AN ANALYSIS OF THE SFERIC WAVEFORM

By

JOE PAT LINDSEY

Bachelor of Science

Oklahoma Agricultural and Mechanical College

Stillwater, Oklahoma

1949

Submitted to the Faculty of the Graduate School of
the Oklahoma Agricultural and Mechanical College
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
1954

AN ANALYSIS OF THE SFERIC WAVEFORM

Thesis Approved:

Herbert L. Jones
Thesis Adviser

A. Naeter

Robert MacVicar
Dean of the Graduate School

PREFACE

This thesis has as its purpose an analysis of the sferic waveform from the standpoints of general characteristics, time duration, and frequency content. No serious effort is made to correlate characteristics of the sferic waveform with meteorological conditions although the theories of other investigators and the opinion of the writer are often given. Only a very brief description of the equipment used in the study is included.

The author was first introduced to the subject of atmospheric disturbances and their intriguing nature by Dr. Herbert L. Jones, whose subsequent help and inspiration was a material aid to the writing of this thesis. Thanks are also due the personnel of the Stillwater Tornado Research Laboratory for their cooperation in obtaining equipment and information related to the subject. The support of the Facilities Branch administrative personnel of the CAA Aeronautical Center at Will Rogers Field in Oklahoma City is also appreciated.

To the writer's family --- Jo, Terry, and Gary --- a word of appreciation is given for their sacrifice of time and companionship.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER ONE

INTRODUCTION

Since man first became aware of the phenomena called "lightning" he has made attempts to explain the mechanics of its action and so remove it from the realm of the mysterious and place it in the category of the understandable. Early records indicate that the task was immediately found to be a difficult one since the occurrence of lightning strokes was not a controllable quantity and the many variations of the phenomena led to an even greater number of claims concerning its nature. Indeed, Pliny the Elder wrote as early as 23 A. D.[1]:

> Of thunderbolts themselves several variations are reported. Those that come with a dry flash do not cause fire but an explosion. The smoky ones do not burn but blacken. There is a third sort called "bright thunderbolts" of extremely remarkable nature; this kind draws casks dry without damaging their lids and without leaving any other trace and melts gold and copper and silver in their bags without singeing the seal.

Since Pliny's time the research into lightning phenomena has taken a more scientific form. Of a necessity the studies have involved cloud physics and meteorology as well as electromagnetism. Through integration of these fields of study the mechanics of the lightning discharge have been clearly outlined for the most part. However it yet remains to determine more

---

[1]C. F. Wagner and G. D. McCann, "Lightning Phenomena." Electrical Transmission And Distribution Reference Book, Third Edition, Chapter 12. (East Pittsburgh, Pennsylvania), Westinghouse Electric And Manufacturing Company, 1944, p. 298.

completely the exact reasons for the varied behavior of lightning and to associate clearly its many forms with other known factors of meteorology and weather. Lightning itself is now more correctly considered as a major part of the science of "sferics" which is the name applied to atmospheric disturbances of an electromagnetic nature.

The study of sferics has been accelerated in the past few years, primarily because of the interest of the military in weather as it affects field and air operations. For both ground and air forces a knowledge of storm locations, intensity, direction of movement and size is a valuable thing. Civilian personnel also show an interest in local thunderstorm activity, particularly if it is of sufficient energy level to cause high winds or spawn a tornado. The tornado has received a large share of the sferic investigator's interest because of its great destructiveness. It often has been called the most violent manifestation of nature known to man.

Research in tornado identification has been carried on at Oklahoma Agricultural and Mechanical College in Stillwater, Oklahoma for over five years. This work has been done under the direction of Dr. Herbert L. Jones, Professor of Electrical Engineering. The major line of approach has been the study of the electromagnetic wave characteristics of the tornado sferic as distinguished from wave characteristics of lower activity thunderstorms. This research has involved a study of the waveform of voltage produced in a vertical antenna and viewed, after amplification, on an oscilloscope. At this writing the waveforms having received most attention were viewed for a period of time not exceeding five hundred microseconds. It has been noted that a large number of the waveforms observed are still undergoing variation at the end of the five hundred micro-second oscilloscope sweep period. It is the purpose of this thesis, therefore, to undertake a study of the waveform for periods of time up to five thousand microseconds from the initial portion of the wave front. This study intends to determine the degree of correlation of its observations for the longer oscilloscope sweep duration with previously observed characteristics of the sferic waveform observed for shorter time durations. It also attempts to add to the information already known about the sferic waveform in general.

Specifically, the study of the sferic waveform will include the following phases:

1. A description of the basic types of waveforms observed, associating them with as many other factors surrounding their occurrence as possible.

2. A study of the incidence of waveforms observed having a given time duration.

3. A study of the frequency spectrum of certain specific waveforms observed as well as a general study of the frequency spectrum for sferics based on all the waveforms observed.

CHAPTER TWO

THE OKLAHOMA CITY SFERIC DETECTING STATION

One of the major problems of the original sferic detecting station at Stillwater, Oklahoma was to find a means of accurately locating thunderstorm activities, particularly those that could produce a tornado. The direction finder in use at the Tornado Laboratory in Stillwater gave good indications if the sferic frequencies were sufficiently low; however when the frequencies in the detected sferics became too high, as was the case with tornadic sferics, ellipses were produced on the direction finder instead of straight lines and as a result the accuracy was seriously affected.

Suitable means of calibrating the direction finder for a full 360° of azimuth, or measuring its error over this range of azimuth angle is yet to be developed. A generator to simulate sferic disturbances is not practical to build and visual observations of lightning discharges for calibration purposes is at best "hit and miss." Consequently a satellite station to observe sferic waveforms and directions was considered desirable because of its value in fixing the location of thunderstorm activities. These fixes could then be compared with indications of the radar at the Stillwater station, and meteorological data obtained from the weather bureau and the air force. By this means the errors of both direction finding stations could be determined.

Also, it was felt that a satellite direction finding station could be useful in developing coordination techniques for tracking the movement of the thunderstorm activity. This had not been attempted as yet, and it was realized that numerous problems would undoubtedly arise that had not been foreseen in coordinating the data from the two stations. In addition, more information concerning thunderstorm activity could be obtained through the data recorded by a second station.

Thus, a station was established at Will Rogers Field near Oklahoma City, Oklahoma for the purposes of obtaining more data on sferic waveforms and determining the effectiveness of two stations working together in fixing the location of thunderstorm activity. The first equipment for the station was installed in the early spring of 1952. This consisted of a direction finder employing crossed loop antennas and two balanced amplifiers, and an oscilloscope for viewing the sferic waveform.

Throughout the summer, fall, and winter following the installation of this equipment, the sferic activity within a radius of approximately 700 miles was observed by Mr. F. G. Smith, Jr. and the writer. No permanent data was taken because of the absence of photographic equipment.

In May and June of 1953, additional equipment was installed which could keep a permanent record of the data observed. This equipment was furnished by Oklahoma Agricultural and Mechanical College. It had been used previously with success by the Tornado Laboratory at Stillwater and was capable of photographing waveforms with a duration of not more than 250 microseconds. It was modified by Mr. F. G. Smith, Jr. for photographing of longer duration. The essential features of the equipment are shown in the block diagram of the completed Oklahoma City Station, Figure 1. The explanation of the operation of each component of the equipment and the description of the modifications made for this study is given in Mr. F. G. Smith's thesis.[1] The portions of the equipment which are of major importance to this thesis are the circuits used to amplify the sferic waveform of which are shown as the solid lines of Figure 1. The progression of the waveform through the equipment is as follows: The electromagnetic disturbance caused by the sferic discharge induces a voltage in the vertical antenna. This voltage variation with respect to time is called the "sferic waveform." It is fed first through the external amplifying circuits whose primary function is to match the high impedance of the vertical antenna to the low impedance of the coaxial cable used to feed the amplified signal some 200 feet into the station. This portion of the equipment was placed away from the rest of the station to minimize 60 cycle interference.

The signal arriving through the coaxial cable is then fed

---

[1] F. G. Smith, Jr. Establishment Of A Satellite Tornado Detection Laboratory At Oklahoma City, Oklahoma. Unpublished Master of Science Thesis. Oklahoma Agricultural & Mechanical College, Stillwater, Oklahoma, 1953.

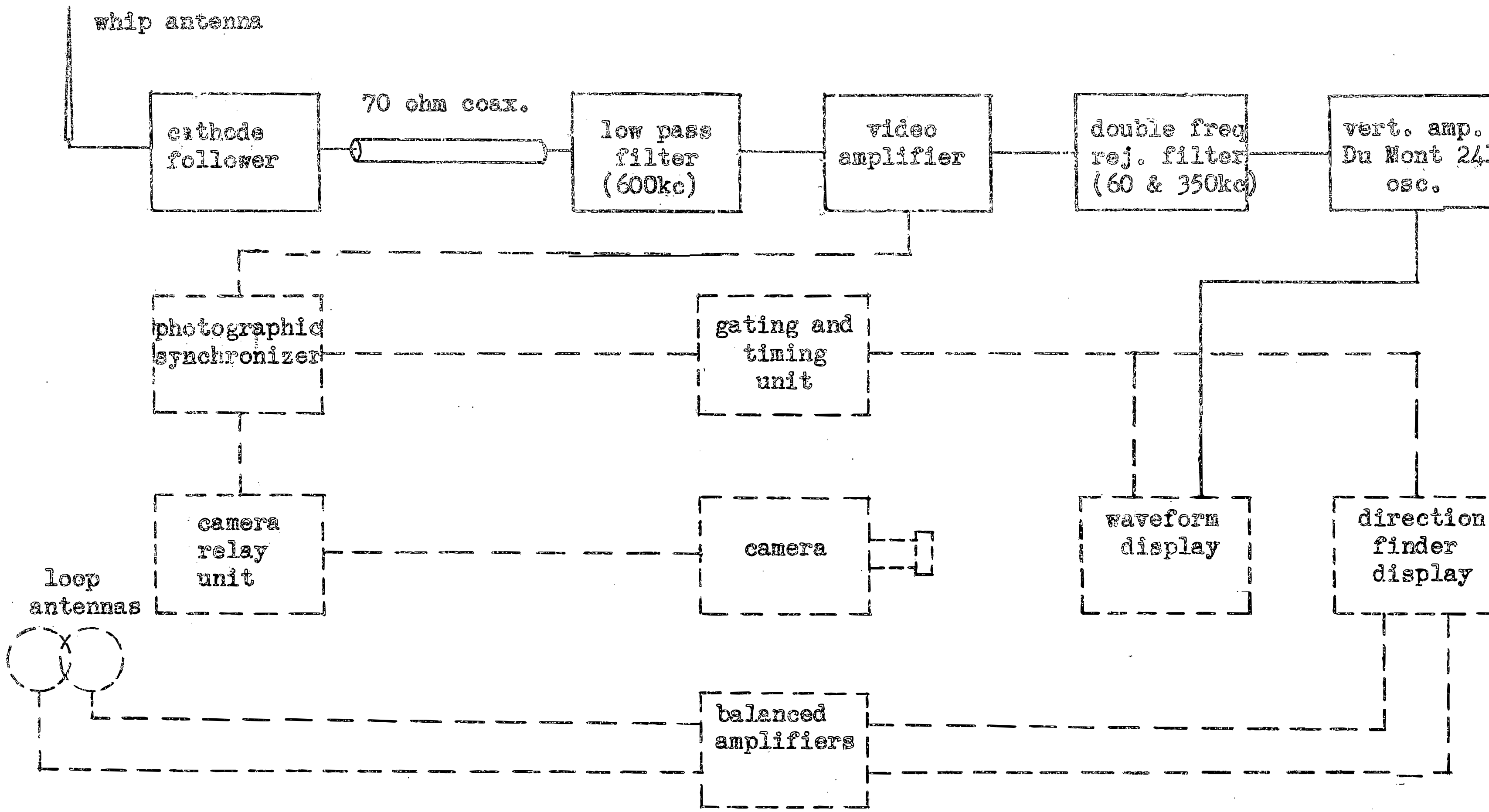


FIGURE 1. SIMPLIFIED BLOCK DIAGRAM, OKLAHOMA CITY STATION

into a low pass filter followed by a video amplifier. The low pass filter was designed to have a cutoff frequency of approximately 600 kilocycles so that interference from broadcast stations would be minimized. The output of the video amplifier is fed through a double frequency rejection filter into the vertical amplifier of a Dumont 241 oscilloscope. The rejection filter was designed by Mr. F. G. Smith, Jr. to eliminate residual 60 cycle pickup from the waveform and to minimize the effects of a low frequency radio range station located approximately one mile from the waveform detector. This filter was sometimes taken out of the circuit when high frequencies were visible in the sferic waveform since it attenuated to a considerable extent the frequencies between 350 kilocycles and 600 kilocycles.

The push-pull output of the oscilloscope amplifier was fed directly to the deflection plates of a Dumont 304 H oscilloscope where it produced a vertical deflection of the electron beam in duplication of the time variation of the voltage induced into the vertical antenna. The oscilloscope used to view the waveform had a variable sweep duration and unblanked time between the ranges of 50 microseconds and 5000 microseconds. This feature was provided by modifications of existing equipment. The electron beam intensity of the Dumont 304 H oscilloscope was modulated with timing markers derived from a 100 kilocycle oscillator and counting circuit. These markers provided accurate timing of the sferic waveform necessary for their analysis.

The frequency response of the waveform amplifying circuits is shown in Figure 2. These response curves illustrate the effects of having the double frequency rejection filter in and out of the waveform circuit. It will be necessary to use these response curves in Chapter Five to weight properly the frequency spectrums developed there for two of the more interesting sferic waveforms recorded.

The station was operated by Mr. F. G. Smith, Jr. and the writer through the month of June and a portion of July whenever thunderstorm activity was within the range of the station equipment. This range was considered to be 700 miles although evidence of activity farther than this was seen on several occasions.

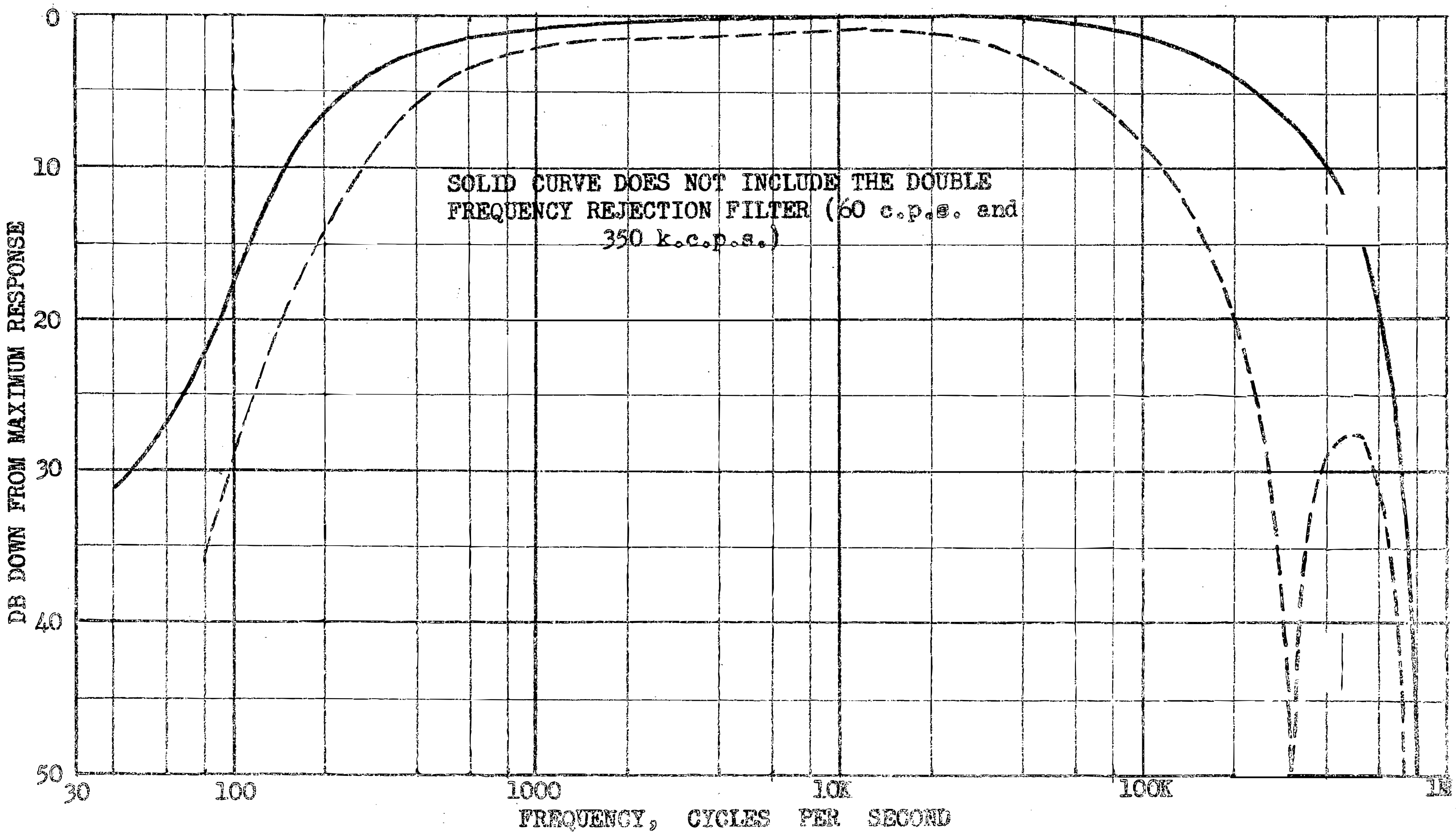


FIGURE 2. FREQUENCY RESPONSE OF WAVEFORM AMPLIFYING CIRCUITS

CHAPTER THREE

EXISTING KNOWLEDGE OF THE SFERIC WAVEFORM

Investigators do not all agree on the reasons for the indications given by the sferic waveform; however, there is reasonable agreement as to its shape, time duration, and frequency spectrum in a general sense. The work done to date in analyzing the sferic waveform has centered around a study of the time variation of the current discharge causing the sferic and a study of the time variation of the electromagnetic field caused by the current discharge. A considerable amount of literature exists concerning the time variation of the current discharge. However, there is less information available about the electromagnetic field caused by the current discharge. The more important observations are given in the following paragraphs.

The Time Variation Of The Current Discharge

Studies of current flow in lightning discharges have brought to light a number of interesting facts concerning the time variation of the current. The current flow in the lightning stroke has been generally agreed upon as having three components: A "pilot streamer," a "stepped leader," and a "return stroke." The process is initiated by the slow movement of the pilot streamer from cloud to ground carry-negative charges. This pilot streamer moves with a velocity of 62 to

1240 miles per second[1] and ionizes a channel through the atmosphere. This current flow produces no visible effects since it has a current magnitude of as low as 0.1 ampere.[2] As the pilot streamer moves from cloud to earth, it is followed and overtaken several times by a higher velocity, higher current magnitude "stepped leader." The stepped leader advances intermittently and approximately 160 feet at a time. It moves at a velocity of about 31,000 miles per second.[3] The stepped leader is usually visible and it reaches the ground at the same time as the pilot streamer. After the stepped leader has reached the earth, the "return stroke" is initiated. This is a flow of electrons from the ionized channel to the earth. The flow begins at the ground end of the channel and progresses upward toward the cloud at a rate of approximately 12,000 to 87,000 miles per second.[4] The return stroke is of much higher intensity and is visible as a brilliant flash. After the crest value of the current has been reached, it decreases, at first rapidly, and then more slowly until about 100 to 1000 amperes are flowing in the channel. This lower current flows for some time longer, lasting in many instances more than one-tenth of

---

[1] L. P. Harrison. Lightning Discharges To Aircraft And Associated Meteorological Conditions. (Technical Note No. 1001). Washington, D.C.: National Advisory Committee For Aeronautics, 1946, pp. 136-137.

[2] Ibid.

[3] Ibid.

[4] Ibid.

a second.

The findings of investigators of the current variation in the discharge indicate that:[5]

(1) the initial front of the current waveform associated with the return stroke lasts for about 10 microseconds and reaches crest values of about 3000 to 30,000 amperes with some few intense strokes approaching 150,000 amperes at the crest value.

(2) the time required for the return stroke current to build up to a crest value and then decay to one-half of the crest value is about 75 microseconds.

(3) the time duration from the beginning of the return stroke to the end of the current discharge is in the range of 100 to 10,000 microseconds for 90% of the direct strokes measured. This duration is for each discharge if there is more than one discharge in the return stroke. (This is often the case).

(4) 93% of the current strokes exceeded 100 microseconds in duration while only 3% exceeded 10,000 microseconds duration. Also, 80% exceeded 200 microseconds duration, 43% exceeded 500 microseconds duration and 15% exceeded 1000 microseconds duration.

(5) strokes that occur in regions of high soil resis-

---

[5]C. F. Wagner and G. D. McCann. Electrical Transmission and Distribution Reference Book, Third Edition. (East Pittsburgh: 1944), pp. 311-322.

tivity may have longer duration and less amplitude than those in regions of lower soil resistivity.

The Time Variation Of The Electric Field

Recordings of the electromagnetic field disturbance in general bear out the findings concerning the current variations in the lightning discharge. Schonland has found that approximately 65% of sferic waveforms are of the type illustrated in Figure 3.[6] The A portion of the waveform is believed to be associated with the stepped leader process. The B and C portions are thought to be associated with the return stroke. The A portion was found to last from 170 to 2000 microseconds. The B portion was found to last from 50 to 150 microseconds and the C portion appeared to last from 70 to 900 microseconds.

The B portion of the waveform of Figure 3 has received the most attention. Investigators at the University of Florida have found that:[7]

(1) the waveform resembles a damped sinusoid with the exception that each successive half cycle has a longer period than the preceding half cycle.

---

[6] A. A. Bless. Propagation And Reception Of Sferics. (A summary and bibliography submitted to the Evans Signal Laboratory by the University of Florida). Gainesville, Florida, 1947, pp. 12-26.

[7] W. K. Kessler. Direction Finding And Ranging On Atmospherics. (A final report submitted to the Evans Signal Laboratory by the University of Florida). Gainesville, Florida, 1948, p. 40.

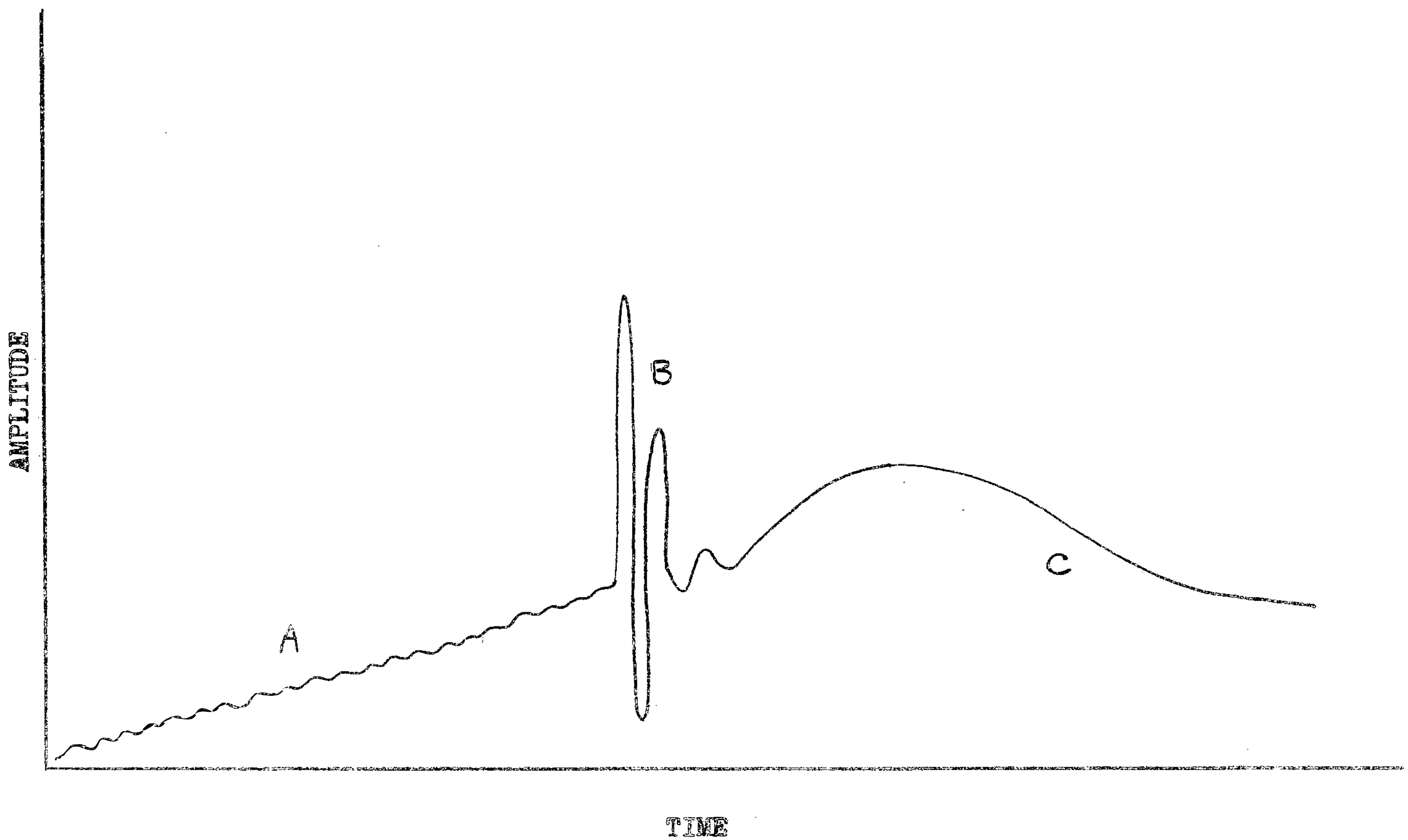


FIGURE 3. TYPICAL SFERIC WAVEFORM

(2) of 100 waveforms analyzed, the average time between the first two maxima in the same polarity is 125 microseconds and the average time of the following cycle is 175 microseconds.

(3) the majority of waveforms showed a progressive decrement. However there were a number that showed an incremental increase of amplitude with respect to time.

Several theories have been proposed to explain the reason for the apparent oscillatory variation of electric field strength associated with the return stroke. One theory is that the oscillations are produced by an effective resistance, capacitance, and inductance of the ionized channel through which the current flows. Another theory is that the oscillations are the result of phenomena associated with current flow through a gaseous medium such as the ionized atmosphere of the discharge channel. Still a third theory is that the oscillations are a result of multiple return strokes, each of which produces a complete oscillation in the radiation field since there is a build-up and a decay of current for each stroke. None of the theories have been proven correct in their explanation of the reasons for the oscillations although all of them deserve additional attention.

The Frequency Spectrum Of Sferic Disturbances

The frequencies present in the oscillatory portion of the sferic waveform have been a subject of study for some time. In general, it has been postulated that the sferics which show low frequencies in the oscillatory portion of the waveform are the result of a long discharge path while those which show higher frequencies are caused by shorter discharge paths. If this is true, the shorter waves would probably signify building up activity in the thunderstorm previous to its becoming "stacked" high enough to produce long strokes.

The work of Dr. H. L. Jones of Oklahoma Agricultural and Mechanical College in Stillwater, Oklahoma has shown that the frequencies present in the sferic waveform will increase with an increase in activity or energy level of the thunderstorm.[8] Waveforms have been recorded at the Tornado Laboratory in Stillwater which indicate frequencies of 100 to more than 1000 kilocycles present in the sferic disturbances from tornado activity. These sferic disturbances however are somewhat unique and probably should be classified separately from the normal sferic disturbance shown in Figure 3.

The predominant frequencies present in the oscillatory portion of the sferic waveform have been identified by Schonland as falling between 5000 cycles per second and 20,000 cycles per second.[9] On the other hand, Austin has found that

---

[8]Herbert L. Jones and Philip N. Hess. "Identification of Tornadoes by Observations of Waveform Atmospherics." Proceedings of the I.R.E. 40 (September, 1952), pp. 1049-1052.

[9]W. J. Kessler. Direction Finding And Ranging On Atmospherics. University of Florida, Gainesville, Florida, 1948, p. 40.

the range of sferic frequencies is between 10,000 cycles per second and 100,000 cycles per second, there being approximately twenty times as many at 17,500 cycles per second as there are at 100,000 cycles per second.[10]

Norinder has found that most sferics are unipolar and have small oscillations superimposed on lower frequencies in the 5000 cycles per second to 10,000 cycles per second range.[11]

No definite frequency spectrum for sferic disturbances was found in the literature. However, it was indicated from several sources that the incidence of sferics of a given frequency decreased with an increase of frequency. This has been accepted as true for some time since experience with radio communications at higher frequencies indicates greater freedom from atmospherics.

In summary, there seems to be some confusion concerning the actual frequency spectrum of sferics in general. This is possibly a result of the fact that the spectrum observed at a point remote from the disturbance is influenced by the medium through which the wave was propagated. This fact is borne out in part at least by the common observance that sferics occurring at night show marked differences from sferics occurring in daylight. Most observers seem to agree that the major portion of the energy in the sferic wave is in the frequency range below 100 kilocycles.

---

[10]Ibid.

[11]Ibid.

CHAPTER FOUR

DESCRIPTION OF DATA

The data taken for this study consisted of simultaneously recording the time variation of the electromagnetic field caused by the lightning discharge, the direction of the discharge with respect to the station, and the time of occurrence of the sferic disturbance. Other information such as the time duration of the waveform trace, whether or not filters were used in the video circuit, and the timing marker spacing was also recorded with the waveform. The permanent record of each sferic discharge was obtained by photographing the direction finder and video oscilloscope presentations. Also shown in each photograph was the clock indicating the time of occurrence and a card with information concerning the time duration of the video trace as well as the condition of the video circuit (i.e., whether or not the double frequency rejection jilter was included). The photograph was made on 35 mm. film strip and approximately 16 pictures per foot were taken.

The direction finder used had no ambiguity resolving circuit to eliminate the 180° ambiguity. Consequently the direction of the sferic could be determined only by knowing additional facts such as the location of a front or squall line from which the sferic could have originated or by triangulation in conjunction with the Tornado Laboratory direction finder at Stillwater. This disadvantage did not prove to be of much consequence since the additional information was at all times available and with a good degree of accuracy.

The data used in this material for analysis of the sferic waveform were taken on four different days. Weather conditions on these four different occasions may be described as follows:

June 2, 1953, 9:00 - 9:30 p.m. --- Weather conditions at Oklahoma City were clear and the sferic activity was at a minimum. Most returns were from the north and were isolated in a sector of about 20° west of north to 10° east of north. These returns were later found to have been coming from northern Nebraska where several tornadoes were reported. This data clearly established the range of the Oklahoma City station as about 700 miles since the gain of the equipment was operated at near maximum to obtain sufficient amplitude for photographing the waveform.

June 4, 1953, 12:15 - 12:30 p.m. --- Weather conditions in Oklahoma City were clear and warm with no visible thunderstorm activity and few clouds. The sferic activity received was from a front in extreme western Oklahoma. The returns were from two major directions -- northwest and southwest. No tornado activity was reported from this front. Two local storms developed, one at Taloga, Oklahoma and the other west of Cherokee, Oklahoma at about 8:30 p.m., but the photographic record of this activity was not readable.

June 5, 1953, 3:35 - 3:45 p.m. --- A squall line in western Oklahoma moved eastward across the state and sferic activity steadily increased during the afternoon of this date. By 3:30 p.m., sferics were occurring considerably more rapid than the equipment would photograph them. This front produced several minor tornadoes before reaching Oklahoma City. It moved through Oklahoma City at 5:30 p.m. causing high winds and some heavy rain. By 8:00 p.m. the front had moved to a distance of about 30 miles east of Oklahoma City and became almost stationary. Its activity greatly decreased between 6:00 p.m. and 7:00 p.m. and by 7:30 p.m. the sferic detector indicated an almost normal level of activity. The lightning associated with the activity as it moved through Oklahoma City was quite visible from the station and almost as many strokes from cloud to cloud were observed as from cloud to ground. The proximity of the activity and the presence of a considerable amount of horizontal component of the electromagnetic field caused the direction finder to indicate elliptical patterns and directions were in general indistinguishable.

June 27, 1953, 4:15 - 4:20 p.m. --- Weather conditions in Oklahoma City were mild with relatively cool temperatures and some thunderclouds but no visible precipitation or lightning. The radar at the Stillwater station indicated precipitation at Medicine Lodge, Kansas and Bartlesville, Oklahoma. The sferics observed at the Oklahoma City station were from north, northeast, and northwest.

Some 6000 photographs in all were taken during the months of June and July of which about 3000 were sufficiently readable to give usable information. Of the 3000 readable photographs, 627 representative records were analyzed for presentation in this material and the rest were visually inspected for general agreement with the information obtained from the 627. One waveform that was observed by the Stillwater station in April of 1953 was analyzed for its frequency spectrum. This waveform was recorded during a storm at Argonia, Kansas.

CHAPTER FIVE

ANALYSIS OF THE WAVEFORMS

The sferic waveforms recorded for this material were analyzed primarily for their time duration and frequency spectrum. The over all appearance of the sferic waveforms was also observed to determine general characteristics.

Basic Types of Waveforms

To the untrained observer, each sferic waveform seems to be different from all the rest and definite patterns of wave shape and duration do not seem to exist. However, continued observation of sferic disturbances eventually leads the observer to believe that there is a possibility of classifying them in several manners. The many photographic records viewed by the writer in the course of this research revealed a marked similarity between many of the waveforms. Many of these similarities already have been observed by others and the following list of general characteristics is intended to principally corroborate the findings of others.

The following characteristics were observed many times although few of the sferic waveforms had all characteristics and some had none:

1. A large number of the waveforms were found to resemble damped sinusoids with a steadily increasing period. This parallels the findings of University of Florida investi-

gators.[1] Because of the rapid dampening, the frequency of the major energy content was found to be very near the frequency computed by measuring the period of the first two or three cycles.

2. Many of the waveforms seemed to have a high frequency component superimposed upon a lower frequency component. These types of waveforms appeared to be associated with only certain directions indicated on the direction finder during any one period of observation. Therefore it is assumed that they were eminating from a single storm or thundercloud. No reason was found for their occurrence in one storm and not others in the same front or at the same time. However, it is felt by the writer that such waveforms might signify a building up of energy level in the storm or cloud since it has been established that higher energy levels produce higher frequency sferics.[2] The higher frequency components did not always come at the first of the waveform, but sometimes appeared as "bursts of hash" at random points along the slower varying portion of the waveform.

3. Some of the waveforms began with a relatively high frequency component for a short period of time followed by an extremely slow variation that seemed to contain no higher

---

[1]Kessler. Direction Finding And Ranging On Atmospherics. Gainesville, Florida.

[2]Herbert L. Jones and Philip N. Hess. "Identification of Tornadoes by Observations of Waveform Atmospherics." Proceedings of the I.R.E., 40 (September, 1952), pp. 1049-1052.

frequency components. These waveforms were also associated with certain directions of reception and were assumed to originate from a single storm or location. The waveform shape is best explained by the theory that the current discharge began with a high energy level, high frequency burst and then was followed by a long decay of current in the ionized channel. No reason was found for the occurrence of this type of sferic rather than a more conventional damped oscillation waveform as discussed in characteristic 1.

4. Waveforms which originated from distant activity were "smoother" than those coming from nearby storms. This may be explained by the greater attenuation of the higher frequency components, thus leaving only the low frequency components to be observed. This characteristic was clearly evident from observation of the waveform and suggests the possibility of determining the range of the sferic disturbance by this method.

5. The waveforms originating from different cloud formations appeared to have different frequency components even though the distances to the different storms were approximately the same. This was expected since storms of different energy level will produce sferics of different frequencies. This difference in frequency content was sufficiently noticeable that one could almost ascertain the direction of the sferic from observing the waveform shape.

6. The waveforms having the highest initial amplitude usually had the longest time duration. The ratio of time duration to amplitude was measurably greater for the higher amplitude waveforms. There were numerous exceptions to this rule; however, the characteristic was sufficiently noticeable to deserve mention.

Many other characteristics were observed but they were for the most part isolated and were not duplicated often or in a definite pattern.

Time Duration Of The Waveform

The time duration of the sferic waveform was found to vary over a wide range. Some few observed were completed in less than 100 microseconds while others were not completed in 5000 microseconds, which was the longest trace used in this study. The average time duration of sferics coming from a given storm was almost always less than 1000 microseconds. However this average time varied slightly from storm to storm. In general, nearby activity had waveforms of shorter duration than storms farther away. This is possibly explained by the fact that, because of the attenuation with distance, more of the sferics coming from a nearby storm were recorded than those of a distant storm. Thus, for reasons stated in characteristic 6, the smaller amplitude disturbances weighted the average of time durations downward.

The distribution of time durations of 93 sferic waveforms recorded on June 2 is shown in Figure 4. The majority

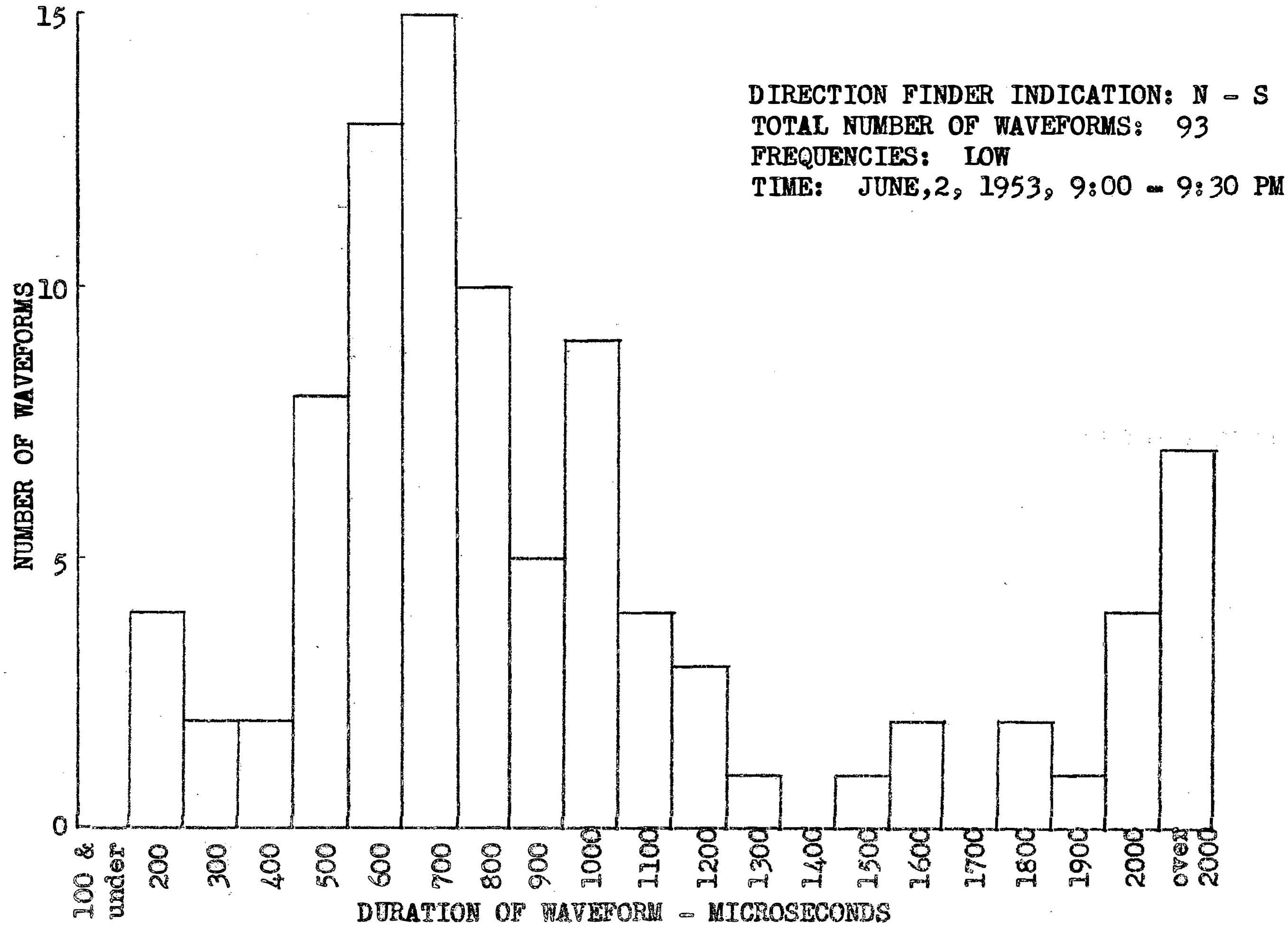
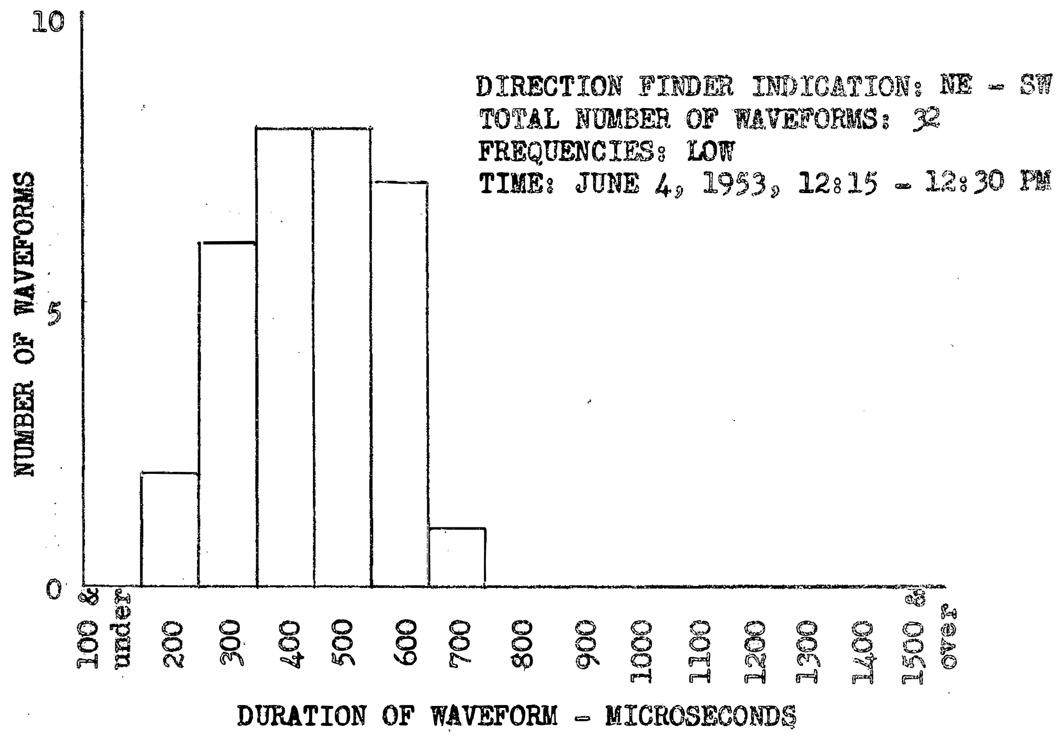


FIGURE 4. DISTRIBUTION OF TIME DURATIONS OF WAVEFORMS OBSERVED JUNE 2

of these sferic disturbances lasted from 500 to 900 microseconds with seven having durations in excess of 2000 microseconds. All the sferics recorded were of the low frequency type (below 20 kilocycles). This activity originated some 700 miles from the station and might be considered the norm for distant activity.

Observations on June 4 of 59 sferics showed two major directions of reception. The distribution of time durations for each direction is shown in Figure 5. These two storms were in the same front in western Oklahoma and they appeared to generate similar sferic waveforms. Frequencies present in these waveforms were also low.

Photographs of 290 waveforms originating from a westerly direction on June 5 were analyzed and the time duration distributions shown in Figure 6 were obtained. This activity was relatively close to Oklahoma City, being approximately 50 miles away, and was the result of a front extending in a north to south direction. This front was increasing in activity and moving toward Oklahoma City when the photographs were taken. Two different sweep speeds were used to check the correlation between the time durations shown by each sweep speed as read from the photographs. The majority of these sferics had time durations of from 300 to 1000 microseconds. Most of the waveforms were of the low frequency type with a few having medium frequency components (20 kilocycles to 100 kilocycles).



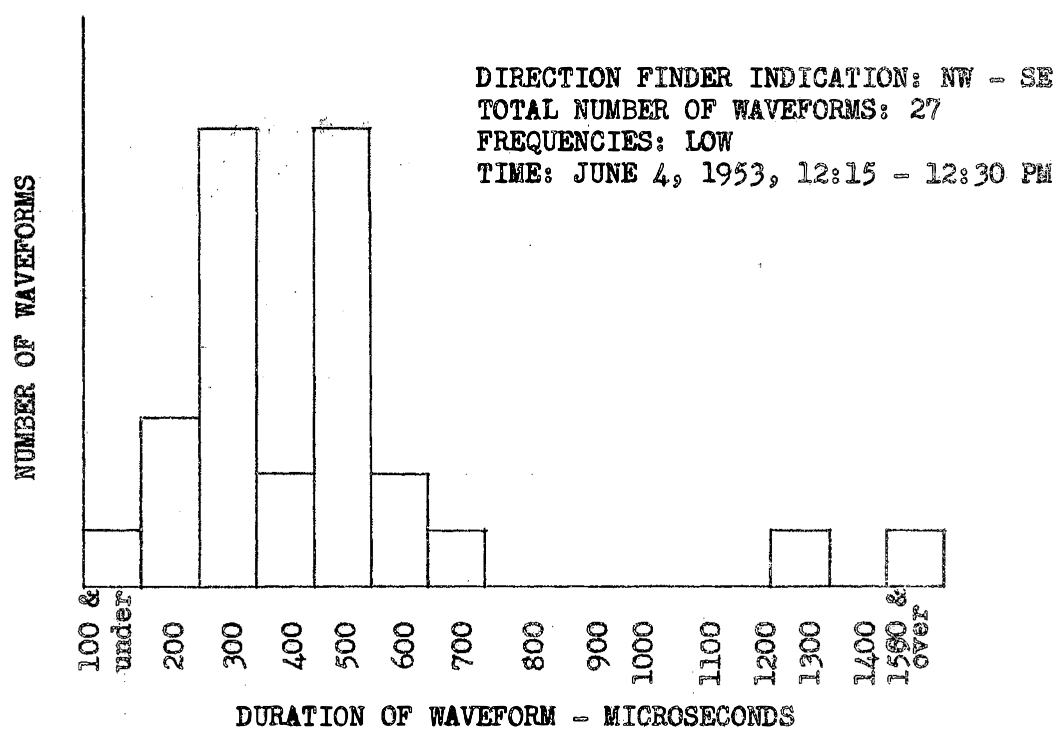
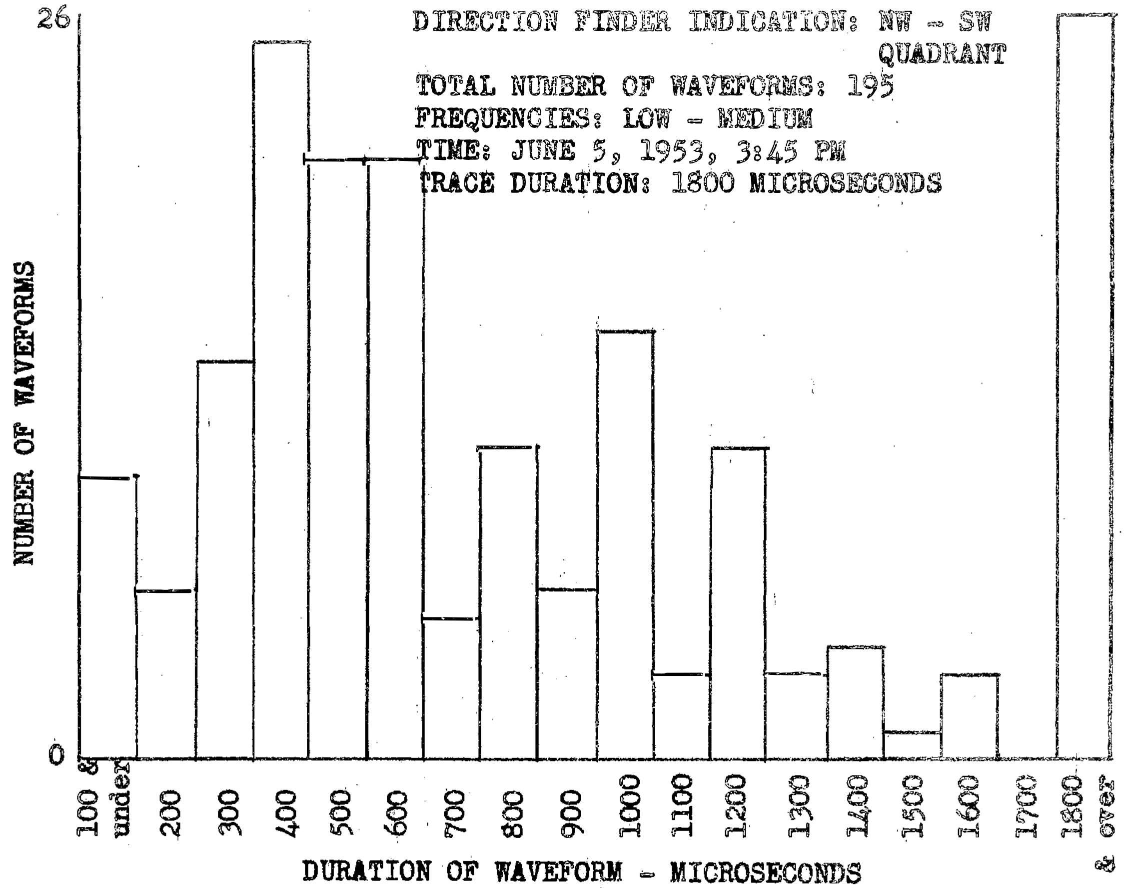


FIGURE 5. DISTRIBUTION OF TIME DURATIONS OF WAVEFORMS OBSERVED JUNE 4



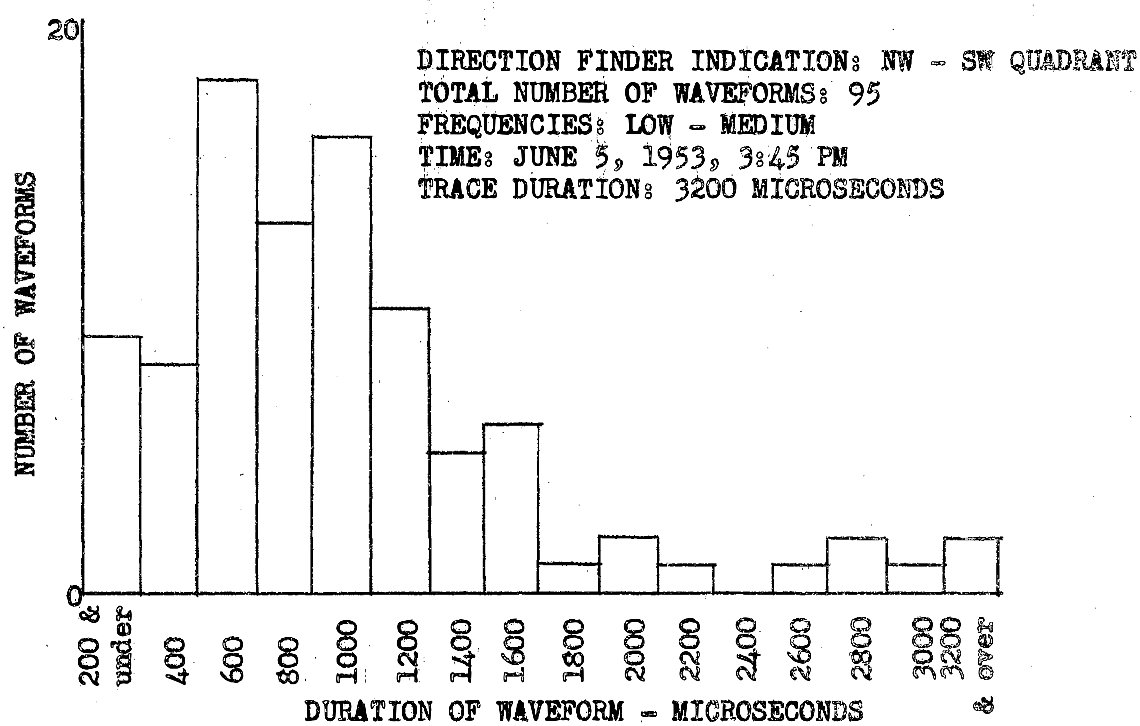


FIGURE 6. DISTRIBUTION OF TIME DURATIONS OF WAVEFORMS OBSERVED JUNE 5

On June 27, some 183 photographs were taken of sferics arriving from three different directions. The results of analysis of these records for time duration distributions of the three sferic sources are shown in Figure 7. A large share of sferics from each direction appear to have time durations of from 400 to 1400 microseconds. All of this activity was some 200 miles from the station. Of interest here is the number of sferics having durations of over 4000 microseconds. This is representative of about 6% of the waveforms observed on this date, which is a somewhat higher percentage than is normally found.

Based on these 615 sferic waveforms analyzed for time durations, it may be stated that a trace duration of 1000 microseconds will show the completion of about 66% of the total number of sferic waveforms, leaving 34% that will still be undergoing variation at the end of the trace. If a 500 microsecond trace duration is used, only 31% of the sferic waveforms will be completed by the end of the trace.

The composite distribution of time durations for the 615 waveforms recorded is shown as the solid line of Figure 8. The dotted line in the figure is a corresponding distribution of time durations of current discharges in lightning strokes as given by Wagner and McCann.[3]

---

[3]C. F. Wagner and G. D. McCann. "Lightning Phenoma." Electrical Transmission and Distribution Reference Book, Chapter 12.

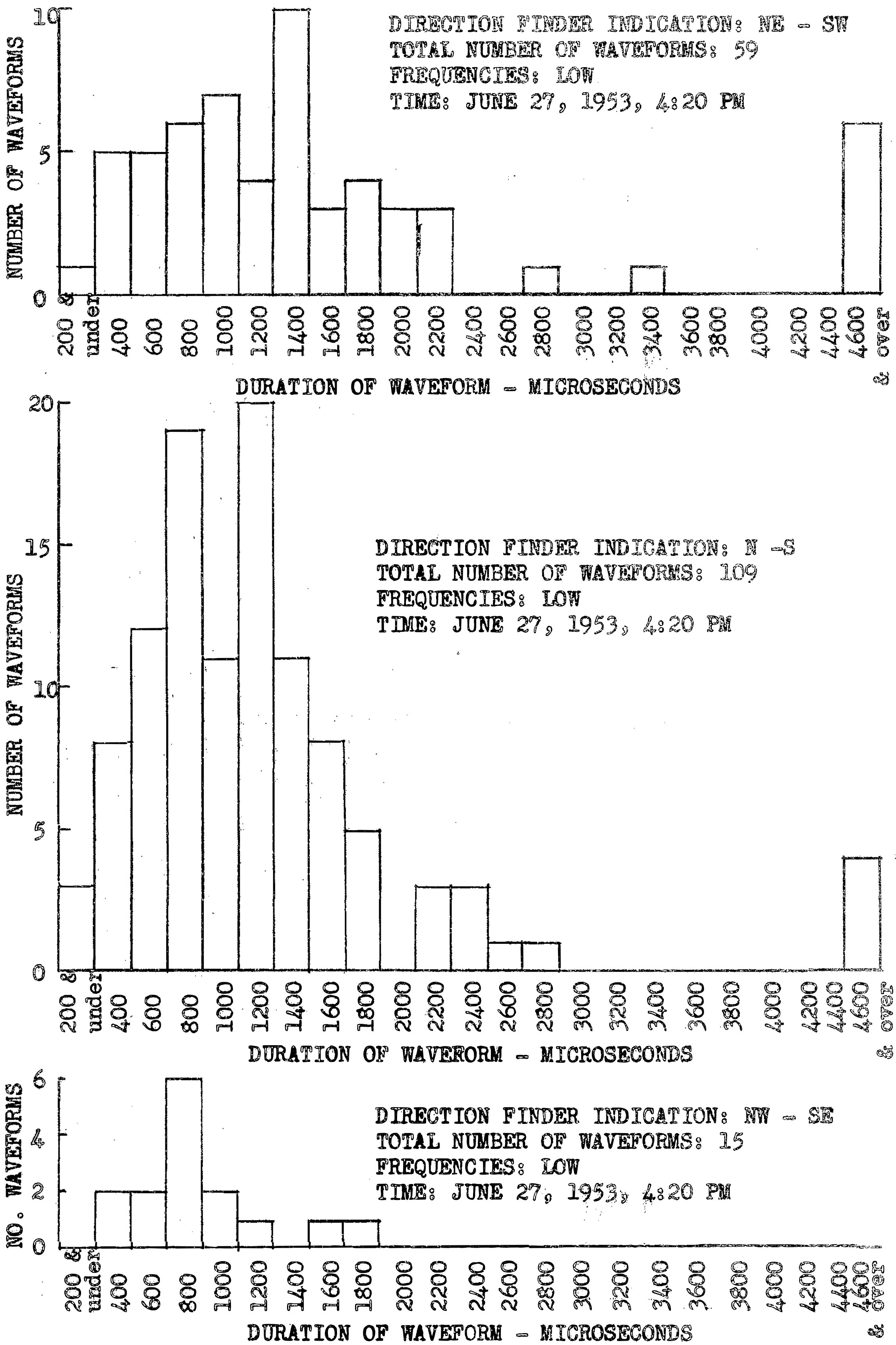


FIGURE 7. DISTRIBUTION OF TIME DURATIONS OF WAVEFORMS OBSERVED JUNE 27

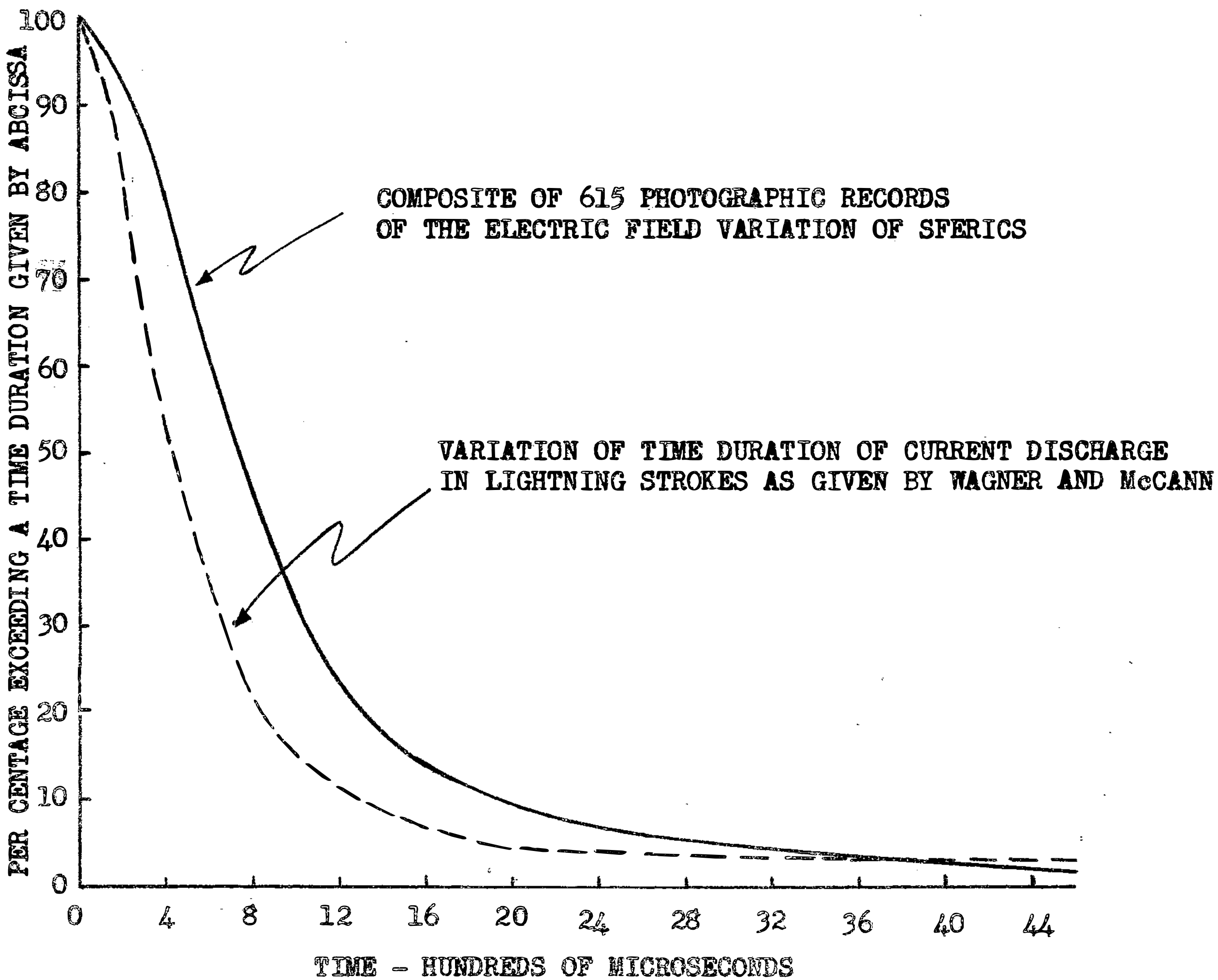


FIGURE 8. COMPARISON OF THE TIME DURATIONS OF SFERIC ELECTRIC FIELD VARIATION AND CURRENT DISCHARGE

Frequency Spectrum of the Sferic Waveform

A function of time, f(t), that does not repeat itself may be expressed as a function of ω by use of the Fourier Integral. The usual form of the Fourier Integral is,

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t}\, dt$$

If the function of time cannot be expressed mathematically, as is the case for a sferic waveform, the transformation from the time domain to the frequency domain through use of the Fourier Integral must be done by graphical means or the equivalent. This can be accomplished by using a function of the form sin x/x as is suggested by H. A. Samulon.[4] The frequency content of a voltage function of time, e(t), is usually limited by the circuit through which the voltage passes. Since the circuit itself will have a cut off frequency, all frequencies above this cut off frequency which were present in the original voltage function will be eliminated when it passes through this circuit. Thus if a frequency f_c may be established, which is the highest frequency present in a given voltage function of time, the function may be represented exactly by the sum of a number of functions of the form sin x/x. The mathematical expression for e(t) will then become,

$$e(t) = \sum_{n=0}^{\infty} A_n \frac{\sin 2\pi f_c (t - n\tau)}{2\pi f_c (t - n\tau)} \quad ; \quad \tau \leq \frac{1}{2 f_c}$$

---

[4] H. A. Samulon. "Spectrum Analysis Of Transient Response Curves," Proceedings of the I.R.E., February, 1951, pp. 175-186, New York.

where A_n is the amplitude of the function of time at the sampling points which are separated by the interval τ. The spectrum of the n-th term of e(t) may be expressed as,

$$e(\omega) = \int_{-\infty}^{+\infty} A_n \frac{\sin 2\pi f_c (t - n\tau)}{2\pi f_c (t - n\tau)} e^{-j\omega t} dt = A_n \frac{e^{-jn\tau\omega}}{2f_c}$$

Thus the spectrum of e(t) will be the sum of the spectrums of each term:

$$E(\omega) = \sum_{n=0}^{\infty} A_n \frac{e^{-jn\tau\omega}}{2f_c} \quad ; \quad \tau = \frac{1}{2f_c}$$

The problem then is resolved to forming the summation indicated in the above equation from the plot of e(t).

The first step in computing the frequency spectrum of a given e(t) is to determine the value of f_c. The value of f_c used in computing the frequency spectrums of the three waveforms in this material was determined by inspection of e(t). The number of cycles of the highest apparent frequency in the waveform was determined and a frequency f_m was computed. A value of f_c was assumed which was from three to five times f_m depending upon the smoothness of the waveform. Although this method of determining f_c is subject to some error, it often allows the use of a value of f_c which is considerably lower than the cut off frequency of the circuit being used to amplify the waveform. This in turn allows the use of a larger time interval τ and thus fewer sampling points on the waveform are required. The error introduced in assuming a value of f_c that is somewhat lower than the highest frequency in the waveform is greatest for the highest frequency in the spectrum. The possibility of error occurring may be minimized however since a judicial choice of f_c will cause the spectrum to include easily frequencies containing 95% of all the energy in the waveform. There is an additional advantage in allowing the choice of f_c to be arbitrary to a certain extent. The time interval τ may be adjusted by means of the choice of f_c so that readings may be taken from e(t) more easily. For example, the choice of a f_c of 300 kilocycles is not as desirable as a choice requires the use of sampling points which are 3.333 microseconds apart and the latter would require a more easily determined sampling point spacing of 3 microseconds.

After establishing the sampling interval, τ , it is necessary to determine the number of frequencies at which $E(\omega)$ must be evaluated in order to give sufficient shape to the outline of the spectrum. It is of advantage to choose a number which is a factor of 180 so that the number of numerical computations may be reduced to a minimum. To show the importance of this choice, the form of the previous expression for $E(\omega)$ may be changed by substituting $1/2f_c$ for the interval τ and $2\pi f$ for ω, both substitutions to be made in the exponent of the natural logarithm base, e:

$$E(\omega) = \sum_{n=0}^{\infty} A_n \frac{e^{-jn\pi\left(\frac{f}{f_c}\right)}}{2f_c}$$

If the term f is assigned a subscript o which is to range in integral values from unity to q, where q is the number of frequencies for which evaluation of $E(\omega)$ is made, $E(\omega)$ becomes $E(\omega_o)$ for each frequency value f_o:

$$E(\omega_o) = \sum_{n=0}^{\infty} A_n \frac{e^{-jn\pi\left(\frac{f_o}{f_c}\right)}}{2f_c}$$

It may be seen from this expression for $E(\omega_o)$ that the effect of summing on n is to change the magnitude of the phasor quantity at random in the manner in which the time variations of e(t) occur, while the change in angle attached to the phasor magnitude is in uniform steps since the quantity f_o/f_c is established for each f_o. It would therefore be desirable to establish the quantity f_o/f_c so that for as many values of f_o as possible the angles $n\pi f_o/f_c$ will have symmetry about the 90°-270° axis. For if this were true, an angle in the first quandrant resulting from one value of n would have the same magnitude of sine and cosine function as another angle in the second quandrant which was the resultant of a larger value of n. Thus in forming the summation on n, fewer sine and cosine products would be necessary since the n-formed phasors associated with these two angles could have their magnitudes algebraically combined before multiplication by the sine and cosine components.

It is found upon attempting to form this symmetry of the angles $n\pi(\frac{f_o}{f_c})$ about the 90°-270° axis that values of q which are factors of 180 seem to fit the required results more satisfactorily than any other possibility. Consequently a value of q of 18 was decided upon for the frequency spectra presented here. Thus there will be 18 frequencies in each spectrum evenly spaced from zero to f_c in value at which $E(\omega)$ has been evaluated.

To perform the actual summation, tables were formed that increased the speed at which computations could be made. A set of summation tables was made for each frequency, f_o, for which computation was made. The table for finding f_2, the second frequency in the spectrum, is given on the following page to indicate the process involved.

To use this table, the algebraic sum of all sampling point magnitudes (A values) having the indicated subscripts in each group is formed. The sign before each subscript number in the table should be included in determining the algebraic sign of each A_n. After summing each group, these summations were then multiplied by their respective numbers in the center column of the table. After each group summation had been made, the sine and cosine columns were totalized to determine the magnitudes of the sine and cosine components of f_2. The polar magnitude of voltage at frequency f_2 was then determined by combining the sine and cosine components in quadrature in the usual manner.

Not all of the frequency analysis tables have the same appearance as the one used for evaluation of the magnitude of f_2. In some cases it is more convenient to associate the

TABLE FOR EVALUATION OF f_2

COSINE TERMS						MULTIPLIER	SINE TERMS					
0 -18	36 -54	72 -90				1.000	9 -27	45 -63	81 -99			
1 -17	35 -19	37 -53	71 -55	73 -89	-91	.985	8 -26	10 -28	44 -62	46 -64	80 -98	82 -100
2 -16	34 -20	38 -52	70 -56	74 -88	-92	.940	7 -25	11 -29	43 -61	47 -65	79 -97	83
3 -15	33 -21	39 -51	69 -57	75 -87	-93	.866	6 -24	12 -30	42 -60	48 -66	78 -96	84
4 -14	32 -22	40 -50	68 -58	76 -86	-94	.766	5 -23	13 -31	41 -59	49 -67	77 -95	85
5 -13	31 -23	41 -49	67 -59	77 -85	-95	.643	4 -22	14 -32	40 -58	50 -68	76 -94	86
6 -12	30 -24	42 -48	66 -60	78 -84	-96	.500	3 -21	15 -33	39 -57	51 -69	75 -93	87
7 -11	29 -25	43 -47	65 -61	79 -83	-97	.342	2 -20	16 -34	38 -56	52 -70	74 -92	88
8 -10	28 -26	44 -46	64 -62	80 -82	100 -98	.174	1 -19	17 -35	37 -55	53 -71	73 -91	89
TOTAL, COSINE TERMS ______							______ TOTAL, SINE TERMS					

algebraic sign with the multiplier rather than the sampling point magnitudes. Some of the tables have fewer multipliers than the one for f_2 while some others have more. The time required for performing the summation for f_2 is representative of the average time required for analysis of each of the other seventeen frequencies.

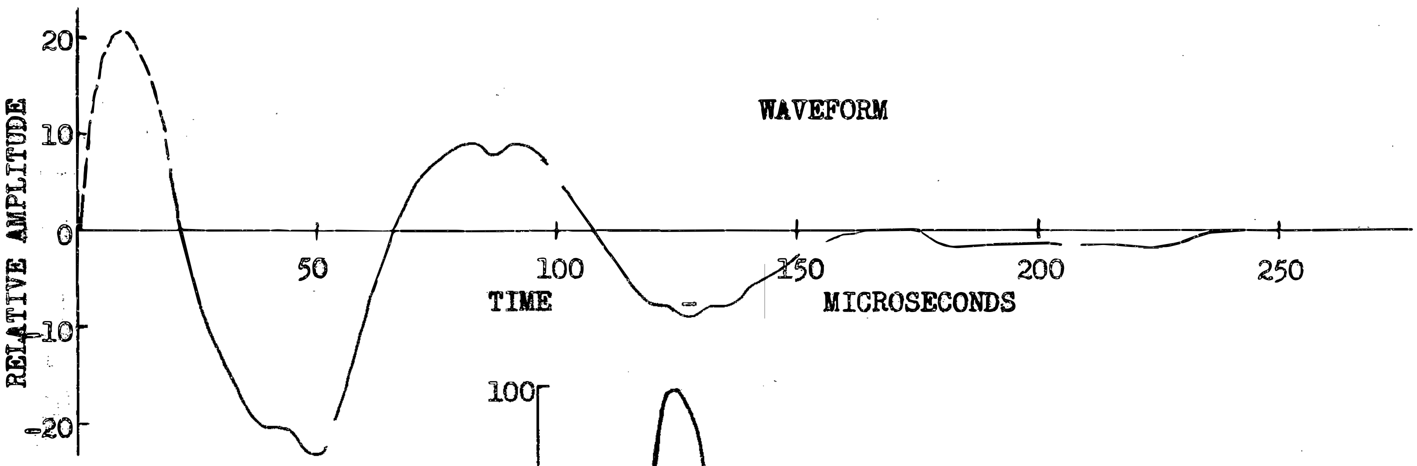
It may be seen that the table is made for a maximum of 100 sampling points since the highest subscript number is 100.

This limits the use of the table to a certain extent. If the total time duration of e(t) is denoted by T, the relation between T and τ (sampling point spacing) must be

$$\frac{T}{\tau} \leqq 100$$

in order to use these tables. In some cases, τ, as set by the value of f_c for a given e(t), is such that the above relation does not hold true. In such a case, use of the 100 point tables will require a larger τ value and will thus lower the f_c value. This introduces error in the computed values of $E(\omega)$ for the higher values of ω in the spectrum. If this error is too great, tables must be devised which allow a sufficiently large number of sampling points.

The three waveforms chosen for spectrum analysis is this material are shown along with their respective spectra in Figures 9, 10, and 11. The waveform of Figure 9 was obtained during a storm near Argonia, Kansas by the Stillwater station. It is representative of a relatively low frequency sferic although the same storm did produce some sferic waveforms with high frequency content. The characteristic damped sinusoid shape with increasing period is displayed here. A cut off frequency (f_c) of 100 kilocycles was chosen for computing this spectrum and the small amount of energy at the high frequency end of the spectrum verifies this choice as being accurate. Most of the energy in this waveform was found to be concentrated at about 12 kilocycles.



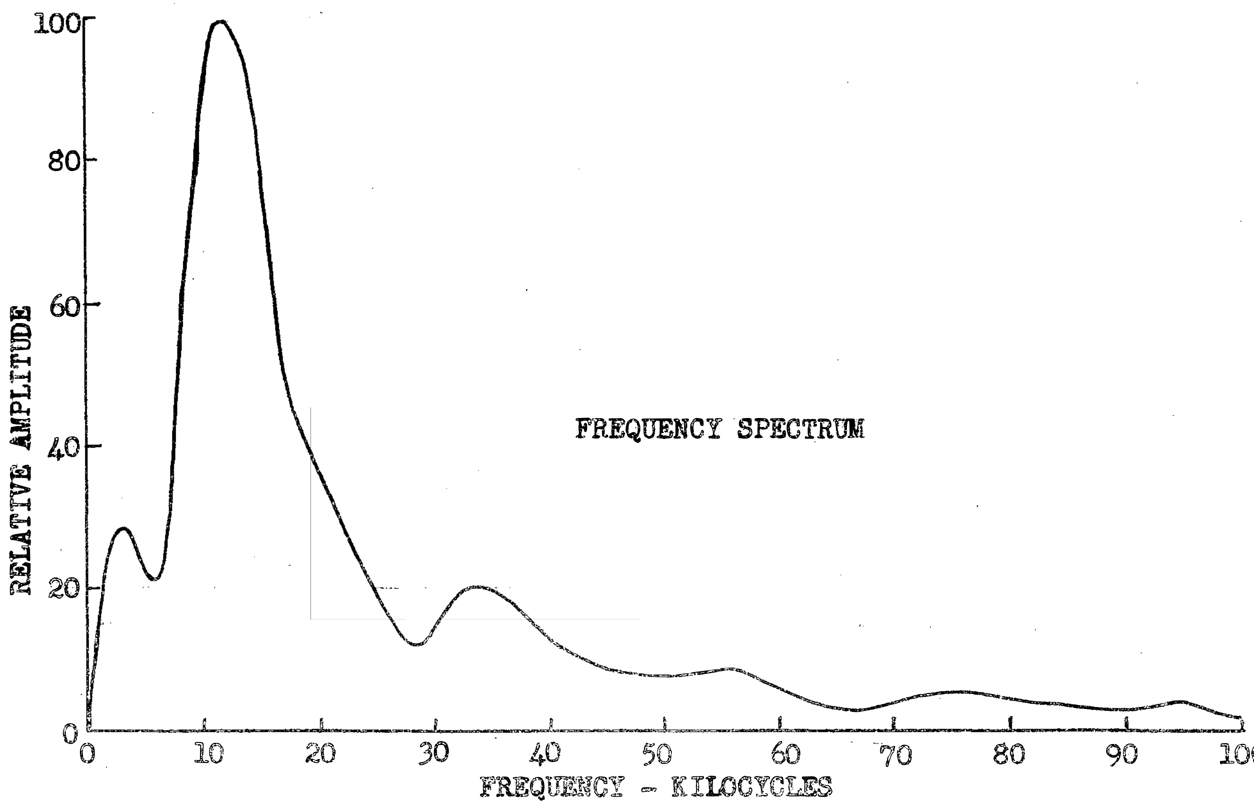
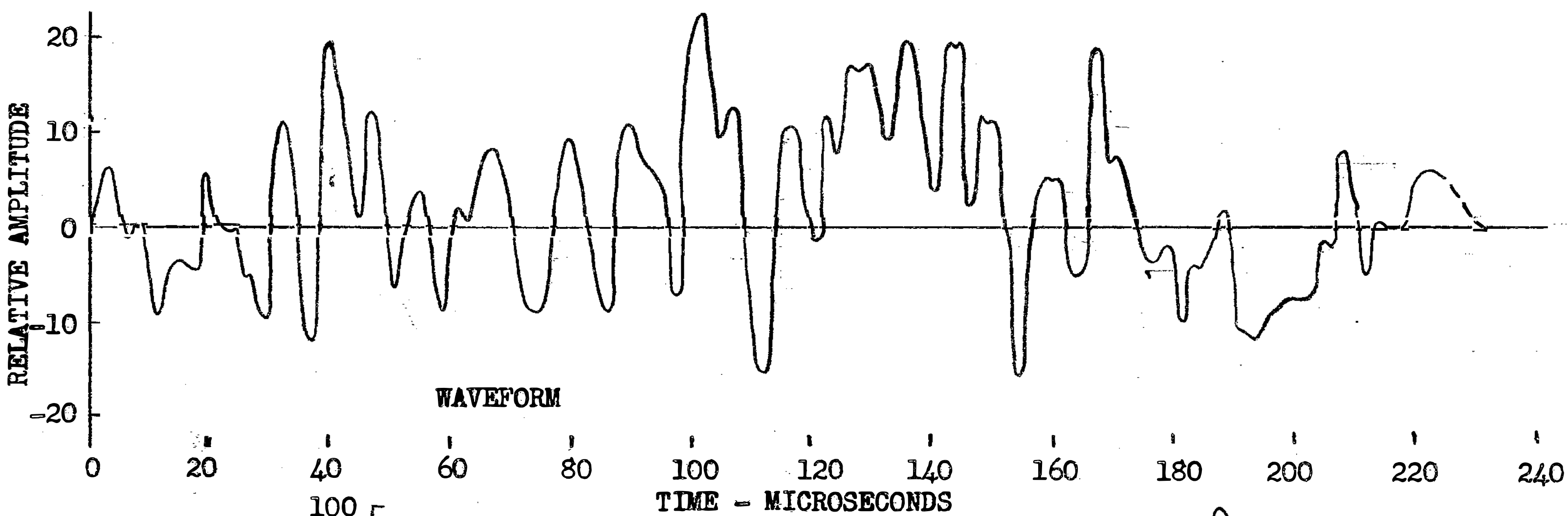


FIGURE 9. WAVEFORM AND FREQUENCY SPECTRUM, LOW FREQUENCY TYPE



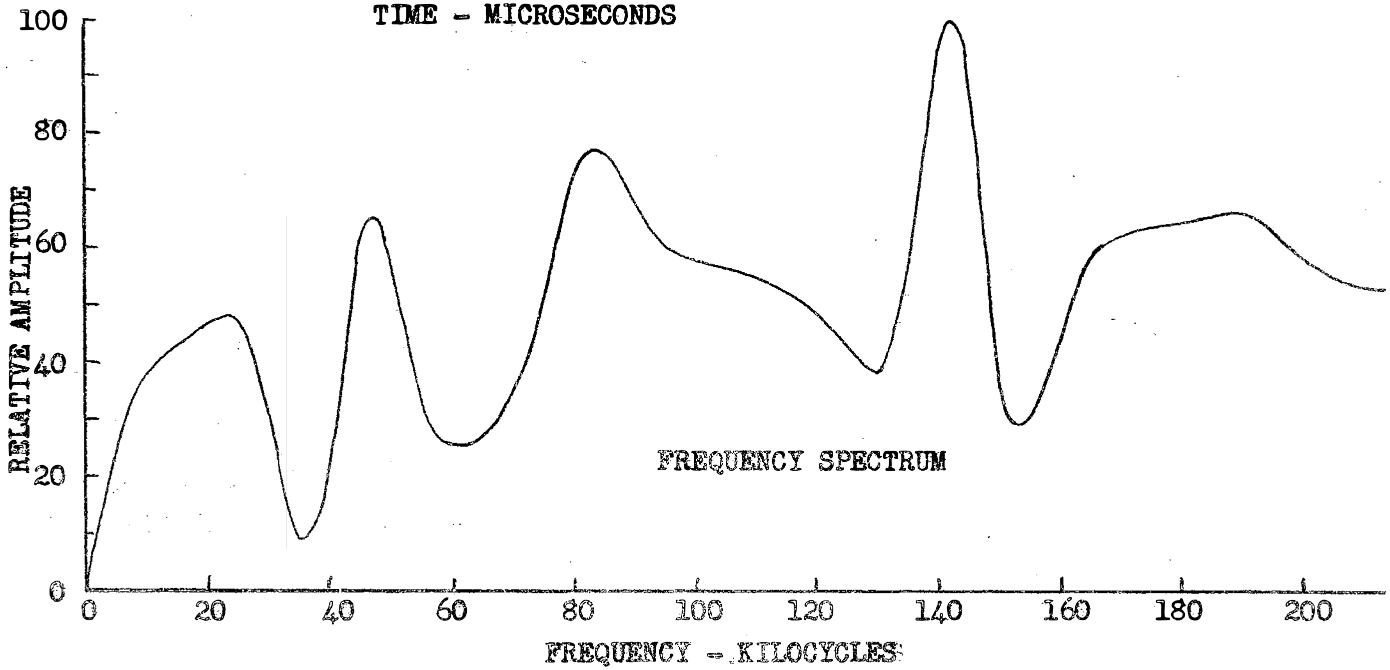


FIGURE 10. WAVEFORM AND FREQUENCY SPECTRUM, HIGHER FREQUENCY TYPE

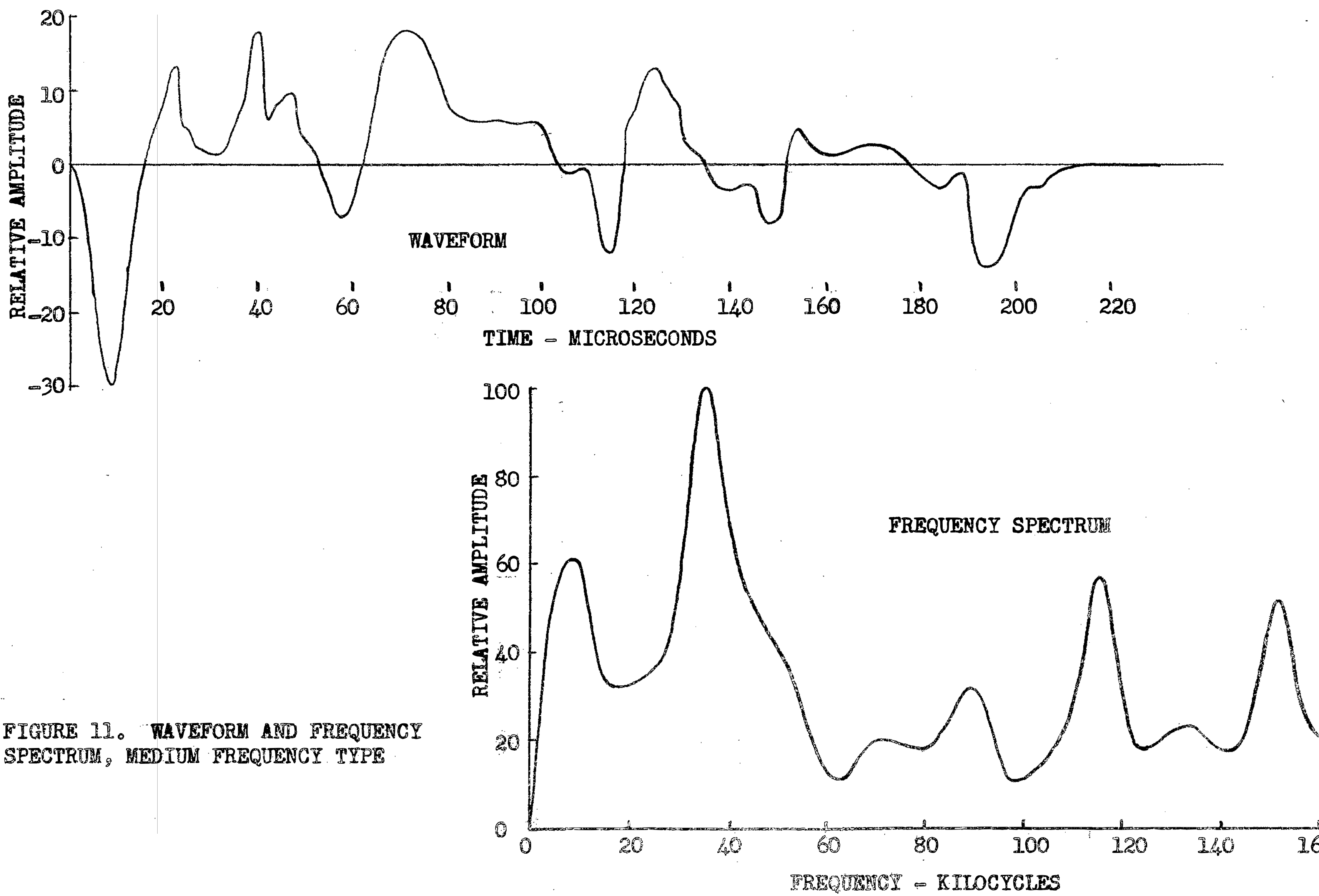


FIGURE 11. WAVEFORM AND FREQUENCY SPECTRUM, MEDIUM FREQUENCY TYPE

The waveform of Figure 10 contains the highest frequencies recorded during the study that were readable from the photographs. Higher frequencies were recorded on several occasions but the exact shape of the waveforms was not discernable. The choice of 214 kilocycles as the cut off frequency for this waveform was made because of the limitations of the tables used as discussed above. The fact that energy of appreciable amount was found at 214 kilocycles indicates the presence of still higher frequency components.

The waveform of Figure 11 is representative of a medium frequency sferic waveform. Its spectrum indicates some low frequency content centered around 10 kilocycles. Superimposed upon this low frequency component are medium frequency components (37 kilocycles) and some high frequency components (116 kilocycles and 151 kilocycles). This waveform originated in a storm front which was 50 miles west of Oklahoma City and moving toward Oklahoma City. At the time the photographic record was made, the frontal activity was building up and the maximum activity of this front occurred about two hours after the photograph was taken. Because of the appreciable amplitude of the spectrum at the cut off frequency, 160 kilocycles, it is apparent that higher frequencies are present.

In addition to these three analyses of frequency content of sferic waveforms, visual observation was made of a large number of waveforms of the type indicated in the B portion of Figure 3. These waveforms indicated the existence of a considerable amount of energy present below the 10 kilocycle point. Some of the waveforms had a predominance of 200 to 400 cycles per second for the lowest frequencies observed with a majority having predominant frequencies of about 2000 to 5000 cycles per second. These were observed as coming from low activity rain storms or thunderclouds. No high frequencies were seen riding upon these low frequency sferics.

CHAPTER SIX

SUMMARY AND CONCLUSIONS

Analysis of the data recorded for this study indicates that the duration of a sferic waveform will amost always be in the range of 100 microseconds to 5000 microseconds with 66% having a duration of 1000 microseconds or longer. The average time duration was found to be near 700 microseconds with 52% of the waveforms being as long as or longer than this in duration.

It was also found that the frequencies present in the sferic waveform varied from 200 cycles per second to over 500 kilocycles per second, depending upon the meteorological conditions at the time of generation of the sferic. Although frequency spectrums were made for three sferic waveforms observed, the computations were too laborious to justify the analysis of a large number of representative waveforms for their frequency content. Thus an over all frequency spectrum is not given.

The characteristics of the sferic waveform were observed and classified in a general way. These observations were very similar for the most part to observations of other investigators. No association of these general characteristics with meteorological conditions was made because of the lack of sufficient data. Such a study will require more equipment and closer coordination with sources of weather information over a large area.

As a result of this study, the following conclusions are drawn:

1. Observations of the general characteristics of the sferic waveform should be made over a period of time of at least 1000 microseconds from the origin of the sferic. This will insure that over 60% of all the waveforms observed will be seen to their completion.

2. The most logical method of securing an over all frequency spectrum for sferic waveforms is probably a combination of selective filtering and counting circuits. Mathematical computation of the frequency spectrum of a waveform is relatively slow even with the use of computing devices and would not be economically feasible for a large number of sferics that may be recorded at a single station during a season's operation.

3. A method must be devised to show in clear detail the high frequency waveforms which are known to occur during tornado activity. Existing equipment can show only part of this type of waveform in sufficient detail to perform mathematical analysis. If the entire waveform of the high frequency type is displayed, the waveform appears to be "hashy" and cannot be analyzed for frequency content.

4. There is a need for simultaneous display of the direction finder indication and the waveform in such a way that an observer could readily associate the waveform with the

direction. Present equipment shows the two displays simultaneously but both cannot be seen at the same time by an observer because of the physical separation of the displays. This problem is near solution by members of the research team at the Stillwater station.

It is recommended that the study of the frequency content of the sferic waveform be continued with possibly the aid of new equipment yet to be designed. It is also recommended that further study be made of the longer duration sferic waveforms in view of the meteorological conditions that cause them. It is the opinion of the writer that the time duration of the sferic waveform may provide a key by means of which the generating mechanism of the high frequency sferic can be perceived.

BIBLIOGRAPHY

Bless, A. A. Propagation and Reception of Sferics. (Summary and Bibliography). Gainesville, Florida; Engineering and Industrial Experiment Station, University of Florida, ----.

Donn, William L. Meteorology With Marine Applications. New York: McGraw-Hill Book Company, 1946.

----. "Du Mont Cathode-ray Oscillograph Type 241." Operating and Maintenance Manual. Instrument Division, Allen B. Du Mont Laboratories, Clifton, New Jersey, ----.

----. "Du Mont Cathode-ray Oscillograph Types 304 and 304-H." Operating and Maintenance Manual. Instrument Division, Allen B. Du Mont Laboratories, Clifton, New Jersey, ----.

Harrison, L. P. Lightning Discharges to Aircraft and Associated Meteorological Conditions. (Technical Note No. 1001) Washington, D. C.: National Advisory Committee for Aeronautics, 1946.

Hess, Philip N. "Installation and Operation of Electronic Sferic Detection Equipment." Unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1950.

Hill, James C. "Sferic Waveform Identification of Destructive Windstorms and Tornadoes." Unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951.

Holzberlein, Thomas M. "A Study of Tornado Tracking Equipment." Unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951.

Jones, Herbert L. and Philip N. Hess. "Identification of Tornadoes by Observations of Waveform Atmospherics." Proceedings of the I.R.E., 40 (September, 1952), 1049-1052.

Jones, Herbert L. "Research on Tornado Identification." First Quarterly Progress Report, File Number 11587-PH-52-91, Signal Corps Research, 1952.

Jones, Herbert L. "Research on Tornado Identification." Second Quarterly Progress Report, File Number 11587-PH-52-91, Signal Corps Research, 1952.

Jones, Herbert L. "Research on Tornado Identification." Third Quarterly Progress Report, File Number 11587-PH-52-91, Signal Corps Research, 1952.

Jones, Herbert L. "Research on Tornado Identification." Fourth Quarterly Progress Report, File Number 11587-PH-52-91, Signal Corps Research, 1953.

Jones, Herbert L. "Research on Tornado Identification." Fifth Quarterly Progress Report, File Number 11587-PH-52-91, Signal Corps Research, 1953.

Jones, Herbert L. A Sferic Method of Tornado Tracking and Identification. Stillwater, Oklahoma: Oklahoma Engineering Experiment Station, Oklahoma Agricultural and Mechanical College, 1952.

Kessler, William J. Direction Finding and Ranging on Atmospherics. (Quarterly Progress Report No. 1 on U.S. Army Signal Corps Engineering Laboratories Contract No. W36-039-sc-38201). Gainesville, Florida: Engineering and Industrial Experiment Station, University of Flordia, 1949.

Kessler, William J. Direction Finding and Ranging on Atmospherics. (Final Report on U.S. Army Signal Corps Laboratories Contract No. W28-003-sc-1306). Gainesville, Florida: Engineering and Industrial Experiment Station, University of Florida, 1948.

Odell, Albert C. "A Study of Tornado Research Equipment." Unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1953.

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

Wade, Vernon D. "Development and Operation of a Crossed Loop Sferic Direction Finder." Unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, 1951.

Wagner, C. F. and G. D. McCann. "Lightning Phenomena." Electrical Transmission and Distribution Reference Book. (Chapter 12). East Pittsburgh, Pennsylvania: Westinghouse Electric and Manufacturing Company, 1944.

VITA

Joe Pat Lindsey
Candidate for the degree of
Master of Science

Thesis: AN ANALYSIS OF THE SFERIC WAVEFORM

Major: Electrical Engineering

Biographical and other Items:

Born: June 7, 1926 at Wichita Falls, Texas
Undergraduate Study: Hardin Junior College, 1943-44; Oklahoma A. & M. College, 1946-49.
Graduate Study: Oklahoma A. & M. College, 1949-54.

Experience: Texas Aircraft Company, 1941; Wichita Engineering Company, 1942; Aviation Electronic Technician, U.S.Navy 1944-46; Instructor in Electronics and Radar, C.A.A. Training Center, at Will Rogers Field, 1949-53; Electronics Engineer, Phillips Petroleum Company, 1953 to present.

Date of Final Examination: May 21, 1954

THESIS TITLE: AN ANALYSIS OF THE SFERIC WAVEFORM

AUTHOR: Joe Pat Lindsey

THESIS ADVISER: Dr. Herbert L. Jones

The content and form have been checked and approved by the author and the thesis adviser. The Graduate School Office assumes no responsibility for errors either in form or content. The copies are sent to the bindery just as they are approved by the author and the faculty adviser.

TYPIST: Betsy S. Driscoll