DEVELOPMENT AND OPERATION OF A CROSSED LOOP SFERIC DIRECTION FINDER

By

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PREFACE

In the fall and spring seasons cold dry artic air masses and warm moist tropical air masses meet in the vicinity of central United States. This area ranges from Montana, North Dakota, and Minnesota on the north to Texas, Louisiana, and Mississippi on the south. In this region the unstable warm air being forced up by the colder air causes some of the most severe thunderstorms experienced anywhere in the world.

Some of these more turbulent storms develop into tornadoes and bring havoc and destruction to certain areas that is almost unbelievable. These storms strike quickly giving very little time to protect life and property. There is very little information concerning their origin and not too much is known of their actual composition. From observation it is certain that the wind velocities around the eye are very high, probably ranging upward to 500 miles per hour. Accompanying these high velocities are extremely high pressure gradients which cause closed buildings to actually explode from within when the eye of the tornado passes over them. It is not known what kind of electrical activity is encountered in the tornado, but the thunderstorms from which the tornado originates are always extremely active electrically. Intense and numerous lightning strokes are observed in and around the turbulent clouds. The tornado itself may be seen and followed by radar. The reflected radar waves are probably coming from the moisture content of the associated cloud.

If there is to be time to take precautions against personal injury and property damage, then there must be a means of detecting the tornado before it actually drops from the clouds and starts its devastation. There is considerable research being conducted in this field of prediction, detection, and tracking of tornadoes. It is the purpose of the research being conducted at Oklahoma A. and M. College to develop, if possible, a way to detect and track a tornado. A system is being developed which will enable the research team at the college to collect valuable data concerning the location of the thunderstorm, number and intensity of lightning discharges, wave shape of the electromagnetic radiation associated with the lightning discharges, and atmospheric potentials as found from a continuous recording magnetometer.

The specific problem being studied in this thesis is the problem of locating the lightning discharge. The device that is to do this job is an instantaneous direction finder which will pick up the radiation from the discharge and give an indication of the direction from which the signal came. By the use of these devices set up at different locations, the two bearings can be used to find the exact location of the lightning discharge by the process of triangulation. Of course, to reach any accurate conclusions and be able to develop the equipment, it is necessary to know as much as possible about the phenomena being studied. This necessitates a study of the formation of a thundercloud and the mechanism of the lightning discharge. With this in mind the following has been made as a logical part of the development of the sferic direction finder.

ACKNOWLEDGMENT

The author is grateful to the staff of the Oklahoma Institute of Technology for all assistance given him while preparing this thesis. Special thanks are due the Research and Development Laboratory for building the loop antennas and Dr. Herbert L. Jones whose suggestions were very helpful in preparing the manuscript.

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CHAPTER I

THE THUNDERSTORM

In the formation of a thunderstorm there are several conditions necessary. They are: (1) the presence of water vapor in the air; (2) the presence of meteorological and (or) topographical conditions favorable to the movement of moisture-laden air up to the condensation level; and (3) conditions favorable to the formation of sustained strong upward convection systems.

Most thunderstorms may be classified as one of five general types or a combination of some of these types. They are the air mass, the mountain, the cold-front, the overrunning cold front, and the warm front thunderstorm.

The air mass thunderstorm is most prevalent on warm humid days when there are relatively weak horizontal pressure gradients. Heating from the sun causes the air next to the earth's surface to be warmed; the warm air expands, becomes lighter than the surrounding air, and starts to rise. As the air rises it encounters less atmospheric pressure and expands still more. This unstable condition continues until the warm air reaches an altitude at which it has the same temperature and pressure conditions as the surrounding air. This condition usually occurs at altitudes of two or three thousand feet up to as high as forty five or fifty thousand feet above the surface of the earth. The important condition that must be satisfied for thunderstorm formation is that there be a dry adiabatic or super-adiabatic temperature gradient from the earth up to the cloud level. This is the condition in which the temperature of the air decreases with increase in height at the same rate or a greater rate than unsaturated air, warmed at the surface, cools as it rises and expands adiabatically. An adiabatic expansion is one in which no heat is added or taken away from the expanding system. This condition is very nearly realized in free air which rises rapidly. It seems that it sometimes takes a day or two of hot weather, and the mixing of convection currents of air before this condition is realized and thunderstorms start developing. When the warm air does reach this condition and rises to the condensation level, the moisture will start condensing, giving up its latent heat of condensation. This heat makes the rising air even warmer than the surrounding air and the convection air current becomes stronger. This violent convection current may also be the main factor in electrifying the cloud.

The air mass thunderstorm will form when (1) the temperature gradient is equal to or greater than the dry adiabatic

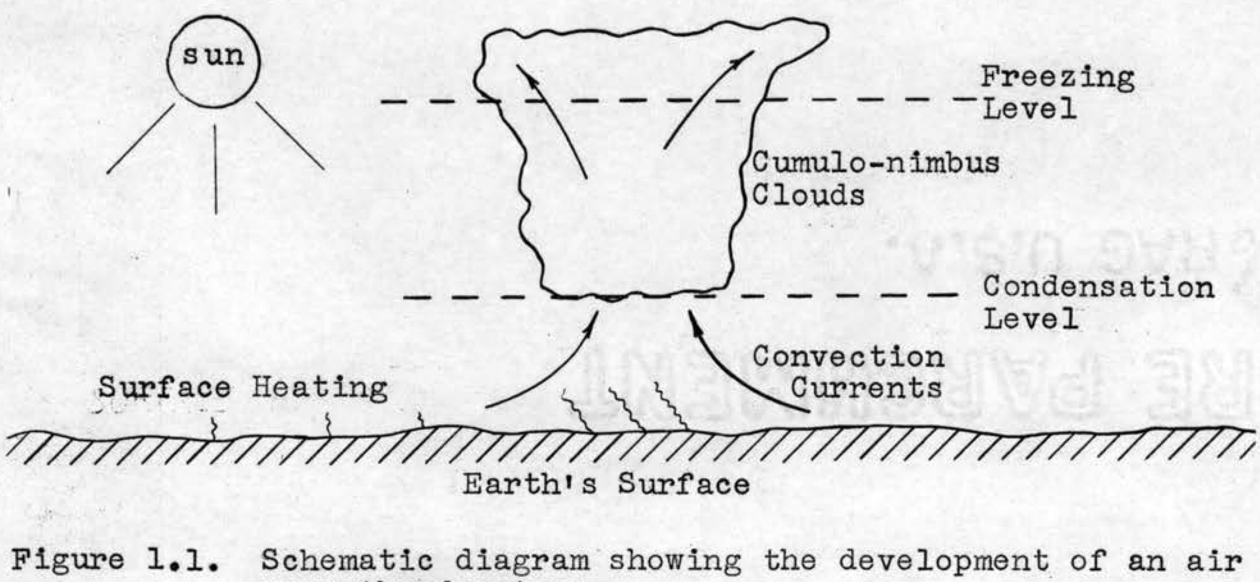

Figure 1.1. Schematic diagram showing the development of an air mass thunderstorm.

which exists between the ground and the condensation level, (2) horizontal pressure gradients are small and result in very little surface wind, and (3) if there is sufficient moisture in the air. This type of thunderstorm can be locally severe with gusty surface winds. The strong convection currents may carry the moisture to the freezing level and produce hail, but it very seldom develops into a tornado type of cloud.

Mountain thunderstorms are very similar in nature to the air mass thunderstorm. The sun's rays striking the side of the mountain causes heating of the air next to the mountain side. This warm air will expand and become lighter than the air away from the mountain, so it will be forced up by the heavier cold air which runs under it. Thus the warm air may be forced up to the condensation level if sufficient moisture is present. In

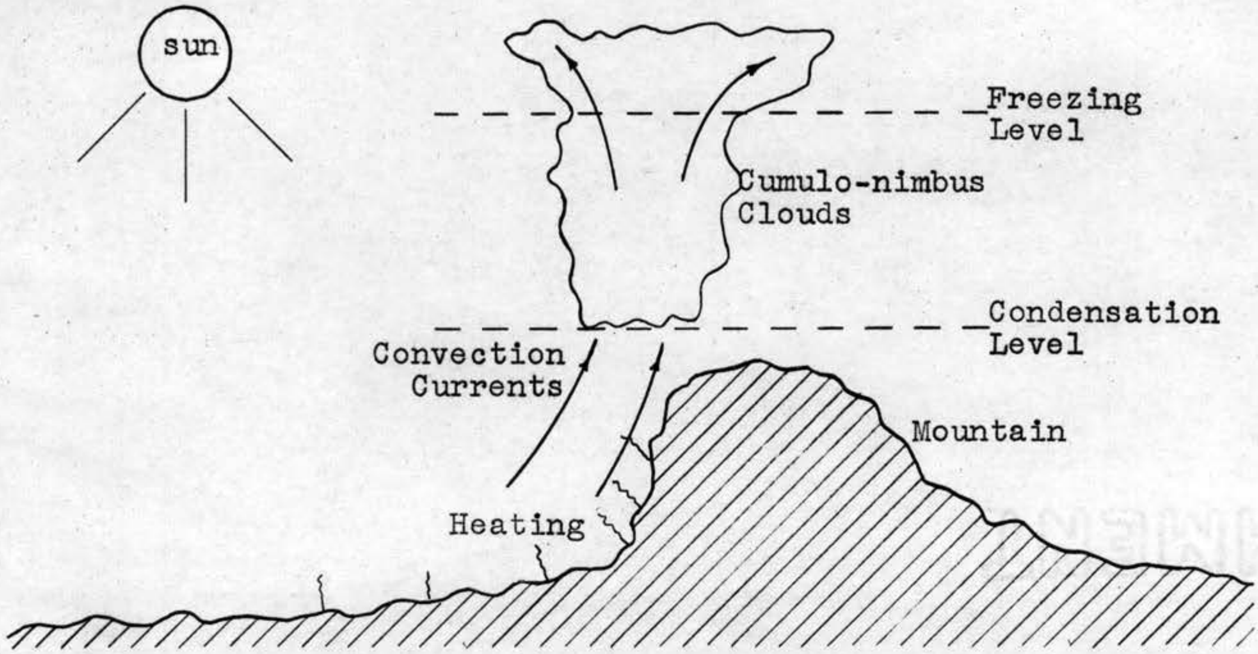

Figure 1.2. Schematic diagram showing the development of a mountain thunderstorm.

this case the thunderstorm will develop without the temperature gradient described as necessary for the air mass thunderstorms. Also mountains may aid the formation of thunderstorms when horizontal pressure gradients force the air up over the mountains. The kinetic energy of the air may carry it above the mountain to the condensation level. If the air is sufficiently unstable after it reaches the condensation level to continue rising in a convection current, then a thunderstorm will develop. This type of storm is also locally severe with rain, possibly hail, and gusty winds. Tornadoes are not usually associated with them.

A cold front is defined as the boundary between a mass of cold dry air and a mass of warm air in a system in which the cold air is replacing the warm air. In the northern hemisphere cold air piles up over the arctic region and then forces its way southward meeting warm tropical moist air. The cold air is the most dense so it tends to run under the tropical air. It is this condition which causes the formation of thunderstorms along a cold front. Those storms created in front of the cold front are called cold front thunderstorms. The forcing up of the warm moist air by the cold front sets up the same conditions as the heating in the air mass and mountain thunderstorms. The warm air becomes unstable when forced up to the condensation level and the strong convection currents are established. These type of storms may develop as much as 50 or 100 miles ahead of the front itself and are very severe along the entire length of the front in many cases. The instability between the two air masses develops tremendous energies, and the thunderstorms are the best breeding places for the tornado.

Ground resistance may retard the outgoing warm air if the cold front is moving rapidly, and the cold air will tend to overrun the warm air for a few miles near the earths surface. This creates an unstable condition in which the warm air near the surface has much colder air above it. The warm light air will rise up through the heavy cold air, and strong convection currents will develop. The storms created by these currents are called overrunning cold front thunderstorms and they are capable of developing into tornadoes.

Cold fronts usually travel from northwest to southeast in the United States, and the tornadoes which develop with the cold-front thunderstorms almost always travel parallel to the cold front, resulting in a line of travel from a southwest to a north-

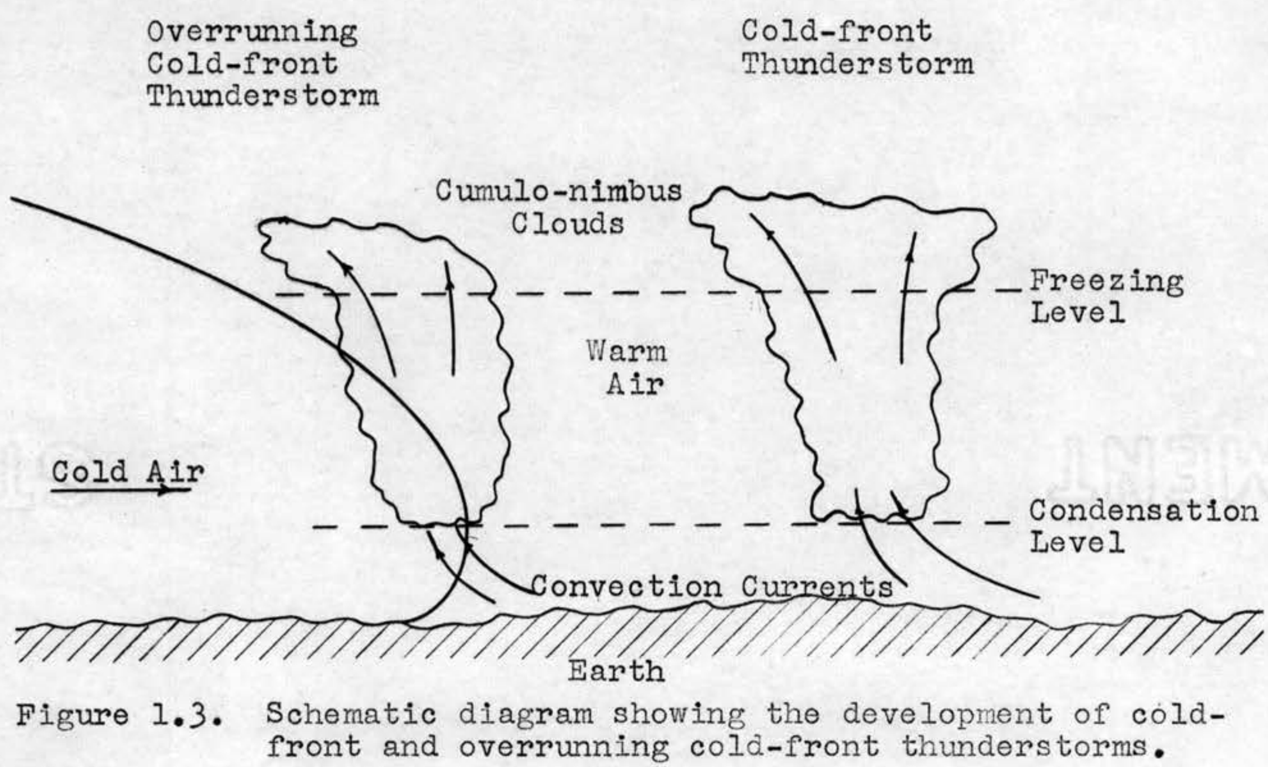

Figure 1.3. Schematic diagram showing the development of cold-front and overrunning cold-front thunderstorms.

east direction. These severe storms continue as long as the cold front continues to move so as to encounter the warm moist air. If the cold air stops and starts to recede, the system becomes a warm front.

The warm front is defined as the boundary between warm air and cold air in a system in which the warm air is replacing the cold air. This type of front and the weather associated with it can usually be predicted fairly accurately several hours in advance. There is a definite sequence in which cloud formations appear. Thin cirrus clouds form as much as two or three hundred miles ahead of the warm front, and as the front approaches the observer, these will be followed by cirro-stratus, stratus, cumulus, and finally the cumulo-numbus clouds which contain the thunderstorms. The clouds gradually lower and become more

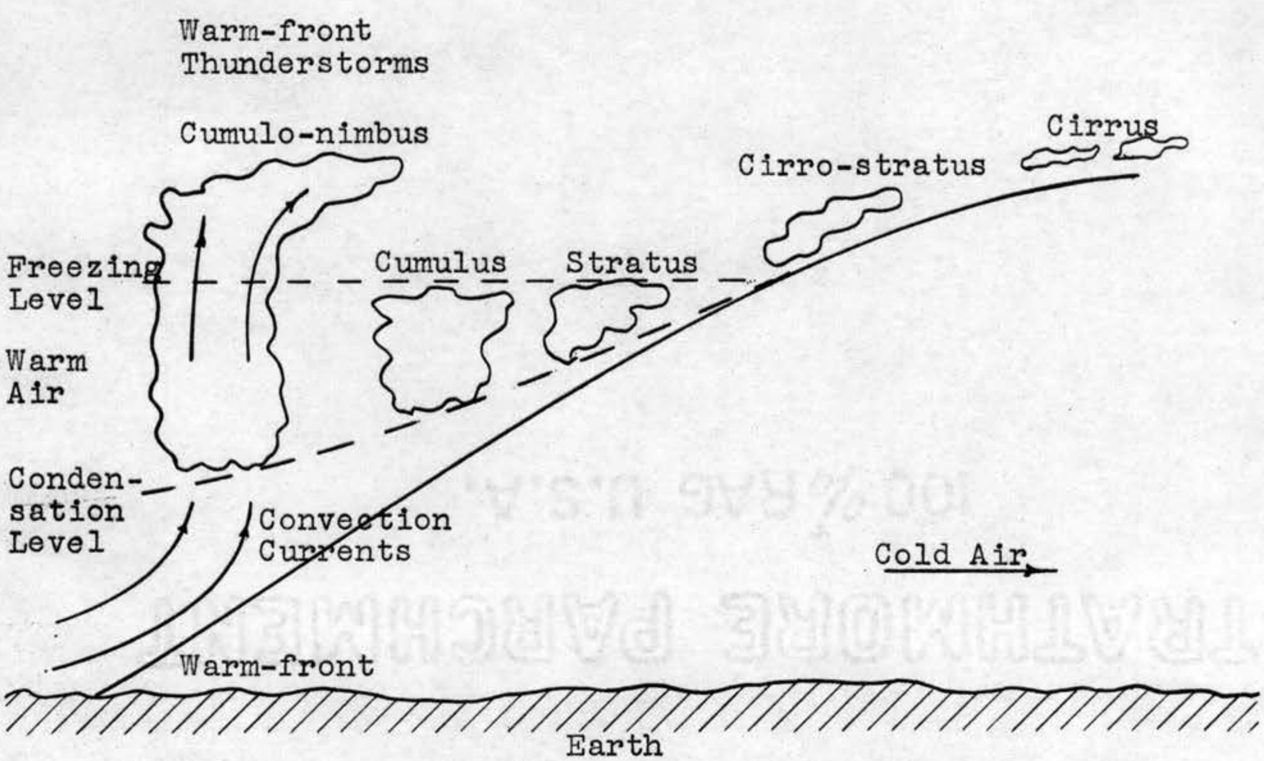

Figure 1.4. Schematic diagram showing the development of the warm-front thunderstorm.

and more dense until rain and thunderstorms develop. The thunderstorms associated with this type of front are usually mild with moderate rain, but they may be accompanied by lightning and some local gusty winds.

Maintenance of Thunderstorms

It could be reasoned that in any of the types of thunderstorms described all activity would cease as soon as the moisture in the cloud falls in the form of rain. However, from observation, this is not true. Humphreys[1] suggested a possible explanation for the maintenance of the storm. He observed that there are two main columns of moving air in the cloud. A strong relatively cold column of air is formed from the cooling due to contact with cold rain in the upper part of the cloud, and also

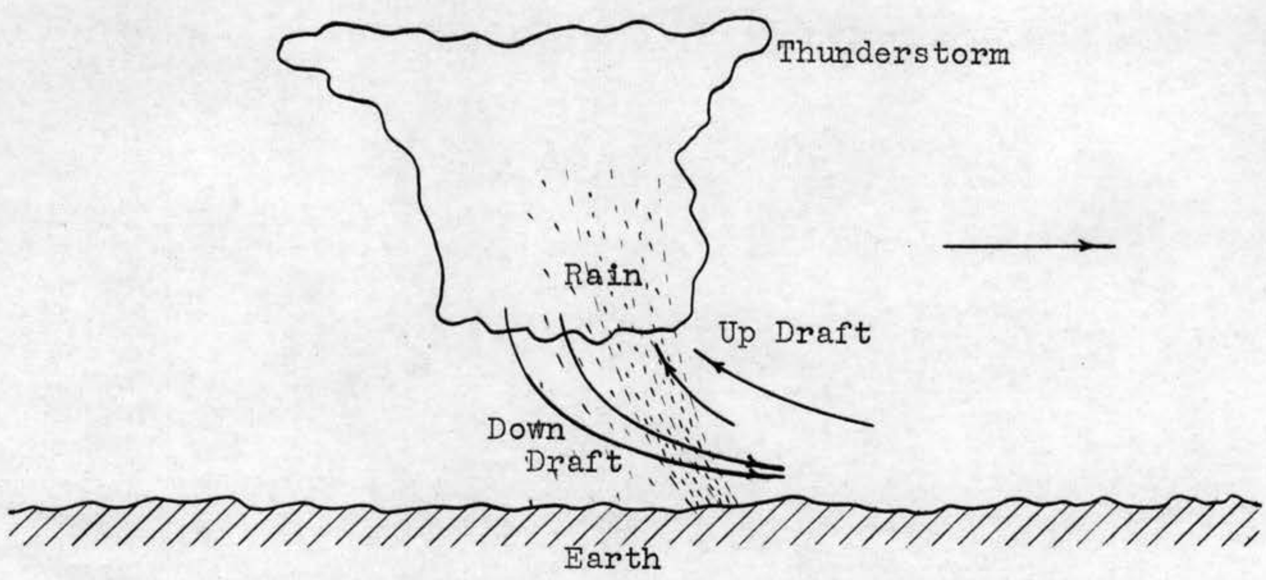

Figure 1.5. A thunderstorm showing the down draft which replenishes the moisture necessary to maintain the thunderstorm.

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1 Humphreys, W. J., Physics of the Air, McGraw-Hill Book Company, Inc. New York, 1929.

from evaporation. This cold column presses down and forward in front of the storm and acts like a hugh shovel or wedge of air which forces the warm moist air in front of the storm up into the clouds. In this way the moisture supply is maintained and the storm continues as long as the conditions remain unchanged. This would seem to be a plausible explanation since a cool blast of air is almost always experienced just before a thunderstorm strikes.

Thundercloud Electrification Theories

It may be of benefit to review the thunderstorm as an electric generator. All thunderstorms are accompanied with lightning of more or less severity. The lower part of the cloud acts as the upper plate of a huge condenser, the air between cloud and ground is the dielectric, and the earth makes up the other plate of this huge capacitor. The cloud is not a conductor since it is composed of many poorly conducting water droplets insulated with air. The charge on the cloud is a volume charge distributed on water droplets and ions throughout the lower regions of the cloud. The accumulation of charge on the cloud induces an opposite charge on the ground and between these charges there is an electric field similar to that in any other condenser. As the charges build up, the electric field becomes more and more intense until a critical value is reached. The air breaks down as a dielectric and an arc jumps across the gap between cloud and ground. This creates the brilliant flash which is called lightning.

The exact process by which the charge builds up on this gigantic condenser is not a known fact at the present time. There are several theories either of which, or a combination thereof, may explain this process.

Simpson's Breaking Drop Theory

G. C. Simpson[2] presented what is now one of the best known and probably the most generally accepted theory. He believes that the charging process is caused by the breaking of the water droplets by the strong convection currents of air. These convection currents carry water vapor up to the condensation level where it condenses into droplets. These droplets combine with others until they become large enough to fall against the updraft of air. As they fall, they join with other drops until they become so large that they must break again. The largest size that any falling drop can attain has been measured and found to be about one half centimeter in diameter.[3] When the drop breaks, negative ions are released, leaving the broken droplets with a positive charge. The negative ions are carried up again on smaller water droplets by the convection currents at a faster rate than the heavier positive water drops. The positive rain is carried up again, falls, breaks, and releases more negative ions. The process continues building up the positive charge in the lower part of the cloud and carrying the

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[2] Simpson, G.C., Electricity of Rain and Its Origin in Thunderstorms, Philos. Trans. Royal Soc., Ser. A, Vol. 209, pp. 379 - 413, 1909.

[3] Lenard, P., Ueber Regen, Meteorological Zeitschr, Vol. 21, p. 249, 1904.

negative charges up and to the back portion of the cloud. No rain can fall in a region where the upward air velocity is greater than eight meters per second, but the generating process will continue even though no rain falls to the ground.

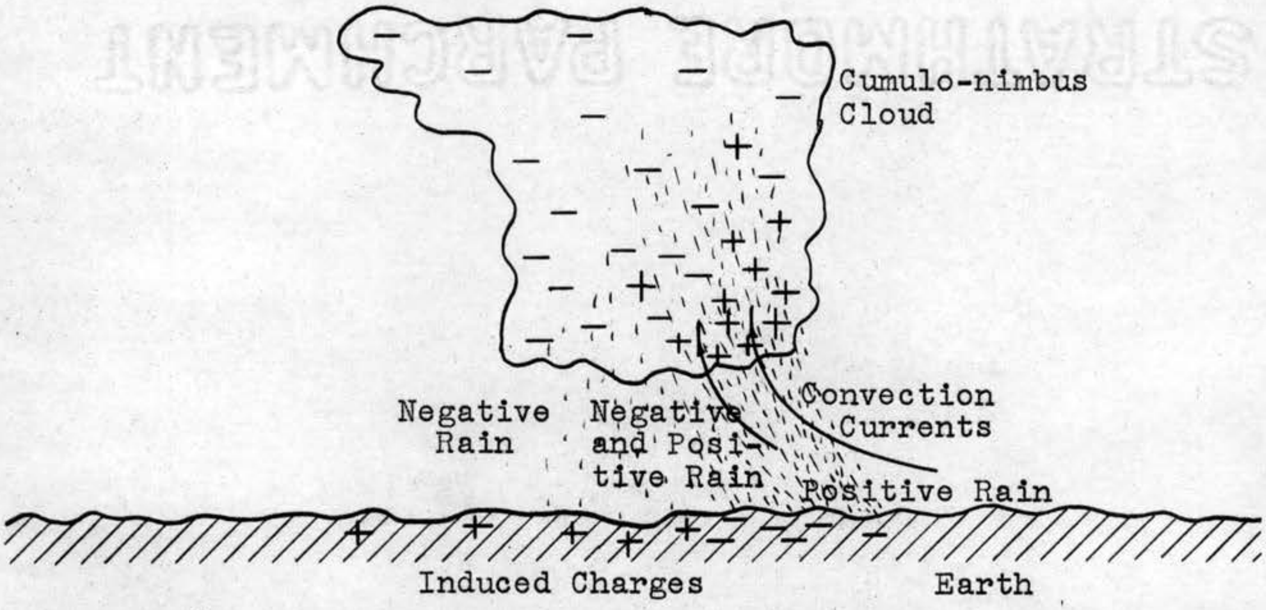

Figure 1.6. Distribution of electric charges in a thunderstorm according to Simpson's theory.

This theory seems to fit most observations. The first rain to fall from a thunderstorm consists of large drops and Simpson found their charge to be positive. Later, a mixture of positive and negative rain was observed, and finally negative rain was predominant. This theory leads to the thunderstorm model shown in Figure 1.6.

<u>Elster and Geitel's Influence Theory</u>

Elster and Geitel[4] had an entirely diffent idea on the elec-

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[4] Elster and Geitel, <u>Bemerkungen Ueber den Electrischen Vorgang in den Gewitterwolken</u>, Wied. Ann., Vol. 25, p. 116, 1885.

trifying of clouds and recently some observations have made their theory more popular. The making and breaking of water droplets by the convection currents is the same as for Simpson's theory. However, they postulated that since the earth is usually charged negatively, there would be induced on the bottom side of the droplets a positive charge even though the droplet is considerably removed from the earth. As the larger drops fall through the upward rising air, they encounter negative charges on the upper side of the smaller droplets. There would thus be a transfer of positive charge from the larger drops to the smaller drops. The small one would be carried on into the upper regions of the cloud and so leave the bottom of the cloud negatively charged. This is interesting because Lewis[5] has found that a large majority of the discharges to transmission lines are from negative clouds. This is good evidence to support this theory.

C T R Wilson's Theory

Wilson[6] outlined a different theory on how the cloud becomes electrified. Like Elster and Geitel he believes that the convection current carries the rain up and that the droplets are polarized, positive on the bottom and negative on top, by induction from the negative earth below.

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5 Lewis, W. W., Lightning Investigation on Transmission Lines, A. I. E. E. Transactions, Vol. 54, pp. 934 - 942, 1935.

6 Wilson, C. T. R., Investigations on Lightning Discharges and on the Electrical Field of Thunderstorms, Philos. Trans. Royal Soc., Ser. A, Vol. 221, pp. 73 - 115, 1920.

In a cubic centimeter of atmosphere there are usually about 1000 positive and 800 negative ions[7] having mobilities of about one centimeter per second when subjected to a field of a volt per centimeter. There are from 1000 to 60,000 larger ions of much smaller mobilities. The number of all the ions is greatly increased by ionization due to the electric field being generated by the cloud. The positive ions travel to the earth while the negative ions go toward the upper part of the cloud.

The falling rain drops encounter many of these ions, and because all of the drops are polarized, drops falling faster than the velocity of the positive ions will not pick up a positive charge since the positive ions and the positive lower portion of the drop will repel each other. A negative ion will be attracted when it meets the positive lower portion of the drop. Therefore the large fast-falling drops become negatively charged by repeated contacts with negative ions. As this charge accumulates in the lower part of the cloud, the electric field produced helps the earth's field in polarizing the drops above and aids in the charging process. Drops falling more slowly than the positive ions will be overtaken by positive ions and the negative upper portion of the drop will attract them. These drops will become positively charged by repeated contacts and due to their relative small size, will be carried up by the air currents. From this line of reasoning Wilson sees the cloud as being positive in the upper regions and negative in the lower part of the

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7 Hess, V. F., The Electrical Conductivity of the Atmosphere and Its Causes, D. Van Nostrand Company, New York, 1928.

thundercloud. He explains the fact that the first drops from a passing thundercloud are positive by pointing out the fact that since the negative field due to the cloud is much stronger than that of the earth, a positive charge is induced on the top of the large falling drops, and that the negative lower portion of the drop attracts the rising positive ions. Thus a drop which leaves the cloud negative becomes positive before it strikes the ground.

Summary of Theories

In summing up it appears that there are desirable features in all three of these theories. Simpson's theory is very attractive because water droplets can be broken in the laboratory and found to be positively charged. This would seem to make the bottom of the cloud positive. This is in direct disagreement with the fact that 95% of the discharges on transmission line towers are from negative based clouds. Such a discrepancy is so great that it is difficult to completely accept this theory.

Actually there is probably a combination of all three processes occurring in the thunderstorm. Evidently, study and observation will be required before the problem of how the cloud obtains its charge will be solved.

CHAPTER II

THE LIGHTNING STROKE

Before many of the effects of lightning can be understood and solutions obtained for the problems involved, a knowledge of the characteristics and mechanism of the discharge of the lightning stroke must be attained. There has been an intensive investigation of lightning the past few years by Dr. K. B. McEachron of the General Electric Company. From direct measurements, and photographic study of many lightning discharges Dr. McEachron has extended our knowledge of the phenomenon of lightning.[1]

Potentials and Field Gradients

There have been many measurements of the electrostatic gradient in the atmosphere during both clear and stormy weather. According to Wilson[2] the clear weather gradient is of the order of 100 volts per meter, and the conducting layers of the upper atmosphere has a positive potential of about 10^6 volts with respect to the ground.

During a thunderstorm the field at any point is composed of a combination of several fields, each due to a concentration of charges in relatively small volumes. After a discharge, the resultant field may increase or decrease, depending on how

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[1] McEachron, K. B., Lightning and the Protection of Electric Systems, General Electric Company, Schenectady, New York, 1939.

[2] Wilson, C. T. R., Investigations on Lightning Discharges and on the Electric Field of Thunderstorms, Phil. Trans. Royal Sox., Ser. A, Vol. 221, pp. 73 - 115, 1920.

the discharged field added or subtracted the components comprising the total field. After a discharge, the gradient recovers at a rate that is approximately exponential until it reaches the point where another discharge occurs.

It does not seem necessary for the field gradient to reach the breakdown value of air all along the discharge path, lightning has been observed striking the ground in areas where the gradient was less than 5 kilovolts per meter. It appears that when the breakdown point is reached in a certain area, the streamer of the lightning stroke starts forming in that area and the propagation of the streamer into areas of relatively low field gradient redistributes the field and raises the gradient to the breakdown point in the areas which previously had a low gradient. Wilson has estimated that the potentials in some thunderstorms may be as much as 10^9 volts.

Wave Shapes

It is very difficult to measure directly the wave shape of a lightning stroke. A study of induced effects some distance away from the stroke may give some valuable information, but it is certain that there is much distortion in these secondary waves. From the study of lightning striking transmission lines, Peek[3] finds the time of discharge to be from 5 to 40 microseconds, while an oscillographic study in Sweden by Norinder[4] found some

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3 Peek, F. W., Lightning, A. I. E. E. Trans., Vol. 50, No. 3, pp. 1077 - 1089, September, 1931.

4 Norinder, Harald, Lightning Currents and Their Variations, Journal of the Franklin Institute, Vol. 220, No. 1, pp. 69 - 92, July, 1935.

discharge intervals up to 60 microseconds. Norinder's data was obtained by using loop antennas symmetrically wound to eliminate electrostatic effects and only vertical strokes were employed in the study. Intervals up to 10 microseconds were found for the rise of the current wave with a maximum rate of change of current as high as 30,000 amperes per microsecond. The average rate of change seemed to be in the order of 4,500 amperes per microsecond.

Current in the Stroke

A number of methods have been used in estimating the current in the lightning stroke. Pockels[5] made measurements on the magnetization of basalt found at points that had been struck by lightning. His measurements indicated currents in the range of 2,000 to 20,000 amperes.

Estimates of currents have been made by Bellaschi[6] to be upward to 200,000 amperes. He bases this on the fusing effects on conductors that have been struck by lightning.

Many measurements of current have been made in the past few years using methods similar to Pockels. The results of this research indicates that there are currents up to 200,000 amperes in lightning strokes. However, currents of this magnitude are rare, with over 50% of the strokes measured being in the order of 26,000 amperes.[7]

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[5] Code for Protection Against Lightning, Handbook No. 17, Bureau of Standards, Washington, D.C.

[6] Bellaschi, P.L., Lightning Currents in Field and Laboratory, A. I. E. E. Trans., Vol. 54, No. 8, pp. 837 - 843, August, 1935.

[7] McEachron, Ibid.

Current measurements by several methods have been quite consistant in establishing the most severe strokes at approximately 200,000 amperes and show that about 95% of the strokes striking transmission lines are from negative clouds. Results obtained by Norinder and Wilson indicate that the negative and positive strokes would be more nearly equal if all strokes to ground were considered.

The Discharge

Because the interval of the lightning discharge is so small, it is impossible to see the step by step development of the lightning stroke with the naked eye. However, this obstacle was overcome by the development of the Boys camera.[8] This camera is a unique device for the recording of moving phenomena on film.

From a series of tests, Schonland and Collens[9] discovered the sequence of events in the discharge. The initial leader stroke, which is of relatively weak intensity, progresses rather rapidly from the cloud to the earth. When the leader reaches the ground the main stroke builds up on the same path at a much higher velocity from earth to cloud. It was also found that this sequence might occur many times in rapid succession, and that each stroke followed approximately the same path. As many as 40 strokes over the same path were observed.

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[8] Lightning and the Protection of Electric Systems, General Electric Company, Schenectady, New York, 1939.

[9] Schonland, B. F. J., and Collens, H., Progressive Lightning, Proc. Royal Society, Series A, Vol. 143, No. 849, pp. 654 - 674, January, 1934.

From a study of the Boys camera photographs, the first initial leader stroke was found to be quite unique. The leader was formed by a series of "darts" projected from cloud to earth at a velocity of about 1/6 that of light. The first dart proceeded only a part of the distance and came to a halt. After about 100 microseconds, the second dart would proceed over the same path as the first, but advance about 50 yards further. It would then halt and a third dart, still over the same path, would proceed for another 50 yards further after an interval of 100 microseconds. This process would continue until the leader made contact with the earth and the brilliant flash of the main stroke would traverse the same path from earth back to the cloud. Sometimes as many as 100 of these step leaders are necessary before contact is made with the ground. Branching of the step leader sometimes occurs, several branches being formed, all pointing earthward, before the main leader ends the activity. The step leader seeks the path of least resistance to ground and sometimes does so along several paths simultaneously. The whole process takes place in less than 0.01 seconds.

The main stroke, characterized by the bright flash, terminates the process by proceeding from the ground at the point of contact upward along the path of the step leader at a speed of about 1/10 that of light. At a branching point of the step leader, the main stroke proceeds simultaneously along the main path and out along each branch to terminate growth of the branches. The main stroke becomes less intense as it approaches the cloud and disappears completely at the base of the cloud.

Strokes which never reach the ground or terminate on another cloud develop by the step leader process, but are not followed by the main stroke and brilliant flash. They apparently develop until all their available energy is dissipated, and then disintegrate.

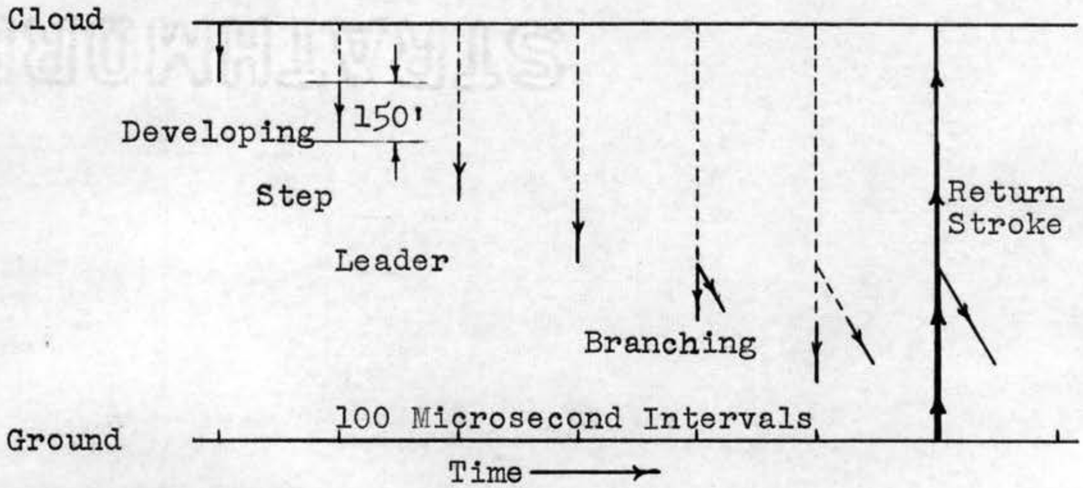

Figure 2.1. Diagram showing development of the step leader in a lightning discharge.

In the case of multiple strokes, only the first stroke develops by the step leader process. After an ionized path to ground has been established, all succeeding discharges take only one step from cloud to ground to initiate the discharge. They follow the main path of the first stroke and are not likely to branch.

From available data, it appears that some thunderstorms produce many multiple strokes, while others produce only a few. From visual observation many of the multiple strokes in a storm can be detected. The total time for completion of a multiple stroke varies from 0.001 to 1 second.

Applications

In this thesis primary consideration will be given to the detection and the direction finding of the discharges. In order to understand the function of the equipment, it is necessary to study the current in the stroke as a function of time.

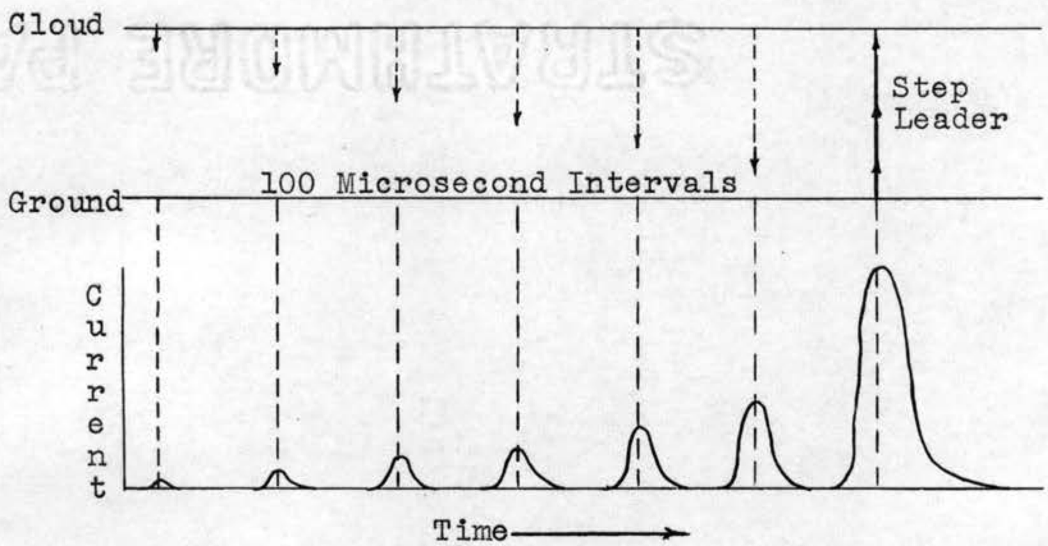

Figure 2.2. Current wave associated with a cloud-to-ground lightning discharge.

The occurrence of each step leader is accompanied by a rise and fall of current. This creates a series of pulses, as shown in Figure 2.2. The time between each step leader is on the average about 100 microseconds, and the frequency of the current pulses is the reciprocal of this period. This results in a in a frequency of 10,000 cycles per second, and therefore the fundamental frequency of the non-sinusoidal wave should be about this value. Experimental results show that the radiated energy from lightning discharges is concentrated in this part of the frequency spectrum. This conclusion is important in the design of the direction finding equipment if the maximum sensitivity from a maximum number of discharges associated with each storm is to be obtained.

CHAPTER III

PRINCIPLES OF DIRECTION FINDING AND LOOP ANTENNAS

Electromagnetic waves are usually propagated along the earth's surface over a great circle route. This characteristic makes electromagnetic direction finding possible. If the bearing of an electromagnetic signal is taken from two separated locations, the point of origin of the signal may be located by triangulation. By this method, the source of "sferics" in the thunderstorm can be found.

The accuracy of the direction finder depends upon how closely the radiation follows the great circle path. Even though the great circle route is usually followed, there are certain conditions under which lateral diviation is appreciable. Lateral deviation of the ground wave occurs when the signal crosses a coast line and the angle between the path of the signal and the coast line is very small. This error will not affect the direction finder when used in Oklahoma because the nearest coastline is several hundred miles away. The same type of error is also often encountered in mountainous areas because the electomagnetic waves are attenuated less when passing over valley areas than when going crosswise across rugged terrain. This error will not be troublesome in Oklahoma because of the relatively level terrain.

At higher ratio frequencies the propagation depends a great deal on the condition of the ionosphere. The ground wave attenuates rapidly, and the reflected sky waves may be considerably scattered if the reflecting ionosphere is not homogeneous. This condition may scatter the electromagnetic waves, causing them to appear to come from several directions simultaneously. The condition is analagous to the reflection of the sun's rays from a lake which is being rippled by the wind. When looking at the reflection the rays appear to be coming from many different sources in the lake. The largest error due to this effect occurs at sunrise and sunset and is also much more pronounced at night time than during the day. It is at these times that the reflecting ionosphere is uneven and consequently this phenomenon is usually referred to as the "night effect". The night effect causes some trouble with the sferic, although not as much as might be expected. The direction finding apparatus is designed to receive and amplify the low frequency components of the sferics which are of the order of 10 kilocycles. The higher frequencies, which are more likely to be coming from the ionosphere, are attenuated. The low frequency that is amplified comes in largely as a ground wave and is affected to a very minor degree by the ionosphere.

The error most prevalent in the sferic direction finder is that due to reradiation from nearby objects. Passing waves striking conduction objects such as overhead wires and fences induce currents that produce new radiation fields. The new fields produce two affects on the incoming wave being received. It alters the apparent direction of the incoming wave, and produces elliptical polarization of the wave. In the crossed loop direction finder the quadrature component due to reradiation tends to destroy the null and decreases the accuracy of the direction finder.

Loop Antennas

The loop antenna is a direction device which produces excellent results in many applications. The main limitation of the loop is that for best results the incoming electromagnetic wave must be vertically polarized; that is, it should contain no components of the electric field in the horizontal plane. However this is not a serious handicap since most ground waves have small horizontal components because of the short circuiting effect of the conduction ground. The loop antenna, when properly balanced and shielded, will give a field pattern like that shown in Figure 3.1.

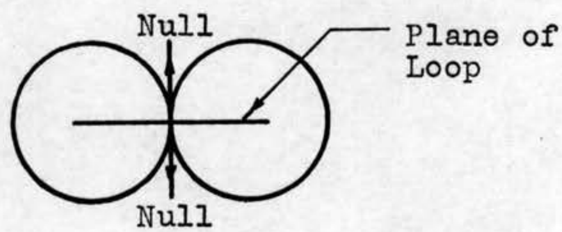

Figure 3.1. Polar radiation characteristics of a loop antenna.

The voltage induced in the loop is approximately proportional to the derivative with respect to time of the incoming signal. If the radius of the loop were zero, the loop would be an exact differentiating device. However so long as the cross sectional dimensions are small in comparison to the shortest wave length, the loop can still be considered as a differentiating device. If this assumption is valid, the signal received by the loop will be proportional to the cosine of the angle between the plane of the loop and the direction from which the signal arrives. Signals coming in perpendicular to the plane of the loop will not be received. However, if the loop is not perfectly balanced, the nulls will not occur at the perpendicular points and will deviate from the perpendicular an amount which is a function of the degree of unbalance.[1]

The loop antenna is a good directional device for locating sferics. The construction of a loop is not difficult, and electrostatic shielding of the coil windings makes the problem of electrostatic balancing with respect to ground an easy one. The loop directional characteristics may be checked by plotting a polar radiation diagram. In the problem of finding the direction of sferics, a unique situation arises in that there is not sufficient time to rotate a single loop antenna to locate a null. Since a sferic never lasts more than a half second, some method is needed for instantaneously detecting the direction. The most practical method is the use of two identical loop antennas whose planes are set perpendicular to each other and perpendicular with respect to ground. The signals from each of the crossed

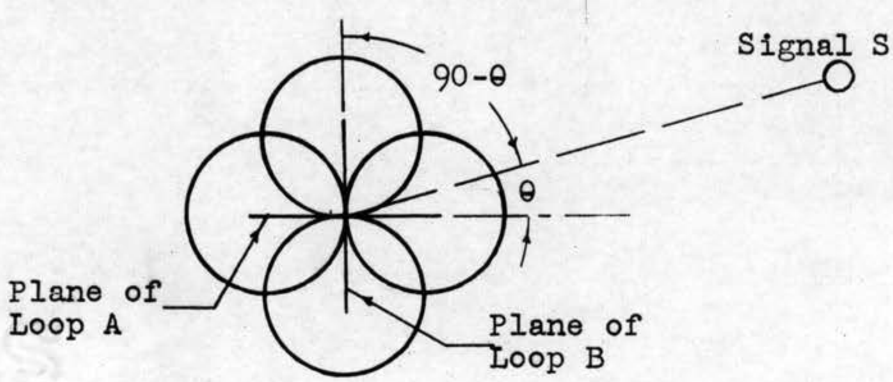

Figure 3.2. Polar radiation plot of crossed loop antennas.

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1 Terman, F. E., Radio Engineering Handbook, McGraw Hill Book Co. New York and London, 1943, p. 876.

loops are fed through identical amplifiers to the horizontal and vertical plates of a cathode ray tube. From Figure 3.2 it is evident that the output of the loops A and B for the signal S shown would be,

$$A_o = K \frac{dS}{dx} \cos \theta,$$

$$B_o = K \frac{dS}{dx} \cos (90^\circ - \theta).$$

The input to the cathode ray tube will be uA_o on the horizontal plates and uB_o on the vertical plates. The electron beam in the cathode ray tube will have horizontal and vertical deflections from the zero position,

$$H = K_1 u K \frac{dS}{dx} \cos \theta$$

$$V = K_1 u K \frac{dS}{dx} \cos (90^\circ - \theta).$$

K_1 = volts per inch deflection of the cathode ray tube

u = voltage gain of the amplifiers

K = the antenna constants

$\frac{dS}{dx}$ = change in vertical component of electric field intensity along the path of the signal at the loop

θ = the angle that the path of the signal makes with the plane of the A loop.

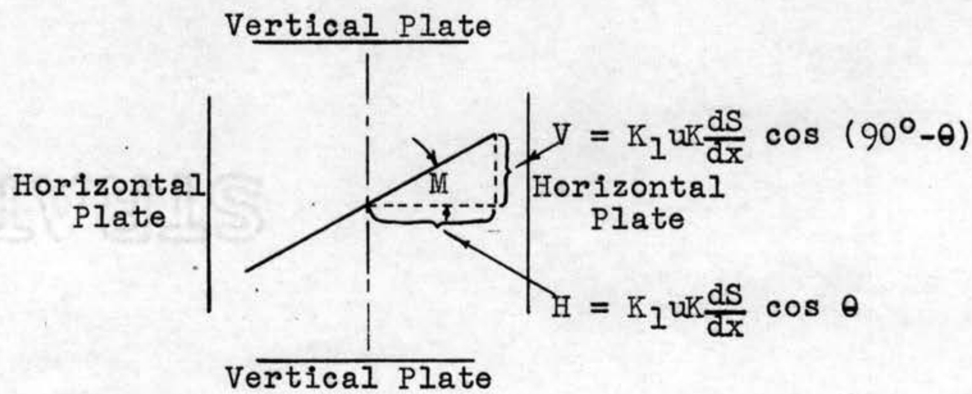


Figure 3.3. Deflection of electron beam in the cathode ray tube from crossed loop signals.

From Figure 3.3,

$$M = \tan^{-1} \frac{K_1 \; u \; K \frac{dS}{dx} \cos (90 - \theta)}{K_1 \; u \; K \frac{dS}{dx} \cos \theta} = \tan^{-1} \frac{\cos (90 - \theta)}{\cos \theta}$$

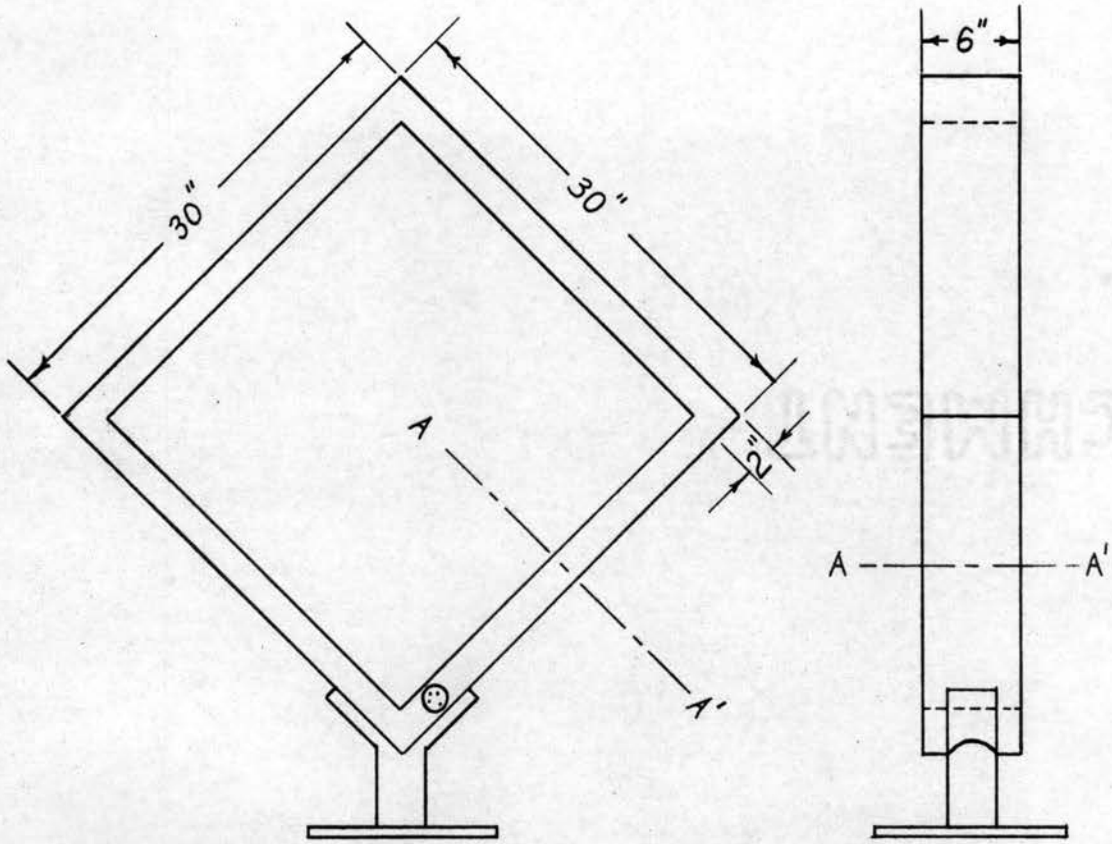
$$= \tan^{-1} \frac{\sin \theta}{\cos \theta} = \tan^{-1} \tan \theta = \theta.$$

Therefore, if the loops are properly oriented with respect to direction and the cathode ray tube calibrated, the bearing of the sferic will be along the line traced by the electron beam. If a permanent record of the trace is desired, it can easily be recorded on film.

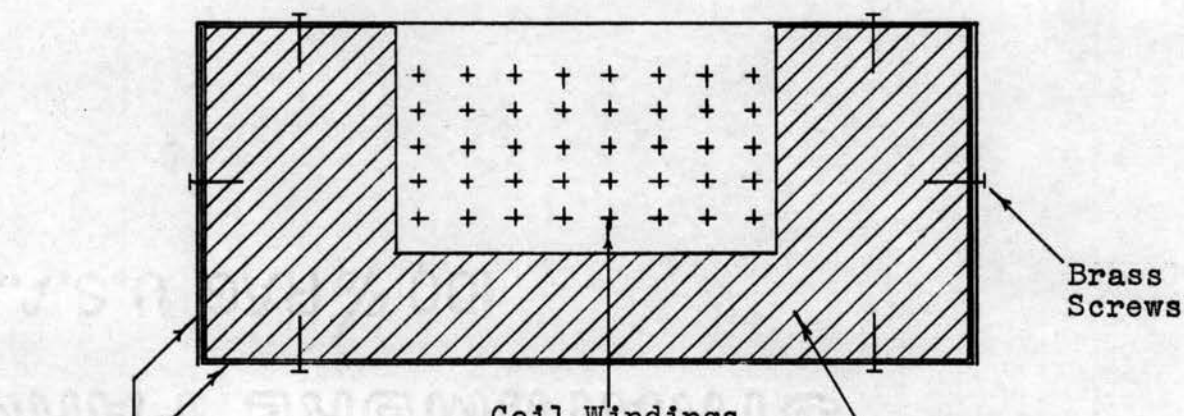
There is inherently an ambiguity of 180 degrees in this method of direction finding. The trace on the cathode ray tube represents a line of position of the point of origin of the sferic. The ambiguity may be removed by differentiating the signal from a vertical whip antenna and using the differentiated signal to intensity modulate the cathode ray tube. A third amplifier with characteristics identical to the other two is necessary for amplifying the differentiated signal. The ambiguity problem was not considered serious enough to warrant intensity modulation in the sferics direction finder. The thunderstorms producing the sferics are usually visible. If this is not the case their approximate position at a given time may be obtained from the United States Weather Bureau.

Description of the Loop Antennas

The two loop antennas that were built for the sferics direction finder have the dimensions shown in figure 3.4. They



Loop Dimensions



Cross Section AA'

Figure 3.4. Loop dimensions in detail.

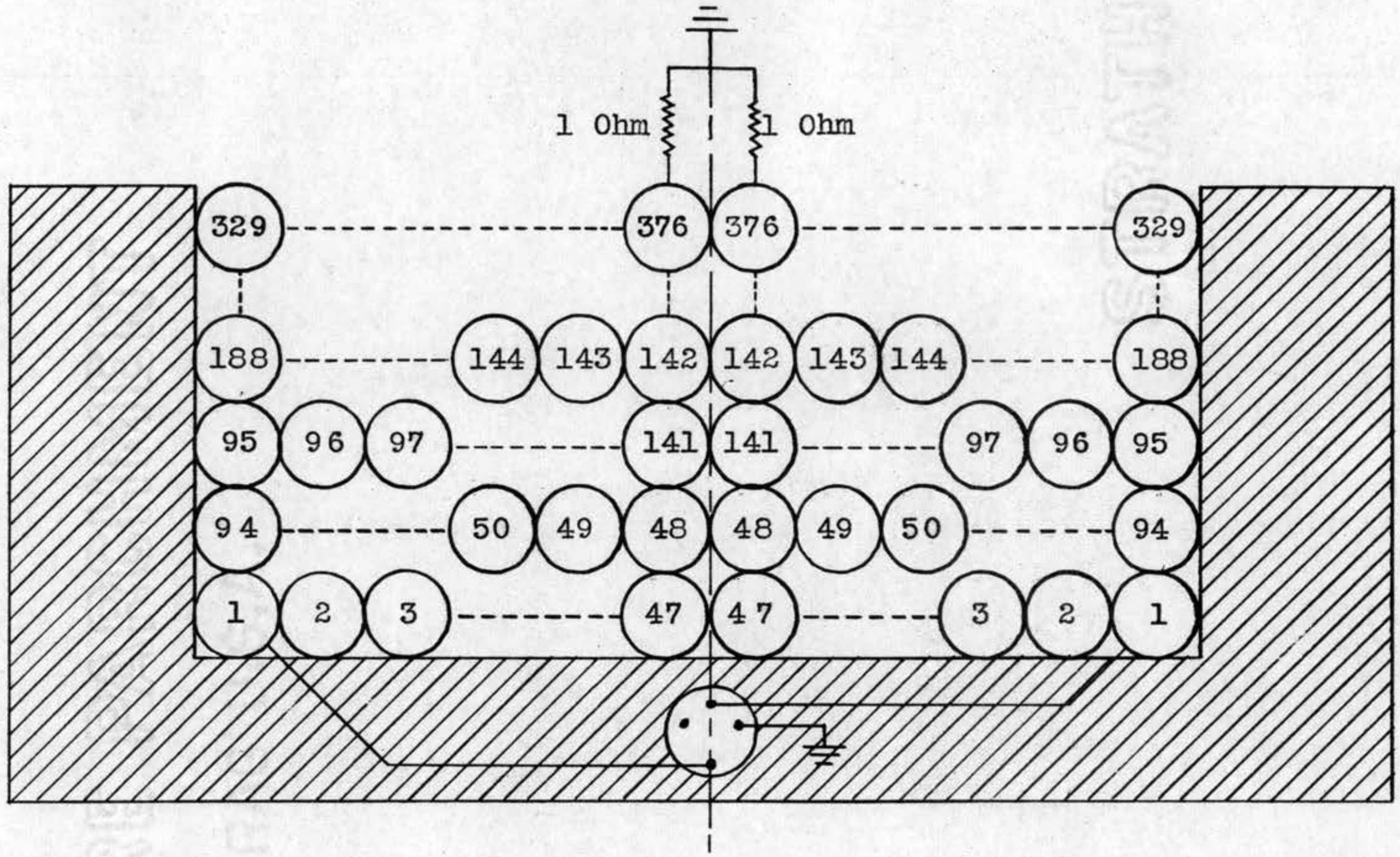


Figure 3.5. Detail of Coil Winding in Loop Antenna
(752 Turns Symmetrically Wound)

are identical so only one description is given. The frame is made of 2 inch by 6 inch pine material. A slot is cut in the frame to contain the windings as shown in one cross section drawing of Figure 3.4. The electrostatic shield is made from two pieces of galvanized sheet iron and fastened to the wood frame with wood screws. The windings consist of 752 turns of number 24 B & S gauge cotton-covered-enamel copper wire symmetrically wound with respect to the grounded shield. A detail drawing showing the winding of the coils is shown in Figure 3.5. The center turn is grounded. The one ohm resistances are inserted so that a dummy signal from a local oscillator may be introduced for tuning the loops and amplifiers. The total inductance of each loop was measured with an American Telephone and Telegraph impedance bridge and found to vary from 246 millihenries at 100 cycles to 105 millihenries at 15,000 cycles. This variation is due to the effects of the distributed capacity between turns in the loop. This variation could have been minimized if the layers of wire had been separated with some insulating material.

The radiation patterns of Figure 3.6 and 3.7 were plotted from data taken on the loops in the open area north of the east hutment. The time was June 18, 1951, between 4 and 6 PM. A group of thunderstorms had passed over the area about noon of that day and was still active on the east horizon. These storms produced sferic voltages which had to be subtracted from the total voltage received by the loop in order to obtain the noise generator voltage above. The interference of the sferics caused the apparent null of the loops to be different from the

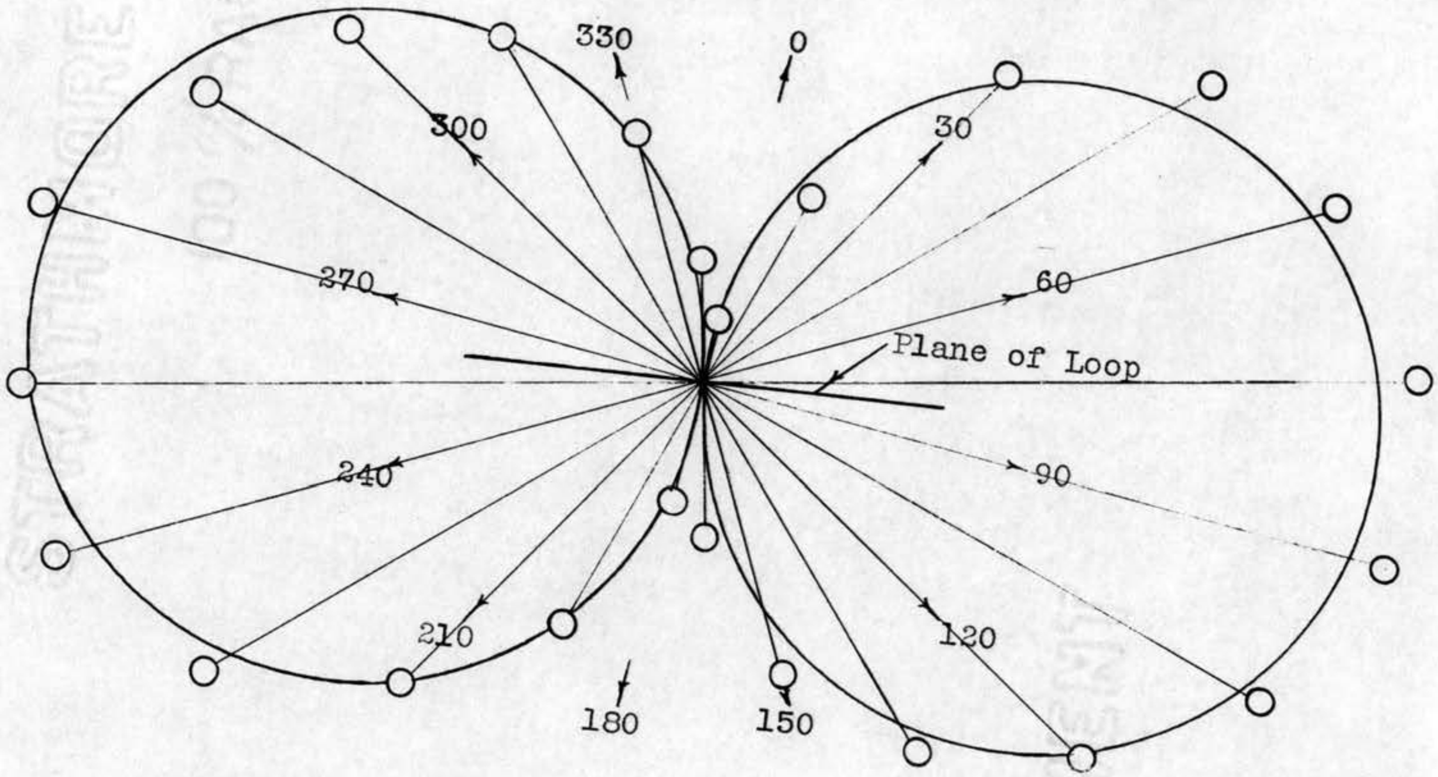


Figure 3.6. Radiation Pattern of Loop A
(East-West Loop)

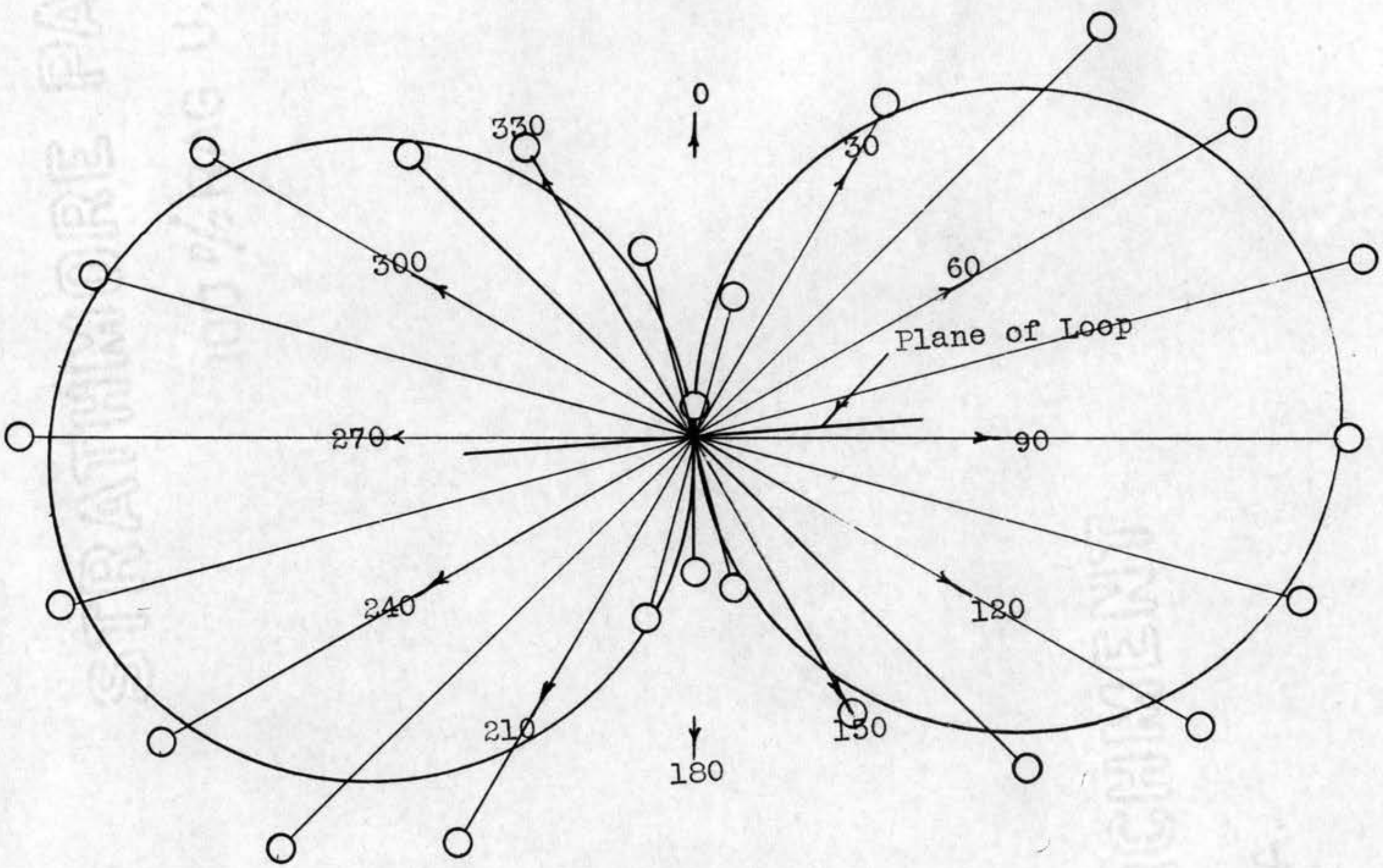


Figure 3.7. Radiation Pattern of Loop B
(North-South Loop)

true null. The zero reference in the polar radiation plots was taken at the apparent null position and does not correspond to the true null position. Actually the noise generator was located perpendicular to the plane of the loop at the true null position.

The signal noise generator was composed of a spark coil connected to a 4 foot vertical whip antenna and a 6 volt dry cell battery. To obtain the data for the polar plots the noise generator was placed about 30 feet from the loop and the loop rotated in steps of 15 degrees from 0° to 360 degrees. The angles were measured with an astrocompass.

The same amplifier was used for testing both loops and the output voltages measured at the deflection plates of the cathode ray tube.

The polar diagrams were plotted using the ratio of the signal voltage at position "θ" to the maximum signal voltage at any position so that variations in the signal generator output would not affect the shape of the polar plots. The plots show that the radiation patterns are very nearly symmetrical and that the directional properties of the crossed loops are satisfactory.

CHAPTER IV

A COMPLETE SFERICS DIRECTION FINDER

The formation of the charge on clouds and the mechanism of the lightning discharge in a thunderstorm has been described in Chapters I and II. The conclusion from Chapter III is that the loop antenna is a satisfactory device for determining the direction of the electromagnetic radiation associated with a lightning discharge. The problem of sferic direction finding is solved completely when the signals from the crossed loop antennas are properly amplified to produce a visual response on the screen of the cathode ray tube.

Amplifiers

Amplifier characteristics for the direction finder is a problem that has to be analyzed carefully. The gain of both the horizontal and vertical amplifiers must be the same for all components of the signal coming from the loop antennas. When this condition is met, the factor u in the equations of Chapter III will be constant and equal for both amplifiers. It is not necessary that the frequency response of the amplifiers be linear as long as they have the same response to all frequencies received by the loop antennas. It is desirable to limit the frequency band of the amplifiers in order to eliminate most of the artificial noise such as low frequency radio stations. The phase shift characteristics of the amplifiers can be anything so long as they are equal for all frequencies. If the phase shift is the same for any input signal, the differential phase will always be zero, and the output will not be affected.

When there is a differential phase angle in the amplifiers, the straight line on the screen of the cathode ray tube will degenerate into an ellipse. The width of the ellipse is an indication of the angular difference in phase shift in the two amplifiers. Some method for eliminating the phase shift is necessary since a straight line is essential for the direction finder.

At first glance, it would appear that non-linearity of any type could be tolerated as long as both amplifiers contained the same non-linearity. This is not true. The amplifiers cannot have a change of gain for different magnitudes of input signal. Even though they have the same gain variations, an error in the direction output will occur since the input signal magnitudes from the loops are, in general, not the same. There is an exception of eight possible directions in which there would be no error due to varying gain characteristics. If a signal arrives parallel to the plane of one loop, it will be perpendicular to the plane of the other loop. The parallel loop will have a large signal voltage induced while the perpendicular loop will receive zero voltage. The amplifier gains will be different if the gains are functions of the input signals, but with zero voltage on one set of deflection plates, the cathode ray tube will give a true bearing. The bearings will be true for each of the directions parallel to the plane of either of the loops. For a signal arriving at 45 degrees the loop outputs will be the same and the gains will be equal. Therefore, the bearings making 45 degrees with the plane of either of the loops will be true. The error due to changes of gain with signal strength can be kept at a minimum by running the amplifiers at low gain.

Two amplifiers were built by the author using the circuit of Figure 4.1. Each component part was selected to be as nearly identical as possible and was mounted in the chassis in identical positions whenever possible.

A cathode follower stage is used to couple the loop antennas to the amplifiers. A potentiometer for the output of the cathode follower provides an excellent means for varying the coupling of the loop signal to the amplifiers.

The first stage of amplification consists of a 6SK7 biased with a 270 ohm cathode resistor and voltage taken from a 100,000 ohm bleeder potentiometer off the direct current power supply. The potentiometer gives good gain control due to the remote cutoff characteristics of the 6SK7. This stage is a resistance coupled amplifier stage designed to pass 10 kilocycles. The ordinary thunderstorm sferic is rich in 10 kilocycle signal and this frequency is sufficiently low to avoid interference with low frequency radio signals.

The second stage in the amplifier is a 6SJ7. This tube has a sharp cutoff characteristic and is more linear for large signals than the 6SK7. The stage is resistance coupled and designed for passing 10 kilocycles.

The output stage is a 6J5 medium mu triode. This tube is capable of delivering 50 volts output with less than 5% distortion. Since the sensitivity of the 2AP1 cathode ray tube is approximately 200 volts per inch deflection, an output voltage of 50 volts is necessary to give a good deflection.

There are no tuned stages in the amplifier because of the difficulty in tuning them to exactly the same frequency. Tuned stages are also more likely to oscillate within themselves when pulsed with a steep wave front. To avoid this difficulty only resistance coupled stages were used.

To correct for difference in phase shift a condenser is shunted across the grid of the 6SJ7 in one of the amplifiers. This correction keeps phase shift difference to an allowable value from frequencies as low as 100 cycles up to 50 kilocycles. The response above 50 kilocycles is small enough to keep the excessive phase shift from affecting the output.

The loop antennas are the only tuned elements in the direction finder. The tuning increases the sensitivity of the loop near 10 kilocycles, but causes the loops to oscillate when excited with a steep wave front. The oscillation can be damped by varying the loop Q, but this cuts down the magnitude of the received signal. Elimination of the loop tuning may prove desirable since there is more gain in the amplifiers than is necessary and the decrease in sensitivity would be more desirable than loop oscillation. It is practically impossible to tune the loops to exactly the same frequency and the cathode ray tube output will show open loops when subjected to the damped oscillation of the loops at unlike frequencies.[1]

Holzberlein, T. M., "A Study of Tornado Tracking Equipment", Master's thesis, Oklahoma A. and M. College, pp. 50-51.

A complete circuit diagram of the amplifiers is shown in Figure 4.2. The values of the components shown are their marked values and are subject to errors of plus or minus 10%. The deviation in the frequency response curves is very likely due to the variation of the circuit component values. By measuring each component accurately with a bridge and selecting components of equal value, the deviation of the response curves could be reduced to a minimum.

Cathode Ray Tube Indicator

The circuit diagram of the cathode ray tube circuit is shown in Figure 4.3. The 15 volt pulse applied to the grid through the .02 microfarad condenser is a blanking pulse which keeps the cathode ray tube cut off except when a sferic occurs. The pulse comes from the pulsing circuit that triggers the sweep of the wave form on the cathode ray tube. It synchronizes the direction finder cathode ray tube with the wave form cathode ray tube so that pictures of both direction and wave form may be taken simultaneously. The pulse consists of a constant negative 15 volt direct current voltage that is instantly reduced to zero when the pulsing relay closes.[2] The voltage appearing on the grid of the cathode ray tube due to the pulsing circuit is a positive 15 volt pulse. By decreasing the steady state intensity of the tube to zero and feeding the positive 15 volt pulse on the grid, the tube will conduct only while the pulse is on. The

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[2] Hess, P. N., "Installation and Operation of Electronic Sferic Detection Equipment", Master's thesis, Oklahoma A. and M. College.

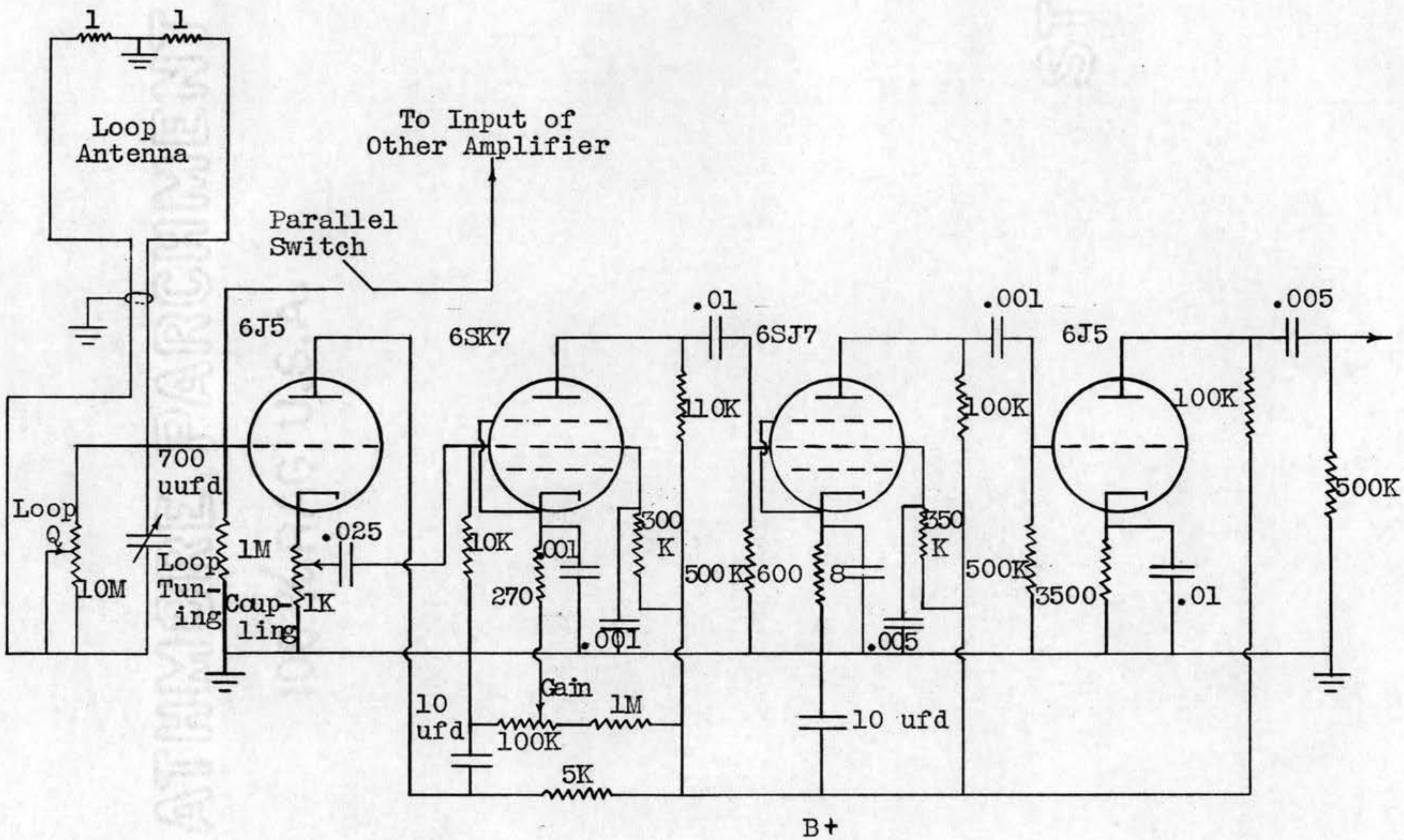


Figure 4.1. Amplifier

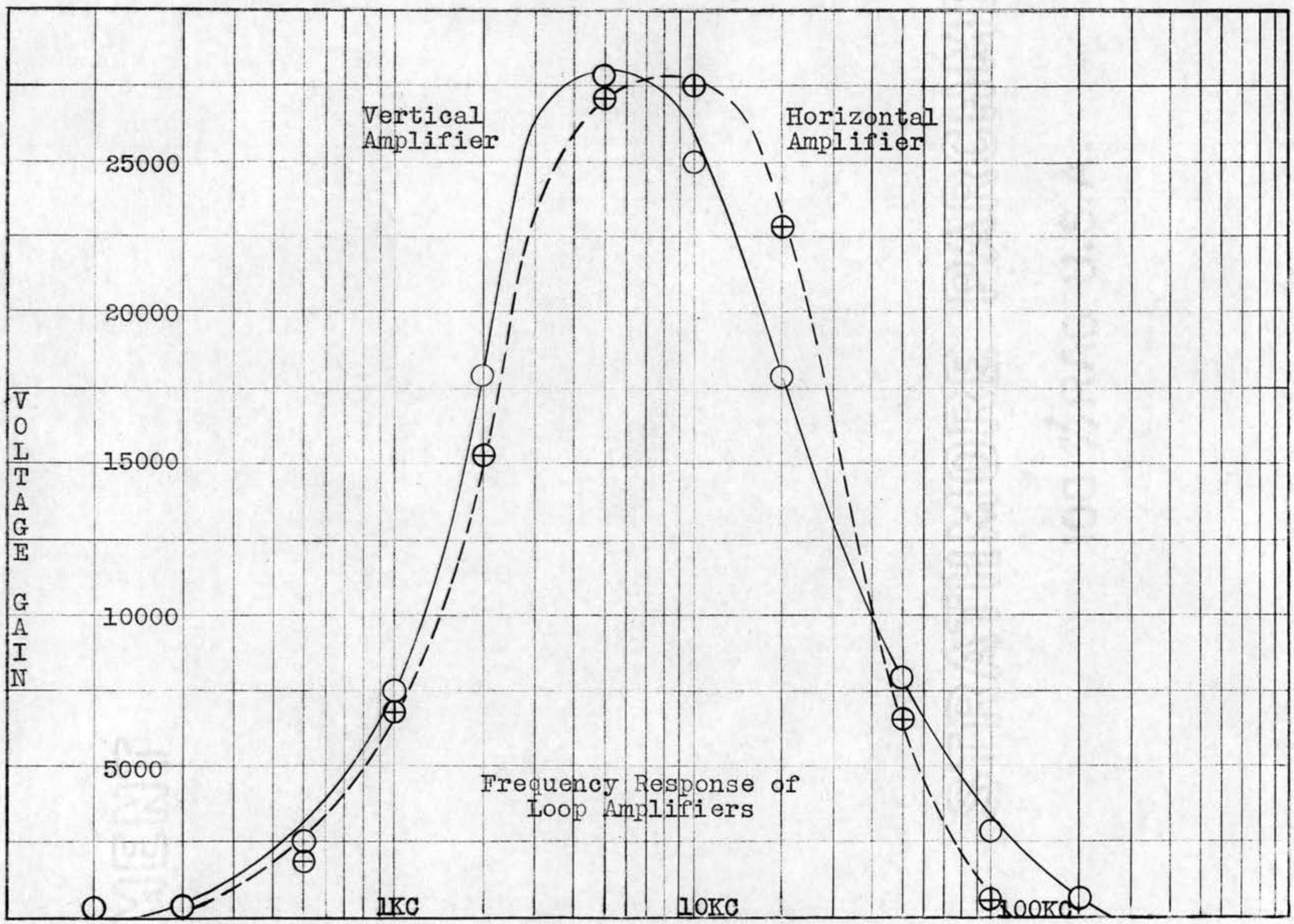


Figure 4.2. Frequency Response

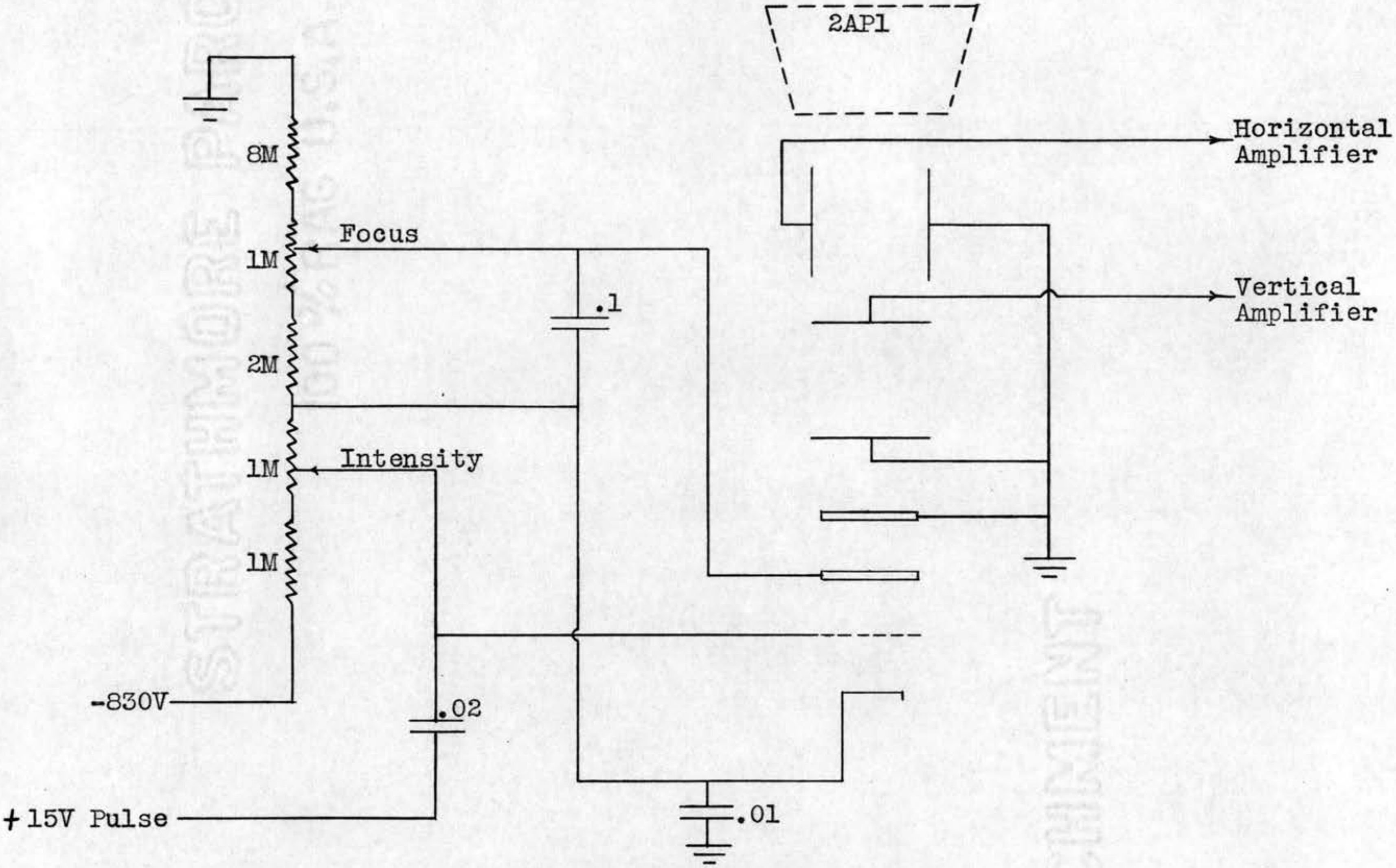


Figure 4.3. Cathode Ray Tube Circuit

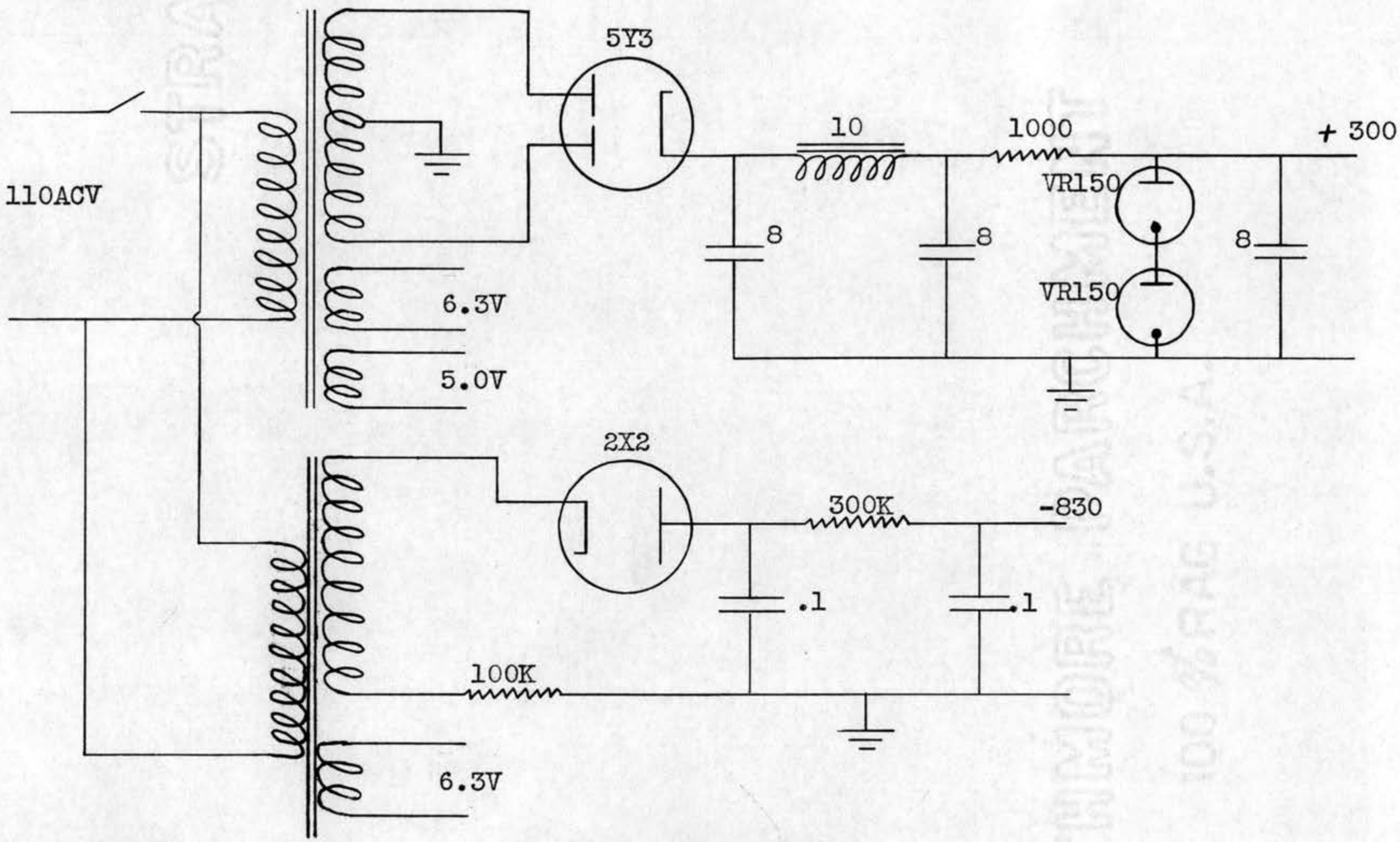


Figure 4.4. Power Supply

time length of the pulse is sufficiently long for the trace to indicate the bearing.

Magnetic deflection of the electron beam in the cathode ray tube due to the presence of the electric clock in the light box causes the beam to appear distorted. Magnetic shielding improved this condition, but some undesirable deflection is still present. Centering control in the cathode ray tube circuit is needed to center the electron beam on the screen. Two potentiometers could be connected across a portion of the negative and positive direct current voltage supplies and the output fed to the vertical and horizontal plates for centering. Having the trace in the center of the screen would make the aligning of the loops and amplifiers less difficult.

Power Supplies

The circuit diagrams of the direct current supplies are shown in Figure 4.4. For improved amplifier performance, B+ is a 300 volt regulated supply. A 5Y3 connected as a full wave rectifier is used with a condenser input pi filter and two series VR150 tubes. The high voltage is obtained from a 2X2 half wave rectifier. The cathode ray tube requires very little current, so an RC condenser input filter is sufficient.

Alignment of the Direction Finder

The crossed loop direction finder must be properly aligned if it is to function and give accurate results. The first necessary step is the tuning of the loops to the same frequency. This may be accomplished by feeding a signal of constant frequency into the loops and varying the loop tuning condensers until the output of each loop is maximum. An input signal can be introduced into the loops by winding a few turns of wire around the loop antennas in the vicinity of the air gap at the top and connecting this loop to an oscillator. By experiment the loops were found to tune more sharply to 7 kilocycles than any other frequency. This was the frequency at which they were tuned when the experimental data in Chapter V was taken.

The amplifier gains must be set so that for a given signal equal vertical and horizontal deflections will appear on the screen of the cathode ray tube. To meet this condition the trace should appear as a diagonal line at 45 degrees from the horizontal when identical signals are fed into the amplifier inputs. Since the vertical and horizontal sensitivity of the cathode ray tube is not equal, the horizontal and vertical gain will also not be equal. To get identical input signals a paralleling switch is mounted on the front panel of the amplifiers. The switch connects the grids of the tubes in the cathode follower stages when at the ON position. Either the gain or the cathode coupling may be varied until the output trace on the cathode ray tube is parallel to the 45 degree reference line. The direction finder seems to give better results when the gain is set at maximum and the aligning is done with the cathode coupling. It is not necessary to use an external signal for setting the relative gains if sferics are present. The sferics serve the purpose equally well. Two things can be checked when setting the gains. With the parallel switch at the ON position, the trace on the screen of the cathode ray tube must be parallel to the 45 degree reference line and for the strongest sferics should be one inch or less in length. The latter condition insures that the strong signals will not overdrive the amplifiers and cause excessive distortion. When the gains are set the paralleling switch should be placed at the OFF position and the direction finder will then indicate the directions of the incoming sferics. When a thunderstorm approaches the gain may have to be reduced to keep from overdriving the amplifiers. This is easily done by turning the parallel switch to ON, then reducing the gain of the amplifiers, being certain that the trace remains at 45 degrees, and finally returning the parallel switch to OFF.

The loop antennas are marked "north-south" and "east-west". If they are oriented with the marked sides pointing in their respective directions, the top of the cathode ray tube will be north, the bottom will be south, the right will be east, and the left will be west. A compass rose can be used to measure the azimuth angle of the incoming sferic.

CHAPTER V

EXPERIMENTAL RESULTS AND CONCLUSIONS

Sferics on July 2, 1951

On the evening of July 2, 1951 pictures were taken of sferics that were being received by the direction finder. These are shown in Figure 5.1. The weather bureau had predicted the arrival of a cold front in the area for that night, but at the time the pictures were made the thunderstorms and lightning accompanying the front were not visible. However low frequency sferics of large magnitude were being received from about 15 degrees east of north. The pictures in Figure 5.1 are typical of the directional sferics indications received from that particular storm. Although the storm was a long distance away, the trace on the cathode ray tube of the direction finder was sharply defined. The azimuth can be measured accurately from the photographs. Lightning was not visible on the horizon so the true bearing of the thunderstorm which was causing the sferics could not be determined. The following day the weather bureau reported thunderstorms in east central Kansas at the approximate times indicated by the clock in the pictures. These storms would have produced the sferics in the direction indicated by the direction finder.

The pictures show that the gain of the amplifiers was set at a value that kept the output well confined to the center portion of the cathode ray tube. The amplifiers were not being overdriven as evidenced by the straight line trace. Since the storm was far away, the sharp wave fronts which are characteristic of some sferics were attenuated and oscillation of the loop antennas due to sudden shock was not experienced.

Sferics on July 3, 1951

The cold front described in the previous paragraphs did not arrive until the following evening. The pictures in Figures 5.2 and 5.3 were taken as the line of thunderstorms accompanying the front approached. Lightning was visible along a line from northeast to northwest with the more severe and numerous strokes arriving from a northwesterly direction. At 9:25 PM the thunderstorms were at least 20 miles away with lightning flashing almost continuously. Figure 5.2a shows three distinct lightning strokes occurring in the interval of duration of the triggering pulse.

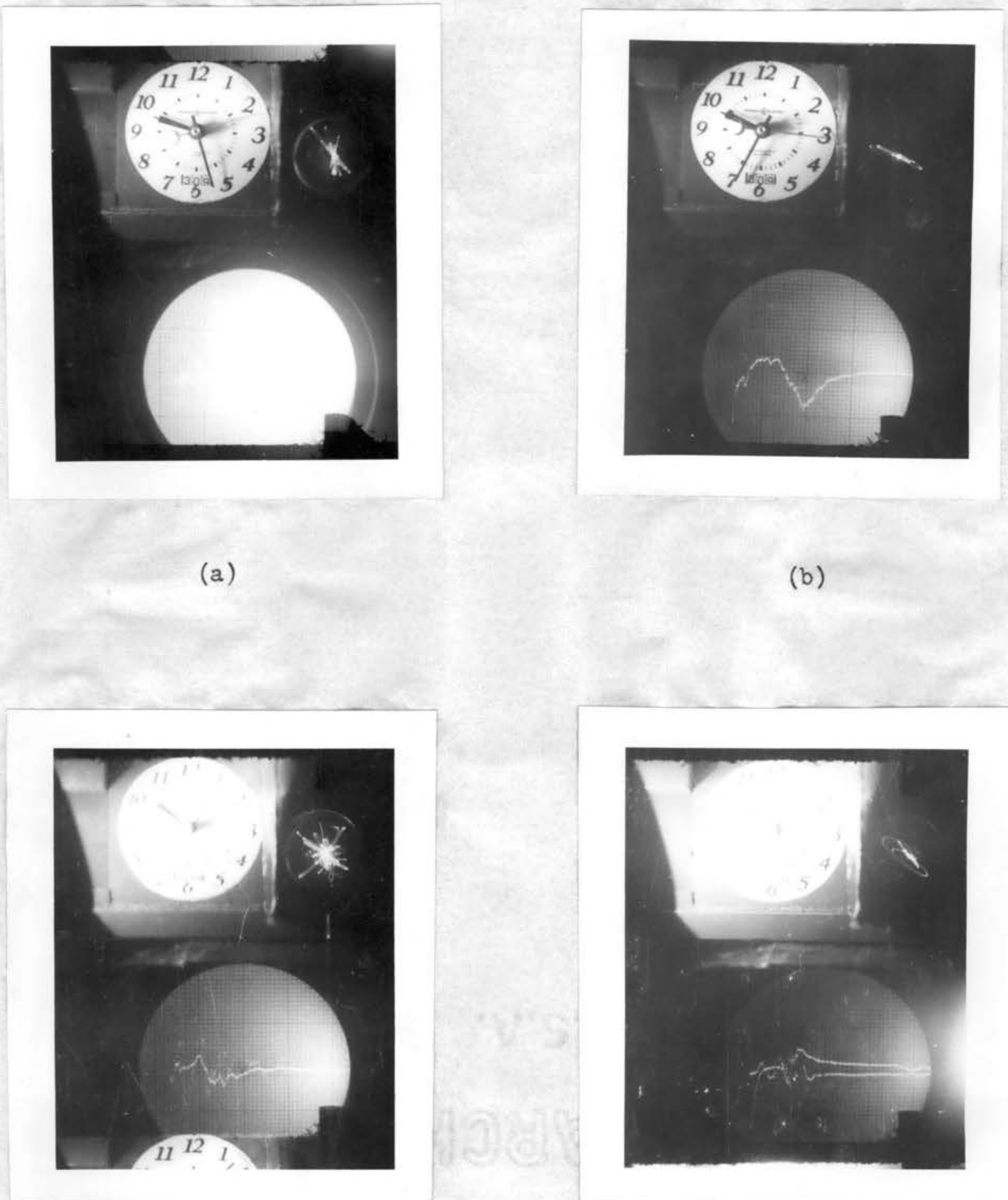
By 10:05 PM the thunderstorms were beginning to pass overhead. A strong wind from the north was active during the time when the pictures of Figures 5.2 and 5.3 were taken. The majority of the lightning strokes was still from a northwesterly direction, but occasional flashes were visible directly overhead. The local strokes were of sufficient intensity to overdrive the amplifiers so as to cause the distortion at the end of the longest traces shown in Figures 5.3b and 5.3d. The gain was set very low throughout the storm, but the distortion in the amplifiers due to local strokes could not be avoided.

Some very prominent loops in the trace output of the direction finder are present in Figures 5.2d and 5.3c. These loops are a result of two conditions. The trace in Figure 5.3c indicates damped loop oscillation while that in figure 5.2d is due to the horizontal components of the electric field of the incoming sferic. The latter condition is prevalent when the lightning strokes occur overhead. Under this condition the loop antennas do not give output voltages proportional to the cosine of the horizontal angle and cannot be depended upon to give accurate results.

The problem of plotting error curves for the direction finder is a difficult one. Isolated thunderstorms whose azimuth can be accurately measured occur very seldom. The problem of obtaining experimental data for the entire 360 degrees around the direction finder would require the measuring of azimuths of isolated thunderstorms in several different directions. The probability of several storms occurring in all directions in a short period of time is very remote. By observing the lightning and the cathode ray tube of the direction finder simultaneously two observers can get a good comparison of directions and estimate the error of the direction finder for any given storm. All observations made by the author indicate that the azimuthal indications of the direction finder is very nearly linear.

(a) (b)

Figure 5.1 Remote Storm of 2 July, 1951

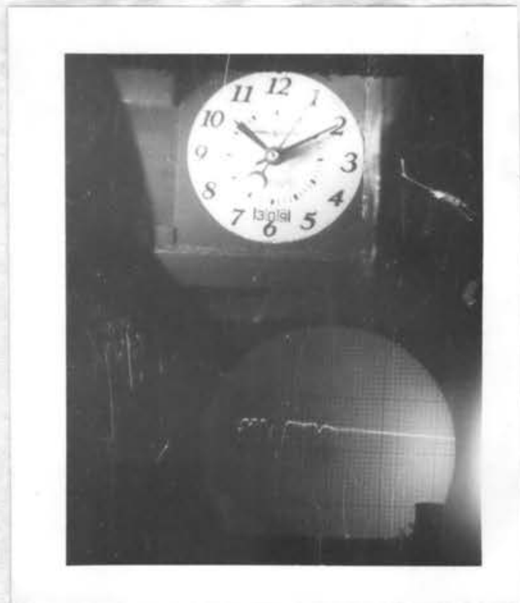


(a) (b)

(c) (d)

Figure 5.2 Storm of 3 July, 1951

(a)

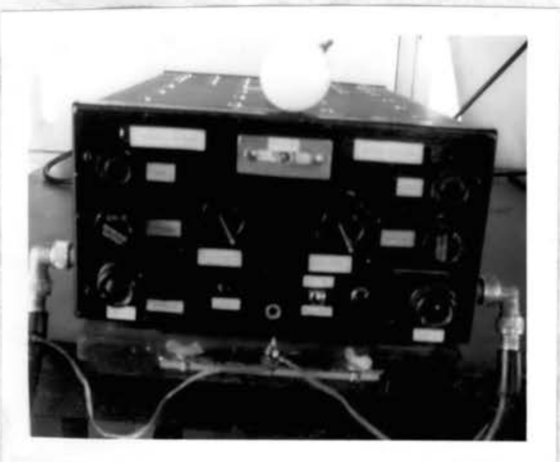


(b)

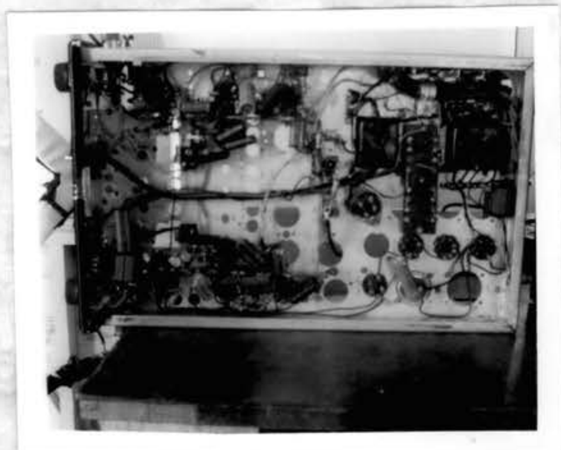
(c)

(d)

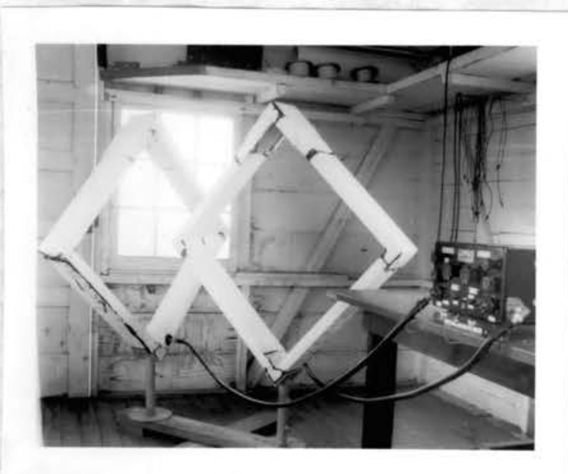
Figure 5.3 Storm of 3 July, 1951



(a) Front View of Amplifier Chassis



(b) Bottom View of Amplifier Chassis



(c) Crossed Loop Antennas and Connecting Cables

(d) Hutment in Which Equipment is Located

Figure 5.4 Pictures of the Direction Finder and the Hutment

Conclusions

The crossed loop antenna system is satisfactory for the direction finding of sferics. The peculiar variety of traces on the direction finder cathode ray tube can be interpreted and evaluated when the characteristics of the complete direction finding system are known. The error of the system is a function of the combination of many factors which were discussed in Chapters III and IV of this thesis.

A change in design of the input circuit of the amplifiers might improve the loop oscillation problem.

The presence of several metallic objects such as the bars on the hutment windows, the oil stove, and the wire fence outside the hutment door undoubtedly have some effect on the accuracy of the direction finder. A large error was observed when the signal noise generator was used to check the system, but no appreciable error has been detected when lightning sferics were observed. The range of the signal generator is so limited (about 30 feet) that it cannot be depended upon for a good error check. To minimize the error due to induced currents in the metal objects the loop antennas should be removed as far as possible from these objects. Mounting the loop antennas on the roof of the hutment would accomplish this purpose nicely.

Errors due to local terrain, night affect, and horizontal components of electric field from local lightning discharges high in the clouds cannot be corrected. These conditions must be recognized and the results properly interpreted.

The most serious problem yet to be solved is that of plotting an error curve. A portable noise generator with a range of one half mile or more is required to check the accuracy of the direction finder in all directions. With the completion of an accurate error curve, the photographic data could be corrected to give the true direction of the observed sferics.

The pictures in Figure 5.4 show the component parts of the direction finder and how they are located with respect to each other. These pictures and the circuit diagrams in Chapter IV should be an aid in servicing or modifying the equipment when the need arises. At present the loop antennas are located in the southwest corner of the hutment. The loops have been set on the base with their planes perpendicular. For true north and south alignment the base is setting in the correct position and a pencil line drawn on the floor outlining the base. This is a very temporary arrangement, and when a permanent place for the loops is selected, they should be aligned and solidly mounted so that the axial direction will not change during normal conditions of operation.

BIBLIOGRAPHY

Bellaschi, P. L. Lightning Currents in Field and Laboratory. American Institute of Electrical Engineers Transactions, (August, 1935).

Code for Protection Against Lightning. Handbook No. 17, Bureau of Standards, Washington, D. C.

Elster and Geitel. Bemerkungen Ueber den Electrichen Vorgang in den Gewitterwolken. Weid. Ann., 1885.

Giacoletto and Stiber. Crossed Loop Direction Finder. Proceedings of the Institute of Radio Engineers, September, 1949.

Glasgow, R. S. Principles of Radio Engineering, First Edition. New York and London: McGraw-Hill Book Co. Inc., 1936.

Hess, P. N. "Installation and Operation of Electronic Sferic Detection Equipment". Unpublished Master's Thesis. Stillwater, Oklahoma: Oklahoma A. and M. College, (1951).

Hess, V. F. The Electrical Conductivity of the Atmosphere and its Causes. New York: D. Van Nostrand Co., (1928).

Holzberlein, T. M. "A Study of Tornado Tracking Equipment." Unpublished Master's Thesis. Stillwater, Oklahoma: Oklahoma A. and M. College, (1951).

Humphreys, W. J. Physics of the Air. New York: McGraw-Hill Book Co. Inc., (1929).

King, Minmo, and Wing. Transmission Lines, Antennas, and Wave Guides. New York: McGraw-Hill Book Co. Inc., 1945.

Leonard, P. Ueber Regen. Meteorological Zeitschr, 1904.

Lewis, W. W. Lightning Investigation on Transmission Lines. American Institute of Electrical Engineers, 1935, Vol. 54.

McEachron, K. B. Lightning and the Protection of Electric Systems. Schenectady, New York: General Electric Co., 1939.

Norinder, Harald. Lightning Currents and Their Variations. Journal of the Franklin Institute, July, 1935, Vol. 20.

Peek, F. W. Lightning. American Institute of Electrical Engineers Transactions, September, 1931, Vol. 50.

Robinson, J. A Method of Direction Finding by Wireless Waves. Radio Review 1, 1920.

Schonland, B. F. J. and Collens, H. Progressive Lightning. Proceedings of the Royal Society, January, 1934, Series A, Vol. 143.

Simpson, G. C. Electricity of Rain and Its Origin in Thunderstorms. Transactions of the Royal Society, 1909, Series A, Vol. 209.

Terman, F. E. Radio Engineering, Third Edition. New York: McGraw-Hill Book Co., Inc., 1947.

Terman, F. E. Radio Engineers Handbook, First Edition. New York: McGraw-Hill Book Co., Inc., 1943.

Wilson, C. T. R. Investigations on Lightning Discharges and on the Electrical Field of Thunderstorms. Transactions of the Royal Society, 1920, Series A, Vol. 221.

THESIS TITLE: DEVELOPMENT AND OPERATION OF A CROSSED LOOP SFERIC DIRECTION FINDER

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