A STUDY OF TORNADO IDENTIFICATION

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By

John Stanley Hutchison

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APPROVED BY:

Herbert L. Jones
Chairman, Thesis Committee

Chas. F. Cameron
Member of the Thesis Committee

A. Naeter
Head of the Department

D. C. McIntosh
Dean of the Graduate School

PREFACE

The work accomplished in this project can be divided into three parts. The first is an introduction of the problem at hand. The second part consists of a summary of the library research covering the vast amount of work now published in the field of atmospherics and lightning phenomena. The third part entails a discussion of the results of this research together with suggestions that may indicate the approach for a more extensive investigation.

A large part of this paper has been devoted to the results of the library research. Though long and tedious, this part of the work is one of the important aspects of the problem. It has been treated as completely as time and library facilities have permitted, and is still by no means complete. However, it is felt that the fundamentals of the subject of atmospherics have been well founded and that with the information contained in this thesis an intelligent study can be made of more recent of the published papers without the necessity of again combing all of the previous literature for the past 30 years. Experience in this work demonstrated that it was impossible to intelligently read the literature of the present without at first having studied the background material covered by the earlier publications.

The possibilities of ultimate success in identifying tornadoes by means of their atmospherics are not unreasonable after study of the theory of atmospheric disturbances. This study has also led to ideas about methods of measurement which have been adopted. Although these new methods and equipment designs have not been put into use at time of the present writing, it is expected that they will be in service very soon.

Expression of appreciation is made for the inspiration and help of Doctor H. L. Jones in carrying out this research. Doctor Clark A. Dunn and the Research and Development Laboratory have given generous assistance, without which the work could not have been carried on. Most sincere thanks are given for their help. The School of Electrical Engineering under the leadership of Professor A. Naeter has been most cooperative during every phase of this work and particular appreciation must be expressed for the high quality oscilloscope which the school made available for these wave-form studies. This report would have been impossible without the most cooperative help of Miss Graves and her library staff. The many suggestions and opinions of Mr. Miller, which were based on his initial work on the subject, have been invaluable. The cooperation and help gained from Dean Weil and his staff at the University of Florida is greatly appreciated. Their experience with the many problems closely allied to this project helped to avoid a multitude of troubles and time delays.

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CHAPTER I

INTRODUCTION

One has only to read the newspapers during a tornado season, of which the spring of 1949 has been typical, to realize the great danger to human life and property incurred by unannounced tornadoes. This weather hazard cannot be prevented but if a warning period were provided the degree of emergency could be alleviated. Some of the newspaper headlines are: "Storms Kill 16 in Arkansas"; "Two Dead as Fierce Wind Storm Sweeps Blaine County Cities"; "80 are Injured in Fierce Blow"; "Tornado Sweeps Across State"; "Tornadoes Hit 23 Towns". The last article declares that 194 families were left homeless and twenty-five people were killed. These facts are given to help emphasize the great need for some type of warning which will allow communities to prepare for the ordeal.

In a recent newspaper column the well-known Roger W. Babson deplores the lack of a warning system for tornadoes.[1] He advocates a method of detection supplemented by some type of standard warning system, for example, a siren alarm of a definite type that will be recognized by all residents. The method of detection has not yet been perfected.

In the hope of solving the problem of tornado prediction and detection this research has been propagated. Mr. Carl Miller initiated a study of possible methods of tornado detection in the autumn of 1947. After considerable research he decided to concentrate on the study of atmospheric peculiarities

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[1] Article in The Daily Oklahoman, (Oklahoma City, Oklahoma), January 23, 1949.

that might be associated with the storm. Equipment was gathered and adapted to the job as clearly outlined in the thesis prepared by Mr. Miller.[2] The study of atmospherics is not complete and therefore wave-form studies have been given further pursuit. Though there may be other approaches to the problem, of tornado identification, this research is restricted to the idea of tornado atmospherics which may be distinguishable from ordinary thunderstorm disturbances.

The School of Electricl Engineering, the Engineering Experiment Station, and Dr. H. L. Jones have been most cooperative and shown great interest in the project. A trip to the University of Florida campus by Dr. Jones and the writer was sponsored by the Oklahoma A. & M. College Engineering Experiment Station. This visit was facilitated to bring this research on atmospherics up to date with the most recent developments. Though the Florida group is interested in atmospherics from the direction finding and ranging aspect, many of our problems are similar to theirs. By conversing with personnel who had been pursuing atmospheric research for many years a greater insight into the problem was gained. Further, having the opportunity to inspect their equipment first hand was invaluable. Many ideas incorporated in the future of this research were those inspired by conference.

The photographic supplies required to obtain data for this research were furnished by the Experiment Station. Mr. Alexander Woods of the Experiment Station, handled the film service and all other technical services connected with photography.

This paper is organized on the plan of presenting pertinent facts and known information about atmospheric electricity, thunderstorms, tornadoes,

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2 Carl W. Miller, "A Proposed Method of Identifying and Tracking Tornadoes," (unpublished Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1948).

lightning, and atmospherics. This has been done in the most satisfactory manner possible with the limited time available. It will become apparent that the written information on atmospheric electricity and its static is far from unified and consists, on the whole, of many separate theories and investigations. However, an effort was made to present that material which appeared to be adaptable to atmospherics originating in tornadoes. The experimental data gathered during activities of this thesis may not be very significant, but the progress achieved by obtaining a better understanding of the problem and making decisions about the methods of attack is of definite value. A study of this report should prepare the reader to go further into the research described above. The many references are used in the footnotes to help locate original work on a particular finding. Some of the references were not reviewed because of lack of availability at the college library, and others because of lack of time to make arrangements for them.

More rapid progress of the research is anticipated after the completion of Mr. Jeske's equipment in June and Mr. Thomason's equipment in August. These equipments are discussed in the chapter on measuring methods.

CHAPTER II

ATMOSPHERIC ELECTRICITY AND THE THUNDERSTORM

Thunderstorms are identified by the thunder and lightning which are associated with them. Through the mechanism of the discharge of atmospheric electricity, lightning together with the accompanying thunder is produced. The discharge is dependent on the phenomenon which generates the atmospheric electricity. If the causes of strong atmospheric electric fields can be clearly understood, a partial understanding of the thunderstorm will be gained. A study of the published work in the realm of atmospheric electricity is the purpose of this chapter.

In common with any field of study where the facts are difficult to ascertain, it is found that many theories of atmospheric electricity exist. The difficulty of the study is further increased in that many of the theories cannot be tried in the laboratory. All of the accepted theories satisfy some part of the physical conditions observed with thunderstorms. This raises the possibility that perhaps the atmospheric electricity associated with thunderclouds is the result of several phenomena contributing to the over-all electric storm. Taking this viewpoint, the more prominent current ideas will be presented.

One of the most popular theories advanced to explain the generation of atmospheric electricity is due to G. C. Simpson.[3] Before discussing Simpson's concept it will be well to review some of the known facts relative to conditions

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[3] G. C. Simpson and F. J. Scrase, "The Distribution of Electricity in Thunderclouds", The Proceedings of the Royal Society of London, CLXI-A, (1937), 309.

that exist during periods in which the weather is fair. It is reported that the electric field in fair weather atmosphere is toward the earth and has a miximum value of about 1 v./cm. This field decreases with heights and becomes negligible at an altitude of 10 to 20 km.[4] It will be recalled that the direction of an electric field is defined as the direction of the force on a positive charge in that field. From this it follows that the earth is negative with respect to the upper atmosphere. This situation is reversed; during a thunderstorm the field between the earth and cloud is in the direction of the cloud. Although the electric field intensity below the cloud is upward, the field within the cloud is downward. In other words, the earth is positive, the underside of the cloud is negative, and the topside of the cloud is positive. The field strength within the cloud is of the order of 120 v./cm. This value is accepted for both thunderclouds and ordinary clouds. It will be recalled that a field strength of 10,000 v./cm. is required to start an arc discharge in damp air. Simpson and Robinson conclude that since there are no large areas where the voltage gradient is sufficient to cause a discharge there must be small areas of high field intensities to start the stroke.[5] The mechanism that accomplishes this phenomenon in a realitively weak field will be discussed later in this paper after the theory has been developed.

Humphreys described Simpson's early work in which a method of producing positive and negative ions by the breaking of distilled water drops was developed.[6]

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[4] J. Frenkel, "Atmospheric Electricity and Lightning", Journal of the Franklin Institute, CCVIIL (April, 1947), 287-307.

[5] G. C. Simpson and G. D. Robinson, "Distribution of Electricity in Thunderclouds", The Proceedings of the Royal Society of London, CLCCVII-A, (February, 1941), 322.

[6] W. J. Humphreys, Physics of the Air, p. 314.

This might be described as the tearing of spray from drops of water by air blasts. The experiments demonstrated that the breaking of water drops is accompanied by the production of both positive and negative ions; and what is really surprising, it developed that three times as many negative ions as positive ions are released, thus leaving the drops charged positively. The spray is made up of the outer layer of the raindrop. This outer layer of the drop seems to be negative while the center is positive. It also has been shown that electrification so produced by a given air blast rapidly increases with the temperature of the ruptured drops. This latter phenomenon would indicate that the amount of lightning should increase with temperature. A strong upward current is one of the outstanding features of a thunderstorm. This current is always evident in the towering turbulent cumulus cloud. The presence of strong updrafts may also be deduced from the fact that hail is often present in a thunderstorm. The formation of hail requires a column of uprushing air of sufficient velocity to support and carry the drops of water into the very low temperature region where the hailstones are formed. As raindrops are carried up into very cold temperatures they form supercooled ice crystals. When these ice crystals arrive at a point in their travel where the air will no longer support them they drop back to the region of moisture. The supercooled crystal accumulates a layer of ice before its temperature rises to just freezing. If it is again caught in a strong updraft the ice pellet repeats the cycle. Repetition of this cycle many times forms a hailstone or appreciable size. The maximum size of the hail is limited by the velocity of the updraft; i. e., when the mass of ice is too great to be carried up it falls to the earth. Very large hailstones have often been observed during violent thunderstorms. During a tornado near South Haven, Kansas, the writer examined a number of hailstones which were approximately three inches in diameter.

When it is remembered that a strong air blast exists in a thunderstorm, it is not unreasonable to assume that the storm area simulates the characteristics of an atmospheric electric generator. Strong ascending air currents tend to rupture the raindrops where coalescence has created large drops of water. This phenomenon will only occur in regions of intense water accumulation. The negative charges released attach themselves to the cloud particles which pass upward with the ascending air currents, and the positively charged raindrops are left behind.[7] Positive charges are concentrated in regions near the base of the cloud where it is possible for the ascending currents to hold large quanitities of water in suspension. The negative electricity is distributed on the cloud particle in the middle and upper portions of the cloud.

Simpson and Scrase describe an exploring device which measures the polarity in the upper atmosphere during the time the apparatus is carried aloft by a balloon.[8] Included in the assembly is equipment which measures the approximate value of the intensity of the electric field. By means of this device, which the experimenters termed an alti-electrograph, many measurements were taken during the formation and progress of thunderstorms. Prior to the invention of the alti-electrograph, Appleton, Watt, and Herd had predicted that a positive charge would exist at the top of a thunder cloud and a negative charge at the bottom.[9] Since these earlier measurements

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[7] G. C. Simpson and F. J. Scrase, Op. cit., p. 348.

[8] Ibid, p. 309.

[9] E. V. Appleton, R. A. Watson Watt, and J. F. Herd, "On the Nature of Atmospherics II and III", The Proceedings of the Royal Society of London, CXI (1926), 615.

were taken from the ground it was not possible for Appleton, Watt, and Herd to determine the distribution of charge in the interior of the thundercloud. By the use of the alti-electrograph Simpson and Scrase made an important discovery. It was found that a small region existed at the base of the thundercloud in which the field intensity was positive and relatively large. Extended investigation of these positive spots disclosed that it was possible for several to exist in the same cloud. These investigations tended to confirm the so-called "breaking-drop" theory invented by Simpson. Regions of concentration of positive electricity are found in the lower parts of the cloud; these regions of positive electricity are closely associated with the active regions of the storm where ascending currents together with heavy rain are most prominent; furthermore, these accumulations of positive charge are found in the part of the cloud where the temperature is above the freezing point.

The "breaking-down" theory accounts for a portion of the negative electricity just above the base of the cloud, and also for the concentrations of positive charge at the base. However, it certainly does not account for all of the negative electricity accumulated in the cloud, nor does it account for the positive electricity to be found in the ice regions of the cloud. It is evident that there are physical processes other than those proposed by Simpson taking place during the separation of positive and negative charges.

A theory advanced by Wilson partially accounts for the existence of positive electricity at the top of a cloud and negative electricity at the bottom of a cloud.[10] In a positive field the upper half of a drop will be negative and the lower half positive. As these polarized drops fall through the ionized air the negative ions are attracted by the positively charged

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[10] Simpson and Scrase, Op. Cit., p. 349.

lower half of the drop, and as a result the drops accumulate a negative charge. It is only natural to suppose that the earth's field will cause a downward drift of the ions. Consequently, it must be postuated that the drops of water must fall at a rate that exceeds the downward drift of the ions; otherwise, there would be no accumulation of charge. It has been demonstrated by several laboratory experiments that drops can accumulate charge in this manner. The observations of Simpson and Scrase have shown quite conclusively that the boundary between the positive electricity in the upper part of the cloud and the negative electricity in the lower part is in every case located in a region of the cloud where the temperature is usually below -10 deg. C. In this part of the cloud raindrops cannot exist. The precipitation in the upper part of a cloud is in the form of crystals, either needles or plates. These crystals tend to lie horizontally and to fall slowly in a series of approximately horizontal motions, first in one direction and then another. These crystals are almost perfect non-conductors and therefore do not become electrically polarized. In case the crystals were conductors, their shape and orientation would not be favorable to the formation of induced charges. It must be noted that the rate of all of the crystals relative to the surrounding air is very small. It is, therefore, evident that the theory proposed by Wilson cannot account for the separation of the charges found in the upper part of the thunderclouds. It has been argued that the presence of hailstones in the low temperature region would help to explain this difficulty. However, since hailstones exist in only a small part of the cloud it cannot be assumed that they could be effective in transferring charge to regions remote to their realm of existence.

In order to produce the electrical effects observed it is therefore apparent that there are two different physical processes taking place in a thunderstorm. One process is confined to the upper parts of the cloud where the temperature is below the freezing point, and the second process occurs in the lower part of the cloud where the temperature is above the freezing point. There is reason to believe that the first process is associated with the presence of ice crystals and the second process with raindrops. The distribution of electricity and air currents as found by Simpson and Scrase by means of the alti-electrograph is shown in Fig. 1. That the charges were arranged as shown in Fig. 1 was verified by the later and more complete work of Simpson and Robinson.[11] Simpson and Robinson attribute the probable cause of the separation of positive and negative electricity in the top cold regions of the cloud to ice crystal collisions in the turbulent air. The crystals are thought to become negatively charged while the surrounding air becomes positive. As the crystals settle through the air the separation of charge is accomplished. A more comprehensive discussion of charge separation in the cold regions will be presented near the end of the chapter.

Still another hypothesis was developed by Frenkel.[12] In many ways the Frenkel concept of the phenomenon is similar to that of Wilson but he has extended the theory to account for the charge distribution found by Simpson and his colleagues.[13] Frenkel's concept postulates that a cloud must be regarded as a disperse system, consisting of small water drops or ice crystals, which are slowly falling through the surrounding air, the latter acting as the dispersive medium.

Through the action of cosmic rays positive and negative ions are present in the atmosphere. These ions are responsible for the conductivity of the

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11 G. C. Simpson and G. D. Robinson, Op. cit., pp. 281-329.

12 J. Frenkel, loc. cit.

13 Cf. ante, p. 7.

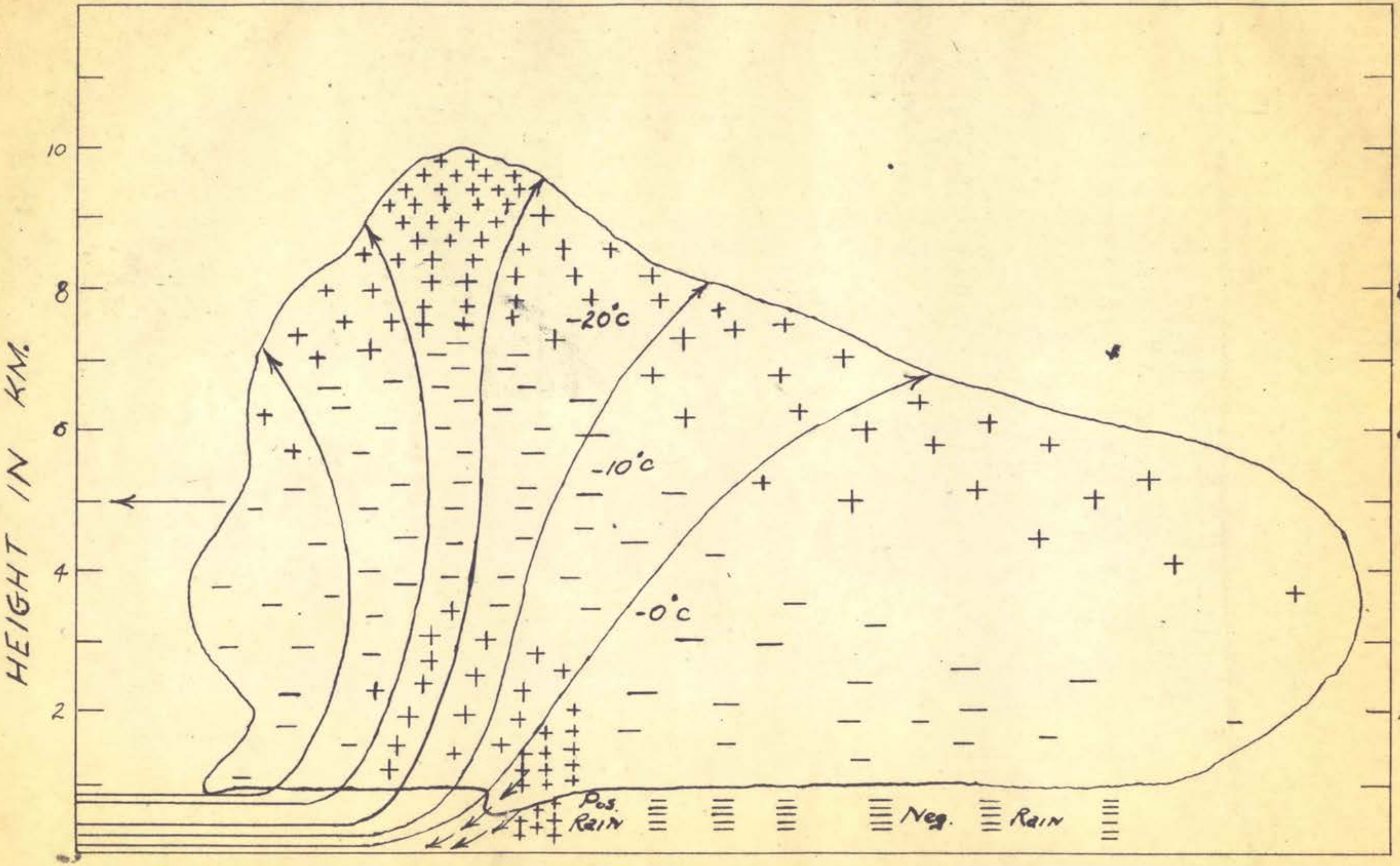

Fig. 1. Generalized diagram showing air currents and distribution of electricity in a typical heat thunderstorm.

air. Near the ground the ions have a concentration of approximately 1,000 per c.c. The ion concentration is much greater at higher altitudes because more and higher energy cosmic rays exist in this region. Consequently, the conductivity of the air at heights of 10 to 12 km. is about 30 times greater than at sea level. The maximum ionization is believed to occur at an altitude of about 18 km. In the presence of positive and negative ions these cloud particles take on a charge of either sign. Frenkel postulates that cloud particles usually attract negative ions more readily than those of the opposite sign. As a result each fog particle takes on a negative charge.

It has been established experimentally that drops of water become negatively charged in an atmosphere of ionized air. This occurs only in the case of small drops. For larger water particles, falling in the form of raindrops or snowflakes, the situation becomes complicated by the polarization resulting from the presence of the electric field of the earth. If the electric field is vertical and downward the top of the drop will be negative and the bottom positive. As would be expected the negatively charged hemisphere attracts positive ions and the positively charged hemisphere attracts negative ions. It would seem that the net charge would be zero but such is not the case. It has been found by experiment that the contribution of charge to the water drop by the positive ions is greater than that of the negative ions. From this it can be assumed that the number of available positive ions is greater than the number of negative ions. This can be accounted for if it is remembered that the small water particles attract and hold a large number of the negative ions. Frenkel states that the ratio of positive ions to negative ions is approximately 1.3.

From the preceing discussion it is evident that the charge on the large drops of water will be positive in an electric field where many cloud particles are dispersed, the positive charge becoming larger as the strength of the electric field increases. It has been determined that if the radius of the drop is equal to or greater than 0.02 cm., the drop begins to take on a positive charge in an electric field of 1 v./cm. It is in this way that the Frenkel theory accounts for the fact that large raindrops arrive at the earth's surface with a positive charge, while the smaller drops arrive with a negative charge.

If the negatively charged cloud particles are falling through the air in which they are partially suspended, the positive charges will be left behind. As a result the upper region of the cloud becomes positive and the lower region negative. It is the relative motion of the cloud particles with respect to the air that is important and it makes no difference whether the air is moving upwards or the cloud particles downwards. While the value of the relative velocity is not important, it must be observed that as the value of the relative velocity is decreased, a longer time is required for charge separation. In the foregoing discussion no consideration has been given to the ionic currents which tend to discharge the established field. It must be observed that the necessary conditions for the establishment of an electric field between the top and bottom of the cloud is that the charging process must be greater than the rate of ionic discharge. The rate of ionic discharge will increase as the established field becomes greater, and equilibrium will be attained when the rates of charge and discharge become equal. Frenkel notes that his theory verifies the findings of Simpson and Robinson in that the average field strength inside an ordinary cloud is the same as that found inside a thundercloud. The value of the field intensity for both types of cloud is approximately 120 v./cm.

It has been observed that the earth is negative with respect to the atmosphere when no clouds are present, the field intensity being about 1 v./cm. If a cloud is represented as a spherical dipole the directions of the field intensities between the cloud and earth will be approximately similar to those shown in Fig. 2. Underneath the cloud the field is directed upward, while at some distance away from under the cloud the field is directed downward. The downward field is found to exist during fair weather conditions while the upward field is found during cloudy conditions. The value of these field strengths are of the order of 1 v./cm. and 100 v./cm. respectively. If the negative charge on the earth is to remain constant the value of the ionic currents charging and discharging the earth must be equal. Consequently, it follows that approximately one one-hundredth of the earth's surface must be clouded over at any given time. Frenkel states that this condition has been found to exist.

So far the part played by lightning discharges has not entered into this discussion. C. T. R. Wilson, the British scientist, believed that all discharge current from the earth occurred in the form of lightning discharges. According to a study made by Wilson there are about 2,000 thunderstorms simultaneously in progress at various parts of the earth. He estimates that an average of 100 lightning discharges strike the earth each second. Each of these discharges carry some 20 to 30 coulombs of negative electricity to the surface of the earth. This will result in a current of about 1500 amperes flowing from the cloud to the ground. Other estimates set this value at about 1700 amperes. If these estimates are to be regarded as representing actual conditions it would necessarily follow that practically all of the negative charge transferred from cloud to ground would necessarily be in the form of lightning discharge. At this point Frenkel declares that the estimates made by Wilson and others are very crude, and that other and better calculations attribute most of the

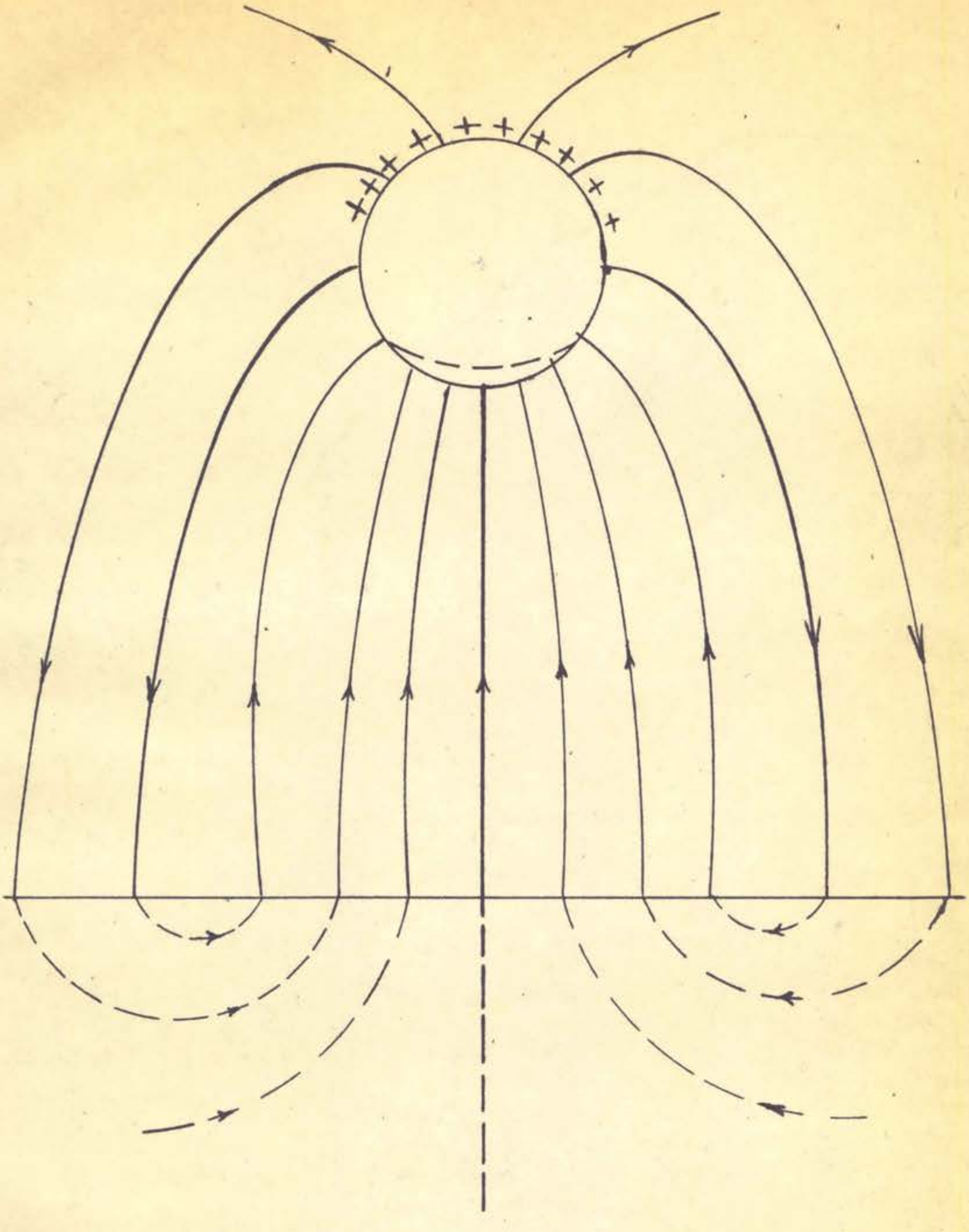

Fig. 2. Spherical cloud and its field.

current flow to corona discharges and not to lightning discharges.[14] The Russian scientist admits, however, that this concept may require additional study.

It is now in order to discuss the lightning discharge mechanism described by Frenkel. Frenkel demonstrates the process by means of which a discharge to earth may be accomplished when a relatively weak field of 100 v./cm. exists between the cloud and ground. It must be remembered that the ionizing stress of air at normal pressures is around 30,000 v./cm. When needle points are attached to the positive and negative terminals of an electrostatic machine the absence of the arc type discharge is to be noted. The extremely high potential which exists at the end of each needle point results in the ionization of the layer of air adjacent to the metallic surface. The high potential condition is transferred from the needle point to the adjacent layers of air between the needle points, and from these layers to the next adjacent layers in a continuous process. The progress of this ionization process is extremely rapid and there results a continuous thin line of ionized air particles joining the needle points. It follows that the ionized path travels like a conductor with a sharp needle point which ionizes as it moves along the path. Lightning rods are designed on the basis of this theory. It must be noted that lightning strokes to the rod will sometimes occur. However, if the lightning rod is well-grounded, the lightning stroke or ionizing current to the rod may deplete the charge of the cloud to such an extent that lightning strokes to surrounding objects may be avoided.

Once an ionized path has been established between cloud and ground it is possible for a lightning stroke to take place over this path. The initial path is formed to sharp objects on the ground surface such as buildings, trees,

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[14] J. Frenkel, Op. cit., p. 303.

and sharp rocky points. Frenkel also attempted to explain the nature of the lightning strokes which take place between clouds. He remarks the coalescence of drops of water as they fall from the higher regions of the thundercloud each drop grows in size by picking up the negatively charged water droplets, and Frenkel assumes that this accumulation of negative charge results in a high strength negative field in the neighborhood of the water drop.[15] He further assumes that this negative field becomes sufficiently high to initiate a glow discharge and the resultant return stroke. If the contentions of Frenkel were correct it would be necessary to discard the "breaking-drop" theory of Simpson, in which case it would be necessary to invent some other mechanism which would explain the existence of the small positively charged region known to exist at the base of the cloud.[16]

Consideration must now be given to the growing raindrop as an agent for initiating the ionized path. It will be recalled that although all clouds have the same average internal field strength, only those at relatively great altitudes are sources of visible lightning. Since it has been developed that falling raindrops within the cloud are necessary for the formation of high field intensities, it follows that rain should always accompany lightning. However, in some cases the rain may evaporate before reaching the earth, particularly when the clouds are very high. This accounts for the rare condition in which lightning is not accompanied by rain.

Workman and Reynolds have quite recently performed an interesting

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15 Cf. ante, p. 12.

16 Cf. ante, p. 5.

experiment dealing with water drops and ice crystals.[17] The drops of water were sprayed on the ice crystals and some of the impinging drops froze to the crystals. An electric potential was found to exist between the impinging water drops and the ice crystals. In order to obtain appreciable results it was necessary to have water which was contaminated by small traces of impurities. In fact, the experimenters compiled data for various concentrations of contaminants. The opinion was expressed that thunderstorm water was also contaminated, though this might be of a very complex nature. It was agreed, however, that the degree of contamination of thunderstorm water should be further investigated. Potential differences of from 70 to 185 v. between the unfrozen solution and the growing ice crystals were observed. The transfer of electrical charges in the amounts of approximately 400,000 c.g.s. units per c.c. of ice frozen was also observed.

A cumulus cloud which has changed into a thundercloud is seen to consist of a number of vertical convection cells. According to the concept of Workman and Reynolds these cells constitute the electrical generating units.[18] The theories of Simpson, Wilson, and with reservations, of Frenkel, all agree on this item. Workman and Reynolds conceed that processes other than the one advanced by them also contribute to cloud generation of electricity in the cloud.

If it is assumed that there is a particular physical process or set of physical processes involved in the production of electricity in thunderstorms, it is also reasonable to assume that the location of these processes may be

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17 E. J. Workman and S. E. Reynolds, "Thunderstorm Electricity", Research and Development Division, New Mexico School of Mines, Final Report Signal Corps Research, Contract No. W-36-039 sc-32226 File No. 15842-PH-46-91 (SCEL), (1948).

18 Ibid, p. 4.

defined somewhat by the terminal points between which the lightning strokes characteristically occur. Thus one considers the characteristic position of a dipole which is frequently dissipated by electric discharges as being a significant feature of a thunderstorm.

An extensive investigation was carried out at the earth's surface. Eight generating voltmeters of the recording type were used to measure the potential gradient under storm conditions. The results of this work indicated that lightning strokes have charge magnitudes of between 10 and 190 coulombs. These strokes transferred negative electricity to the ground in cloud to ground discharges. Cloud to cloud discharges were also observed. It was found that a typical thunderstorm has a negative charge center about 1.5 miles above the base of the cloud and near to the vertical cell. A positive charge center was found to exist about 0.5 miles above the negative charge center. Both positive and negative charge centers were found to exist above the calculated zero isotherm. Cloud to ground strokes were found to be more frequent in the early stages of the development of an active thunderstorm. As the thundercloud developed the number of ground strokes decreased while the number of cloud to cloud strokes increased.

Workman and Reynolds summed up their work with the following conclusions.[19]

1. The thunderstorm cell is a vertical or nearly vertical development involving relatively great height.
2. The cloud base must extend some distance below the zero isotherm.
3. It's top must extend to a sufficient height to allow (initially, at least) for the formation of ice crystals by direct sublimation (-20 deg. to -40 deg. C.)
4. Electric charge separation is a phenomena of precipitation and convection and does not take place until precipitation processes are well under way.
5. The temperature elevation in which the charge separation occurs is in the lower portion of the cloud, from 0 deg. C. to -15 deg. C., and more likely around -5 deg. to -10 deg. C.

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[19] Ibid, p. 7.

6. The negative charge center constitutes the lower end of a dipole with the positive charge center above the negative center.

7. In the earliest stages the positive center appears to be realtively close to the negative center and as the storm progresses it moves upward and, in many cases, outward from the original position, whereas the negative center appears to be fixed in the precipitation zone of the thunderstorm cell and at a fairly definite altitude.

8. The positive center has the appearnce of occupying a diffuse area of the cloud, as if it were blown upward by convection currents.

9. An important feature of the electrical storm is the fact that although the negative charge center appears to be located in the precipitation zone of the cloud, it does not, except perhaps in late stages of the storm, extend downward to positions below the cloud base.

10. Precipitation as it occurs in thunderstorms involves the ice phase of water in the form of hail.

The interesting description of the process by which the freezing water might generate the atmospheric electricity is given by the authors. High up in the top of the cloud the moisture sublimes to ice crystals. As these crystals fall in the gravitational field they eventually arrive in a region of supercooled rain drops. As the drops splash against the ice, some of the resulting spray is frozen to the crystals and the rest are blown upwards by the ascending air currents. This results in the formation of positive water droplets and negative ice crystals. The ice in the meantime may have settled into a region of higher temperatures where freezing no longer takes place. Impinging raindrops will then only assume a negative charge from contact with the negative hail. There is no charge produced unless actual freezing occurs. This theory accounts for the existence of a positive charge at the top of the cloud and a negative charge at the bottom. Again, however, no explanation is given for the small positive regions found by Simpson.

CHAPTER III

THE THUNDERSTORM

The various theories invented to account for the separation of the electrical charges in clouds agree on one important characteristic, that is, the existence of a turbulent column of uprushing air in the inner portion of the cloud. Practically this rising column of air has been detected by experiments performed with kites, by airplane pilots, and by soundings taken with balloons. In order to better understand the cause for the rising columns of air, Humphreys examines several possible theories and finally advances a theory which appears to be reasonable.[20] If, for a reason to be discussed, a body of moist air is forced upward, adiabatic expansion will take place with consequent cooling. As the air cools the saturation point will be reached and dew or fog will begin to form. At this stage of the cooling process the rate of cooling will be decreased because of the latent heat absorbed by the water as it condenses. The temperature of the ascending column of air will be higher than that of the surrounding air through which it is moving. This process becomes more and more pronounced as the process continues, and as long as it persists there will be a gain in velocity. When the density of the rising air becomes equal to or greater than that of the surrounding air, acceleration will cease and the velocity will begin to decrease. As the velocity of the rising column of air increases the moisture will be left behind and the rising air will begin to cool at a very rapid rate. There

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20 W. J. Humphreys, Op. cit., p. 318.

will be a point on the column at which the temperature of the rising air will equal that of the surrounding air. Above this point of equilibrium the rising air will become supercooled and will tend to fall back. At the beginning of the process the inrushing air will come from the bottom of the cloud, but as the condensed moisture falls in the form of rain it will cool the air at the bottom of the cloud so that it will no longer possess an upward velocity. The supply of air for the rising column will then come from the air in the front part of the cloud as it moves along. It will be noted that the process is self-generating after the initial upsurge of warm moist air. If this initial upsurge does not occur the process will never get underway. For this reason many clouds with a bottom layer of warm moist air do not become cumulus thunderclouds.

In order to account for the existence of the initial upsurge of warm moist air Humphreys considers a number of possibilities.[21]

> 1. Strong surface heating, especially in regions of light winds; a frequent occurrence. The condition that the winds be light is essential to it simply because winds, by thoroughly mixing the air, prevent the formation of isolated rising columns, the progenitors of this particular type of storm.
>
> 2. The overruning of one layer of air by another at a temperature sufficiently lower to induce convection. This apparently is the cause of some thunderstorms, especially in the warm sector, or interfrontal region of a cyclone.
>
> 3. The underrunning and consequent uplift of a saturated layer of air by a denser layer; a frequent occurrence along a "squall line" or "cold front" and therefore the cause of many thunderstorms.
>
> Here the underrunning air lifts both the saturated layer and the superincumbent unsaturated layer, and thereby forces each to cool adiabatically. But as both layers are lifted equally, while, because of the latent heat of condensation, the saturated layer cools much slower than the dry, it follows that a sufficient mechanical lift of a saturated layer of air would establish, between it and the nonsaturated layer above, a superadiabatic temperature gradient, and, thereby, produce local convection, cumulus clouds, and, often, a thunderstorm. Indeed, condensation begun in conditionally unstable air, that is, air whose lapse rate

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21 W. J. Humphreys, Op. cit., p. 322.

is between the adiabatic lapse rates of dry and saturated air, respectively, often so grows as to produce a large cumulus cloud and a thunderstorm.

4. The ascent of warm, humid air up a sloping obstacle-a mountain or an intercepting mass of cool air, such as characterizes the "warm front".

From the foregoing discussion the conditions that initiate a thunderstorm can be determined. An upward moving column of warm moist air is the first necessity. This condition is most usual on a hot humid afternoon. Most thunderstorms occur in the summer months because of the higher temperatures existing during that season. One exception must be noted. In the central portion of the United States thunderstorms are most frequent at night. Statistics have shown that wet years are warm anddry years relatively colder. The weather will either be wet and warm, or dry and cool. Therefore, one would expect more tunderstorms in years of great rainfall than in years of little rainfall.

Thunderstorms may be grouped according to the conditions which cause them. These groups are heat, cyclonic or warm front, and squall or cold front thunderstorms. Heat thunderstorms are due to surface heating. Cyclonic or warm front thunderstorms are usually the result of warm air flowing up over a mass of heavy cold air. The squall or cold front is caused by cold air over running warm moist air. It will be shown later that this cold front is the condition to most likely form a tornado which makes the latter a special case of the thunderstorm.

It is now possible to present a more complete description of the actual air currents of a typical thundercloud. By the methods mentioned in the preceding discussion the formation of cumulus clouds is initiated. To replace the rising air, more air enters the column from all sides and starts to move upwards. Normally the entire cloud will be moving along at a velocity comparable to the velocity of wind at that altitude. If the wind velocity is appreciable most of the air supply will be from under the front side of the cloud. As previously mentioned there is considerable precipitation at points located higher in the cloud, and as this rain falls towards the rear of the cloud it cools the air by evaporation, conduction, and convection. The density of the air increases as it cools and falls with an appreciable velocity, at the same time continuing to move forward with the velocity of the storm. As a result there exists a column of air moving upwards and towards the rear of the cloud together with a column of moving air. This latter column of air is now also traveling forward with the velocity of the storm. It might be assumed that this mechanism constitutes a circulation of air, but such is not the case. The motivation for each column is independent and unique and there results a simple exchange of air between upper and lower levels. A change in the direction of wind occurs. During intervals when a change in the direction of the wind occurs the air movements become very gusty, and not in any definite direction. Once the process of thundercloud formation has started, it will continue and becomes self-sustaining for as long a time as the storm moves with an appreciable velocity.

An item of human and scientific interest is the so-called "Rain Gush". Everyone, at some time or other, has noticed that a clap of thunder will seem to come just ahead of a gush of rain. Because of this sequence it is generally thought that the lightning stroke initiates the downpour of rain. From the foregoing analysis it developed that the opposite is true. If a sudden downpour of rain occurs in the cloud a greater concentration of atmospheric electricity will be generated and this immediately results in a lightning discharge. When it is remembered that the rain falls with a relatively small velocity it becomes evident that the downpour will arrive after the thunder and lightning. Hail is commonly associated with thunderstorms. Under proper conditions the strong updraft will suspend the hailstones in vertical oscillation until the stones grow to an appreciable size.[22]

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22 *Cf. ante*, p. 6

CHAPTER IV

THE TORNADO, A TYPE OF THUNDERSTORM

Humphreys defines the tornado as, "a slightly funnel-shaped, hollow, circular column of upward spiraling winds of destructive velocity". He also states that "it is the most violent, least extensive, and the most sharply defined of all storms".[23] The destruction of life and property which one of these storms can perpetuate has already been mentioned. It has also been noted that the tornado is a special form of thunderstorm.[24] Knowledge of a number of the outstanding characteristics of tornadoes has been acquired by experience. It has been found that tornadoes exist most commonly in the southeastern and central portions of the United States. In fact, tornadoes do not occur to any appreciable extent in any region outside of the United States. Tornadoes have been reported in Southern Australia, but these observations have been challenged by meteorologists. It is, therefore, apparent that any tornado alarm system that may be developed will find its greatest application in the United States. Other facts relative to tornadoes can best be presented in an itemized form.[25]

Meterological Location--- Southeastern section, or, more exactly, east of the wind-shift line, of a cyclone, of moderate to decided intensity.

Kind of Cyclone -- The trough or V shaped, the kind productive of secondary cyclones, is very favorable, especially when the V protrusion

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23 W. J. Humphreys, Op. cit., p. 218.

24 Cf. ante, p. 23.

25 W. J. Humphreys, Op. cit., p. 219.

points southward or, more particulary, southwestward. However, tornadoes occur also when this protrusion of the isobars is not conspicuous, if, indeed, present at all, at the surface of the earth.

Other Pressure Distribution -- A moderate anticyclone to the rear, that is, west or northwest (southwest in the southern hemisphere) of the cyclone, appears to be an invariable condition; but even if this pressure distribution is essential, as we believe it is, to the genesis of the tornado there is no proof of it from statistical evidence alone, since normally the extratropical cyclone has an anticyclone to its rear.

Surface Pressure Gradient in Region of Tornado -- Usually moderate to steep in comparison with the average cyclone.

Horizontal Temperature Gradient -- Usually steep along a portion of the border between cyclone and anticyclone.

Previous Wind -- Moderate to fresh southerly often southwest, in the northern hemisphere, similarly in the southern.

Following Wind -- Moderate to fresh northerly, often northwest, in the northern hemisphere, similarly in the southern.

Following Temperature -- Distinctly lower than just before the storm.

Previous Humidity -- Excessive--making the air, at its high temperature, sultry and oppressive, from hours to even days before.

Clouds---Heavy cumulonimbus, from which a funnel-shaped cloud depends. (Cumulonimbus cloud is a cumulous from which heavy rain is falling.) Sometimes this cumulus is isolated and very towering, but, when not isolated, often preceded briefly to an hour or longer by mammatocumuli. (Mammatocumuli clouds are cumulus clouds in reverse, i.e., low pockets in the cloud form because of localized downdrafts caused by snow and ice that may have drifted in from an adjacent cloud.)

Precipitation -- Rain and usually, hail 10 to 30 minutes before; light precipitation at instant of storm (funnel cloud often clearly seen and occasionally photographed); deluge of rain, mixed at times with small hail, shortly after.

Lightning -- Nearly, or quite, invariably lightning accompanies the tornado, but seldom, if at all, occurs in the funnel cloud.

Sounds -- There always is a loud rumbling or roaring noise while the whirling, pendent cloud is in touch with, or even closely approaches the earth.

Direction of Tornado Winds -- Spirally upward around a traveling axis, and in the same sense as the accompanying cyclone-counterclockwise in the northern hemisphere.

Horizonal Velocity of the Wind in Tornado -- Unmeasured, but destructively great.

Vertical Velocity of Wind in Tornado -- Also unmeasured, but sufficient to carry up pieces of lumber and other objects of considerable weight-say 100 to 200 miles per hour.

Location of Initial and Sustained Whirl -- Above, probably close above, the general cloud base.

Velocity of Storm Travel -- Usually 25 to 40 miles per hour.

Length of Path -- Anything up to possibly 300 miles, usually 20 to 40 miles.

Direction of Travel -- Roughly, parallel to travel of the center of the general, or cyclonic storm, hence usually northeastward in the northern hemisphere, southeastward in the southern.

Width of Storm -- Anything from 40 to 50 feet up to rarely, a mile or even more, but averaging around 1000 feet. Many are only 500 to 600 feet across and others, as stated, even much less.

Number -- Usually several, often in groups, in connection with the same low-pressure system, and on the same day.

Time of Year -- Mainly spring, and early to midsummer, but occasionally also at other seasons.

Time of Day -- Usually midafternoon, or 3 to 5 p.m.

It should be borne in mind that the above observations are not infallible, but do contain some element of truth and are thus worthy of note. Because of the limited area of operation and the speed of travel of a tornado the difficulties in obtaining accurate data are many. It was stated that the location of the origin of the whirl together with its region of generation is near or just above the cloud base. The mechanism of the tornado generation must now be considered. Tornado action is believed to begin with an unstable condition such as exists in mammatocumuli cloud formations. Again, a reaction between cyclone and anticyclone along the wind shift line may give rise to the swirl. In the former case, we have the condition of a cold front that passes over a layer of warm moist air. This causes instability of sufficient magnitude to cause a sudden localized vertical convection. If the moisture in this air condenses, the action is self-sustaining and the air may rise to a great height and be accompanied by lightning and hail. If, after convection has started, the air drawn into the convection stream from different directions retains a part of its original velocity, a torque is created that will produce a whirling motion. By the law of the conservation of momentum, it follows that when the moving air is drawn in toward the center of motion there will result an increase in velocity. The product of the moment of inertia and angular velocity is a constant, and since the moment of inertia is proportional to the second power of the radius, it follows that the angular velocity will increase inversely to the second power of the radius. Again, the linear velocity is directly proportional to the radius and there results also an increase in linear velocity which is inversely proportional to the radius. The air pressure will decrease as the velocity of the air increases. Tremendous velocities will be developed at the center of the swirl, and centripetal force will push still more air particles upward and outward. As a result a nearly perfect vacuum will exist at the center of the whirl. The funnel thus developed is open at the top and bottom. The original air at the center was expelled from the top and as the air drawn from below is whirled about until it arrives at the top. This action results in the formation of a pressure cap at the top of the centrifuge. This pressure cap not only prevents air from entering into the funnel from the top but it also prevents the whirling air inside the funnel from escaping from the top. As a result a pressure is formed in a downward direction which forces the entire whirling mass towards the ground. As more and more air is taken in from the bottom, the tornado burrows deeper and deeper until it reaches the earth. There the bottom is sealed against the earth's surface. Unless the whirl is very violent and possessed of unusual energy it will spend itself before it reaches the earth.

The reaction along the wind shift line of a cold front will result in a torque action which may cause violent convection currents that initiate the whirl that forms into a tornado. Tornadoes always rotate counterclockwise in the northern hemisphere and clockwise in the southern hemisphere. This may be attributed to the fact that air nearest the equator necessarily travels slower than the air towards the poles. This might account for the difference in the original velocities required for the formation of a swirl. Small whirlwinds on the ground are caused by wind flowing toward a convection current, but which miss the center and consequently may whirl in either direction.

One of the important points developed in the preceding concerns the very large convection current which travels upwards through the center of the tornado. This convection current is very similar to a vertical chimney to be found in the cumulus thundercloud. For this reason the tornado may be considered as a special type of thundercloud.

The writer personally witnessed a tornado during the spring of 1935 near South Haven, Kansas.[26] The damage done by the wind and hail at a distance of three miles from the funnel was quite extensive. When the funnel was about 4 miles away it appeared to be a vertical, dark wall about one-half mile in width which extended down to the earth's surface. The afternoon had been very warm and balmy and it was noticed that there was no wind at the time of the approach of the tornado. After the storm had passed and it was safe to leave the storm cave, it was noticed that the ambient temperature was very low and uncomfortable. This was something of a contrast to the relatively high temperature which existed prior to the storm. These personal observations are similar to the descriptions of tornadoes collected by Humphreys as outlined.

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26 <u>Cf.</u> <u>ante</u>, p. 6.

CHAPTER V

LIGHTNING AND THE NATURE OF ATMOSPHERICS

Atmospherics may be defined as electromagnetic disturbances produced by atmospheric conditions.[27] In the United States the term "static" has come to be used quite generally for atmospherics. However, the short term "spherics" is more commonly employed by the investigators and research groups.

Lightning is an electric discharge occurring in the atmosphere, one terminal of which is a cloud.[28] From this definition, which has been accepted by the American Standards Association, it becomes apparent that lightning may exist even when there is no visible discharge.

A great deal of work has been done in the field of atmospherics. Early work was performed with electrometers and string galvanometers for indicating devices. Later the cathode-ray oscilloscope appeared as an additional aid by means of which progress in the field was accelerated. The cathode-ray tube and the associated electronic circuits have undergone much evolution since they were first used, and measurements made in 1920 appear to be very crude when compared to recent observations. Measurements taken with the older and now obsolete equipment are very difficult to evaluate. This adds to the difficulty encountered in making a survey of a field that is so inherently controversial. Some of the fundamental concepts on the subject of atmospherics occur only in the early literature and are not to be found in text books. These concepts are used, but not explained, in the papers that followed later.

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27 American Standard Definitions of Electrical Terms, p. 206.

28 Ibid, p. 95.

Consequently, in order to read the modern literature, it is necessary to make a survey of a portion of the earlier work on the subject. For example, a series of articles "On the Nature of Atmospherics", has appeared in six different articles in The Proceedings of the Royal Society of London, Series A. The first article was published in 1923 and the last in 1939. Each article in this series is based on the concepts established in the first article. The research that led to the series of articles just mentioned was sponsored by the Radio Research Board of the Department of Scientific and Industrial Research of Great Britain. Without specifically referring to the original work to be found in the first three articles[29,30] the findings and observations are summed up by the introduction to the fourth article of the series.[31]

> The modern study of the rapid changes of the earth's electric field associated with lightning flashes was initiated by C. T. R. Wilson in 1916.[32] Wilson made observations on the net changes of the earth's field due to the destruction of near-by thundercloud moments by lightning flashes and, since interest was centered solely in the magnitude of the initial and final values of the field, a relatively sluggish electrical indicator (capillary electrometer) was found most convenient. In observations of essentially the same character, Appleton, Watt, and Herd, using a string electrometer as well as a capillary electrometer, made measurements at greater distances from the discharge channel.[33] The

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29 R. A. Watson Watt and E. V. Appleton, "On the Nature of Atmospherics I", The Proceedings of the Royal Society of London, CIII-A, (April, 1923), 84-102.

30 E. V. Appleton, R. A. Watson Watt, and J. F. Herd, "On the Nature of Atmospherics II and III", The Proceedings of the Royal Society of London, CXI-A, (1926), 615.

31 E. V. Appleton and F. W. Chapman, "Atmospherics IV", The Proceedings of the Royal Society of London, CLVIII-A, (1937).

32 C. T. R. Wilson, "n.n.", The Proceedings of the Royal Society of London, VIIIC-A, (1916), 555.

33 E. V. Appleton, R. A. Watson Watt, and J. F. Herd, loc. cit.

work of Wilson, at distances usually within the region of audible thunder, had shown that the net changes of the earth's field associated with lightning flashes were more frequently positive than negative in sign. On the other hand, Appleton, Watt, and Herd found the opposite preponderance, and thus led them to conclude that a thundercloud is frequently, if not always, bipolar and further, that in order to account for the signs of the field changes it must be assumed that a very frequently occurring type of bipolar thundercloud is one with the positive charge uppermost. These conclusions were later confirmed by Schonland and Craib in observations made in South African thunderstorms.[34]

The measurements made by Appleton, Watt, and Herd on disturbances of the earth's electric field also included observations on the wave-form of those naturally occurring electric waves known to radio-engineers as atmospherics. In this series of observations the potential variations developed across a condenser or resistance included in a damped wireless antenna were examined visually by means of a sensitive cathode-ray oscillograph. The results of a statictical analysis of a large number of individual drawings of wave-forms showed the type of atmospheric observed to be a relatively long aperiodic or quasi-periodic electrical disturbance of duration 2 to 3 milliseconds (msec) and intensity 0.1 volt per meter. High-frequency ripples on the main gross structure of quasi-frequencies up to 10 kilocycles per second were, however, noted and the interferent effects of atmospherics were attributed to such high-frequency components rather than to the effect of the relatively slow main disturbance.

Since there is no lack of evidence that we must look to thunderstorms, up to very considerable distances, as important sources of atmospherics, it appeared to us to be of interest to attempt to link up the observations of Wilson and others on the electrostatic field changes due to the destruction of thundercloud moments with the radiation field changes of atmospherics as studied by Appleton, Watt, and Herd; to study, in fact, the evolution of the atmospheric wave-form from the original disturbance. Our observations have thus been confined to those made within about 200-300 km. from the discharge channel.

In repeating observations of the same type as those made by Appleton, Watt, and Herd, an attempt has been made to remove certain weaknesses in the technique which have been the subject of criticism. For example, the visual recording of the earlier series of observations has been replaced by photography of the transient disturbance as delineated on the cathode-ray screen. Moreover, by using the combination of a Wilson sphere as the exposed conductor connected to the input circuit of an electrometer triode as the essential device by means of which the earth's electric field changes were recorded, it has been possible to vary the time constant of this circuit, and to satisfy ourselves that it exercised no deciding factor in the determination of the observed transient. Now it has been maintained by Lejay that the earlier visual observation of atmospheric wave forms were vitiated by the fact that the aerial system used had a time constant of the order of 2×10^{-2} seconds, and that it was this

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34 Schonland and Craib, "n.n.", The Proceedings of the Royal Society of London, CXIV-A, (1927), 229.

instrument quantity which determined the observed durations and not the atmospheric which was the cause of the changes of potential in the aerial system. The arguments of Lejay we consider to be invalid for two reasons. In the first case he has confused the influence of a net change of field with the influence of a radiation field change. A net change of field would, it is true, cause a disturbance with a duration determined by the aerial time constant, but such disturbances were, as stated in the earlier paper readily recognizable by their characteristic and realitively long duration, and were easily distinguished from the shorter atmospherics of distant origin which took place in an interval usually less than one-tenth of the time constant. Also, secondly, we have, in the present series, not been limited in our control of the aerial time constant and by varying it, have satisfied ourselves that it exercises no recognizable influence on the delineation of wave forms of the type and duration noted in earlier observation.

At the same time, the present series of observations in which cathode-ray photography is employed, shows that the earlier observations by visual methods gave a limited and somewhat inadequate conception of the high-frequency components of atmospherics and that, in the visual series the observer watching the oscillograph screen was liable to note the relatively large smooth radiation field and omit the record the short higher frequency component which we now find always accompanies it. Our conception of atmospheric wave-forms, especially as regards their interferent properties, is thus made much more satisfactory.

In the present series of observations the attempt has been to supplement the rate of change of field (i.e., on dE/dt), where t is the time). In this way the study of the high-frequency components has been very much facilitated. Also, by confining our attention in a section of the work to atmospherics of known thunderstorm origin it has been possible to follow the somewhat remarkable sequence of alterations of wave-form with distance.

This alteration of wave-form is found to be partly such as might be expected from the simple laws of electrodynamics, the ratio of the radiation field to the electrostatic field increasing with distance. But there is also found marked evidence that the propagation of the atmospheric waves is subject to a dispersive influence which causes the high frequency components to travel with a higher group velocity than the low-frequency components. Quite apart from the question of the nature and origin of atmospherics, observations on the net change of field due to near-by lightning flashes especially if the rapid changes can be followed, may be expected to give us information concerning the electrical nature of a lightning discharge since, at short distances, the variation of the electric field is proportional to the variation of the thundercloud moment during the flash.

There are two items in the preceding discussion that should be clarified for the reader. The authors refer to the concept of a bipolar cloud the top of which is positive, and bottom negative. This fact has been verified by balloon soundings.[35] The term "cloud moment" was defined in an earlier paper

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[35] *Cf.* *ante*, p. 7.

as the value of the cloud charge multiplied by twice it's height above the earth.[36]

In the study of atmospherics careful attention must be given to methods of reception. Particular attention must be given to the subject of antennas. The investigator must know the kind of signal which may be expected, and the specific conditions which must be met to obtain certain results. Appleton and Chapman discuss the antenna and signal voltage arrangements that permit of both E and dE/dt where the symbol E represents electric intensity.[37] They used a Wilson sphere for the antenna; however, they might have employed any other type of antenna in which the voltage generated in the antenna is a function of the field intensity with respect to time. Examination of the circuits shown in Fig. 3 demonstrates that the time constant of the circuit is too small to distort the voltage which is generated in the antenna. This voltage appears in undistorted form across the capacity C_o. The capacity C_s is effectively shorted out by the resistance R. The equivalent circuit of the assembly is shown in Fig. 3b. The effective height of the antenna is represented by h and the electric intensity, a function of t, is represented by E. The product of E and h is equal to the generated voltage. The effective height, h, is defined as the antenna voltage divided by the electric intensity. If a current i is flowing in the circuit of Fig. 3 the following equation may be written,

$$V = iR = C_o \times \frac{d(hE)}{dt} \times R$$

and therefore,

$$\frac{dE}{dt} = \frac{V}{C_o h R}$$

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36 Cf. post, p. 49

37 E. V. Appleton and F. W. Chapman, Op. cit., p. 4.

From these relationships it is seen that the voltage obtained across the resister R is proportional to the derivative of the electric intensity with respect to time. This voltage may be fed directly to the amplifiers. This type of signal was found to be very useful for the study of high frequency disturbances. Measurements of the electric intensity are of major importance in the field of atmospherics. Consequently, Appleton and Chapman developed the circuit shown in Fig. 4a. The resistance R is small and therefore the voltage across the capacity C_1 is the same as the voltage across C_0 at all frequencies encountered.

If Kirchhoff's voltage law is applied to the loop of Fig. 4b there results,

$$hE = \frac{Q}{C_1+C_s} + \frac{Q}{C_0} = V + \frac{Q}{C_0}$$

where Q is the charge and V is the voltage across C_1. Therefore,

$$Q = \frac{C_s + C_1}{V}$$

and

$$Eh = V\frac{(C_s+C_1)}{C_0} + V = V\left(1 + \frac{C_s+C_1}{C_0}\right)$$

and hence

$$E = \frac{V}{h}\,\frac{(C_0 + C_s + C_1)}{C_0}$$

From this it follows that the antenna signal across capacity C_1 gives a voltage which is directly proportional to the field intensity E. In both cases the resistance R is made sufficiently large to critically damp the antenna. This prevents any shock or signal from setting the antenna circuit into oscillation.

In the circuit of Fig. 4 no consideration was given to the input resistance of the amplifier. Appleton and Chapman used an electrometer triode. This consisted of a Pliotron FP-54 manufactured by General Electric Company. The complete antenna assembly, including the sphere lead-in system, together

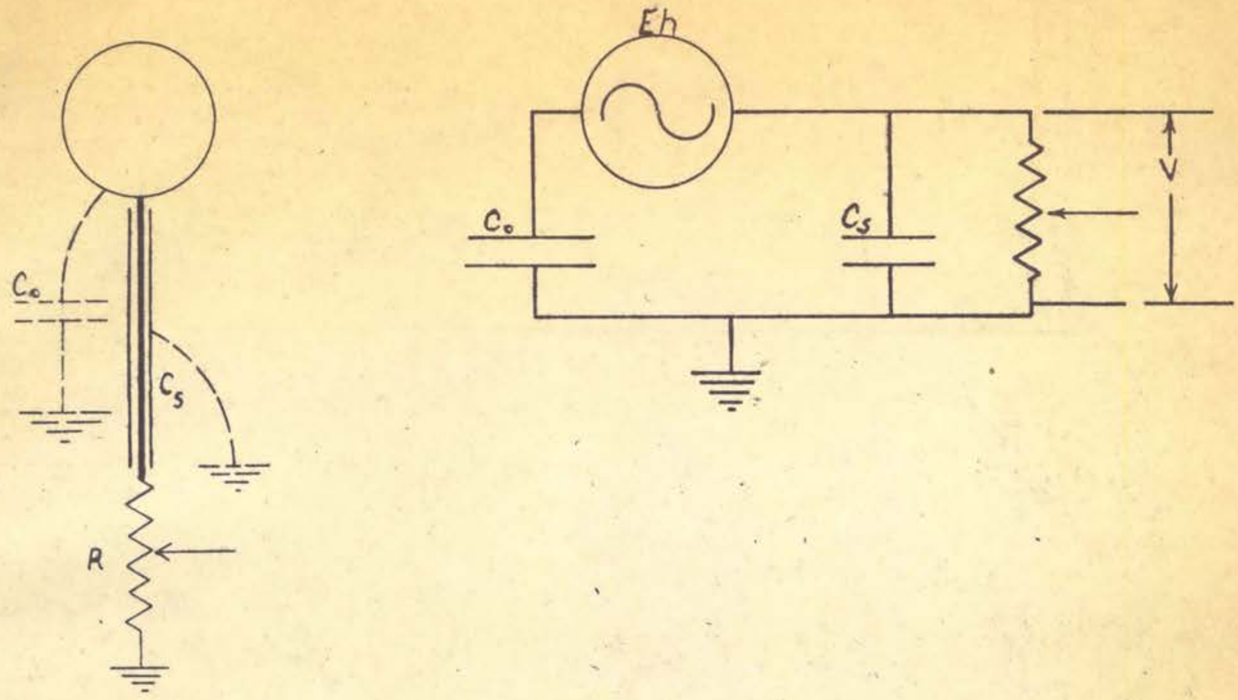

Fig. 3. Illustrating the aerial system used for measurements of the rate of change of the earth's electric field.

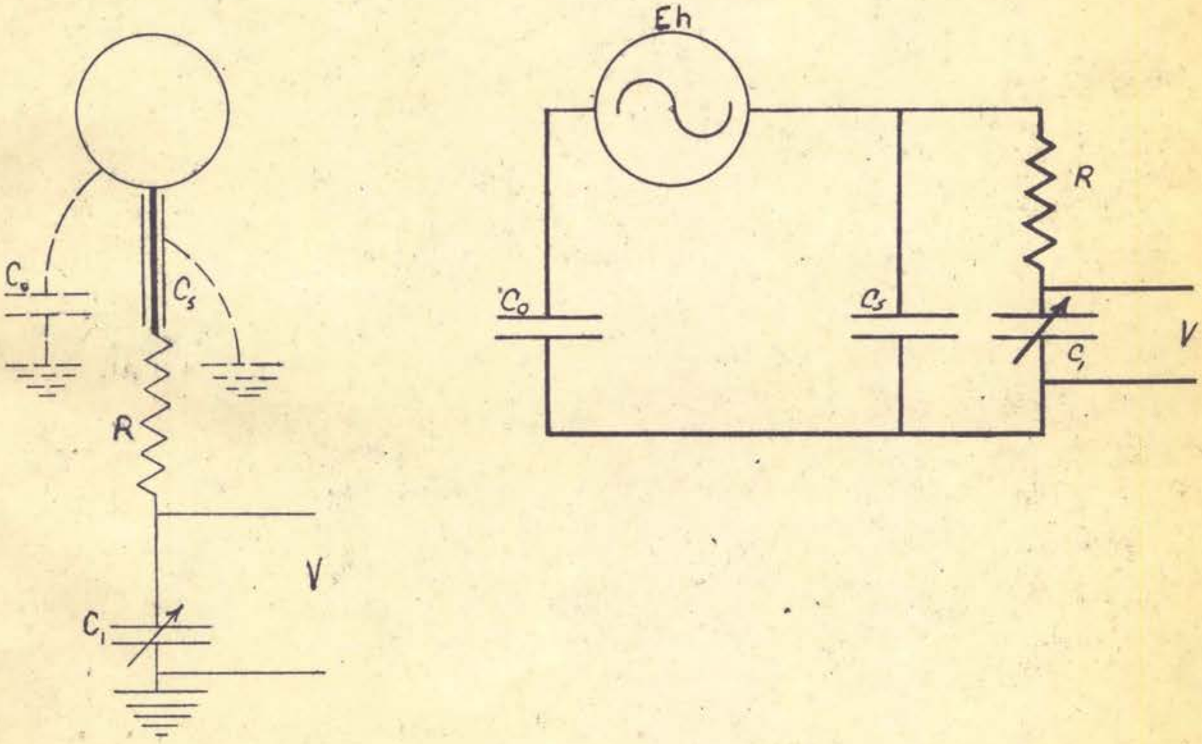

Fig. 4. Illustrating the aerial system used for measurements of the earth's field.

with the electrometer triode was shielded electrostatically. The shield consisted of a metal case and included a dehydrating agent to prevent surface leakage. This construction made it possible to maintain the input resistance of the electrometer triode at approximately 10^{16} ohms. However, because of slow variation of the earth's field it was necessary to introduce resistance of 10 megohms in the grid circuit of the electrometer tube. A diagrammatic illustration of the arrangement is shown in Fig. 5.

Early circuits employed a resistance-coupled amplifier in the output of the FP-54. However, a capacity coupled amplifier was finally substituted in order to improve the stability of the system. The modified circuit was eventually designed to cover, without distortion, a frequency band from 10 to 10^5 c.p.s. Due to great advances in amplifier and oscillograph design since the time of Appleton and Chapman, no additional details involving their equipment will be considered in this paper.

The findings of Appleton and Chapman, together with their discussions of the evolution of an atmospheric disturbance, are most valuable and interesting.[38] They found that the net change of field usually consists of either two or three parts, as shown in Fig. 6. In the first part there is a smooth variation of the field in the direction of the final net change. This change usually requires from 1 to 10 msec. to reach completion and is then followed by a very rapid change of field on which occur superimposed ripples. The field may cease to vary at this stage, or again it may gradually increase, possibly with ripples to some slightly larger final value. A typical net change of this type observed at a distance of 3 km., is illustrated in Fig. 6. As has been mentioned, the third part, (c) in the diagram is very frequently either non-existent or not very large. The magnitude of the change of field in part (a) is generally about equal to that in (b). The transition

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38 E. V. Appleton and F. W. Chapman, <u>Op. cit.</u>, p. 12.

from (a) to (b) is very abrupt. Records obtained using much greater vertical gain and a faster time sweep showed that part (a) was not a smooth variation. It contained a fine structure consisting of pulses separated by about 0.1 msec.[39] The record of the atmospheric thundercloud moment is obtained from the time variation as depicted in Fig. 6 of the cloud moment. The change in cloud moment is proportional to the electric intensity.[40] In the case at hand the net field change is 1000 v/m. At greater distances from the discharge one would expect less net changes.[41] Typical wave forms delineated at the various distances are shown in Table I.[42] The values shown in the first column of Table I are the distances to the channels of discharges. The distance to a discharge channel was determined either by a measurement of the interval between the lightning and the thunder or, in the case of the more distant storms, from the information given concerning storm centers in the daily weather reports of the Meteorological Office. Values of the electrostatic field change, E_s, are to be found in the second column, while estimated values of the radiation field, E_r, are to be found in the third column. In column four are drawn pictures of the typical wave-forms at the various distances. In order to show all the wave-forms as about the same height, the vertical gain is increased as the distance to the field disturbance increases. This table clearly indicates that part (b) of the discharge contains the main component of radiation. At distances of 200 km. or greater the wave-form of

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[39] Cf. post, p. 51

[40] Cf. post, p. 49

[41] Loc. cit.

[42] E. V. Appleton and F. W. Chapman, Op. cit., p. 14.

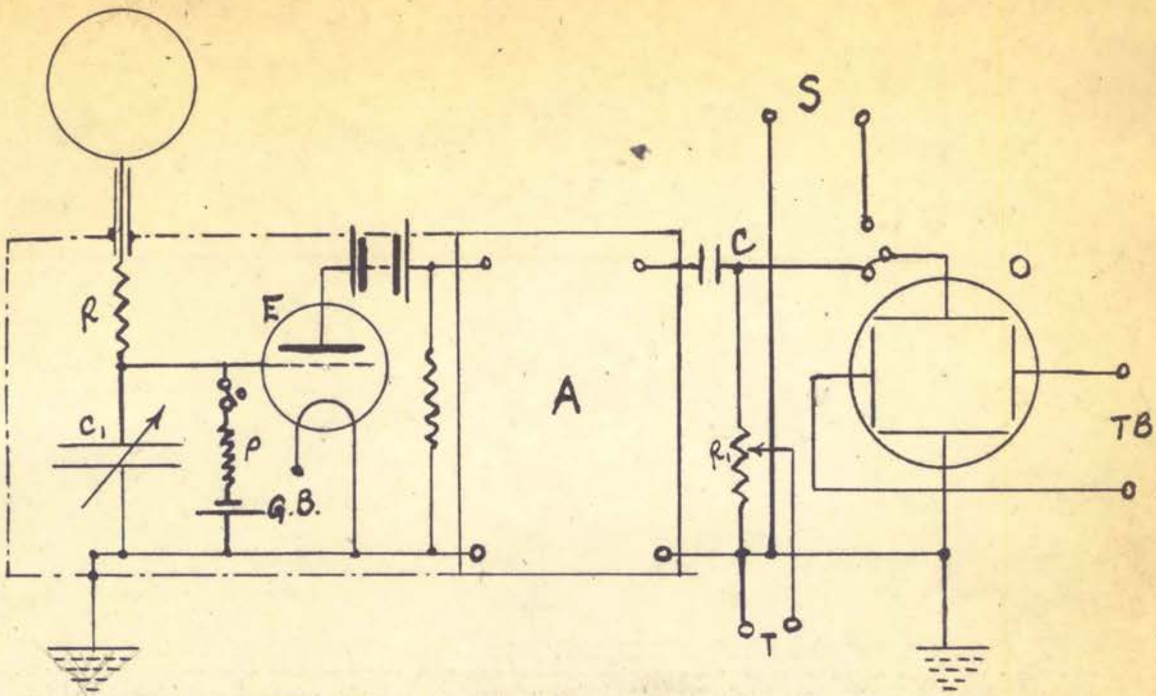

Fig. 5. Showing diagrammatically the aerial system, amplifier, and recording cathode-ray oscillograph. E, electrometer tube; A, resistance capacity coupled tube amplifier;), cathode-ray oscillograph; T, to thyratron camera shutter relay; S, to time calibrating oscillator; T.B., to linear time-base.

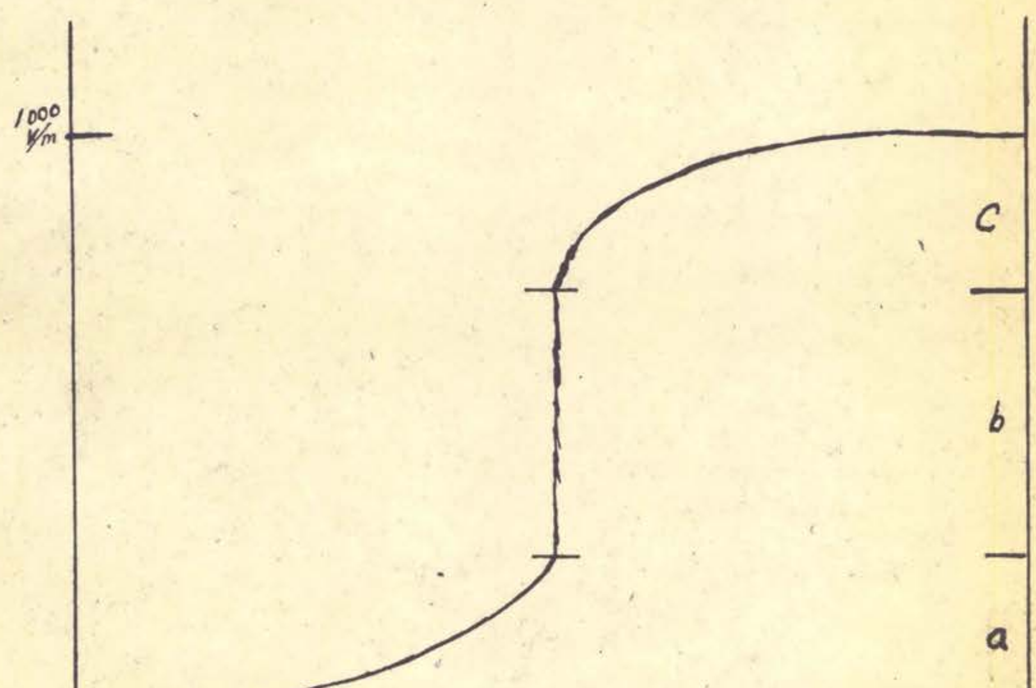

Fig. 6. The typical variation of thundercloud moment during a single lightning flash, as determined by the earth's electric field variation at a short distance from the discharge.

an atmospheric is determined practicaly entirely by the radiation field component. Throughout the distance range from 60 km. to 200 km. certain marked changes of wave form are noticed. First, the total duration of the atmospheric appears to increase; second, the wave-form becomes more regular and the higher frequency ripples less prominent; and third, the number of half-cycles observable in the atmospheric seems to increase.

For the more distant disturbances having a smooth wave-form, it may be noted that the quasi-half-cycle increases throughout the duration of the atmospheric. At a distance of 200 km. a new phenomenon is often observed. Many of the radiation wave-forms develop a slow-tail of abouttwo rounded half-cycles. It will be noticed that this type of wave-form is exactly the type drawn by Appleton, Watt, and Herd for their series of visual observations.[43,44]

Close range measurements made with the circuit shown in Fig. 3 brought out in detail the oscillatory fine structure in part (b) and (c) of the time discharge curve. When close to the disturbance these oscillations were difficult to detect with the circuit of Fig. 4 because they were masked by the dominant electrostatic component. The quasi-period of oscillations was found to vary from 0.01 to 0.25 msec. These periods are equivalent to frequencies from 4 to 100 kc. The duration of such a train of quasi-oscillations might be as long as 1.0 msec.

From the foregoing discussion one may conclude that in its totality the lightning discharge is aperiodic, but that during the periods of both slow and rapid changes of moment there exists superimposed minor pulsations. The

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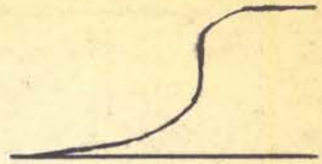
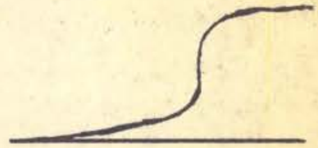
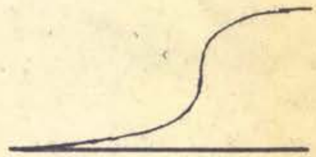
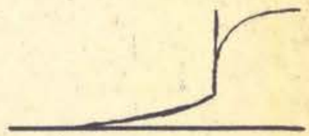
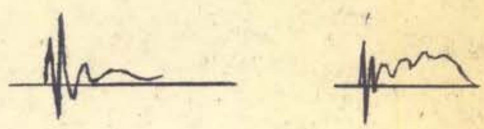
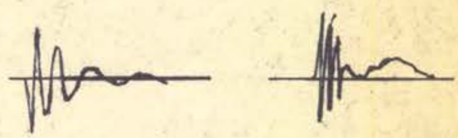
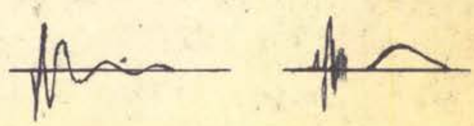
[43] E. V. Appleton, R. A. Watson Watt, and J. F. Herd, loc. cit.

[44] C. W. Miller, loc. cit.

TABLE I

Distance in km.	E_s in v./m.	E_r in v./m.	Typical wave-form
3-5	1300	Not observed	
10	700	Not observed	
20-30	45	Not observed	
45-50	12	5	
60	3	3	
100	0.6	1.7	
150-200	0.1	Maximum peak value 0.8	
300-400	Not observed	Maximum peak value 0.3	

pulsations that occur during part (b) of the time discharge curve are the largest. A discharge of this type corresponds very closely to the electrical mechanism suggested by Simpson who said,[45]

> There can be little doubt that the resistance of a fully developed lightning channel when most highly ionized may well be less than the critical value, and the channel therefore able to oscillate. The oscillations will be superimposed upon the main current but will not reverse its direction of flow...The effect is somewhat similar to that of a "singing arc" in which the conducting path through the air between the electrodes is maintained by a unidirectional current while oscillations which give rise to the musical note are superimposed upon the current according to the frequency of the circuit.

Appleton and Chapman continued their discussion with the observation that the most frequent type of atmospheric consists of a brief wave-train of about 8 half-cycles with quasi-period 0.1 to 0.15 msec. This wave-form is characterized by a very steep front and has a sequence of quasi-half-cycles of increasing duration. The so-called "slow-tail" occurs only in a minority of cases and requires some explanation. The fact that it appears only when the discharge is more than 200 km. distant would indicate that it is a characteristic of the transmission medium. Transmission line theory would cause the high frequency components to travel faster than the low. Experimenters have also found that long-wave radio radiation travels faster than short-wave lengths. Another answer might envolve reflections from the ionisphere. The three effects might account for the phenomena.

It will now be necessary to review part V of the series of articles under discussion.[46] Particular attention was given to the "slow-tail" phenomena as well as to the presentation of the more accurate data by the use of more

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45 G. C. Simpson, "n.n.", Journal of the Institution of Electrical Engineers, LXVII, (1929), 1275, cited by E. V. Appleton and F. W. Chapman, Op. cit., p. 17.

46 R. A. Watson Watt, J. F. Herd, and F. E. Lutkin, "Atmospherics V", Proceedings of the Royal Society of London, CLXLL-A, (1937), 267-291.

precise equipment. Their facilities were improved for detail study. A new instrument was described which consisted essentially of a rotating drum on which the film was mounted. If the cathode-ray spot remained stationary a spiral would be traced on the film.[47] This was brought about by a continuous axial motion of the drum. Two stations were operated simultaneously, one at either end of a 560 km. base line. By means of direction finders at each station it was possible to locate the source of the atmospherics by triangulation.[48] A film speed of one-half m./sec. was employed. The antenna at one station consisted of a type T antenna located 25 m. above the ground and 500 m. in length. This antenna fed the resistance-coupled amplifier.[49] The other antenna was 15 m. high and had a single-wire top of 65 m. length. Early in the observations it became obvious that the difference in antennas had no appreciable effect on the wave forms received.

The resistance-coupled amplifiers were replaced by capacitance coupled amplifiers in order to improve the stability at high frequencies. It also became obvious that there was little need for amplification below 100 c.p.s. The response of the amplifier was linear over a band from 10 c.p.s. to 15,000 c.p.s., with a gain of approximately 1,000.

Utilizing the new type of drum camera delineation disclosed the multiple stroke phenomenon. The typical multiple stroke atmospheric, when received from a distance of 200 to 4,000 km., was found to consist of a succession of comparable elements separated by time intervals of the order of 10 to 50 msec. one such series was described which eleven components occurred in a time less than 500

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47 F. E. Lutkin, "A Drum Camera for Recording Transient Electrical Phenomena", Journal of Scientific Instruments, XIV, (1937), 210-212.

48 R. A. Watson Watt, J. F. Herd, and L. S. Bainbridge-Bell, Applications of the Cathode-Ray Oscillograph in Radio Research, pp. 101-109.

49 E. V. Appleton, R. A. Watson Watt, and J. F. Herd, loc. cit.

msec.; each component had its own "slow-form". It must be remarked that in the literature the terms "slow-form" and "slow-tail" are synonymous.

An oscillatory component was present in all but about 1 per cent of the recorded forms. This component assumed the form of a train of some eight or ten oscillations of appreciable amplitude with logarithimic decrement. The most prominent frequencies within the oscillatory component were of the order of 5 to 20 kc.p.s., the quasi-period of the oscillations arriving first being shorter than that of the oscillations that followed. It was found that the average frequency of these oscillations during the summer was lower than during the winter. The "slow-form" had a first "half-cycle" of between 1.5 and 2.5 msec. duration for distances of a few hundred km. This time rose to 6 msec. at 4,000 km. After construction of a scatter diagram of the oscillation intervals plotted in relation to the distance to the origin of the atmospheric, it was discovered that no correlation could be obtained. Therefore, it was decided that this relationship could not be used for the purpose of ranging. Some idea of the complexities involved may be obtained from one discovery which resulted from the new arrangement of equipment. It was found that no correlation existed in the field strength of disturbances originating from the same area when these field strengths were measured at the two receiving stations separated by the 560 km. base line. Oscillograms clearly demonstrated this fact. A study of the data led to the conslusion that the ratio of amplitudes of the oscillatory portion of the discharge to the non-oscillatory portion of the atmospheric decreases with distance. However, the oscillatory portion possesses the greater amplitude.

At the present time part VI is the most recent of the series of publications under consideration.[50] Film speeds up to 20 m./sec. were employed.

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[50] F. E. Lutkin, "The Nature of Atmospherics VI", The Proceedings of the Royal Society of London, CLXXI-A, (1939), 285-313.

Two series of data were obtained. The first series consisted of observations of atmospherics arriving from storms a great distance away. This series was principally for testing the equipment. The second series consisted of records from disturbances that occurred close to one of the receivers. A method for recognizing simultaneous observations of the same event was employed and was correlated with the direction of each recorded atmospheric.[51] Once again dissimilar antennas were used. One antenna consisted of a wire "cage" supported by a 75 ft. wooden tower. The other was a 60 ft. high type T antenna which was 230 ft. in length. The new equipment was designed to measure the field strength and the direction of the initial surge of voltage. It was found that 65 per cent of the wave forms had a positive initial surge and 31 per cent negative surge. The sign of the initial swing could not be determined for 4 per cent of the wave-forms. It is to be understood that a positive swing at the input to the amplifier indicates a positive field change accompanying a discharge of negative electricity to the ground. By taking advantage of the great resolving power of this equipment it was determined that the head of the oscillatory train had a frequency of 10 kc. p. s. The frequencies at the end of the train was 2 kc.p.s. The train was considered to end when the amplitude was one-tenth the peak value. Wave-forms originating from over the Atlantic Ocean were of longer duration than those from over the land. However, the former waves were of much longer duration than the latter. It was also found that there existed occasional complex sequences consisting of multiple wave structures grouped so close together that it was difficult to obtain adequate separation. These forms originated most frequently from storms occurring over land. The "precusor" of the wave becomes more prominent

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[51] R. A. Watson Watt, J. F. Herd, and L. J. Bainbridge-Bell, loc. cit.

as the origin of the disturbance approaches the receiving station. The "precusor" occurrs in the (a) portion of the field change.

It might be remarked that for nearby storms a 10 ft. vertical antenna was used in place of the antenna described previously. This change resulted in a much shorter time constant. In all cases it was observed that when the same atmospheric was recorded by both stations, the initial change in the two records was the same. The wave-forms might be quite different, however, because of the difference in distance to the storm center.

Lutkin classifies atmospherics into three groups. The group 1 type of atmospheric originates in the main discharge which occurs down the channel ionized by the "leader strokes". Lutkin compares a typical group 1 wave-form on the same time base with a reproduction of a flash photograph by Schonland, Malan, and Collens.[52] The comparison shows how the light and dark streaks at comparative intervals of time compare well with cycles of the wave-form. This is a great help in the analysis of the mechanism of the discharge. The radiation field change at distances of a few hundred km. from a flash will be proportional to d^2M/dt^2 where M is expressed as $M = 2hQ$ and represents the cloud moment destroyed.[53] Assuming that the bands of illumination indicate current pulses flowing in the same direction, the curve of moment destruction versus time will be similar to Fig. 9, curve (a). Differentiating this curve gives curve (b) and differentiating again results in curve (c). Curve (c) is similar to the wave-form of the delineated radiation field.

This is a confirmation of Simpson's theory that the ionized path of the stroke will oscillate and give rise to radiation from a unidirectional current with periodic pulses that shock the long ionized conductor into oscillation. The frequency would shift as the constants of the path varied when changes

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52 B. B. J. Schonland, D. J. Malan, and H. Collens, "Progressive Lightning II", The Proceedings of the Royal Society of London, CLII-A, (1935), 595.

53 Cf post, p.

occurred in the length of the stroke and the capacity of the cloud to ground. Where the initial cloud moment destroyed is positive, it has been found that sometimes the current reverses and proceeds to destroy the negative moment. This is attributed to the exhaustion of the small localized positive charge at the base of the cloud followed by a discharge from the neighboring negative charge.[54] The atmospherics of group 2 are found to originate in the leader stroke which proceeds the first component discharge. This leader, or "precusor", appears to occur in two types. In one type the leader to earth is followed immediately by the main stroke while in the other the leader stroke slows down as the ground is approached. By the time it reaches the ground the rate of travel is then so slow that only a small radiation field results, while that of the main discharge is relatively enormous. Often in a group 2 type of discharge a quiet period of a millisecond will elapse between the last visible oscillations of the leader stroke and the main discharge. In some cases two or three successive patterns of group 2 have been found preceding the main stroke, suggesting several attempts of the leader to reach the earth before the channel is finally established. Accepting this hypothesis of origin it must be expected that many cases will be found in flash photography in which the leader stroke is unaccompanied by a succeeding main stroke. Of the 225 forms registered only 48 were followed by main strokes. The frequency of these non-return strokes averaged about 14 kc.p.s.

The atmospherics in group 3 are similar to those in group 2 except that a longer time interval occurs between pulses. The reason for this is not explained. It is, however, very interesting to find that the isolated pulses of this type of flash produce at a distance only 3 half-cycles instead of the dampted train of 3 or 4 cycles characteristic of the oscillatory component of the first group. The period of these oscillations was from 50 to 100

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[54] Cf. ante, p. 8.

microsec.

In order to better understand the manner in which the wave forms are produced it will be necessary to introduce the hypothesis that a thundercloud is discharged by a succession of unidirectional vertical bursts of current. The electric intensity will be considered made up of three components, electrostatic, induction, and radiation. For the two charges shown in Fig. 7, the potential at a given point, P, is the sum of the potentials due to the individual charges. The potential at a point may be found by integrating the work performed on a unit charge when the charge is carried from infinity to the given point. This gives $V = Q/R$. Referring to Fig. 7, the potential at point, P, is

$$V = \frac{Q}{R_1} - \frac{Q}{R_2} = \frac{Q}{R - \frac{L}{2}\cos\theta} - \frac{Q}{R + \frac{L}{2}\cos\theta} = \frac{QL\cos\theta}{R^2 + \frac{L^2}{4}\cos^2\theta}$$

and if L^2 is negligible compared with R^2

$$V = \frac{QL\cos\theta}{R^2} = \frac{M\cos\theta}{R^2}$$

M is called the moment of the dipole.

$$E_R = \frac{-\partial V}{\partial R} = \frac{2M\cos\theta}{R^3}$$

$$E_\theta = \frac{-\partial V}{R\partial\theta} = \frac{M\sin\theta}{R^3}$$

where E_R and E_θ are the radial and tangential components, respectively, of the electric intensity. The above equations will now be applied to a charged cloud located above the surface of the earth. It is assumed that the surface of the earth is an equipotential. Since a plane midway between the charges of a dipole and perpendicular to a line connecting the charges, is an equipotential surface, the electric field about a dipole is identical with the field of a cloud charge. This being true, the latter may be analyzed by using an image charge below the earth's surface. Such an arrangement is shown in Fig. 8. Using the previous expressions for E_R and E_θ it is seen that $M = 2hQ$, $E_R = 0$ since $\theta = 90$ deg., and E_θ is the only component.

$$E_\theta = E = \frac{M \sin\theta}{R^3} = \frac{2hQ}{R^3} = \frac{M}{R^3}$$

This equation for field intensity in terms of cloud moment holds only if $(2h)^2 \ll R^2$, as was specified in the derivation.

It is now advantageous to present the equation that expresses electric intensity in terms of cloud moment, following the work of Lutkin and Norinder.[55] The relation

$$E = \frac{M}{R^3} + \frac{1}{CR^2}\frac{dM}{dt} + \frac{1}{C^2R}\frac{d^2M}{dt^2}$$

could be written

$$E = \frac{2hQ}{R^3} + \frac{2h}{CR^2}\frac{dQ}{dt} + \frac{2h}{C^2R}\frac{d^2Q}{dt^2}$$

where the quantities involving M are the retarded values of the components of the field intensity obtained at a time $(t - R/c)$. Since E is a vector the equation implies that vector addition is in order. Furthermore, M is designated as the change in moment just as E is the change in electric intensity. The first term of the above equation is the electrostatic component and is in a vertical direction. The second term in induced electric field and the third term is the radiation component. Perhaps the best way to correlate this equation which is in terms of cloud moment, is to compare it with the field equations which may be found in most standard textbooks covering the subject of antenna radiation. Consider, for example, the equation developed and written by Skilling,[56]

$$E_\theta = \frac{Il}{4\pi\epsilon R}\sin\theta\left[\frac{1}{\omega R^2}\cos\omega\left(t-\frac{R}{v}\right) + \frac{1}{Rv}\sin\omega\left(t-\frac{R}{v}\right) + \frac{\omega}{v^2}\cos\omega\left(t-\frac{R}{v}\right)\right]$$

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55 Harold Norinder, "Cathode-Ray Oscillographic Investigations on Atmospherics", The Proceedings of the Institute of Radio Engineers, XXIV, (February, 1936), 287-304.

56 H. H. Skilling, Fundamentals of Electric Waves, p. 166.

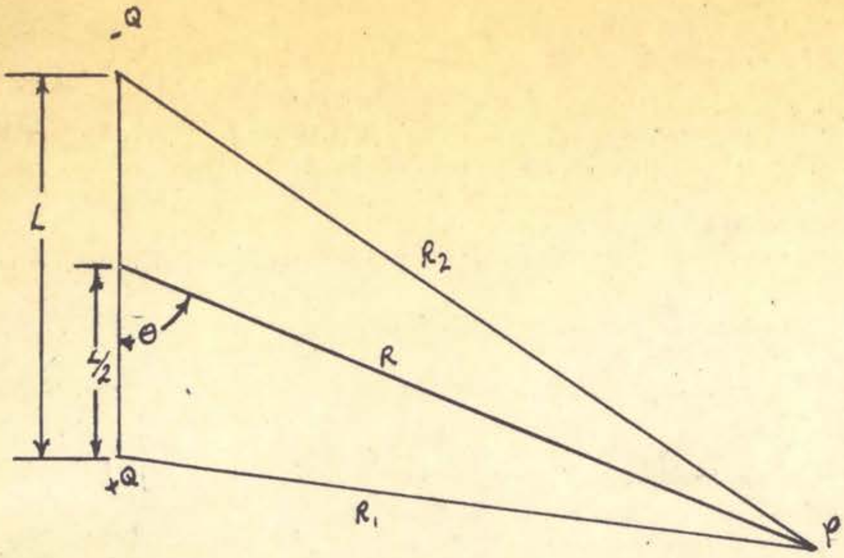

Fig. 7. Depicting a dipole.

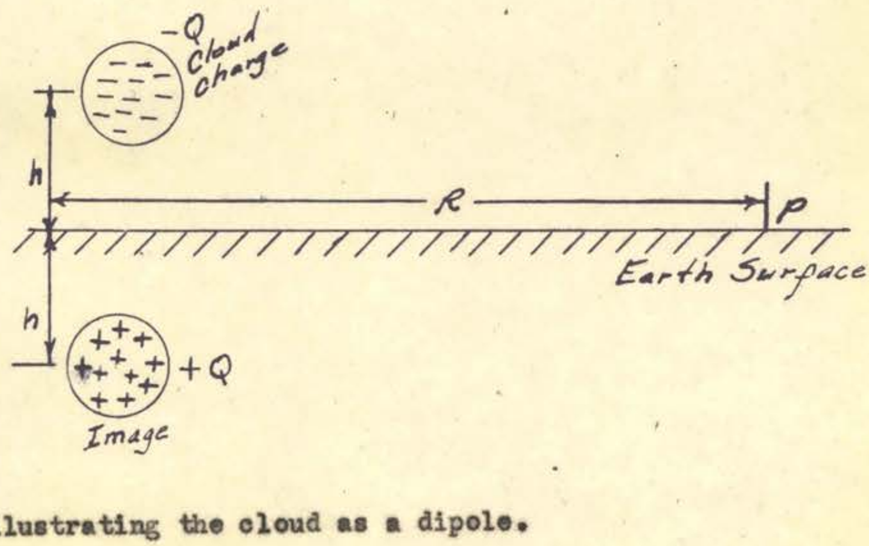

Fig. 8. Illustrating the cloud as a dipole.

This equation is in rationalized M.K.S. units.

Since the lightning path, the conductor, is perpendicular to the earth and since only the vertical component of the electric intensity can exist if the surface of the earth is to be an equipotential, only E_θ is considered. That the two sets of equations for the field are similar can be recognized by noticing the variable R. It can be remarked that in case of either the moment equation or the current equation, the first term is a function of the third power of R, the Second term the second power of R, and the third term the first power of R. Although the equations are written in different units, the comparison of the variables is still possible. For a given time and wave length the only variables are current, charge, and distance. If it is recalled that in an oscillating electric doublet or in an antenna, the current will be

$$i = I \sin \omega t$$

and differentiating

$$\frac{di}{dt} = \omega I \cos \omega t$$

and by integrating

$$\int i = \int I \sin \omega t = -\frac{I}{\omega} \cos \omega t$$

furthermore, since

$$i = \frac{dQ}{dt}$$

there results

$$Q = \int i\,dt$$

If the components of each equation are taken one at a time their qualitative equivalence may be demonstrated as shown in Table II.

TABLE II

COMPONENT	MOMENT EQUATION	CURRENT EQUATION
electrostatic	$\frac{2hQ}{R^3}$	$\frac{Il}{R^3\omega} = \frac{2h}{R^3}\int i\,dt = \frac{2hQ}{R^3}$
induction	$\frac{2h}{R^2}\frac{dQ}{dt}$	$\frac{Il}{R^2} = \frac{2h}{R^2}\frac{dQ}{dt}$
radiation	$\frac{2h}{R}\frac{d^2Q}{dt^2}$	$\frac{Il\omega}{R} = \frac{2h}{R}\frac{di}{dt} = \frac{2h}{R}\frac{d^2Q}{dt^2}$

The preceding relationships were demonstrated for the sole purpose of correlating the concept of electric intensity established by a change in the charge on the cloud with the more familiar antenna current equations. For a complete development of electric intensity in terms of charge reference can be made to the works of Page and Adams.[57] It, therefore, follows that,

$$E = \frac{M}{R^3} + \frac{1}{C}\frac{dM}{dt} + \frac{1}{C^2R}\frac{d^2M}{dt^2}$$

Lutkin proposes a typical wave form orginating from a discharge which is very close to the observer. Consequently, the electrostatic component is assumed to predominate. Such a condition is shown by curve (a) of Fig. 9. Differentiating once results in curve (b) and differentiating again gives curve (c). Curve (a) compares with the (b) and (c) part of a discharge discussed previously.[58]

The equations derived for atmospherics can easily be correlated with the forms observed earlier for various distances from points of discharge.[59] The "slow-tail" effect isn't accounted for by the theory. A table can be

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57 Leigh Page and N. I. Adams, Principles of Electricity, p. 580.

58 Cf. ante, p. 38.

59 Cf. ante, p. 42.

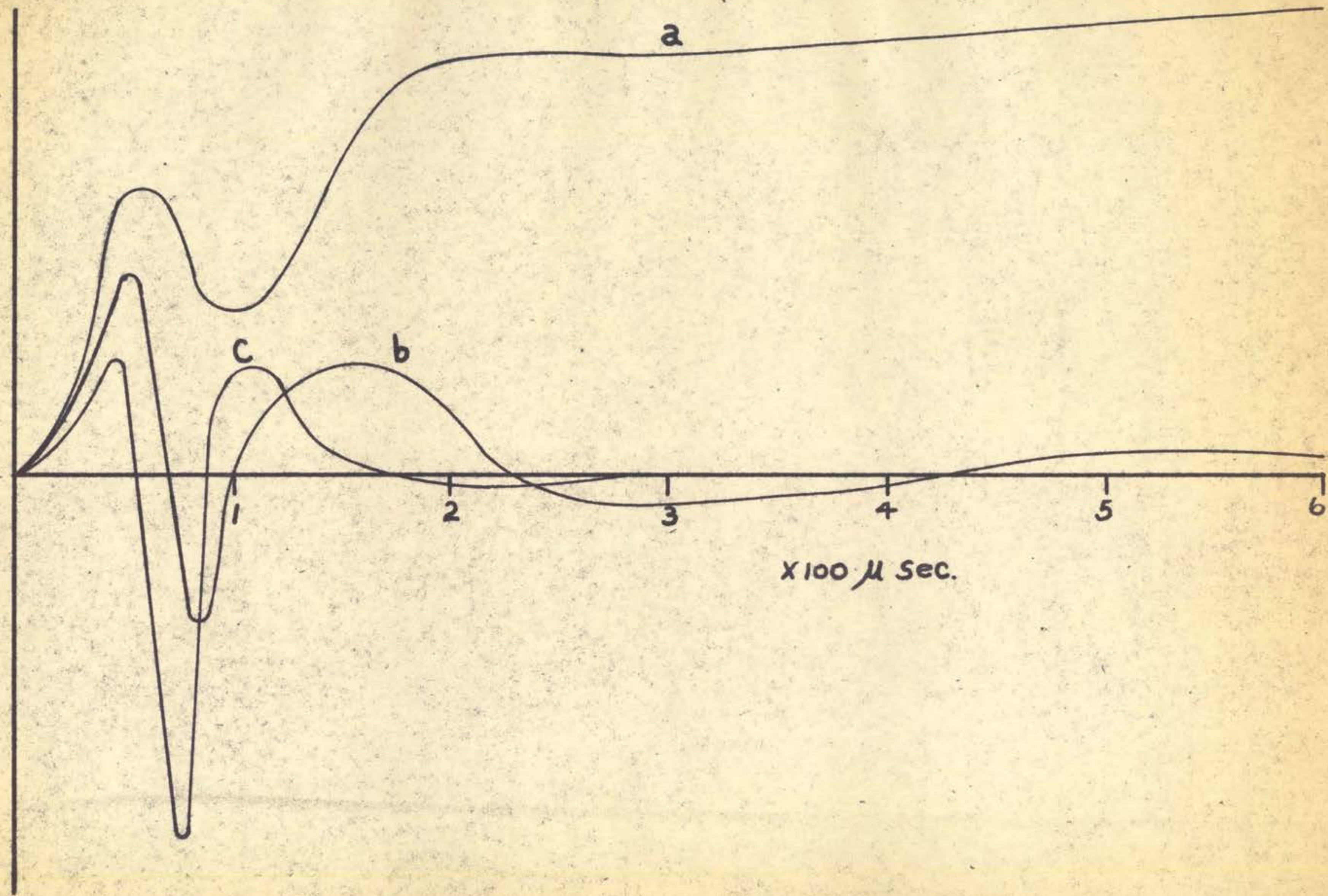

Fig. 9. Cloud Moment Change and Its First and Second Derivatives with Respect to Time.

constructed from the computed values of the three components for various distances. Lutkin constructed such a table from calculated values and predicted the wave-form at various desired distances with fair accuracy. For distances of 10 to 100 km. he found that all three components are present and succeeded in accounting for many of the peculiar wave-forms in this category. From his calculations, it can be seen that only the radiation component is appreciable beyond 100 km. Looking again to the region of 30 to 100 km., Lutkin admits that the presence of more than one component does not account for the total complexity of wave-forms observed. Australian investigators claim to have discovered evidence of reflections from the ionispheric layers at 30 km. which produce a repetition and elongation of the observed patterns.[60] If this is the case, a simple explanation for peak multiplication and wave complexity will be provided. No evidence was found to support the possibility of additional oscillations in the branches of the main channel. The complex wave-forms become evident at distances of 15 km., and since reflections from scattered low ionized regions are possible for this distance, the reflection theory provides the most probable explanation.

An attempt was made to calculate fidd strength at various distances from the source. The calculations were made for a storm which was located at a receiving station 500 km. from the second station at which the check measurements were taken. Good results were obtained. From this data it was possible to calculate the value of the discharge current. It was found that the average discharge transferred a charge of 0.5 coulombs at a current of 30,000 amps. Occasional discharge values of 3 coulombs at 200,000 amperes

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60 T. H. Laby, F. G. Nicholls and A. F. B. Webster, "n.n.", Nature, London, CXXXIX, (n.d.), 837-838, cited by F. E. Lutkin, Op. cit., p. 305.

were obtained. These values check closely with current measurements made by Mc. Eacheron on strokes to the mast of the Empire State Building.

Tabulations of statistical studies for various types of discharges were made to show the variation with respect to time of day and time of year. A number of conclusions were drawn.

1. Positive changes were obtained more frequently during summer than autumn. It must be remembered that a positive change destroys a negative cloud moment, or negative cloud charge. This observation suggests that summer storms of the heat type produce a high percentage of positive changes, while storms associated with meterological fronts give rise to about equal numbers of positive and negative changes.

2. It was found that during the early part of a summer day some 30 per cent of the recorded discharges indicate the destruction of positive cloud moments. During the evening practically all the moments destroyed were negative. The majority of the discharges belonged to group 1, most of which were discharges to ground though some intercloud discharges were present. About 20 per cent belonged to group 2. In some of these no main discharge was observed to follow the multiple "leader".

Lutkin expressed the opinion that his observations checked those of Simpson and Scrase.[61]

An excellent series of papers has been written on the subject of "Progressive Lightning" and are published in The Proceedings of the Royal Society of London. These publications have developed from research performed under the direction of The Lightning Research Committee of The South African Institution of Electrical Engineers. The first work was published in 1934.

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61 Cf. ante, p. 7.

It is believed that the first three articles of this series contribute very little to our study of tornado identification, and hence they will only receive passing mention.

In Article I Scholand and Collens described eleven flashes of lightning which were photographed with a rotating lens type of camera which was based upon the design of C. V. Boys. The speed was sufficiently high to permit a study of the progation of the discharge.[62] In Article II Schonland and Malan and Collens give a general account which is based on the study of 95 flashes recorded with the Boys and other cameras. These studies relate to the mode of development of the lightning discharge.[63] Article III of the series deals with the fine structure of the return lightning strokes.[64] Analyses of the luminosity-time relationship in the return stroke shows definitely that within the limits of the resolving power of the camera, which is of the order of 10 microses., the only important variations in luminosity are those connected with the development of branches.

Article IV of the "Progressive Lightning" research series deals with the discharge mechanism, a subject which is considered very significant in the study of tornado lightning.[65] It seems that in every stroke studied by Schonland, the cloud acted as a cathode during the slow lowering and sudden destruction of a negative cloud charge. Also, in every case it was observed that the leader stroke traveled downward. It must be mentioned, however, that other observers have noted an initial positive cloud charge which was

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62 B.F.J. Schonland and H. Collens, "Progressive Lightning I", The Proceedings of the Royal Society of London, CVIIL, (1933-1934), 654.

63 B.F.J. Schonland, D. J. Malan, and H. Collens, "Progressive Lightning II", loc. cit.

64 D. J. Malan and H. Collens, "Progressive Lightning III", The Proceedings of the Royal Society of London, CLXII-A, (1937), 175.

65 B.J.J. Schonland, "Progressive Lightning IV", The Proceedings of the Royal Society of London, CLXIV-A, (1938), 132.

destroyed by a positive discharge before a negative discharge dissipated the remaining negative charge.[66] This is in accordance with the theory that the heavy rain in the small positive region of the thundercloud may initiate the discharge path, which is used by nearby negative charges as an escape to ground.[67] The latter process was not observed by Schonland partially because his polarity study did not extend to the subject of multiple discharge. Schonland's observations of the discharge process are most easily understood from a study of Fig. 10 which shows the conditions and sequence for this phenomena.

Each of the successive strokes or partial discharges which make up a complete lightning discharge to ground takes place in two stages, the downward moving leader stroke being followed by an upward-moving return stroke. These processes are described as the leader and the return streamer. Such a steamer is a conducting filament of ionized gas which extends its length by virtue of ionizing processes occurring in the strong field in front of its tip. It is electrically charged throughout its length and because of the potential drop along its extended length is not at the same potential as the electrode from which it started. This drop of potential provides a field which drives a current through the stem of the streamer and this current serves to charge newly formed sections of the stem to the potential necessary for further progress. The current continues at the tip of the streamer as a convection current due to the charge situated there, and beyond the tip as a displacement current.[68] Light is emitted by the streamer as a result of excitation processes

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[66] Harold Norinder, "n.n.", Journal of the Franklin Institute, CCXXV, (1936), 69, Cited by loc. cit.

[67] Cf. ante, p. 48.

[68] Cf. post, p. 62.

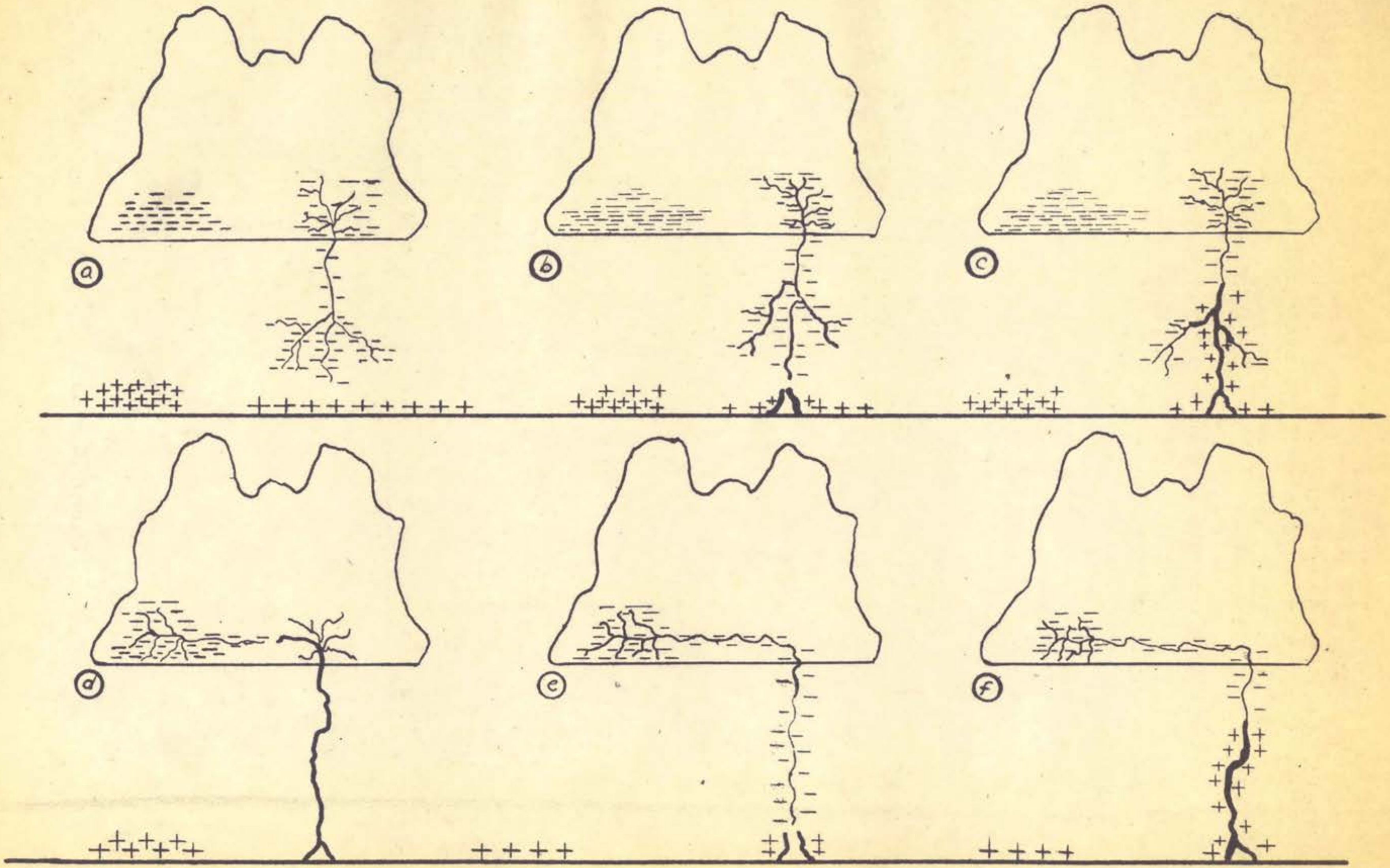

Fig. 10. Progression of cloud discharge.

at the tip. Apart from this the luminosity associated with the streamer is small and it can therefore be inferred that the field in the stem behind the tip is insufficient to cause excitation by electron impact.

The sequence of events detailed in Fig. 10 may be compared with those shown in Fig. 6. The designations in Fig. 6 were used by Appleton and Chapman to describe the evolution of a discahrge when studied with respect to a field change located a short distance from the discharge.[69] Fig. 9, parts (a) and (b), correspond to part (a) of the field change study and Fig. 9 (c) to the (b) portion of the field change study. As the current continues in the streamer part (c) of the field change is established.

It is implied in this description of the discharge process that separate strokes tap different centers of charge within the same thundercloud. This is illustrated in Fig. 9 parts (d), (e), and (f).

In the case of the lightning discharge there are three types of streamers; the dart leader streamer which is followed by subsequent strokes in multi-stroke discharges; the return streamer which follows all strokes; and the step streamer which follows the pilot streamer. There is a vital difference in the mechanism of the advance of the first leaders to the first and to the subsequent strokes. The dart streamer invariably follows the path traced out by a previous stroke, even to shifting its track laterally if a wind has blown this path aside. This and other features connected with its velocity under changing conditions indicate that its mechanism is that of a streamer advancing along a previously ionized channel.

The leader, which precedes the first return stroke is characterized by an advance into air which apparently is completely unionized. This involves

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69 <u>Cf. ante</u>, p. 38

a different type of mechanism. It is to be noted that the term "return" is used because the main streamer advances from the direction toward which the leader originally traveled. Associated with the stepped leader are two velocities. The step streamers advance at more than 10^9 cm./sec., but the effective velocity of the process as a whole is much lower, most frequently about 1.5×10^7 cm./sec. This minimum velocity in the step process is an important clue to the mechanism involved. It can be shown that there is strong presumptive evidence that the smaller of the two velocities is actually the velocity of the preliminary streamer which precedes the step streamer. Schonland considers two possible mechanisms that might explain the advance of negative pilot streamers into unionized air. The process might be a result of the ionization produced either by electrons situated in the tip of the streamer or by photelectrons generated in front of the tip. After citing many scientific works on the subject Schonland concludes that the minimum velocity of a negative pilot streamer is 10^7 cm./sec. This value corresponds to the minimum average velocity of the stepped leader. Allibone has produced some excellent material on the laboratory reproduction of spark discharges.[70] It is gratifying that Schonland has incorporated the findings of Allibone with his own calculations and observations. It was found in the laboratory that positive pilot streamers, under minimum field conditions, travel with much less minimum velocity than the negative. This strengthens the previous conclusion that the leader streamers are negative. From this it can be deduced that a minimum velocity is associated with a field just strong enough to give free electrons sufficient velocity to ionize the atmosphere.

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70 T. E. Allibone and J. M. Meek, "The Development of the Spark Discharge", The Proceedings of the Royal Society of London, CLXVI-A (1938), 97.

In order to show the relationship between the various quantities involved, Schonland introduced the equation

$$V_c = \sqrt{2 E_c e \lambda / \pi m}$$

where V_c is the critical velocity of ionization, E_c the critical voltage of ionization, is the length of the mean free path, and e and m are the charge and mass of the electron respectively.[71]

It can, therefore, be concluded that a negative air streamer in unionized air travels continuously downwards in form of the step streamer process with a velocity equal to the effective velocity of the step steamer. Upon this, so far unrecorded pilot steamer, the steps are periodically superimposed. It follows that the step streamers in common with the dart streamers of subsequent strokes travel along a previously ionized channel provided by the slower moving pilot streamer which precedes them. Schonland, Malan, and Collens found that the length of each step, divided by the time between that step and the previous step always resulted in the effective over-all velocity.[72] This fact supports the supposition that there is an invisible pilot streamer moving downward at a constant velocity. The diagram shown in Fig. 11 illustrates the form of a phythetical picture that could be taken with a camera with a fixed lense and with a film which moves from left to right if the pilot streamer were not invisible. The pilot streamer is shown as a dotted line, and the succeeding step streamers as heavy lines. In order to understand the reason for the tortuous nature and branching of the first leader channel, it is necessary to remember that in the majority of cases the effective or

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71 B. F. J. Schonland, Op. cit., p. 136.

72 B. F. J. Schonland, D. J. Malan, and H. Collens, Loc. cit.

pilot velocity is less than $1/5 \times 10^7$ cm./sec., which is not much different from the critical minimum velocity of 10^7 cm./sec. The direction of the leader will, therefore, be controlled by the structure of the electric field in the immediate neighborhood of the pilot streamer tip, and by the variations in the density of local space charge.

In order to better understand the mechanism that enables a streamer to advance along a previously ionized trail it will be necessary to examine Fig. 12. Section AB represents the stem of the streamer while the shaded portion BC represents the trail in front of the tip, of the streamer which was previously ionized. The area CD represents the region over which the electric field exceeds the critical value necessary for impact ionization by the electrons. In the case of a negative streamer, either dart or step, the original free electrons in part BC create other free electrons as they move forward, and in the case of a positive streamer additional electrons move toward the streamer tip.

As soon as the area represented by BC has been rendered sufficiently conducting due to the formation of electron avalanches, the streamer will be effectively extended to position C. It is thus unnecessary for any electrons to travel the full distance BC and the streamer velocity V can considerably exceed the mean electron drift velocity $\bar{v}$. Consideration must be given to the time necessary for effective ionization of the region BC. This is the time required for this region to be effectively interlaced by a network of small ionization trails, each trail starting from an initial free electron. If it is assumed that t is the time necessary for each initial free electron to cover the mean distance from its starting point to the

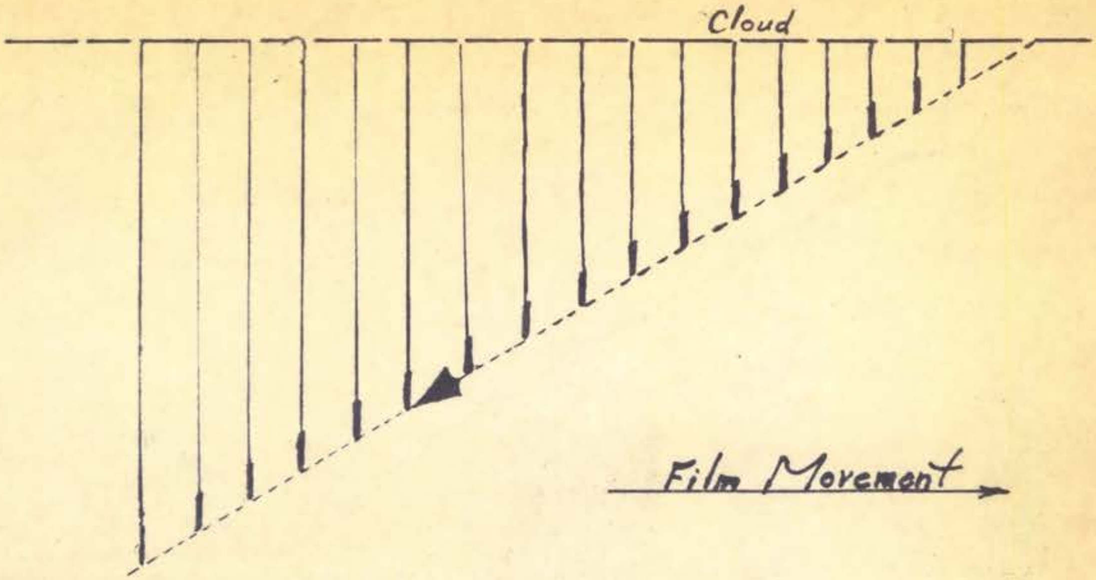

Fig. 11. Leader progression as would be observed on moving film.

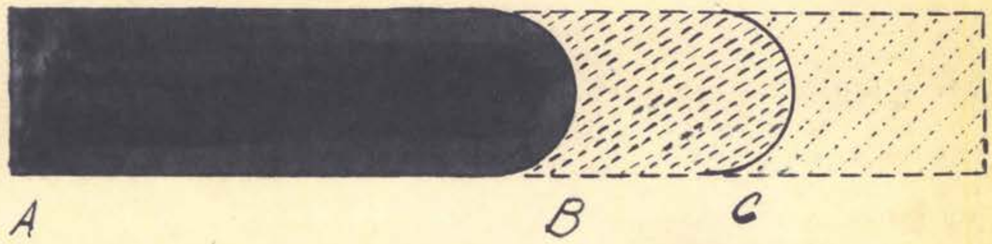

Fig. 12. Streamer advance along a previously ionized trail.

than the velocity at the end of the stroke.

The time elapsed between successive steps in the stepped-leader process occupies a remarkably narrow range of values for this type of discharge. For the many leaders examined 90 per cent followed the preceding stroke after a time interval of between 50 and 90 microsec.[74] The elapsed time may be considered as the time necessary for the field about the tip to approach the critical value for ionization. There are two theories concerning the manner in which this growth can occur. According to the first theory the growth can be accounted for by the increase in electron density in the stem of the pilot streamer. This streamer carries a current which is maintained by the electron drift in the stem. If, however, the electron density is decreasing as a result of the capture and recombination processes, the current can only be maintained by an increase in the field strength in the stem. Ultimately, this field becomes large enough to effect the start of the step-streamer.

According to the second theory the elapsed time is actually the time required for a positive space charge to build up from the positive ions in the pilot stem. This includes the time necessary for the positive ions to gather in the neighborhood of the tip of the ste-streamer in order to establish a strong starting field.

In passing it may be of interest to note that in all probability the current in pilot streamers is never greater than 100 amperes, and usually less. However, it is estimated that the currents in the dart streamers are around 1,000 to 10,000 amperes and about 130,000 amperes for return streamers. These values are based on a charge destruction of 1 coulomb in 10^{-3} to 10^{-4} seconds for the dart streamers and a charge destruction of 1 coulomb in from 50 to 100 microsec. for the return streamers.

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74 Cf. ante, p. 49.

region of the molecule which is to be ionized, then it follows that

$$t = \frac{1}{n^{1/3} \times \bar{v}}$$

and the velocity of the streamer, V, is

$$V = \frac{d}{t} = n^{1/3} \times \bar{v} \times d$$

where d is equal to the distance BC in Fig. 11, n represents the density of the free electrons and $\bar{v}$ is the mean electron drift velocity.

It is, therefore, evident that the streamer velocity depends on the pre-existing electron density of the trail to be ionized, as well as on the electric field in front of the tip, which in turn determines the values of $\bar{v}$ and d. By substituting typical values into the equation just developed Schonland calculated the velocity of a streamer to be 1.03×10^9 cm./sec., which is 15 times as great as the velocity previously calculated for the pilot leader as it advances into unionized air.[73] It is evident, therefore, that all streamers which advance over paths which have been previously ionized travel much faster than the pilot streamer.

It is immediately apparent that the concentration of free electrons in the ionized trail decreases with time, and consequently, as the elapsed time between streamers becomes greater, the velocity of the streamer will become smaller. This conclusion has been verified photographically. It is also apparent that the velocity at the start of a return stroke is much larger

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[73] Cf. ante, p. 60.

It has already been mentioned that streamer luminosity is restricted to the leading tip and trailing regions. This luminosity depends on the value of the current. Leader and dart streamers are followed by lighttrails which are about 50 m. long, while the trail of light behind a return streamer is about 500 m. in length. In the latter case, however, it is observed that the base of the channel falls off considerably before the bright tip of the streamer has advanced half of the distance between ground and cloud. This localization of the main source of light implies that the light arises from excitation processes in the strong fields at the tip of the streamer where atoms and molecules are excited to high energy levels by electron impact. Since the tip has passed on before the particles can return to their normal states, the emmission of light, and the continued luminosity thus produced will be spread over a distance D behind the tip whose length is given by

$$D \geqq v\tau$$

where $\bar{v}$ is the velocity of the streamer and τ the mean life-time of an excited state. The symbol $>$ indicates the effect of those excited atoms which have a longer excitation time than the mean for the particles in the emitting region. Substitution of typical values of D and v in the above equation results in values of τ in the vicinity of 5×10^{-6} sec. This value checks with values of τ found in the laboratory.[75]

As the velocity of the streamers increase the brightness of the streamer also increases. This is to be expected because the velocity of the streamer is a function of the mean drift velocity, $\bar{v}$, of the electrons in a region ahead of the tip. The probability of excitation is known to rsie sharply with the electron velocity in the neighborhood of the ionization potential.

It may also be noted that the increased luminosity of a very fast streamer

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[75] K. Compton and I. Langmuir, "n.n. I", Review of Modern Physics, II, (1930), No. 2, cited by B.F.J. Schonland, Op. cit., p. 140.

implies a high field in front of the tip of the streamer, a large value of v, and a per centage of ionization which is larger than usual. This increased ionization provides the stem of the streamer with the conductivity necessary for it to carry the streamer current without an excessive fall of potential. As a result the potential at the tip is maintained at the value necessary for rapid progress.

It is now possible, from available photographic evidence, to distinguish two different types of stepped leader development. The most frequent, which may be termed type α, to be found when the leader process moves in a fairly regular manner to ground and without excessive branching. In such a leader the pilot or effective velocity is not much greater than the critical minimum for progress and ranges from 10^7 cm./sec. to 5×10^7 cm./sec. The field in front of the pilot is therefore not much greater than the critical breakdown field. Such leaders are found to be associated with the type of field-change record described by Appleton and Chapman as part (a) of an atmospheric.[76]

The second, or β-type of leader, occurred in about 30 per cent of the cases examined by Schonland. This type is, in its initial stages, very much faster and brighter than the α-type. All the high effective velocities which have been observed were found during the first portion of the path for this type of leader. This portion is always associated with an extensive branching process at the end. In a number of cases the discharge has ended in the air while still in the branched condition. More usually, however, the process continues onward to the ground with reduced velocity and ends in steps which faint and short. Occasionally the extensive branching and subsequent slower doenward development is repeated several times. It is natural to associate

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[76] Cf. ante, Fig. 6, p. 40.

the behavior of the leader process with the existence in the air of concentrations of positive space charge formed by the processes of point discharges first suggested by Wilson.[77] Such concentrations would lead to the formation of stronger electric fields than are usual between the cloud charge and the space charge, and this would explain the higher pilot velocities of the streamers which travel to them. Below such a concentration the field would be low and the pilot velocity would be much reduced.

Multiple stroke discharges were mentioned in connection with Fig. 10. It has been observed that single stroke discharges are the most frequent and that discharges with more than six strokes are rare. Furthermore, the multiple stroke discharge is more usually associated with the extensive and violent frontal type of thunderstorm than it is with the type which owes its origin to thermal convection.[78] Several explanations have been advanced to explain how multiple strokes are generated. Schonland's theory, as previously indicated, consists of the concept that charge centers employ the same ionized channel for their individual discharges.[79] After the necessary estimations and calculations it was concluded that the distance between cloud centers must be about 6 km. This appears to be excessive until the size of the cloud is considered. The diameter of a single charged cloud center is estimated at 1 km.

Since the work by Schonland is long and tedious, it will help to repeat

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[77] C.T.R. Wilson, "n.n.", Proceedings of the Physical Society, XXXVII(1925), 32d, cited by B. F. J. Schonland, Op. cit., p. 147.

[78] H. Norinder, "Some Aspects and Recent Results of Electro-Magnetic Effects of Thunderstorms. I and II", Journal of the Franklin Institute, CCVIL (August and September, 1947), 203.

[79] Cf. ante, p. 57.

the summary prepared by him.[80]

1. Oscillographic observations indicate that all processes in the discharge to ground observed in South Africa involve a cloud cathode and an earth anode.

2. The first lightning stroke appears to involve:

(a). The development of a pilot streamer, a negative streamer proceeding from the cloud into virgin air.

(b). The periodical catching up of this pilot streamer by a much faster step streamer, a negative streamer advancing along an ionized path.

(c). The distribution by this leader process of the greater portion of the cloud charge tapped by it upon a branched leader channel in the air below the cloud.

(d). The passage of this charge to ground in the return stroke, a positive streamer travelling along an ionized and oppositely charged path.

3. The second and subsequent strokes involve:

(a). A fast dart streamer, a negative streamer advancing along an ionized path.

(b). A return stroke streamer similar to 2d.

4. The mechanisms of the three types of streamers are investigated. Satisfactory explanation of their behaviour can be derived.

5. Discussions are given of the currents in the various streamer processes, of the luminosity associated with their movement, and the effect of space charge on leader development.

6. Evidence is given which indicates that the occurrence of separate strokes in the discharge is due to the presence in the cloud of separate charge-generating centers.

The last article available in the series on progressive lightning is part V. This article makes a comparison of the photographic and electrical approaches to the discharge process.[81] The investigators used the same Boy's camera arrangement employed for the earlier observations.[82] Electrical equipment similar to that first described by Appleton and Chapman was added.[83] For nearby storms Schonland, Hodges, and Collens used a short 2.4 m. length vertical antenna which was 33 cm. above the roof of a truck, which was driven

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80 B. F. J. Schonland, Op. cit., p. 149.

81 B. J. J. Schonland and D. F. Hodges, "Progressive Lightning V", The Proceedings of the Royal Society of London, CLXVI-A, (1938), 56-76.

82 Cf. ante, p. 57.

83 Cf. ante, p. 40. Fig. 5.

to the vicinity of the storms. For storms which were more than 20 km. from the laboratory a long stationary antenna was employed.

Records of the field changes produced by seventy-one discharges to ground and a much larger number of discharges within the cloud, have been obtained with this equipment. The data were gathered from more than thirty different thunderstorms. The greater portion of the paper is concerned with discharges to ground. From both the oscillographic and the photographic information it was possible to divide these discharges into two main classes.[84] An examination of Fig. 13 will recall the description of the "α" type of discharge, and, likewise, a study of Fig. 14 will reveal the nature of the "β" type of discharge. If these figures are compared with Fig. 6 it is possible to gain a better understanding of the parts of the discharge curve previously designated as parts (a), (b), and (c). About 65 per cent of all discharges to ground gave photographic records of the α-type, and 35 per cent the β-type.

A comparison can now be made of the discharge characteristics when examined by the two methods. Some of the comparisons made were itemized as follows:

(a) Identification of major field changes with successive strokes of the discharge.

(b) Identification of the field change with the leader process.

(c) The (b) and (c) field changes in the case of first strokes.

(d) The (b) and (c) changes for subsequent strokes.

(e) The polarity of discharge to ground.

Good correlation for the preceding comparisons were obtained by both field studies and by flash photography, except in case (e) where polarity

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[84] Cf. ante, p. 68.

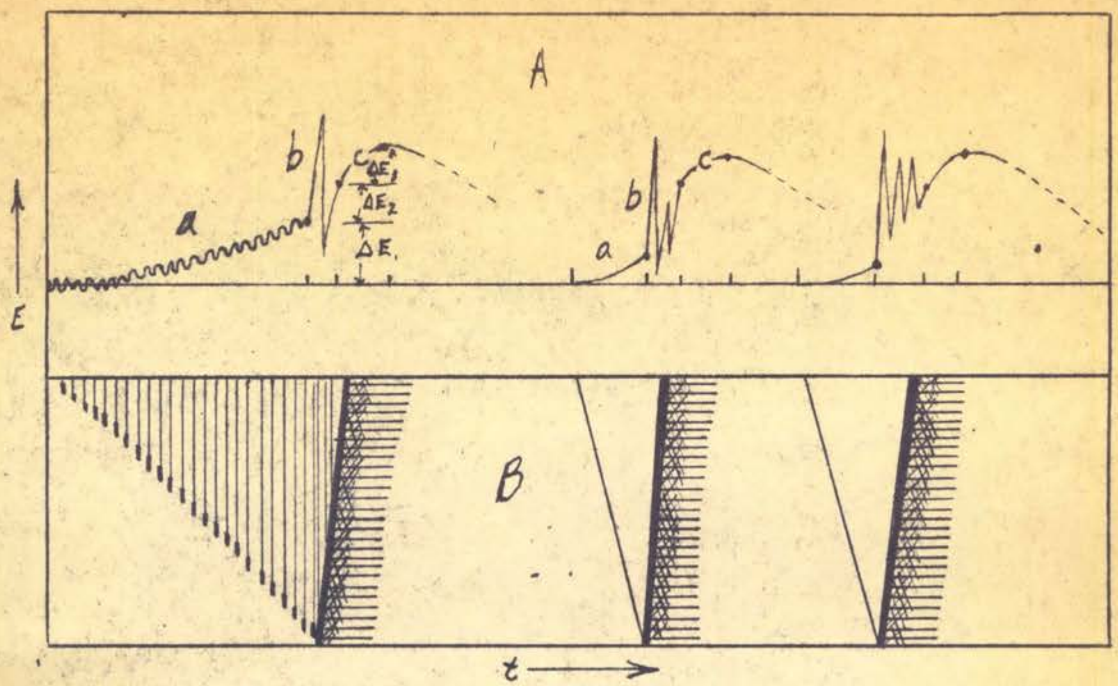

Fig. 13. Illustrating the corresponding parts of an α discharge when recorded by wave-form and flash photography.

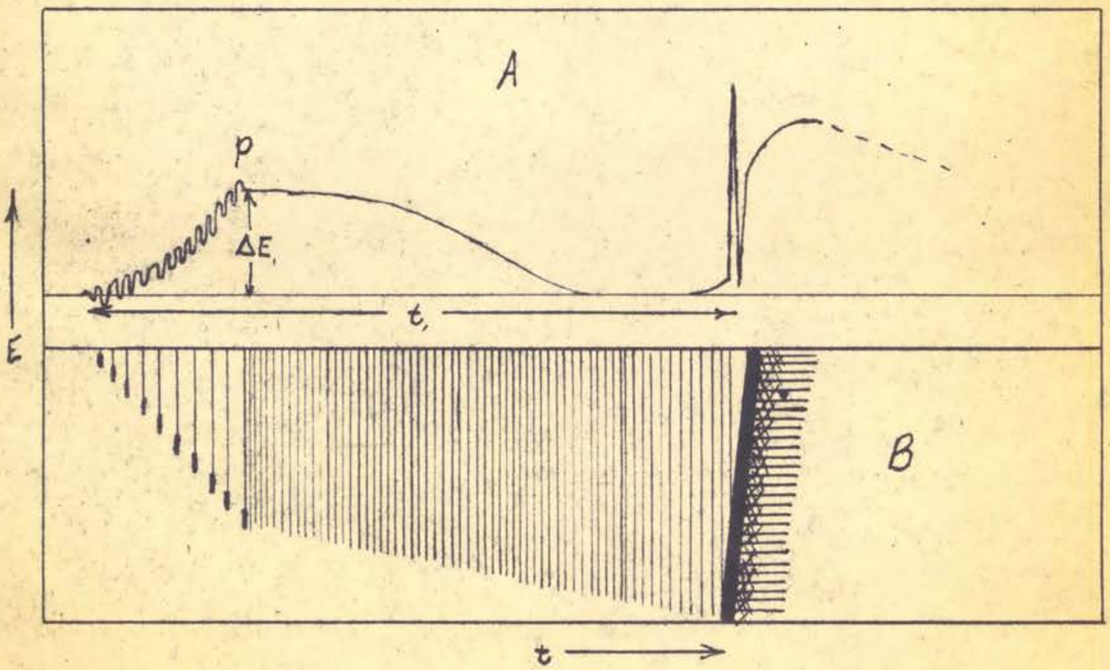

Fig. 14. Illustrating the corresponding parts of a β discharge when recorded by wave-form and flash photography.

comparisons were made. Only one flash to ground was observed which destroyed a positive cloud moment. It will be recalled that quite a high percentage of this type were observed during the field change studies of Norinder and others.[85]

A lengthy study was made of the electostatic field changes during the discharge to ground. Although these calculations and observations are restricted to ground strokes, many of the results will be applicable to all types of discharges. It is desirable to express field change in terms of charge per unit length of the streamer, cloud charge center height, velocity of streamer travel, and distance from the discharge. To follow this development the reader should be familiar with the charge phenomenon of a cloud.[86] It is postulated that a vertical streamer of downward uniform velocity v and charge q per unit length is lowering charge from the cloud to maintain newly formed sections. Such a leader streamer which has moved vertically downwards from a cloud center at a height H above the ground, will have reached a height H - vt after time t, and will carry a charge qvt upon its stem. The total electric moment of this charge, together with its image is 2qvt(h-vt/2), and this moment will produce a vertical field at a point on the ground at a distance L which will have the value

$$E = 2qvt(H - Vt/2)/L^3 \qquad \text{if } L \gg H$$

The expression H-vt gives the length of the stem, the electrical center of which is removed from the end a distance of vt/2. Since the charge qvt was initially at a height H, the resulting change of field is given by the

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85 <u>Cf.</u> <u>ante</u>, p. 57.

86 <u>Cf.</u> <u>ante</u>, p. 49.

relation

$$\Delta E = 2 q v t [H - (H - vt/2)]/L^3$$
$$= q v^2 t^2 / L^3$$

If, as has been supposed both q and v are constant; then there results for a given distance L, $E \propto t^2$. This means that the form taken by the field-change record of the leader process will be a parabola which is concave upwards. This parabolic curve is a characteristic feature of a field change and is clearly evidenced in some of the reporduced traces, and as illustrated in Fig. 13.

For a straight leader channel at an angle θ to the vertical a similar treatment yields,

$$\Delta E = q v^2 t^2 / \cos\theta \, L^3$$

which is again a parabolic relationship. Thus it happens that a leader which begins with a channel which is practically horizontal will produce an initial field change which is small compared to that due to its latter and more nearly vertical channel. Discharges from a horizontal channel are quite often observed and field changes of a corresponding nature are frequently found.

Since a β-type leader travels at high velocity in its first phase, cathode-ray photographs show a very pronounced parabola for this first phase and then no activity until the return stroke occurs. In fact, the pause between the fast leader and return stroke was greater than the time constant. and the trace dropped to zero. This is shown in Fig. 13.

The effect produced by tortuosity in the channel must be examined in detail. In the case to be considered the leader travels vertically for a time t_1 and then moves at an angle θ to the vertical for a further time t_2. If q and v are again constant, the field change after a time $t_1 + t_2$ will be

$$\Delta E = q v^2 (t_1^2 + 2 t_1 t_2 - t_2^2 \cos\theta)/L^3$$

In practice θ does not often exceed $\pi/2$ radians, and in this case

$$\Delta E = (q v^2 t_1^2 + 2 q v^2 t_1 t_2)/L^3$$

$$= [\Delta E]_{t_1} + \left\{\frac{d}{dt}[\Delta E]_{t_1}\right\} t_2$$

Thus if the streamer turns abruptly from the vertical to the horizontal at t_1 the next field change after this event will follow a straight line tangential to the parabola at t_1. For a turn of less than $\pi/2$ radians the field change will be intermediate between the parabola and its tangent at t_1.

Up to this point of the discussion it has been assumed that q is uniform along the channel. This can be verified by finding the ratio between $\Delta E_1/\Delta E_2$ as determined by using the equations involving a uniform q together with the measured values recorded on the field change equipment. Let Q be the total charge distributed along the leader channel at the moment it reaches the ground, and H/n it's effective height above the ground. For a straight channel and uniform charge per unit length, n= 2. It is seen that the total leader field change is given by

$$\Delta E_1 = \frac{2QH}{L^3} - \frac{2QH}{nL^3} = \frac{2QH}{L^3}\left(1 - \frac{1}{n}\right)$$

$$= \frac{2QH}{L^3}\left(\frac{n-1}{n}\right)$$

It must be remembered that these equations were deived with the limitation that $L \gg H$.

The leader field change, which effectively lowers Q from H to H/n, is followed by the return, or part (b) field change, which lowers it from H/n to ground and follows the relation

$$\Delta E_2 = \frac{2QH}{nL^3}$$

There now results

$$\frac{\Delta E_2}{\Delta E_1} = \frac{2QH/nL^3}{2QH(n-1)/nL^3} = \frac{1}{n-1}$$

and if n=2, as previously stated, it follows that

$$\frac{\Delta E_2}{\Delta E_1} = 1$$

Statistical data verified the value of unity for this ratio. This result in turn verifies the assumption of uniform charge distributed along the stem. It has been found in the case for β-type leaders that the ratio of ΔE_2 to ΔE_1 is generally about 0.1. This smaller value supposedly results from a space charge which neutralizes the charge postulated by Schonland.[87]

Schonland, Hodges, and Collens claim that the field will reverse if the observer is sufficiently close to the discharge. Since the preceding equations were derived for L H, they do not apply to this case.

There is always a possibility that some of the charge may be left behind on the cloud after (a) and (b) portions of the discharge. It must be kept in mind that the changes in field intensity, ΔE_1 and ΔE_2 are associated with the part (a) and part (b), respectively. The field change due to the return stroke lowers a charge Q to the ground, and is given by the relation,

$$\Delta E_1 + \Delta E_2 = 2QH/L^3$$

If the whole of the final field part (c) is due to the subsequent passage to ground of a charge Q' which was left by the return streamer in the original center of charge in the cloud, this final charge is given by

$$\Delta E_3 = 2Q'H/L^3$$

Therefore

$$\frac{Q'}{Q} = \frac{\Delta E_3}{\Delta E_1 + \Delta E_2}$$

or

$$\frac{Q'}{Q+Q'} = \frac{\Delta E_3}{\Delta E_1 + \Delta E_2 + \Delta E_3}$$

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87 Cf. ante, p.68.

The latter is an equation from which can be estimated the fractional part of the original charge left in the cloud after the leader process has reached the ground. A distribution curve of experimental observations shows that 30 per cent of the charge most frequently remains behind for first strokes and 50 per cent for subsequent strokes.

So far only the electrostatic field has been dealt with. Recalling that

$$E = E_s + E_i + E_r = \frac{M}{L^3} + \frac{1}{CL^2}\frac{dM}{dt} + \frac{1}{C^2L}\frac{d^2M}{dt^2}$$

where M is the total moment of all the cloud charges at time t- L/c, there results

$$\frac{E_i}{E_s} = \left[\frac{1}{M}\frac{dM}{dt}\right]\frac{L}{C} \quad \text{and} \quad \frac{E_r}{E_s} = \left[\frac{1}{M}\frac{d^2M}{dt^2}\right]\frac{L^2}{C^2}$$

For all measurements taken L/C was of the order of 5×10^{-5} henries/farad. Therefore, unless the rate of moment destruction is tremendous the values are negligible. As previously concluded the rapid step leaders and return stroke are most evident and good correlation of photographic data was obtained. This includes the β-type leader.

Field changes due to discharges within the cloud have often been found to be without the (b) part of the discharge process. The usual field change obtained from an internal cloud discharge consists of a simple slow rise to a final maximum. This rise usually carries superimposed pulsations of the same kind as those found for the stepped leader process and accompanied by the same time intervals between pulsations. This type of discharge was very similar to the β-type discharges, which is also a space discharge. Schonland, Hodges and Collens claim to have established a difference between cloud and ground atmospherics. This work should provide a starting point for classification studies.

There are many more excellent references on the subject of atmospherics, but only a few can be treated here. A scientist who has done work of acclaim in the last quarter century or more is Harold Norinder of Sweden.[88,89,90,91] His work verifies many of the early discoveries of the British group reviewed in the early part of this chapter.[92]

Of particular interest is the most recent work of Norinder in which an analysis is made of the lightning stroke in terms of its magnetic field and the associated current.[93] The reason for this angle of approach is immediately obvious when it is disclosed that a shielded loop was used for the antenna. It was found that intergration of the induced antenna voltage was necessary because the induced voltage was proportional to dH/dt. Integration was performed by an RC circuit incorporated in the antenna arrangement. Amperes law was employed to deduce the relation between the induced antenna voltage and lightning current.

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88 H. Norinder, "On the Nature of Lightning Discharges", _Journal of the Franklin Institute_, CCXVIII, (December, 1934), 717.

89 H. Norinder, "Lightning Currents and their Variations", _Journal of the Franklin Institute_, CCXX, (July, 1935), 69.

90 H. Norinder, "Cathode-Ray Oscillographic Investigations on Atmospherics", _Proceedings of the Institute of Radio Engineers_, XXIV, (February, 1936), 287-304.

91 H. Norinder, "Some Aspects and Recent Results of Electromagnetic Effects of Thunderstorms I and II", _Journal of the Franklin Institute_, CCVIL, (August and September, 1947), 109-130 and 167-207.

92 _Cf. ante_, p. 32.

93 H. Norinder, _Loc. cit._, "Some Aspects and Recent Results of Electromagnetic Effects of Thunderstorms I and II".

Some notable work on atmospherics has been accomplished in the United States by Mc. Eachron in the high voltage laboratory of the General Electric Company in Pitsfield, Mass. For many years measurements were taken on lightning currents. Lately many flash photographs have been obtained from the top of the Empire State Building and a number of significant articles have been prepared.[94,95,96,97,98,99,100,101] Improved techniques have been evolved for obtaining high and low speed records of current changes.

The current is measured from the drop across a nonlinear thyrite resistor. The equipment is started by the lightning discharge, and a complete record was obtained by the use of delay network. Complete details on the measuring

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94 K. B. Mc. Eachron and W. A. Mc. Morris, "The Lightning Stroke: Mechanism of Discharge", General Electric Review, XXXIX, (October, 1936), 487.

95 K. B. Mc. Eacheron, "Lightning to Empire State Building", Journal of the Franklin Institute, CCXXVII, (February, 1939), 194-217.

96 J. H. Hagenguth, "Lightning Recording Instruments I", General Electric Review, VIIL, (May, 1940), 195-201.

97 J. H. Hagenguth, "Lightning Recording Instruments II", General Electric Review, VIIL, (June, 1940), 248-255.

98 J. W. Flowers, "Direct Measurement of Lightning Current", Journal of the Franklin Institute, CCXXXII, (November, 1941), 425-450.

99 C. F. Wagner and F. McCann, "Lightning Phenomena", Electrical Engineering, LX, (August, September, October, 1941), 374-384, 438-443, 483-500.

100 K. B. Mc. Eacheron, "Lightning to Empire State Building", Electrical Engineering, LX, (September, 1941), Trans.

101 G. D. McCann, "The Measurement of Lightning Currents Direct Strokes", American Institute of Electrical Engineers, (May, 1944, Transactions.

equipment and its use are given by the author.[102, 103] Some of the findings which may be of interest to this project are:[104]

1. Oscillograms and/or moving film Boy's camera photographs have been taken of 55 strokes to the Empire State Building.
2. Direct current arcs, with or without superimposed current peaks, extending between the cloud and the building continuing as long as 0.4 seconds, have been measured. These are called continuing strokes.
3. Upward leaders from the building which developed into continuing strokes have been photographed and data as to velocity of propagation secured. (upward leader velocities range between 0.17 ft/microsec. and 2109 ft./microsec. with an average of 0.84 ft./microsec.)
4. Currents measured during build-up of upward stepped leaders range from 50 to 650 amperes.
5. Branching was found to be in the direction of propagation of initial leader strokes.
6. At least 50 per cent of the strokes had a charge of 35 coulombs or more with a maximum of 164. These values are several times as large as heretofore believed probable.
7. All strokes to the building began with the cloud negative. 3 strokes changed to positive at or near the end of the stroke. About 3 per cent of the total charge measured was associated with the positive portion of the strokes.
8. Downward stepped leaders to the building were observed in one case only which had a velocity of 14 ft./microsec. A stroke to a building 200 ft. in height had a downward stepped leader velocity of 5 ft./microsec.
9. Leaders on all discharges after the first were always downward whenever found, whether the initial leader was upward or downward. Such downward leaders had velocities ranging from 1.9 ft./microsec. to 128 ft./microsec, with an average of 39 ft./microsec.
10. Return stroke velocities following initial stepped downward leaders were 340 ft./microsec. and 150 ft./microsec. in the two cases recorded, while the return stroke velocities following continuous leaders ranged from 98 ft./microsec.
11. Every stroke, but two, of which Mc. Eachron has recorded either struck the highest point on the Building or outside a cone whose base radius at the ground level was equal to the building height.

Of considerable interest is a very recent study on wave-forms now being conducted at the University of Florida.[105] These investigations were carried

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102 J. W. Flowers, loc. cit.

103 G. D. Mc. Cann, loc. cit.

104 K. B. Mc.Eacheron, Op. cit., (1939), p. 212.

105 "Direction Finding and Ranging on Atmospherics", Department of Electrical Engineering and Industrial Experiment Station, University of Florida, Gainsville, Florida, Final Report to the U. S. Army Signal Corps Engineering Laboratories, Contract No. w 28-003-SC-1306, (September 17, 1948).

out in an attempt to establish a method for the ranging of atmospherics on the basis of a wave-form change that might possibly be a function of distance. The first efforts were based on the use of reflections from the ionisphere. By assuming that the period of an atmospheric could be determined by the time required for a reflection to return from the ionisphere, it was considered possible that a relationship might be found that would permit the determination of the distance to the atmospheric source. Observation of daytime atmospherics demonstrated that the wave-form is unaffected by the distance of propagation. The ranges of the atmospherics investigated were well over 200 km. The investigators are now in the process of gathering data from night atmospherics. A study of the spectrum contained in the atmospheric as a function of the distance to its origin is also being conducted.

The investigators in Florida came to the conclusion that atmospheric wave-forms are not modified by long distance propagation. In contrast to these conclusions is a statement recently made to the contrary by Wormell and Pierce in England.[106] This is not especially alarming because this condition is typical of most of the literature in the field of atmospheric studies. When the enormous complexity of the problem with its attendant difficulties is realized, such divergence of opinions is easily understood.

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106 T. W. Wormell and E. T. Pierce, "Atmospherics", Journal of the Institution of Electrical Engineers, VC, Part III, (September, 1948), 331.

CHAPTER VI

MEASURING METHODS

The present research project has for its objective the continuation of the work that was started by Mr. Carl Miller during the spring of 1948 on the development of methods and equipment for the detection and tracking of tornadoes.[107] In the time allotted for his thesis, Mr. Miller was able to get the project well under way. He originated many of the ideas that may later lead to a successful completion of the project, and succeeded in developing preliminary equipment with which a thorough survey of the field could be made. The equipment that was designed to detect and amplify the field strength pattern of an atmospheric so that it would appear undistorted on the screen of an oscilloscrope, from which photographs could be taken by a moving-film camera. The receiver was a modified piece of aircraft equipment with its original loop antenna operated at 200 kc.p.c. The detected wave-form was picked up at the output of the intermediate frequency amplifier and fed to the vertical amplifier of the oscilloscope. The camera was a 16 mm. model with the moving-film adjusted to take 16 frames per second. With this equipment, Mr. Miller was able to obtain pictures of the characteristic wave-forms of the atmospherics that were produced by thunderstorms in the Oklahoma area. At the same time he established a preliminary routine that was designed to lead to the study of tornado characteristics. Mr. Miller relinquished the

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[107] Carl W. Miller, "A Proposed Method of Identifying and Tracking Tornadoes," (unpublished Master's thesis, Oklahoma A. & M. College, Stillwater, Oklahoma, 1948).

project to the author of this thesis in the fall of 1948. In order to facilitate the study of any tornadoes that might occur in the spring of 1949 it was decided to make some changes in the equipment. Mr. Miller had spent considerable time in his careful redesign of the receiver circuit and had succeeded in producing a final design that fulfilled the rigorous requirements necessary for a receiver intended for the detection and faithful reproduction of atmospheric wave-forms.

Since the receiver was adequate for the proposed project it was decided to improve on the auxiliary equipment in order that it might more adequately perform the task for which it was intended.

Through the cooperation of the Engineering Research and Development Laboratory of the Oklahoma A. and M. College there was constructed a new type of hood and stand that would permit more convenient and better photography. In order to facilitate high quality delineation of the wave-forms a model 250 Dumont Oscillograph was purchased by the School of Electrical Engineering. Whatever turn the research may take in the future, this oscillograph will undoubtedly suffice, because it is so well suited for transient studies. It has many excellent features which lend to it's value in research problems. A 5CP11-A cathode-ray tube was ordered with the oscillograph in order to obtain better photographys, and a 5CP2-A was included for visual use where long persistance is a necessity.

As experience was gained by using the equipment it became obvious that better methods for obtaining the data would be developed. However, since the tornado season was approaching, it was decided to use the existing equipment for the spring and summer of 1949, and in the meantime complete the design of the proposed equipment. The existing equipment and methods have several drawbacks, of which a few will be mentioned. The moving film camera exposes film at the rate of 16 frames per second. Film is used much too fast for economy. This condition assumes an even more serious aspect when it is realized that it is only by chance that the shutter will be open during the time a trace appears on the oscillograph screen. Again, it is desirable to change the equipment used in receiving the atmospherics. The 200 kc.p.s. band is too far above the 10 kc.p.s. band in which the major part of the energy of an atmospheric exists. The detected wave-form now being received at 200 kc.p.s. is the rectified envelope of the electromagnetic wave. From the previous chapter, it will be recalled that the "slow-tail" was the smoothed form of the high frequency components.[108]

It was decided that in order to better satisfy present requirements a different system of receiving, delineation, and recording should be adopted. The use of an anticipatory circuit was considered but this idea was discarded on the grounds that such a system would bring only those atmospherics with a prescribed type of precusor characteristic.[109] After a study of the system used by the British, it was adopted after a number of modifications had been decided upon.[110]

It soon became obvious that the writer would not have sufficient time to design and build all of the new equipment. At this time Mr. Harold Jeske became interested in the project from the equipment standpoint. He has agreed to build the receiving equipment, control circuits, and to direct the modification of a 35 mm. camera by the Research and Development Laboratory. This

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108 Cf. ante, p. 42.

109 B. J. J. Schonland and J. S. Elder, "Anticipatory Triggering Devices for Lightning and Static Investigations", Journal of the Franklin Institute, CCXXXI, (January, 1941), 39-47.

110 R. A. Watson Watt, J. F. Herd, and L. H. Bainbridge-Bell, Applications of the Cathode-Ray Oscillograph in Radio Research, pp. 75-80.

work is progressing very well at the present time and it is expected that final tests can be completed before the end of the semester. It is now desirable to discuss the new equipment from a functional viewpoint. Some of the features of the equipment under construction are:

1. Omnidirectional antenna.
2. Frequency coverage from below 100 c.p.s. to 200 kc.p.s.
3. Integrating circuit for values of dE/dt received from antenna.
4. Triggered single sweep per wave-form.
5. Camera shutter open at all times.
6. An atmospheric oscillogram on every picture frame.
7. The time and date on every picture.
8. Triggered beam control; no cathode-ray spot between traces.
9. Adjustable threshold triggering signal.
10. Conservation of film.
11. Equipment that will operate unattended in order to obtain recorded samplings over long storm periods.
12. Adjustable blocking off time in order to regulate time between samplings.
13. Remote antenna to eliminating local noise.
14. Timing markers on the oscillogram with the wave-form.

The value of most of these features is evident. Some explanation should be made for others. In order to determine the existence of a storm which is beyond the horizon it will be necessary to receive atmospherics from all directions. Included in the design of the apparatus must be a direction finding device which will indicate the azmuth of the detected storm. To accomplish this an antenna arrangement very similar to that used at the University of Florida will be employed.[111] In view of the fact that it is

111 "Direction Finding and Ranging on Atmospherics", Op. cit., p. 30.

not certain what peculiarities in wave-form might be found, it is best to receive any and all appreciable signals; this is the purpose of the low frequency amplifier of a 200 kc.p.s. range that is included in the specifications.

It is of the utmost importance to know the exact time and date of every oscillogram. The facilities of the U. S. Weather Bureau, while not designed to furnish immediate reports of tornado action, are set up to provide accurate accounts of a tornado which has passed through a given area. Therefore, it becomes necessary for the investigator to record the atmospherics during all storms in accordance with the requirements of the wave-form studies, in order that the particular oscillograms taken during the reported time of a tornado may be singled out for study. When storm periods exist for a day or so, it is necessary that samples be taken over the total time. If the equipment can be designed so as to automatically take a sample at determined intervals, considerable time and film will be conserved. It is necessary that the antenna be placed far enough from the recording equipment to eliminate 60 c.p.c. power disturbances. It is understood, of course, that the station must be located some distance outside the city so that the fields from heavy power lines and equipment will not be present. The site for the station will be determined experimentally.

It is of interest to mention briefly the system used at the University of Florida. As mentioned before, the antenna circuit was similar to that used in England, except that the impedance from ground to antenna was maintained about 1 megohm and the signal was not integrated. The oscillograph was triggered by a signal of proper strength to start the cathode-ray beam. The 35 mm. camera provided a 1 in. p.s. film speed. This is negligible compared to the sweep speed of the oscillograph. A simultaneous "direction finding trace" appears on a second CRO tube which is adjacent to the CRO tube which carries the wave-form. By means of this arrangement both the wave-form and its direction are photographed simultaneously. The indication of direction has a 180 deg. ambiguity due to the nature of the crossed loop antenna direction finding system. Triangulation methods are employed in order to overcome this difficulty. In fact, three stations are employed in order to accurately locate the storm area. Time signals were projected on the flim by a small neon lamp which was actuated by the time signals from station WWV at Washington, D. C. Since the film was moving a dash was recorded for the one second intervals, while the five minute time intervals were recorded in Morse code. A reproduction of a typical record taken at the University of Florida is included in Fig. 15. The time marker is a very desirable feature. Mr. Jeske intends to incorporate this device in the new equipment.

Since the direction indication is very necessary for tornado identification studies, it is very important that this feature be incorporated into the equipment. Mr. Thomas Thomason is at present working on the design and development of this part of the equipment. This feature will be incorporated into the equipment provided by Mr. Jeske. Mr. Thomason expects to have his equipment built and tested by the end of July. The design and construction of the new equipment should be completed so that it will be ready to function by the time the Autumn storms begin to appear.

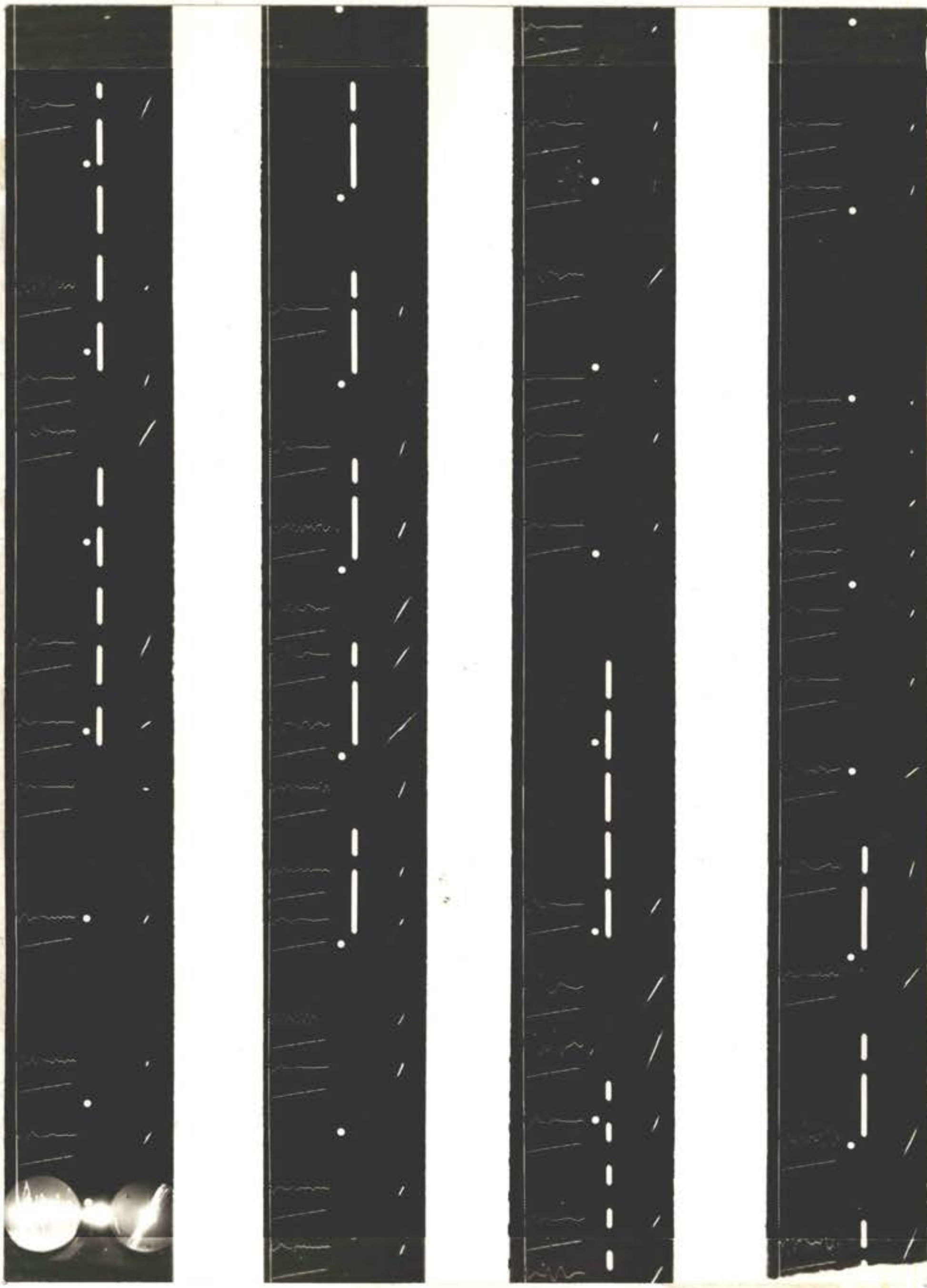

Fig. 15. Typical Wave Form Records Taken at the University of Florida.

CHAPTER VII

ANALYSIS OF RESULTS

Oscillograms are reproduced in Figs. 16 to 33, inclusive. These are typical of the atmospherics that were received from November, 1948 to May, 1949. The particular wave-forms shown are from several storms in May. In the discussion of equipment it was explained that a moving film type of camera was used. The picture, if any, was dependent on the appearance of a trace at the instant when the shutter was open. Since atmospherics occur at random, about 75 per cent of the developed frames were blank. The film was edited by clipping out all of the oscillograms that were usable. If the storm period was very heavy with atmospherics a higher percentage of desirable oscillograms were obtained. The oscillograph sweep period was 1/240 sec., or 4,170 microsec. This particular period was employed because of the ease of adjusting the sweep when a frequency of 60 c.p.s. was applied to the input of the vertical amplifier. An expanded sweep was used for part of the pictures. However, this reduced the probability of obtaining a picture and resulted in more film waste. It was first thought that an expanded sweep would be desirable, but it developed that the lower persistence of the 5CP11-A cathode-ray tube was found to be much shorter than that of the 5LP1 cathode-ray tube used by Miller. The expanded sweep consisted of a 60 c.p.s. frequency which was adjusted so that only a quarter of a cycle appeared on the screen. The camera was operated at 16 frames per second for all data except that taken on March 26, 1949. At that time it was operated at a speed of 32 frames per sec. The only purpose served by the higher speed was that of

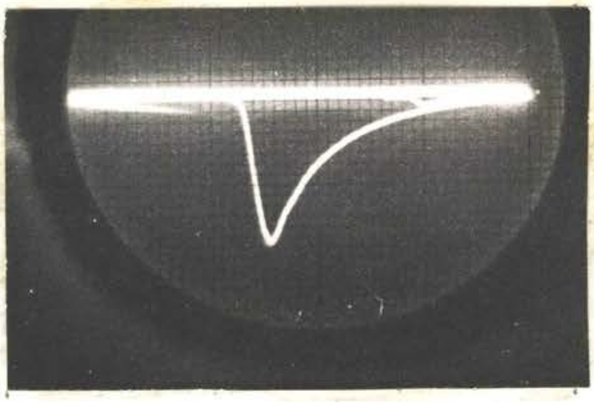

Fig. 16.

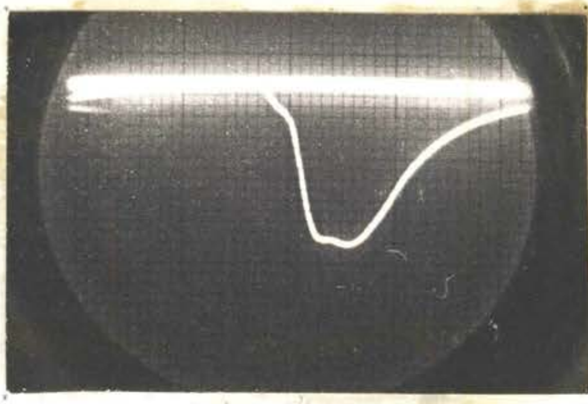

Fig. 17.

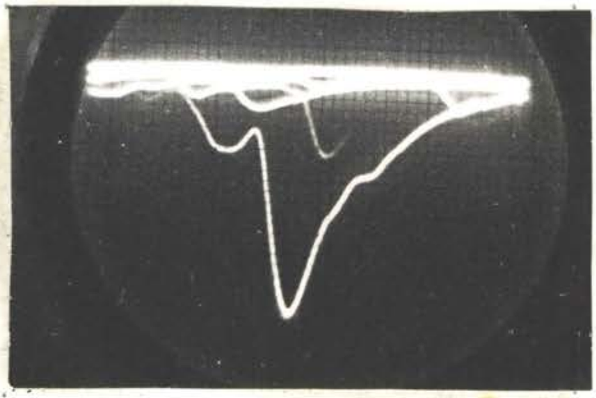

Fig. 18.

Fig. 19.

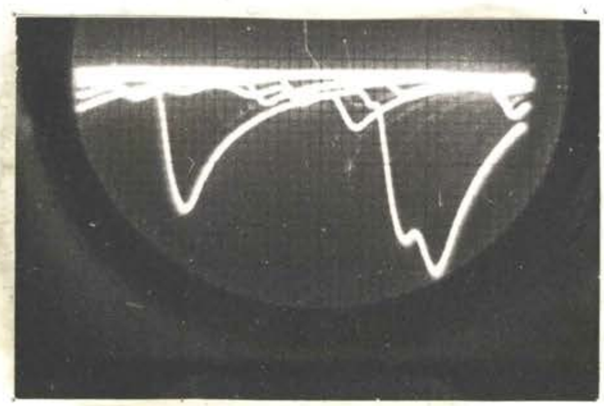

Fig. 20.

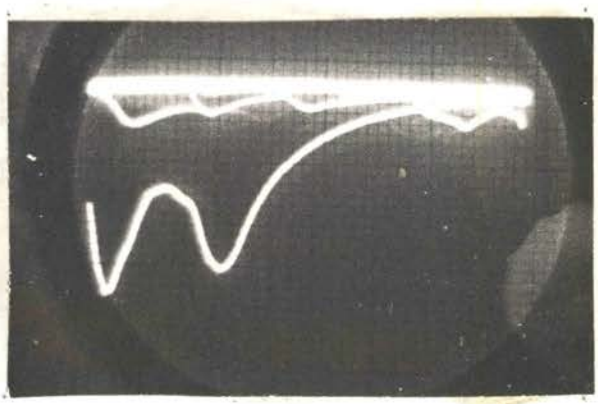

Fig. 21.

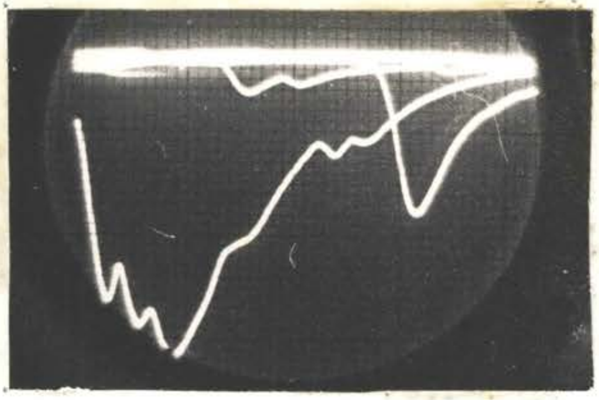

Fig. 22.

Fig. 23.

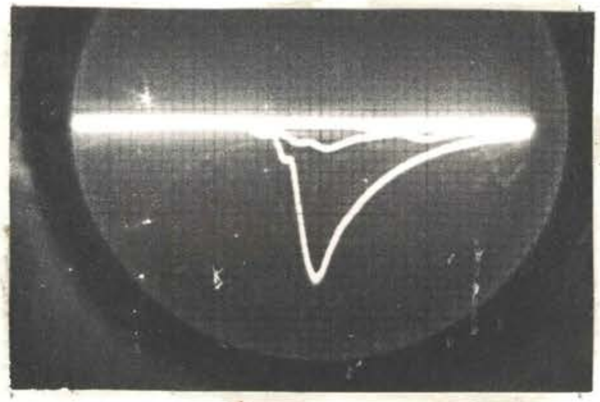

Fig. 24.

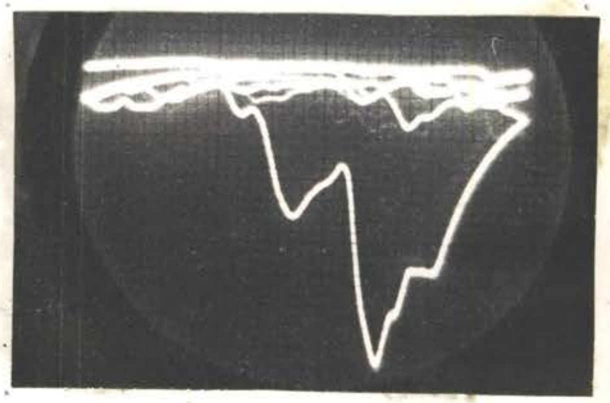

Fig. 25.

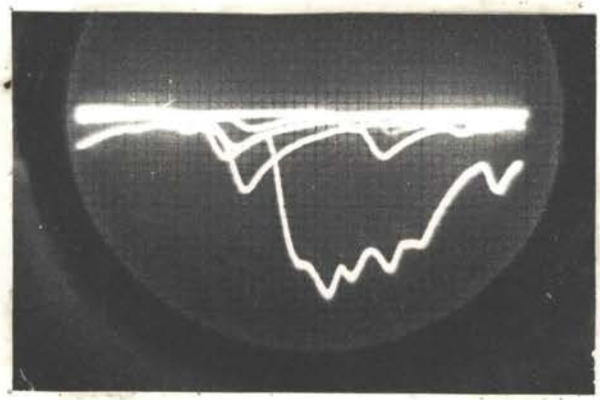

Fig. 26.

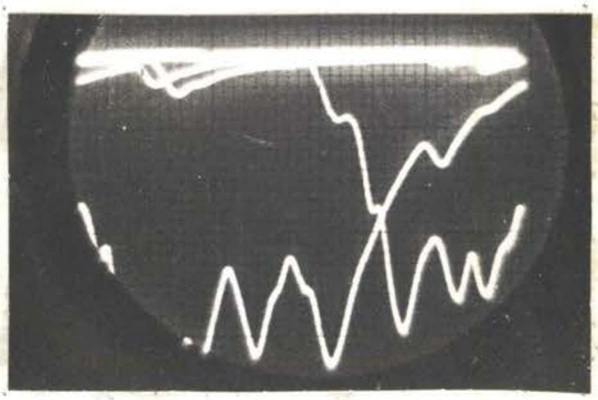

Fig. 27.

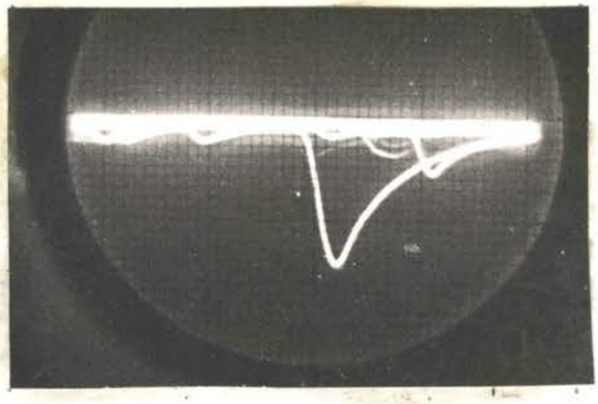

Fig. 28.

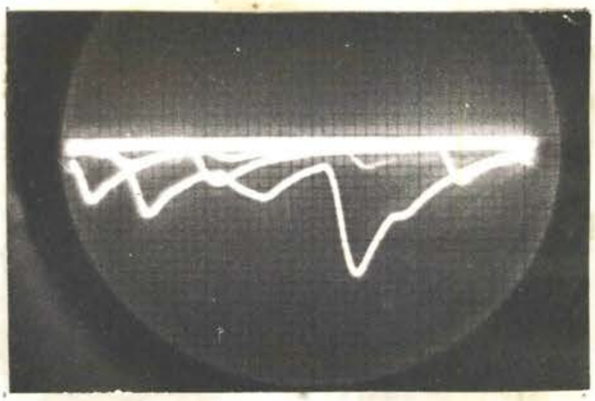

Fig. 29.

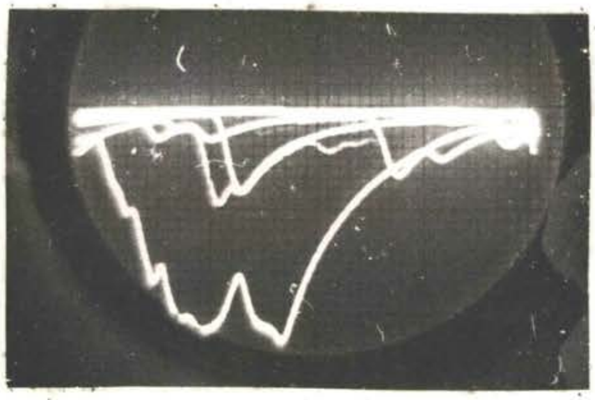

Fig. 30.

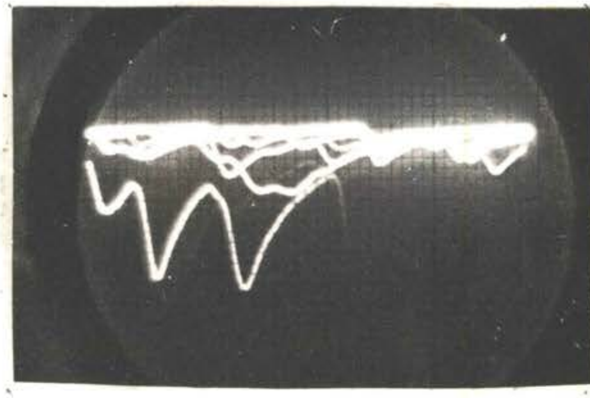

Fig. 31.

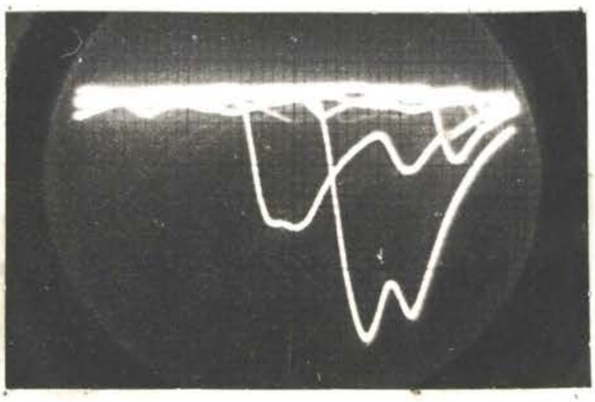

Fig. 32.

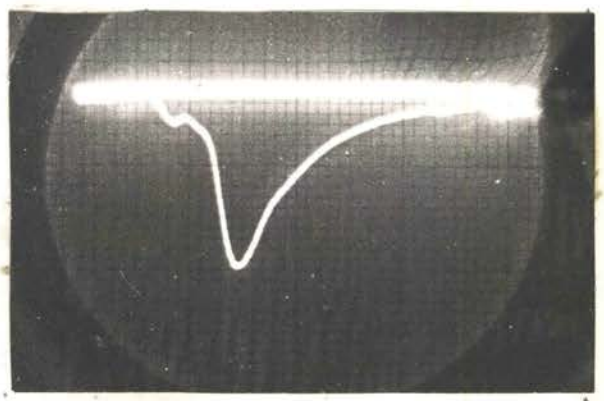

Fig. 33.

investigation. From the results obtained in this it was decided that 16 frames per second is the most satisfactory. The film used throughout was 16 mm. Cin'e-Kodak, Super-XX high speed panchromatic safety. By operating with the oscilloscrope adjusted to full intensity and with a camera speed of 16 frames per second, very sharp contrast resulted.

So far no data has been recorded at the exact time a tornado has been known to be in progress. However, data has been obtained with a short time of the occurrence of two tornadoes. At 3:15 a.m., March 26, 1949, a tornado struck Crowder, Oklahoma; data was taken at 12:15 a.m. on the same day. At 12:15 a.m., March 30, 1949, a devastating tornado demolished Canton, Oklahoma, and at 3:15 a.m. of the same morning did damage at Blackwell, Oklahoma; data was taken at 9:30 p.m. and 10:30 p.m. or some three hours before the tornado struck. Though this data wasn't taken at the exact time of tornado damage, it is possible that the tornado cloud may have been in the process of formation during the time the records were made. Again it must be stressed that with the present equipment it is not possible to know which, if any, of the atmospherics originated at the tornado area. When the equipment now under construction is finished, this difficulty will be almost entirely overcome.

In regard to the wave-forms depicted by the oscillogram, it should be understood that the receiver output is a detected half-enveloped of the 200 kc.p.s. atmospheric. The signal as received consisted of a frequency of approximately 200 kc.p.s. This signal was amplified in the intermediate stages, and passed on to the detector. The out-put voltage from the receiver was taken directly from the detector and fed to the vertical amplifier of the oscilloscope. The pictures have been reproduced in such a way that the sweep is shown as operating from left to right. This results in a picture of the oscillogram that is exactly the same as the original trace on the front of the oscilloscope.

It is the opinion of the writer that nearly all of the wave-forms are the detected envelopes of a 200 kc.p.s. damped oscillation which may or may not be modified by other type of interference. In Fig. 16 is shown a typical example of this type of unmodified envelope. Note that the rise is quite sharp and is a function of the build-up time for the oscillation. The steepness of rise varies from wave-form to wave-form. The decrease of this wave-form closely simulates a logarithmic decreement that is characteristic of a damped oscillation. Previous indications also found this to be the case for the α-type and β-type leaders.[112] Since the receiver was tuned to 200 kc.p.s. it is quite likely that the leaders contributed to oscillograms shown here.[113] Many times the atmospherics were very numerous in spite of the fact that no lightning was visible. There is a possibility that these disturbances consisted of group 2 or group 3 leaders as classified by Lutkin. This cannot be definitely determined by the present observations, however, because the directions and distance from the disturbance are unknown.

It is to be expected that the wave-forms detected in the present research would have characteristics in common with the "slow-form" reported by Appleton, Watt, and Herd.[114] The slow-form was reported to have a period of 1.5 to 2.5 msec. in its first quasi-half cycle. When it is recalled that the time base of the present oscillograms is 4.17 msec. it will be seen that the results agree remarkably well. It will also be noted that the wave-form

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112 <u>Cf.</u> <u>ante</u>, p. 64, Figs. 12 and 13.

113 <u>Cf.</u> <u>ante</u>, p. 48.

114 <u>Cf.</u> <u>ante</u>, p. 45.

shapes obtained by Miller corresponded with the hand-delineated wave-forms obtained by the early experimenters.

The oscillograms shown in Fig. 17 to 33 inclusive are typical of wave-forms found frequently in aggregate data. These wave-forms are similar to that shown in Fig. 16 except for various modifying transients which appear on the oscillograms. The source of these stray oscillations might be traced to far distant thunderstorms, or to the reflections of the same disturbances from the ioisphere. The University of Florida has conducted some significant investigations on reflections from the ionisphere. These investigators are particularly interested in eliminating the errors that exist in the direction finding and ranging of atmospherics. It is considered possible that at least some of these additional transients might be attributed to the other two field components that were found by Lutkin to produce similar complexities when the source of the atmospherics was less than 100 km. away.[115]

There remains a possibility that these various wave-form modifications are due to some peculiarity of the return stroke. It is not possible at the present time to decide this matter definitely. Search is still under way for some peculiarity in the atmospheric discharge that will permit definite identification of a tornado by its atmospheric wave form. Up to the present time nothing conclusive has been found that will establish this identification. On the basis of visual observation of the lightning discharges of a tornado it is believed that there is a reasonable possibility that such wave-form characteristics exist. When these are found it will be possible to track the tornado.

It is in order to include a few statements relative to the status of the present project, the equipment, and the objectives to be attained.

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115 Cf. ante, p. 54.

1. So far atmospherics have been received only in the range of the spectrum around the frequency of 200 kc.p.s. The maximum energy of an atmospheric is found at about 10 kc.p.s.
2. New untuned receiving equipment is planned which will provide an oscillogram of the actual atmospheric as received.
3. The present antenna is to be replaced by a omnidirectional antenna.
4. The new equipment will result in a picture on every frame.
5. Atmospheric wave-form samples will be selected by the equipment and the necessity for classifying great quantities of similar data will no longer exist.
6. The equipment will be automatic in operation and will greatly increase the probability of obtaining wave-forms from a tornado.
7. A direction will appear on the oscillogram, so that the direction of the source of a particular atmospheric may be known.
8. Many factors discussed in this paper have a bearing on the wave-form. Among these factors can be listed distance, ionispheric reflection, multiple strokes, and atmospherics which are received simultaneously.
9. There are a number of possible approaches which should be considered in the future.
   (a). Long spark-discharges about which air is moving at high velocity should be investigated.
   (b). The precusors for the β -type discharges which might occur during a tornado should be studied by use of high speed film on a rotating drum.
   (c). Time variations of multiple strokes in tornadoes should be investigated.

(d). The possibility of tracking tornadoes with Radar and identifying them by atmospherics wave-forms should be considered.

(e). At least two receiving stations should be employed in order to eliminate the 180 degree ambiguity that results when only one station is used.

(f). The field station should be established in an area some distance from the city in order to avoid local interference. The Florida station is several miles from Gainsville.

(g). Investigation should be made of the application of antennas when used with untuned circuits for wide band reception.

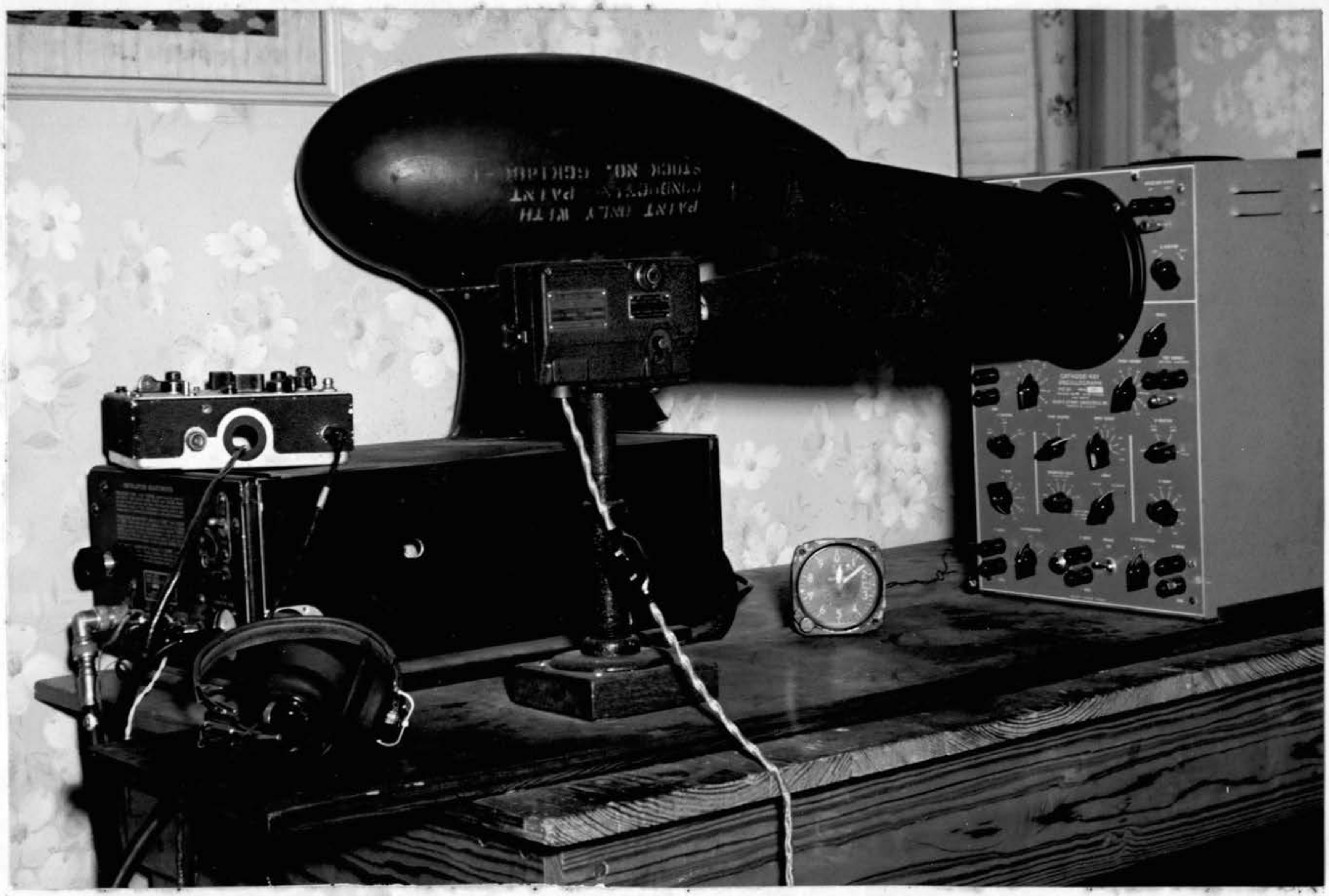

Fig. 34. Photograph of the equipment used to obtain data for this research.

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Typed by:

Velma L. Lanman