A STUDY OF THE FREQUENCY CHARACTERISTICS OF LIGHTNING DISCHARGES

By

RAY LORAN CALKINS

Bachelor of Science
Purdue University
West Lafayette, Indiana
1951

Master of Science
Oklahoma State University
Stillwater, Oklahoma
1958

Submitted to the Faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
DOCTOR OF PHILOSOPHY
May, 1965

A STUDY OF THE FREQUENCY CHARACTERISTICS OF LIGHTNING DISCHARGES

Thesis Approved:

Herbert L. Jones
Thesis Adviser

Wm. L. Hughes

Paul A. McCollum

H. Harrington

John G. Hoffman

J. H. Boggs
Dean of the Graduate School

PREFACE

The study of lightning and of its association with electromagnetic signals has been actively pursued for many years. It has become well known that the signals generated by the changing charges can be useful, such as for investigating radio propagation paths.

Under the direction of Dr. H. L. Jones, research has been carried out at Oklahoma State University to develop a method of using the signals from lightning, called atmospherics or sferics, to identify and track severe storms, especially those which contain tornadoes.

During the early years of his work, Dr. Jones established an apparent relationship between the type of lightning present during a severe storm and the severity of the storm.

It was the intention of the work undertaken for this thesis to help establish an identification technique which would associate the type of lightning with the waveform of the recorded sferic. The equipment developed and the analyses made have indicated the direction which must be taken to fulfill the requirements.

This work was carried out under the direction of, and with much assistance from, Dr. H. L. Jones. Mr. J. C. Hamilton and Mr. R. L. Caswell, both project engineers and graduate students at Oklahoma State University, did excellent jobs of designing the Waveform Discriminator and the Periscope Camera, respectively. Without the guidance of Dr. Jones and the assistance of Mr. Hamilton and Mr. Caswell, this

thesis would not have been possible.

A special word of thanks is due Dr. W. L. Hughes for his suggestions and assistance on the analysis of the data. My thanks also go to Dr. H. E. Harrington, Professor P. A. McCollum, and Professor J. E. Hoffman for their aid and encouragement, and to Mrs. Barbara Adams for typing the manuscript.

TABLE OF CONTENTS

Chapter Page

I. INTRODUCTION 1

II. EXAMINATION OF PREVIOUS RESULTS. 3

Physical Process. 3
Sferic Waveform Studies 8
Lightning and Severe Storms 11

III. DISCUSSION OF EQUIPMENT. 14

IV. PRESENTATION AND DISCUSSION OF DATA. 30

General 30
Flash Number 1. 31
Flash Number 2. 34
Flash Number 3. 39
Flash Number 4. 41
Flash Number 5. 43
Flashes Number 6, 7, and 8. 43
Flashes Number 9 and 10 46
Flash Number 11 46
Flash Number 12 52
Flash Number 13 55
Flash Number 14 55
Conclusions 60

V. CONCLUSIONS. 61

VI. RECOMMENDATIONS. 68

A SELECTED BIBLIOGRAPHY 71

LIST OF TABLES

Table Page

I. Antenna Impedance Measurements 20

II. Dominant Frequencies of Waveforms. 64

LIST OF ILLUSTRATIONS

Figure Page

3.1. System Block Diagram 14

3.2. Periscope-Camera System. 16

3.3. Frequency Response of Waveform Amplifier 23

3.4. Amplifier Pulse Response 25

3.5. Triangular Pulse Response. 26

3.6. Typical Waveforms. 27

4.1. Cloud-to-Ground Strokes and Waveforms. 32

4.2. Cloud-to-Ground Flash. 35

4.3. Cloud-to-Ground Waveforms. 37

4.4. Cloud-to-Ground Waveforms. 38

4.5. Cloud-to-Ground Flash. 40

4.6. Cloud-to-Ground Flash. 42

4.7. Cloud-to-Ground Flash. 44

4.8. Three Cloud-to-Ground Flashes. 45

4.9. Two Cloud-to-Ground Flashes. 47

4.10. Cloud-to-Ground Flash. 48

4.11. Waveforms for Cloud-to-Ground Flash. 49

4.12. Waveforms for Cloud-to-Ground Flash. 50

4.13. Cloud-to-Cloud Flash 53

4.14. Cloud-to-Cloud Flash 54

4.15. Cloud-to-Ground Flash. 56

Figure Page

4.16. Waveforms for Cloud-to-Ground Flash. 57

4.17. Waveforms for Cloud-to-Ground Flash. 58

4.18. Cloud-to-Cloud Flash 59

5.1. Fourier Spectra. 66

CHAPTER I

INTRODUCTION

One of the most important research projects at this University during the past fifteen years has been the study of atmospherics and their relation to severe storms.

Although much has been accomplished, as with any project of this type, each new answer raises many new questions. The over-all purpose of the project discussed in this thesis was to begin a thorough investigation of some of the particular electromagnetic field changes, or sferics, which were associated with known types of lightning flashes.

As a first step, it was necessary to obtain an understanding of the physical process of the lightning discharge. A literature survey led to the realization that a substantial amount has been written on the lightning discharge without furnishing a complete picture. Many of the details of charge separation, distribution, and recombination are still subject to much speculation. In spite of this situation, a complete-enough picture was obtained to provide a basis for planning the research program.

The instrumentation for the study was a combination of existing equipment and equipment which had to be designed and built. The basic existing equipments were a Q-3 sferics detection unit and a 150-kilocycle direction-finder unit which have been in operation at the Atmospherics Laboratory for some time. The equipment which had to be designed and built consisted of two principal units. One was the Periscope-Camera unit which provided the important function of photographing the actual lightning flashes in a manner which made it possible to separate the individual strokes in each lightning flash. A second piece of basic equipment which proved extremely useful was the Waveform Discriminator. This unit made it possible to separate the signals of primary interest from the many signals that normally obscure them. A full explanation of these equipments is given in the third chapter.

A recording technique was developed which provides a photographic record of the lightning strokes and a record of sferic waveforms and directional-indicating pips generated by the strokes. A time-signal generator of the crystal-controlled oscillator type was used to produce time signals on the film records to provide an accurate method of film coordination. Using the system developed, the times on the two-film systems can be coordinated to within one millisecond in most cases.

The data presentation and analysis of the waveforms in a general manner are discussed in the fourth chapter, while in Chapter V there is a discussion of attempts to perform a spectrum analysis and of the difficulties which were discovered.

The procedures which must be followed in order to obtain the data in a form which can be used to arrive at a complete analysis are discussed in the final chapter.

CHAPTER II

EXAMINATION OF PREVIOUS RESULTS

Physical Process

Lightning is such a spectacular and impressive event that it is not surprising that it has been the object of scientific interest and study for many years. Since the time Franklin proposed the experiments which established the electrical nature of lightning, the investigations have been many and varied. Various workers have tried to determine the sources of the charges involved, the processes which separate the charges, and the processes of recombination of the charges. Many studies have contributed to the information known on each of the topics, but none of them is thought to be fully understood. Of most importance to this study has been the literature on the discharge process itself.

One aspect which has received a large share of interest has been the electromagnetic waves generated by the lightning stroke and its associated charge movements. One approach to the study of the electromagnetic waves, which are commonly called atmospherics or sferics, has been to investigate the relationship of these sferics to the breakdown-discharge process as recorded photographically.

Some of the most thorough photographic studies of lightning were started in the early 1930's. These studies were carried out in South

Africa by B. F. J. Schonland and his associates and were reported in a series of papers.[1,2,3,4,5,6] By using a camera designed by C. V. Boys, high-speed photography was utilized to study lightning from the initial breakdown of the air to the final return stroke. The first of these studies was limited to the parts of the process which result in emission of enough visible light to expose the film. From this start, the first detailed theories were formulated to describe the complete lightning process.

In the first of the afore-mentioned papers, the authors described the stepped leader and the return stroke. Their photographs were the first to show the visible light emitted from a breakdown process which progressed from the cloud to the ground in a series of discrete steps. Pictures of twenty lightning flashes were examined to determine that the

---

[1] B. F. J. Schonland and H. Collens, "Progressive Lightning," Proc. of Roy. Soc. of Lon., Vol. 143, Series A, February, 1934, pp. 654-674.

[2] B. F. J. Schonland, D. J. Malan, and H. Collens, "Progressive Lightning, II," Proc. of Roy. Soc. of Lon., Vol. 152, Series A, November, 1935, pp. 595-625.

[3] D. J. Malan and H. Collens, "Progressive Lightning, III--The Fine Structure of Return Lightning Strokes," Proc. of Roy. Soc. of Lon., Vol. 162, Series A, September, 1937, pp. 175-203.

[4] B. F. J. Schonland, "Progressive Lightning, IV--The Discharge Mechanism," Proc. of Roy. Soc. of Lon., Volume 164, Series A, January, 1938, pp. 132-150.

[5] B. F. J. Schonland, D. B. Hodges, and H. Collens, "Progressive Lightning, V--A Comparison of Photographic and Electrical Studies of the Discharge Process," Proc. of Roy. Soc. of Lon., Vol. 200, Series A, October, 1938, pp. 56-75.

[6] B. F. J. Schonland, "The Pilot Streamer in Lightning and the Long Spark," Proc. of Roy. Soc. of Lon., Vol. 220, Series A, October, 1953, pp. 25-38.

lengths of the steps were from 25 meters to 112 meters, with a mean length of 54 meters. After the stepped leader reaches the ground, there is a large surge of current traveling from the ground up to the cloud. The intense luminosity generated by the upward current is what is visible to the ordinary observer when he sees lightning. The name given to this upward-traveling surge was the return stroke.

In the second paper of the series, the authors went into more detail on the velocities and durations of the components of the lightning flashes. A study of 95 lightning flashes composed of 200 strokes was made to determine that each flash was composed of from one to 27 strokes. The strokes of a given flash varied in time separation from 0.6 milliseconds to 530 milliseconds. In this context a stroke is a return stroke, and all of the strokes making up a flash follow the same path in space, either completely or partially.

The stepped leader was found to occur always before the first stroke of a flash. The average length of each step was about 50 meters. The pause between steps was on the order of 100 microseconds, while the velocity determined for each step was on the order of 5×10^9 cm./sec. Many of the stepped-leader processes exhibited branching, where the branches either ended in space or went to ground separately from the main part.

The details of the return stroke were given in the third paper of the series. The return strokes were found to differ from each other in some respects. Usually the first return stroke had branches corresponding to the branches of the stepped leader. The following return strokes of a sequence often follow the same path as the first return stroke without the branches; however, many times they only followed a portion of the original path, the remainder being different. Most often the changed path of the return stroke was through what had been one of the branches of the original stroke.

The luminosity of the return strokes was observed to travel from the ground up to the cloud. The individual return strokes were found to be made up of pulses, or surges, apparently one for each branch of the stepped leader. The velocity of the luminous front was most often about 3.5×10^9 cm./sec.

Although the first return stroke of a flash was the only one which was preceded by a stepped-leader breakdown process, each of the succeeding return strokes of the same flash was preceded by a phenomenon called the dart leader. The dart leader was very dim, as was the stepped leader, but constituted a breakdown of the path in one continuous action rather than in steps. The velocity determined for the dart leader was about 2×10^8 cm./sec.

After the initial photographic studies, Schonland supplemented his work with an investigation of the electrostatic field changes recorded at the time of a lightning flash. These studies were discussed in the fifth paper of the series. The electrostatic field measurements gave total time durations of the stepped-leader process of from 240 microseconds to 3,000 microseconds. Corresponding times measured from photographs of the flashes were 170 microseconds to 1,900 microseconds. The differences in the results were attributed to the hiding of the initial part of the path by clouds in the lightning photographs.

An author who surveyed the literature[7] found that the times

---

[7] J. D. Craggs and J. M. Meek, Electrical Breakdown of Gases, (London, 1953), p. 246.

recorded for the current in the return stroke to reach a peak varied from 1 to 19 microseconds, while the average value was about 6 microseconds. From 7 to 115 microseconds was the range given for the current to fall to half of the peak value, with the average time being about 24 microseconds.

After studying his original work, Schonland developed a theory in which he postulated the existence of a weakly-ionized pilot leader.[8] It was suggested that this pilot leader precedes the stepped leader and is, in fact, a continuous, slower-moving discharge which the stepped leader overtakes periodically.

Whereas the preceding discussion offers an interesting explanation of the photographic evidence, there are some parts of the physical processes that remain rather vague and incomplete. One of the more recent investigations has offered another explanation of the breakdown, or stepped-leader, process.[9] This prestrike theory describes the initial leader and the form of the ionized region in terms of the critical gradient of the air. Calculations are given which support the suggestion that the ionized path to ground is an advancing, pestle-shaped region whose diameter can be in the order of 20 meters. The description given does not alter the fact that the process is a stepped one, but rather it offers a more easily accepted explanation for the process.

---

[8] B. F. J. Schonland, "The Pilot Streamer in Lightning and the Long Spark," Proc. of Roy. Soc. of Lon., Vol. 220, Series A, October, 1953, pp. 25-38.

[9] S. B. Griscomb, "The Prestrike Theory and Other Effects in the Lighting Stroke," A.I.E.E. Transactions, Vol. 77, Pt. III, 1958, pp. 919-933.

Sferic Waveform Studies

The sferics, as the electromagnetic waves from lightning are called, have been observed both usefully and as a nuisance for as long as we have had electronic communication systems. These sferics are observed on radio and wireless telegraphy systems as noise or static. The useful aspects of sferics have been the study of the propagation of electromagnetic waves and the location of distant thunderstorms.[10]

Several countries have used networks of direction-finding antennas to locate and record the position of thunderstorms, which may be thousands of miles away. Descriptions of these networks can be found in the literature.[11] Basically, most of the systems amplify signals received on crossed-loop antennas and apply them to the deflection plates of a cathode-ray oscilloscope.

Propagation of the very-low-frequency waves has been studied by many workers using sferics,[12] but since this subject is not of direct interest in this thesis, it will not be reviewed here.

At various times different investigators have been concerned with studying the spectra of the waveforms of the sferics. Although much information has been obtained from these studies, there is much that remains to be done in order to complete the analysis.

---

[10] Harold Norinder, "Long Distance Location of Thunderstorms," Thunderstorm Electricity, ed. H. R. Byers (Chicago, 1953), pp. 276-327.

[11] Ibid., p. 308.

[12] K. G. Budden, "The Propagation of a Radio Atmospheric," Phil. Mag., Vol. 42, 1951 (a), pp. 1-19.

Much of the spectral-analysis work has been confined to relatively small sections of the spectrum. A project of the National Bureau of Standards was directed at obtaining the spectral analysis of sferics arriving from distances between 165 kilometers and 620 kilometers.[13] The portion of the spectrum determined was from 1,000 c.p.s. to 40,000 c.p.s. Sferic waveforms were recorded using amplifiers having an amplitude response which was 3 db down at 1,000 c.p.s. and at 100 kilocycles per second and having linear-phase response in the pass band. The spectra were calculated at intervals of 1 kilocycle per second using a digital computer programmed to evaluate the Fourier integral

$$F\ (f) = \int_{0}^{\tau} G\ (t)\ e^{-j\ 2\pi\ ft}\ dt \qquad (2.1)$$

where

$$G\ (t) = 0 \qquad t \leq 0$$

and

$$G\ (t) = 0 \qquad t \geq \tau \ .$$

The sferics analyzed were assumed to have been generated by cloud-to-ground strokes if the directional pips, which were recorded simultaneously, did not exhibit any ellipticity. This assumption about ellipticity was based on the reasoning that a cloud-to-ground stroke will produce a

---

[13] A. G. Jean and W. L. Taylor, "Very-Low-Frequency Radiation Spectra of Lightning Discharges," Jour. of Res. of the N.B.S., Vol. 63D, No. 2, September-October, 1959, pp. 199-204.

vertically-polarized wave, while a cloud-to-cloud stroke will produce a wave having a considerable component which is horizontally polarized.

A report has been published[14] on some recent work which involved measurements made at frequencies between 400 megacycles per second and 1,000 megacycles per second. This investigation was made using a narrow-band-pass, 1.5 megacycles, receiver tuned at various frequencies in the band of interest. The frequencies discussed were 420 and 850 megacycles per second, with similar results obtained at both frequencies. The authors found that the signals received appeared to be generated most often by the stepped leaders and dart leaders. In some cases they received signals which were apparently generated by the return strokes, but these were usually found to occur from 60 to 100 microseconds after the start of the return stroke. Electrostatic field measurements were used to determine the times of the various components of the strokes, thus providing the basis for deciding the generating process of the high-frequency sferic.

A related study has been made using the spectra of sferics as a means of determining propagation-attenuation characteristics as a function of distance.[15,16] Data taken at recording stations as far as

---

[14] M. Brook and Kitagawa, "Radiation from Lightning Discharges in the Frequency Range 400 to 1,000 Mc/S," Jour. of Geoph. Res., Vol. 69, No. 12, June 15, 1964, pp. 2431-2434.

[15] William L. Taylor and L. Jerome Lange, "Some Characteristics of VLF Propagation Using Atmospheric Waveforms," Recent Advances in Atmospheric Electricity, ed. L. G. Smith (Pergamon Press, 1958), pp. 609-617.

[16] William L. Taylor, "Daytime Attenuation Rates in the Very-Low-Frequency Band Using Atmospherics," Jour. of Res. of the N.B.S., Vol. 64D, No. 4, July-August, 1960, pp. 349-355.

6,500 kilometers and as close as 1,200 kilometers were analyzed by using a Fourier integral. The spectra from 1,000 to 75,000 cycles per second were compared to determine the attenuation characteristics of the atmosphere.

Lightning and Severe Storms

Investigations carried out at Oklahoma State University have been directed toward determining the association of lightning and severe thunderstorms, especially those that develop tornadoes. Early in his work,[17] Jones found a strong increase in lightning activity in the storm cells containing tornado funnels. From cathode-ray oscilloscope presentations, it was noted that there were strong increases in the number of sferic waveforms containing higher than normal frequencies.

Some waveform analyses of these sferics indicated the value of the high-frequency content was in the neighborhood of 150 kilocycles per second.[18]

Based on the results of these early studies, the decision was made to design and build equipment which was especially sensitive to the higher frequencies.[19,20]

---

[17] H. L. Jones and P. N. Hess, "Identification of Tornadoes by Observation of Waveform Atmospherics," Proc. of I.R.E., Vol. 40, No. 9, September, 1952, pp. 1049-1052.

[18] Joe Pat Lindsay, "An Analysis of the Sferic Waveform" (unpub. Master's Thesis, Oklahoma State University, 1954).

[19] H. B. Ferguson, "Tornado Tracking by High-Frequency Sferics" (unpub. Ph.D. dissertation, Oklahoma State University, 1956).

[20] Ruben D. Kelly, "Development of Electronic Equipment for Tornado Detection and Tracking" (unpub. Ph.D. dissertation, Oklahoma State University, 1957).

One of these systems which proved to be of particular value was the H.F.D.F. or High-Frequency Direction Finder. This equipment followed the basic design, used for many years, of applying the signals from crossed-loop antennas to the deflection plates of a cathode-ray oscilloscope. The new feature was the use of narrow-band amplifiers, tuned to 150 kilocycles per second, in the circuits. Using this new direction finder, studies were conducted to determine the possibility of a correlation between the severity of the thunderstorm and the rapidity of repetition of the high-frequency sferics.

Such a correlation was strongly indicated during the time of the disastrous tornado which heavily damaged Blackwell, Oklahoma, and Udall, Kansas.[21] During and before this storm, Jones was operating the equipment discussed above. It was verified that there was a significant increase in the activity of the H.F.D.F. during the time the funnel was known to be in existence. At the same time it was observed that there was a decrease in the activity of a standard direction finder tuned at the lower frequency of 10 kilocycles per second.

The results of the above experiments led to the problem of finding the source of the high-frequency sferics and, if they are generated by a particular type of lightning, associating that type with the severe thunderstorms.

---

[21] H. L. Jones, "The Identification of Lightning Discharges by Sferic Characteristics," Recent Advances in Atmospheric Electricity, ed. L. G. Smith (Pergamon Press, 1958), pp. 543-556.

It has been postulated[22] that there exists a process, unique to the very heavy thunderstorms and tornadoes, which produces the particular type of lightning which generates a preponderance of the high-frequency components. This process has been named the "Tornado Pulse Generator" by Jones, as suggested informally by R. Holzer of the University of California at Los Angeles.

---

[22] H. L. Jones and R. L. Calkins, "The Tornado Pulse Generator as the Criteria for the Definition of the Severe Storm," _Proc. of the Third Conference on Severe Storms_, University of Illinois, November, 1963.

CHAPTER III

DISCUSSION OF EQUIPMENT

This section includes a description of the over-all equipment system, the component subsystems, and an analysis of the waveform-recording subsystem.

The general purpose of the equipment used was to provide a means of simultaneously recording both the waveforms for sferics generated by nearby lightning strokes and the photographs of these strokes. An obvious problem was to include suitable timing indications on the recording films to permit proper coordination between the two recording cameras.

An over-all block diagram of the system is shown in Figure 3.1.

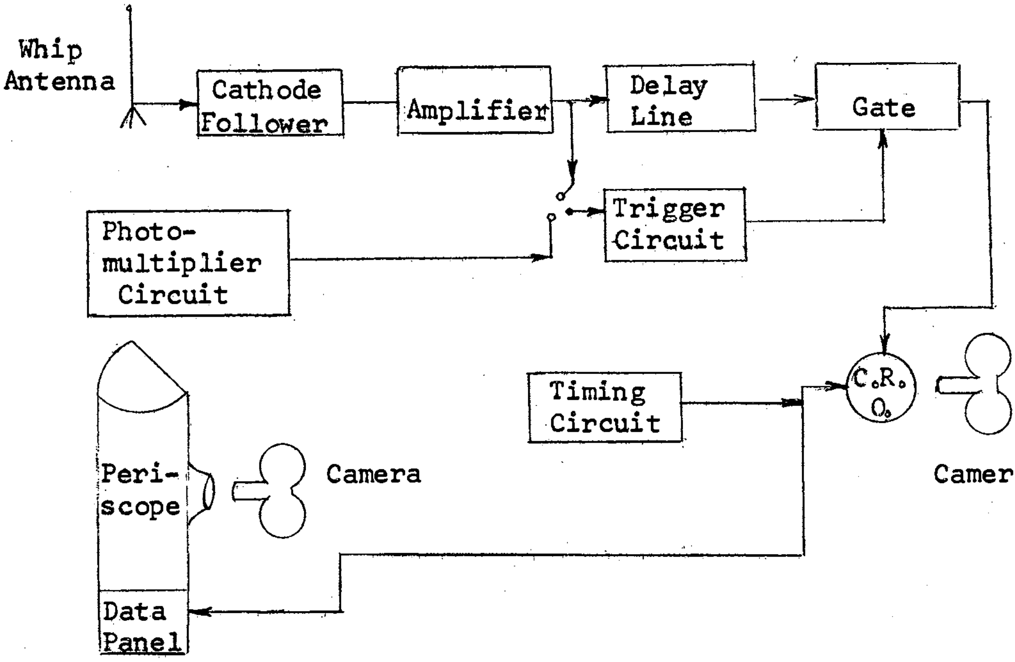


Figure 3.1. System Block Diagram

A very convenient piece of equipment was developed by a co-worker for accomplishing the photographic requirement of this project.[1] The principal component is an adapted surplus gunsight periscope. The periscope was mounted through the roof of the Atmospherics Laboratory at Oklahoma State University. By using a special lens, a system of mirrors, and a beam-splitting prism, the camera was made to see both the view of the sky through the periscope and the data panel. The data panel is used to record azimuth, elevation, and time information. The azimuth and elevation of the center of the field of view is recorded by using selsyns to drive indicating dials. Timing is recorded by using a combination of flashing neon bulbs and a digital clock. The neon bulbs indicate the whole, tenth, and hundredth seconds. The clock face is illuminated every six seconds by a flash bulb, as are the azimuth and elevation dials.

A picture of the periscope camera is shown in Figure 3.2. The field of view of the periscope is about 40°. A bull's-eye-type reticule is illuminated by the lightning stroke being photographed and is necessary in determining the exact time of the stroke.

Closely associated with the periscope camera is the device used to selectively trigger the waveform circuit. When a storm front is in the vicinity of the laboratory, there are often many active storm cells, each of which is the source of many lightning flashes. During any moderate-to-strong storm, the rapidity of lightning flashes from all directions is usually enough to provide so many waveforms that it

---

[1] R. L. Caswell, "Development of a High-Speed Lightning Camera" (unpub. Master's Thesis, Oklahoma State University, 1963).

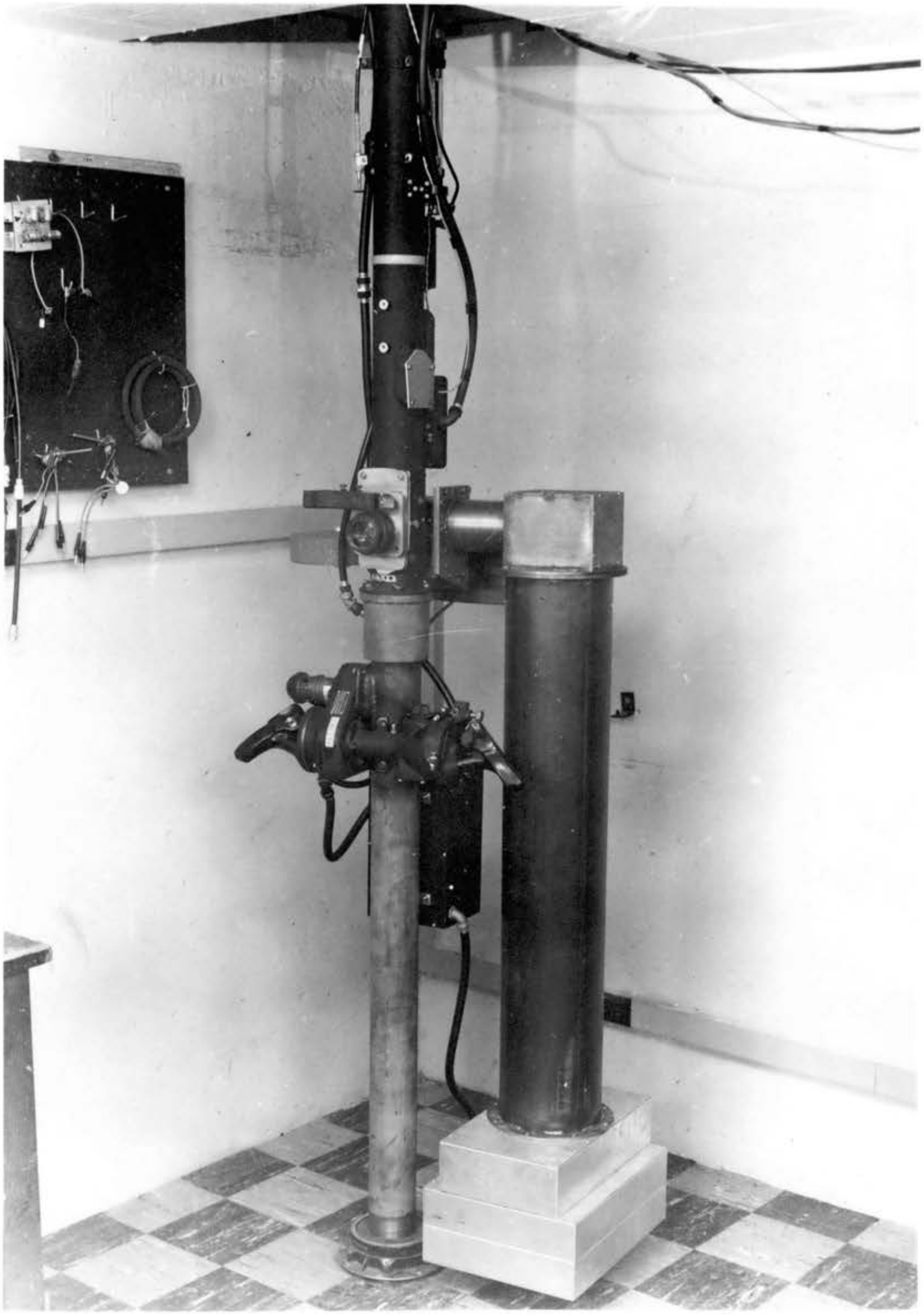


Figure 3.2. Periscope-Camera System

is impossible to distinguish one from another. At least this is the case when the sferic amplitude alone is used to trigger the waveform circuit. To eliminate this unfortunate situation, a system was designed and built to trigger the waveform circuit with a pulse derived from the light of the lightning stroke. This system was designed and built by another co-worker on the project.[2]

The Waveform Discriminator, as the equipment mentioned in the preceding paragraph is called, uses the light emitted from the lightning stroke to generate a voltage pulse in a photomultiplier-tube circuit. The resulting pulse is used to trigger the waveform circuit, thus displaying only the waveforms which result when the particular stroke occurs. Obviously some delay line is needed in the waveform circuitry, since the light and the electromagnetic waves travel at much the same speed and since it takes a finite amount of time to generate the voltage pulse from the light energy. The long delay, 250 microseconds, also provides the opportunity to record some of the waveform which might be generated before the luminosity is great enough to operate the pulse-trigger circuit.

The field of view of the photomultiplier tube was designed to be essentially the same as that of the periscope camera. In order to have the same area visible to both systems, the photomultiplier tube was mounted on a bracket attached to the periscope.

The discriminator accomplishes the purpose for which it was

---

[2] J. C. Hamilton, "An Instrument for Detecting Sferics from Visible Lightning Discharges" (unpub. Master's Thesis, Oklahoma State University, 1962).

designed satisfactorily. One improvement that would be useful, however, is a system which would allow recording of even more of the waveforms generated before the bright return stroke occurs. The waveforms now recorded using this system are limited to 250 microseconds of the signal from the stepped-leader process and 250 microseconds of the signal from the return stroke. These 250 microseconds may represent a small fraction of the total time of the stepped-leader process.

To be able to ascertain the spectrum of the electromagnetic field at the antenna, it is necessary to know the amplitude and phase response of the total waveform system, from the antenna to the output of the final amplifier. If this system response is known, it should be possible to determine the input spectrum from the output waveform.

An analysis of the whip antenna used in this project has been carried out. The antenna is twelve feet high and is mounted above a good ground plane, which is made of a square of chicken wire about 40 feet on a side with ground rods in the corners and at the center.

The first step in the analysis was to determine the terminal radiation resistance of the antenna. Since the antenna is located over a good ground plane, it was considered in the same manner as a center-fed dipole in free space, with the total length of the dipole being 7.32 meters.

The method used to find the radiation resistance of an elemental dipole is discussed in standard textbooks.[3] The usual procedure is to assume a current distribution, calculate the E and H fields, and use

---

[3] Robert Plonsey and Robert E. Collin, Principles and Applications of Electromagnetic Fields (McGraw-Hill, New York, 1961), pp. 394-396.

them to compute the Poynting vector. This vector gives the direction and amplitude of the power-flow density. Integrating over a sphere containing the dipole gives the average power radiated. The radiation resistance is the equivalent resistance which would dissipate the same power with the given current. In the case of a short dipole, $L < \lambda/20$, where L is the length of one side of the dipole and λ is the wavelength, it has been shown that the current distribution to be assumed is a triangular distribution with maximum in the center and zero at each end of the dipole. Using this assumption leads to a formula for the radiation resistance

$$R_r = 197.5 \left(\frac{\ell}{\lambda} \right)^2 , \qquad (3.1)$$

where ℓ is the total length of the dipole.[4] Application of the above formula led to the following values for the whip antenna used and the frequencies indicated:

FREQUENCY (C.P.S.)	R_r (OHMS)
10^2	1.18×10^{-9}
10^3	1.18×10^{-7}
10^4	1.18×10^{-5}
10^5	1.18×10^{-3}
10^6	1.18×10^{-1}

Since the largest of these values is only 0.118 ohms, it is apparent that, for the frequencies of interest, the radiation resistance is an

---

[4] R. G. Brown, R. A. Sharpe, and W. L. Hughes, Lines, Waves, and Antennas (New York, 1961), pp. 210-212.

insignificant part of the antenna impedance. Further discussion will bear out this conclusion.

The next step was to determine the terminal impedance of the antenna. This was done experimentally, then checked theoretically. The measurements all indicated a capacitive impedance. The following table lists the results of measurements made with three sets of equipment. The Group A measurements were made using a GR 1330-A Bridge Oscillator, a GR 1606-A R-F Bridge, and a BC 348-H Receiver. The Group B measurements were made using the same oscillator and bridge, but with a GR 1212-A Null Detector instead of the receiver. The Group C measurements were made using a H.P. 200 AB Audio Oscillator, a GR 1603-A Z-Y Bridge, and a H.P. 400-D V.T.V.M. This last set of measurements covered the lower frequencies.

TABLE I

ANTENNA IMPEDANCE MEASUREMENTS

	CAPACITY (μμf)		
FREQUENCY	A	B	C
1 MC		60.7	
900 KC		60.7	
800 KC		60.7	
700 KC		61	
600 KC		61	
500 KC	62.4	61.4	
400 KC	62.4	61.4	
300 KC	62.4	61.4	
200 KC	62.4	61.5	
100 KC		63.6	
30 KC			65.3
20 KC			66.9
10 KC			65.3
5 KC			56.7-63.7
2 KC			79.6-92.3
1 KC			66.9
500 C			60.5
200 C			79.6

A separate measurement was made to determine the capacitance of the lead wires, without the antenna. The measured value of this capacitance was 9.5 μμf.

A mathematical determination of the capacitance was accomplished using a published equation.[5] The equation chosen was developed to give the capacitance of a vertical wire above a ground plane and is given as

$$C = \frac{7.36\ m}{\log_{10} \frac{2m}{d} - k}\ \mu\mu f \quad , \qquad (3.2)$$

where m is the length of the vertical wire, in feet; d is the diameter of the wire, in feet; and k is a constant which is dependent upon the ratio of the height of the bottom of the antenna, h', to the length of the antenna. Calculations made using Equation 3.2 for the antenna with the constants, $m = 12$ feet, $d = 1/48$ foot, $h' = 1$ foot, and $k = 0.356$, gave a capacitance of 42.7 μμf. A similar calculation letting $h' = 1/4$ foot resulted in a capacitance of 43.7 μμf. The second calculation was made because the physical configuration of the antenna made it very difficult to determine the actual height of the base of the antenna. Obviously, it makes very little difference in the calculated value of capacitance.

Since the data from measurements made between 100 KC and 1 MC were the most consistent and since the data from the lower-frequency

---

[5] Frederick W. Grover, "Methods, Formulas, and Tables for the Calculations of Antenna Capacity," *U. S. Bureau of Standards Scientific Paper*, Vol. 22, No. 568, 1927-1928.

measurements show indications of agreement, it seems reasonable to assume the impedance of the antenna is represented by a capacitor of about 50 μμf. This figure was obtained by subtracting the meter lead capacitance from the total measured capacitance, then rounding off for convenience.

Realizing that neither the calculated values nor the measured values are highly accurate, it appears there is good agreement between the two.

Using the above value of capacitance, the basic impedance function is given by substituting into

$$Z = -j/2\pi\ fc, \qquad (3.3)$$

At a frequency of 100 c.p.s. $Z_{100} = -j$ 32 megohms, while at a frequency of 1 M.C. $Z = -j$ 3,200 ohms. In either case the reactive impedance is many orders of magnitude larger than the calculated radiation resistance.

The amplitude response of the antenna cathode follower was measured and found to be very flat from 1,000 cycles to 1 megacycle. The low-frequency response dropped off with a 6 db/octave slope with the 3 db point at 160 cycles per second.

The amplitude response of the waveform amplifier was measured and is shown in Figure 3.3. The 3 db points are at 700 cycles and 230 kilocycles, with a very sharp cut-off rate, about 24 db/octave, at the high end. The amplifier included a 250-microsecond delay line which was used when recording all of the waveforms shown in this thesis.

In order to further test the response of the waveform amplifier, both rectangular- and triangular-test pulses were fed into the amplifier; and the resulting output pulses recorded.

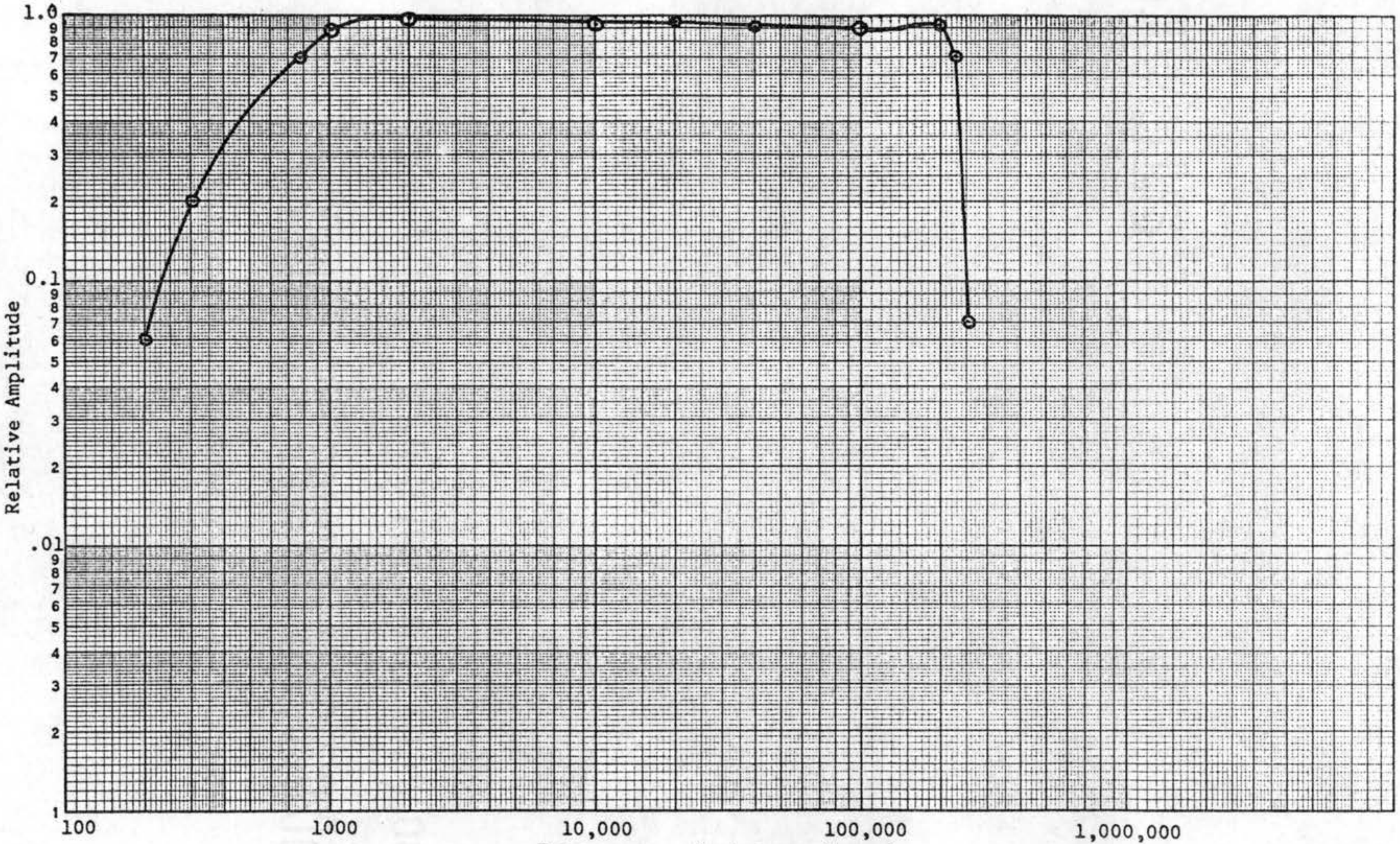
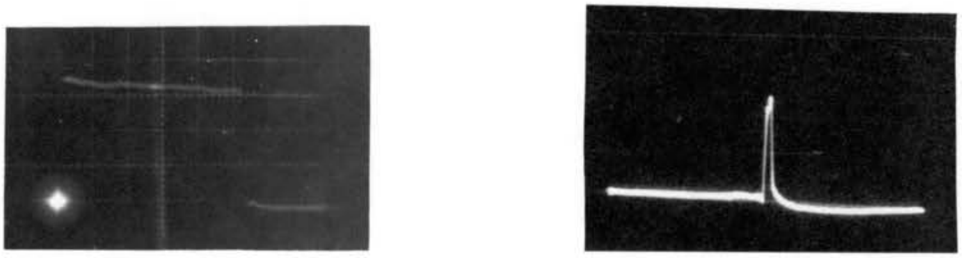


Figure 3.3. Frequency Response of Waveform Amplifier

Figure 3.4 shows the output of the waveform amplifier when a rectangular pulse was applied at the input. The picture in the upper, left corner is of the input pulse as seen on a Tektronix 502 oscilloscope. The time scale is 2 microseconds per division. This sweep time is much faster than that used on the oscilloscope displaying the output waveform. It can be seen that the 10-microsecond pulse is reasonably rectangular with a rise time and a fall time in the neighborhood of 1/4 microsecond. The other three photographs show the output with various gain settings of the amplifier and using a 500-microsecond sweep. The last two photographs show indications of very high-frequency noise, well above the frequencies present on the sferic waveforms. If the waveforms shown are compared with the sferic waveforms in Figure 3.6, it will be noticed that the enlargements are essentially the same, showing the high frequencies of the sferics to be significantly less than those shown on these test pulses. The 250-microsecond delay line accounts for the pulse appearing in the middle of the trace.

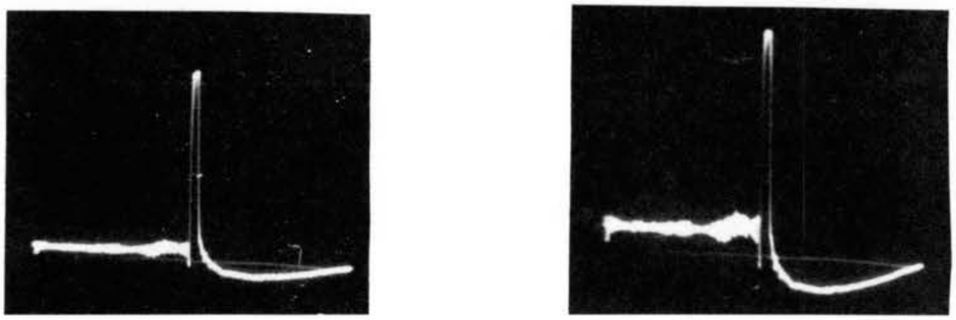
Figure 3.5 is a reproduction of the filmed results of triangular pulses applied to the amplifier. The input pulses were taken from the sweep circuit of a Tektronix 535 oscilloscope. The input pulse of the first series shown at the top of the figure had a rise time of 10 microseconds and a fall time of 8 microseconds. The input pulse of the second series had a rise time of 1 microsecond and a fall time of 6 microseconds. Again, the amplifier gain was varied to get the various amplitudes shown. The input pulses are not shown in this figure.

Figure 3.6 shows a typical group of sferic waveforms chosen to point out the fact that many contain the high frequencies, around 150



Input

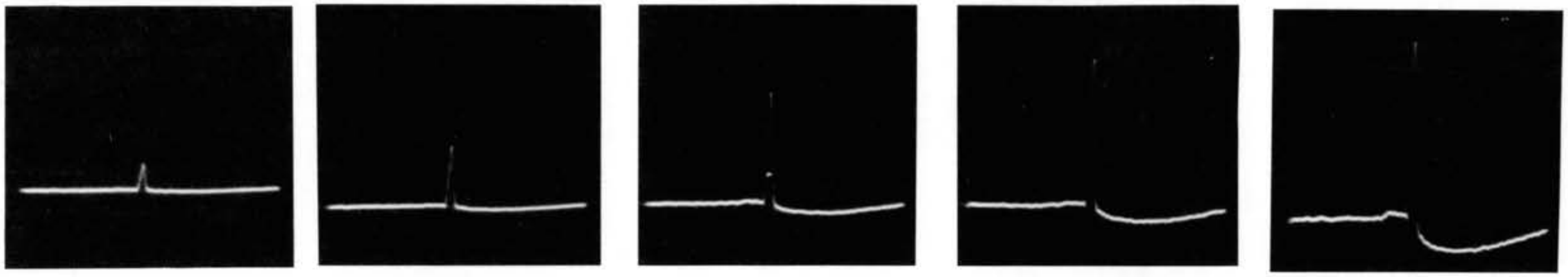
Output
Low Gain



Output
Medium Gain

Output
High Gain

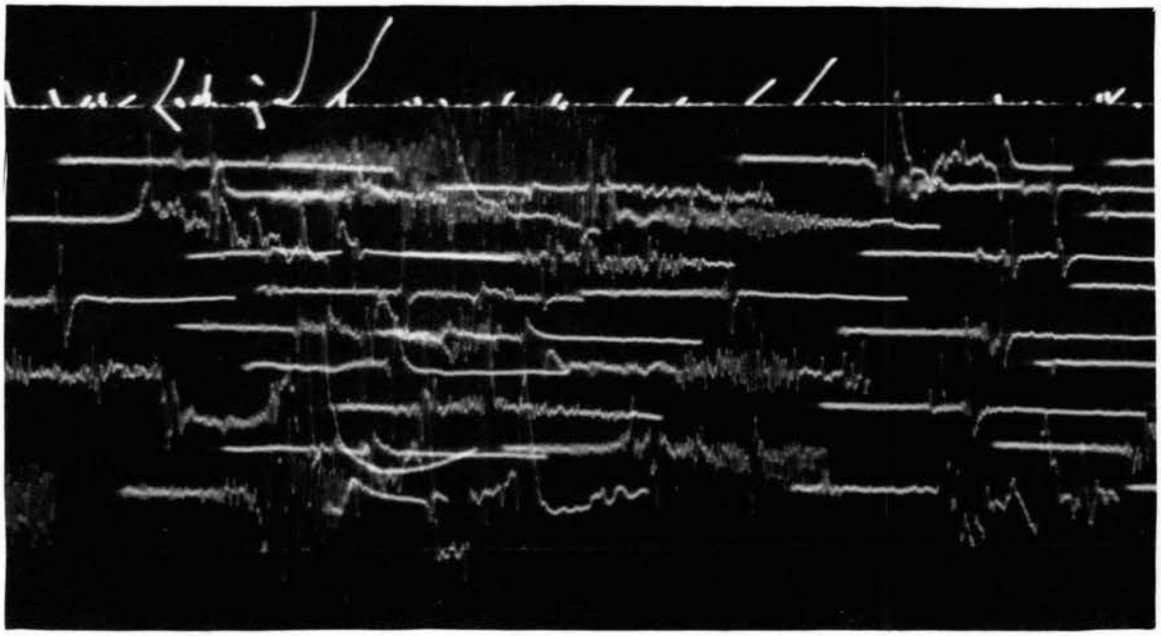
Figure 3.4. Amplifier Pulse Response



Series Number 1. 10 μ Sec. Rise Time; 8 μ Sec. Fall Time

Series Number 2. 1 μ Sec. Rise Time; 6 μ Sec. Fall Time

Figure 3.5. Triangular Pulse Response



Approximate Time is 2239:26

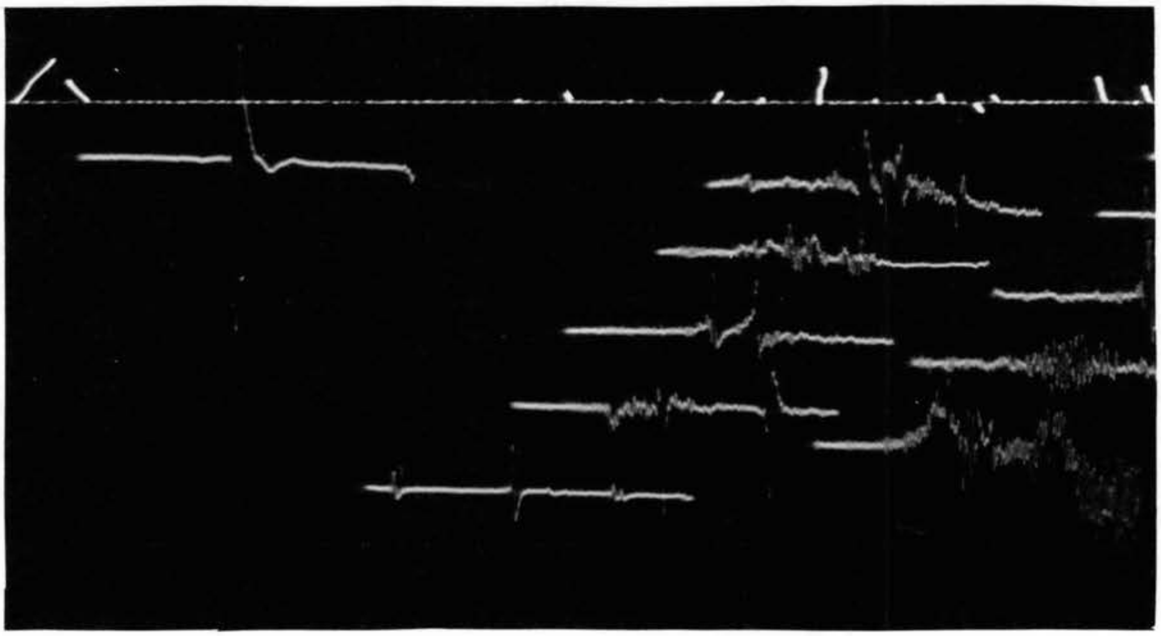


Figure 3.6. Typical Waveforms

kilocycles, and others do not. The two pictures are continuous with time advancing from right to left, while the waveform sweep is from left to right. Close observation shows numerous waveforms with large amplitude pulses but no apparent high frequency. The total time covered is on the order of 3/10 second, while the approximate absolute time is indicated on the figure.

In order to establish the relationship of the waveforms and the photographs of lightning, an accurate timing system had to be used. Such a system was available on the waveform-recording equipment, which was originally Air Force Q-3 sferic-detection equipment. The source of the 100-KC standard time signal was a crystal-controlled local oscillator which has provisions for synchronization with the WWV time signal. This 100-KC signal is divided to obtain the pulses which mark the seconds and the fractions of seconds and to obtain the 100-cycle signal which drives the digital clocks. Since timing systems for both cameras are derived from the same source, they indicate the same times; provided, of course, the clocks are set the same originally.

On the camera recording the waveforms, the time is recorded by a stroboscopic light exposure of the digital clock every six seconds and by the deflection of an extra beam in the cathode-ray tube every second. Interpolation is used to determine the time to the nearest millisecond with very good results. As was mentioned earlier, whole, tenths, and hundredths of seconds are recorded on the periscope-camera film.

As for recording the data, both parts of the system are recorded on 35 mm tri-x panchromatic film by cameras using open shutters. On the periscope camera the duration of each stroke is short enough to prevent blurring, except on certain occasions as discussed in the data analysis. For the waveform recording the total sweep time of the waveform is 500 microseconds, which gives negligible distortion by the film movement of 200 inches per minute. The periscope camera was operated at a film speed of 600 inches per minute to provide better separation of the component strokes of each flash.

CHAPTER IV

PRESENTATION AND DISCUSSION OF DATA

General

As mentioned previously, all of the data taken in this study were recorded on 35 mm film. Most of the data analysis is done by viewing the film in microfilm viewers; but, of course, photographic enlargements had to be made for this presentation. It should be recognized that some of the detail observable on the viewers is lost in the enlargement process.

In most of the following figures, four significant types of data are shown: the lightning photographs, the sferic waveforms, the 10-kilocycle directional indicator, and the 150-kilocycle directional indicator.

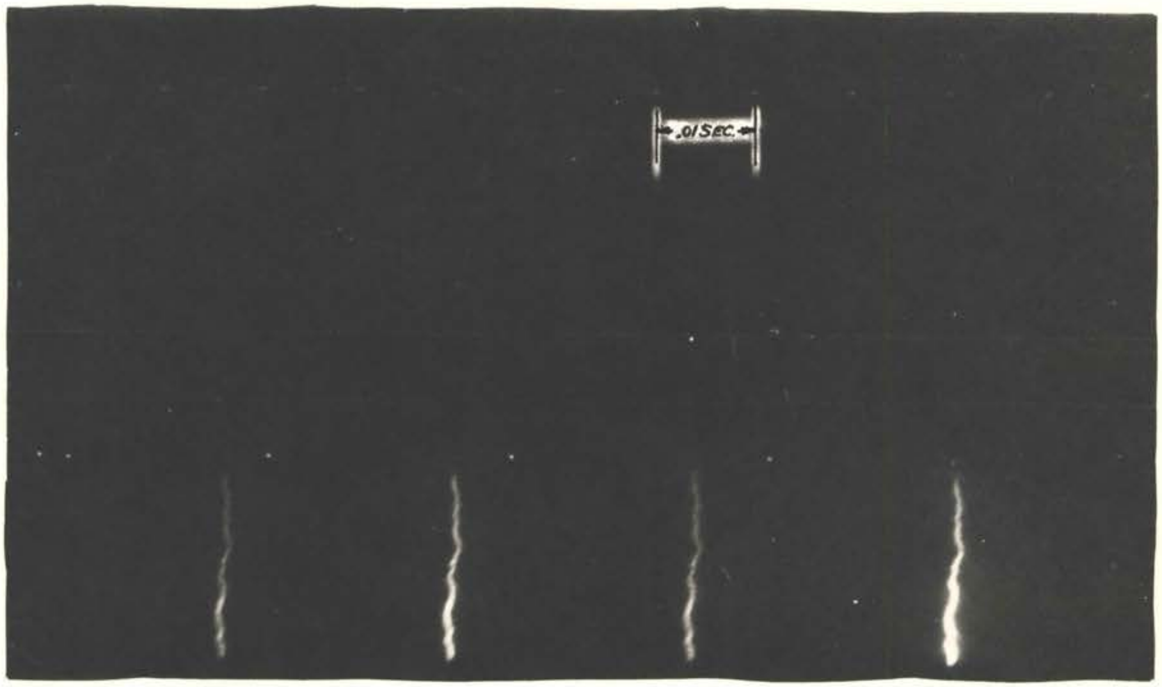
All of the data presented here were obtained during the night of August 6, 1964. This storm lasted for several hours and had enough concentrated lightning activity to provide several very good examples. In order to help provide the reader with an indication of the time scale on the figures which follow, the time of the first lightning stroke of each flash will be given in hours, minutes, seconds, and fractions of a second to three decimal places, using a 24-hour time reference. For example, if a particular stroke occurred at 5.351 seconds after 10:15 P.M., the time indication would be written 2215:05.351. Successive strokes will be indicated only by the seconds and fractions thereof.

It should be recalled that the data are recorded using open-shutter cameras, but the lightning photographs show the separate strokes of each flash if the time between successive strokes is sufficient for the film motion to separate them. In most cases separations of 1 millisecond or more are distinguishable.

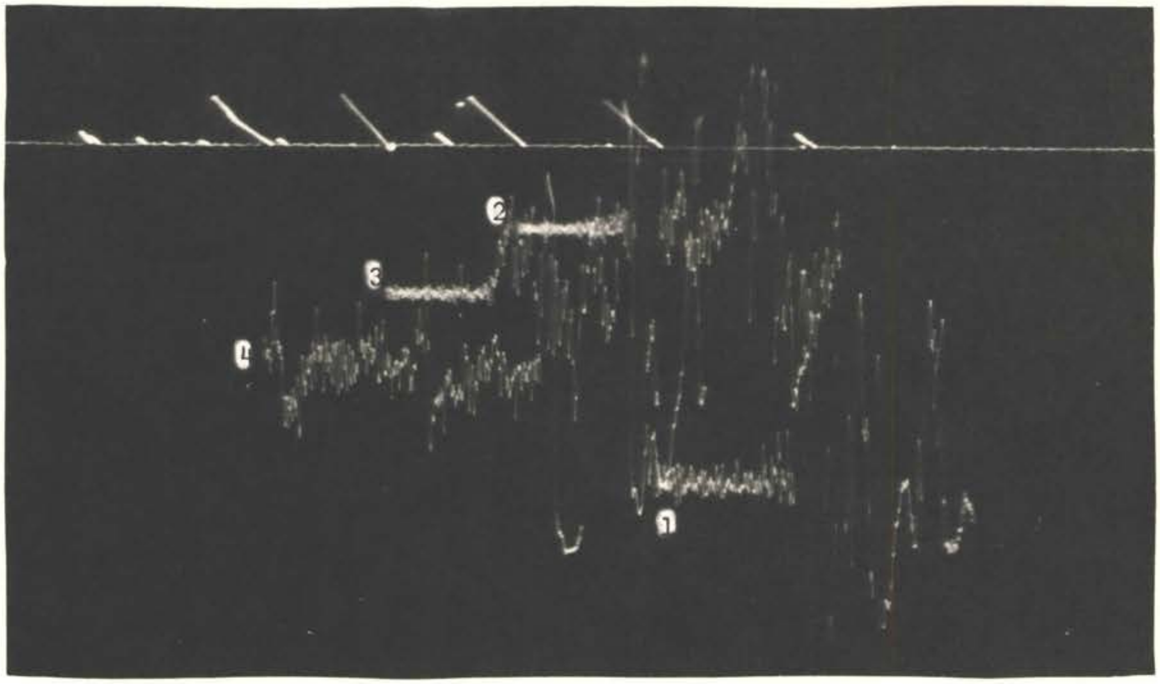
Flash Number 1

In Figure 4.1 there are four distinct strokes of one cloud-to-ground flash shown in part A. It is apparent that the four strokes are over the same path because of the exact similarity of their shapes. It is even more apparent when the viewer is used; and the reticule, or bull's-eye, shows beside each stroke. The film motion is such that time increases from right to left, as it does on all of the succeeding figures. Rather dimly visible about three-eighths of an inch below the top of the photograph is a row of white spots about one-half an inch apart. These spots are the 0.010 second time marks. One of the interesting features of this sequence is the even spacing between strokes. The first two are separated by 26 milliseconds, the second and third by 25 milliseconds, and the last two by 23 milliseconds.

Part B of Figure 4.1 shows the four sferic waveforms associated with the four strokes and the 10-kilocycle directional indicators. The film movement is slow enough so that the film can be considered stopped during each individual 500-microsecond waveform sweep. The waveform signal is superimposed upon a staircase voltage which provides the offset to help reduce overlap of the sferics. Here also the time moves from right to left, although the sweep of the individual waveforms is



A 46.305 46.282 46.257 2226:46.231
4 3 2 1



B Waveforms and 10-KC Directional Indicator

C 150-KC Directional Indicator

Figure 4.1. Cloud-to-Ground Strokes and Waveforms

from left to right. Thus, the first waveform occurs farthest to the right and lowest. The second waveform is the closest to the top of the picture and then, of course, come the third and fourth waveforms.

Before discussing these sferic waveforms in more detail, a comment should be inserted concerning the directional indicators. The signal which is used to generate each of the directional indicators occurs fast enough to produce either a line, or at worst an ellipse, on the film at the position where the corresponding waveform begins. It will be noticed that the first waveform is associated with a single 10-KC directional indicator, whereas the corresponding 150-KC directional indicator was preceded by many more, apparently from the same direction. Each of the other three waveforms is associated with a relatively isolated directional indicator. This activity shown by the 150-KC directional trace is taken as evidence to support the theory that a large share of the higher-frequency content is generated by the step-leader process.

Fortunately, the waveform discriminator was in use during the time of this sequence of strokes, thus eliminating extraneous waveforms. All four waveforms have an ample quantity of the higher frequencies, that is, in the neighborhood of 150 kilocycles per second. A close measurement on the film viewer of the first 250-microsecond portion of the waveforms indicated that if the peaks and valleys of the waveforms were considered as those of a sinusoidal wave, the frequency would be about 160 kilocycles per second for the first, third, and fourth waveforms and closer to 200 kilocycles per second for the second waveform. On each of these waveforms the 160 kilocycles per second is evident for the duration of the sweep, superimposed on the lower-frequency, large pulses.

Part C of Figure 4.1 is a reproduction of the 150-KC directional indicator. The angle of this directional indicator appears to be slightly different than that of the 10-KC directional indicator. Two factors contributed to this disagreement; one is that the crossed-loop antennas are individually adjustable and the other is that little effort was spent in maintenance on the directional-indicator amplifiers. Consequently, the antennas may have been at somewhat different angles, and the amplifiers obviously were not working as good as they could have been. The directional pips of the 150-KC indicator are not as distinct as those of the 10-KC indicator, primarily because of receiver adjustments.

The usefulness of the 250-microsecond delay line in the waveform circuit is apparent on these waveform pictures. The first waveform shows the presence of considerable activity during the 250 microseconds before the large pulses associated with the luminescence causing the triggering. The high-frequency activity on this portion of the waveform adds further support to the theory that the stepped-leader process generates the higher frequencies.

Flash Number 2

Figure 4.2 shows the periscope-camera pictures of a 14-stroke, cloud-to-ground lightning flash. In this figure time advances from right to left and from top to bottom. Several of the strokes were so dim that they are almost indistinguishable in the print, even though they were visible on the film viewer. Between the second and third strokes, the long time delay of 0.281 seconds is indicated by the break in the printed film strip. The ninth stroke is essentially

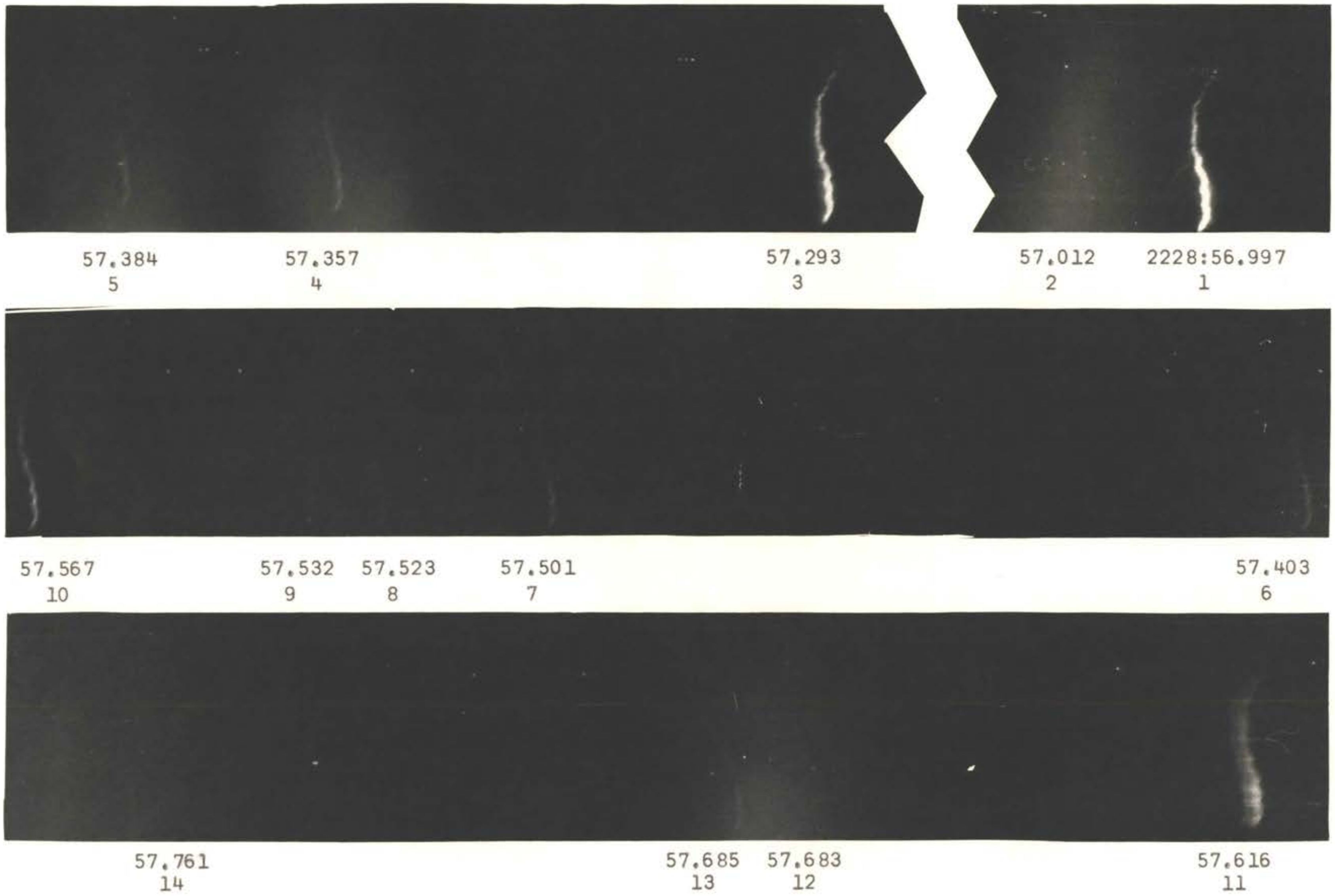
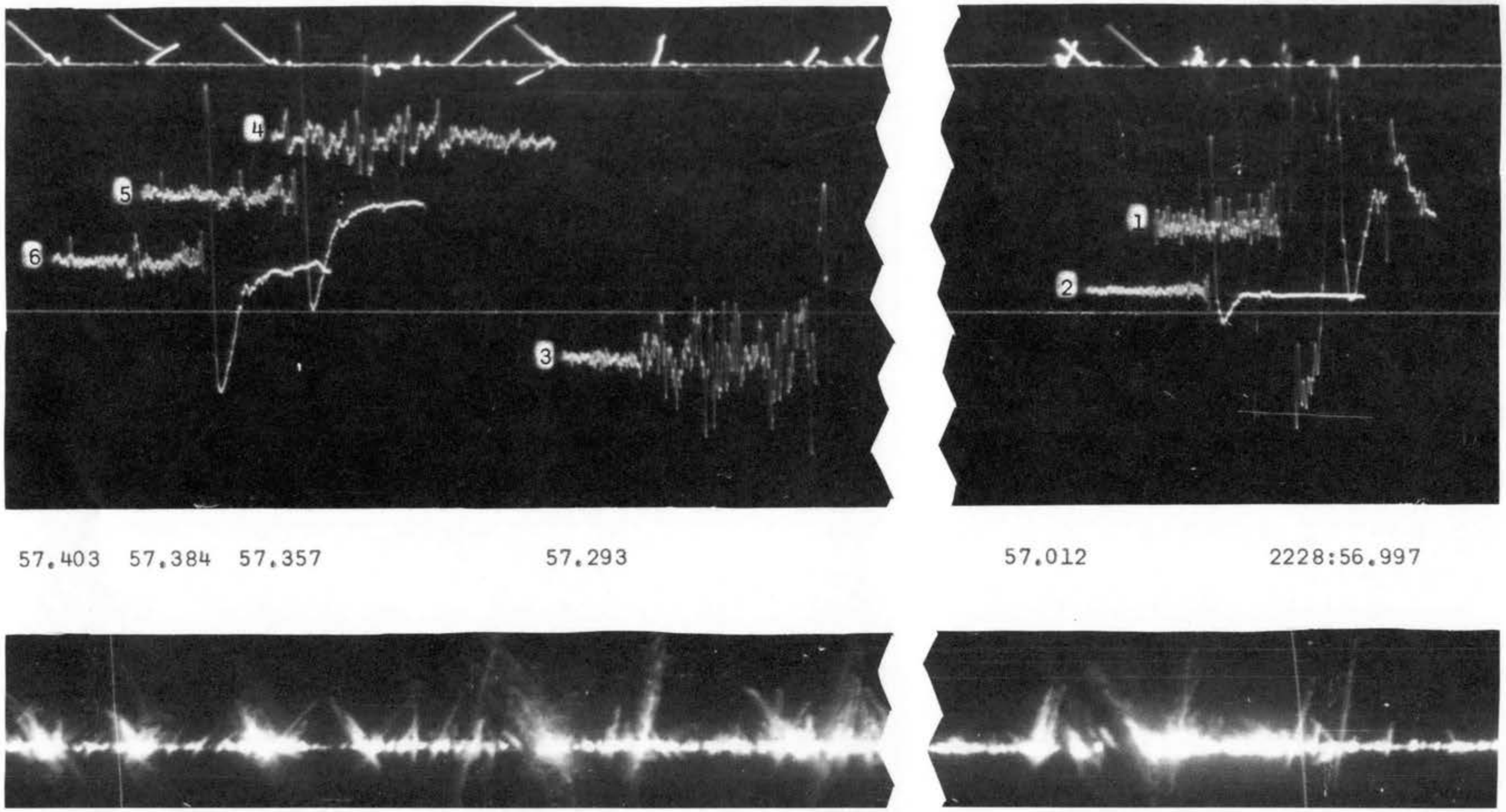


Figure 4.2. Cloud-to-Ground Flash

indistinguishable, while the eleventh stroke is apparently a combination of several strokes in very rapid succession. The twelfth and thirteenth strokes are very close together, being separated in time by only two milliseconds. As before, the strokes all follow the same path in space.

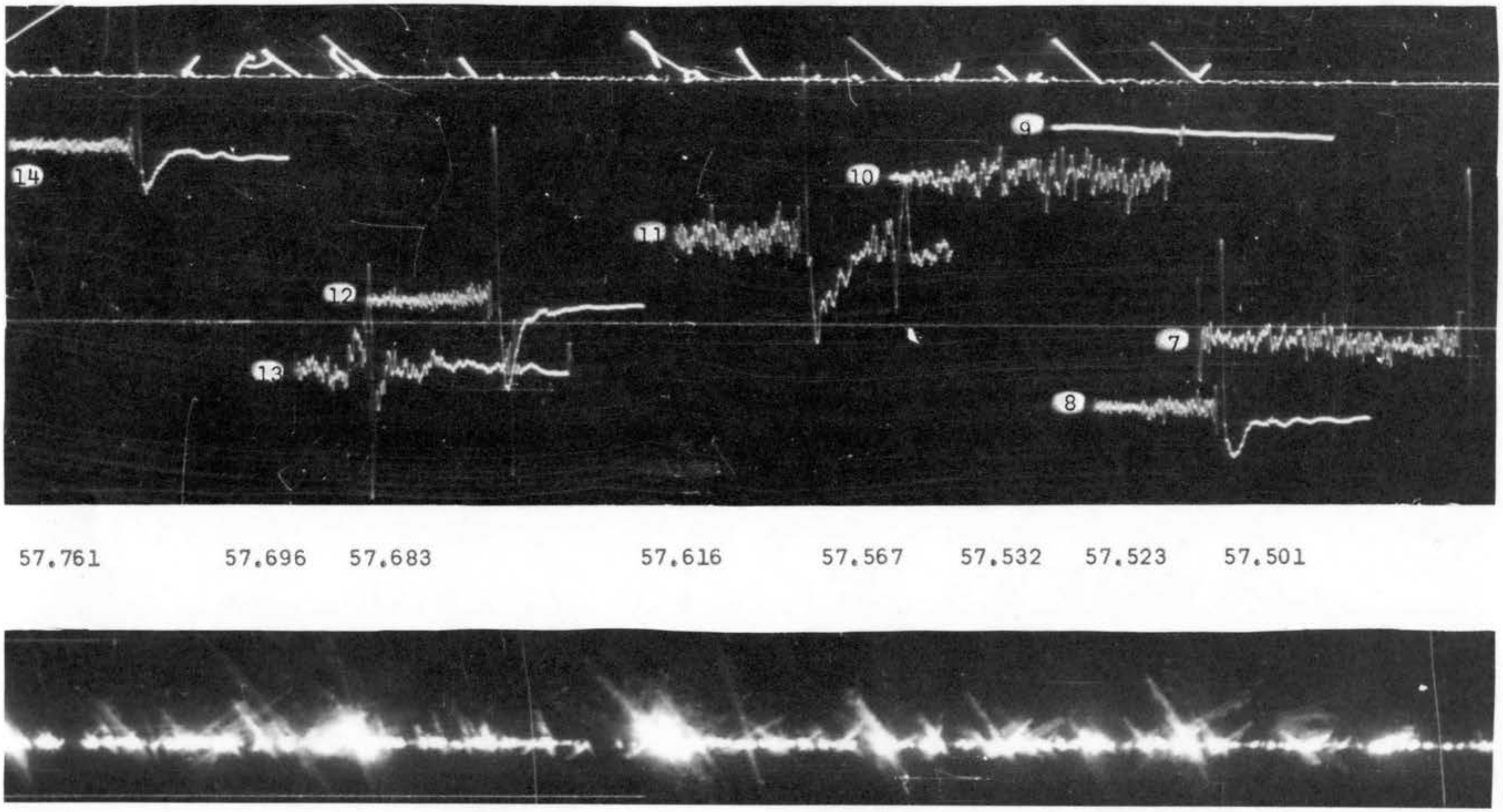
The waveforms and directional-indication traces of this sequence of strokes are shown in Figures 4.3 and 4.4. Again, time advances from right to left, and the waveform sweep is from left to right. The first waveform has a large amount of high-frequency content, whereas the second one has very little. The third waveform contains considerable high frequency with a good share of it appearing during the first 250 microseconds of the sweep. The only large pulse in this waveform occurs at the end of the sweep. The fourth waveform contains only high frequencies. The fifth and sixth waveforms are very interesting because of their remarkable similarity. They appear to be almost duplicates of each other. Waveform number seven has a medium-sized pulse at the beginning and a large pulse at the end with only high frequency in between. Number eight contains very little high frequency, and number nine consists of only a very small pulse. This ninth waveform corresponds to the stroke which was so dim it did not show on the print. The eleventh waveform is of particular interest, because it displays two distinct pulses which could very well correspond to two of the multiple strokes showing on the photograph of the eleventh stroke.

There is something wrong with the thirteenth waveform; that is, it comes at the wrong time. The thirteenth stroke is only two milliseconds after the twelfth stroke, but the thirteenth waveform starts 13 milliseconds after the twelfth one.



150-KC Directional Indicator

Figure 4.3. Cloud-to-Ground Waveforms



150-KC Directional Indicator

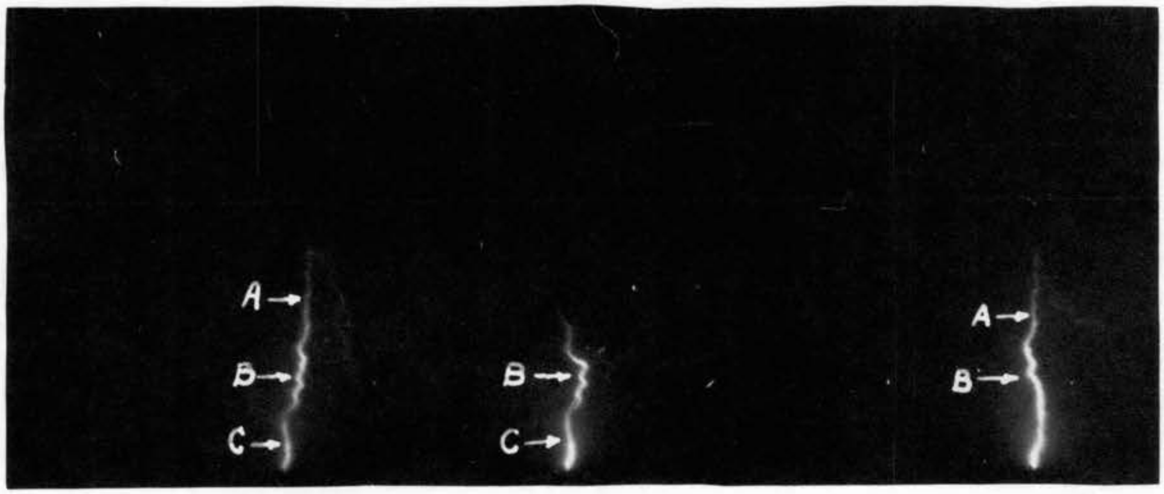
Figure 4.4. Cloud-to-Ground Waveforms

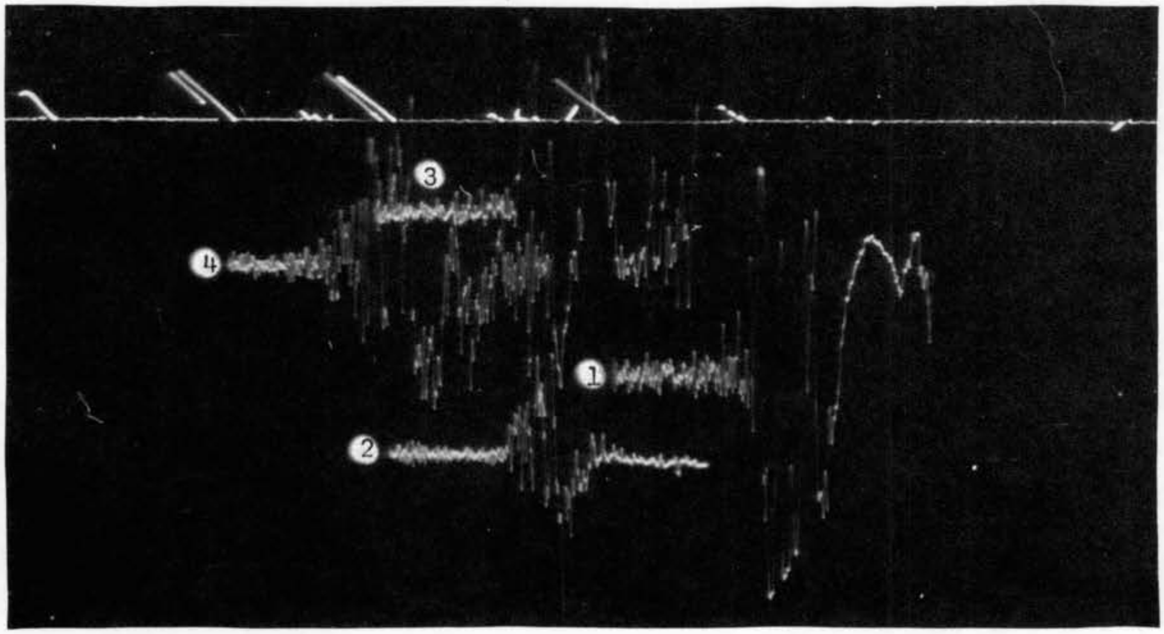
Flash Number 3

Figure 4.5 illustrates a four-stroke sequence which differs from the previous ones in that the paths are not identical, except for the second and third strokes. For ease in description, identifying letters have been included on the picture. Similar parts of the first, third, and fourth strokes have been marked with the same letter. The only part of the path of the second and third strokes that is the same as the path of the first stroke is the center portion. The fourth stroke has the top and middle of its path the same as the first stroke and the lower portion the same as that of the second and third strokes.

Although the lightning strokes are of interest, the primary purpose of this study is to examine the waveforms. In this example the waveforms have very good time correlation with the strokes. As evidenced by the activity indicated by the 150-KC direction indicator, there was a lot of interference; and once again the usefulness of the waveform discriminator is obvious. The waveforms for this sequence all contain a considerable amount of high frequency. Measured as a sinusoidal wave, the predominant frequency would be about 160 kilocycles per second. There is actually a fairly large amount of mixing of the third and fourth waveforms.

Obviously it is necessary to record more of the waveform with some method of obtaining greater resolution in order to make use of spectral-analysis techniques for these waveforms. It is the opinion of the author that these analysis techniques are necessary in order to establish any definite statistical relationships between the waveforms and the strokes. One technique which has been suggested is to obtain the





Waveforms and 10-KC Directional Indicator

150-KC Directional Indicator

Figure 4.5. Cloud-to-Ground Flash

spectra of many waveforms using a Fourier series representation, then average these spectra, at the same time finding the standard deviation, and study the average, looking for significant frequency components. The data obtained from the waveforms recorded in this study have proved insufficient for a complete study of this type.

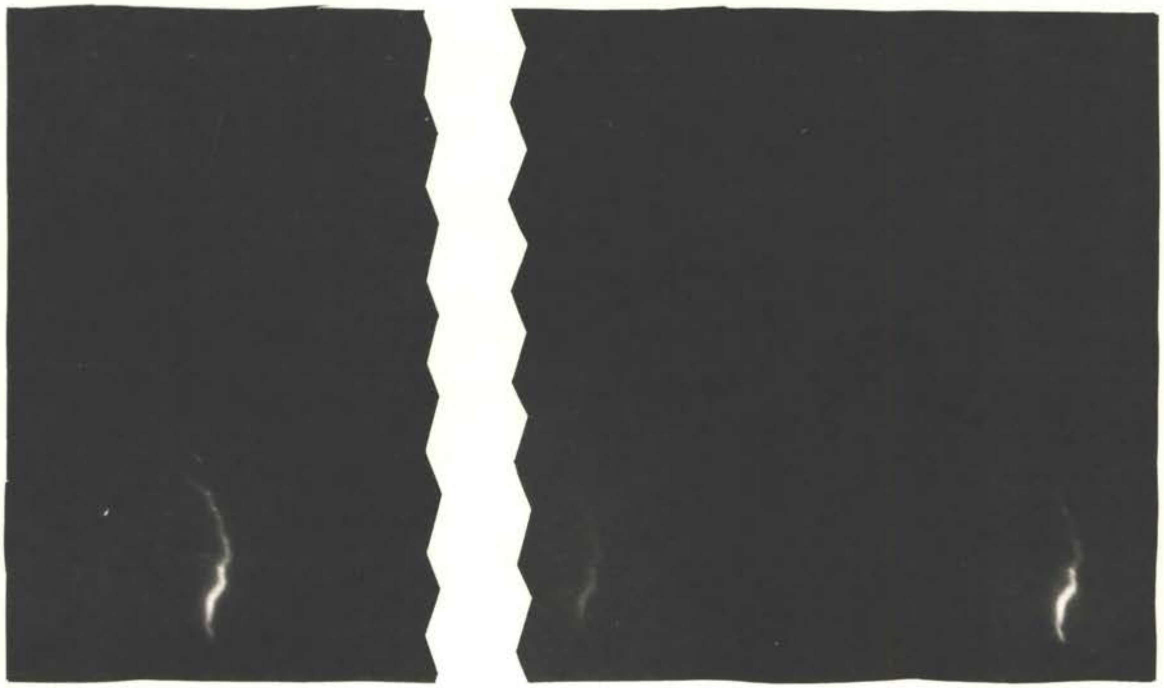
Flash Number 4

Figure 4.6 is another example of a multiple-stroke, cloud-to-ground lightning flash. This example has three strokes with the time of 0.130 seconds between the second and third strokes indicated by a break in the print.

One of the interesting features of this figure is the extra waveform which is present. The waveform associated with the second stroke is the first of the two waveforms which appear at nearly the same time. If the 10-KC directional indicator is examined, it will be noticed that there are two indicating pips at nearly the same angle and time. It is believed that the stroke responsible for the extra waveform was just out of range of the periscope camera but close enough to trigger the photomultiplier system.

The high-frequency component in the waveforms of Figure 4.6 appears to be very nearly 200 kilocycles per second, measured as before. The third waveform exhibits nothing but the high frequency, much of it present in the early part of the waveform which indicates it was present before the circuit was triggered.

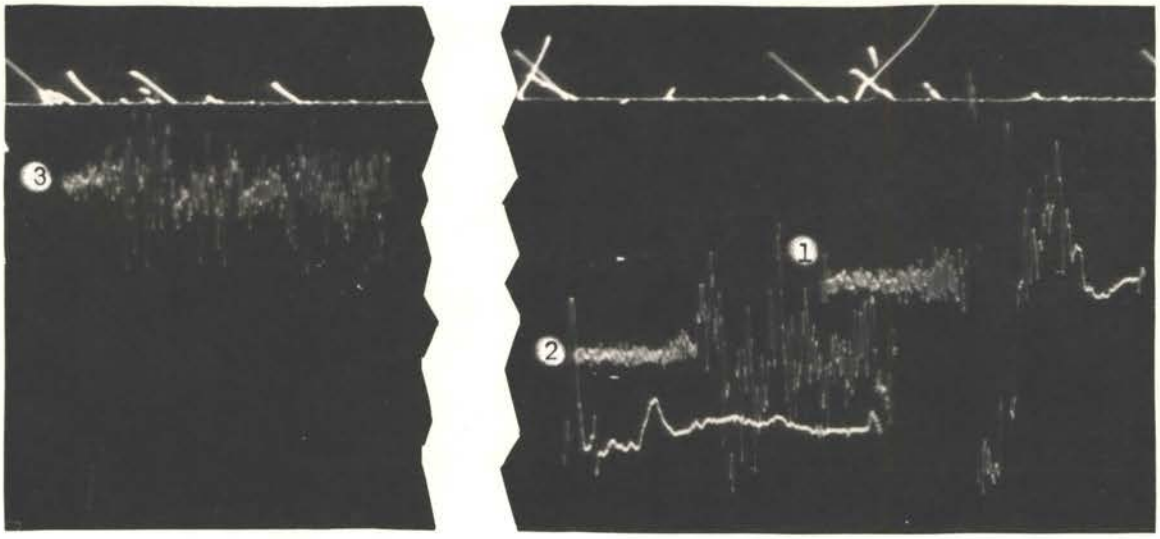
Both the 10-KC and the 150-KC directional indicators show evidence of much activity from several directions. If the waveform discriminator had not been in use, the waveform section of the film would have been a



2228:00.001 3

59.871 2

2227:59.822 1



Waveforms and 10-KC Directional Indicator

150-KC Directional Indicator

Figure 4.6. Cloud-to-Ground Flash

mad jumble with very few of the waveforms distinguishable. An example of such an occurrence will be shown later.

Flash Number 5

In Figure 4.7 there is shown another cloud-to-ground sequence of strokes in which the paths are not completely the same. In this case the first stroke differs from the following three only in the bottom portion.

The waveforms shown in Figure 4.7 have several interesting features. The second and third waveforms have rather large amplitudes and apparently contain primarily high-frequency components with much of the signal occurring during the first 250 microseconds of the sweep. The second waveform is badly mixed with an unaccounted for waveform. In the fourth waveform the high-frequency component is of very small amplitude, and the main feature of the whole waveform is the single pulse. The corresponding lightning stroke photograph is very dim.

Flashes Number 6, 7, and 8

Figure 4.8 shows three separate strokes which occurred within a 0.384-second interval, yet are over separate paths and apparently unrelated. The 150-KC directional indicator shows that this was a time of great activity of the storm cells. The indicating pips are many in number and from many directions.

All three of the waveforms in Figure 4.8 show the presence of high-frequency components, with the first having the least. The second waveform has at least four distinct pulses which may come from separate current surges in the pictured stroke but which may also come from

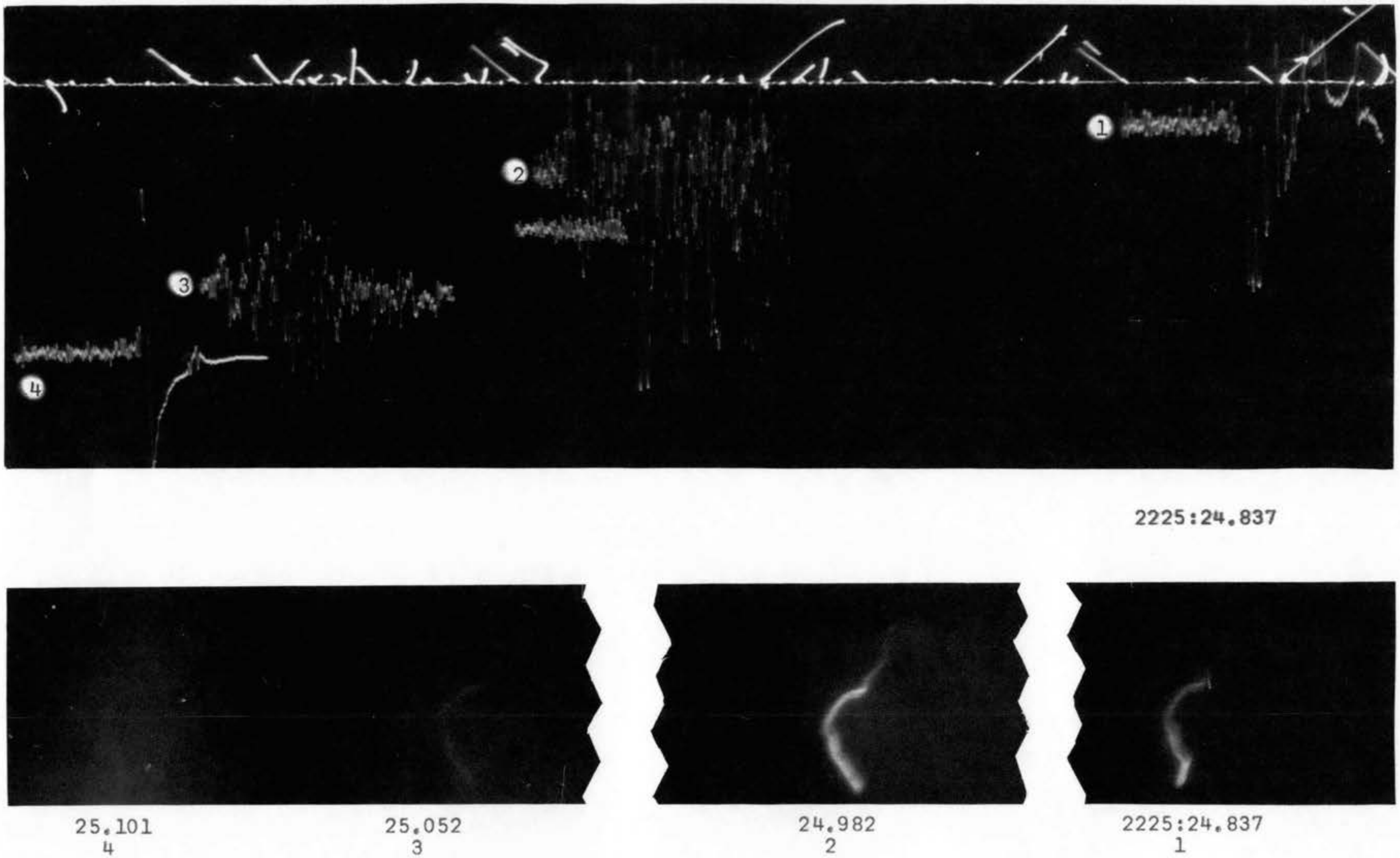
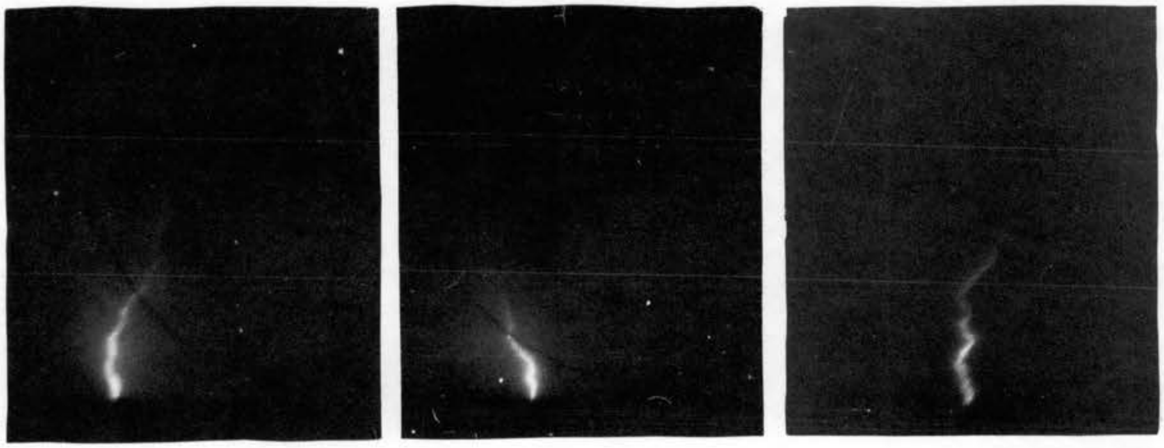
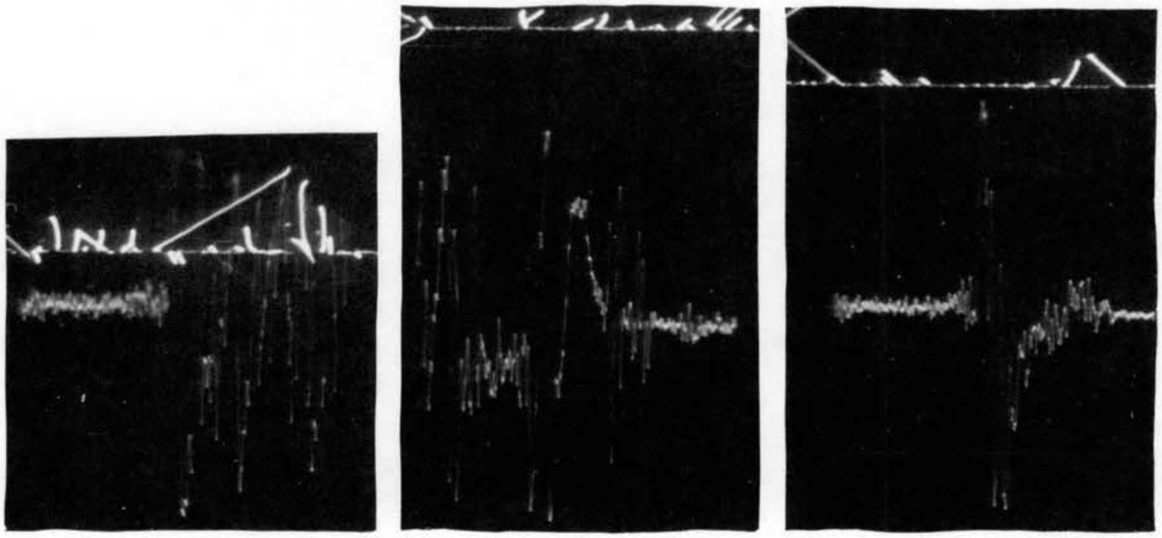


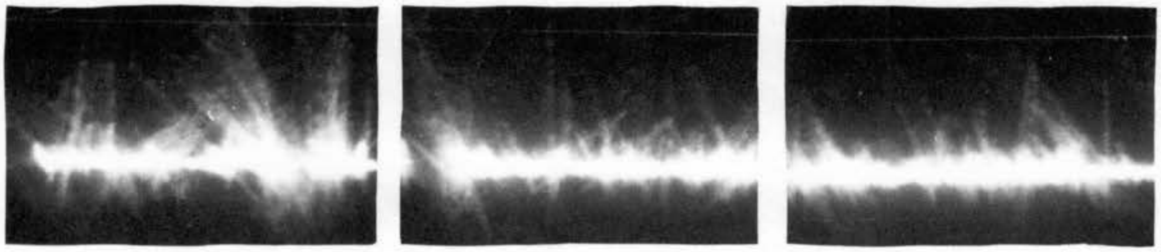
Figure 4.7. Cloud-to-Ground Flash



2222:29.062 2228:28.761 2228:28.678



Waveforms and 10-KC Directional Indicators



150-KC Directional Indicators

Figure 4.8. Three Cloud-to-Ground Flashes

almost simultaneous strokes in other directions. This possibility is always present and is one of the reasons a statistical analysis should be made.

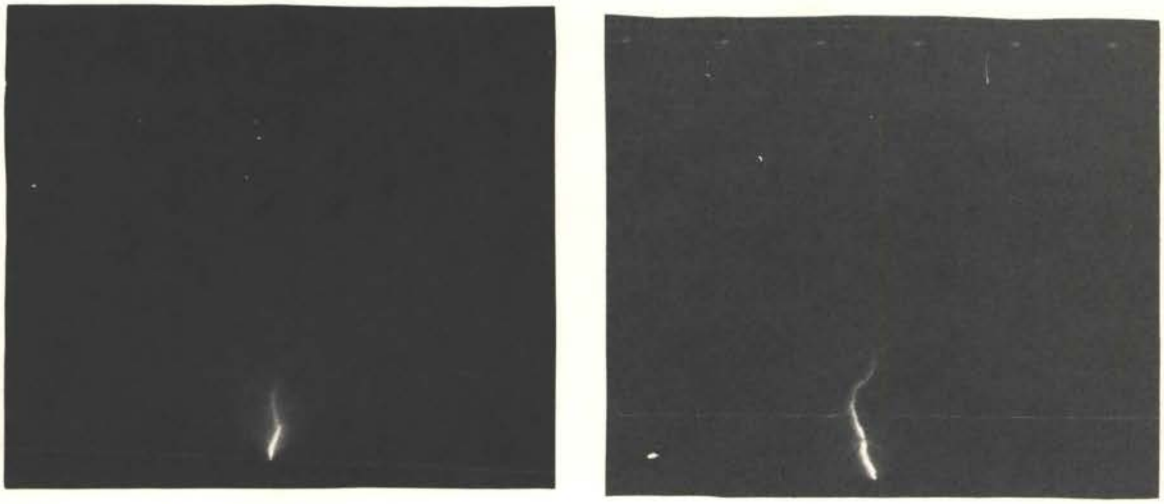
Flashes Number 9 and 10

The photographs in Figure 4.9 show two more cloud-to-ground flashes. Each of these consisted of one single stroke. The first waveform has a high-frequency component of very low amplitude during the 250-microsecond postion which represents the signal before triggering, while the last half of the waveform has a considerable high-frequency content. The second waveform appears to exhibit quite a bit of the high frequency for the whole sweep.

Flash Number 11

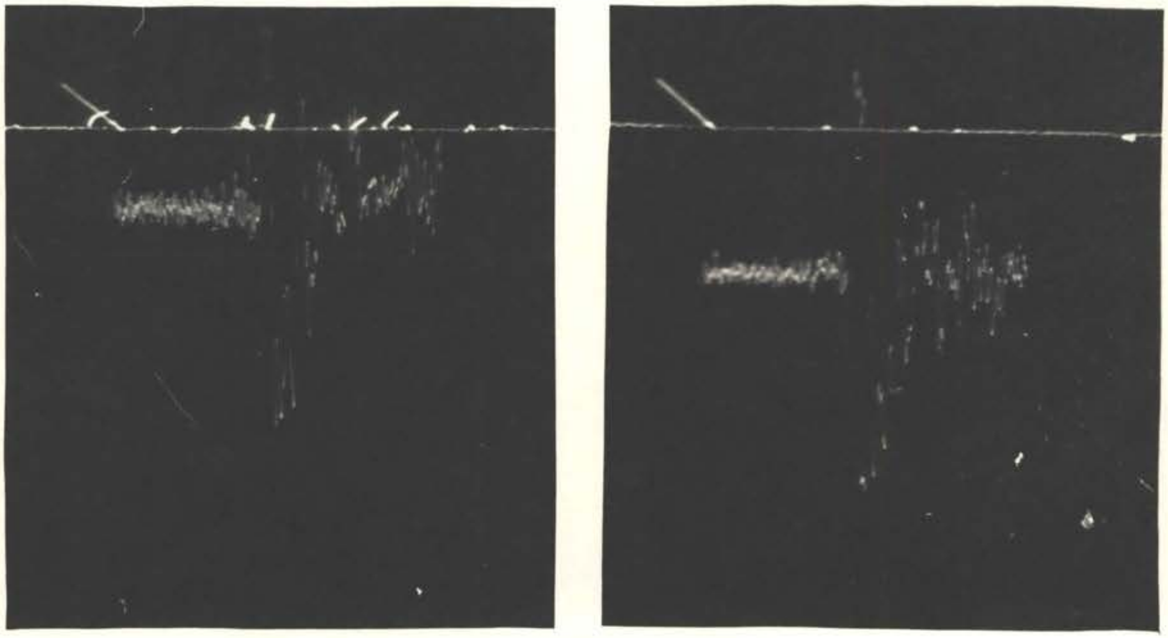
Next, there is another example of a multiple, cloud-to-ground lightning flash. This example, where the periscope-camera picture is shown in Figure 4.10, consists of ten strokes following the same path. Again, a long time between the ninth and tenth strokes is indicated by a break in the print.

Waveforms and directional-indicating signals for this sequence are shown in the next two figures. The first five waveforms appear on Figure 4.11 and the last five on Figure 4.12. It is immediately obvious that something has changed from previous examples. There are many extra waveforms present on these figures. The reason for the extra waveforms is that a different triggering system was used during the portion of the storm recorded here. Whereas the previous examples demonstrated the use of the waveform discriminator, this example shows

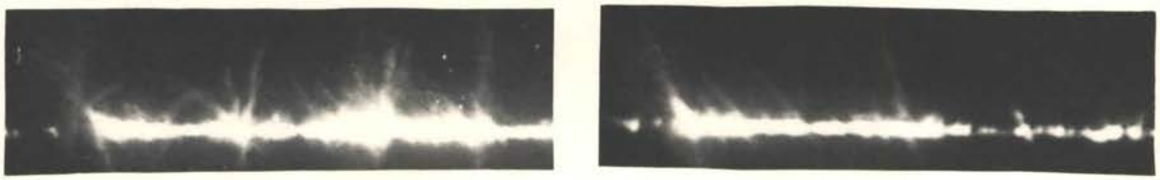


2225:57.570

2202:15.860



Waveforms and 10-KC Directional Indicator



150-KC Directional Indicator

Figure 4.9. Two Cloud-to-Ground Flashes

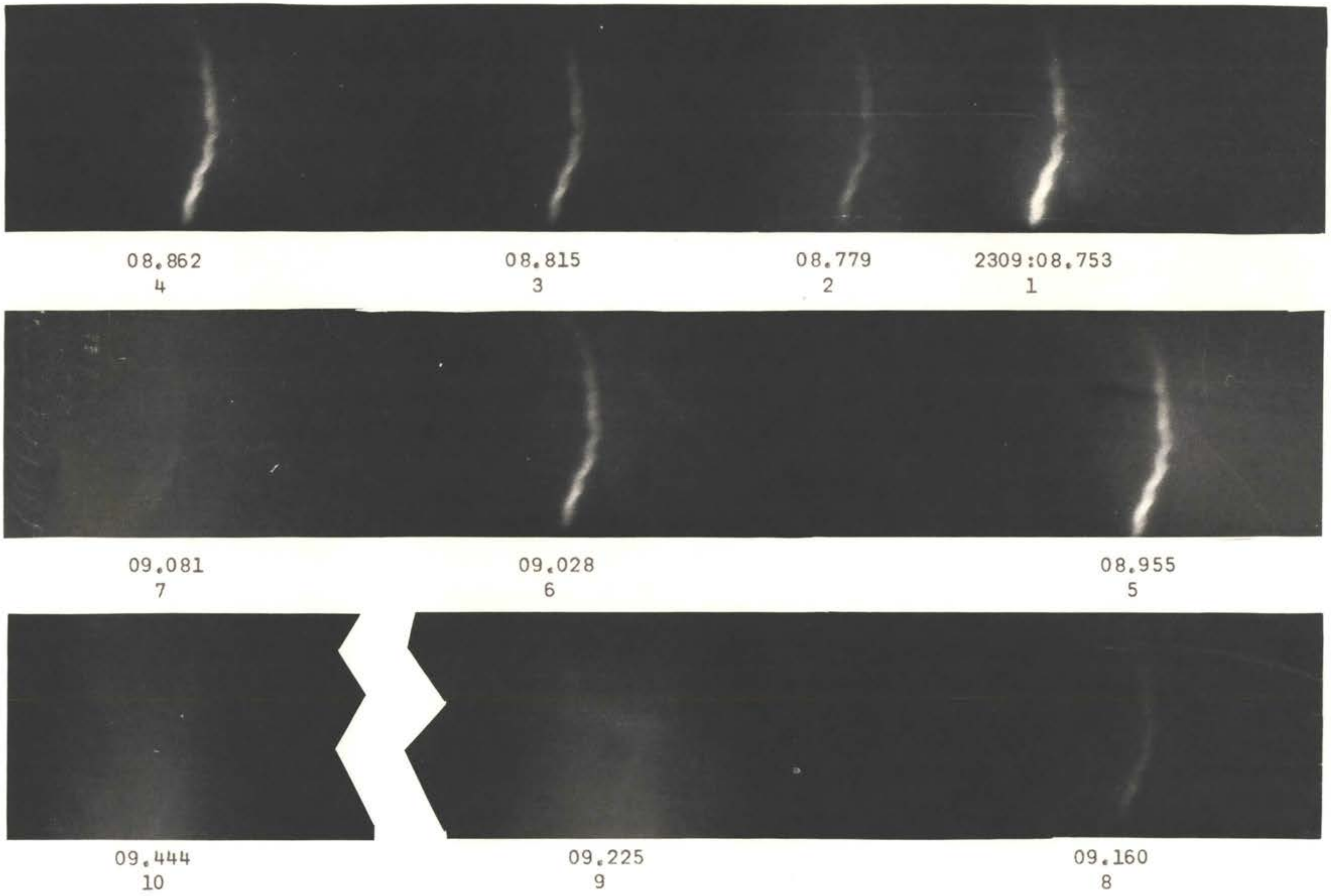
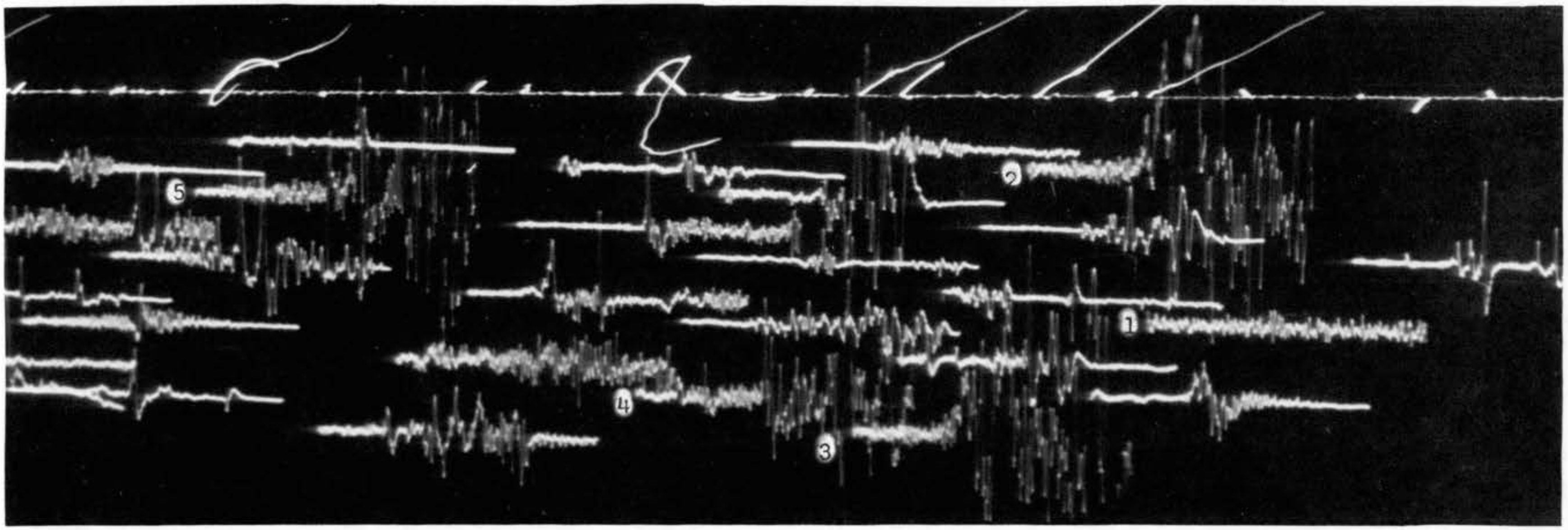


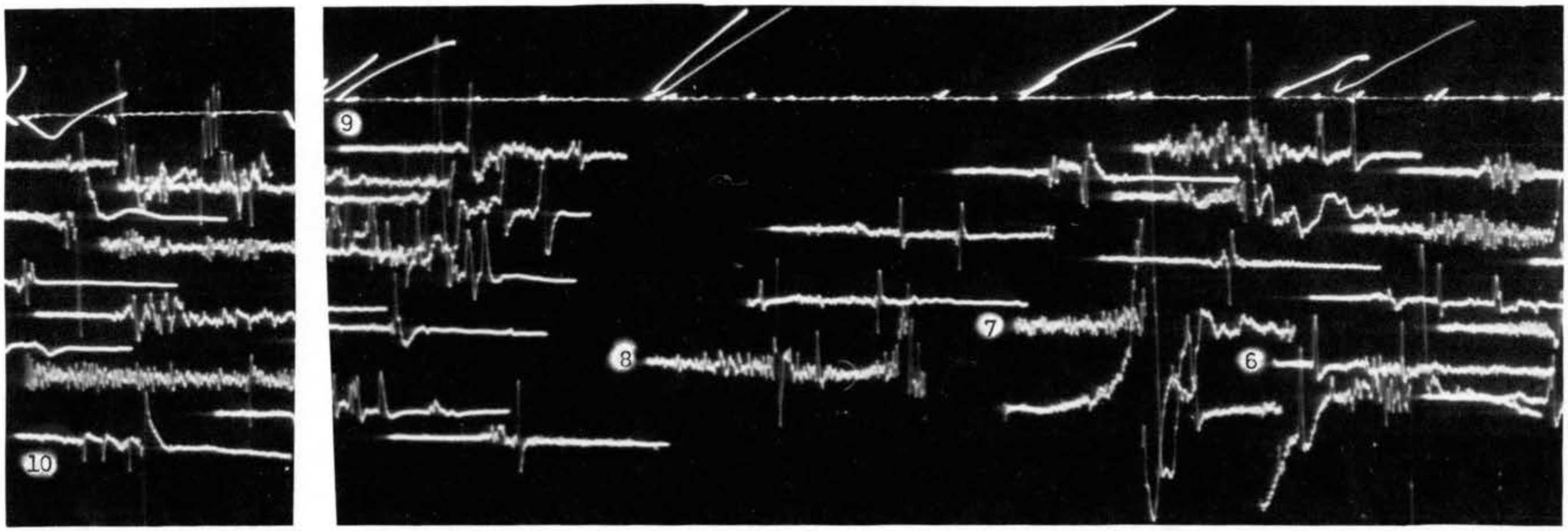
Figure 4.10. Cloud-to-Ground Flash



Waveforms

150-KC Directional Indicator

Figure 4.11. Waveforms for Cloud-to-Ground Flash



Waveforms

150-KC Directional Indicator

Figure 4.12. Waveforms for Cloud-to-Ground Flash

a reasonably successful attempt to use the 150-KC directional signal amplitude to trigger the waveform circuit. Essentially the waveform was triggered anytime a signal contained a reasonable amount of energy in the 150-kilocycle-per-second range. At this particular period the storm was low enough in activity so the waveforms are not impossibly mixed.

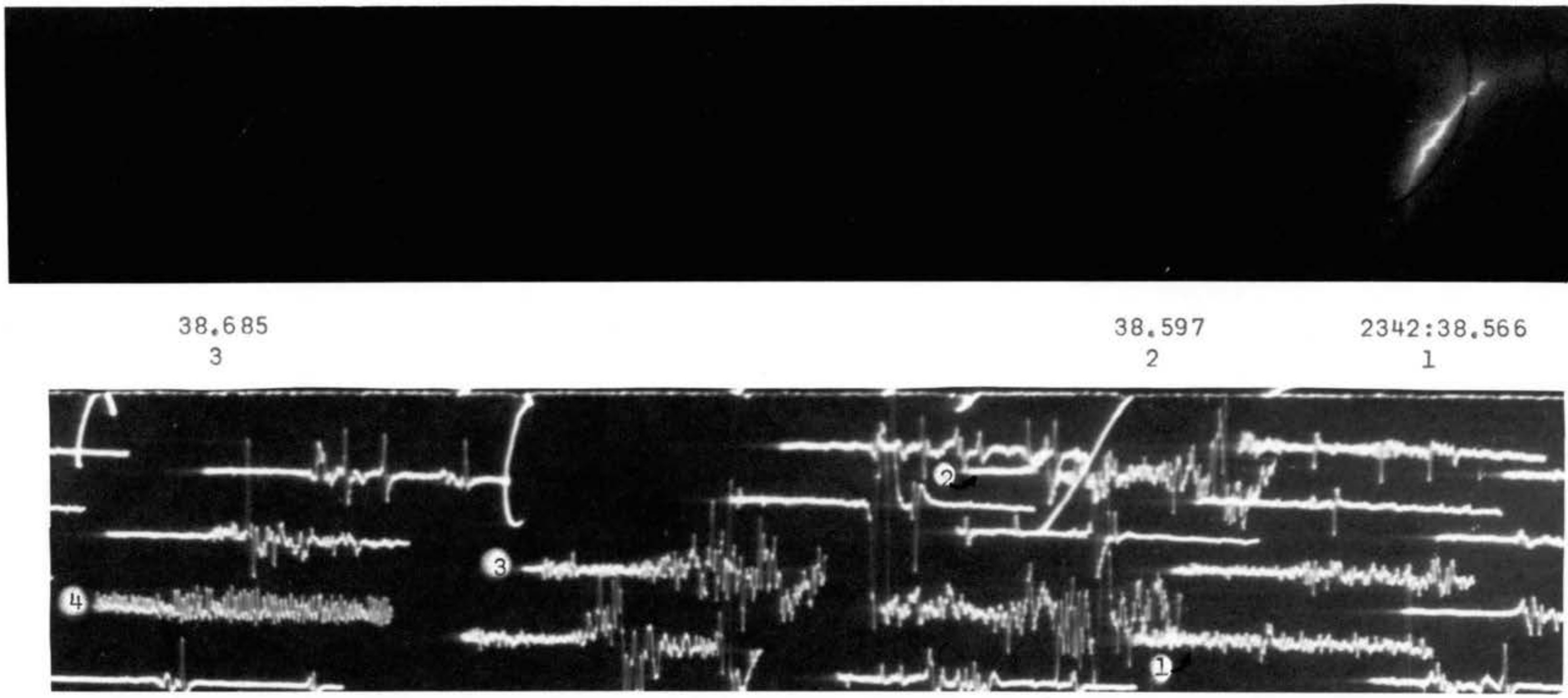
Waveform number one of this series is of very low amplitude and appears to contain only high-frequency components. Waveform number two is similar to many of the preceding examples, because it contains a mixture of high-frequency energy and pulses with durations equivalent to the period of about 20-kilocycle-per-second sinusoids. The third waveform is similar to the second, with a smaller amplitude during the first one-third of the sweep. The fourth and fifth waveforms are very similar in appearance, with both containing a preponderance of high frequency. Waveform number six is completely different than the others. It contains several small, sharp pulses and essentially nothing else. The seventh waveform contains a very-large-amplitude pulse as well as a more significant indication of the high frequency. The three pulses in the eighth waveform could come from surges in the associated stroke, but again this is speculation. The ninth waveform is very quiet before the small pulse that was responsible for triggering it. Waveform number ten has several unusual features. In the first place it has very low amplitude except for three small pulses and one large pulse. There is no evidence of the high-frequency oscillatory waveform. The second unusual feature is that the pulses move downward, or negative, first. A majority of the pulses on other waveforms are just opposite in this respect. Since the photographs of the ninth and tenth strokes are very dim, this example could be used as evidence to support the association of higher luminosity with the presence of high-frequency components. Once again it should be pointed out that the strokes are more evident when the film is observed on the film viewer than they are the prints.

Flash Number 12

The only good example of a cloud-to-cloud lightning flash is shown in Figures 4.13 and 4.14. This flash consists of six strokes of various intensities. The first stroke is the brightest and the only one which shows any branching. All of the other strokes follow the same path as the main part of the first stroke.

Once again the waveforms are distinguishable, even though they were triggered by the 150-KC directional-signal amplitude. There is some mixing of waveforms but, in general, not enough to obscure those of interest.

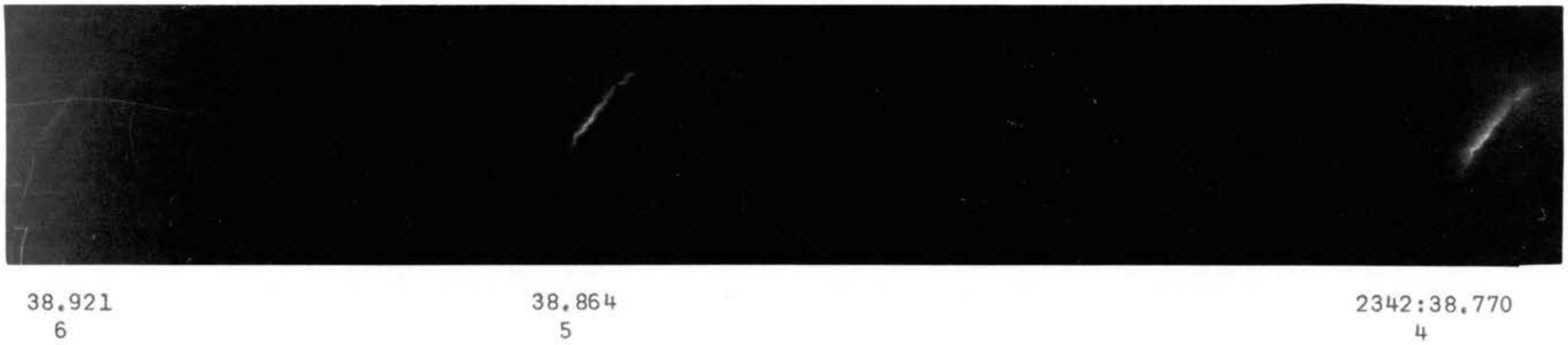
It is interesting to note that the first waveform, corresponding to the bright, branched stroke, is of low amplitude and high frequency. None of the waveforms of this sequence contain any of the large-amplitude, low-frequency pulses that were so often observed in the waveforms associated with the cloud-to-ground strokes. Only more research will establish a possible significance to this observation. Although waveform number two is somewhat difficult to distinguish, it is possible to determine that it also is primarily of high frequency. Waveform number three also exhibits a high-frequency appearance, with some indication of low-amplitude, low-frequency components. The fourth waveform, which is present on both figures, has what might be termed a comb appearance; that is, it looks as if it is a sequence of pulses

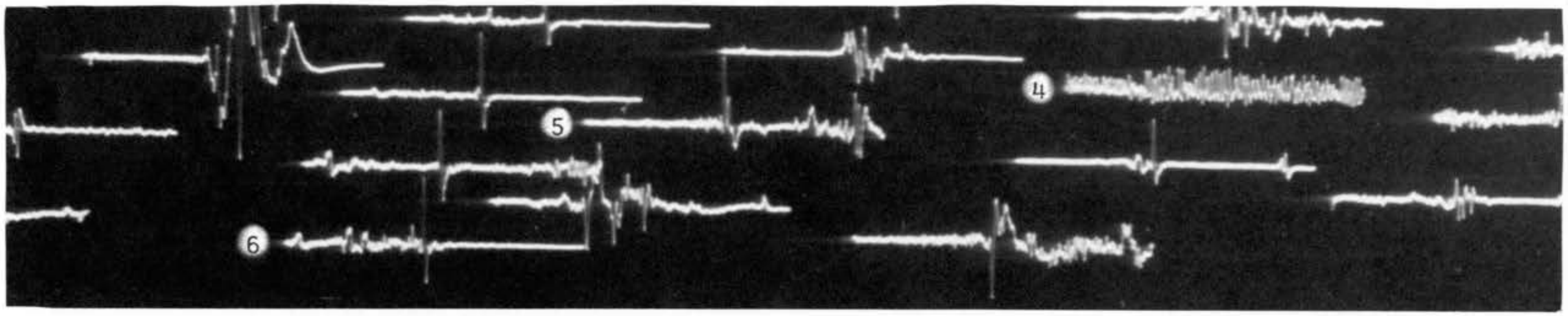


Waveforms

150-KC Directional Indicator

Figure 4.13. Cloud-to-Cloud Flash





Waveforms

150-KC Directional Indicator

Figure 4.14. Cloud-to-Cloud Flash

sticking up from a base line. The fifth waveform consists mostly of three small pulses on a quiet trace. Several factors contribute to a suspicion that the sixth waveform may actually come from a source other than the photographed stroke. For one thing the waveform is very similar to the two extraneous waveforms immediately preceding it. Another source of suspicion is the 150-KC directional indicator which shows directional pips from several directions almost simultaneously and at the time of the questionable waveform. If an analysis were to be made, it would seem desirable to cast out the data from this waveform because of its uncertainty.

Flash Number 13

Figure 4.15 is a rather striking example of a nine-stroke, cloud-to-ground flash. The first stroke is very bright and contains many branches. Figures 4.16 and 4.17 are the waveform pictures associated with the strokes of the flash. The principal usefulness of these figures is to demonstrate the desirability of using the waveform discriminator. The waveforms are practically hopelessly mixed.

Flash Number 14

Figure 4.18 shows the second example of a cloud-to-cloud lightning flash that was obtained during the storm which produced the data shown in this thesis. In this case also the waveforms are badly mixed, but they can be seen clearly enough to make some general observations. The first and second waveforms apparently consist only of high-frequency components and a few narrow pulses. The third waveform, however, appears to consist primarily of one large pulse with a fairly long duration.

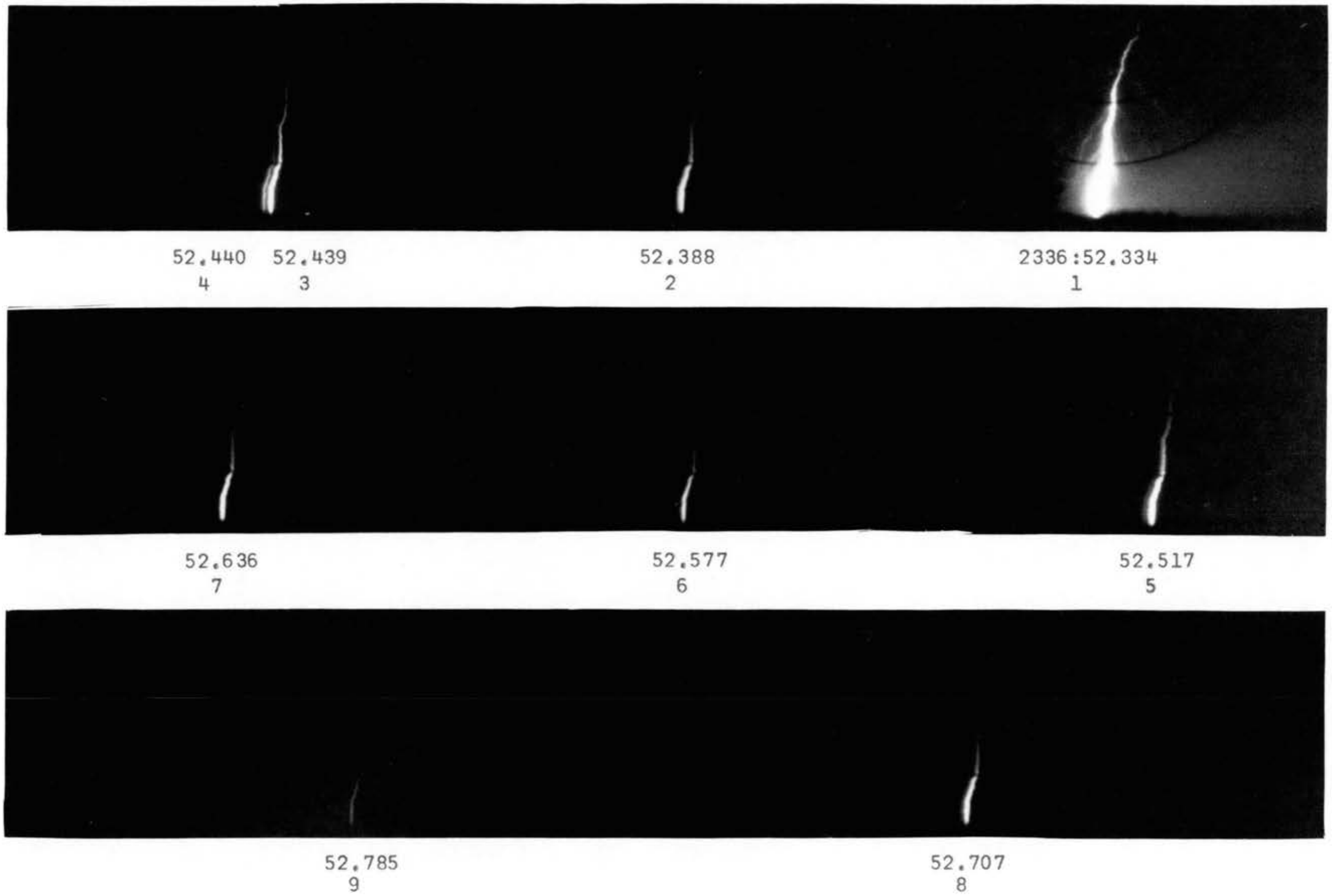
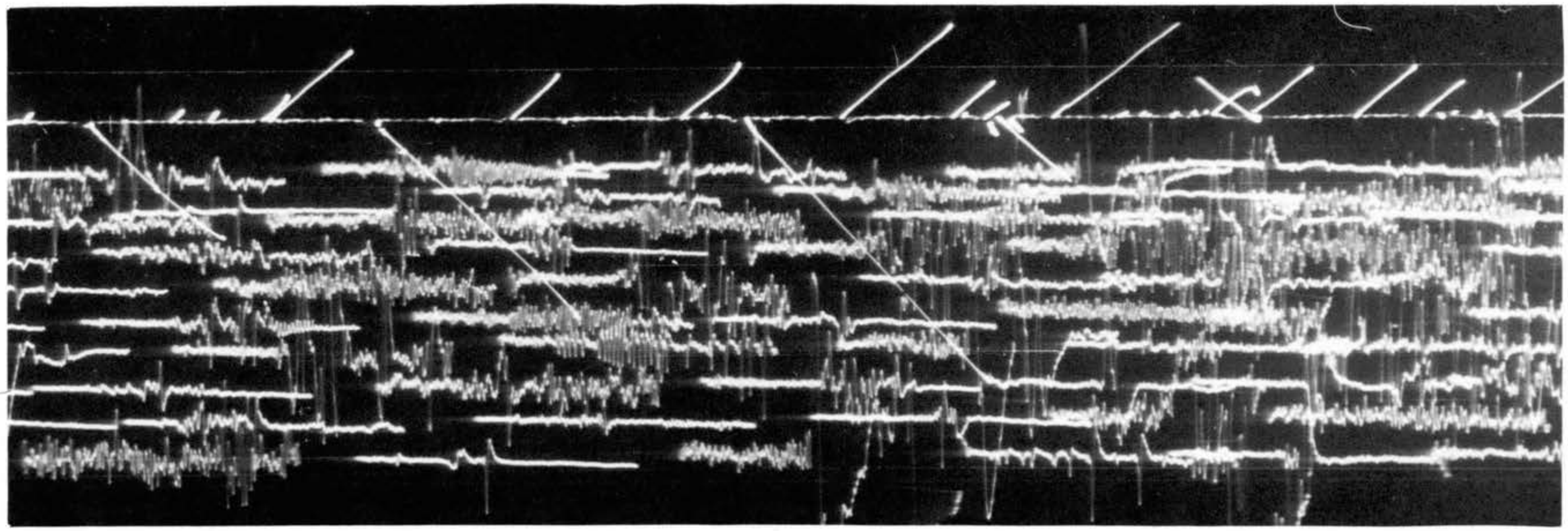


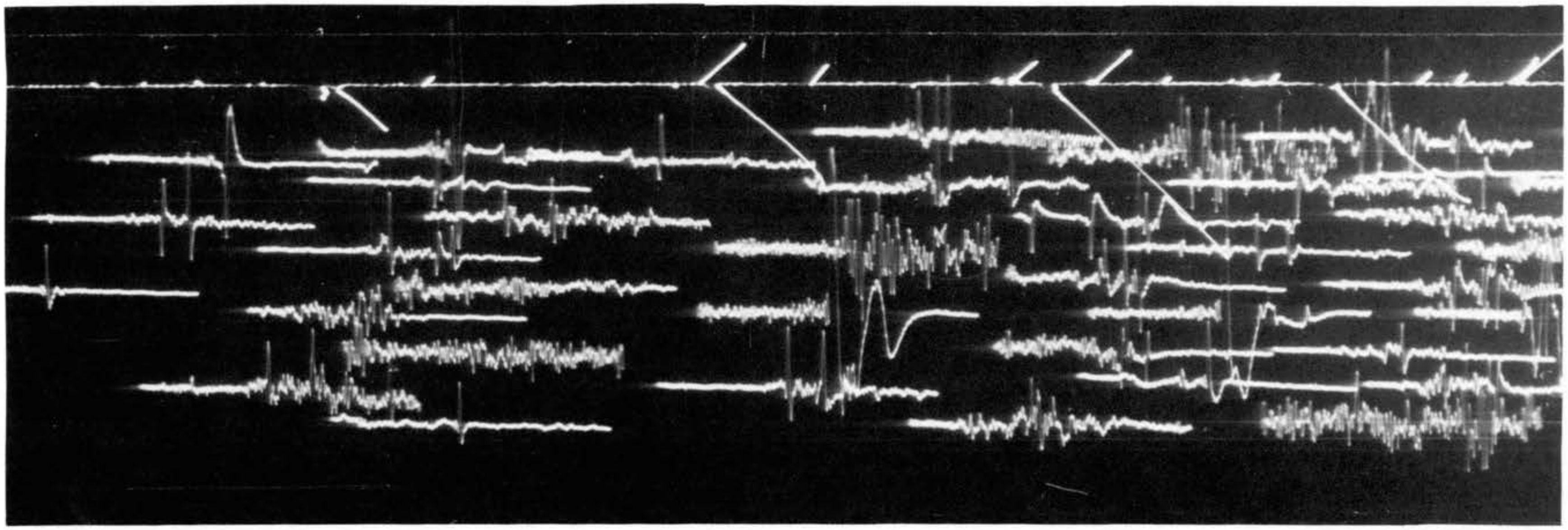
Figure 4.15. Cloud-to-Ground Flash



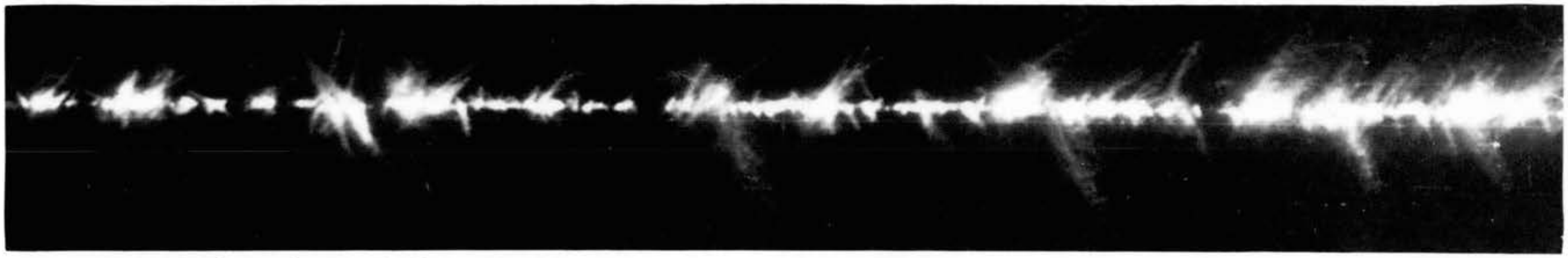
Waveforms

150-KC Directional Indicator

Figure 4.16. Waveforms for Cloud-to-Ground Flash

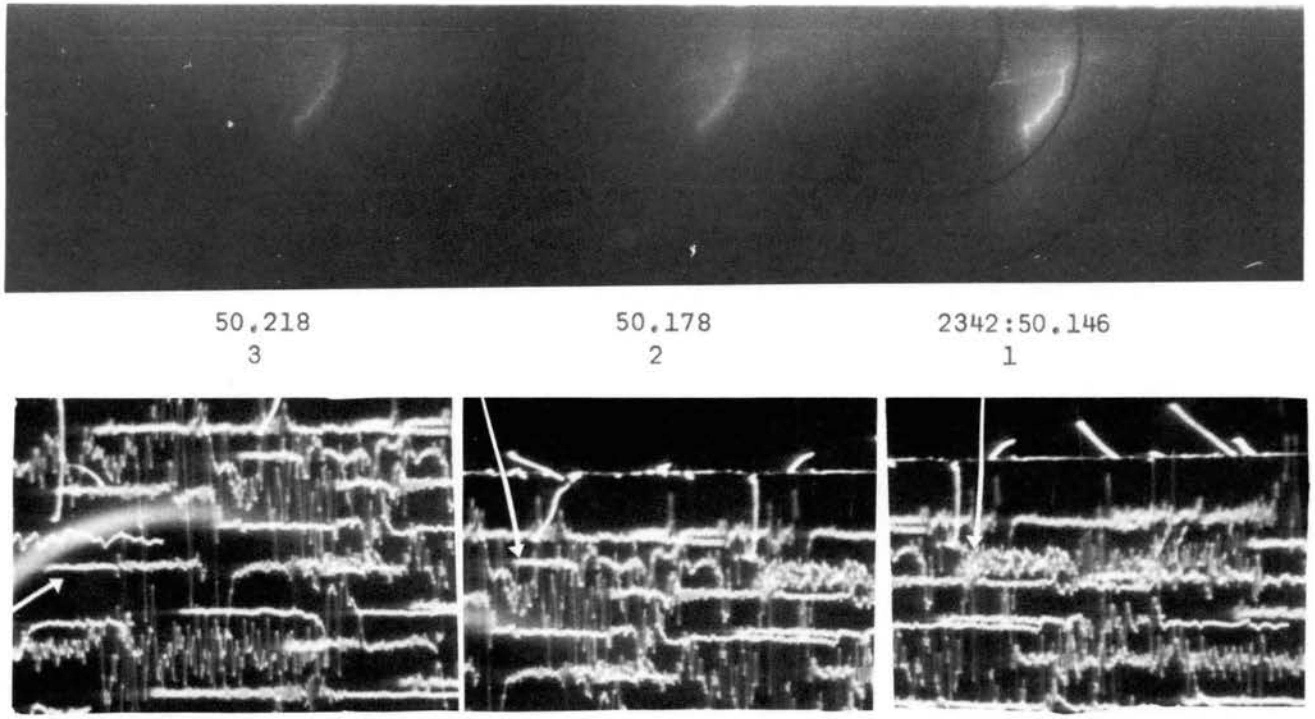


Waveforms



150-KC Directional Indicator

Figure 4.17. Waveforms for Cloud-to-Ground Flash



Waveforms

150-KC Directional Indicator

Figure 4.18. Cloud-to-Cloud Flash

Conclusions

In comparing the waveforms which have been presented, it is not evident that there are any significant characteristics which may be used to identify the type of stroke which generated the waveform. This is not meant to imply that such identifying characteristics may not exist but rather to point up their subtlety. It appears very likely that a thorough statistical study using spectral analysis may uncover the desired result.

One of the interesting features of the waveforms shown is the frequent presence of the component in the neighborhood of 150 kilocycles per second. It seems very possible that much of this high frequency is generated during the breakdown, or stepped-leader, process. This possibility is supported by the presence of so much of the high-frequency oscillation during the 250 microseconds preceding the triggering luminosity.

CHAPTER V

CONCLUSIONS

Although atmospherics have been known and studied for many years, it is the conclusion of the author that much useful information remains to be found and utilized. The use of the atmospheric to identify the type of lightning stroke from which it was generated is only the first step toward several possible goals. Of primary interest to this investigator is the possible identification and location of severe thunderstorms from the sferics generated therein. The next logical step would be to use the sferics accurately as a measure of the intensity of the storm, to the extent that tornadoes could be identified, tracked, and forecast.

As a first step toward the over-all goal, it was the purpose of this study to start a project which would lead to the identification of various types of lightning strokes by means of the sferics generated. In order to accomplish this step, it is, of course, necessary to record some sferics generated by lightning strokes with some means of identifying the type of stroke and of assuring that the correct sferic is recorded.

The equipment needed was gathered or built and placed in operation. This equipment included the periscope camera for recording the lightning strokes photographically, the waveform and directional-indicating equipment, and the timing system for use in accurate correlation of the various systems.

Success was obtained in isolating some waveforms associated with two types of lightning strokes, cloud-to-ground strokes and cloud-to-cloud strokes. Unfortunately, only one example of the latter was clearly recorded. Future study may also indicate an important difference between lightning flashes consisting of single strokes and those consisting of multiple strokes.

General observation of those waveforms recorded lead to the conclusion that much of the higher frequency (100-200 kilocycles) is generated by the stepped-leader process of the lightning stroke. Since the high-frequency signal was present in the delay line before the waveform system was triggered, it must have been generated by the part of the lightning process preceding the highly luminous return stroke. This, then, indicates generation by the breakdown process.

The generation of the frequencies in the 100- to 200-kilocycle-per-second range is of particular interest to those interested in severe thunderstorm investigations. Since studies previously indicated a correlation between signals received on a direction finder tuned to 150 kilocycles per second and the severity of the thunderstorm, the source of the signals could be of great importance.

Dr. H. L. Jones' studies, which were mentioned in Chapter II, indicated, for a storm generating a tornado, not only an increase in the number of directional pips per second on the 150-kilocycle-per-second direction finder, but a simultaneous decrease in the signals on the 10-kilocycle direction finder. Visual observations taken at the time of the recordings used indicated a preponderance of intra-cloud, or cloud-to-cloud, lightning and very little cloud-to-ground lightning.

The indications of this study are that the generation of the higher frequencies is associated with the breakdown process of the lightning flash. The conclusion may be made that the energy radiated from cloud-to-cloud lightning flashes is primarily that generated during the breakdown process. Since the cloud-to-cloud strokes radiate considerably less energy at the lower-frequency range, that is, around 10 kilocycles per second, it may be inferred that these strokes do not have the same type of return stroke that characterizes the cloud-to-ground strokes.

Although the cloud-to-ground strokes also radiate energy in the 100- to 200-kilocycle-per-second region, the large amount of lower-frequency content could be used to indicate the actual type of strokes responsible for the signals.

A study of 52 waveforms that contained this high-frequency component during the first 250 microseconds of the waveform revealed the results tabulated in Table II. It should be clearly understood that the frequencies indicated are those of a sinusoidal wave with the same number of cycles per second as the recorded waveform had pulses or undulations. In other words, it is realized that the recorded waveforms are really continuous in the frequency domain and not just unique frequencies.

It has become obvious that a more thorough analysis of the waveforms is required to discover the necessary identifying characteristics. In order to accomplish the desired analysis, a more sophisticated recording system is also required. It is apparent that a longer time record should be taken of each sferic, and it should be taken so that a more detailed analysis can be made. These are conflicting requirements if the recording system now in use is to be utilized. The first requires a longer time sweep, and the second requires a shorter time sweep. An alternate system will be discussed in the following chapter.

TABLE II

DOMINANT FREQUENCIES OF WAVEFORMS

Frequency Range Kilocycles Per Second	Number of Waveforms With This Apparent Primary Frequency
100-120	6
120-140	1
140-160	26
160-180	4
180-200	15

Assuming waveform recording providing sufficient resolution and record length, it would appear advisable to use a Fourier analysis to obtain the spectrum of the individual sferic waveforms, then average the spectra of those from the same types of strokes in order to reduce the effects of noise in the system. This average, as well as the standard deviation, could very possibly give the type of identifying characteristics desired. The system noise, of course, includes random errors in amplitude measurements made on the sferic waveforms.

Following the example of Samulon,[1] an attempt was made to determine

---

[1] H. A. Samulon, "Spectrum Analysis of Transient Response Curves," Proc. of the I.R.E., Vol. 39, No. 2, February, 1951, pp. 175-186.

the spectrum of one of the output waveforms. He demonstrated the use of a series of (sin x)/x functions to approximate the time function, thus resulting in a Fourier spectrum expressed as a summation which lends itself to digital computer computation. A program was written and used to calculate the spectrum of one of the typical sferic waveforms. Samulon pointed out that the sampling period had to be equal to or less than 1/2 f_c where no frequencies higher than f_c are passed by the system. Using f_c = 250 kilocycles per second, this specifies a sampling period of 2 microseconds for this case. Unfortunately, the recording of the waveforms on 35 mm film results in such a small picture that enlargements large enough to use for amplitude measurements are too blurred to permit the resolution needed for giving a detailed picture between 150-200 kilocycles per second. This deficiency became clearly evident when the same waveform was analyzed twice with dissimilar results. Two sets of amplitude measurements were taken from the given waveform, using different time increments for the two sets. For one set the 500-microsecond waveform was measured at 252 points, while for the other set it was measured at 343 points. The spectra from these measurements are shown in Figure 5.1.

A discussion by Blackman[2] indicates that this disagreement should be expected because of the methods and measurements used. Based on his derivations, the frequency-spectrum resolution which can be obtained from a single waveform in this case is about 27 kilocycles per second. It is explained that to achieve the 2,000-cycle-per-second resolution

---

[2] R. B. Blackman and J. W. Tukey, The Measurement of Power Spectra (New York, 1958), pp. 56-57.

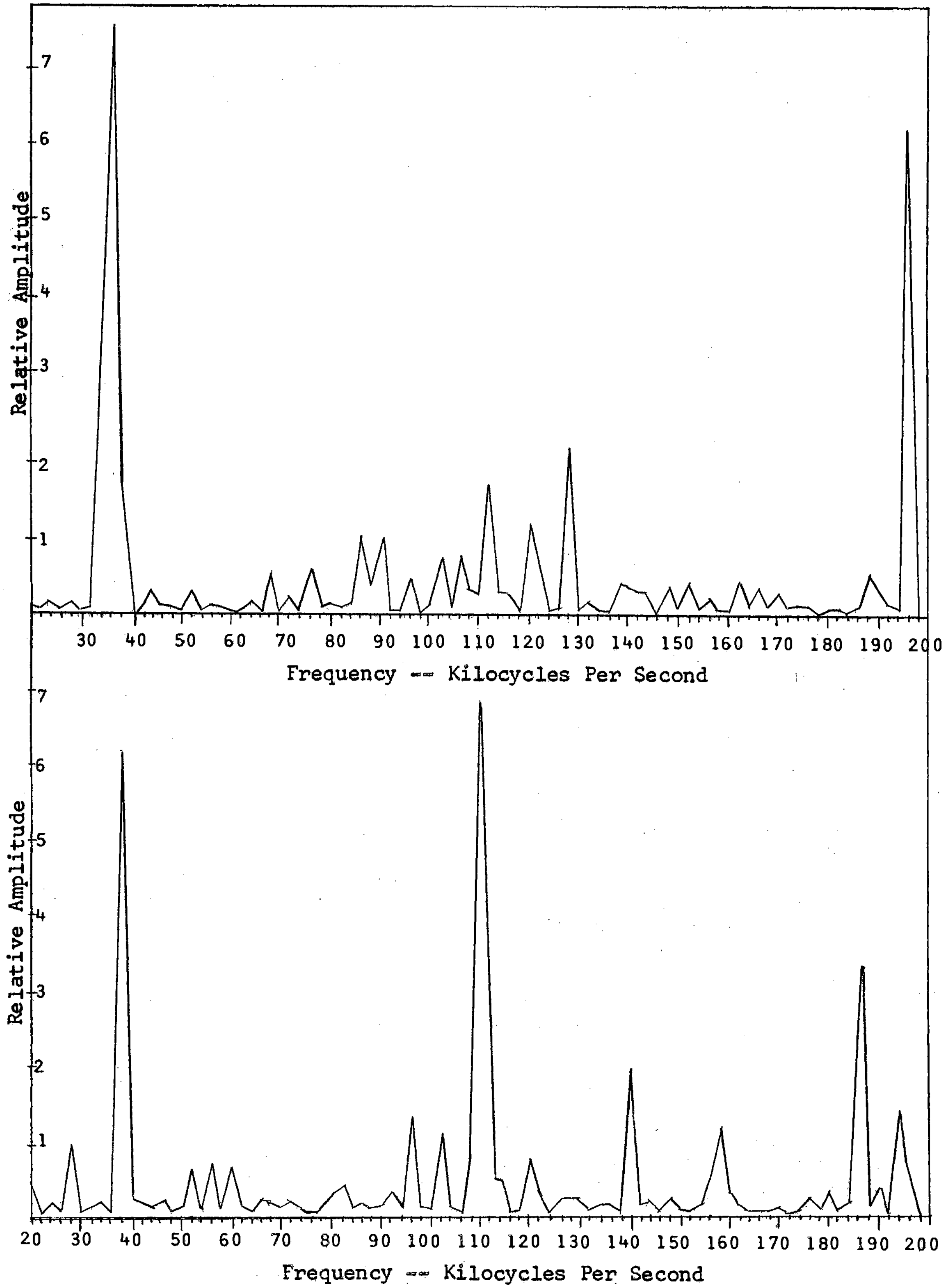


Figure 5.1. Fourier Spectra

attempted, approximately 20 waveforms of the type recorded should be used for analysis. This information suggests that waveforms from at least twenty apparently similar strokes should be analyzed to determine the average spectrum characteristics. Of course, this procedure would present the problem of choosing the similar waveforms.

One additional difficulty was encountered in the attempted analysis. Using an IBM 1410 computer, the time required for the computation of the spectrum of one waveform was 0.81 hours. It would not take very many waveforms until the computing time required was considerable, especially if all of the spectra were averaged and analyzed on a statistical basis.

CHAPTER VI

RECOMMENDATIONS

The work done for this thesis has established the firm conclusion that a more sophisticated system is required for complete fulfillment of the project's objectives. A system has been suggested[1] that would provide a means for satisfactorily accomplishing this task. A partial description of the proposed system follows.

In order to completely describe the electromagnetic field changes caused by a lightning stroke, it is suggested that two recording systems be used. One system would receive signals from an antenna sensitive to the vertically-polarized components of the field, while the other system would get its signals from an antenna sensitive to the horizontally-polarized components of the field.

It would appear advisable to record the signals in a manner which would provide a maximum of information about the frequency distribution. If possible, it would be desirable to have the frequency response of the recording system flat over the range from D.C. to several megacycles per second. This very wide range, as well as the analyzing requirements, has suggested the feasibility of using a magnetic-tape

---

[1] "A Proposal for Wide-Band Recording and Analysis of Horizontally- and Vertically-Polarized Electromagnetic Fields Caused by Near Electrical Storms," Unpublished Research Proposal by the School of Electrical Engineering, Oklahoma State University, 1964.

system to record the sferic data.

The most feasible system appears to be one which would divide the required bandwidth into many smaller bandwidths by an appropriate RF mixing and filtering system. Each narrower bandwidth would then be recorded on a separate magnetic track and subsequently analyzed separately. As an example of this procedure, consider the recording of the frequencies between 500 kilocycles per second and 1 megacycle per second. It is possible to use direct-recording techniques to record frequencies up to 0.5 megacycles per second. The problem, then, is to convert the desired band of frequencies to the band from 0 to 0.5 megacycles per second.

The first step is to mix the signal with the output of a 9.5-megacycle-per-second sinusoid from a crystal-controlled oscillator. The mixed product is passed through an active filter whose band pass is from 10.0 to 10.5 megacycles per second. The output of the filter would then contain the information which was originally contained in the 0.5- to 1.0-megacycle-per-second portion of the input signal. When the output of this filter is mixed with the output of a crystal-controlled oscillator whose frequency is 10 megacycles per second and then passed through a low-pass filter whose pass band is from 0 to 0.5 megacycles, the desired result is accomplished. The information in the frequency band of interest, that is, 0.5 to 1.0 megacycles per second, has been converted to a frequency band between 0 and 0.5 megacycles per second, which can be recorded on a channel of a magnetic tape.

By using appropriate oscillators, each 0.5-megacycle frequency band could likewise be converted to the same 0- to 0.5-megacycle-per-second band.

Because the frequencies below several hundred cycles per second would not be recorded with a faithful amplitude response, the bandwidth of the filters used in the conversion would have to be made somewhat wider than stated in the example. In order to record the frequencies in the signal which are in the 0- to 10-kilocycle-per-second range, it is proposed to use a frequency-modulation system to record them on a separate channel of the tape.

To analyze the signals after they have been recorded on the tape, it is proposed that the tape speed be slowed down by a factor of 64. By doing this, the highest frequency of the output would be roughly 7,800 cycles per second. Equipment capable of computing at this rate is available.

By taking advantage of the speed reduction, analog equipment can be used to perform the various analyses which might be beneficial, such as Fourier spectral analyses, autocorrelation function analyses, and power spectral density analyses. A necessary piece of equipment for some of this analysis would be a magnetic-tape delay line, which would be a loop of tape with adjustable delay between the record head and the reproduce head. Such equipment is available commercially.

The output data from the analyzing equipment could be recorded on strip-chart recorders, thus providing the visual information needed by those interpreting the data.

Until a thorough study has been made using equipment such as that just described, the association of sferic waveforms with particular types of lightning will remain a matter of conjecture. Once a conclusive association has been established, a useful and fast method of severe-storm identification, location, and even prediction may be produced.

A SELECTED BIBLIOGRAPHY

Blackman, R. B., and J. W. Tukey. *The Measurement of Power Spectra.* New York: Dover, 1958.

Brook, M., and Kitagawa. "Radiation from Lightning Discharges in the Frequency Range 400 to 1,000 Mc/S." *Journal of Geoph. Res.*, Vol. 69 (June 15, 1964), 2431-2434.

Brown, R. G., R. A. Sharpe, and W. L. Hughes. *Lines, Waves, and Antennas.* New York: Ronald Press, 1961.

Budden, K. G. "The Propagation of a Radio Atmospheric." *Phil. Mag.*, Vol. 42 (1951), 1-19.

Caswell, R. L. "Development of a High-Speed Lightning Camera." Unpublished M.S. Thesis, Oklahoma State University, 1963.

Craggs, J. D., and J. M. Meek. *Electrical Breakdown of Gases.* London: Oxford University Press, 1953.

Ferguson, H. B. "Torando Tracking by High-Frequency Sferics." Unpublished Ph.D. Dissertation, Oklahoma State University, 1956.

Griscomb, S. B. "The Prestrike Theory and Other Effects in the Lightning Stroke." *A.I.E.E. Transactions*, Vol. 77, Part III (1958), 919-933.

Grover, Frederick W. "Methods, Formulas, and Tables for the Calculations of Antenna Capacity." *U. S. Bureau of Standards Scientific Paper*, Vol. 22, No. 568, 1927-1928.

Hamilton, J. C. "An Instrument for Detecting Sferics from Visible Lightning Discharges." Unpublished M.S. Thesis, Oklahoma State University, 1962.

Jean, A. G., and W. L. Taylor. "Very-Low-Frequency Radiation Spectra of Lighting Discharges." *Journal of Res. of the N.B.S.*, Vol. 63D (September-October, 1959), 199-204.

Jones, H. L. "The Identification of Lightning Discharges by Sferic Characteristics." *Recent Advances in Atmospheric Electricity*, Ed. L. C. Smith. New York: Pergamon Press (1958), 543-556.

_____, and P. N. Hess. "Identification of Tornadoes by Observation of Waveform Atmospherics." *Proc. of I.R.E.*, Vol. 40 (September, 1952), 1049-1052.

Jones, H. L., and R. L. Calkins. "The Torando Pulse Generator as the Criteria for the Definition of the Severe Storm." Proc. of the Third Conference on Severe Storms, University of Illinois, November, 1963.

Kelly, Ruben D. "Development of Electronic Equipment for Torando Detection and Tracking." Unpublished Ph.D. Dissertation, Oklahoma State University, 1957.

Lindsay, Joe Pat. "An Analysis of the Sferic Waveform." Unpublished M. S. Thesis, Oklahoma State University, 1954.

Malan, D. J., and H. Collens. "Progressive Lightning, III--The Fine Structure of Return Lightning Strokes." Proc. of Roy. Soc. of Lon., Vol. 162, Series A (September, 1937), 175-203.

Norinder, Harold. "Long Distance Location of Thunderstorms." Thunderstorm Electricity, Ed. H. R. Byers. Chicago: University Press (1953), 276-327.

Plonsey, Robert, and Robert E. Collin. Principles and Applications of Electromagnetic Fields. New York: McGraw-Hill, 1961.

Samulon, H. A. "Spectrum Analysis of Transient Response Curves." Proc. of the I.R.E., Vol. 39 (February, 1951), 175-186.

Schonland, B. F. J., and H. Collens. "Progressive Lightning." Proc. of Roy. Soc. of Lon., Vol. 143, Series A (February, 1934), 654-674.

_____, D. J. Malan, and H. Collens. "Progressive Lightning, II." Proc. of Roy. Soc. of Lon., Vol. 152, Series A (November, 1935), 595-625.

_____. "Progressive Lightning, IV--The Discharge Mechanism." Proc. of Roy. Soc. of Lon., Vol. 164, Series A (January, 1938), 132-150.

_____, D. B. Hodges, and H. Collens. "Progressive Lightning, V--A Comparison of Photographic and Electrical Studies of the Discharge Process." Proc. of Roy. Soc. of Lon., Vol. 200, Series A (October, 1938), 56-75.

_____. "The Pilot Streamer in Lightning and the Long Spark." Proc. of Roy. Soc. of Lon., Vol. 220, Series A (October, 1953), 25-38.

Taylor, W. L. "Daytime Attentuation Rates in the Very-Low-Frequency Band Using Atmospherics." Journal of Res. of the N.B.S., Vol. 64D, No. 4 (July-August, 1960), 349-355.

_____, and L. Jerome Lange. "Some Characteristics of VLF Propagation Using Atmospheric Waveforms." Recent Advances in Atmospheric Electricity, Ed. L. C. Smith. New York: Pergamon Press (1958), 609-617.

"A proposal for Wide-Band Recording and Analysis of Horizontally- and Vertically-Polarized Electromagnetic Fields Caused by Near Electrical Storms." Unpublished Research Proposal by the School of Electrical Engineering, Oklahoma State University, 1964.

VITA

Ray Loran Calkins

Candidate for the Degree of

Doctor of Philosophy

Thesis: A STUDY OF THE FREQUENCY CHARACTERISTICS OF LIGHTNING DISCHARGES

Major Field: Engineering

Biographical:

Personal Data: Born in Eagle Grove, Iowa, March 21, 1927, the son of Homer F. and Lillian Calkins.

Education: Received the Bachelor of Science degree from Purdue University, with a major in Electrical Engineering, in January, 1951; received the Master of Science degree from the Oklahoma State University, with a major in Electrical Engineering, in May, 1958; completed requirements for the Doctor of Philosophy degree in May, 1965.

Professional Experience: Served in the United States Army Air Force from July, 1945, to December, 1946; employed as Research Engineer by Jersey Production Research Company, Tulsa, Oklahoma, from February, 1951, until August, 1960; employed as Instructor and Research Engineer by Oklahoma State University from August, 1960, until July, 1964; employed as Senior Research Engineer by The Atlantic Refining Company, Dallas, Texas, since November, 1964.