantly quite accurate. It can indicate the range, the distance to the object, and it can accurately indicate the direction in which any electromagnetic reflecting material is located. By the use of a special oscilloscope projection radar can also plot a polar diagram or map of the surrounding area.

The first question that arises is whether or not radar can pick up tornado clouds. As yet this remains an unanswered question. It is more than probable that the moisture in the tornado cloud will give a good echo. Most tornado type clouds are heavily laden with rain and hail, all of which would indicate favorable conditions for strong echo response.

The proposed use of radar would require the aid of an indicating device and a direction finder to make sure that the cloud picked up by the radar would be the correct cloud. A detecting device suitable for this purpose has been carefully studied and developed so that it gives good information. At present the direction finder is in the stage of development and the rest of this thesis will be devoted to the theory, operation and proposed additions to the present equipment built by Mr. Vernon D. Wade.

The operation of the direction finder depends upon the ability of the crossed directional loop antennas to separate a wave into its quadrature components. Each component is amplified in exactly the same way and is applied to the deflection system of an oscilloscope tube. The resultant deflection is in the direction of the received signal. Unfortunately, although the direction is shown, there is at present no sense indication. Or more simply the direction indicator indicates the line of travel but not the direction from which the signal comes. In a later chapter there will be shown a circuit design by means of which this ambiguity can be eliminated.

The block diagram of the present sferic direction finding equipment in use at Oklahoma A. and M. College is shown in Figure 5.

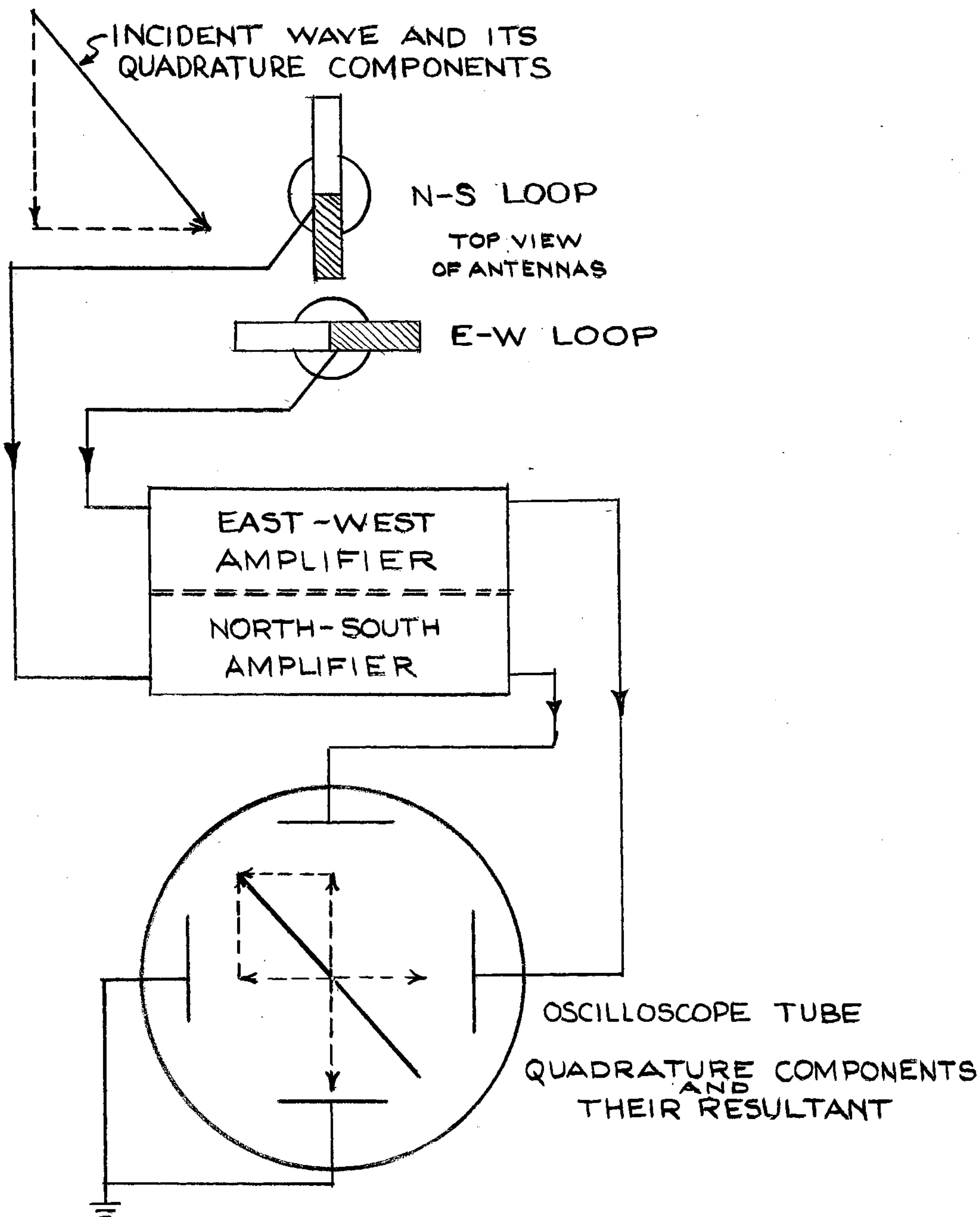


FIGURE 5

Block diagram showing the operation of the directionfinder used at Oklahoma A&M College

CHAPTER II

LOOP ANTENNA THEORY

The directional antenna is of such great importance to the radio direction finder that its theory should be thoroughly understood. The limitations and possiblities of the equipment must be known in order to proceed with design and maintenance of the associated auxiliary equipment.

The sferic direction finding antenna used at Oklahoma A. and M. College is made up of two square loop antennas each of which is mounted on one of its corners so that a diagonal of each square loop is horizontal. The planes of the loops are mounted so that they are perpendicular to each other with one antenna plane standing in the north-south direction and the other antenna plane in the east-west direction.

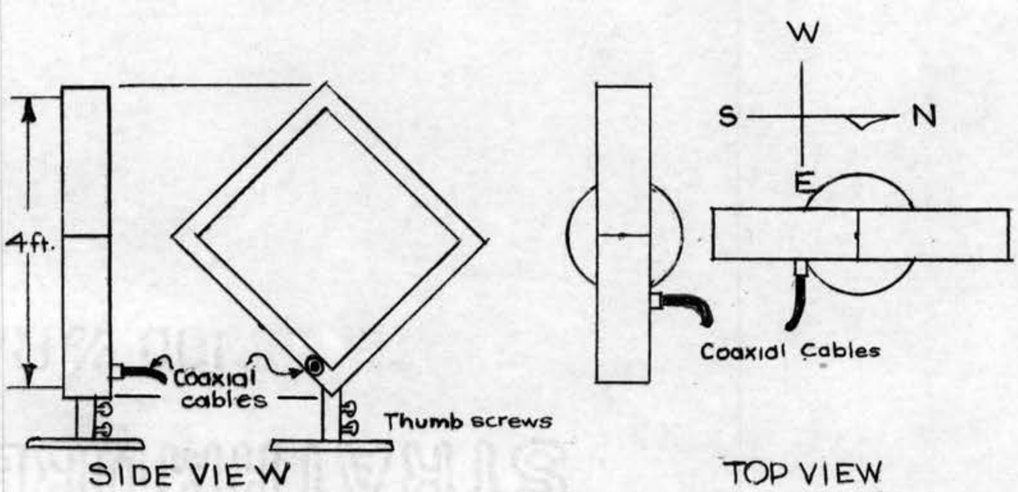


Figure 6.

The loop antennas

Figure 6 shows the outside appearance with the antenna shields in place. The actual construction is to be covered in a thesis by Vernon D. Wade.

Each loop is made up of 752 turns of copper wire. The loop is center tapped for the purpose of electrically balancing the antenna. The output plug contains three wires, two of which are the loop ends and the other the grounded center tap. The cable that feeds the signal to the receiver is shielded to decrease interference. These details are shown in Figure 7.

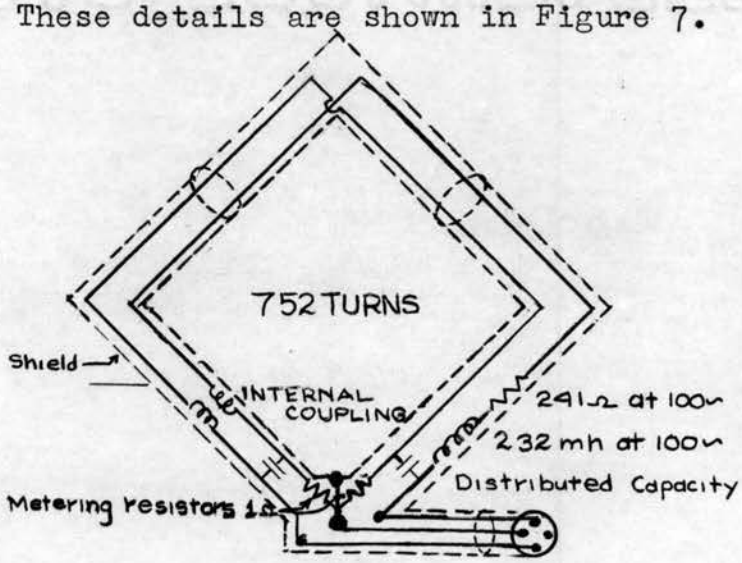
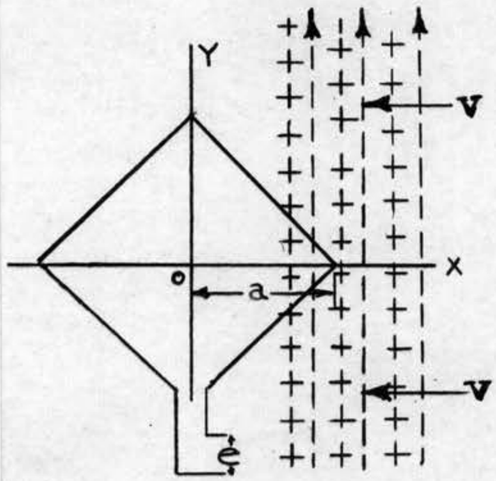


Figure 7.
Schematic diagram of antenna

Around the antenna there is a galvanized sheet iron shield which is grounded to maintain a uniform ground capacity to all sides of the antenna loop. This is necessary in order to avoid faulty direction indications.

Now with some idea as to the actual antenna arrangement the next step will be to derive the general equation of output voltage. The restrictions imposed on the derivations that follow are that the received wave must be vertically polarized, must be traveling along the plane of the loop and parallel to the ground, it must also be a plane wave. Later these restrictions will be removed or qualified for the purposes for which we will use the loop.

With a vertically polarized electromagnetic wave traveling along the plane of the loop we find that in figure 8 the magnetic flux cuts the right hand side of the antenna first. Later this same flux cuts the second half of the loop inducing an identical voltage to that which was induced in the first half. Except for the time delay the voltages induced are equal; therefore it can be surmised that the output voltage is affected by the time delay. This is the actual case and will be demonstrated analytically in this chapter.



In figure 8

v is the velocity of propagation,

↑ designates an electric flux line,

+ designates a magetic flux line flowing into paper.

It is noted that the electric field is perpendicular to the magnetic field.

Figure 8.

An antenna set up on a Cartesian coordinate system, being cut by an electromagnetic field traveling in the negative X direction.

For purposes of analysis the antenra will be separated into sections that lie in each quadrant. Each of these sections may be resolved into incremental components as shown in quadrant 1 of Fig. 9.

For this section of the antenna $x = a - y$. Therefore

H(x) becomes H(a - y) and the expression of voltage induced at any instant of time between the ends of this section is a summa-

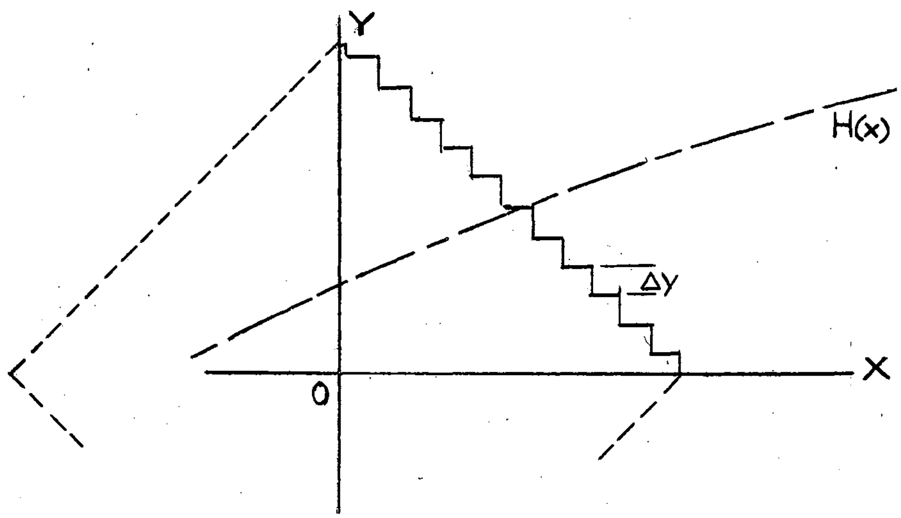


Figure 9.

tion of voltages induced in all of the Δy elements as shown in the following relationship,

$$e_1 = K_1 \lim_{n\to\infty} \sum_{y=1}^{n} H(a - y)\,\Delta y \qquad = K_1 \int_0^a H(a - y)\,dy$$

It is to be noted that H(a - y) is the magnetic field intensity as a function of x where

$$x = (a - y).$$

When this equation is expanded for the whole loop, the section in the fourth quadrant, because of symmetry, would have an induced voltage exactly equal to the above expression. Therefore the voltage equation for the half of the loop lying on the positive side of the Y axis is

$$e_1 = 2K_1 \int_0^a H(a - y)\,dy.$$

The section on the minus side of the Y axis is such that $x = y - a$ at the top; therefore the integral equation for the voltage is

$$e_2 = 2K_2 \int_a^0 H(y - a)\,dy \, .$$

By the same reasoning as before the bottom section will add to this section the same amount of voltage as the top. Because the antenna was carefully constructed so that the sides are balanced $K_1 = K_2$ and the final equation is the difference between the two bucking voltages e_1 and e_2, therefore

$$e_{out} = 2K_1 \int_0^a H(a - y)\,dy - \int_a^0 H(y - a)\,dy$$

The factor K_1 is proportional to the number of turns on the antenna, the velocity of propagation, the physical dimensions of the loop and the system of units used in calculation.

Careful scrutiny of the last equation indicates that the voltage equation may be approximated to make mathematical manipulation easier.

In order to find an approximation it is best to assume a sinusoidal waveform for the field. The wave length should be many times greater than the width of the antenna loop. Since all waveforms may be broken down into the summation of a series of sine waves, this type of analysis will be employed. Although the series is infinite the frequency components in sferics above the frequency under investigation are so small that even the worst distortion would result in no detectable difference in the received wave. It should be stated here that frequencies above those investigated will be greatly distorted. As frequency reaches the point where the wave length equals one half the length of the diagonal of the antenna, there is complete cancellation and zero voltage is developed at the antenna terminals. Near this frequency the crossed loop directional indications are quite erratic since the antenna which is almost facing the wave broadside will have a larger signal output than the one which ordinarily would generate the greater signal. Above this frequency of zero output there is an addition of voltage in both halves of the loop. Beyond that another null and difference again results, alternating from difference to sum and back as the frequency continues to increase. This paragraph was written primarily to point out the limitations of the antenna in the event that higher frequency reception should be necessary. The only means of correcting this limitation would be to build smaller antenna loops.

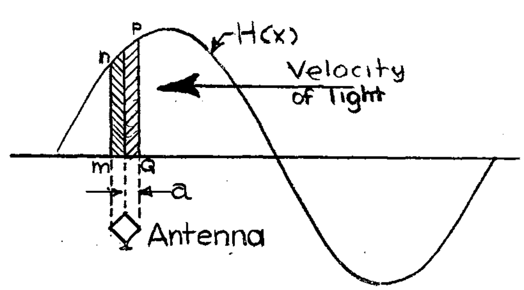


Figure 10a.

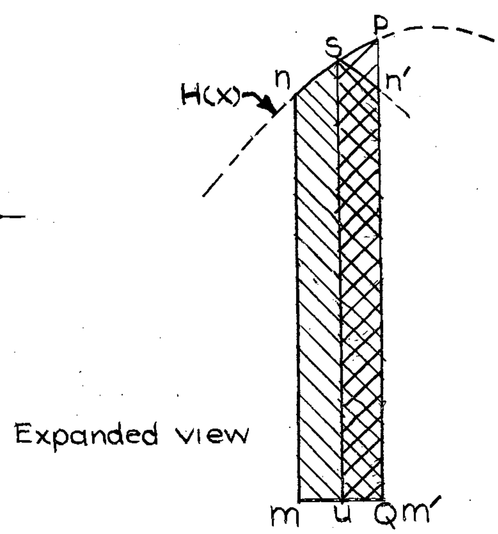


Figure 10b.

In the figure 10 the exact integrals of H(x) are shown as the areas under the H(x) curve. The voltage is equal to2K times the area under the curve. The voltage produced by area (mnsu) is the negative of the voltage of area (uspq) so by rotating side (mn) to (m'n'), using line (us) as an axis it is found that the area (usm'n') is cancelled and the voltage output is equal to2K times the area (spn'). This K is the same constant defined previously.

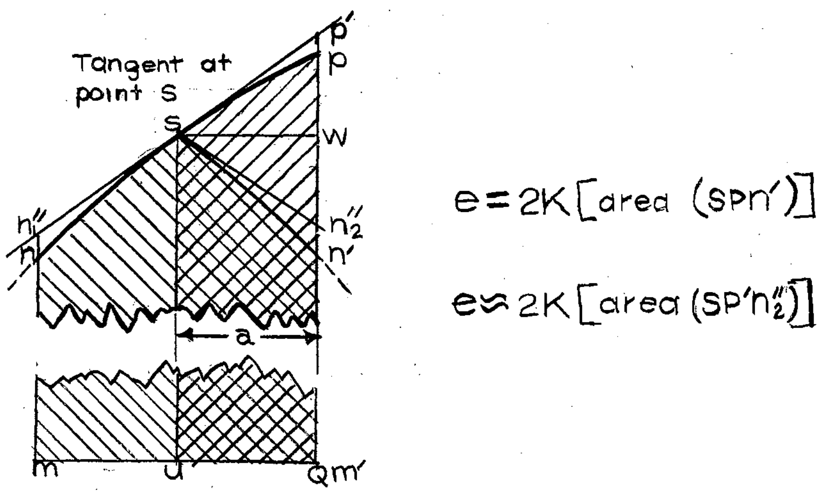


Figure 11.

In figure 11, area (spn') is approximated by the area $(sp'n''_2)$. Area $(sp'n''_2)$ is equal to 2 times area (sp'w). Here area (sp'w) is the product of the base (a) times the height divided by 2. The height is given by

h = (slope)(base) = a df(y)/dx.

It should be noted that df(y)/dx is evaluated at point (s). The area of $(sp'n''_2)$ gives the approximate voltage

$$e \approx 2K\ a\left(a\ \frac{df(y)}{dx}\right).$$

This is the general equation.

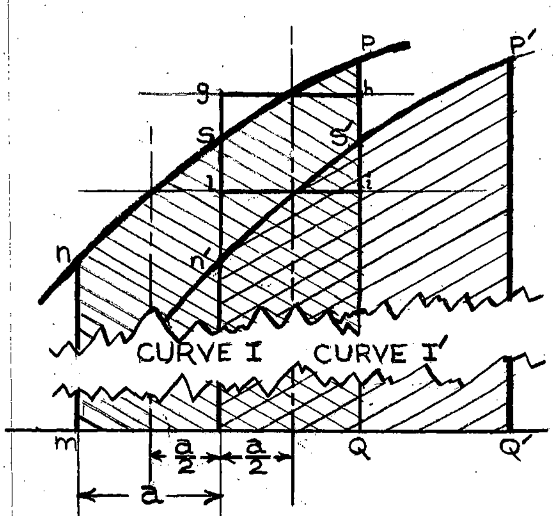
It follows that the approximate waveform of the antenna output is the differential of the incident wave. For the case where

$f(y) = \sin \omega t$

the expression of the approximate output is, employing the slope method,

$e = 2K\omega a^2 \cos (\omega t).$

The approximation gives a simple mathematical expression which is good for many cases of a general nature. However when the sferic is broken down into a multitude of sine functions and the derivative of each of these functions is obtained, then the wave components must be added together to obtain the resultant wave. For complex waveforms this problem extends from the realm of the tedious to the impossible. If the areas under the H(x) curve subtended by each half of the antenna are assumed to be rectangular a simple graphical solution will become apparent. The height of each rectangle is assumed to be the same as the height of H(x) at the midpoint between the sides of the area that it approximates. This is shown in figure 12. This figure shows the same wave segment as that shown in figure 11, but



This curve is constructed by tracing the H wave over itself with a displacement equal to distance (a).

Figure 12

instead of folding one area over the other to obtain the difference area the left hand area is displaced to the right by a distance (a). The exact difference between these areas is the area (sps'n'), and the output voltage is 2K times this area (sps'n'). But area (sps'n') can be approximated by the difference area of the two rectangles. This difference area is the small rectangle (ghil). The area of this rectangle is equal to the difference in H between midpoints of the two sections multiplied by the displacement distance (a). The resultant approximate equation for the output voltage is

$$e \approx 2Ka(\text{vertical distance from curve I' to curve I}).$$

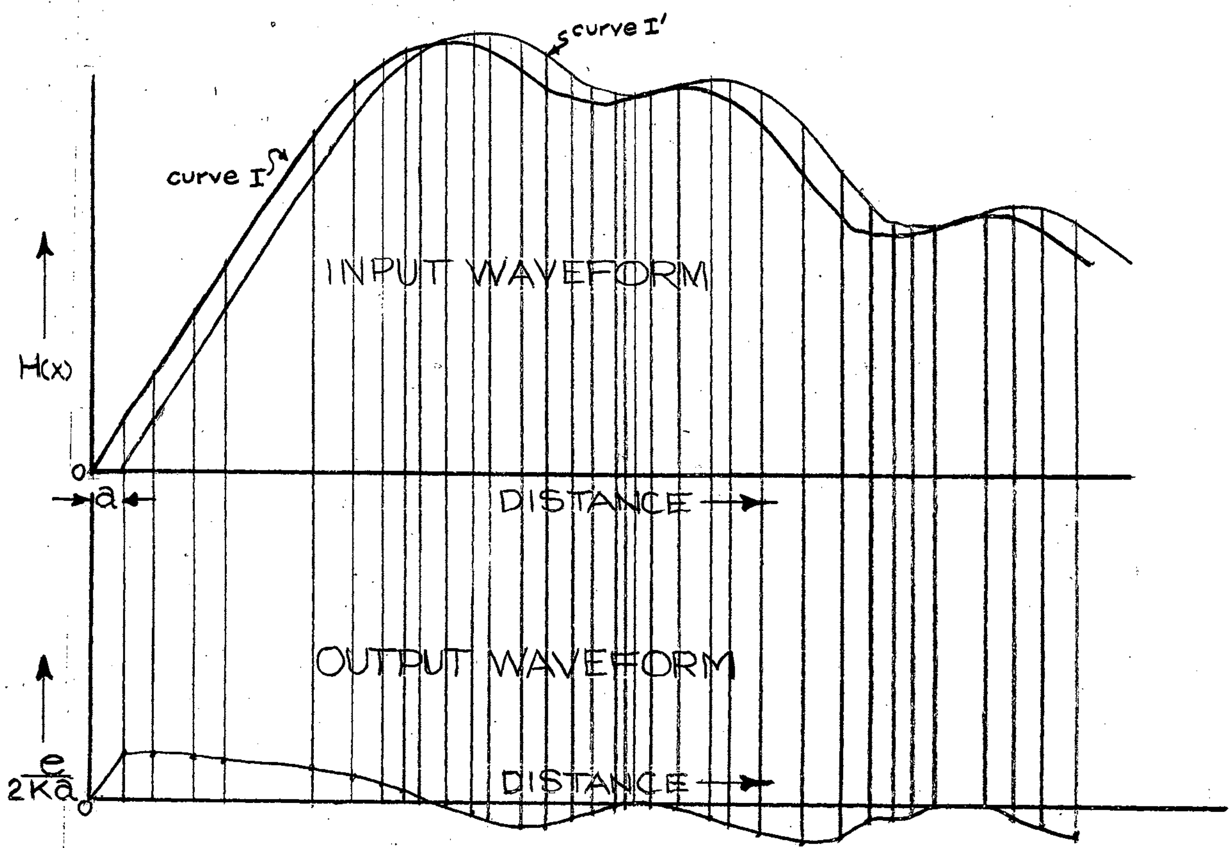


Figure 13.

The steps in a graphical solution are to trace a curve, then with a right hand displacement of (a) trace another curve. With a pair of dividers plot a curve of the vertical distance from the second curve to the first. The curve so plotted is a curve of the voltage divided by (2Ka). To convert to a direct reading voltage curve multiply each number on the vertical axis of the new curve by (2Ka). Care must be taken to be certain that the displacement (a) is in the correct system of units for the horizontal scale of the input waveform, also the vertical distance must be measured from the second curve to the first. This will give the negative polarity when there is an actual voltage reversal.

Table of errors calculated for case when antenna subtends 20° of an input sine wave

Phase angle of antenna midpoint	exact output factor	slope method approximation	per cent error	per cent error of max	displacement approximation	per cent error	per cent error of max
80.0°	.005276	.005289	.246	.172	.005289	.246	.172
82.5°	.003965	.003966	.02	.013	.003971	.404	.211
85.0°	.002649	.002655	.22	.079	.002651	.11	.039
87.5°	.001324	.0013288	.378	.066	.001327	.226	.039
88.5°	.000795	.0007974	.241	.026	.000796	.176	.018
90.0°	0	0	0	0	0	0	0

TABLE I

When approximate equations are used it is necessary to calculate the error that they introduce to avoid erroneous results. From figures 10b and 11 and the previous discussion, it may be seen that the shorter the wave length the larger the error introduced. The greatest error will occur near the crest of the sine wave. This error is approximately a function of the second derivative of the input wave. Near the crest of a function that is symmetrical around its peak value the error is no longer a function of the second derivative, but begins to cancel and result in zero error at the peak.

In the case explored in the Table I, the frequency was such that the antenna spanned twenty degrees of a sinusoidal wave. The exact values were calculated. The corresponding approximate values were then calculated and compared to the exact values. Six place trigonometry tables were used in the calculations but the values of the cosine are so small near the ninety degree mark that when the difference between the exact and the approximate value was taken only one or two significant figures remained. Erratic data appears in the error table because the last figures have been rounded off in making up the trigonometric table that was used. The cases investigated were places where the values of maximum error would occur. The largest error found is much less than 3/10 of one per cent of the maximum value. This error was always less than 1/2 of one per cent of the instantaneous value of voltage at the point investigated. Therefore any wave of this frequency or below introduces no detectable error on the oscilloscope. Fortunately this frequency is at the upper end of the sferic frequency spectrum. The table of per cent error was made up of trigonometric calculations without multiplying by the loop constants. This introduces no error since all of these constants would have cancelled out in the calculation of the percentage.

In the early part of this chapter there were several rigid stipulations placed upon the wave being used in the antenna calculations. It was to travel parallel to the plane of the antenna. This stipulation is removed by the use of a circle diagram which shows the variation in antenna voltage when a given signal approaches from different angles, as shown in figure 14a. The mathematics of this was developed by Mr. T. H. Thomason.[1]

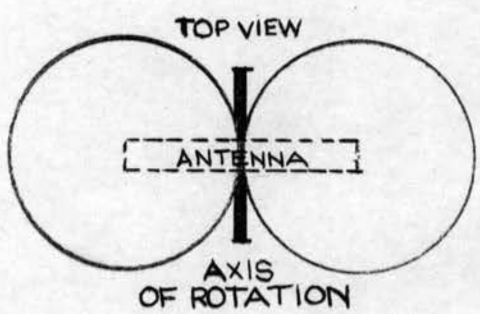


Figure 14a.

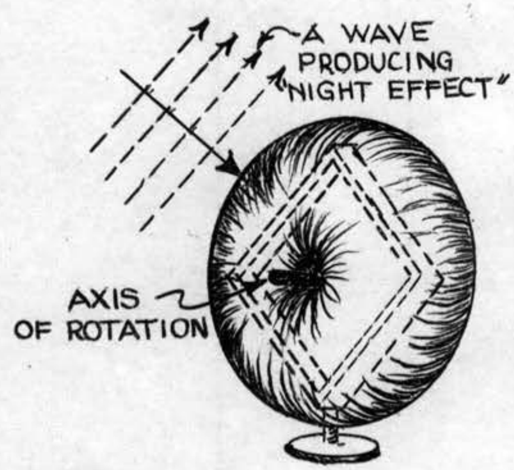


Figure 14b.

The polar diagrams of the loop are shown in Figure 14a. This indicates the antenna output as a function of the angle of incidence. Figure 14b indicates the complete reception pattern. It is obtained by rotating Figure 14a on the axis indicated.

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[1] Thomason, Thomas H., The Development of a Sferic Direction Finder, Master of Science Thesis, Oklahoma A. and M. College, 1949, p. 14.

The donut shape of figure 14b indicates that there is erroneous reception of waves whose line of travel may be perpendicular to the loop in the horizontal plane but which have a vertical component parallel with the loop. This error is called "night effect" and its maximum value may be close to 90 degrees in the crossed loop circuits. This error is by no means negligible in the case where lightning is either coming from overhead or from the sky wave. This is a theoretical source of error which will not be too objectional in actual practice because night effect from the sky wave is not very likely with a maximum range of 200 miles and lightning overhead may be easily seen by eye without relying upon the direction finder. Since a steeply descending ground wave is always possible, however, it is well to keep the "night effect" in mind.

Another stipulation was that the wave be vertically polarized. This indicates that the magnetic flux lies in the horizontal plane. The removal of this stipulation may be approached from the standpoint that the output voltage is dependent upon the amount of magnetic flux linking through the loop. For any wave traveling in the horizontal plane but polarized at an angle other than vertical the amount of magnetic flux linkage would depend upon the cosine of the angle that this flux made with the horizontal plane. An angle other than horizontal will give this cosine reduction in antenna output. Each antenna will have the same reduction factor, however, and no error will be introduced.

The last stipulation was that the wave must be a plane wave. For all practical purposes all sferic waves are plane waves when they reach the loop. This does not introduce any limitation except in calibrating the crossed loops with an outside source located near the antennas.

Other errors in actual operation of loops will be discussed in the chapter on alignment because they are affected by considerations other than the theory of the loop.

With the theory of single loops as a background, it is now possible to investigate the operation of both loops together. Two loops, operating in unison, may be shown to have concentric vertical center lines. Although physically this is far from true it is theoretically a very close approximation at sferic frequencies. By drawing the loops as having the same vertical center line it can be shown geometrically that the components of voltage generated in each loop will be in exact ratio to their respective quadrature components in the generating field.

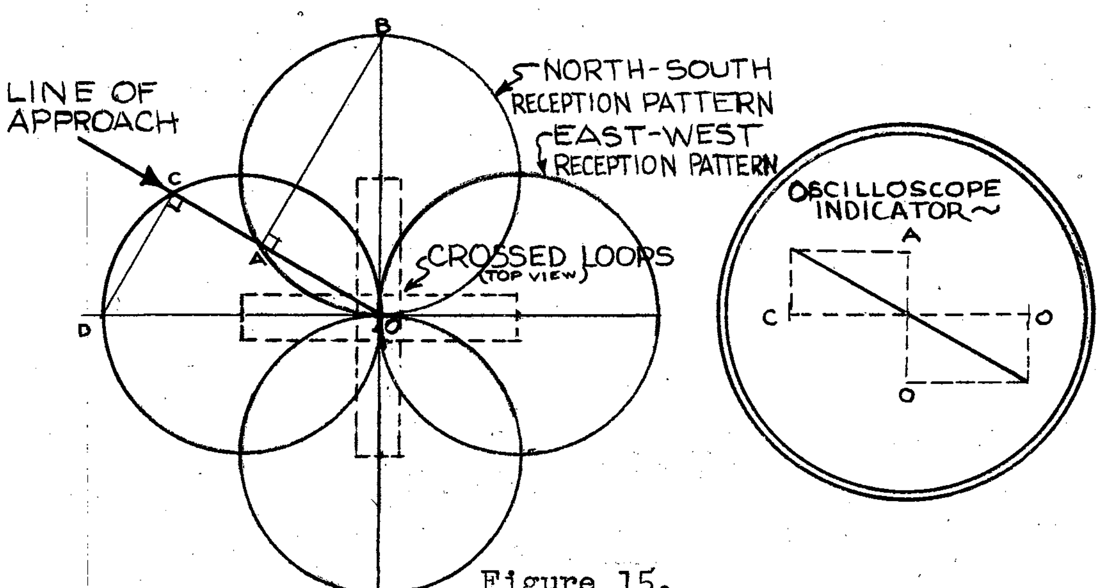

Figure 15.

Referring to figure 15 the proof of this statement becomes,

(a) Triangle OAB is congruent to triangle OCD because all three angles are equal.

(b) Angle A = Angle C because a triangle inscribed in a semicircle with one side as the diameter is a right triangle.

(c) Angle ABO is the complement of Angle AOB because acute angles of right triangles are complementary.

(d) Angle ABO = Angle COD because complements of equal angles are equal.

(e) Angle CDO = Angle AOB by the same reasoning given above.

(f) Therefore the wave developes voltages in each loop proportional to its quadrature components.

The diagram of the oscilloscope screen shows the addition of these components and the correct direction indication.

CHAPTER III

THE AMPLIFIER SYSTEM

The thesis of Mr. Vernon D. Wade, who executed the design and construction of the present direction finder equipment, will cover the construction and operation of the amplifier system. This chapter will include the actual and equivalent radio frequency circuits together with brief discussions of the points of interest in each.

A coaxial cable carries the loop signal to the amplifier chassis. At the chassis the two input leads are shunted with a ten megohm variable resistor and a tuning capacitor. These components act as loop circuit balancing devices so that the two loop antennas may be tuned to the same frequency and damped to the same decrement. This is the only tuned circuit in the entire system. Resonance introduces serious phase changes and the possibilities of upsetting the phase equality between the two circuits. For this reason R-C coupling is used throughout the system.

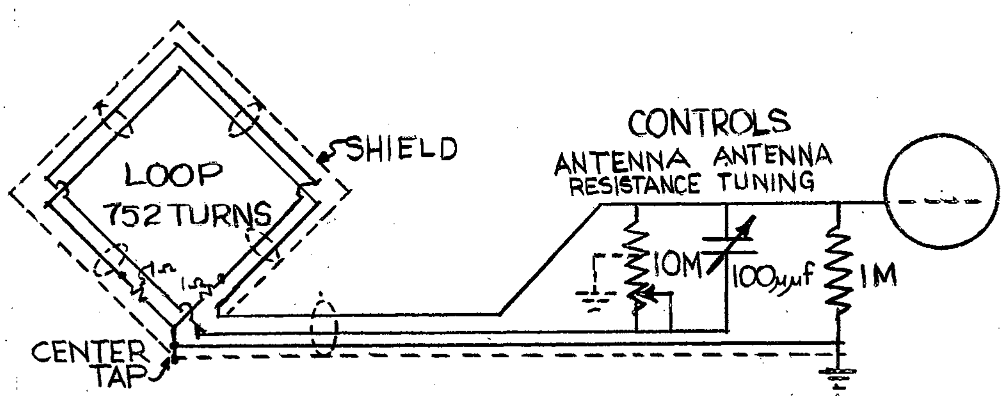

Figure 16.

The antenna input circuit.

In the antenna circuit of figure 16 it can be seen that the signal appears to come from only one half of the antenna loop. This is true only in part. Both halves of the loop are wound closely together so that there is inductive coupling from one half to the other. In figure 16 the ground point is shown as a phantom ground, this makes the operation of the input circuit to the buffer stage of the cathode follower more obvious.

The cathode follower stage working as a buffer is used for several reasons. First, it has very high input impedance which means little loading effect on the antenna loop. Second, there is much less chance for feedback through this type of buffer compared with other types of amplifier stages. Third, the circuit arrangement nearly eliminates the shunting effects of the tube capacities. This feature is very good when there is danger of a frequency change of the resonant antenna circuit because of temperature variation of the tube capacities during the heating period. The cathode follower induces little noise into the circuit and has little or no nonlinear distortion due to the extreme values of negative feedback in the cathode circuit.

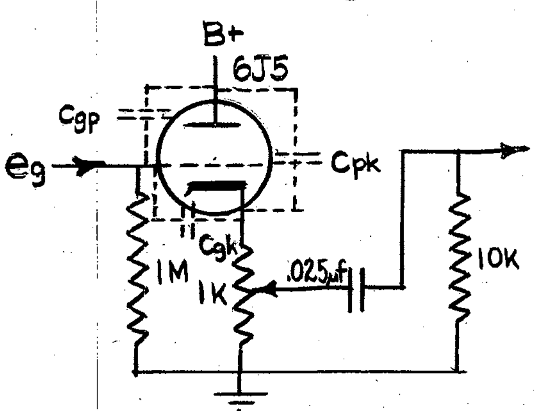

Figure 17a.

Cathode follower.

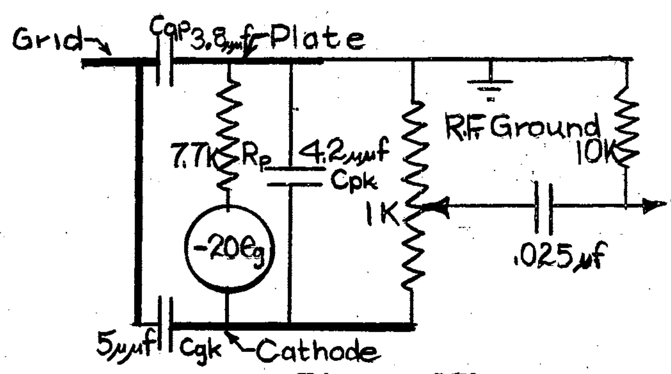

Figure 17b.

Equivalent circuit for circuit on the left.

It should be mentioned that even though the equivalent circuit of the cathode follower, figure 17b shows the capacitor between the grid and cathode as large compared with the others; the phase of the cathode is such that there is a rise and fall of potential on either side of the capacitor simultaneously. This means that there is very little voltage change across this element. Hence, there is almost no conduction. The formula for the equivalent capacity is

$$C_{gk(equiv.)} = (1 - A)C_{gk},$$

where A is the amplification.

The capacity C_{pg} is not reduced by this system but is quite small in comparison with the equivalent C_{pg} of a conventional amplifier. In the conventional amplifier C_{pg} is increased by the factor of $(1 + A)$. This is called the Miller effect which is the effect of an opposite change in plate potential from that of the grid so that the AC plate voltage plus the AC grid voltage appear across the capacitor. This gives a greatly increased capacitor current, and a high resultant equivalent capacity.

The cathode follower output is a voltage divider which feeds into the remote cut off 6SK7 amplifier shown in figure 18a. The reason for the small grid leak resistance in the 6SK7 circuit is two-fold. It more nearly matches impedance of the cathode follower and it also reduces the noise which is proportional to the square root of the resistance of the input resistor. Noise is necessarily objectionable because it obscures weak signals.

The 6SK7 is a remote cut off tube. The gain control is a variable cathode bias which changes the amplification factor of the tube. A large bias swing of around fifty volts is obtained with a bleeder resistor from B+ to the cathode potentiometer. This bleeder resistor gives a better control than the use of self bias on the cathode. To protect the tube there has been a

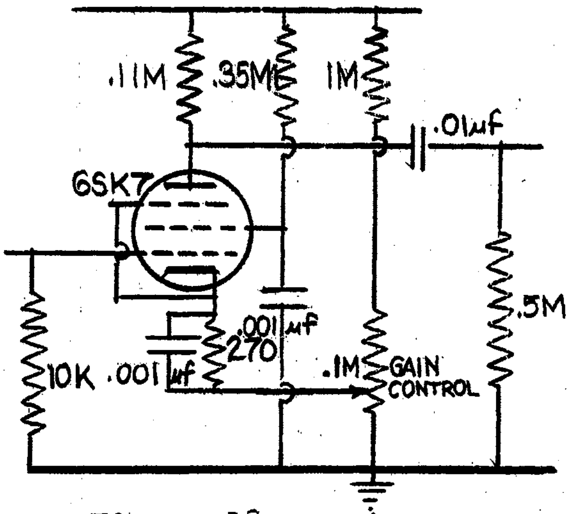

Figure 18a.

First Amplifier

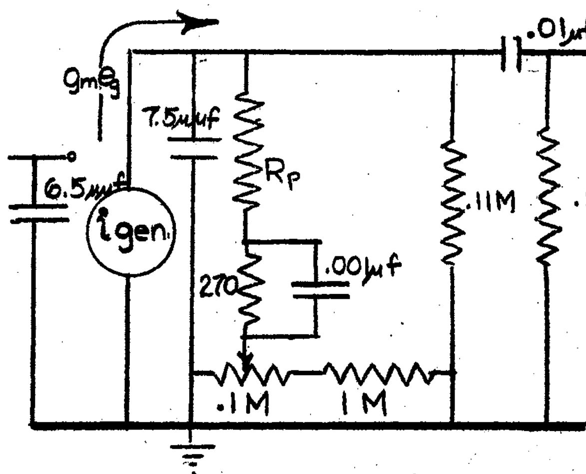

Figure 18b.

Equivalent constant current circuit with lumped input capacities from RCA tube manual.

constant self biasing cathode resistor employed which holds the plate current within a safe operating range. This is necessary when the gain control is turned to maximum gain. This self bias is by-passed by a by-pass capacitor to avoid negative feedback when the gain is turned up. The bias control potentiometer, however, induces negative feedback when the gain is turned down. This is the result of not by-passing the potentiometer resistance. Negative feedback results in a reduction of nonlinear distortion and increased control. The rest of the circuit is conventional for a resistance coupled pentode circuit.

The following stage is a conventional 6SJ7 pentode circuit, figure 19. The sole purpose of this amplifier is to increase the gain of the system; therefore, it incorporates a typical high voltage gain circuit. A sharp cut off tube such as this gives good linear amplification and hence can be used without negative feedback, as was done in this circuit.

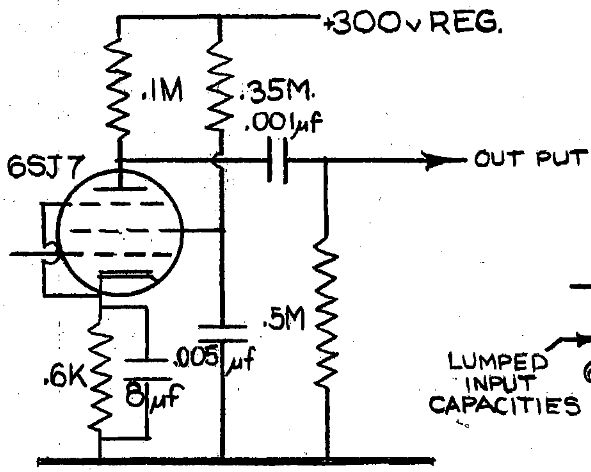

Figure 19a.

Resistance coupled amplifier.

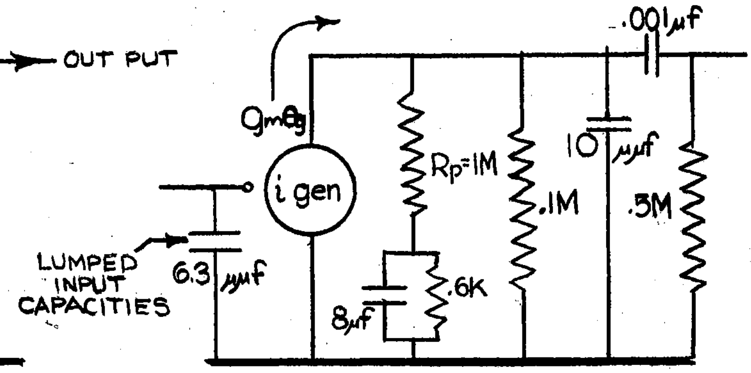

Figure 19b.

Equivalent circuit of the amplifier stage pictured at the left.

The lumping of the shunting capacities in figures 19 and 20 may seem inconsistant with accurate engineering calculations but the RCA Receiving Tube Manual[1] lumps this capacity as a maximum value so that there is no danger of producing a response curve that is less accurate than that calculated from the values given. In both of the pentode equivalent circuits the screen circuit is left out because the lumped capacity includes the shunting effect of the screen. Other than shielding the plate

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[1] RCA Receiving Tube Manual, p. 131.

from the control grid the screen grid has no active function in radio frequency tube operation. Screen shielding reduces C_{pg} by a factor of about 1/100.

The final driving stage of this amplifier section is a high mu triode with enough power output to drive the high impedance load oscilloscope. The 6J5 tube is used for this job and has proven to be a good choice. The triode tube characteristically has much nonlinear distortion of the second harmonic type. Hence the use of negative feedback is necessary. In the circuit shown in figure 20a it is found that there is no cathode by-pass capacitor. This fact indicates that there is negative feedback introduced in the cathode circuit. This tends to correct the distortion of the tube.

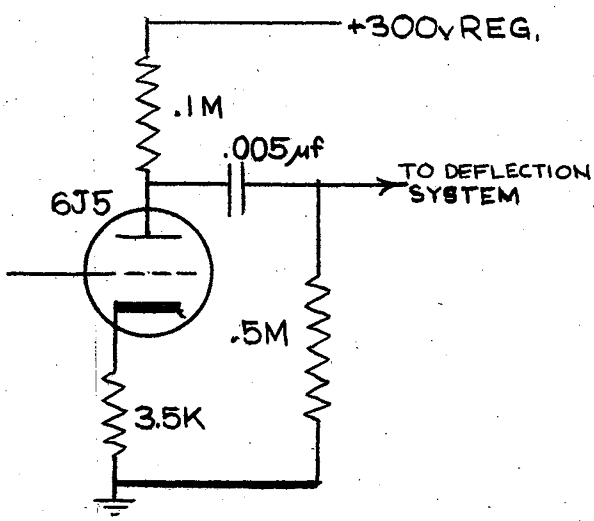


Figure 20a.

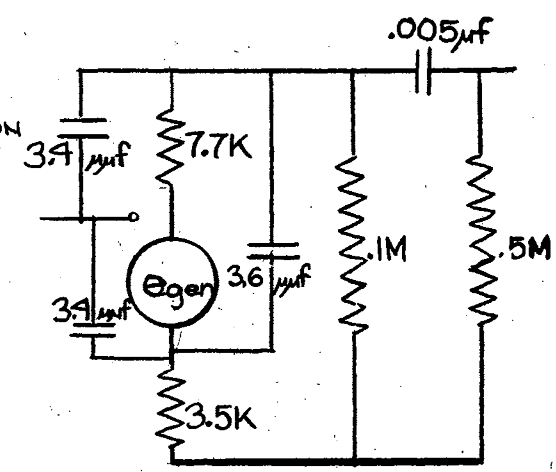


Figure 20b.
Equivalent circuit of Figure 20a.

The output voltage, E_{gen}, of this circuit will be

$$E_{gen} = -eg\ 1-\mu \frac{R_k}{(R_1+R_k)R_p j\omega c+R_p+R_1+R_k(1+\mu)}$$

It is to be noted that the factor C in this equation is the lumped equivalent capacity between the cathode and plate.

Once the equivalent circuits are set up, the point of inflection for the high frequency amplification may be calculated. The response curve of the system may be corrected by redesigning the amplifiers with the poorest response curves.

A complete circuit of this equipment may be found in figures 21, 22, 23, and 24. The power supply is made up of two sections. The standard amplifier supply which is a +300v regulated supply, and the oscilloscope accelerator supply which produces -1000v. This high voltage supply does not require good regulation and has a very small current drain. This makes it possible to use a resistance-capacitance filter. A filter such as this is more practical at high potentials than the more elaborate low voltage filter systems. The reason for bringing up this point is to show that this supply cannot be used for negative bias in future work because of filter hum.

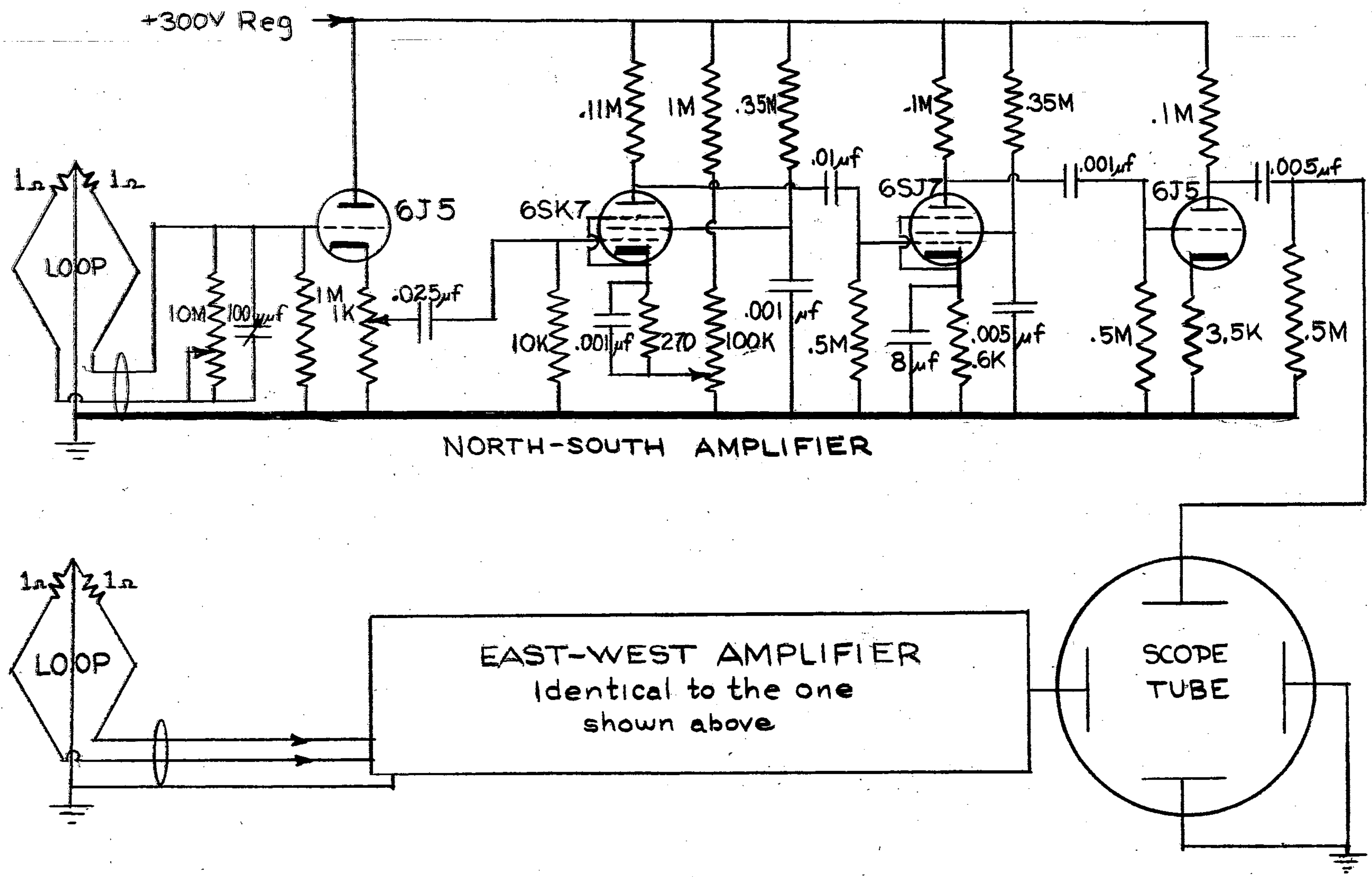


FIGURE 21
COMPLETE AMPLIFIER CIRCUIT

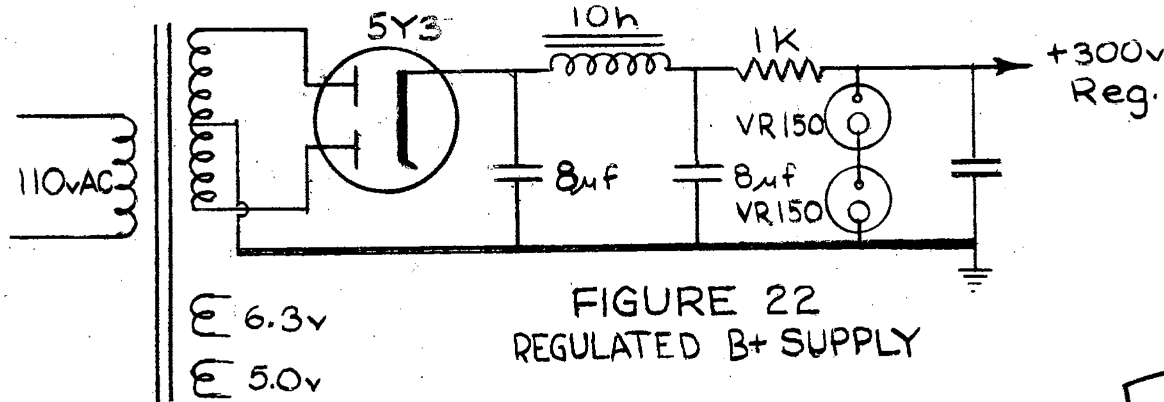


FIGURE 22
REGULATED B+ SUPPLY

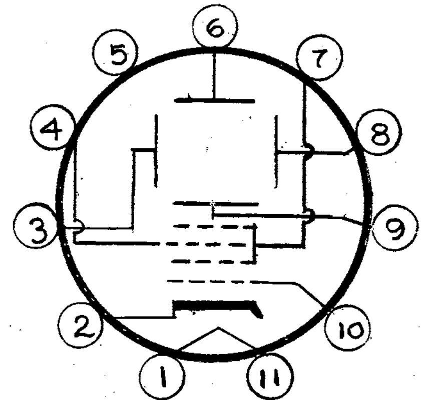


FIGURE 24
SCOPE TUBE
2AP1

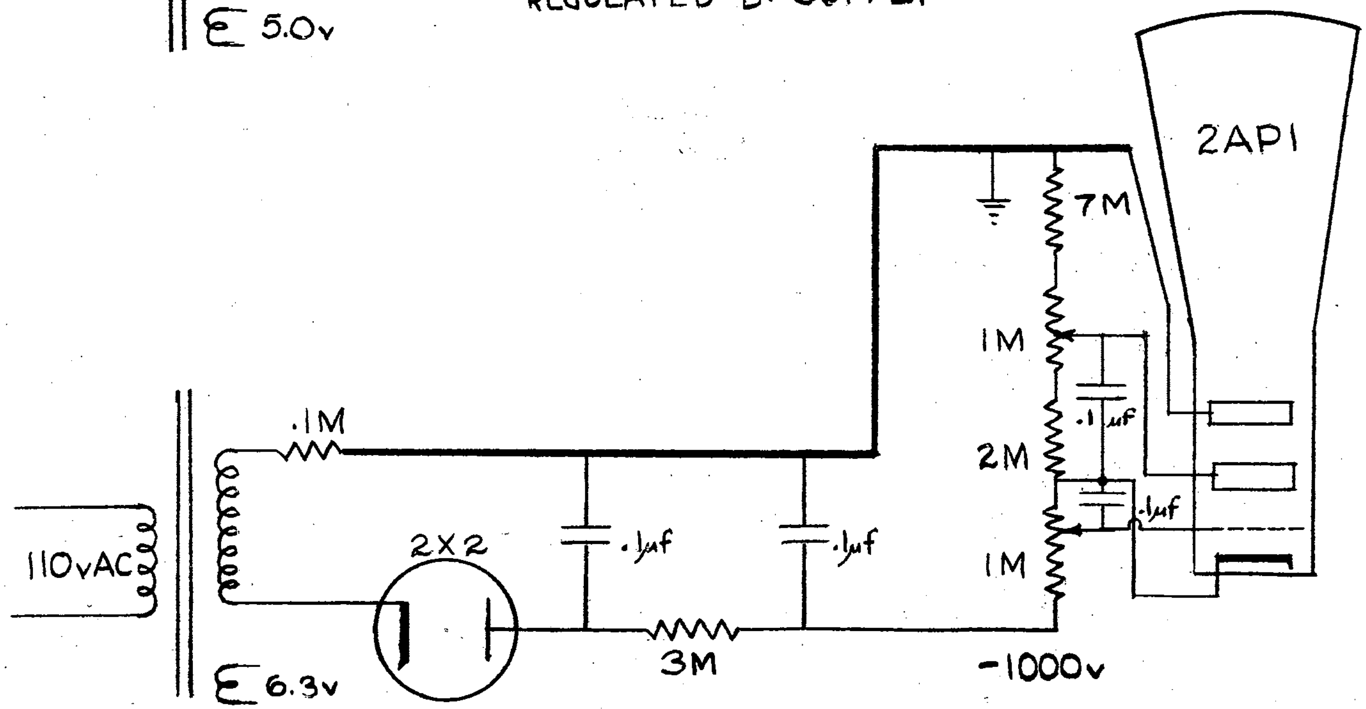


FIGURE 23 OSCILLOSCOPE POWER SUPPLY

CHAPTER IV

PROPOSED DIRECTION AMBIGUITY ELIMINATION CIRCUITS

One of the obvious drawbacks to the use of the crossed loop direction indication system is that there is a possibility of a 180 degree ambiguity error. If two tornadoes should be active on almost diametrically opposite bearings one or the other could be easily overlooked by the operator. While working with radar this would be a decided disadvantage because radar will pick up many objects other than tornadoes. The doubling of the number of echoes from which to choose will make its use even more difficult.

It would be advantageous to have some means of correcting this shortcoming. The author has designed two circuits which should prove effective for this purpose. This chapter is a discussion of the theory and ciruitry of these proposals.

It is necessary to understand how the inverse direction indication comes about. It is readily seen that the side of the antenna which is first encountered by the field of the wave will experience the initial induced voltage. This voltage will be in the direction of the E vector component of the incident wave. The voltage of this half of the antenna will predominate as long as the wave front continues to increase. When the wave ceases to increase both halves of the antenna will have the same induced voltage and they will exactly cancel each other. As the field decreases, even of the same polarity as before, the output voltage is reversed because the opposite section of the antenna now has the maximum induced voltage. This is the reason that an

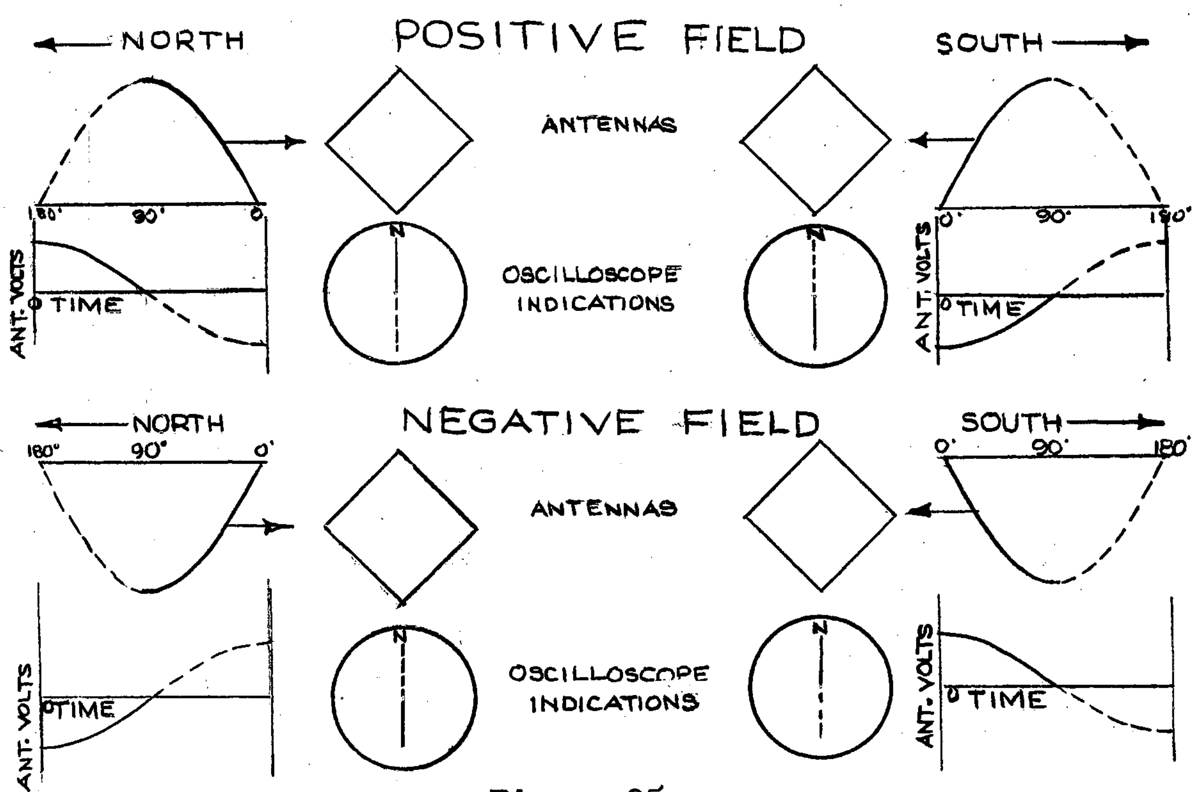


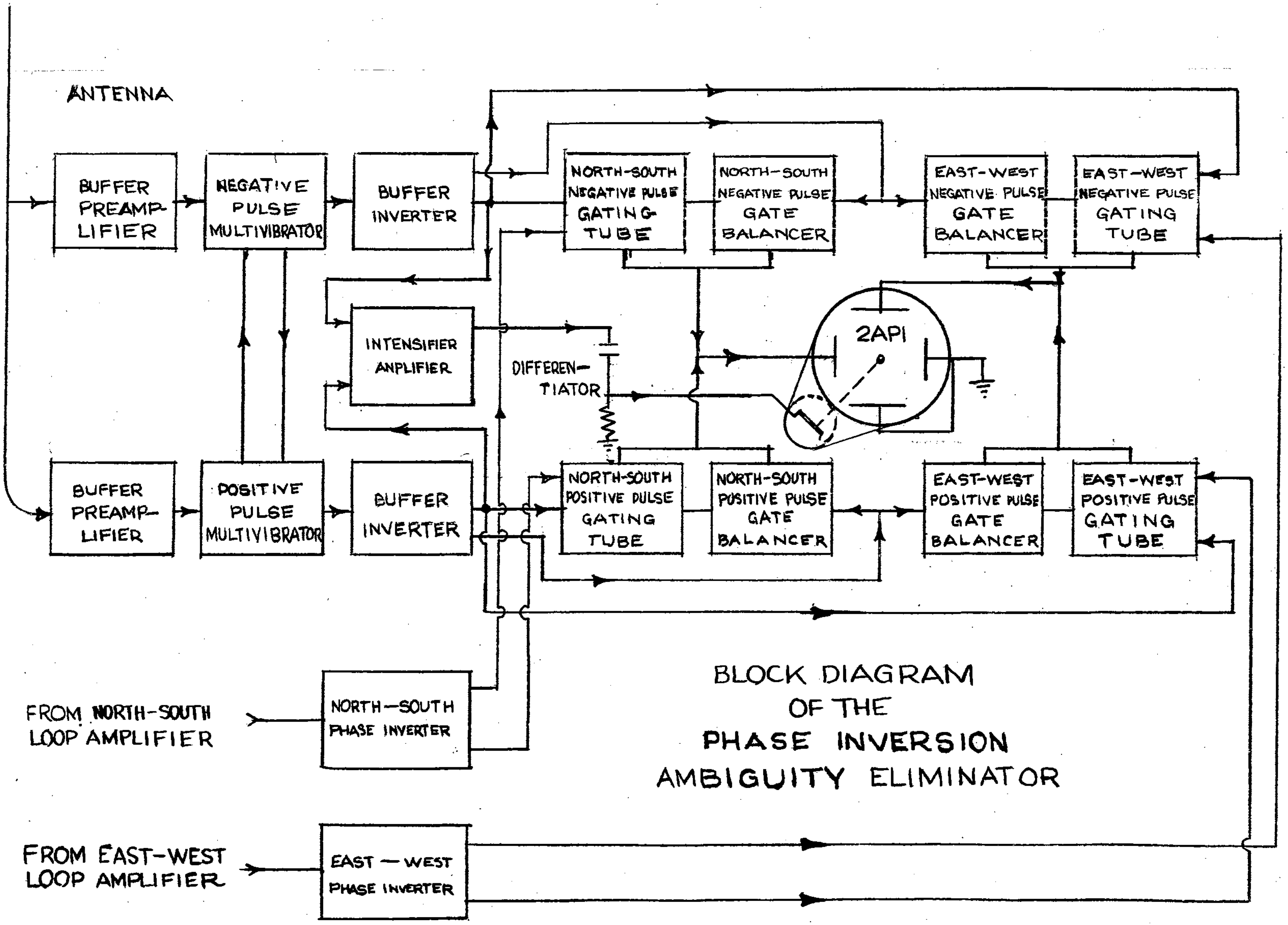
Figure 25.

all-positive wave can give both a positive and a negative indication on the oscilloscope. By reversing the direction of incidence the reverse indication would appear on the indicator face. By blanking out the oscilloscope during the negative half of the wave only the correct direction would be indicated provided that only waves of one polarity are received. In the event that the wave is polarized in the opposite direction the deflection voltage would be of the wrong polarity giving a 180 degree indicator error. To overcome this problem the polarity of the incoming waving must be determined. If the wave is of inverted polarity a phase inverter will correct the deflection voltage so that the indicator scale may be read directly. On the other hand the intensity may remain cut off until the correct deflection voltage is applied. These two methods of correction led to the design of the following two pieces of equipment.

The first method designed to eliminate ambiguity is the phase inversion method. In order to discover the polarity of the incoming signal a vertical whip antenna should be used, the output of which is polarized in phase with the incident wave. The wave is then amplified and applied to a set of selective multivibrators. If the wave is polarized for correct indications one multivibrator will operate, open a gating circuit, and pass the signal to the deflection system. When the polarity of the electromagnetic wave is of the opposite phase the other multivibrator will operate to actuate the reverse phase gate and allow the inverted signal from the phase inverter to pass to the deflection system. The resultant direction will then be indicated for the initial portion of the wave.

The elimination of the reverse sweep will be handled by the use of a pulse from the multivibrator output. This square pulse will be applied to a differentiator and then to the oscilloscopic cathode terminal. This will intensify the electron beam for a definite period of time which will be set shorter than the period of one polarity of the average loop output wave. The time during which the intensifier is on is the same for each cycle of operation and therefore may not be perfect for every sferic.

The block diagram, Figure 26, indicates the sequence of operation of this type of ambiguity eliminator circuit.



BLOCK DIAGRAM
OF THE
PHASE INVERSION
AMBIGUITY ELIMINATOR

FIGURE 26.

A brief discussion will be given to each component circuit so that the peculiarities may be understood. The buffer ampli-

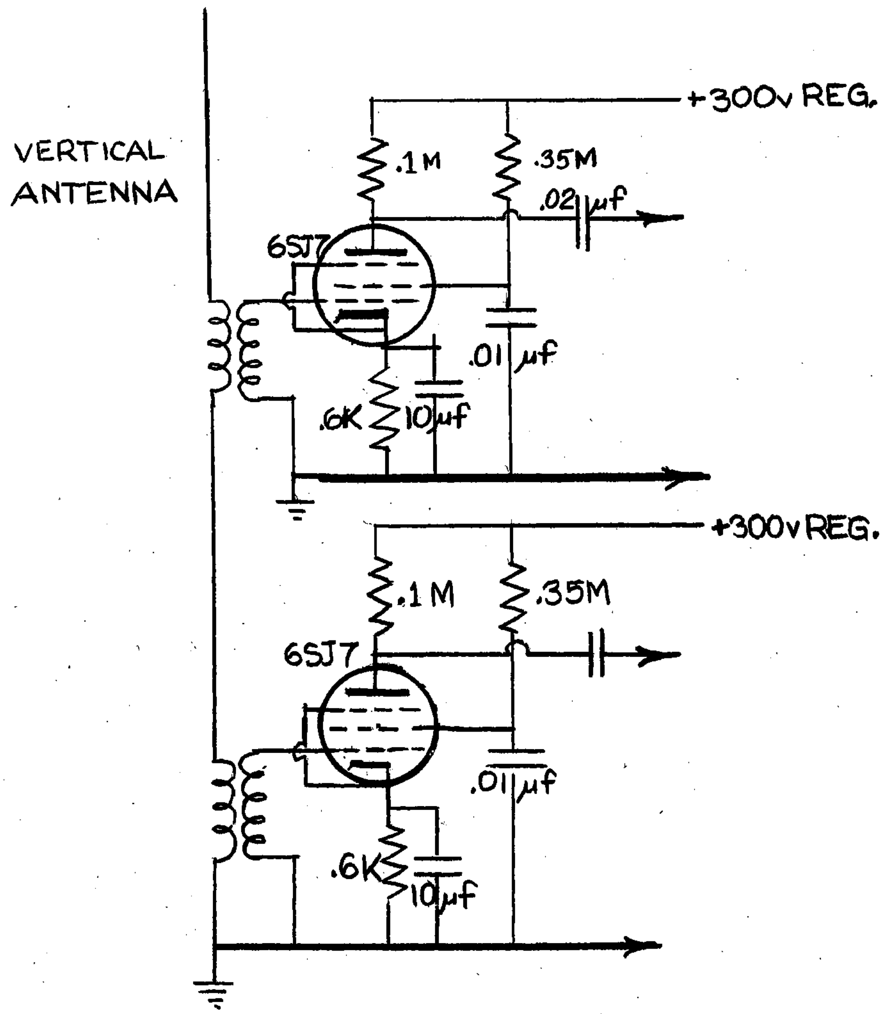


Figure 27.

fiers are used to eliminate interaction between the grid circuits of the selective multivibrators. They also raise the signal strength to an amount that will actuate the multivibrators early in the cycle of the wave. The circuit shown in Figure 27 is taken from the operating circuit used by Mr. Wade in the loop amplifier systems, as shown in Figure 19, page 29.

The selective multivibrators are of the Eccles-Jordan type with some modifications. They are one shot multivibrators which return to their origional rest condition after one cycle. Another modification is the use of a triode in the cathode circuit, as shown in figure 28. This is used to block each multivibrator while the other is in operation. Thus subsequent reversals of polarity of the incoming wave will not cause both gate circuits to be opened at the same time. As soon as the multivibrator

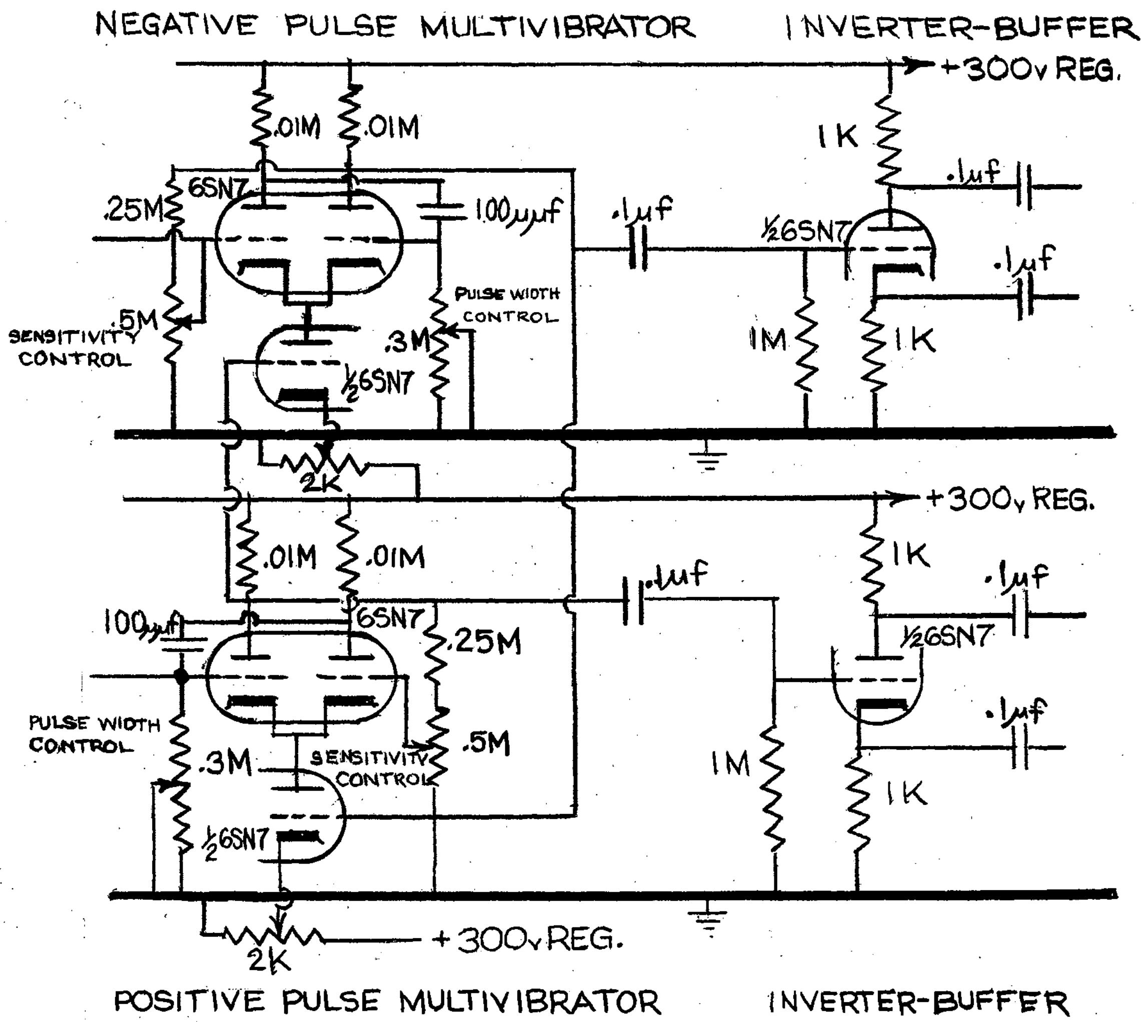


Figure 28.

Circuit for multivibrator

falls back into a quiescent state both circuits are ready to be triggered by the next sferic. The series resistance and capacitance in the grid circuits of each multivibrator in figure 28 are used to determine the pulse width of the multivibrator square wave. The other controls are sensitivity and balancing controls. They must be balanced together for proper adjustment.

The buffer phase inverter which follows the multivibrator is used to avoid loading the multivibrators with screen current from the gating tube. Thus there is also produced a negative voltage wave to apply to the D.C. balancer tube. This circuit is shown in Figure 29.

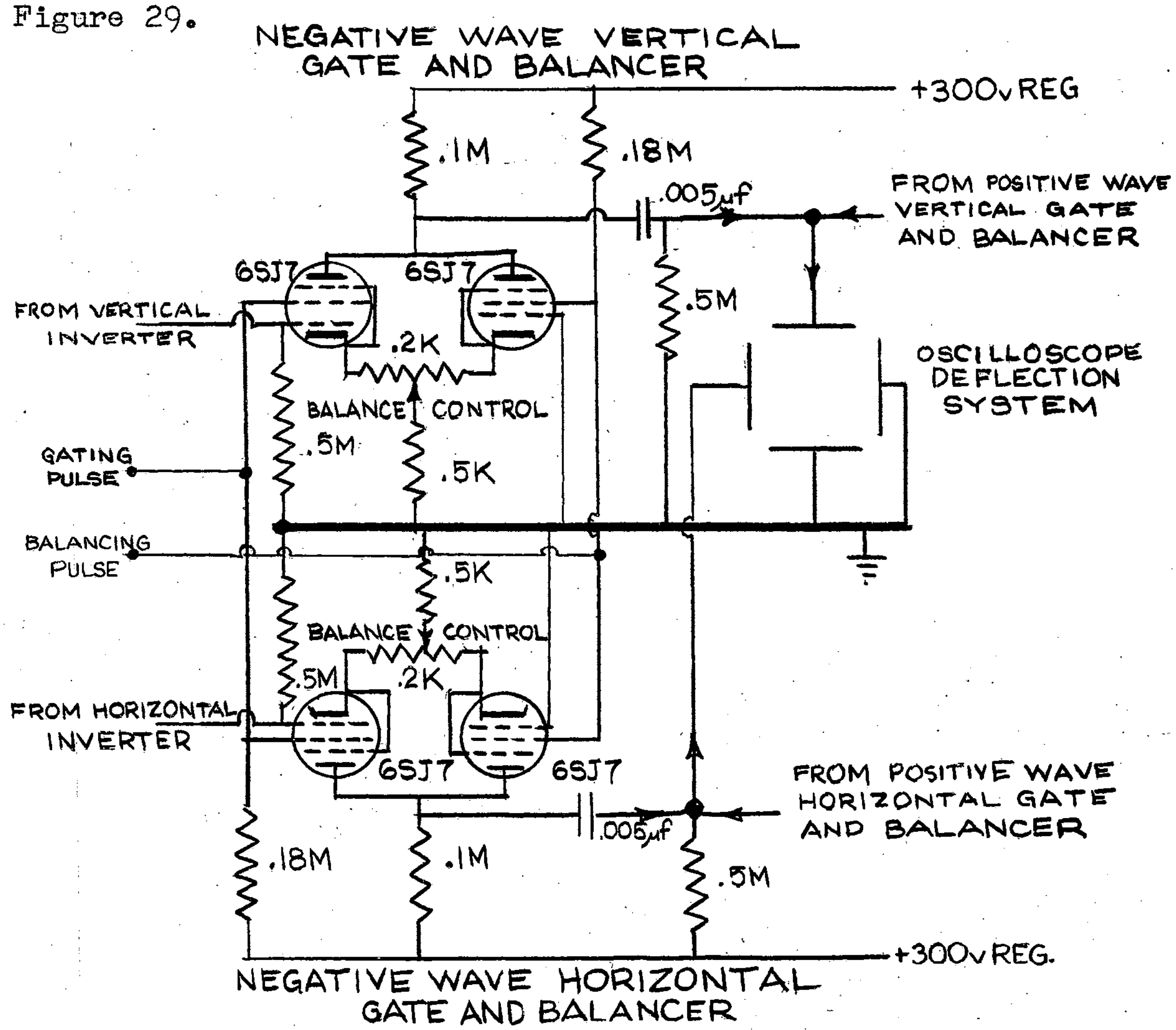


Figure 29.

The positive and negative wave gating systems are identical so only one will be treated here. It must be remembered that the other circuit shown in the block diagram must be employed in order for the system to work. A 6SJ7 pentode is used as a gating tube. The control grid carries the signal while the screen is used for blocking the unwanted signal. Since the tube must be operated class A there would have been a large transient voltage induced in the plate circuit during each gating change had the balancer not been employed. The plate voltage of these two tubes remains constant due to the conduction of the balancer when the gate is turned off and vice versa. The potentiometer in the cathode circuit of these tubes is used to obtain a true balance. It might be well to note that a north-south gate and an east-west gate must be actuated at the same time so the screen circuits of both are tied together. Therefore, the same gating pulse will operate both of them. This may lead to some feedback from one circuit to the other in the common screen resistor. This feedback will give a slight error on signals near the north-south or east-west direction and zero error at 45 degrees. If this proves to be the case the use of beam power gating tubes may help this problem since they have much less screen current. Buffers would completely eliminate feedback but would add to the expense and complexity of the circuit.

Figure 30 shows only the north-south phase inverter diagram. The east-west circuit is identical to it. The phase inverter makes use of the output phase relationships of both the conventional amplifier and the cathode follower. The plate of the inverter tube has a polarity opposite to that of the grid while the cathode follows the grid voltage directly. Since the plate current flows through both cathode and plate resistances the voltage magnitude is the same if the resistances are identical. Equal output is the criterion of phase inverter design. This circuit has no amplification and has little loading effect on

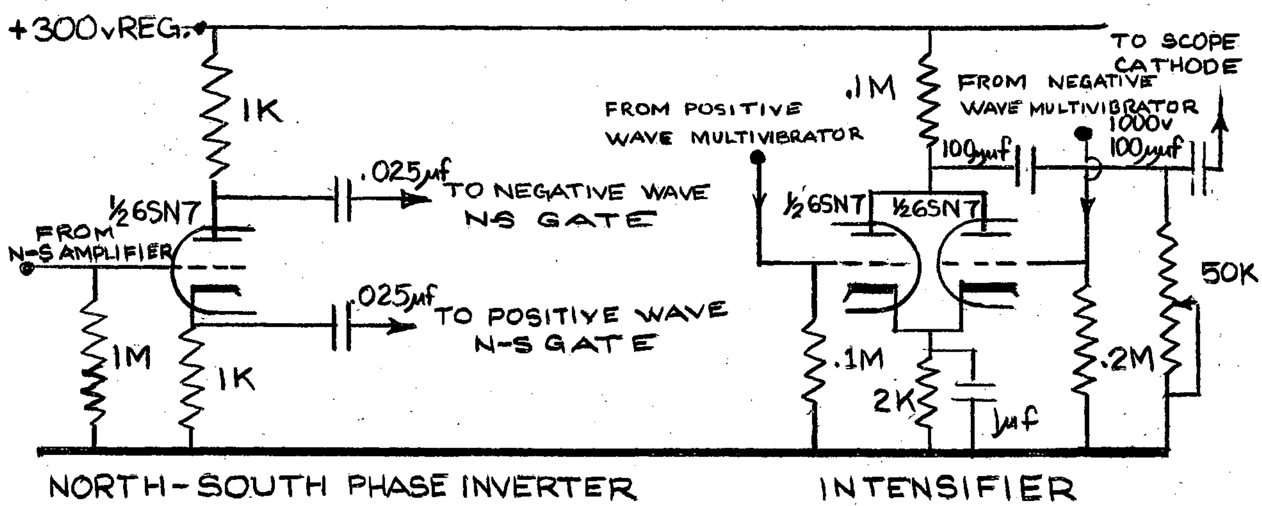


Figure 30.

the other circuits. The use of 6SN7 tubes for this circuit is convenient since the other triode in the envelope can be used in the intensifier circuit. The same tube was not used for both phase inverters because the capacity coupling of cathode followers to the filament could cause error due to interaction of the two sets of elements. The remaining triode in each envelope is used in the intensifier circuit which is not a cathode follower.

The intensifier is essentially an amplifier buffer stage. It takes the output of either multivibrator, differentiates it to the proper time length for the average initial pulse of sferics and applies this pulse to the cathode of a scope tube. This negative pulse accelerates the electron stream for an instant to give brilliant intensity. The stream then is allowed to die out before the deflection system is driven in the opposite direction. Thus no negative deflection is seen. To accomplish this the intensity is turned down by manual control just below the threshold of visibility while no signal is present, thus there is no spot visible until the intensifier pulse hits the screen.

The time relationship between the multivibrators and the loop signal is not critical so long as the loop signal can be delayed until the multivibrators actuate. The time relationships may be corrected in the multivibrator circuit and the intensifier circuit. The loop signal must not arrive before the gates are opened or some of the sweep will be missing on the scope face and the oscilloscope sweep will not appear to leave the center of the screen.

The second system for the elimination of ambiguity is called the "selective intensifier system". The "selective intensifier" circuit shown in figure 32 makes use of another principle. Instead of reversing the inverted voltage wave the intensifier pulse is not applied until the correct direction is indicated on the oscilloscope.

This system uses a wave of a form identical to that of the loop output as an intensity pulse. The loop output can not be used because a reverse in its polarity could be caused by either a reverse direction of incidence or an inverted wave front.

By using a whip antenna the waveform of the output is of the same shape and polarity as the generating field regardless of the direction of approach. This wave is then differentiated so that its waveform is identical with that of the induced voltage of the loop antenna. The differentiated wave is amplified through a buffer and fed into a resonant circuit designed to have the same characteristics as the loop antenna. The artificial antenna output is fed into an amplifier identical to the loop amplifier system shown in figure 21, page 32. The output stage feeds a negative pulse clipper to give a more uniform intensity thorughout the intensifier pulse.

If the input field is of such a polarity as to give a correct direction the intensifier and the loop antenna output will be applied to the oscilloscope simultaneously. When the direction indicator goes negative the intensity is turned off. If a field of the opposite polarity cuts the antenna both the intensifier and the direction indication voltage will be reversed. The intensifier will be dormant until the correct voltage is applied to the deflection system. The instant that the deflection voltage changes polarity, the intensifier voltage changes also and the intensity is energized.

The first circuit in Figure 31 is a high gain pentode circuit that amplifies the whip antenna signal and feeds it into a

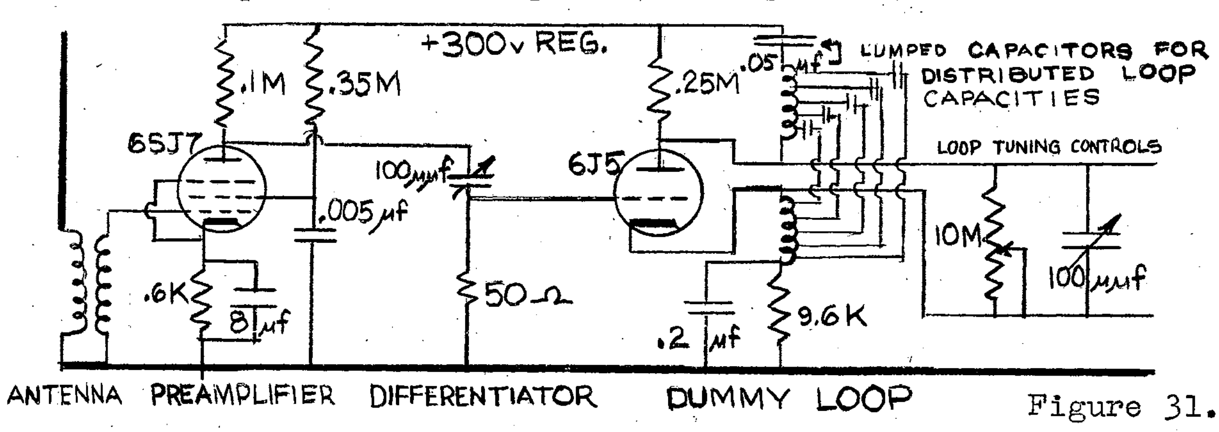


Figure 31.

differentiating circuit.

The output of the differentiating circuit is fed into the second circuit of figure 31. This is the driver for the artificial antenna loop. The network must have nearly the same transient response as the loop antenna in the direction finder circuit. Its design will require considerable adjustment since there are many distributed capacities in the antenna loop that can not be measured. The output of the artificial loop is shunted with the "Antenna Tuning" control and the "Antenna Resistance" control the same as in the actual loop circuit. The amplifier circuit is the same as the loop antenna amplifiers shown in figure 21, Chapter III, and will not be shown here.

The output of this amplifier feeds the cathode of the oscilloscope instead of the deflection system.

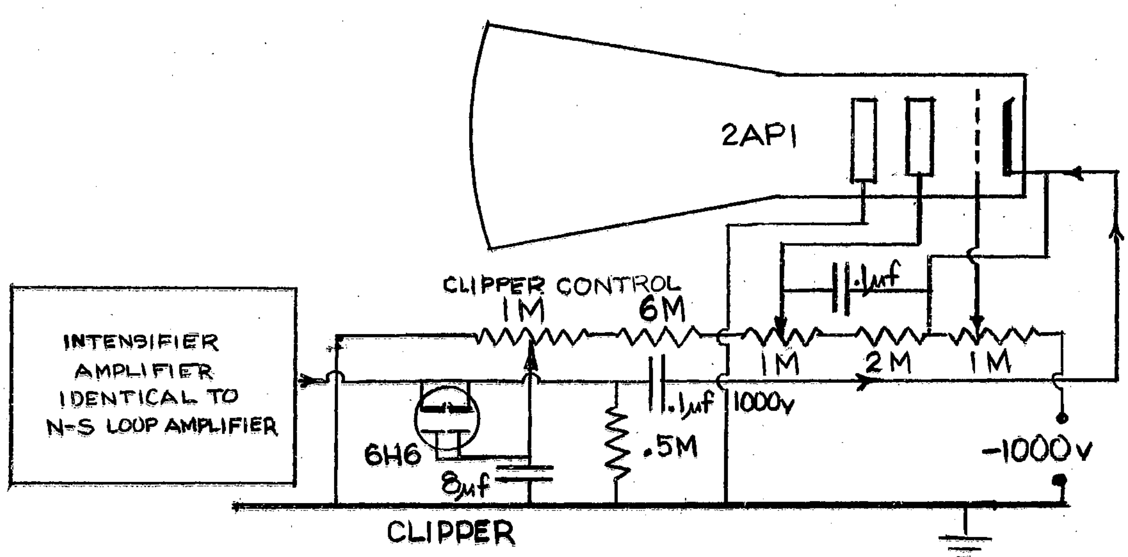


Figure 32.

A diode limiter is applied as shown in figure 32. The diode clipper acts as a low resistance path to all voltages above that set on the clipper control.

In figure 33 is shown a visual sequence of the correction process for either of the systems described. A careful study of this sequence will indicate the principle on which these circuits operate. This sequence also points out the basic difference in the two circuits.

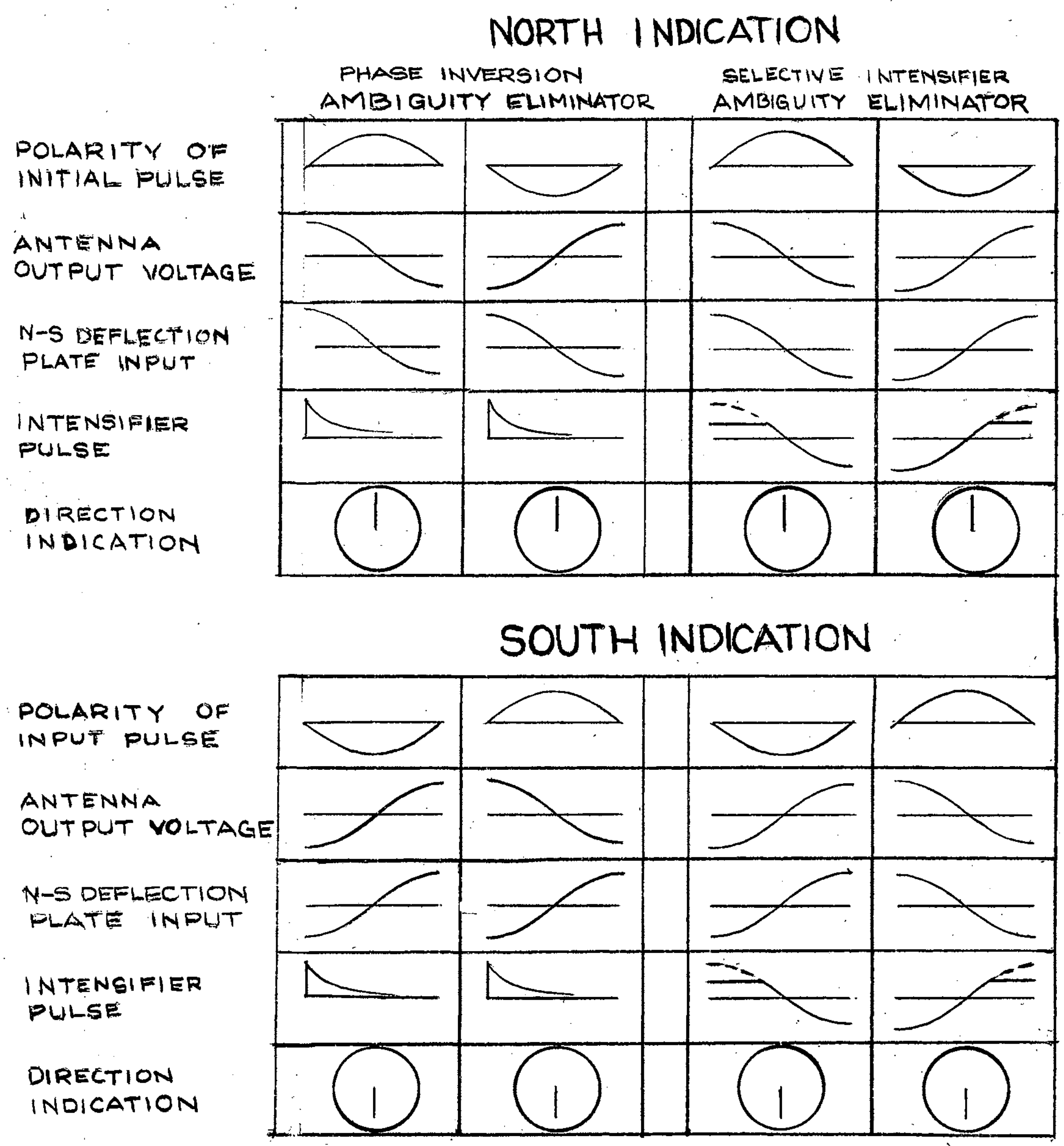


Figure 33.

CHAPTER V

ALIGNMENT PROCEDURE

All controls for the alignment of the loop amplifiers now used at Oklahoma A. and M. College are shown in figure 34. Each knob on the front of the chassis affects the alignment so none may be moved without upsetting the calibration.

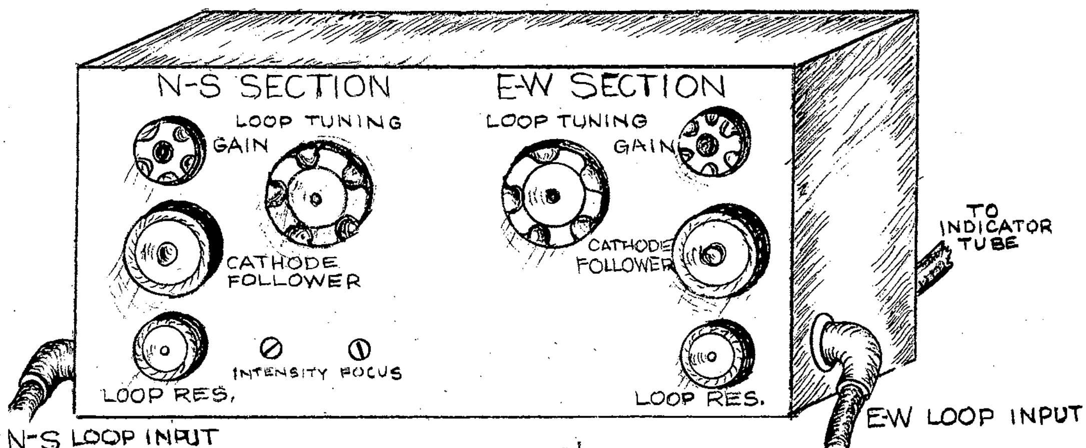


Figure 34.

When the amplifiers are perfectly aligned they will give identical amplification. With the loop disconnected and the same signal applied to both receivers the output should be on the 45° mark of the oscilloscope face. If the trace on the oscilloscope should appear to the east of the north-east mark, the gain of the north-south amplifier should be increased until the indicator sweep is on the 45° mark. On the other hand if oscilloscope indicates direction north of the north-east mark, the gain of the east-west amplifier should be increased. To align the entire system the antennas should be connected to the circuit. The spark generator should be set on a 45° angle

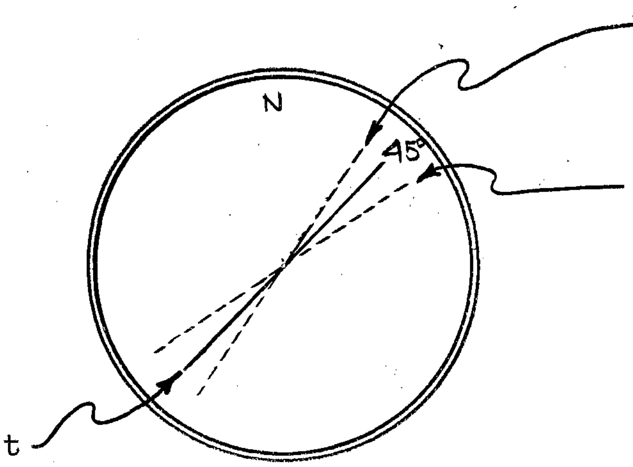


Figure 35.

from the antenna axis and as far from the antenna as is practical. However, the generator should be close enough to produce a readable bearing indication. The deflection should be on the 45° mark when the entire circuit is correctly prealigned. If this is not the case a check can be made by moving the spark generator to the other 45° line with respect to the antenna. If the deflection is always in the east-west direction of the 45° point, the north-south gain must be adjusted again. This might indicate that one antenna output was weaker than the other.

In the event that the received signal is oriented toward the east-west direction when the spark generator is on one 45° line and toward the north-south direction when it is located on the other 45° line, the antennas are probably not quite at right angles with each other. This can be checked and readjustments made with a carpenter's square. If the antennas are properly set at right angles and this error is still present there is some type of reflection interference. Reflection interference cannot be corrected except by either removing the reflecting surface or by a maze of balancing reflectors. This is seldom practical and it is better to construct a calibration curve for the equipment.

The spark generator should not be used to make the calibration curve. Visible lightning is much better for this purpose. The point source of the spark generator will produce reflection characteristics quite different from those of a wave from a distant source.

It should be stated that a properly aligned deflection system indicates north as the direction toward which the north-south antenna is oriented. Therefore the entire antenna system must be oriented with the true north in order for the indicator to designate true bearings. This alignment will require a good compass and a correction chart. The preceding discussion assumes that the antennas are tuned and that the amplifiers are operating properly.

If the indication on the face of the oscilloscope is non-linear, as shown in figure 36, the north-south amplifier is being

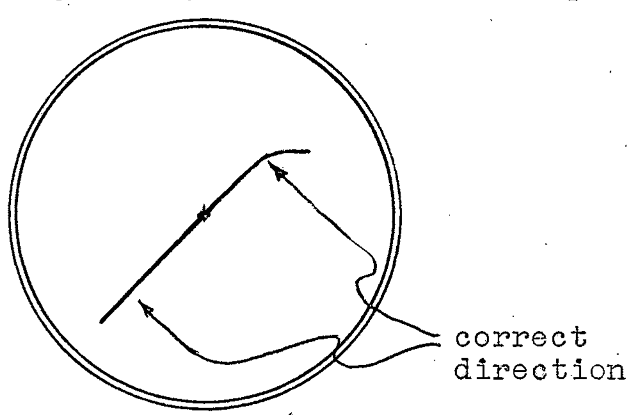


Figure 36

This type of distortion is caused by over driving one stage of north-south amplifier section adjust "cathode follower" and "gain" controls.

driven into saturation. To correct this the output of the cathode follower should be increased by means of the North-South Cathode Follower Gain Control, and the gain of the north-south amplifier should be reduced. This process lowers the amplifier bias so that it is operating below saturation and final adjustment should give a good linear sweep. If this procedure fails to correct the fault it follows that some circuit element in the north-south amplifier is at fault. Either a tube is old and has low emission or a bias resistor has changed value with age. It is good practice to check tubes before checking other elements because the failure rate for tubes is high.

If the pattern obtained is as shown in figure 37, the same procedure should be followed for the east-west amplifier as was followed for the north-south amplifier in the previous paragraph.

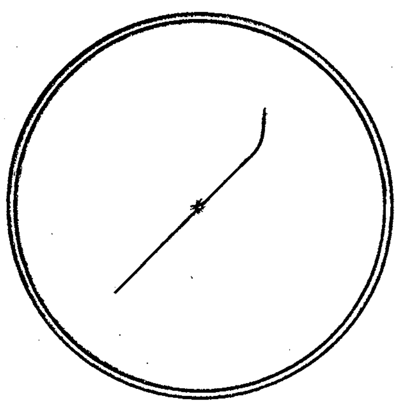


Figure 37.

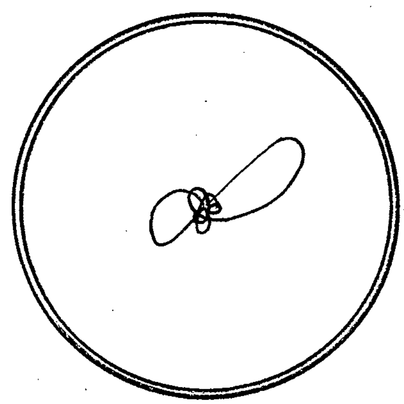
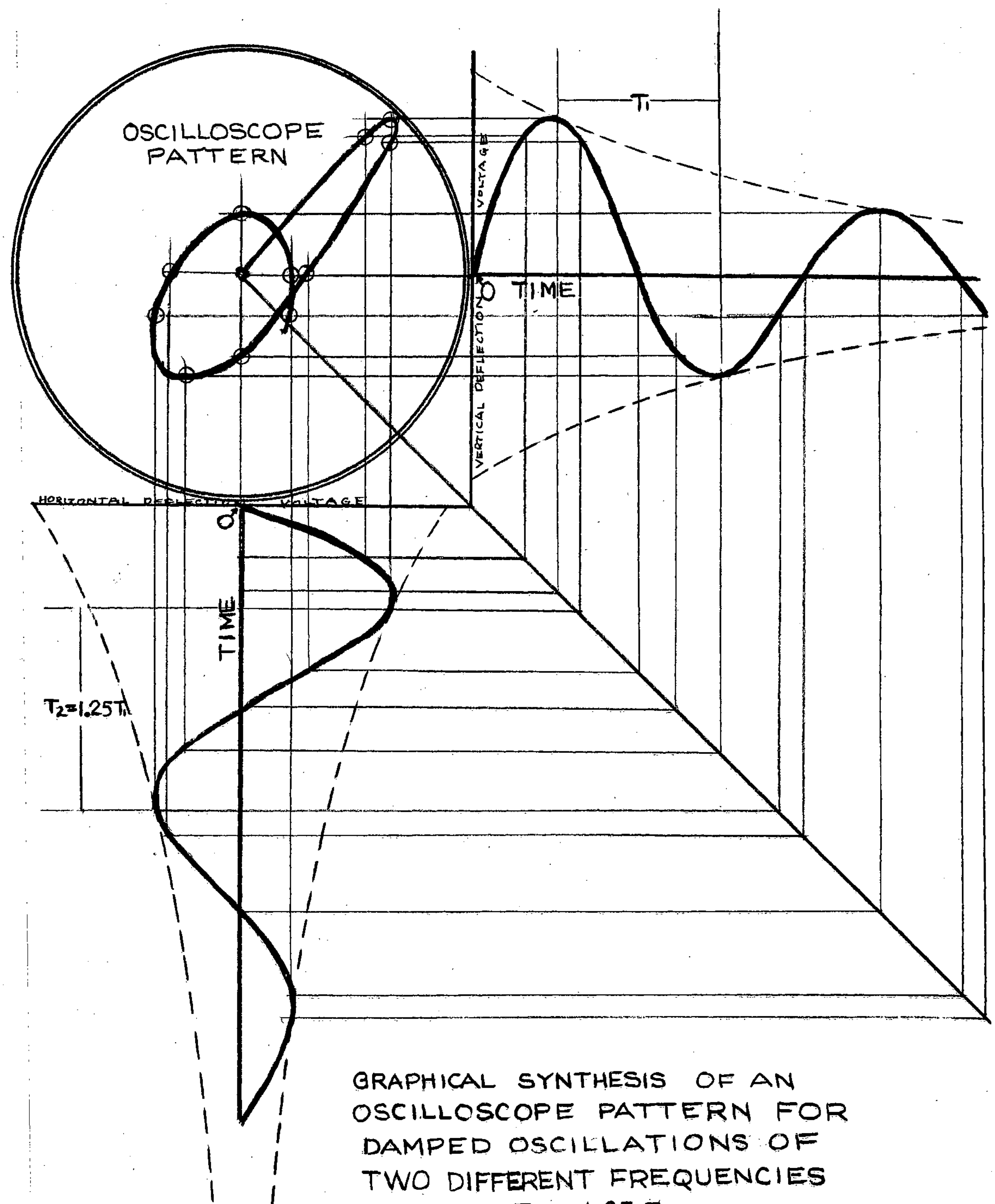


Figure 38.

If the pattern appears as a series of loops, the antennas are resonant. To correct this the antennas should be tuned until the looping effect is reduced to a minimum. Then the antenna resistance should be adjusted until the looping effect is completely eliminated. The theoretical development of these patterns is produced graphically in figure 39 for the case of



GRAPHICAL SYNTHESIS OF AN OSCILLOSCOPE PATTERN FOR DAMPED OSCILLATIONS OF TWO DIFFERENT FREQUENCIES

$F_1 = 1.25 F_2$

FIGURE 39

two resonant antennas that differ in frequency. This same type of graphical construction can be used to synthesize the indication pattern from any given set of input waveforms.

Should the spot on the scope face become fuzzy the focus control may require adjustment. There is also an intensity control to change the brightness of the spot. These are screwdriver adjustments on the front of the amplifier control panel. In figure 40 are shown hum, noise, and stray pickup indications.

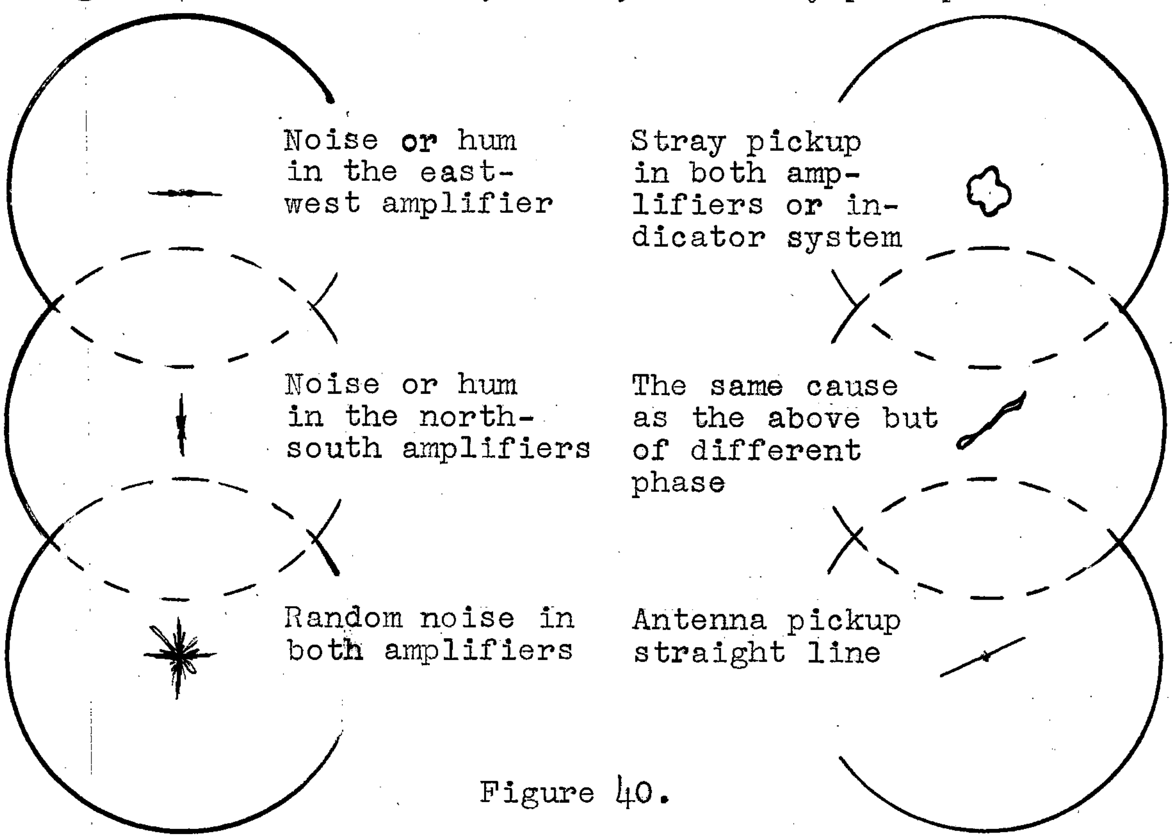


Figure 40.

All of these patterns are permanent until the fault is corrected.

The magnetic flux of a small clock motor in the photographic recorder which is located approximately 6 inches away from the indicator tube caused a deflection of nearly 100% of the indicator beam. This was corrected by covering the oscilloscope tube with a piece of 2" iron pipe to magnetically shield the deflection system. The iron pipe covers the entire tube. This shield reduced the pickup pattern from about one and one half inches of deflection to a distorted loop about the size of a pencil eraser. An aluminmun foil shield was used to further reduce the deflection pattern until at present the use of the direction indicator inside the photographic recorder is quite satisfactory.

A calibrated face was made of soft translucent plastic so that it could be oriented with its center over the center spot on the indicator screen. The scale was drawn with an ink solution consisting of fingernail polish diluted with polish remover. The scale proved to be impractical because the indicator tube was being constantly moved about and the scale was dropped off in handling. It could not be fixed permanently because there was no means of electrically centering the electron beam under the scale. This method of scale construction will be effective however when the indicator tube is mounted in a permanent position.

CHAPTER VI

AUXILIARY EQUIPMENT FOR ALIGNMENT

To calibrate the loop antenna direction finder equipment it is necessary to produce a test signal. The frequency of this signal should be comparable to the component frequencies of the sferics.

Any standard broadcast radio frequency oscillator can perform this function for the prealignment of the amplifiers.

For actual alignment of antennas and receivers it is best to use an outside source. This generator should have considerable power output and should have a complex wave form similar to the waveform of a sferic. Several systems were tried but the final generator decided upon was a Model T Ford ignition coil.

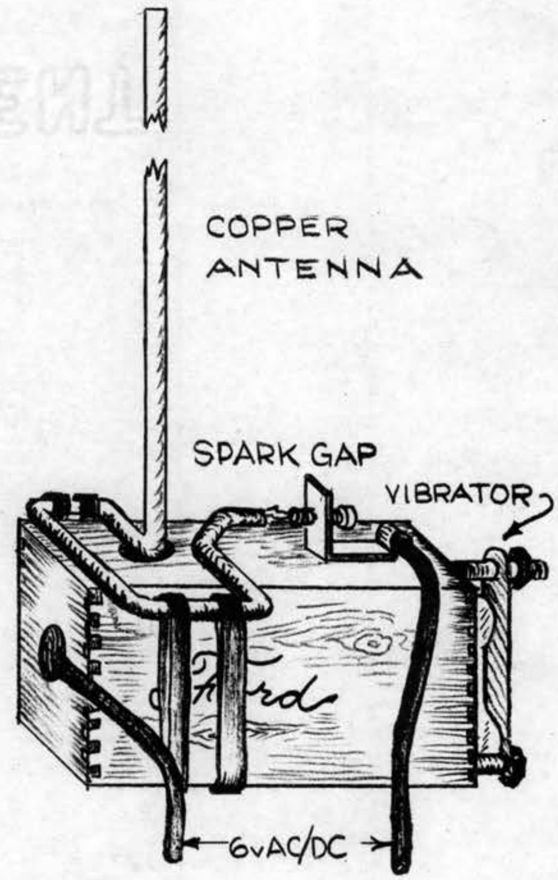


Figure 41.

Static generator (Model T Ford ignition coil.)

The coil shown in figure 41 uses a vibrator to produce the interrupted voltage. This gives a constant stream of noise, and produces a solid line on the indicator face. This feature simplifies calibration. The power output was great enough to allow about a 50 foot radius of reception, which was greater than any other proposed system. Another advantage is that the coil is portable and may be easily carried from place to place in one hand. In order to better propogate the energy a copper antenna was soldered to the high voltage contact. The wire was bent so that it could be easily bound to the case with an insulating material.

A spark gap was installed in order to produce a greater output, but was found to be ineffective.

In Chapter VII a permanent outdoor installation is proposed. It would be well to install the coil inside of an Army Surplus ammunition box, which should be mounted on a post nearly level with the loop antennas and as far away from them as practical.

It would be well to use a permanent 6v A.C. supply with a keying circuit for this installation. This will eliminate the problem of replacing batteries or having to go out in foul weather to turn on the spark generator.

In the initial alignment a surveyor's compass or astro-compass will be needed to set up the antenna system in an accurate north-south, east-west direction.

To calibrate on a visible lightning a transit table with the telescope removed and some nonmagnifying system of sights will probably give best results. The transit table will give the bearing angle when the sights are lined up with a lightning streamer. A telescope is not used because the lightning flashes are of such short duration that there is not time to line a telescope on the streamers, whereas the sights on a plane table can readily be aligned to the approximate direction.

CHAPTER VII

CONCLUSIONS

It may be seen from the latter part of the first chapter that there are at least two methods of tornado location. These methods are the triangulation method which incorporates the use of direction finder equipment alone, and the radar method which incorporates the use of radar in conjunction with the direction finder equipment. Either system has advantages over the other. The problem of evaluation will be approached by first listing these advantages in tabulated form.

The triangulation method requires the use of three receiving stations, a plotting system, and an intercommunication system common to the three stations. The advantages of this system over the radar system are:

1. The equipment to be used in the triangulation system of sferic location has been proven to be very effective for tornado location. Radar has not as yet been used in this capacity and information concerning its effectiveness is lacking.

2. The range of sferic direction finders is longer than that of radar for storm detection and tracking.

3. The circuits of the direction finder are easily aligned and practically trouble free. Radar equipment is made up of many complex circuits which require critical adjustments. This fact would indicate a greater probability of equipment failure in the radar system.

4. In the event of the failure of one of the three direction finder stations, tracking would still be possible except when the tornado was in line with the two stations. This would introduce, however, a greater probability of error in the indications. In the event of failure of the radar station the public would be without warning during the period of failure.

It is believed that the advantages for the triangulation method are more than offset by the advantages of the radar system of tornado location. The proposed radar system uses both the tornado sferic detection and bearing indication equipment as auxiliaries to the radar. The advantages of this system are given in the following table.

1. The determination of an ideal location for one station is more easily accomplished than for three stations.

2. The elaborate interstation communication system required by the triangulation method is completely eliminated by the use of a radar which is centralized in one building.

3. The radar range and bearing indications are accurate even at maximum range. Night effect errors, reflection phasing errors, and triangulation errors which are common to the direction finder system are not inherent in the radar.

4. Radar is capable of giving the relative location of a tornado with respect to towns in the surrounding area.

5. Once the radar operator has recognized the tornado echo, auxiliary indication and detection equipment will no longer be needed. The operators of this equipment are then relieved to communicate information to the public warning system or help the radar operator.

From this tabulated information it can be concluded that the radar system of tornado detection is the more practical system of the two.

Radar has other advantages which cannot be compared with the triangulation system. One of these advantages is the possibilty of detecting whether the tornado is active or in its incipient stages. This possibility depends upon the operators ability to detect a cloud with debris in its funnel. Considerable research covering tornado cloud echos will be necessary in order to accomplish this objective. Another possibility for distinguishing tornado clouds is offered by the Doppler effect which might possibly produce a frequency change of an echo when the reflecting surface is in motion, which would be the case for the high velocity debris in the cloud funnel. This information might also given an indication of the energy present and the possible life expectancy of a tornado. Again this application of Doppler effect would require considerable engineering research. Thus the radar system not only has the advantages listed in the table but also offers other possibilities that have not as yet been investigated.

The largest part of this thesis was devoted to the study of sferic direction finders. During this period of study the necessity for several possible improvements became apparent.

Possible improvements are as follows:

1. The loop antennas should be waterproofed and located outside of the station. This would reduce the possibility of reflection errors from objects in the station and would also

reduce the noise pickup from the relays associated with the sferic detecting device.

2. The indicator tube should have a permanent scale mounted or drawn on the screen so that accurate bearings may be obtained.

3. The indicating tube circuits should incorporate a beam centering control so that the center of the beam may be positioned to the center of the bearing scale.

4. The operation of the equipment may be improved by the use of two indicating tubes, one to serve as an accurate indicating device to be used in locating the tornado, the other to be used in the photographic recorder for the permanent record.

5. The indicating tube should be located so that the person using the controls for alignment can easily view the screen.

6. A spark generator should be permanently located on a 45° line from the antennas. When the entire system is properly aligned this spark generator should be turned on and the indication permanently marked on the oscilloscope scale. This would act as a very good check on the operation of the equipment.

7. An ambiguity eliminator circuit should be incorporated in the direction indication equipment.

The direction ambiguity elimination circuits presented in this thesis have never been constructed and therefore the discussion of their merits must be considered as entirely theoretical. The comparitive merits of the two systems may be determined from a study of the advantages of each. The phase inversion method of ambiguity elimination has several favorable characteristics.

1. The initial input pulse from the loop antenna amplifiers always appears on the screen. This pulse in general has the longest duration time and is the one most likely to give readable information for long ranges.

2. With the phase inversion method, lines of equal intensity appear on the screen regardless of the strength of the received signal.

3. It is quite simple to make the center spot appear on the screen for a constant check on the centering of the electron beam.

4. There is no special care required in connection with the correlation of the phasing and timing of this circuit with the antenna loop circuit. This is not the case with the selective intensifier circuit.

Again the selective intensifier method has several advantages which make it the more desirable of the two systems.

1. There are no inherent trick circuits or critical adjustments.

2. This system does not require as many electron tubes. This not only reduces the initial cost but also reduces the probable lost time required for maintenance.

3. The intensifier in the selective intensifier system is always in step with the incoming wave. This will eliminate the possibility of error due to reverse signal indication of double sferics. This reverse signal indication would occur when a relatively weak wave is immediately followed by a much

stronger sferic pulse. The second pulse will tend to override the initial pulse and give an erroneous bearing indication.

Although the selective intensifier system has the least number of tabulated merits, it is believed that it is far superior to the phase inversion system. The trouble free operation of the amplifier system for the loop antennas is a characteristic that is unique for this system. The fact that the initial adjustment of the time and phase relationships would require more time is offset by the fact that the electron tubes have relatively little effect on these settings with the consequent possibility that the system will require few readjustments. The fact that long range signals may not be of sufficient strength to give strong intensities does not affect the operation of this equipment in relation to the detection equipment. The detection equipment will be found to have a range that is less than that of the direction finder. By introducing more amplification and including a clipping circuit the intensity may be made nearly constant for all signals that are strong enough to give readable bearing indications.

As is generally true for all research projects, the possibilities for extended research in new fields became apparent as work progressed on the initial project. It is desirable that the material presented in this thesis will help in the future study of tornado locating devices, and will hasten the day when accurate and dependable tornado warnings will give the public a definite assurance of safety.

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