IDENTIFICATION OF INTERCLOUD LIGHTNING DISCHARGES BY ANALYSIS OF SFERIC WAVEFORMS

By

CHARLES DONALD STEARNS

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Oklahoma State University

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IDENTIFICATION OF INTERCLOUD LIGHTNING DISCHARGES BY ANALYSIS OF SFERIC WAVEFORMS

Thesis Approved:

Herbert L. Jones
Thesis Adviser

Chas. F. Cameron

Robert MacVicar
Dean of the Graduate School

PREFACE

During the past ten years, an exhaustive study has been made regarding the electrical phenomena associated with such atmospheric disturbances as thunderstorms and tornadoes. The primary goal of this research has been the development of a satisfactory method of forcasting severe weather far enough in advance to alert communities in the danger area so that they might seek safety. Considerable progress has been made in this field, the most notable effort being the sferics-radar method of storm detection developed by Dr. Herbert L. Jones and his staff at Oklahoma State University.

Whenever research effort is concentrated in an effort to solve a particular problem, some interesting facets of the basic research must be sacrificed in the interest of time and manpower. One such facet is the investigation of lightning strokes from one cloud to another rather than the usual cloud to ground type. Continuing investigations in the field of sferics propagation demand that every type of discharge be accurately identified by some means. It is the purpose of this thesis to examine intercloud lightning discharges and to provide a means of identification of these strokes by their waveforms as recorded by standard sferics receiving equipment.

Research for this thesis was conducted at the Tornado Laboratory of the Oklahoma State University using the equipment already available with only minor modifications to facillitate recording of cloud to cloud sferics waveforms.

The writer would like to express his appreciation to the project engineers, Mr. Felix Boudreaux, Mr. Don Scouten, and Mr. H. D. Lovelace, for taking time from their own research to explain the function and operation of the various pieces of equipment at the laboratory.

Particular gratitude must be expressed for the encouragement and advice of Dr. Jones. His guidance over the past several months has been instrumental in the completion of this project.

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CHAPTER I

INTRODUCTION

Man's progress during his relatively short existence on earth has been governed more by scientific investigation and understanding of his environment than any other single factor. For thousands of years after the advent of man, progress was insignificant. Compared with these early years, the scientific advances of the past two centuries have been phenomenal but the human animal is still only at the beginning of an understanding of his oldest enemy, weather.

Most of the work done to combat this enemy of environment has been directed toward finding means of shelter from the elements when they are at their worst and hoping and praying for their benefits when needed. At best, the situation is frustrating. Man must rely on nature to provide rain and sun in the desired ratio if crops are to be adequate for his existance. On the other hand, he must defend himself against severe weather as surely as he must defend against the more common enemies.

In the midwestern portion of the United States, the problem is perhaps greater than anywhere else in the world. Thunderstorms and tornadoes are associated with providing a major portion of the moisture falling on this area. When the spring severe weather season has passed, this area begs for moisture with little relief except an occasional shower. The fields are fertile, the sunshine is more than adequate. Crop failure or record harvest is determined almost entirely by rainfall. It is immediately evident that if man can learn to control the weather, even to a limited degree, his standard of living will ultimately reach new heights.

The first step in control of the weather is understanding. The problem cannot be fully comprehended until all aspects of weather formation have been determined and no solution can be possible until the problem is fully comprehended. During the past decade, great strides have been taken toward full understanding of the nature of severe thunderstorms and tornadoes by the Tornado Laboratory of Oklahoma State University in cooperation with the United States Weather Bureau.

In 1950, Jones and Hess (12) discovered a new type of atmospheric radiation present in severe thunderstorm cells and subsequently developed the sferics-radar system for identification of such cells and tracking them. Effort has been focused since that time on a means of forecasting tornadoes with the result that many other aspects of severe weather have had to be disregarded for lack of time and research personnel. One such aspect is the cloud-to-cloud lightning stroke.

Many types of cloud-to-cloud discharge have been observed from the Tornado Laboratory. One common type is a very long, horizontal discharge at least 10 to 15 miles in length. This type of discharge produces a spray of directional sferics covering relatively large angles. These angles at times approached values greater than 90°. (11) It is this type of discharge which is the object of the present investigation.

Severe Weather

In order to effect an understanding of the electrical discharges common to thunderstorms it is essential to examine the conditions which lead to the formation of thunderstorms and the tremendous electric fields associated with them.

Thunderstorms generally have the same physical features regardless of location or time. However, they do differ in intensity, degree of development, and in associated weather such as hail, turbulence, and electrical discharges. They are usually classified according to the manner in which moist, unstable air is lifted to form cumulus clouds. Two broad classifications are frontal and airmass thunderstorms. The degree of development is usually described by three stages: cumulus, mature, and anvil. (17)

Thunderstorms form only under certain combinations of atmospheric conditions. The necessary conditions are unstable air of relative high moisture content combined with some type of lifting action. When these conditions are present, a cumulus cloud is formed to begin the <u>initial</u> stage of development. The method by which lifting action is provided determines the classification of the thunderstorm. When the moist, unstable air is forced up and over mountainous regions, an orographic thunderstorm of the air mass type is formed. The initial lifting action for the convective thunderstorm of the air mass type is provided by the convective currents produced by heating lower layers of the air that are in contact with warm land or water masses. Lifting action for the frontal type of thunderstorm is provided by the rising of the warm air mass over the colder air mass which is displacing or overrunning it.

The <u>mature</u> stage of development is reached when moisture begins to fall from the cloud. This stage is reached when the water droplets in the cumulus cloud grow to the extent that they can no longer be supported by the updrafts. By this time the cloud top has reached a height of 25,000 to 35,000 feet. As the raindrops fall, they drag air along with them. This drag is believed to be a factor in the formation of downdrafts which are associated with mature thunderstorms. Downdrafts form in the middle regions of the cell and gradually increase first vertically and then horizontally. When the downdraft air current reach the surface, they spread out horizontally and produce strong and gusty surface winds. A mature thunderstorm is depicted in Figure 1.

The dissipating or anvil stage is reached when the top of a thunderstorm begins trailing off downwind. The name is rather misleading as the thunderstorm has reached its maximum growth at this stage when as a result of intense updrafts, the structure sometimes grows to heights in excess of 60,000 feet. The vertical drafts abate and the surface rain decreases as the dissipation continues, due to the heating and drying process caused by the downdrafts. (3)

Thunderstorm Electrification

The thunderstorm cell develops from an atmospheric density imbalance. Updrafts rapidly carry moisture-laden air up to the levels of the atmosphere where the temperature is well below freezing so that ice crystals can form. Effective electrification involves the presence of snow, ice and hail in the upper levels of the cell as well as that of water.

The cumulus or initial stage usually lasts about 20 minutes after which the cell loses some of its energy. Updrafts are greatly reduced and rain falls. This rain is a combination of water droplets which were not elevated to the freezing level, melting snow flakes, ice crystals, and hail. This combination of water in various forms comes under the broader classification of "hydrometeors". (15)

Experiments with water and ice have revealed that very high

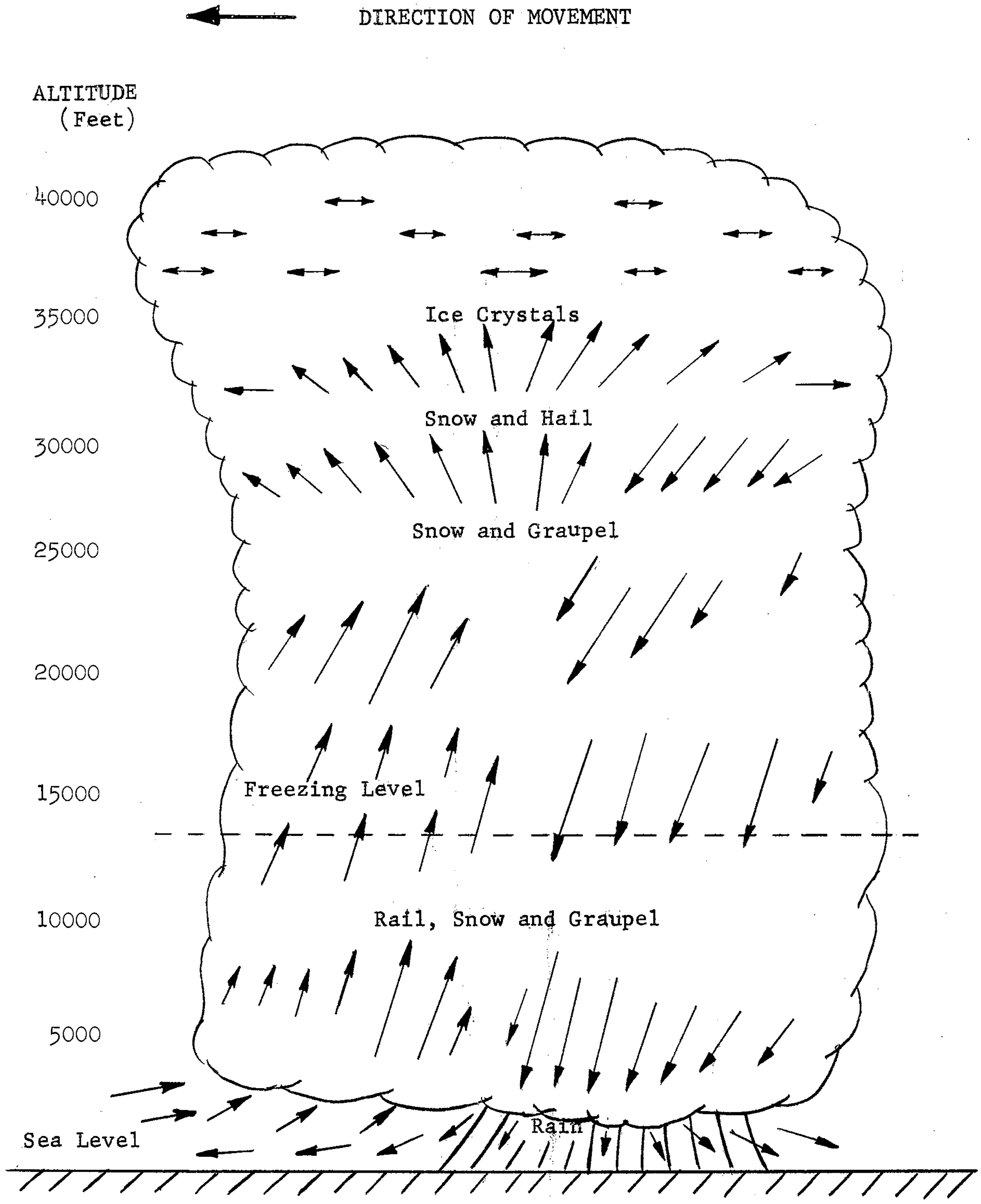

Figure 1. An Idealized Diagram of a Mature Thunderstorm Showing Wind Vectors and Precipitation Content

electrical potentials exist between the water phase and the ice phase and it is believed that this is the source of nearly all thunderstorm electrification. As the hydrometeors fall through the cloud, the gusty winds within the cloud blow the water in the liquid phase away from the solid ice. The ice continues to melt as it falls and, as soon as sufficient water assumes the liquid phase, the water is blown away. The net effect of this process, which is simultaneously taking place in millions of ice crystals, is a buildup of electrical charge which ultimately results in one or more lightning strokes. The rain which falls from the cloud is negative in charge as is the base of the cloud. When the charge at the base of the cloud becomes high enough, a stroke of lightning discharges the cloud through a flow of current to the earth, which is positive.

Due the differences in the air currents, moisture content and temperature of separate thunderstorm cells, potential differences are often developed to the extent that a cloud-to-cloud discharge occurs. Strokes also occur between oppositely charged regions of the same cloud and it it thought that cloud-to-troposphere discharges are occasionally propagated.

Regardless of the type of lightning stroke, its synthesis is essentially the same. (16) It is not a single arc from negative to positive as is usually thought. On the contrary, the discharge occurs in a series of steps from one accumulation of charge to the other. As the potential reaches a value sufficient for the propagation of a stroke, a pilot leader emerges from the negative charge and creates a short ionized path. This is followed by a stepped leader which seemingly investigates several paths and ionizes them. This leader is followed by another stepped leader which takes one of the previously ionized paths and investigates several others, ionizing them. Each stepped leader is from 10 to 200 meters in length requiring many leaders in a succession of ionizations to completely pave the way for the actual lightning stroke. When the ionized channel comes within ten meters of the earth or other positive charge, it is met by an oppositely directed positive streamer which closes the gap and leads to the blinding flash of the return stroke. The stroke is not one but a series of discharges which neutralizes first the lower, then upper levels of the cloud.

The current in the pilot leader and stepped leaders may amount to 50 to 600 amperes while the return stroke builds a channel which carries currents as high as 500,000 amperes. The average current is probably in the range between 5000 and 30,000 amperes since the peak current lasts only 100 to 1000 microseconds. Power in the heaviest strokes approximates 2.4×10^{11} kilowatts. (15)

Heating due to the enormous power carried by the stroke produces an adiabatic expansion which creates a shock wave causing a sharp crack. The heat remaining after the stroke causes the channel to expand to large dimensions and oscillate, giving the familiar low frequency rumble know as thunder.

During the life of a thunderstorm cell, there will be several rechargings of the cloud at intervals of one to ten minutes, depending upon its activity. Each such recharging leads to new strokes initiated by stepped leaders which follow the pilot leader. (15) Figure 2 depicts the formation and accumulation of charge within the cloud and the manner in which a cloud-to-ground and a cloud-to-cloud stroke are propagated.

In June 1752, Benjamin Franklin made his famous kite experiment and confirmed the electrical nature of lightning. (7) Since then, the method of investigation into this wonder of nature has become more and

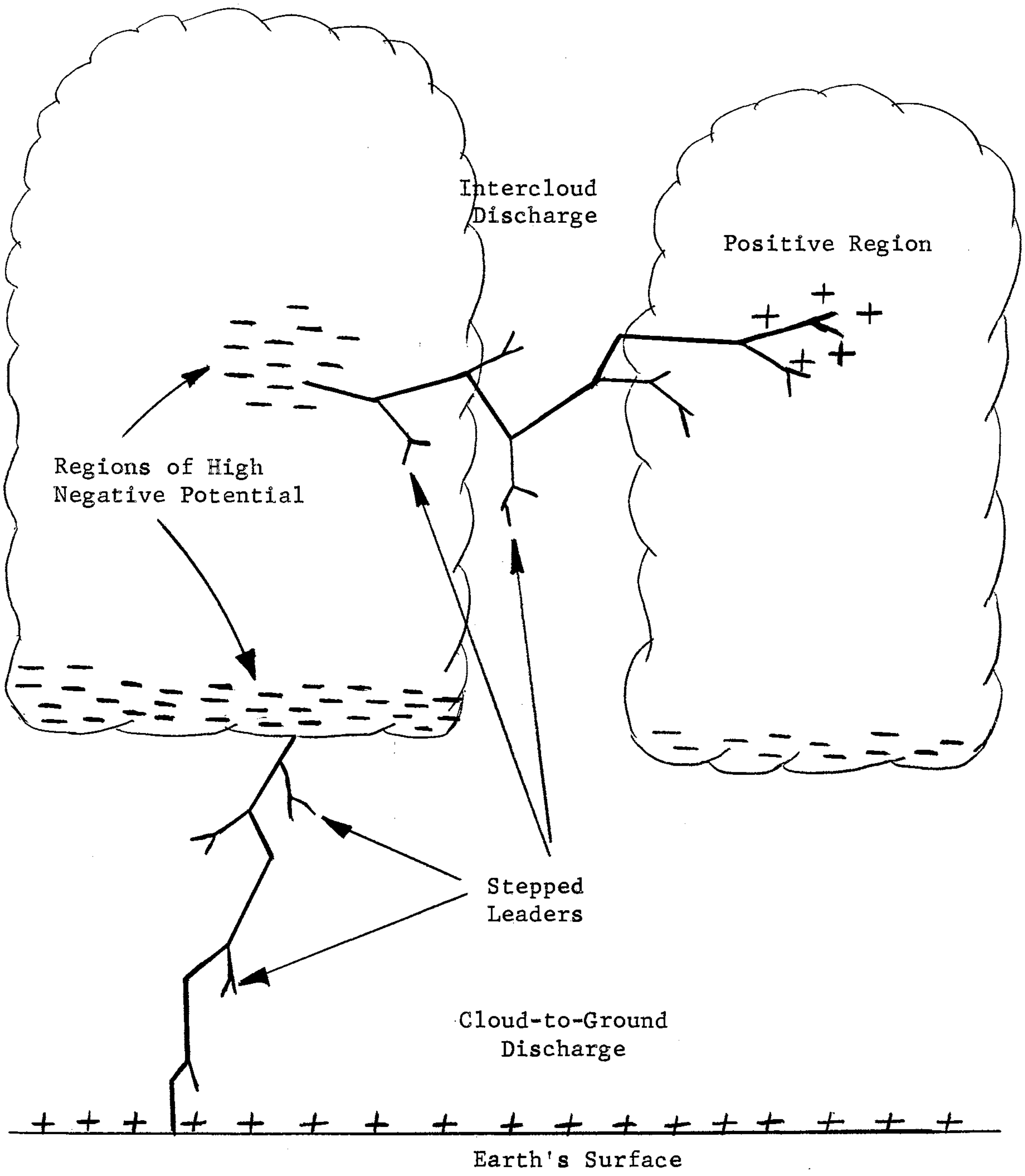

Figure 2. Charge Distribution of Clouds and Earth Resulting in Two Types of Discharge

more refined. Present day experiments are concentrated in receiving and recording the waveforms of the electromagnetic radiation from the thunderstorm. Continuing research demands that each of the various types of discharge be readily identified as it appears on the permanent records obtained.

CHAPTER II

SFERICS RECEIVING EQUIPMENT

The equipment used for the reception and recording of sferics waveforms at the Oklahoma State University Tornado Laboratory has been furnished by the U.S. Air Force under a government research contract. It is designated the Q-3 Equipment and is designed to receive sferic electromagnetic radiation energy at various frequencies between 3 kilocycles and 10 megacycles, and to photographically record data on the sferics received. The recorded data includes the time of arrival, the angle of arrival, the waveform and received energy levels at 10, 75 and 150 kilocycles. (1)

Figure 3 shows overall signal circuit block diagram. (For clarity, the various power sources are not shown.) In the analysis of the type of signals received by the Q-3, it is desirable that the time and angle of arrival be known. It is also highly desirable to know how the energy in the sferic signal pulse is distributed with respect to frequency. This information can be obtained mathematically by Fourier Analysis, a very difficult and time consuming process without the use of electronic computers. To obtain some information about energy distribution with respect to frequency more directly, the Q-3 incorporates, in addition to its waveform capability, four narrow band receivers which give an indication of the energy content of the waveform at the four frequencies to which the receivers are tuned.

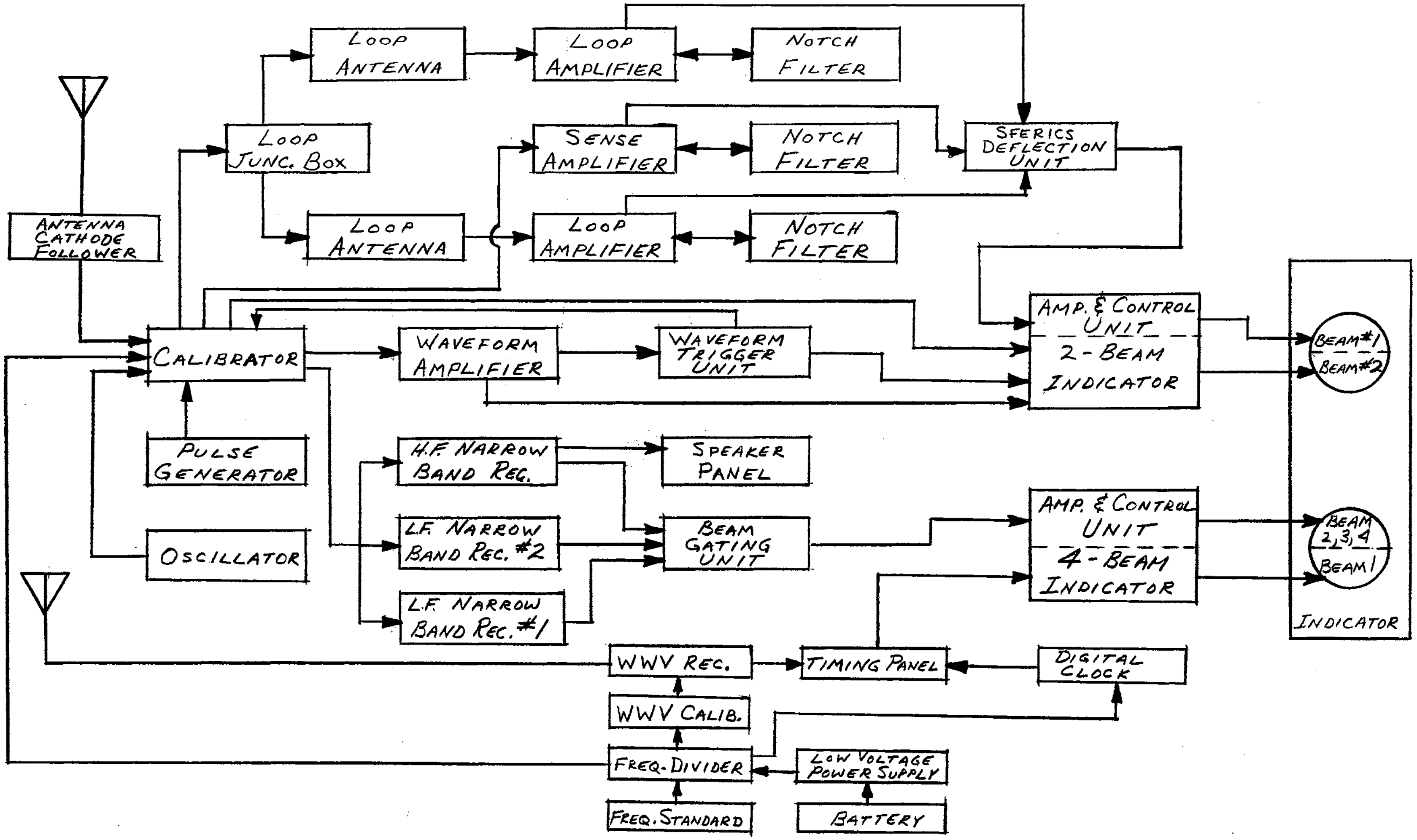

Figure 3. Block Diagram of Q-3 Signal Circuit

Vertical Antenna Section

The vertical antenna section receives electromagnetic radiations by means of a vertical whip antenna and converts them into electrical voltages suitable for amplification and use by vacuum tube circuits. The outputs from this section consist of two frequency bands; 3 to 300 kilocycles and 5 to 10 megacycles. Both outputs are injected into the circuits of the calibration section.

Calibration Section

Normally, the signals received from the vertical antenna section are passed through the calibration section without interruption. The 3 to 300 kc. signal is fed to the direction finding section for use as a sensing signal to eliminate the directional ambiguity produced by loop antennas. This signal is also connected to the waveform section and to two low frequency narrow band amplifiers in the frequency sampling section. The 5 to 10 mc. signal is connected only to a high frequency narrow band amplifier in the frequency sampling section. During the calibration of this equipment, the calibrator unit interrupts the signals from the vertical antenna section and is able to inject, in their place, signals that are used to calibrate the direction finding waveform, and narrow band sections. The calibration signals are obtained from equipment located within the calibrating section, except for one type of signal, which is obtained from the timing section. The calibration section also serves as test and trouble-shooting equipment.

Direction Finding Section

The direction finding section receives the electromagnetic radiation by means of two loop antennas tuned to a frequency of 10 kc. with a bandwidth of 1 kc. After the signal is amplified by the loop amplifiers and the sensing signal received from the vertical antenna section and amplified by the sense amplifier, the sferics deflection unit eliminates the directional ambiguity and, in conjunction with the circuits of the amplifier and control unit for the two-beam cathode ray tube (CRT), prepares the 10 kc. component of the received signal for presentation on the face of that tube. This signal indicates, by its amplitude, the energy of the 10 kc. component of the signal, and, by its angular displacement from a chosen reference, the angle of arrival of the sferic pulse.

Waveform Section

The waveform section receives, in the 3 to 300 kilocycle band, from the vertical antenna section through the calibration section, the actual waveform of the sferic pulse. The circuits of the waveform amplifier provide a means of eliminating undesired signals prior to the signal being fed to the waveform trigger unit. The waveform trigger unit prepares the ten step raster sweep that is fed with the signal to the amplifier circuits of the amplifier and control unit of the two-beam CRT. Each sferic waveform will appear on this CRT on one sweep of the ten step raster and will be separated by the space difference between two consecutive sweeps of the raster. At the end of the tenth sweep, the raster will be completed and the eleventh pulse will initiate the start of another raster.

Frequencies Sampling Section

Two receivers in the frequencies sampling section receive the 3 to 300 kilocycle signal from the vertical antenna section through the calibration and the third receiver receives signals between 5 and 10 megacycles. One low frequency receiver is tuned near 20 kc. and the other is tuned near 75 kc. while the high frequency receiver may be tuned to any frequency within its band. These signals are fed to the beam gating unit where CRT intensifying pulses are formed and these pulses, with the signals, are fed through the amplifier and control unit for the four-beam CRT to three guns of that tube. These three presentations indicate the energy content of the sferic pulse at each of the frequencies sampled.

Timing Section

The timing section produces accurate timing information to record the time of arrival of each sferic pulse and in addition, provides calibration frequencies to the calibration section. The frequency standard provides a 100 kilocycle signal to the frequency divider which in turn provides a 100 kc. and a 10 kc. calibration signal to the calibrator unit. A 100 cycle per second voltage is fed to the motor of the synchronous timing clock. One and six second switch contacts on this clock are used to provide one and six second indicator pulses through the amplifier and control unit for the 4-beam CRT to one gun of that tube. The six second pulse is used to illuminate the clock face for photographic purposes. A receiver capable of receiving National Bureau of Standards radio station WWV and a WWV calibrator unit are also a part of the timing section. These items are provided in order to compare the local timing system against the WWV standard reference.

Recording Section

The recording section consists of the camera box and the strip film camera. This camera records on continuous 35mm film the face of both CRT's and the face of the timing clock. Figure 4 is a drawing of a typical film strip showing the manner of recording each of the bits of information.

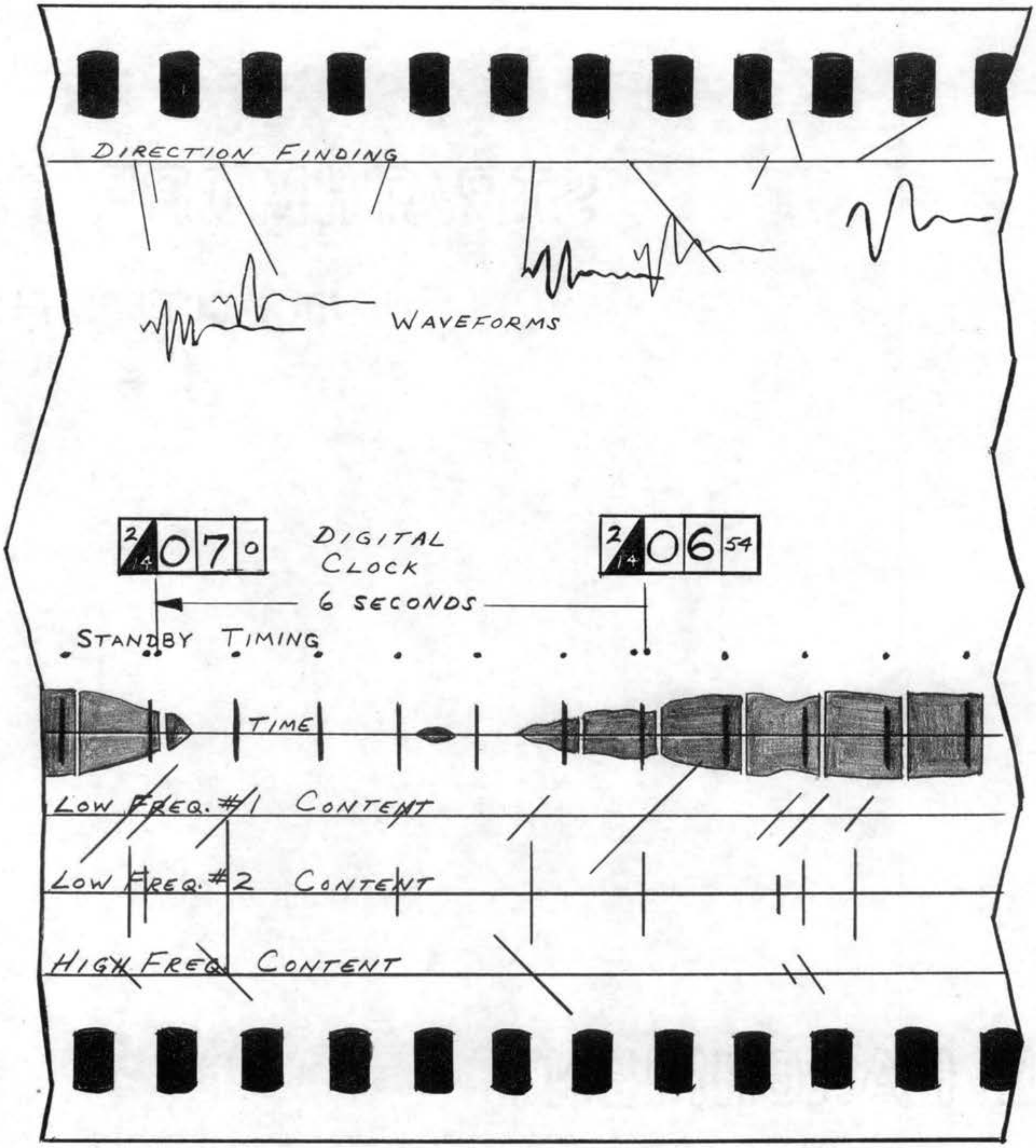

Figure 4. Typical Q-3 Film Record Showing Waveform, Direction Finding, Frequency Content, and Timing Traces

CHAPTER III

THEORY OF OPERATION

As discussed briefly in Chapter II, the Q-3 equipment is designed to perform several recording functions simultaneously, i.e. direction finding, waveform presentation, frequency sampling and timing. It is the purpose of this chapter to view the first two of these functions in greater detail.

Direction Finding Section

One of the purposes of the direction finding section of the Q-3 is to produce an indication of the angle of arrival of a signal and thus an indication of the direction of its source. This is accomplished through the use of two loop antennas and a vertical sense antenna to receive the electromagnetic radiation.

The electromagnetic field (18) is composed of interdependent and interrelated electric (E) fields and magnetic (H) fields. These waves are in time phase and perpendicular to each other. Electromagnetic radiation is propagated in wave motion and at an appreciable distance from the radiator the wave is apparently a polarized wave. In general, the apparent propagation of electromagnetic wave motion is a straight line between points. It is this principle upon which radio direction finder operation is based. When viewed in cross section, propagation of electromagnetic waves may be parallel to the earth's surface or may skip between that surface and ionospheric layers in a manner dependent upon many factors including the frequency of the radiation. In general, the lower the frequency, the greater the distance over which the wave is reliably propagated and received.

Loop antennas may be large coils of any convenient section; rectangular, octagonal, triangular or circular. Such an antenna abstracts energy from passing electromagnetic waves as a result of the phase difference between the voltages induced in opposite legs or sides. (1) The special value of the loop antenna arises from the facts that it is very directional, that it is independent of the ground as far as reception of vertically polarized waves is concerned, that its characteristics may be accurately determined by calculation and that it is relatively small in size considering the other antennas used for low frequency reception.

In the Q-3 antenna system, two loops are set at 90° angles to each other in the vertical plane. Figure 5 depicts the field pattern of the individual antennas and their combination. Also shown is their connection to the deflection plates of the CRT.

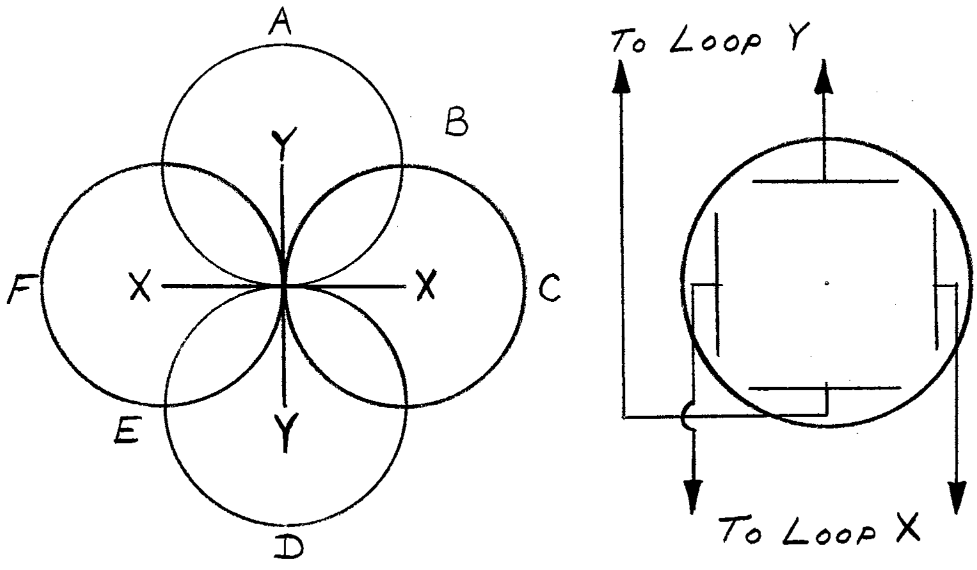

Figure 5. Loop antenna field patterns and connection to cathode ray tube deflection plates.

If, as in the above figure, loop X is fed to the horizontal deflection plates, then the following conditions are true:

a. If the point of origin of radiation is located at point A, then the X loop will provide no deflection voltages to the horizontal plates and the Y loop will provide maximum deflection voltages to the vertical plates. This will produce the CRT indication shown in Figure 6a. This may be interpreted to indicate that the signal came from point A (correctly) or that it came from point D (incorrectly). Thus, an ambiguity exists that must be eliminated prior to determination of the correct azimuth.

b. If the origin of the radiation is at point B, both the X and Y loop will provide deflection voltages to the respective deflection plates and the scope will be shown as in Figure 6b. Again, a directional ambiguity exists.

c. If the origin of the radiation is at point C, then the X loop will provide maximum voltage to the horizontal deflection plates and the Y loop will provide zero voltage to the vertical deflection plates and the CRT indication will be as shown in Figure 6c. Again, the ambiguity exists.

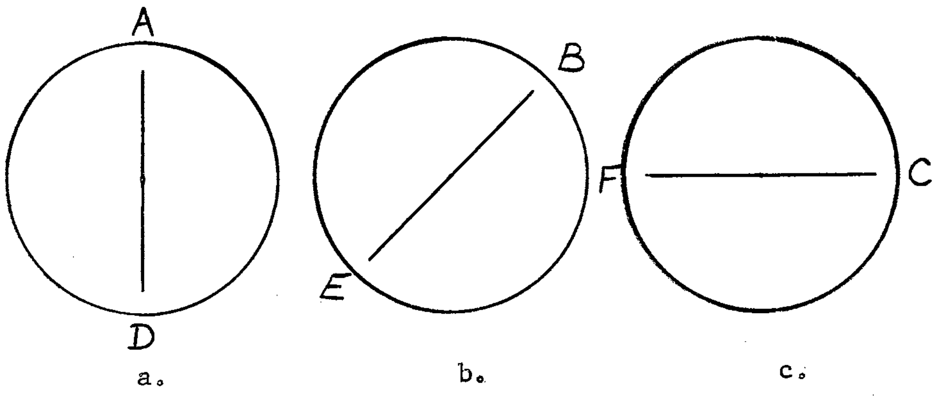

Figure 6. Angular Presentation

The ambiguity in directional indications is eliminated by use of a sensing voltage derived from the non-directional vertical whip antenna. The output of the loop antenna is either in or out (180°) of phase with the incident wave depending upon the relative direction from which it arrived. The output of the vertical antenna is always in phase with the wave. If the positive half cycles of the sense signals are fed to the CRT control grid they intensify the correct directional indication given by the deflection plates and blank out the incorrect indication. The use of this combination of loop and sense antennas results in a directional indication outward from the zero reference dot of the cathode ray tube.

In order to obtain the most advantageous use of recording film space, the direction indication is shifted clockwise 45°. This causes a direction of north to appear where northeast would normally appear.

Waveform Presentation

The purpose of the Waveform Section is to produce a deflection on the face of the CRT for each desired sferic signal received that will indicate the actual wave shape of the signal. (1) Since the frequency range of the sferic signals is extremely broad, the exact wave shape is impossible to reproduce but, by using a bandwidth between 3 and 300 kc., enough of the frequencies are retained to give a very close approximation of the true wave shape.

The Waveform Amplifier amplifies the input waveform signals to a sufficient level to drive the horizontal deflection amplifier of a CRT and to eliminate undesirable signals that may occur within the 3 to 300 kc. band. The unit consists of three two-stage feedback amplifiers, two isolating cathode followers, one low-pass filter, two notch filters and a 50 microsecond delay line. The filters eliminate the undesired nonsferic signals by providing notches in the overall frequency response curve or by limiting this response to certain fixed limits. The 50 microsecond delay cable enables the system to record the beginning of the waveform by causing the waveform to reach the cathode ray tube simultaneously with or a little later than the sweep start which takes a finite period of time to generate. This delay permits the display of the entire sferic waveform, especially the important first pulse.

Envelope detection is accomplished by the Sferics Deflection Unit in order that only the envelope of the sferic signal will be used for deflection in the waveform cathode ray tube. The primary advantage of using only the envelope is that a much clearer film record can be obtained. Phase sensitive rectifiers are used in the X and Y loop deflection circuits to divide the signal into positive and negative halves. The signals are then filtered to produce positive and negative half envelopes which are fed to loop output amplifiers and ultimately to the CRT deflection plates.

For further clarity of the film record, a stepped raster is utilized on the waveform CRT. An electronic decade counter causes the reference for each successive waveform to be located slightly to the right of the previous waveform reference. When the tenth waveform is presented, its reference is to the extreme right side of the CRT. The eleventh waveform returns to the position on the scope which was occupied by the first waveform.

Variable speed of the camera also permits adjustment for better film recording. Film speed can be slow during times of low sferics activity, higher for moderate activity and very fast for periods of intense activity. The higher the film speed, the more space will appear between successive waveforms on the same position of the CRT.

CHAPTER IV

METHOD OF INVESTIGATION

The basic problem to be investigated was the determination of some means of identifying the cloud-to-cloud lightning discharge by analysis of the data normally recorded by the Q-3 equipment in use by the U.S. Weather Bureau stations. Most suitable for this task was, of course, a Q-3 installation with modification to permit indication of the occurrence of a cloud-to-cloud stroke.

The Q-3 equipment already installed at the Oklahoma State University Tornado Laboratory was used to collect data. The camera box was modified to include a neon lamp at the base of the clock. This lamp, operated by a hand pushbutton, caused a mark to be placed on the film along the timing strip whenever the button was depressed. An observer outside the laboratory pushed the button when a cloud-to-cloud stroke was sighted and thus marked the film. By estimating the observer's reaction time and noting the direction of the discharge from the laboratory, the sferic waveform associated with the discharge was pinpointed on the Q-3 film. The reaction time of the observer was generally within 0.1 to 0.2 second, a period of time representing a rather small distance of film travel.

Previous experience in observation of direction finding pulses during severe storms (11) indicated that a spray of directional sferics could be expected when a long cloud-to-cloud stroke occurred near the laboratory. The film record was also examined for this spray sferic pattern.

It is immediately apparent that the method of visually observing a cloud-to-cloud stroke has both advantages and disadvantages. The delay in sighting and recording time due to the observer's reaction time has been mentioned and necessitates extra care in analyzing film data. The visual method also prohibits the notation of some intercloud discharges which are within the range of the electronic equipment but hidden from the observer by clouds or precipitation. This means that many cloud-to-cloud strokes will appear on the film record without the film being marked to so indicate. The argument in favor of visual observation is that only long cloud-to-cloud discharges which are definitely identified by a human being are marked on the film. From the marked waveforms, identifying characteristics were sought which would permit the differentiation of the intercloud lightning stroke. The results of this investigation are discussed in the following chapter.

CHAPTER V

ANALYSIS OF RESULTS

The nature of this investigation, i.e. visual observation of cloud-to-cloud lightning discharges, imposed severe limitations upon the accumulation of data. Best results could be obtained only at night when the strokes were clearly visible and when the storms were close to the point of observation with no intervening clouds. For these reasons, all of the data included in this study were collected in two storm conditions, the nights of May 17 and June 11, 1959. Although some cloud-to-cloud discharging occurs in virtually every thunderstorm situation, these nights were the occasions of particularly high intercloud activity.

Atmospheric Situation

Squall lines in the midwestern portion of the United States most frequently travel from the southwest to the northeast (8). Observation during the spring of 1959 has indicated that cloud-to-cloud discharges occur more often when the storms travel the less common path from north to south or northeast to southwest. Deviation from the southwest to northeast path usually results when the storms are of the air mass type and buildup is caused by abundant moisture and intense diurnal heating. Frontal thunderstorms usually form ahead of a cold front and are pushed northeastward by the strong southwest winds ahead of the front. (3).

Both of the storm situations considered in this study were of the air mass variety. Air at the higher altitudes was relative warm and stable and, except for the concentrated moisture and heating at the surface, conditions were not conducive to the formation of thunderstorms. Although it is not the purpose of this thesis to explain the meteorological characteristics of severe weather, it is felt that the aforementioned conditions were largely responsible for the high ratio of cloud-to-cloud strokes to cloud-to-ground strokes. High activity of the cloud-to-cloud type has long been referred to as "heat lightning" (5) because of its coincidence with very hot, humid weather.

Direction Finding Indication

As mentioned in the preceeding chapter, a spray of direction finding sferics was expected to accompany the cloud-to-cloud stroke and this proved to be true. Figure 7 shows how a spray can occur as the stroke proceeds across the sky. In Figure 7a, the stroke is starting along the path ionized by the stepped leaders. The accompanying direction finding indication shows deflection of the electron beam in the direction of the discharge. Figure 7b shows the same stroke halfway along the ionized path. The D/F now indicates the direction to the <u>average</u> position of the discharge. In Figure 7c, the stroke extends along the entire ionized path and the D/F again sees the average position of the discharge. At the termination of the flow of current, the direction finding indicator returns to its zero position completing the trace of the spray or fan-shaped pattern. Successive strokes along the same ionized channel produce successive traces similar to the first on the direction finding record.

Figure 8 depicts a series of cloud-to-cloud strokes, the first two of which contain sixteen and seventeen pulses respectively as shown by the number of individual traces of their direction finding record. These strokes were recorded during the storm of June 11, 1959 and were observed

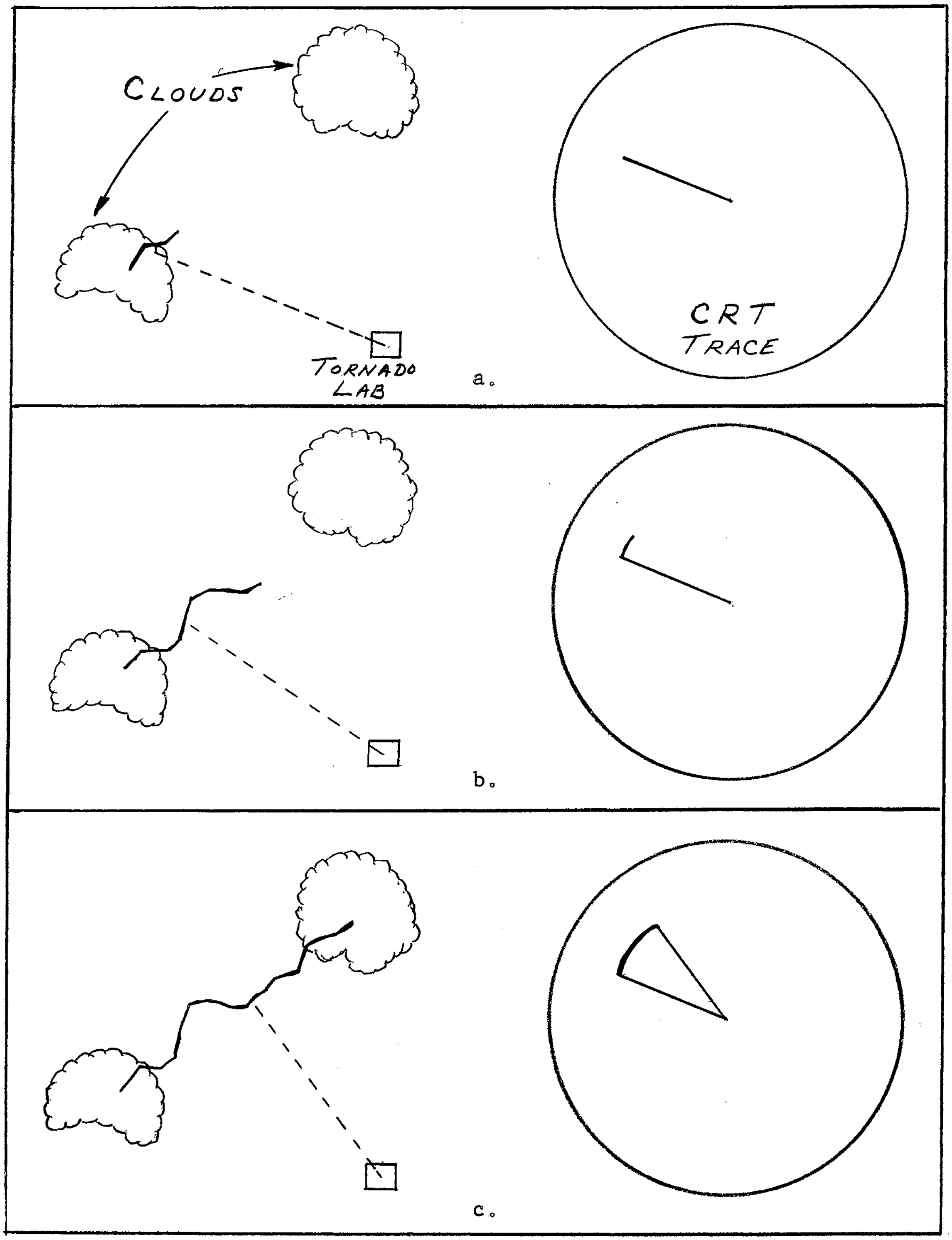

Figure 7. Formation of Direction Finding Spray Pattern Due to Intercloud Discharge

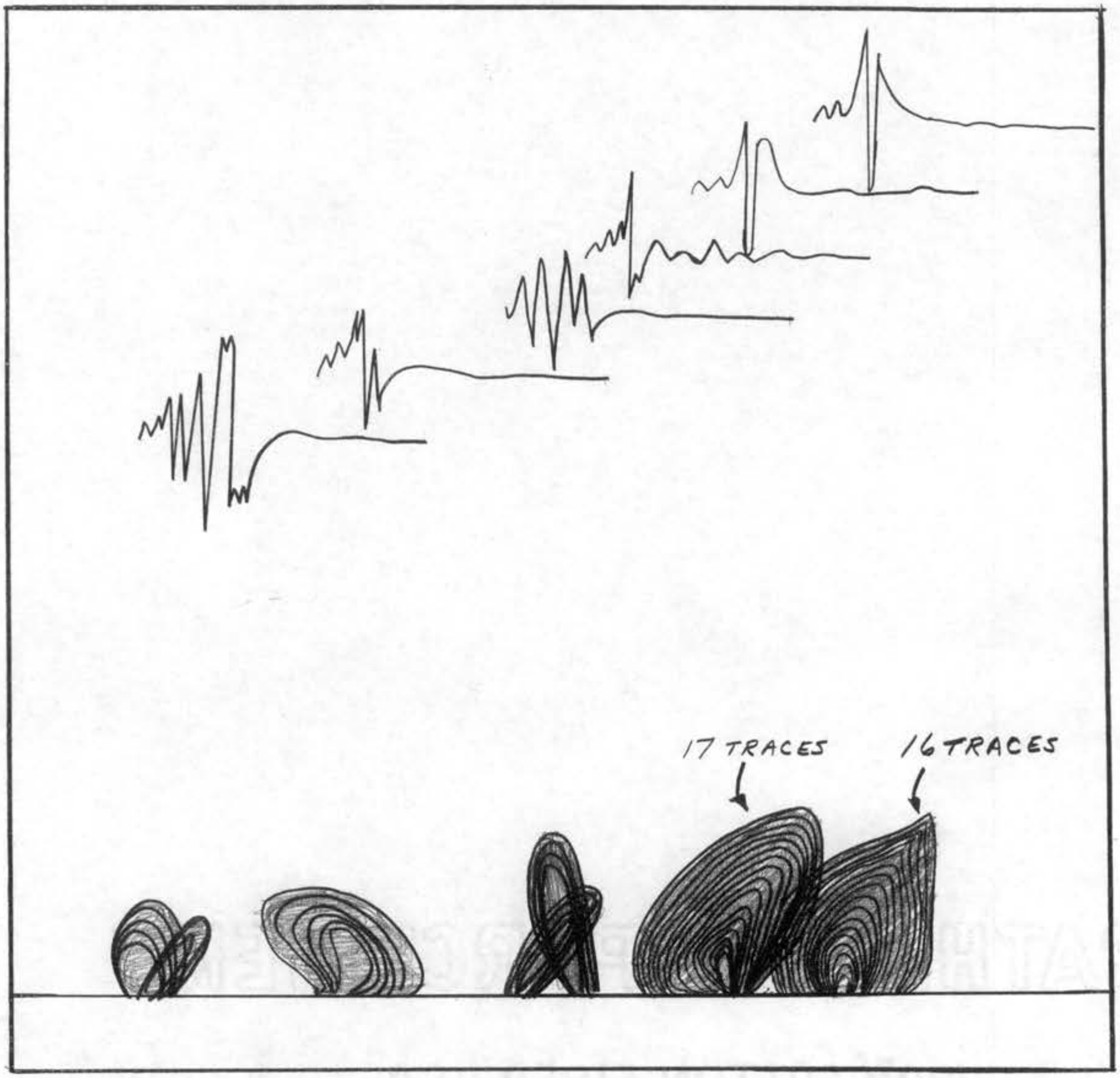

Figure 8. Sferics Waveforms and Direction Finding Traces Showing Multiple Directional Traces (June 11, 1959, 2237 CST).

to be several miles in length. Generally, when the stroke is normal to a line extending radially from the laboratory its angle measured from one end to the other is twice the angle included on the direction finding record. This is due to the characteristic of the equipment that measures the average direction to the source of the sferic.

A cloud-to-ground discharge has no variation in azimuth since it proceeds from the cloud to a point on the earth's surface directly below the cloud. It's representation then is a straight line in the direction of the discharge with a magnitude equivalent to the intensity of the stroke. Successive discharges along the same ionized channel retrace the same directional indication and, regardless of the intensity, only one line appears on the direction finding record. Figure 9 clearly shows the difference between cloud-to-cloud and cloud-to-ground discharges as recorded on the direction finding trace. This difference is the most reliable means of identifying the intercloud stroke.

Repetitive Strokes

During the analysis of the film records of the two storm situations, it became apparent that the intercloud discharges were consistantly of repetitive nature. That is to say an intercloud sferic waveform was usually followed by from three to nine other waveforms of almost identical shape. These strokes followed within milliseconds of each other as measured on the film. Figures 10 through 14 show several series of waveforms which have almost identical characteristics. The series differ radically from each other, but all of the waveforms in a given series are quite alike. No such repetition was noted among cloud-to-ground lightning strokes.

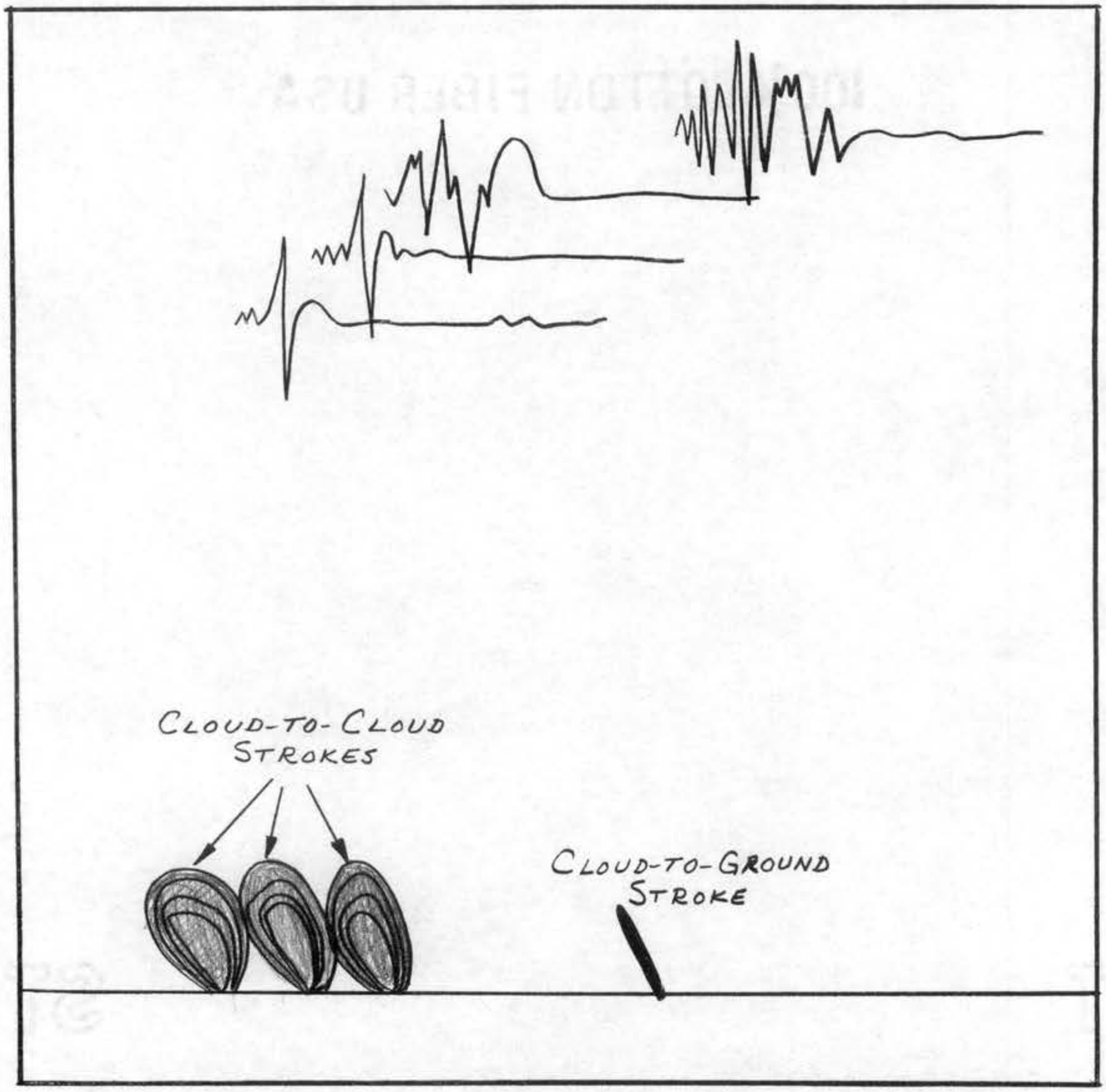

Figure 9. Comparison of Cloud-to-Cloud and Cloud-to-Ground Direction Finding Records (June 11, 1959, 2336 CST).

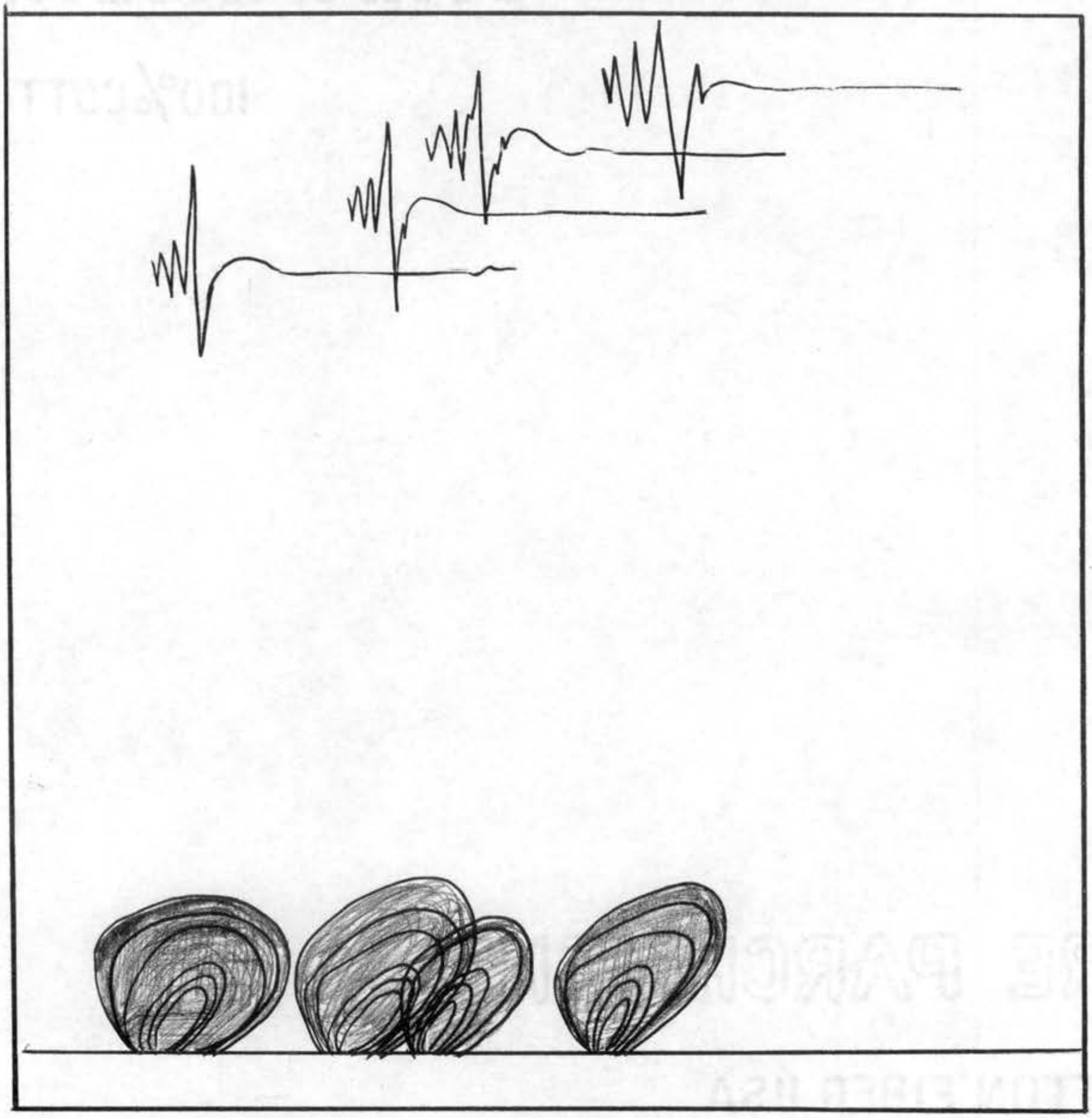

Figure 10. Repetitive Waveforms of Multiple Intercloud Discharges (June 11, 1959, 2336 CST)

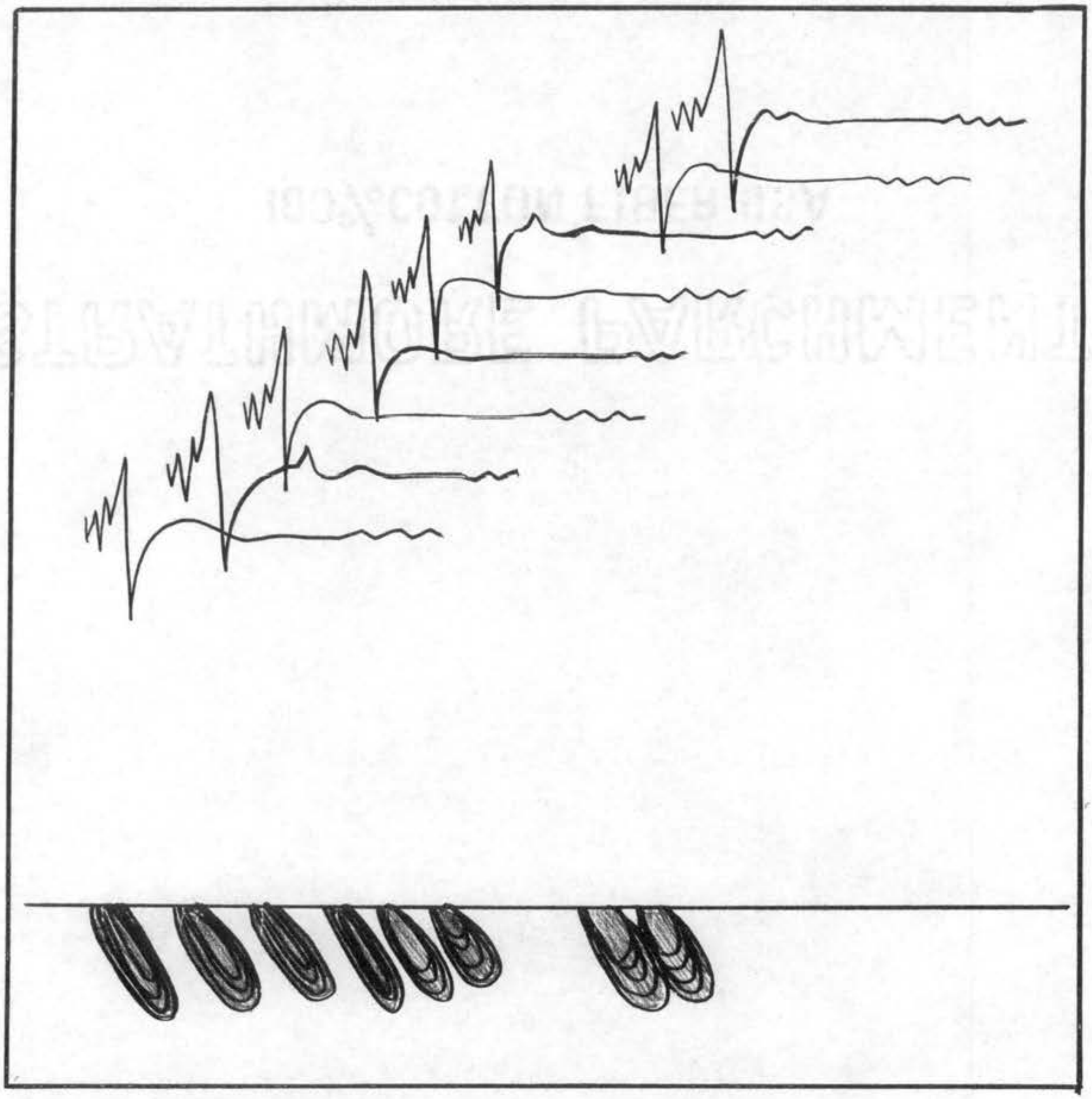

Figure 11. Repetitive Waveforms of Multiple Intercloud Discharges
(May 17, 1959, 2227 CST)

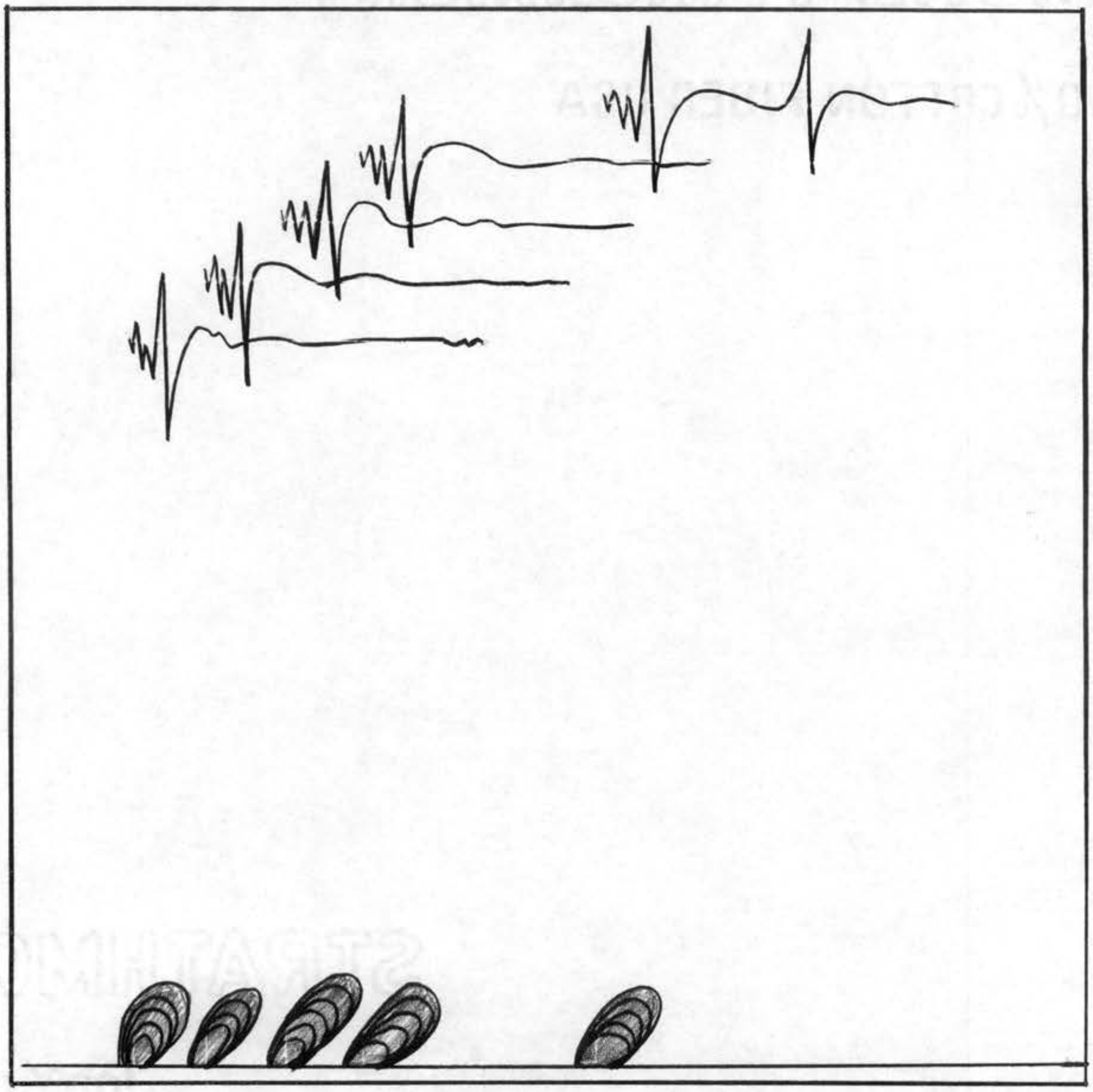

Figure 12. Repetitive Waveforms of Multiple Intercloud Discharges
(May 17, 1959, 2226 CST)

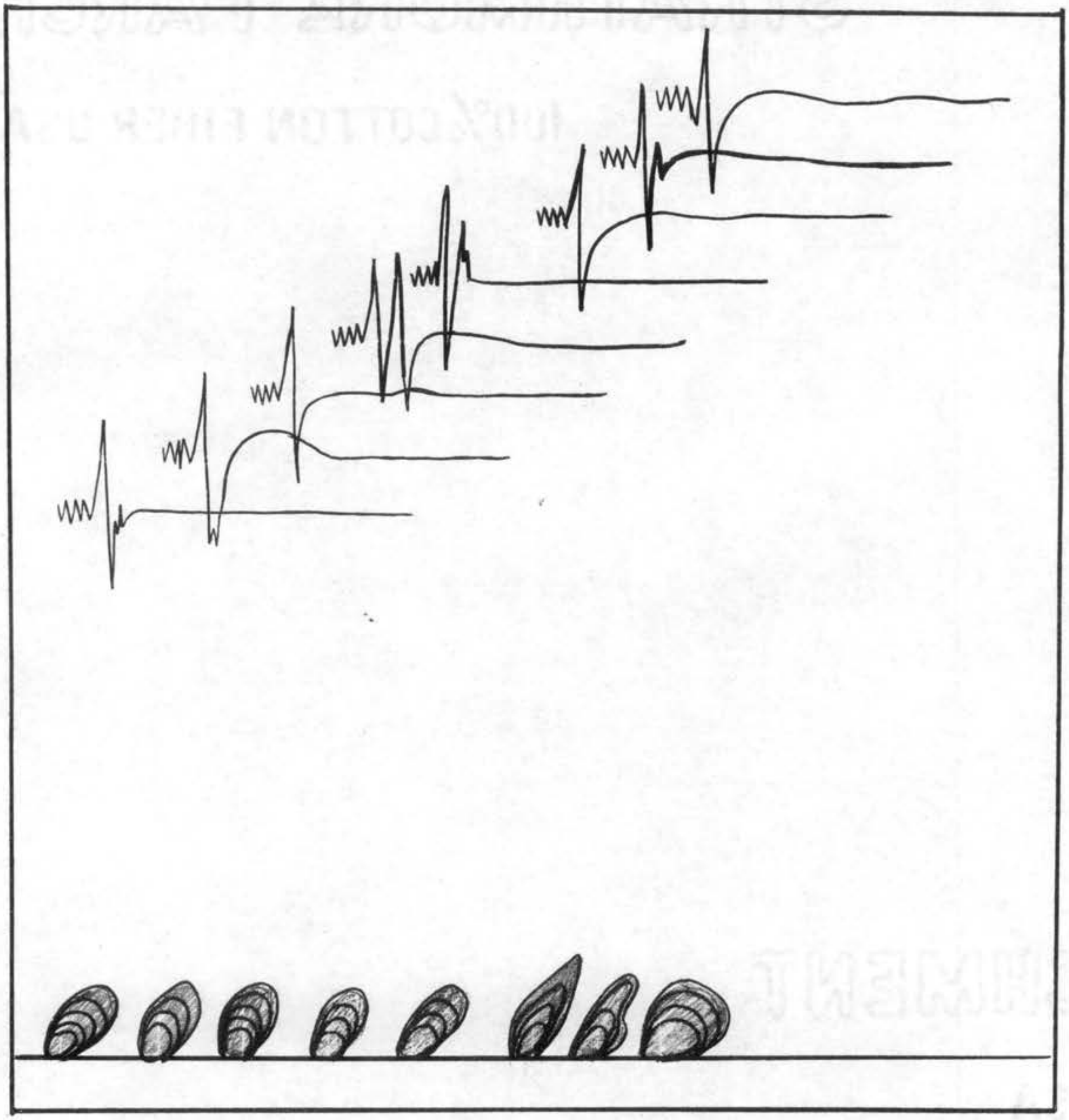

Figure 13. Repetitive Waveforms of Multiple Intercloud Discharges (May 17, 1959, 2224 CST)

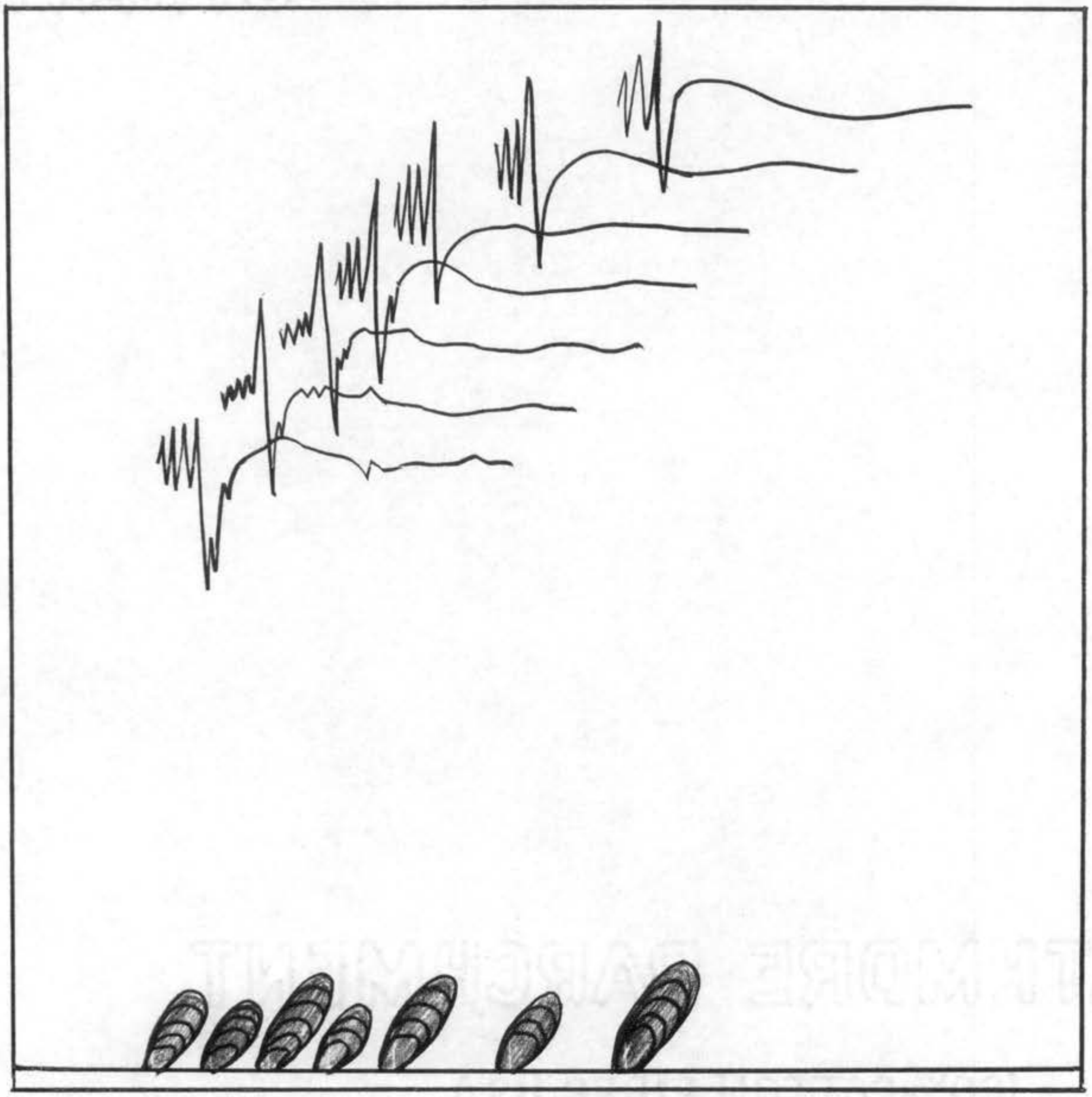

Figure 14. Repetitive Waveforms of Multiple Intercloud Discharges (May 17, 1959, 2222 CST)

Comparison of Isolated Discharges

No extreme differences were observed between the waveforms of intercloud discharges and those of the cloud-to-ground variety. Figure 15 is a waveform of an isolated cloud-to-cloud discharge and Figure 16 is a waveform of an isolated cloud-to-ground discharge. Although the two strokes differ in frequency content, this cannot be considered an identifying feature. Both types of strokes can contain either predominantly high or low frequencies. It should, however, be noted that frequency of sferic propagation is, among other things, dependent upon the length of the stroke. In the case of a long intercloud discharge, the frequency could be expected to be relatively low. A shorter intercloud discharge would have approximately the same resonant length as a cloud-to-ground discharge and hence, the same frequency content.

Change in Polarity

An apparent change in polarity was noted on some occasions when a stroke at one azimuth occurred along with strokes at a considerable difference in azimuth. This did not occur often enough to be significant, but might be worthy of further investigation. Figure 17 shows one such occurrence on the night of May 17. A cloud-to-cloud stroke northeast of the laboratory was closely followed by a series of three similar strokes to the southeast. The first waveform peaks positively, then negatively and finally approaches the zero intensity from the negative direction. The three strokes to the southeast peak first negatively, then positively and approach zero from the positive direction.

Stepped Leaders

In all of the data collected, every stroke was begun with a rela-

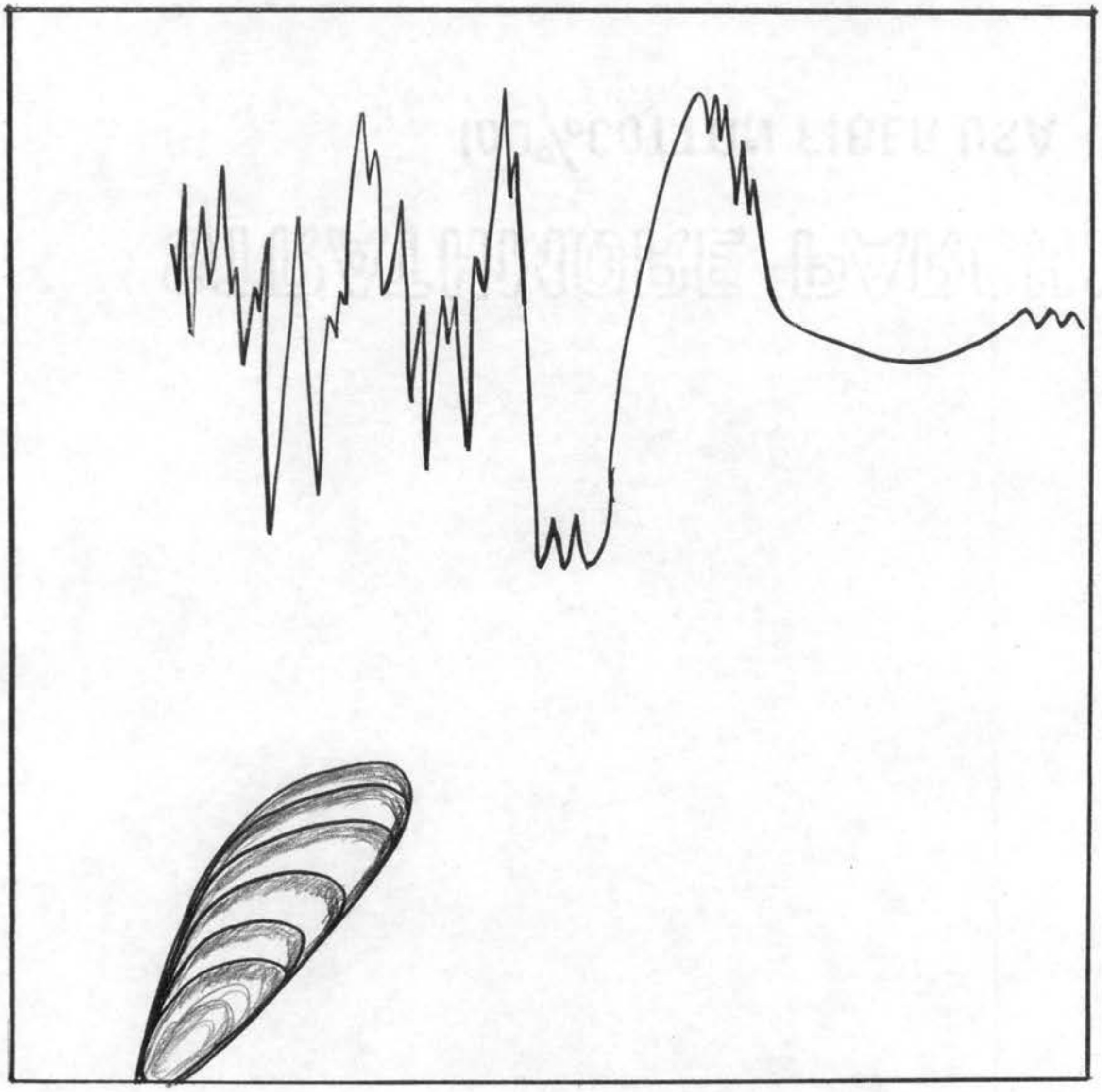

Figure 15. Waveform and Directional Trace of an Isolated Cloud-to-Cloud Stroke (May 17, 1959, 2222 CST)

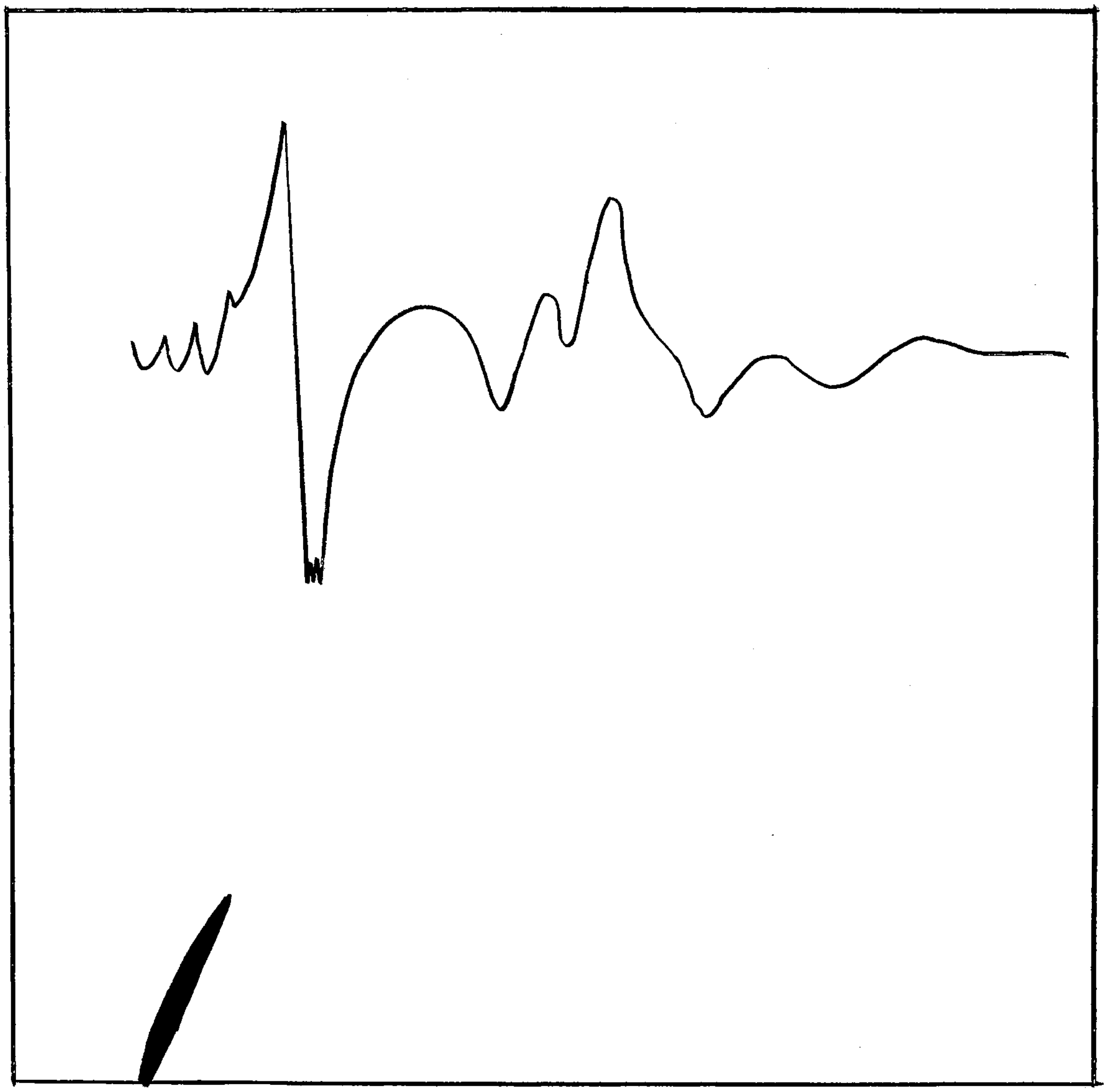

Figure 16. Waveform and Directional Trace of an Isolated Cloud-to-Ground Stroke (May 17, 1959, 2226 CST)

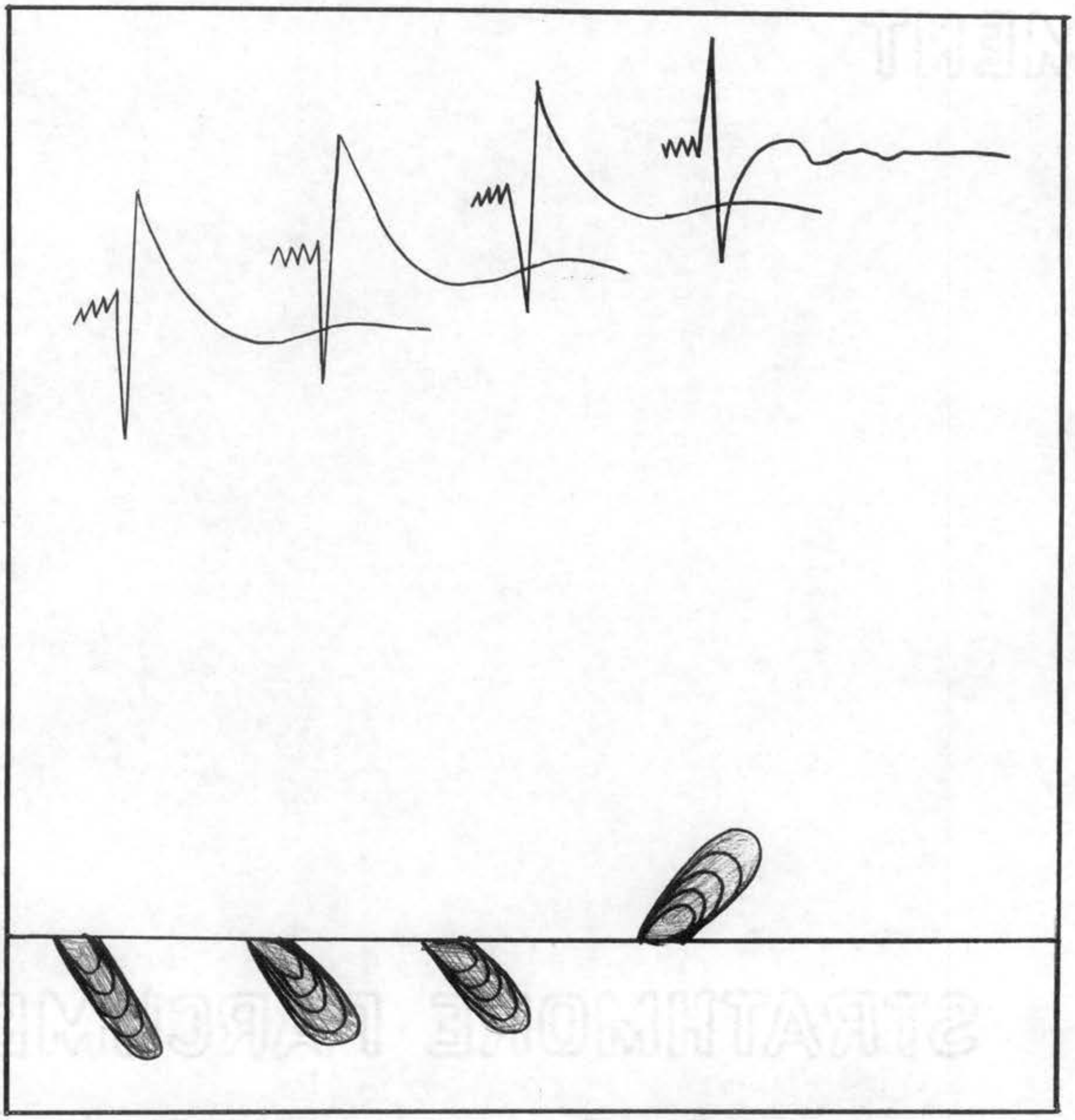

Figure 17. Apparent Change in Polarity According to Azimuth
(May 17, 1959, 2226 CST)

tively low power oscillation due to the presence of stepped leaders. The leaders are immediately followed by a high intensity stroke and diminishing oscillations of the subsequent discharges. The indication on the film record bears out the statement of B. F. J. Schonland (16) that "discharges which do not reach the ground are of the leader type without the usual return process." Visual observation has also supported the stepped leader theory.

CHAPTER VI

SUMMARY AND CONCLUSIONS

It has been the purpose of this thesis to examine the nature of thunderstorm electrification in general and the intercloud lightning discharge in particular in an effort to better understand this aspect of our environment. Continuing study in the field of severe atmospheric disturbances dictates the necessity for being able to identify each type of electrical discharge associated with these disturbances. The cloud-to-cloud stroke has been studied for identifying characteristics recorded by standard sferics receiving equipment and the following conclusions are presented.

Conclusions

1. Although the cloud-to-cloud lightning discharge is generally polarized horizontally, enough of its radiation is vertical to permit its being received by the antenna system now in use with the Q-3 installation.

2. Intercloud discharges begin at one azimuth and end at another which is often widely displaced from the first. This causes the direction finding representation on the Q-3 film record to show a spray or fan of directional sferics. It is this spray on the direction finding trace which provides the most accurate identification of the cloud-to-cloud stroke.

3. Cloud-to-cloud lightning discharges often occur in series of

from three to nine repetitive waveforms spaced by only a few milliseconds. The waveforms are nearly identical in shape and magnitude.

4. Waveforms of cloud-to-ground strokes do not differ radically from those of intercloud strokes. Their frequency contents may vary considerably over the spectrum with either type capable of both high and low frequencies. In general, the long cloud-to-cloud discharges will be of lower frequency due to the longer resonant lengths.

5. Cloud-to-cloud strokes, as well as cloud-to-ground strokes, have propagation initiated by stepped leaders which may be identified on the Q-3 film record. They appear as low power oscillations preceeding the high intensity strokes.

6. An apparent change in polarity was noted for strokes occurring at widely separated azimuths. Further study of this phenomenon should be made to determine if it is consistantly true and if it can be used as another means of identification.

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VITA

Charles Donald Stearns

Candidate for the Degree of

Master of Science

Thesis: IDENTIFICATION OF INTERCLOUD LIGHTNING DISCHARGES BY ANALYSIS OF SFERIC WAVEFORMS

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Cincinnati, Ohio, January 9, 1931, the son of Charles L. and Margaret M. Stearns.

Education: Attended grade school in Cincinnati, Ohio. Graduated from Withrow High School, Cincinnati, Ohio in 1948. Attended University of Cincinnati Evening College, Cincinnati, Ohio, 1948-50. Attended McNeese State College, Lake Charles, Louisiana, 1952. Attended San Angelo College, San Angelo, Texas, 1954-56. Completed the requirements for the Bachelor of Science Degree in Electrical Engineering at Oklahoma State University in January 1959, receiving the degree in May 1959. Completed the requirements for the Master of Science Degree in Electrical Engineering in August 1959.

Professional Experience: Employed as Production Expeditor by the General Electric Co., Evendale, Ohio from January 1949 to January 1951. Entered the United State Air Force in February 1951. Served as a radio mechanic until entry into pilot training in September 1952. Commissioned a Second Lieutenant and rated a Pilot in the U.S. Air Force in November 1953. Performed the duties of Instructor Pilot, Single and Multi-Engine, at Goodfellow Air Force Base, San Angelo, Texas from January 1954 to January 1957 in the rank of First Lieutenant.

Member: American Institute of Electrical Engineers, Institute of Radio Engineers, Eta Kappa Nu, Air Force Association.