FREQUENCY PROPAGATION CAUSED BY SEVERE ATMOSPHERIC DISTURBANCES

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PREFACE

The citizens of the Great Plains area of the United States are perenially accosted by tornadoes, the most violent form of storm on the face of the earth. As has been the case with other weather phenomena, "everybody talks about it but nobody does anything about it". In fact, until very recently, each family has had to depend on its own alertness and resourcefulness in defending against this menace. No warning service of any type was provided on a systematic basis. It was not until after World War II that man began to take advantage of the technologies available to him.

After a careful study of the meteorological conditions that existed at the time of tornadoes for a period of approximately twenty years, a theory was established by two U. S. Air Force Air Weather Service officers which represented a major contribution to existing knowledge of the meteorological conditions accompanying tornadoes. Lt. Col. E. J. Fawbush and Major R. C. Miller determined that a certain combination of meteorological conditions, which are listed later in this report, are necessary at a given location before a tornado will be formed.

Of these conditions, the one most amenable to continuous quantitative measurements is the thunderstorm. Under the capable direction of Dr. Herbert L. Jones, Professor of Electrical Engineering, a research project was initiated in 1947 at the Oklahoma A. & M. College in order to study whether it would be possible using electronic means to locate and track tornadoes. This project has been aided during phases of its development by the contributions of various agencies, including the following: The Army Signal Corps, which has furnished direct financial and equipment support, and numerous worth-while suggestions for improvement of techniques; the U. S. Air Force Air Weather Service, which has established a special mobile squadron to assist in the evaluation of the theories developed by Dr. Jones; and the U. S. Weather Bureau, which provided a capable young meteorologist to make a complete analysis of a particularly destructive tornado.

Also, some twenty-one candidates for the Master of Science degree and two candidates for the Doctor of Philosophy degree have assisted materially in the research. This thesis represents the author's contribution to this project, and is a study of the electrical conditions that are characteristic of a tornado bearing thunderstorm.

The writer is indebted to Dr. Jones for the valuable guidance and excellent sources of reference which he has furnished. Gratitude is also due to Assistant Professor R. D. Kelly, the project engineer, who has carefully explained the functioning of the various research instruments at the Tornado Lab, and to Mr. E. Alan Roemer, a graduate assistant, whose painstaking photographic work is reflected in the illustrations contained in this thesis. Also, the educational program of the U. S. Air Force Institute of Technology has enabled the writer to be assigned to duty at the Oklahoma A. & M. College in order to accomplish his graduate studies.

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CHAPTER I

INTRODUCTION

General Background

Since time immemorial, man has had a tremendous fear of thunderstorms with their accompanying lightning. To the Norsemen, this phenomenon was caused by the fierce, red-headed god Thor, who would throw his magic hammer Mjollner upon the anvil-topped clouds of heaven.[1] Most forms of civilization known have shown respect for this manifestation of the forces of nature by attributing to it the workings of their particular gods.

Those thunderstorms which bring tornadoes with them are the most feared, because of their terrible destructiveness. Although tornadoes occur in every part of the world, their most frequent and most severe form occurs in the Great Plains area of the United States.[2]

Despite Nature's continuous harassment of mankind with thunderstorms and tornadoes, until recent years there has been comparatively little serious study of a scientific nature into their nature and origin.

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[1]B. F. J. Schonland, The Flight of Thunderbolts, Oxford, 1950), p. 1.

[2]Edward M. Brooks, "Tornadoes and Related Phenomena", Compendium of Meteorology, ed. Thomas F. Malone, Baltimore: Waverly Press, 1951, pp. 674-680.

Early Investigations

The first identification of lightning as an electrical discharge was made by Wall in 1708. He observed cracklings and a flash with amber held a small distance from his finger, and stated that it seemed to be of the same nature as thunder and lightning.[3] Benjamin Franklin is credited with being the first to suggest the possibility of obtaining electricity from thunderclouds by means of pointed conductors. His famous kite experiment of 1752 was related as follows by Joseph Priestly, the great chemist, who obtained the details from Franklin:[4]

> Preparing, therefore, a large silk handkerchief and two cross-sticks of a proper length on which to extend it, he took the opportunity of the first approaching thunderstorm. . . The kite being raised, a considerable time elapsed before there was any appearance of it being electrified. . . at length, just as he was beginning to despair of his contrivance, he observed some loose threads of the hempen string to stand erect and to avoid one another, just as if they had been suspended on a common conductor. (The string ended in an insulating silk ribbon.) Struck with this promising appearance, he immediately presented his knuckle to the key (hung on the string) and, let the reader judge of the exquisite pleasure he must have felt at that moment, the discovery was complete. He perceived a very evident electric spark. . . This happened in June 1752, a month after the electricians in France had verified the same theory, but before he had heard of anything they had done.

Franklin's experiments initiated the widespread use of lightning rods and other lightning protection devices that are so common today.

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[3] J. Alan Chalmers, Atmospheric Electricity, Oxford, 1949, p. 1.

[4] B. F. J. Schonland, The Flight of Thunderbolts, Oxford, 1950, p. 21.

However, it was not until 1902 that an instrument was developed to measure the velocity of the lightning stroke.[5] Sir Charles Boys invented a camera that bears his name. The principle on which it is based is the comparison of a picture of a lightning stroke taken by a fixed lens camera with the picture from a camera whose lens is moved very rapidly in front of its film. This will cause the picture of the stroke to be offset in the case of the camera with the moving lens. Finding the distance of the flash from the camera by timing the interval between the lightning and subsequent thunder, the particular times of the movement of the stroke from point to point along the channel can be measured. Dr. B. F. J. Schonland[6] has continued the work that Boys started, and has developed several theories of the actual mechanics of lightning strokes.

The transmission of electromagnetic waves during thunderstorms is familiar to anyone who has attempted to listen to his radio receiver during such a storm. These disturbances have been given various names, such as "static", "strays", "X's", "atmospherics", and as has been popularized in recent times in the United States, "sferics." The term "sferics" will be used to denote these electromagnetic radiations throughout this paper.

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[5]B. F. J. Schonland, <u>The Flight of Thunderbolts</u>, Oxford, 1950, pp. 63-70.

[6]Ibid, pp. 81-148.

The Russian scientist Popoff is credited by Norinder with being the first to furnish proof that lightning strokes are the source of sferics.[7] Using a circuit containing an electric bell trembler and a coherer [a metallic powder in a glass tube, which had comparatively high resistance under normal conditions, but decreased in resistance when subjected to an electrical impulse], he showed that lightning causes an electrical impulse that can be fed through an antenna to the coherer circuit and activate the bell trembler. The bell, powered by an external battery source, causes a vibration which has the property of restoring the high resistivity of the coherer, thus restoring the circuit to a receptive state.

Austin's Work

In 1921, L. W. Austin, under sponsorship of the U. S. Navy, in attempting to find a means of improving radio communications with Europe, decided that the logical way to study radio disturbances was to determine the direction from which these disturbances emanated.[8] Austin used a directional loop antenna with a null detection system, and was able to measure definite signal levels from various

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[7]Harald Norinder, "Long-Distance Location of Thunderstorms", Thunderstorm Electricity, ed. Horace R. Byers, Chicago: The University of Chicago Press, 1953, pp. 277-280.

[8]L. W. Austin, "Determination of the Direction of Atmospheric Disturbances or Static in Radio Telegraphy", Jour. Franklin Inst., V, No. 191 (1921), pp. 610-20.

azimuths. Although he did not recognize the source of the sferics as being lightning discharges, it is interesting to note that he stated:

"At present it is impossible to formulate any completely satisfactory theory of the origin of static, but it appears probable that it originates in the upper atmosphere in powerful discharges between air bodies at different potentials, though it is difficult to understand how such discharges which give rise to electrical waves more powerful than those from the largest radio station, can take place without luminous phenomena. . . The results of the observations thus far made, fragmentary as they are, indicate plainly the importance of taking static directional observations wherever radio stations are situated, and warrant plans for a general static survey which shall extend eventually to all parts of the world."

A study such as recommended by Austin has recently been completed by the National Bureau of Standards, and a report of the results is now available.[9]

Based on Austin's experiments, various improvements in direction finder techniques were developed during the 1920's and 1930's, and the use of recording devices and cathode ray tubes was introduced.

Thus, during the period prior to World War II, a considerable amount of fundamental research was undertaken concerning the relationship of lightning strokes to sferics. As will be discussed in succeeding chapters, most of the practical application of this fundamental knowledge has been accomplished since the second World War.

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[9] W. Q. Crichlow et al., Worldwide Radio Noise Levels Expected in the Frequency Band 10 Kilocycles to 100 Megacycles, National Bureau of Standards Circular 557, 25 August 1955.

The Fawbush Hypothesis

The study of the meteorological aspects of thunderstorm development has lagged far behind the electrical aspects. The military requirements of World War II spurred an interest in the development of the science of meteorology. The study of tornadoes as functions of the atmosphere has inspired a large number of theories. An excellent abstract of the more important meteorological ones as well as a comprehensive review of current theories on the electrification process involved in a thunderstorm, is contained in Lt. Col. E. A. Wright's unpublished Master of Science report, A Survey of Thunderstorm Electricity and Its Application to Tornado Detection, August 1956. The meteorological theory that is generally becoming the most accepted one was propounded in its present form by Lt. Col. E. J. Fawbush and Major R. C. Miller of the USAF Air Weather Service, and lists the following conditions necessary for the formation of a tornado:[10]

1. A layer of moist air near the earth's surface must be surmounted by a deep layer of dry air.

2. The horizontal moisture distribution within the moist layer must exhibit a distinct maximum along a relatively narrow band [i.e., a moisture wedge or ridge].

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[10] E. J. Fawbush, R. C. Miller, and L. G. Starrett, "An Empirical Method of Forecasting Tornado Development", Bulletin of the American Meteorological Society, II, 1, pp. 1-9, quoted in E. A. Wright, A Survey of Thunderstorm Electricity and Its Application to Tornado Detection, Unpublished Master of Science Report, Oklahoma A. & M., 1956.

3. The horizontal distribution of winds aloft must exhibit a maximum of speed along a relatively narrow band at some level between 10,000 and 20,000 feet, with the maximum exceeding 35 knots.

4. The vertical projection of the axis of wind maximum must intersect the axis of the moisture ridge.

5. The temperature distribution of the air column as a whole must be such as to indicate conditional instability.

6. The moist layer must be subjected to appreciable lifting.

7. There must be a thunderstorm in existence to trigger the tornadic process.

In accordance with the theory of Fawbush and Miller, it is necessary that all seven conditions occur simultaneously within an area in order that the formation of a tornado may be initiated. Of these factors, the thunderstorm lends itself best to positive identification and detailed study. Current studies of thunderstorms as a means of identifying tornadoes are discussed in Chapter II. Chapter III contains a description of the research tools utilized by the Oklahoma Agricultural and Mechanical College Tornado Laboratory, and its study of the characteristics of electromagnetic radiation originating in the type of thunderstorm formation that culminates in a tornado. The procurement and specific analysis of selected data taken during thunderstorms at the Tornado Laboratory are the substance of Chapter IV, while the conclusions reached and recommendations for further study are contained in Chapter V.

CHAPTER II

CONTEMPORARY THUNDERSTORM DETECTION RESEARCH

The research listed in the first chapter is not intended to be a comprehensive listing of all studies made concerning the phenomenon of lightning and the formation of thunderstorms; rather, it is intended to serve as an indication of some of the earlier discoveries by eminent scientists which had a direct bearing on the types of thunderstorm detection methods currently used. This chapter provides a description of several notable thunderstorm studies which have been initiated since World War II.

Thunderstorm Studies at the University of New Mexico

From April to November 1945, an investigation was effected by the Department of Physics of the University of New Mexico at the request and sponsorship of the National Defense Research Committee.[1] Visual and electrical measurements of thunderstorms were made from two stations in the vicinity of Albuquerque, New Mexico, and

[1]Robert E. Holzer, "Simultaneous Measurement of Sferics Signals and Thunderstorm Activity", Thunderstorm Electricity, ed. Horace R. Byers, Chicago: The University of Chicago Press, 1953, pp. 267-275.

a mobile sferics station was built and manned by Army Signal Corps personnel, which contained direction finding and wave form equipment. The direction finders used loop antennas, and the wave form equipment included a vertical antenna, an amplifier with constant gain between 200 cycles and 250 kilocycles, fed into an oscilloscope, with the sferics signal triggering the sweep circuit of the oscilloscope. In their study of wave form patterns, they found that there were in general three basically different types:

(1) Wave forms having prominent, easily distinguished features, recognizable as being similar to sinusoidal exponentially decaying electrical transients.

(2) Wave forms with interference patterns suggesting overlapping or intermodulated pulses.

(3) Very complicated wave forms, with no discernible systematic pattern.

Because of the limited duration and scope of the tests made, no definite conclusions could be made based solely on the measurements obtained. However, the researchers noted that the results strongly indicated the possibility of close correlation of the power generated by a storm and both the frequency and multiplicity of lightning discharges as measured by sferics techniques. This relationship will be discussed in greater detail in Chapters III and IV.

Joint Thunderstorm Project Headed by Dr. Byers

A joint research project conducted by the Air Force, Navy, Weather Bureau, and the National Advisory Committee for Aeronautics in 1946 and 1947 dissolved a great deal of confusion regarding the nature of the physical structure of the thunderstorm.[2] The project was initiated in Florida in the summer of 1946 and concluded in Ohio in the summer of 1957. It was found that the life cycle of a typical thunderstorm cell is divided into three parts: (a) cumulus stage - characterized by updraft throughout the cell, (b) mature stage - characterized by the presence of both updrafts and downdrafts, at least in the lower half of the cell, and (c) dissipating stage - characterized by weak downdrafts prevailing throughout the cell.[3] The Thunderstorm Project report lists one-half hour as the average life of a thunderstorm. While this is true of the thunderstorms they studied, the type of thunderstorm which frequents the Great Plains states often lasts twelve hours or longer, receiving sustaining energy from moist air pulled up from the Gulf of Mexico.

The Thunderstorm Project study of electrical fields produced in thunderstorms was not as thorough as their research on meteorological dynamics. However, the work

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[2]H. R. Byers and R. R. Braham, Jr., "Thunderstorm Structure and Circulation", The Thunderstorm - Report of the Thunderstorm Project, Air Force, Navy, National Advisory Committee for Aeronautics and Weather Bureau, U. S. Department of Commerce Weather Bureau unnumbered publication, Washington, D. C., U. S. Government Printing Office, 1949, pp. 17-38.

[3]Horace R. Byers and Roscoe R. Braham, Jr., "Thunderstorm Structure and Dynamics", Thunderstorm Electricity, ed. Horace R. Byers, Chicago: The University of Chicago Press, 1953, pp. 46-65.

they did was significant in that it correlates well with experimental conclusions reached by Dr. Jones at Oklahoma A. & M. These general tendencies were observed:[4]

1. The cloud tops (radar precipitation echo tops) reached a height where the environmental temperature was not less than -20° C before the first lightning occurred.

2. The maximum lightning frequency occurs at the same time as the cell reaches its maximum height.

3. As the height of the cell top decreases, the frequency of lightning also decreases.

4. It appears that a greater cell height (or lower temperature of the cloud top) is necessary to initiate lightning than is required to maintain it, once it has started.

5. The maximum frequency of lightning precedes the time of the maximum 5 minute rainfall.

Based on this and the theories of Fawbush and Miller [See Chapter I], it would seem that a tornado would most likely develop during the early part of the mature stage of the thunderstorm. Studies of tornadoes show that most

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[4] "Electric Fields Inside the Thunderstorm", The Thunderstorm - Report of the Thunderstorm Project, Air Force, Navy, National Advisory Committee for Aeronautics and Weather Bureau. U. S. Department of Commerce Weather Bureau unnumbered publication, Washington, D. C., U. S. Government Printing Office, 1949, p. 89.

tornadoes do occur just ahead of the rain, and frequently after a light hail.[5]

Tornado Detection by the A. & M. College of Texas

In 1953, tornadoes were particularly destructive, both in loss of life and property. Storms were encountered in Urbana, Illinois; Worcester, Massachusetts; and Waco, Bryan, Crockett, and Victoria, Texas. These storms, plus a knowledge of progress made in the field of tornado identification by various other agencies in the United States, were determining factors in the formation of the "Texas Radar Tornado Network".[6] This network has been described in true Texas fashion as "one of the most dynamic enterprises in the history of meteorology in this country".[7]

The Texas A. & M. tornado study was initiated early in 1955, and was accomplished primarily by the Radar Meteorology Section of the college. The study consisted mainly of an analysis of radar photographs of severe storms, and did not have as an immediate operational mission the operation

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[5]E. A. Wright, A Survey of Thunderstorm Electricity and Its Application to Tornado Detection, Unpublished Master of Science Report, Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma, 1956, pp. 9-11.

[6]E. Adolfe, "Tornado Coming", Town Journal, April 1956, pp. 14-15.

[7]Myron G. H. Ligda et al., The Use of Radar in Severe Storm Detection, Hydrology, and Climatology, Final Report, The A. & M. College of Texas Department of Oceanography and Meteorology Project No. 132, October 1956, pp. 1.

of a tornado warning net, such as established by the USAF Air Weather Service in conjunction with the Oklahoma A. & M. Tornado Lab. [See later portions of this chapter and Chapter III].

An anonymous Air Weather Service bulletin in 1945 contained a description of a tornado near Maxwell AFB, Alabama, and stated that the precipitation echo presentation on a 10 centimeter wavelength radar was shaped like a figure "6".[8] This article did not attract much attention at the time. It was not until more than a dozen observations of tornadic activity, each describing a characteristic "6" shape with a hole in the body of the "6", had been recorded that meteorologists began to take a serious interest in its possibilities as a tornado indicator.

The Texas A. & M. project was afforded the use of radar facilities of ten Aircraft Control and Warning Squadrons of the 33rd Air Division of the USAF Air Defense Command. However, since this assistance was not directly related to their primary defense mission, no effort was made to have an optimum radar adjustment for the receipt of storm information. Radarscope photographs were taken by the Air Defense Command radar units based upon severe weather warnings issued by the USAF Air Weather Service Severe Weather Warning Center. As a result of the analysis

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[8]"Radar for Storm Research", Air Weather Service Bulletin, 3:7, July - Aug. 1945, pp. 17-19.

of data taken during the 1955 and 1956 seasons, the following are some of the pattern traits of the precipitation echo pattern that were observed:[9]

1. The hook is in the trailing half of the echo, with respect to its motion, and in most cases develops cyclonically.

2. The hook often occupies a larger sector of the radar screen than the accompanying tornado.

3. The hooked echoes observed were nearly always in isolated storms.

4. Most hooked echoes observed were within 40 miles or the particular radar station concerned.

These pattern characteristics significantly lead to certain conclusions regarding the limitations of using radar observations as the sole means of tornado detection. The following limitations as listed in the Texas A. & M. report, apply particularly to the operational methods used in their study, but their application to the more general case may easily be seen.[10]

1. The horizontal radar beam width may have been too great to resolve fine features.

2. The tornado may have occurred on the side of the storm opposite to the radar, and precipitation attenuation prevented detection.

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[9]Ligda et al., p. 2.

[10]Ibid., pp. 10-11.

3. The tornado may have occurred in the middle of a rain area, and no distinctive features were observed.

4. The tornado formed at some distance from heavy precipitation, and no detectable hydrometeors were drawn toward and around the vortex.

5. Gain settings were used which were too high.

6. The storms were observed on too small a scale to permit resolution of fine detail -- in other words, too long a range setting was employed.

It should be noted that the second, third, and fourth factor listed above might still be causes for errors in tornado determination, even with radar specifically adapted for weather observations. Another consideration that should be noted is that a number of cloud formations cause "pseudo-hooked echoes", which might possibly be a source or error even for trained operators.

It is likely that with improved equipment and operating techniques, it may be possible through the use of radar observations alone, to identify and issue warnings for a certain number of tornadoes that occur. A study of the meteorological conditions that accompany tornadoes, as is being made at Texas A. & M., will undoubtedly increase the probability of accurately forecasting severe storms. However, it is the opinion of the author that it will be necessary to combine radar observation techniques with some other means of definitely identifying the sources of tornadoes, in order to have a forecasting certainty commensurate with the risk to the populace and property that is involved. A further discussion of this is contained in Chapter IV.

Tornado Forecasting by the United States Air Force Air Weather Service

Following a tornado in 1948 which caused extensive aircraft damage at Tinker Air Force Base, Oklahoma, a study of the meteorological conditions relating to tornadoes was initiated by Lt. Col. Fawbush, Major Miller, and a small staff.[11] After intensive research for two years, the conditions necessary for the formation of a tornado were announced [See Chapter I]. Although this work represented an important stride in the progress of the science of meteorology, an adequate system of predicting the exact location of tornadoes and issuing timely warning had not been developed.

By 1954, the work of Dr. Jones and his staff at the Oklahoma A. & M. College Tornado Laboratory had gained considerable prominence. The United States Air Force Air Weather Service established a project "Tornado-Sferics", with the following objectives:[12]

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[11] E. A. Wright, A Survey of Thunderstorm Electricity and Its Application to Tornado Detection, Unpublished Master of Science Report, Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma, 1956, p. iii.

[12] Ernest J. Fawbush, "Final Report Phase 1954 Unclassified Project Tornado-Sferics," 6th Weather Squadron, Tinker Air Force Base, Oklahoma City, Oklahoma, 15 November 1954, p. 2.

1. To identify, locate, track, and determine the intensity of severe storms throughout the midwest United States.

2. To provide data for an evaluation of the technique of tornado identification developed by Dr. Jones of Oklahoma A. & M. on a basis of a four station network.

3. To ascertain the overall usefulness of these observational data in conjunction with the severe weather warnings issued by the Severe Weather Warning Center in support of Air Research and Development Command's overall program in Tornado Research.

In accordance with this mission, sites were established at McConnell AFB, Kansas; Camp Chaffee, Arkansas; and Altus AFB, Oklahoma; while the "Net Control Station", or central control and operating point, was Oklahoma A. & M.'s Tornado Laboratory. Each of the first three sites mentioned was equipped with an AN/GRD-1A, a low frequency [10 kilocycle] direction finder. The purpose of having three stations was to obtain "fixes" from all three sites, thus providing better accuracy than could be obtained from one or two stations alone. The method of operation was to take a fifteen second exposure of the direction finder presentation on a cathode ray tube, develop the film, and relay the results into the net control station, where a triangulation would be made, and a "fix" established. The results of this method were determined to be unsatisfactory with respect to both accuracy and timeliness. By revising the sampling process, somewhat better results were obtained. The greatest operational trouble encountered was the difficulty of interpreting elliptical presentations of the low frequency direction finder, caused by strong signals from nearby sferics.

This experimental work was continued during the 1955 and 1956 tornado seasons, and a careful analysis was published at the end of each season.[13, 14] The station locations were changed to Barksdale AFB, Louisiana; Amarillo AFB, Texas; and Grandview AFB, Mississippi; while the net control station was placed at the Severe Weather Warning Center [SWWC] in Kansas City, Missouri. Special sferics telemetering equipment was developed, which automatically relayed the direction finder data from the three stations to the SWWC and plotted the triangulated fix as a spot of light on a twelve inch cathode ray tube under a map overlay. Also, a remote scope from an AN/CPS-9 radar was provided in the SWWC so that precipitation and cloud patterns could be observed simultaneously with the

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[13] Robert C. Miller, "Final Report Phase 1955 Project Tornado-Sferics", 6th Weather Squadron, Tinker Air Force Base, Oklahoma City, Oklahoma, November 1955.

[14] Robert C. Miller, "Final Report Phase 1956 Project Tornado-Sferics", 6th Weather Squadron, Tinker Air Force Base, Oklahoma City, Oklahoma, 31 October 1956.

direction finder fixes. Thus during the 1956 season, data was made available for tornado forecasting and warning by three different methods:

(a) Number of sferic pips for ten-degree sectors. This was the original method used during the 1954 and 1955 seasons and did not attain a particularly satisfactory accuracy.

(b) Bursts of sferics pips. A burst is defined as a series of five or more pips, no two of which are separated by more than one-tenth second on the film, and all azimuths of pips falling within three degrees of the most common of the series. It was found that where tornadic activity was reported, there were frequently long bursts of pips. However, the results from the 10 kc direction finder were quite erratic; wide variations in sferic readings were encountered from tornadic activities of equal intensities. For this reason, high counts were read on only 25% of the tornadic situations in 1956. The 6th Weather Squadron has recommended the procurement of equipment for their project which would have a more satisfactory operating frequency. The telemetering system, which has been installed, represents, in theory, a great improvement over the film developing method; however, due to electronic difficulties, this system could be considered only experimental during the 1956 season.

(c) Sferics-radar method. The Oklahoma A. & M. Tornado Lab stroke counter or "Tornado Meter" measured the average number of pips per second for each degree of azimuth. /‾A more detailed discussion of work at the Tornado Lab is contained in succeeding chapters._7 Since no film processing was involved, the results were made immediately available to the Severe Weather Warning Center. Also, the Tornado Lab direction finder was operating on a frequency of 150 kilocycles, which proved much more reliable. A radar presentation showing cloud formation was also available at the Tornado Lab, so it was possible to correlate the maximum sferic activity azimuths with a particular cloud formation, and thus provide a rapid fix on possible areas of tornadic activity. /‾Fifteen pips per second is considered the treshold of tornadic activity._7 This method was evaluated by the 6th Weather Squadron as being 75% effective where the pips per second reach 15, and 90% effective when 20 or more pips per second are measured.[13]

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[13]Robert C. Miller, "Final Report Phase 1956 Project Tornado-Sferics", 6th Weather Squadron, Tinker Air Force Base, Oklahoma City, Oklahoma, 31 October 1956, p. 2.

CHAPTER III

THE OKLAHOMA A. & M. TORNADO LABORATORY

Initiation of Research

In 1946, a tornado struck Woodward, Oklahoma, killing 123 persons.[1] The particularly ironic factor of this disaster was that this tornado had travelled about 125 miles during its existence of almost two hours, and yet the city of Woodward had not been warned. This was the impetus for the initiation of research at Oklahoma A. & M. into the phenomenon of tornadoes.

Since Dr. Herbert L. Jones had formerly been on the staff of the University of New Mexico, and was familiar with work at that university [See Chapter II] and with the investigations of Workman and Reynolds concerning thunderstorm electricity, it was only logical that he should be selected as project director for tornado research at Oklahoma A. & M.[2, 3] This early work was hampered by

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[1] E. A. Wright, A Survey of Thunderstorm Electricity and Its Application to Tornado Detection, Unpublished Master of Science Report, Oklahoma Agricultural & Mechanical College, Stillwater, Oklahoma, 1956, pp. 27-28.

[2] E. J. Workman and S. E. Reynolds, "Structure and Electrification", Thunderstorm Electricity, ed. Horace R. Byers, Chicago: The University of Chicago Press, 1953, pp. 139-149.

[3] S. E. Reynolds, "Thunderstorm Electricity", Final Report, U. S. Army Signal Corps Project 172B, 7 August 1955, New Mexico Institute of Mining and Technology.

lack of funds and the necessary research equipment. In 1951, when the University of Florida terminated its contract with the U. S. Army Signal Corps, Dr. Jones flew to the Signal Corps laboratory at Fort Monmouth, New Jersey and negotiated a contract for tornado research at Oklahoma A. & M. College.

Each year since the initiation of the Signal Corps contract, there has been a substantial improvement in the equipment and the techniques used by the Oklahoma A. & M. Tornado Laboratory. In order to furnish background substance to the data analysis presented in Chapter IV, the following is a description of the Tornado Laboratory equipment and its utilization during the 1956 tornado season.[4]

Equipment - General

The major equipment to be described consists of an AN/APQ-13 radar set, 3 centimeter wave length, on loan from the Signal Corps; an AN/GRD-1A 10 kilocycle low frequency direction finder, also on loan from the Army Signal Corps; a 150 kilocycle high frequency direction finder, designed and built by personnel working on the Tornado Project; a sferic stroke counter, designed and constructed by Mr. R. D. Kelly, the Project Engineer;

[4]Jones, Herbert L. "Research on Tornado Identification, Fifth Quarterly Progress Report, Signal Corps Project No. 172B, 1956, pp. 5-17.

a video amplifier, to receive and amplify sferic waveforms from a vertical whip antenna; and a composite picture unit, which provides a means of obtaining a film record of information obtained from the other equipment. The general arrangement of equipment is shown in Figure 1, which was extracted in its entirety from Dr. Jones' Fifth Quarterly Progress Report.[1]

Low Frequency Direction Finder

The AN/GRD-1A as used for sferic direction finding consists of two single turn coaxial loop antennas oriented in the north-south and east-west directions, respectively. The antenna output is fed into two identical tuned radio frequency receivers. The receiver outputs are fed to the vertical and horizontal deflection plates, respectively, of a 5CP11 cathode ray tube (CRT). The 180 degree ambiguity normally resulting from crossed loop direction finders is eliminated to a large degree with both low and high frequency direction finders by use of a vertical whip antenna, which feeds a sense receiver, with the output controlling the electron gun or control grid of the CRT. "A wave front arriving from one direction induces a voltage of one polarity in the antenna, and a wave front arriving from the opposite direction induces a voltage of opposite

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[5]Herbert L. Jones, Research on Tornado Identification, Fifth Quarterly Progress Report, Signal Corps Project No. 172B, 1956, p. 7.

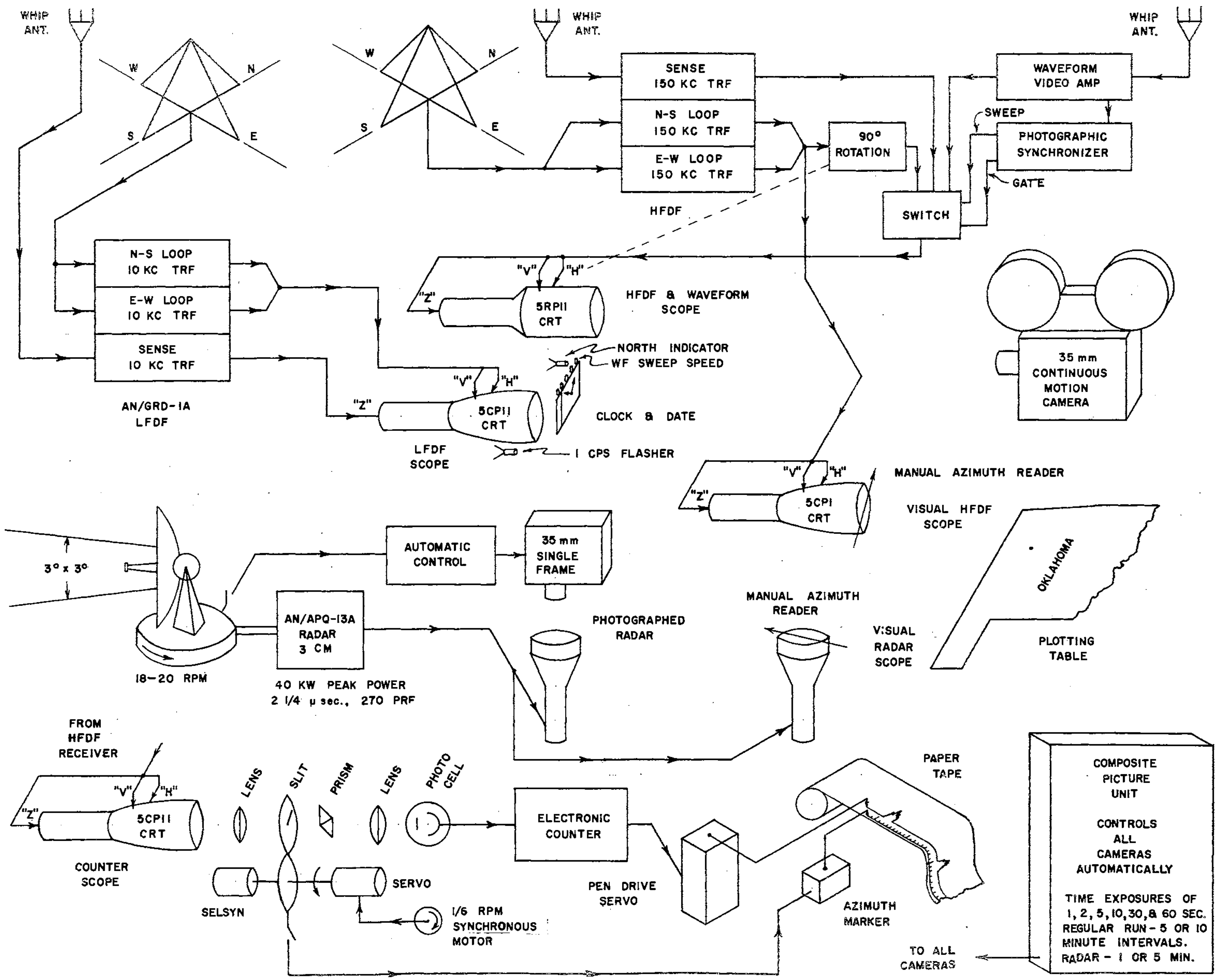

Figure 1. Schematic Diagram of Tornado Lab Equipment

polarity. If the intensity of the cathode ray tube is adjusted so that it is very faint at zero signal from the sensing amplifier, the positive peaks of voltage will intensify the trace and the negative peaks will 'blank' the trace. The oscilloscope trace will thus be intensified in the direction from which the wave front came..."[6]

The presentation of the low frequency direction finder on the cathode ray tube is a line of light extending outward from the center of the CRT. The azimuth of this line of light, with respect to the left side of the tube corresponding to north, indicates the direction from which the sferic electromagnetic wave has emanated.

High Frequency Direction Finder

From an antenna similar to that used for the low frequency direction finder, the signal is fed to the 150 kilocycle tuned radio frequency receivers, and then into a 5RP11 cathode ray tube. There is a switching device associated with this circuit, since this tube is also used for wave form presentations. During phases of the photographic runs, the film is fed at a constant velocity past a shutterless lens. When the principal sferic activity, as presented by the CRT, is aligned with the direction of film travel, interpretations of the photographic record are very difficult to make. For this reason, provision

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[6]Norinder, Harald "Long-Distance Location of Thunderstorms", Thunderstorm Electricity, Edited by Horace R. Byers, Chicago: The University of Chicago Press, 1953, pp. 17-18.

is made for a 90 degree rotation of the output from the two amplifiers, in order that the maximum sferic activity will be more nearly transverse to the direction of film travel. This in effect rotates the north direction of the tube face an angle of 90 degrees.

Wave Form Recorder

As mentioned above, the 5RP11 is also used for wave form presentations. A vertical whip antenna feeds the sferic signal into the waveform video amplifier, and the signal is then fed to the vertical deflection plates of the 5RP11 CRT, and also to the photographic synchronizer. The photographic synchronizer, by means of amplitude discrimination, selects certain of the higher amplitude sferic waveforms and presents them on the 5RP11 CRT along a pre-selected time base. The time bases for the data in Chapter IV are 200, 500, and 1000 micro-seconds.

Stroke Counter

The high frequency direction finder signal is fed to a 5CP 11 cathode ray tube, and the light output of this tube is fed through a slit and a lens system to the face of a photoelectric cell. The voltage generated in the photo tube goes to a counter circuit which operates a pen recorder by means of a servo system. The slit mentioned above consists of two Gillette Thin razor blades, separated about the thickness of a razor blade.[7] The slit is placed radially about 3/16th of an inch from the face of the cathode ray tube, and thus has an effective slit width of 5 to 8 degrees of azimuth of the high frequency direction finder presentation. The slit is rotated radially one degree per second; so it scans the full 360 degrees each 6 minutes. Thus, light impulses on the cathode ray tube from a particular azimuth cause a voltage to be produced in the counter circuit which is proportional to the repetition rate of the sferics. This voltage drives a servo-motor which actuates a pen, recording the fluctuations of voltage on a continuously moving paper tape. An electrical switch actuates another pen, which marks each ten degrees in azimuth, with slightly longer marks each 90 degrees, and an additional short marker at 4 degrees azimuth for orientation.

Radar

The radar on loan from the U. S. Army Signal Corps is an AN/APQ-13A, modified for weather observations. It has a peak power of 40 KW, wavelength 3 centimeters, pulse duration of 2 1/4 seconds, pulse reoccurrence frequency of 270, antenna speed of 18 to 20 RPM, and 3 degree beam width. A PPI scope is remoted into the operations

[7]Herbert L. Jones, Research on Tornado Identification, Seventh Quarterly Progress Report, Signal Corps Project No. 172B, 1956, pp. 5-7.

building for convenience. Provision is made for obtaining a photographic record of radar displays.

Composite Picture Unit

This unit consists of a 35 millimeter continuous motion picture camera, and an associated relay control panel. Evaluation of film records of previous years showed the desirability of having time exposures of lengths 1, 2, 5, 10, 30 and 60 seconds duration.[8] In addition to these time exposures or "composites", the film can be run at constant velocity past the shutterless lens. The relay control panel circuitry is designed to divide a predetermined interval into a sequence of eight different modes. The first mode is with the film moving at constant velocity for a predetermined period, making a simultaneous record of both the high and low frequency cathode ray tube presentations. Then comes a period with the film still moving, but with a presentation of the low frequency direction finder signals and the high frequency wave forms. Next is a one second composite showing both the low and high frequency presentations. With the necessary switching operations, this sequence consumes ten seconds. The two-second time exposure also takes ten seconds while the fourth through the eighth modes require five seconds for each switching operation plus the time consumed in making

[8]Herbert L. Jones, Research on Tornado Identification, Fifth Quarterly Progress Report, Signal Corps Project No. 172B, 1956, pp. 13-15.

the time exposures. When the control unit has been synchronized with Station WWV, the above sequence of records can be made automatically for the desired time interval. During the periods when the film is moving, there is an electronic flasher which illuminates the clock face once each second.

CHAPTER IV

PREPARATION AND ANALYSIS OF DATA

Operating Procedures at the Tornado Lab

The Severe Weather Warning Center of the USAF Air Weather Service in Kansas City has at its disposal meteorological data from the world-wide Air Weather Service meteorological observation stations, as well as information from the U. S. Weather Bureau. During the season when tornadoes are most likely to occur, there is a telephone line between the SWWC and the Tornado Lab. It is a standard procedure for the SWWC to furnish advisories in advance of possible severe weather situations, thus allowing operators an adequate amount of time to put the system into operation. The operators align the direction finding equipment and synchronize all clocks and synchronously driven units with the time signals broadcast from the Bureau of Standards station WWV. Date cards are placed in the recording units, and camera equipment is checked for proper operation. During actual operation, an operator is facing the remoted scope from the radar, which is provided with a cursor calibrated in degrees so that the azimuth to any precipitation echo can be read directly. A visual high frequency direction finder scope adjacent the remoted radar scope provides a means for an operator to visually note the angles of greatest sferic activity. The cursor on the face of the radar scope is placed at these angles of maximum sferic activity, and the intersection of the cursor hairline with a precipitation echo on the radar scope indicates a possible source of sferic propagation. The maximum range of the high frequency direction finder is approximately 250 miles, while the range or the radar is 120 nautical miles; thus the closer sferics sources should appear on the radar scope. An aeronautical map of Oklahoma on a plotting table protected with a plastic covering enables the operator to keep track of squall lines within the range of his equipment by marking them with a grease pencil. The stroke counter is at a separate operator's position, and should be frequently monitored, in order to have specific quantitative information of the pips per second [pps] from active azimuths. It is believed that the variation of this stroke count, under appropriate meteorological conditions outlined in Chapter I, is an indication of the formation of a tornadic condition. During periods of low sferic activity, one operator can monitor all the equipment; however, three operators can be used to good advantage during intense storms.

Collection of Data

The data discussed in the remainder of this chapter was taken during operational conditions at the Tornado Lab during the 1956 season. The specific times chosen for study were selected for two reasons. First, these times correspond to "fixes" obtained by the three Air Weather Service direction finder stations as furnished by Capt. Dickson of the SWWC, and have been related to officially observed tornadoes. Second, the times were chosen to represent typical patterns during various tornadic situations.

It is felt that an observation at this point would be in order. Tornado reporting is far from being a science. It is necessary that reliable witnesses be obtained before a tornado is declared "official". Because of poor visibility conditions during thunderstorms, their frequency of occurrence during the early hours of the morning and in sparsely settled regions, it is likely that a large number of tornadoes are unreported during at least a portion of their path. This may represent a possible source of "error" as reported by the AWS report. [See Chapter II.] Personnel of the Tornado Lab have walked along the length of a few tornado paths, possibly representing the most careful study of the capricious nature of these paths that has been made to date.

<u>The Storm of 21 March 1956</u>

At 1400 CST on the 21st of March 1956, the AWS [Air Weather Service] direction finder net made a "fix" on a point 20 miles southeast of Victoria, Texas, at azimuths of 177° and 184°. The Oklahoma A. & M. stroke counter recorded the following readings at that time:

Pips/second	Azimuth	Time
2	118°	1355:58
2	145°	1356:25
2	168°	1356:48

A ten second composite photograph of the high frequency direction finder at 1400 CST shows some activity, primarily at an azimuth of about 160°. A photograph of wave form recordings at 1400:09 CST is shown in Figure 2. Unfortunately the low frequency direction finder was not functioning on this date, so a comparison of this instrument's readings cannot be made. The above readings remained fairly constant over a period of the next hour and a half.

A destructive tornado was officially reported near Moody and Marlin, Texas, at 1500 CST, and a tornado cloud touched the ground near Alice, Texas at 1555. However, from the above data, it is highly questionable whether the Tornado Lab readings were on the tornadic storm or not. First, the azimuths involved usually correspond much more closely as will be shown in succeeding pages. Second, the stroke count was too low for a tornadic storm. Third, the wave form is not of the type usually associated with a high intensity storm, as will be discussed later.

Referring the wave form in Figure 2, it will be noted that it is of the exponentially decaying sinusoidal type. Since the wave form recording circuit employs the actual

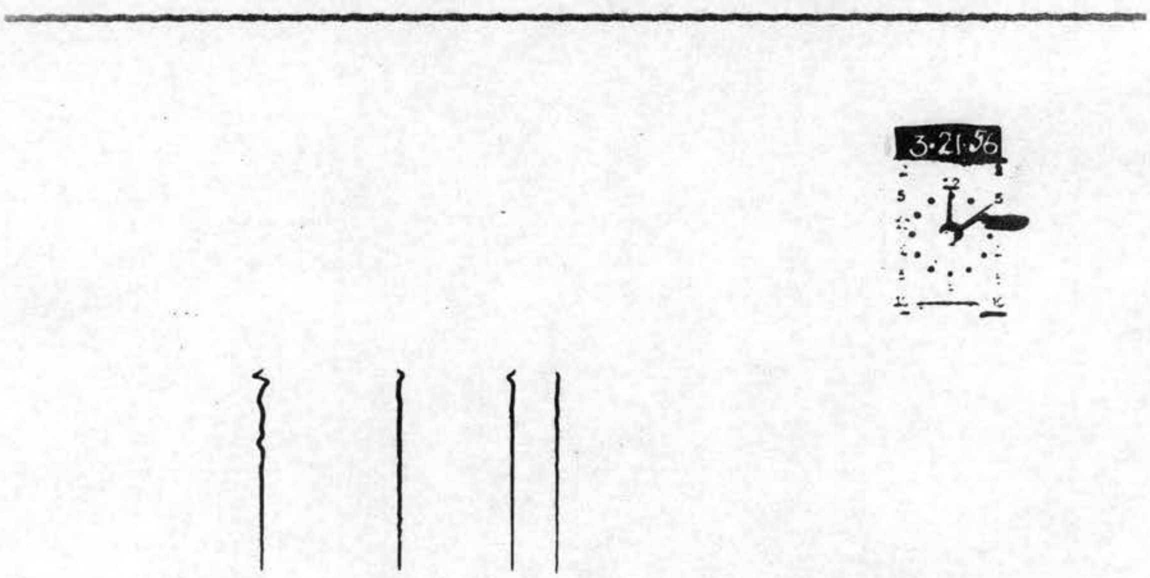

Figure 2. Film Record of Sferic Waveforms, 1359:09 CST, 21 March 1956

wave form pulse to trigger the sweep circuit, the initial portion of the wave form does not appear in the photograph. The numbers to the left and right of the clock face in vertical lines indicate the time base of the sweep circuit, ranging from 200 micro-seconds corresponding to the top numeral "2" to 1000 micro-seconds for the "10". In Figure 2, the 1000 micro-second time base was used. A simple relationship is used to calculate the approximate frequency content of this type of wave. A complete cyclic variation occupying the entire time base would have a frequency of 1/1000th of a microsecond, or 1000 cycles per second. The frequency of the wave form can then be computed since its wavelength is linearly proportional to the length of the time base. The wave forms pictured have a frequency content in the range of 7,000 to 14,000 cycles per second.

The above discussion tends to emphasize the range limitations of the high frequency equipment. The distance to Victoria, Texas, is approximately 500 miles, while the maximum effective range of the high frequency equipment is estimated at about 250 miles. However, the compensating advantage of high frequency equipment is that one can be fairly sure that radiations from a particular storm cloud emanate from a precipitation echo within the range of the radar scope. In order to effectively track severe storms throughout their course in the United States, it would be necessary to have a series of tornado detection stations, with a comprehensive communications network.

The Storm of 27 March 1956

Two funnel clouds were reported near Savetha, Kansas, during the afternoon of this date; and a tornado caused damage at Talihina, Oklahoma, at 1930. An AWS fix at 1630, at an azimuth of 125° from the Tornado Lab, is verified by the high frequency direction finder presentation shown in Figure 3. In this case, the output from the direction finder amplifiers had been rotated 90°, so that north is toward the right of the photograph. The stroke counter readings were:

Pips/second	Azimuth	Time
7	115°	1631:55
8	122°	1632:02

It is interesting to note that the number of strokes, as counted directly from the photograph, is above 30. The reason for this discrepancy is that the stroke counter rejects pips below a certain length, as determined by the particular gain setting on the cathode ray tube circuit. Thus the calibration of the stroke counter record is a function of this gain setting. Static calibration tests during the 1956 season showed that two basic calibrations were necessary: one for dial settings of .5 and over; and another for under .5. It is understood that dynamic calibration tests are planned during the 1957 season in order to have test conditions more nearly like actual operations.

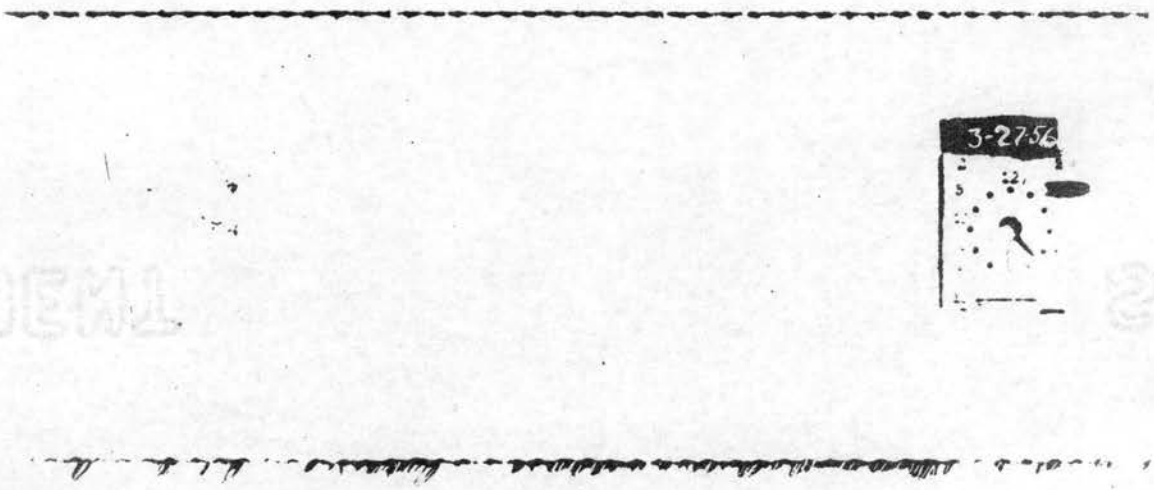

Figure 3. Film Record of HFDF, 1630:03 CST, 27 March 1956

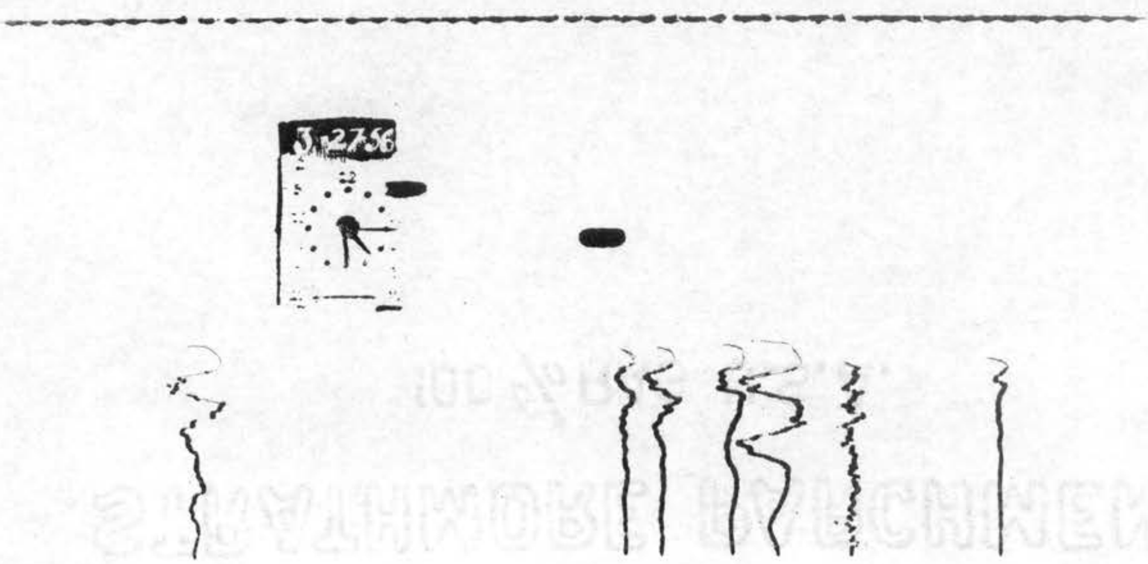

Figure 4. Film Record of Sferic Waveforms, 1630:15 CST, 27 March 1956

As can be seen, an actual count of strokes on the photograph would indicate that the stroke count is well above the threshold for tornadic conditions, even though not indicated on the stroke counter. This situation can be improved by more accurate calibration to reflect varying degrees of attenuation of high frequency strokes at different distances from the Tornado Lab; however, it would be desirable not to rely solely on one instrument as a tornado indicator. Further recommendations on this subject are included in Chapter V, and in later sections of this chapter.

Figure 4 is a photograph of waveforms taken at 1630:15 CST with a 500 micro-second time base. Since the direction finder showed practically all the sferic activity at an azimuth of 125°, corresponding to the AWS fix, for a period of time both before and after the waveforms, it can be safely assumed that these are waveforms of sferics propagated by a tornadic storm. A Fourier analysis of the waveform to determine the frequency content will not be attempted here as it would be principally a duplication of work previously accomplished by Mr. Joe Pat Lindsey.[1] Mr. Lindsey's analysis of waves of this type showed energy maxima at frequencies of 25, 45, 85, and 145 kilocycles,

[1] Joe Pat Lindsey, "An Analysis of the Sferic Waveform", an unpublished Master of Science Thesis, Oklahoma Agricultural and Mechanical College, Stillwater, Oklahoma, 1954, pp. 34-45.

plus a large undetermined portion of energy at 170 kilocycles and above. This type of very active waveform has by far the greatest share of its energy above 80 kilocycles, representing a very marked shift of frequency from the example shown in Figure 2. A logical extension of this reasoning would point the need for an instrument specifically designed to instantaneously measure the frequency content of sferics, as a possible indicator of the formation of a tornado.

Figures 5 and 6 are photographs of high frequency direction finder and wave form patterns at 1830:09 and 1830:10 CST, respectively. During this period of time, the stroke count per the direction finder was about 33 pps accompanied by quite active wave forms; however, the counter readings were:

Pips/second	Azimuth	Time
10	110°	1831:50
10	115°	1831:55
10	123°	1832:03
12	128°	1832:08

The lower magnitude of the counter readings apparently was due to the counter's rejection of small pips. For storms near the limits of the range of the high frequency equipment this type of discrepancy in readings was quite consistant.

The situation about an hour later is shown in Figures 7 and 8. The heavy stroke count was still evident, but

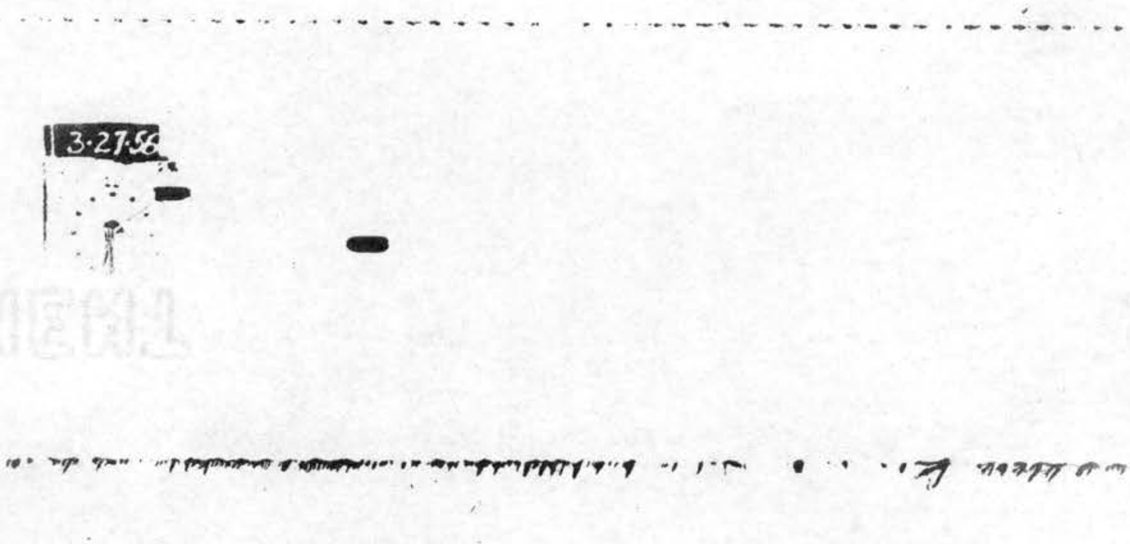

Figure 5. Film Record of HFDF, 1830:09 CST, 27 March 1956

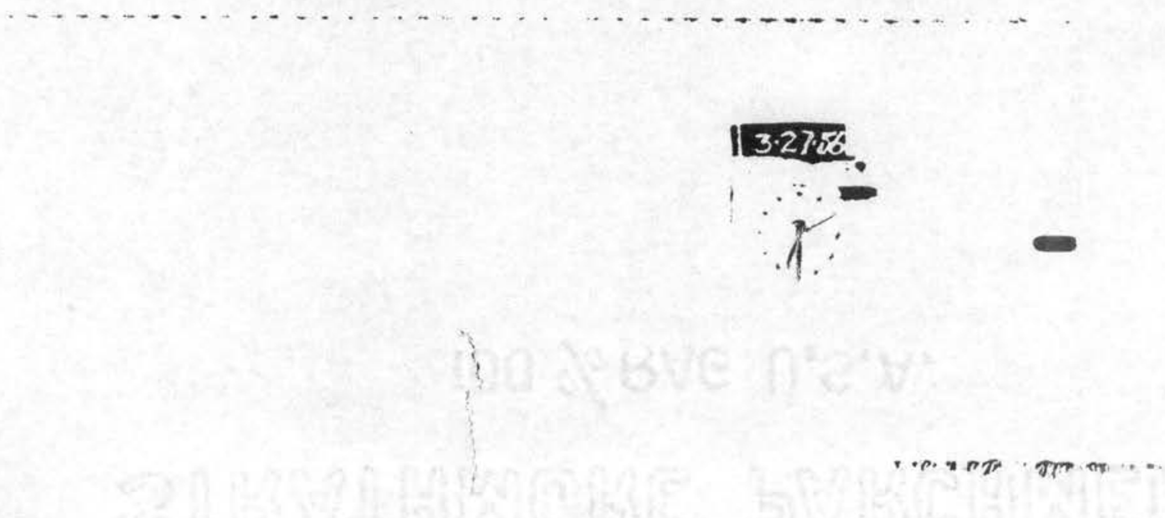

Figure 6. Film Record of HFDF and Sferic Waveform, 1830:10 CST, March 27, 1956

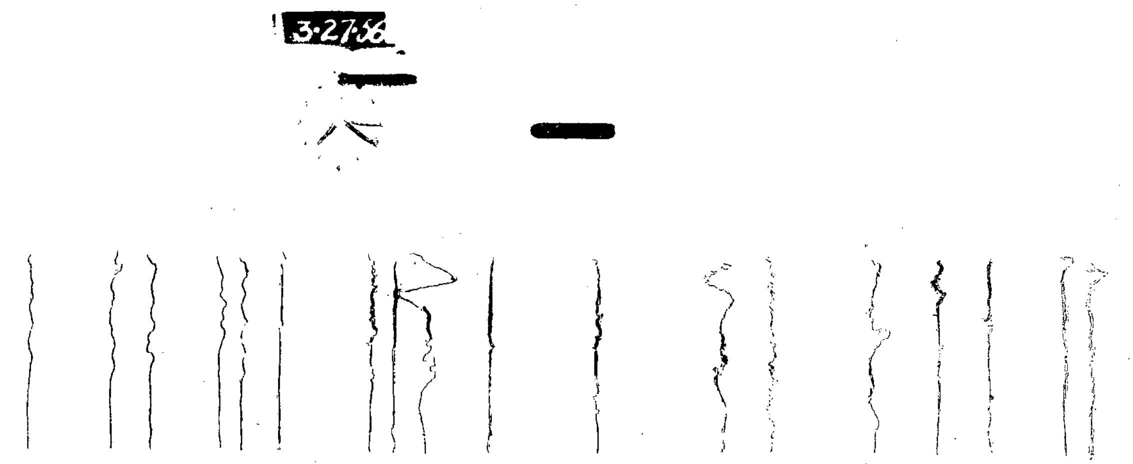

Figure 7. Film Record of Sferic Waveform, 1920:16 CST, 27 March 1956

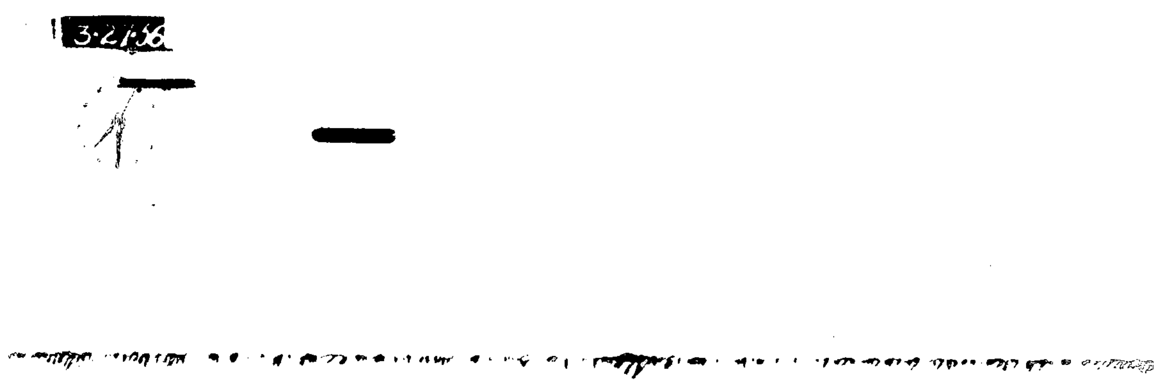

Figure 8. Film Record of HFDF, 1930:04 CST, 27 March 1956

the angles from which the sferics were arriving had spread between 90° and 110°. It should be noted here that these waveforms, with a 500 micro-second time base are much easier to interpret than those with a longer time base.

The Storm of 2 April 1956

The storm of 2 April 1956 is probably best known as the originator of the tornado that destroyed portions of Drumright in the evening. However, the storm itself had been active earlier in the day, spawning a tornado that went through the northeast section of Tulsa, Oklahoma, at 1030 CST. Figure 9 gives a relative gauge of the strength of the storm at 1103. In this case, north is to the right of the photograph, and there is a stroke count in excess of 30 at an angle of approximately 70°. Figure 10 shows the type of waveform present at this time. A 1000 micro-second time base was used, and it is somewhat more difficult to determine the shape of the waveforms. There is evidence, though, of the more active type, which has a large portion of its energy in the frequency spectrum above 80 kilocycles. It is evident from Figure 9 that there is a considerable amount of energy in the 150 kilocycle region.

It is interesting to note that this storm furnished an excellent opportunity to check the accuracy of the azimuth readings of the high frequency direction finder. A little after noon there was an isolated precipitation echo on the radar. Dr. Jones made the following comparison of the

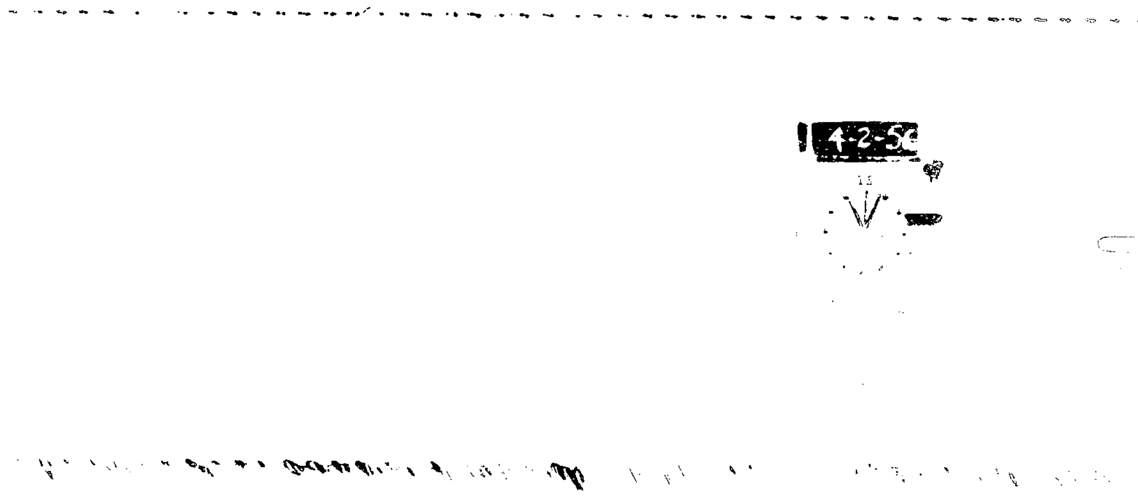

Figure 9. Film Record of HFDF, 1103:00 CST, 2 April 1956

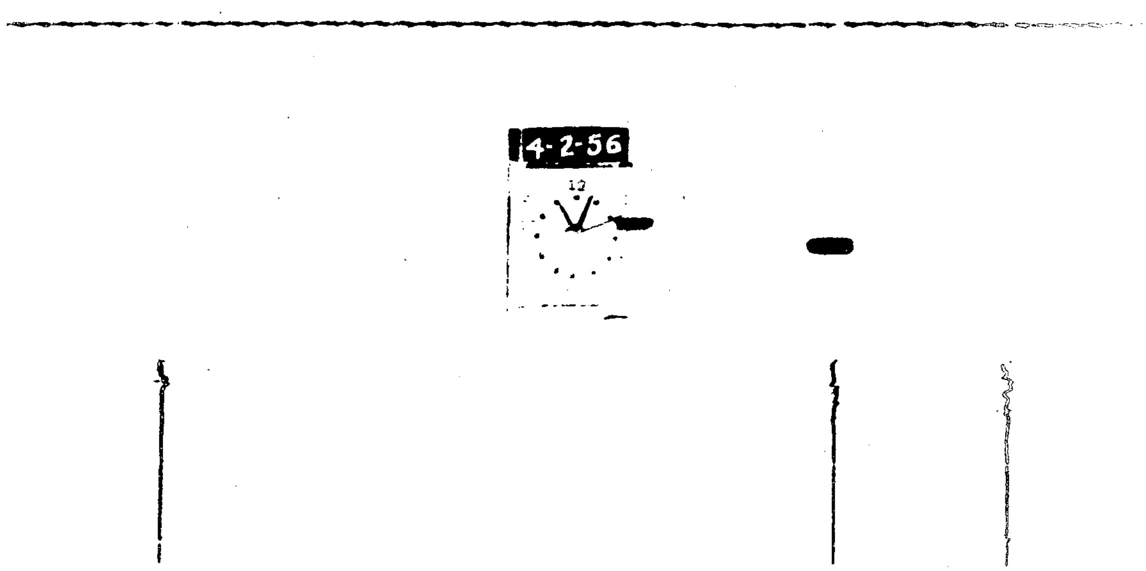

Figure 10. Film Record of Sferic Waveforms, 1104:11 CST, 2 April 1956

radar echo azimuths with the direction finder readings:[2]

	RADAR		HFDF
Time	Azimuth	Distance	Azimuth
1250	336°	60 miles	336°
1303	334°	66 "	334°
1325	350°	80 "	350°
	354°	73 "	354.5°
1355	8°	100 "	7.5°
	2.5°	90 "	3°

The above figures certainly speak well for the quality of the design and maintenance of the high frequency direction finder by the Project Engineer, Mr. R. D. Kelly.

As shown by the stroke count record in Figure 11, the activity at 8° azimuth had moved to 18-25° by 1700 CST, and had increased greatly, while the activity which had now moved to 317° had subsided somewhat. The important readings were as follows:

Pips/second	Azimuth	Time
25	18°	1700:18 CST
22	21°	1700:21 CST
24	25°	1700:25 CST

The ten second composite of Figure 12 clearly shows the angles of greatest intensity, although it is difficult to make a comparison of the relative intensities from such a photograph. Also, as it is a composite photograph, it should be remembered that the operator does not have this

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[2]Herbert L. Jones, Research on Tornado Identification, Final Report, Signal Corps Project No. 172B, 1956, p. 12.

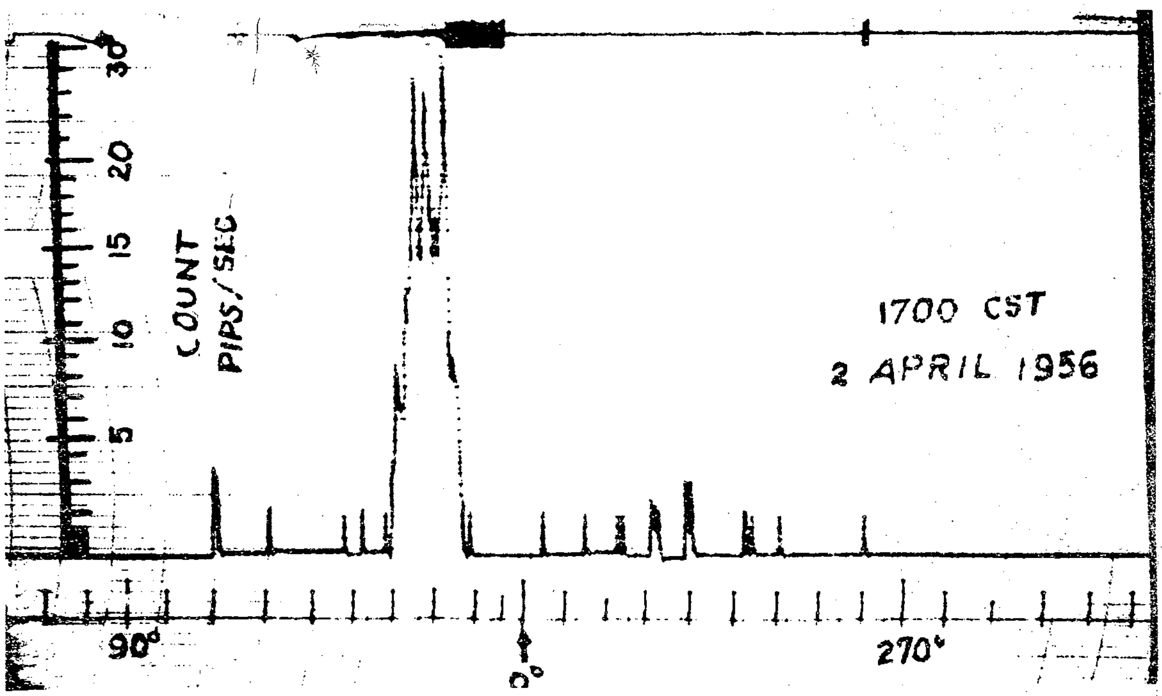

Figure 11. Stroke Counter Record, 1700-1705 CST, 2 April 1956

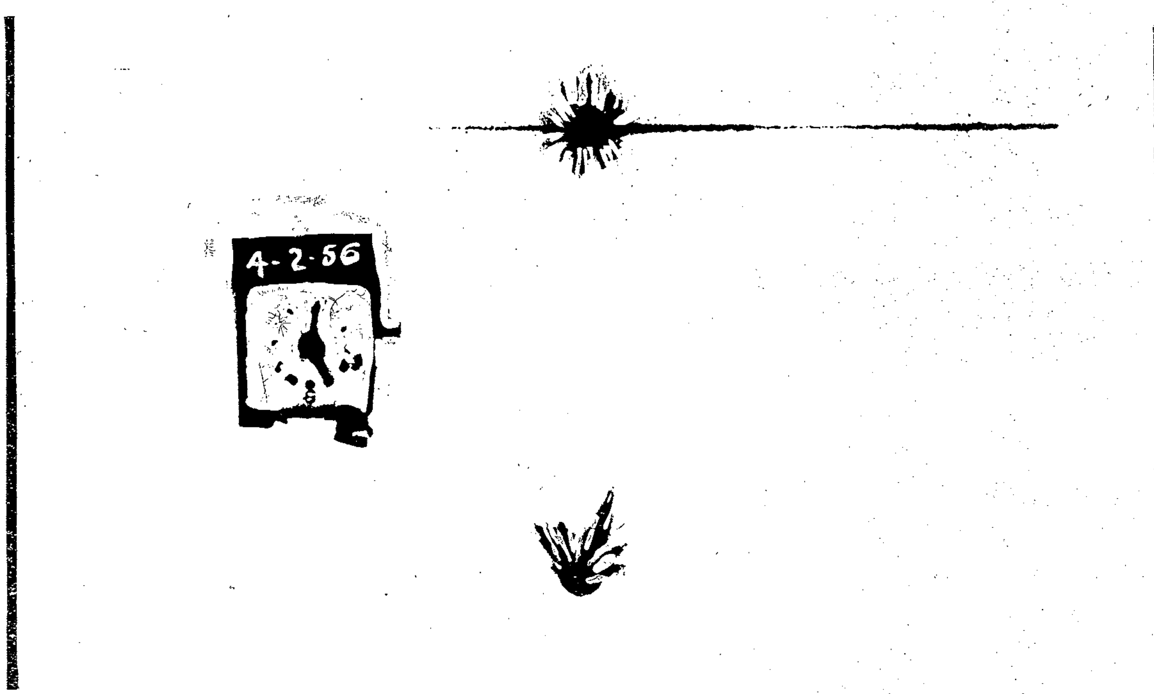

Figure 12. 10 Second Composite of HFDF, 1701 CST, 2 April 1956

particular display available. Since there is no rapid film developing service at the Tornado Lab as is provided at the Air Weather Service sites, [See Chapter II], the value of this type of presentation is limited to studies subsequent to a storm. However, the instantaneous presentation on the visual HFDF scope provides essentially the same information as a one second composite.

Figures 13 through 16 show the activity at around 1730 CST. In this case, north is at the top of the photograph, and it will be noted from Figure 13 that the maximum activity is from an azimuth of 323° with a count of about 25 pps. However, the composite photograph of the HFDF, Figure 15, indicates that sferics are also emanating from 20°. The waveforms of Figures 14 and 16 have some strokes exhibiting higher frequency activity, but there are several that apparently are of lower frequency content. A possible explanation may be that since the storm being tracked was principally in Kansas at this time, there was a large amount of attenuation of the higher frequency sferics. For this reason, some of the waveforms reproduced may have originated from this storm, while others may be the low frequency components of storms hundreds of miles away. With the gain settings used and the 1000 microsecond time base, it would be difficult to identify these waveforms with those associated with tornadoes elsewhere in this report.

The storm discussed above caused a great deal of destructiveness, for the Air Weather Service has confirmed

Figure 13. Film Record of HFDF, 1730:07 CST, 2 April 1956

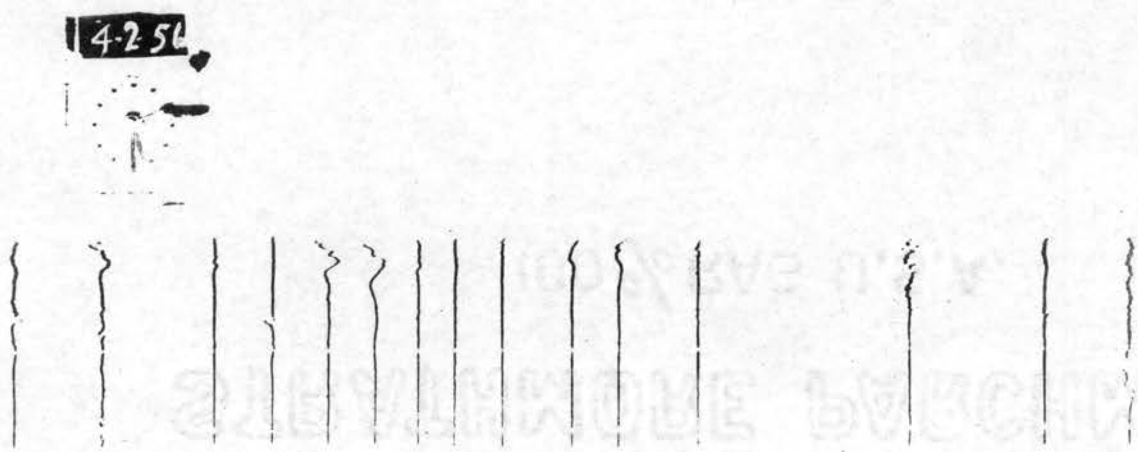

Figure 14. Film Record of Sferic Waveforms, 1730:10 CST, 2 April 1956

Figure 15. One Minute Composite of HFDF, 1732-1733 CST, 2 April 1956

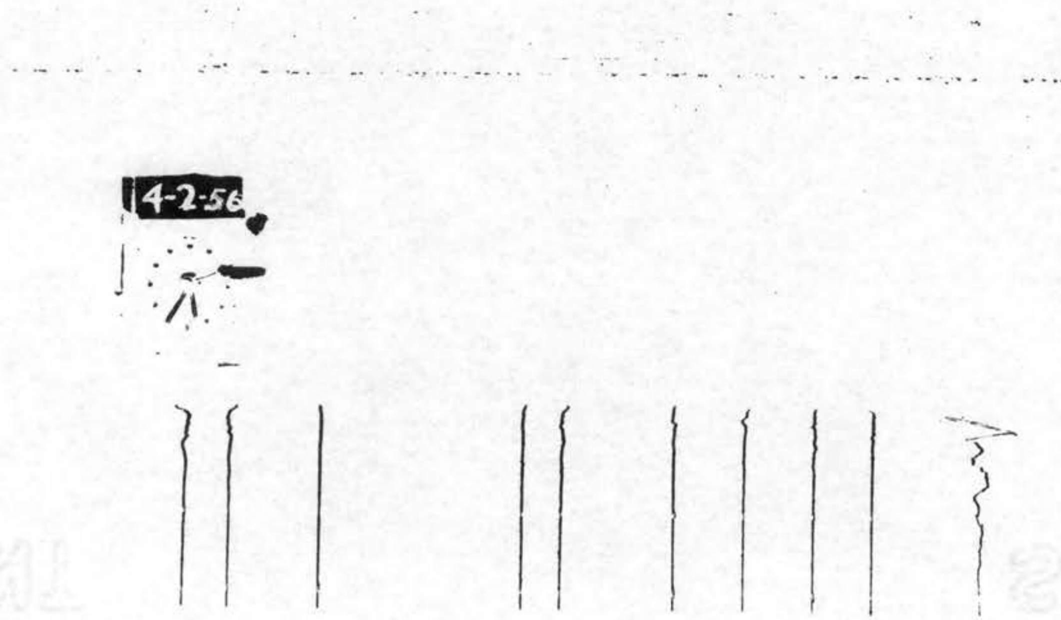

Figure 16. Film Record of Sferic Waveforms, 1735:10 CST, 2 April 1956

tornadoes at Radium, Kansas, at 1800 CST; at Attica, Kansas, at 1910 CST; at Ellinwood, Kansas, at 2045 CST; at Maple City, Otto, and Grenola, Kansas, at 2210 CST. However, the tornado that struck Drumright, Oklahoma, on the same evening, came as a distinct shock to the personnel of the Tornado Lab, for there had not been sufficient sferic activity at an azimuth of 107° to warrant attention. This was particularly serious, as it indicated a possible source of error in the sferic method of tornado forecasting and tracking. It is speculated that one or a combination of the following might have been a cause of the omission of sferic activity:

1. It may be possible that there was a particular combination of meteorological conditions that will cause a tornado without accompanying atmospheric radiations. It is known that there was a low surface moisture content, which is contrary to one of Lt. Col. Fawbush's criteria [See Chapter I].

2. Electromagnetic radiations emanating from the tornado spawning thunderstorm may not have been identified at the Tornado Lab because of the experimental apparatus used. It has been noted generally that as the thunderstorm activity increases in fury, the energy distribution in the frequency spectrum shows a shift to higher frequencies. It may be possible that the frequency shift was above the range of the equipment used.

<u>The Storm of 5 April 1956</u>

A confirmed tornado occurred at Bryan, Texas, at

1515 CST on 5 April 1956. A study of this storm is of interest due to the fact that Bryan is located approximately 380 miles from the Tornado Lab, which is beyond the normal daytime operating range of the high frequency equipment. This storm is a contrast to the storm near Victoria, Texas, on 21 March 1956, from which no measurable sferic pips were received. Figures 17 and 18 show the situation at 1400 CST. In Figure 17 there is evidence of the higher frequency content of the two more active waveforms, even though a 1000 microsecond base was used. Since the photograph was taken during an interval when most of the activity was from an azimuth of 150° and 181°, as shown in Figure 18, the assumption is made that the source of the waveforms was the storm near Bryan, Texas.

The waveform record at 1430 CST shown in Figure 19 indicates that there were still higher frequency emissions at this time. Figure 20 shows that the sferic activity had become somewhat more scattered by 1442 CST, with active high frequency sferics principally from azimuths of 176°, 145°, and 132°. Note that the low frequency equipment was functioning at this time, indicating radiations from 200°, and 20°. It would be difficult to determine the storm center from which these sferics came, since it can safely be assumed that it was well beyond the range of the high frequency equipment. However, it is believed that the indication at 20° is actually in error, and is simply the back azimuth of the 200° reading, with the "sense"

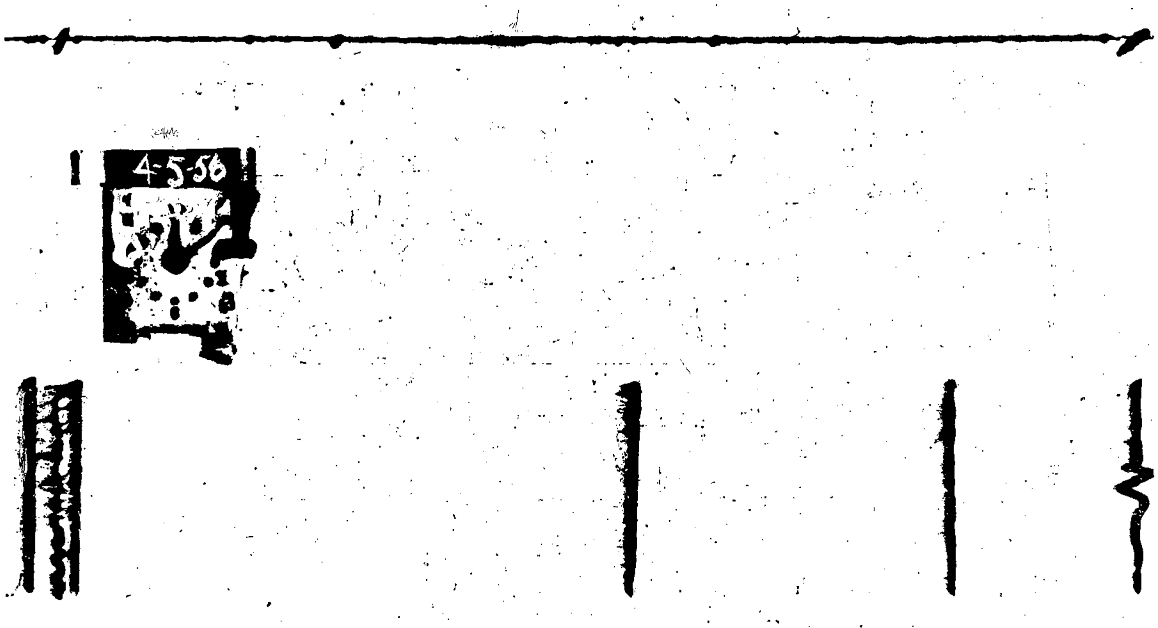

Figure 17. Film Record of Sferic Waveforms, 1400:09 CST, 5 April 1956

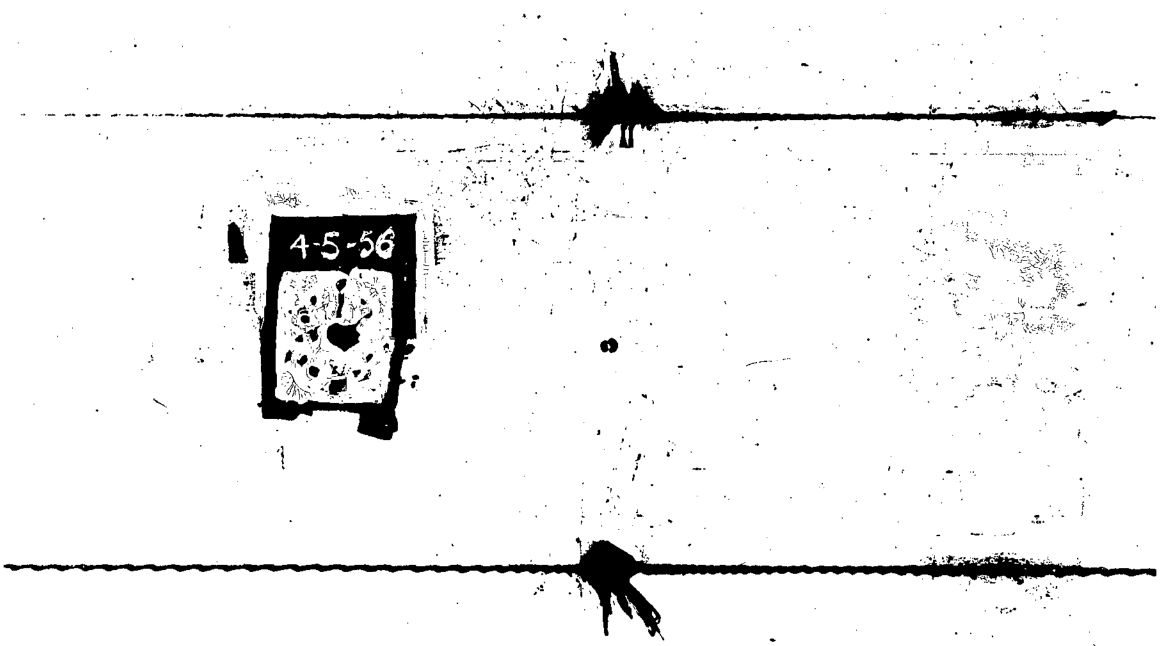

Figure 18. Two Second Composite of HFDF, 1400 CST, 5 April 1956

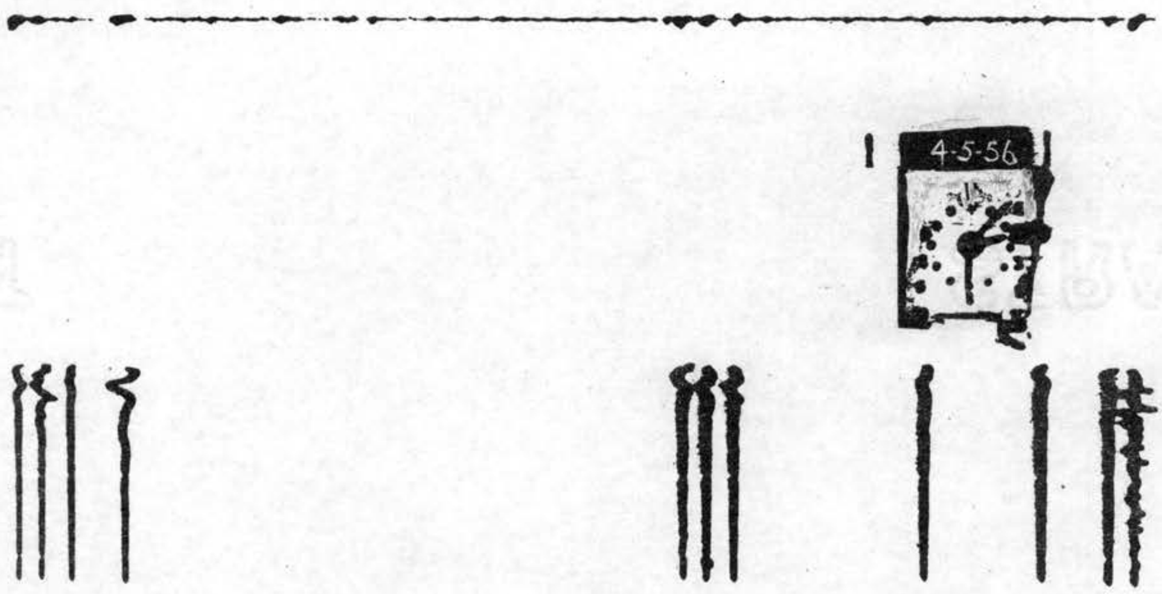

Figure 19. Film Record of Sferic Waveforms, 1430:07 CST, 5 April 1956

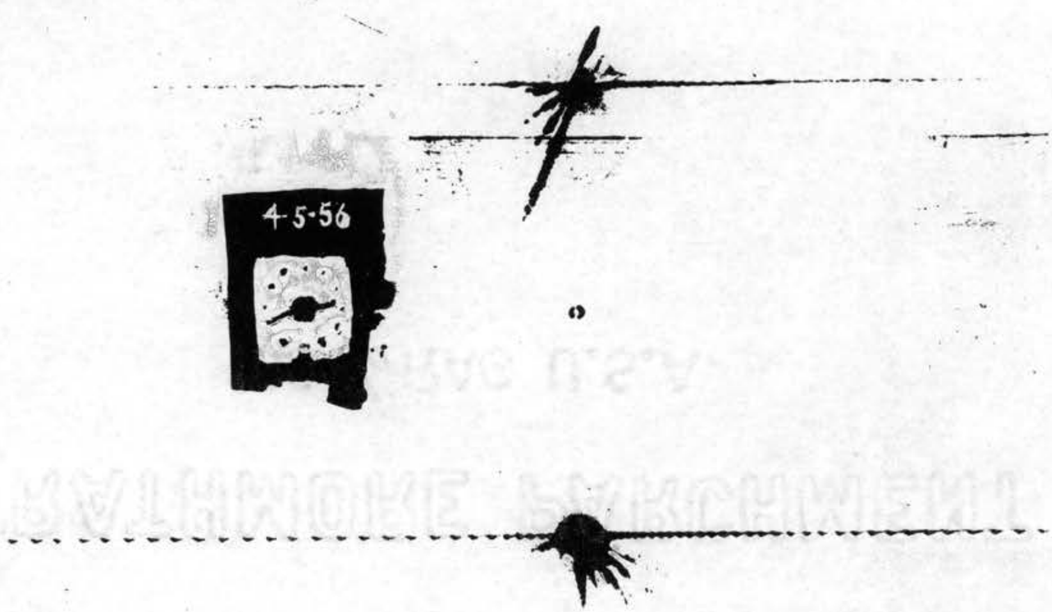

Figure 20. Ten Second Composite of HFDF and LFDF, 1447 CST, 5 April 1956

equipment of the low frequency direction finder not working properly.

By 1500 CST, the principal active angles were 138° to 141°, and 176°, as per Figure 21. Figure 22 contains waveforms of high frequency energy. The waveform that is second from the left is unusual in that it contains one burst of particularly large magnitude that appears to be a fairly simple harmonic motion. Note that this waveform also is aligned vertically with a low frequency pip, which is at the same instant in time. Unfortunately, a combined record of the low and high frequency direction finders, as well as the waveforms, is not available. Thus, it cannot be determined whether the low and high frequency portions arrived from the same azimuth, possibly coming from the same storm center, or whether the time coincidence was simply a random effect.

During the entire tracking period of the Bryan tornado, the stroke counter rate did not exceed about 3 pps. This would not seem to be in consonance with the high stroke rate shown in Figure 21; however, it should be considered that the stroke counter does not register any strokes below a certain length. Therefore, even though a subsequent count of the film record showed definite evidence of a stroke rate that may be associated with tornadic type storms, the counter record, which is the only quantitative information available during tracking operations, would indicate only light activity. As stated previously, this

Figure 21. Film Record of HFDF and LFDF 1500:02 CST, 5 April 1956

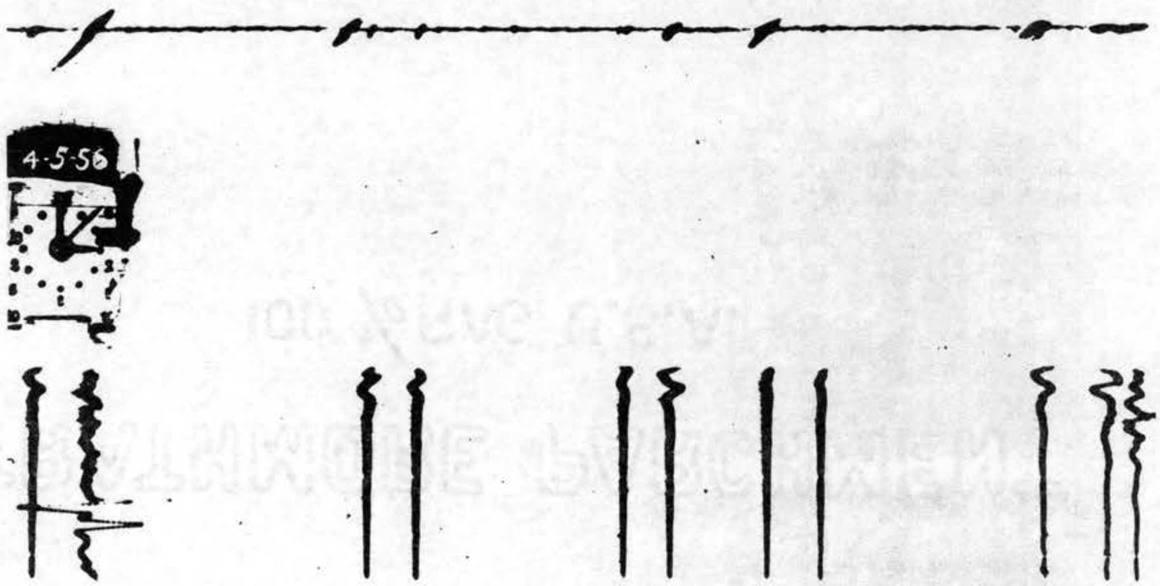

Figure 22. Film Record of Sferic Waveforms and LFDF, 1500:07 CST, 5 April 1956

storm was actually beyond the effective range of the high frequency equipment, definitely establishing a range limitation, at least with the calibration used.

The Storm of 8 April 1956

A comprehensive treatment of the storm of this date is contained in Dr. Jones' Fifth and Seventh Quarterly Reports.[3, 4] Of particular significance in these reports is the description of visual observations of the possible source of the high frequency sferics in tornadic type storms. As the storm moved north of the Tornado Lab, there were recurring areas of illumination at an estimated angle of 50 or 60 degrees to the horizontal. These illuminated areas were circular or elliptical in shape, and were blue or purple in color. They varied cyclically with time, with periods of maximum intensity not over two seconds apart. Similar occurrences have been observed by Dr. Jones on three different occasions, and it would seem appropriate to relate this phenomenon with recorded observations. As discussed in Chapter II, one type of analysis used by the USAF Air Weather Service is based on the observation of recurring bursts of pips. A quantitative study of a large portion

[3]Herbert L. Jones, Research on Tornado Identification, Fifth Quarterly Progress Report, Signal Corps Project No. 172B, 1956, pp. 21-25.

[4]Herbert L. Jones, Research on Tornado Identification, Seventh Quarterly Progress Report, Signal Corps Project No. 172B, 1956, pp. 7-34.

of the film taken at the Tornado Lab during the 1956 season generally indicates this cyclic variation. Also, the AWS researchers have found that about half an hour before the development of a tornado, the low frequency sferics maximize, thendiminish rapidly. Thus, when a tornado develops, it may well be that the cloud-to-ground strokes, which are associated primarily with the low frequency sferics, are reduced severely. In their place, this recurring circular type of sferic activity may build up within the center of the storm cloud itself, accounting for the shift of energy to the higher frequencies. The fact that there is much greater turbulence within the center of the cloud may cause more breaks in the ionization path of the lightning strokes, resulting in shorter individual paths. Since the wave-length of the electromagnetic radiations is probably directly proportional to the ionization paths, much higher frequencies would then be propagated.

Figure 23 is a photograph of the waveforms occuring at 2300 CST, at which time the Air Weather Service confirmed that two tornadoes occurred 25 miles northeast of Enid, Oklahoma. At first glace, the waveform to the right of this picture would have particular significance, since it appears so active. However, note that it is aligned vertically with a high amplitude low frequency pip, partially elliptical in shape. This pip was caused by a nearby low frequency stroke, and apparently was of such magnitude as to be beyond the ballistic capabilities of

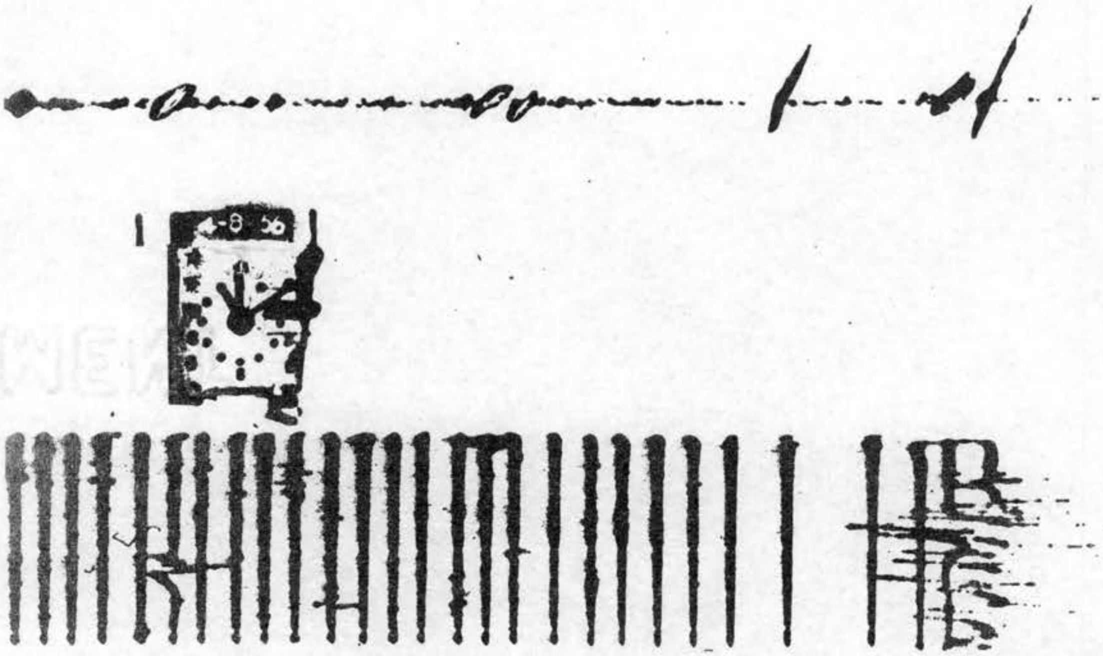

Figure 23. Film Record of Sferic Waveforms and LFDF, 2300:09 CST, 8 April 1956

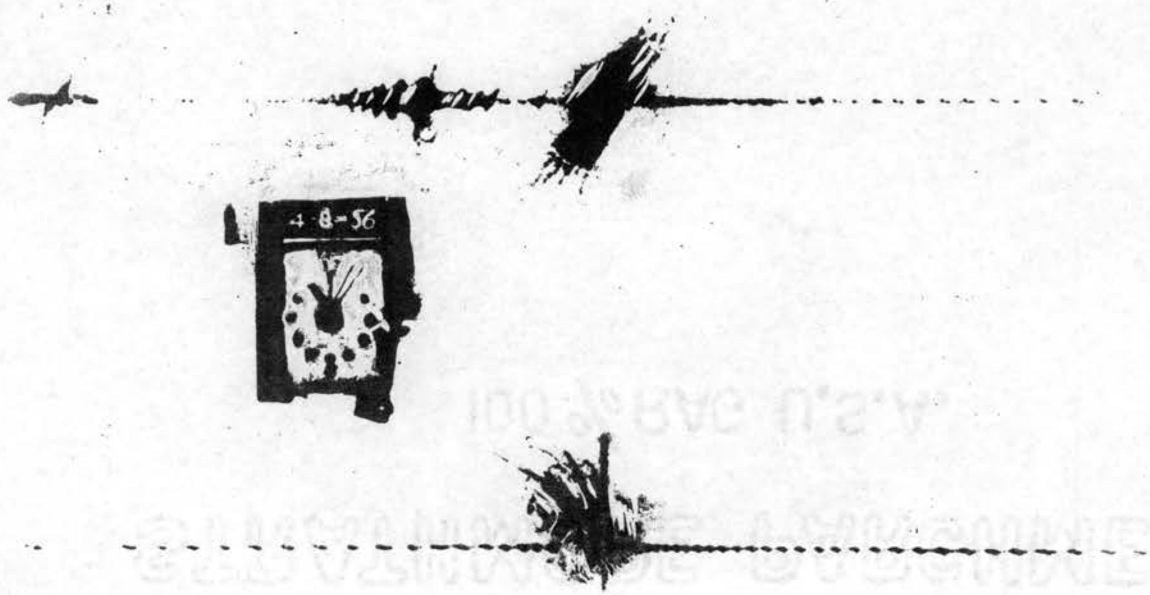

Figure 24. One Second Composite of HFDF and LFDF, 2300 CST, 8 April 1956

the wave form recorder. In similar extreme cases that have been observed, the wave form meanders in such a way along the time base that it appears to actually "gain" time. For this reason, it is believed that this type of wave form should be ignored. There are, however, several waveforms in Figure 23 that show a high frequency content. A one-second composite of the high frequency direction finder, in the lower portion of Figure 24, shows the major activity in the region 320° to 0°. Note that the low frequency component, shown in the upper portion of this figure, had an azimuth of 220°, again with a back azimuth of 40°, neither azimuth being in the direction of Enid. This confirms the contention that, within the range of the equipment, a frequent occurrence of high frequency sferics are associated with tornadic storms, while simultaneous low frequency signals may be from storms several hundred or thousand miles beyond the range of the high frequency equipment.

<u>The Storm of 14 April 1956</u>

At 2030 CST, an Air Weather Service fix was established at a point 15 miles south of Bartlesville, Oklahoma, which is at an azimuth of 55° from the Tornado Lab. Figure 25 is the stroke counter record at this time, and shows that the principal counts were:

Pips/second	Azimuth	Time
15	320°	2029:20
30 ≠	55°	2030:55

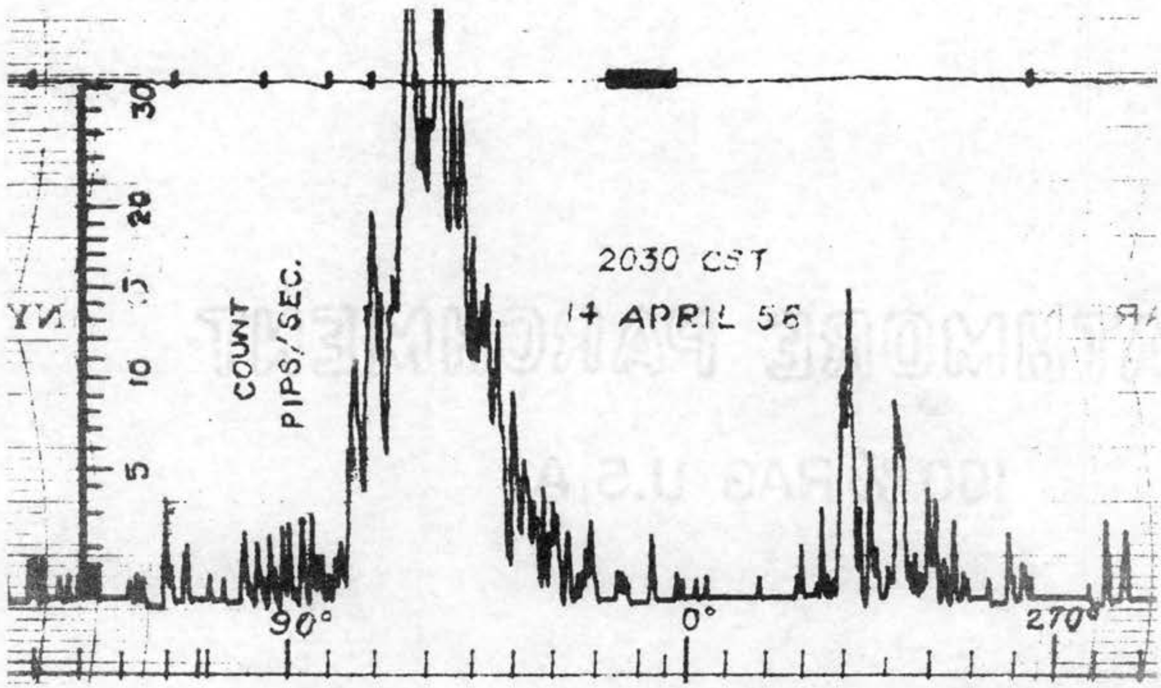

Figure 25. Stroke Counter Record, 2029-2031 CST, 14 April 1956

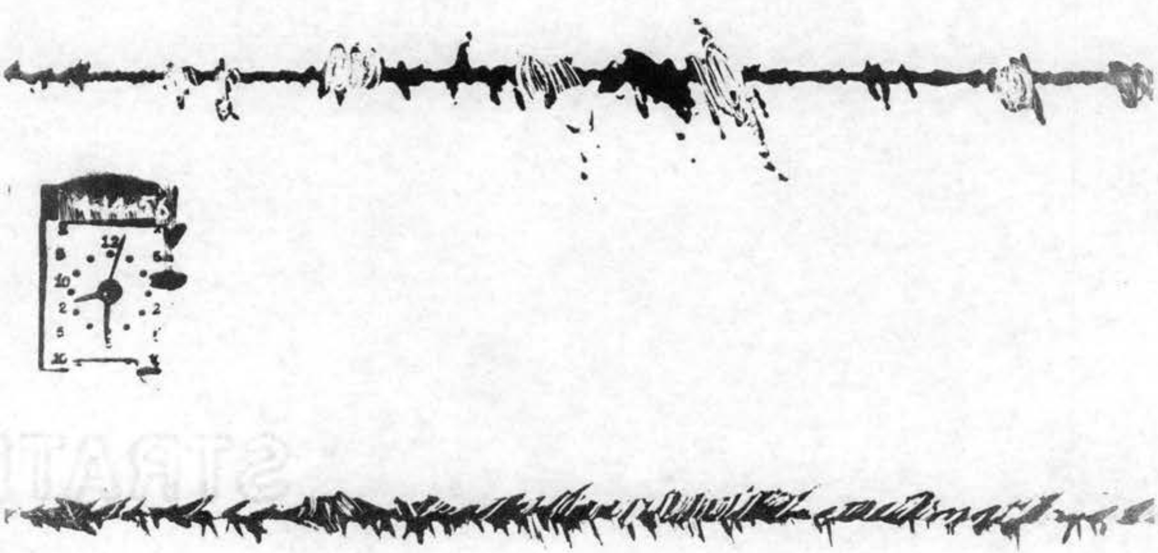

Figure 26. Film Record of HFDFaand LFDF, 2030:02 CST, 14 April 1956

Pips/second	Azimuth	Time
30 ≁	65°	2031:05
22	72°	2031:12

Figure 26 shows the high and low frequency direction finder activity at this time. Several of the low frequency strokes consist of series of concentric ellipses, but the major axis of each ellipse does not have the same azimuth. This makes the problem of determining the direction of these pips quite difficult. The waveforms in Figure 27 for the most part may be aligned vertically with corresponding low frequency pips, indicating that there is a low frequency component present. However, the significant aspect of the low and high frequency comparison, particularly in Figure 26, is that the number of high frequency pips greatly exceeds the low frequency ones. Based on the assumptions previously stated, this storm appeared to have great likelihood either of harboring or being in the process of developing a tornadic situation. However, confirmed tornadoes were not reported until over an hour and a half later.

By 2100, the most active angles were between 48° and 60°, with the high count being 17 at 60°. In Figure 28, the azimuth of the high frequency sferics corroborates the measurements of the stroke counter, but the low frequency sferics do not furnish a satisfactory correspondence. Since the elliptically shaped pips are from nearby strokes, well within the range of the high frequency equipment, it

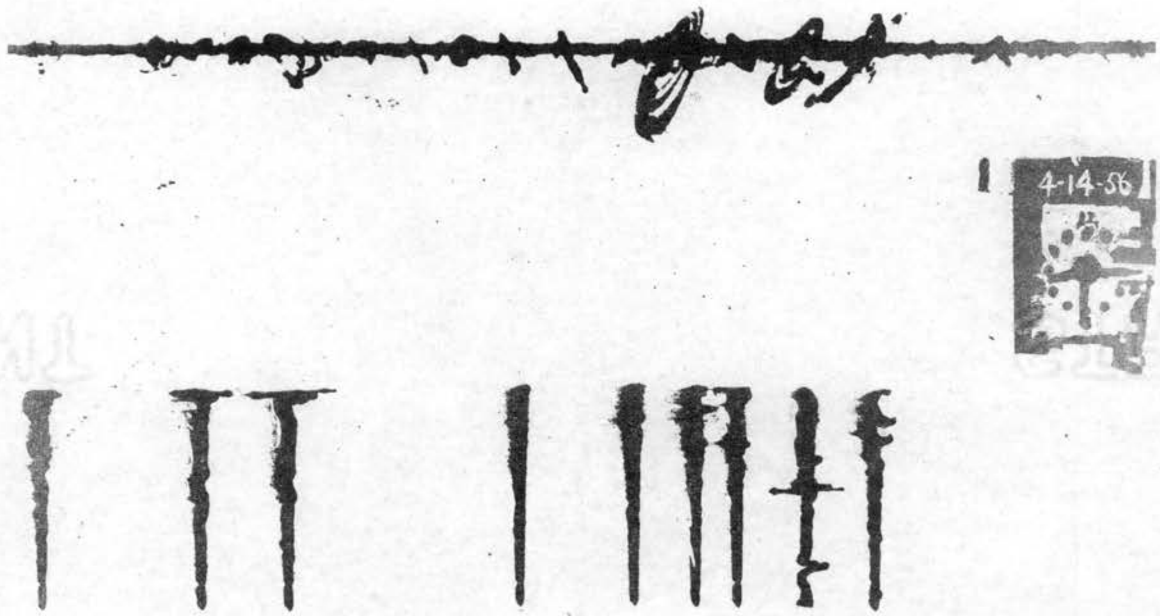

Figure 27. Film Record of Sferic Waveforms and LFDF, 2030:15 CST, 14 April 1956

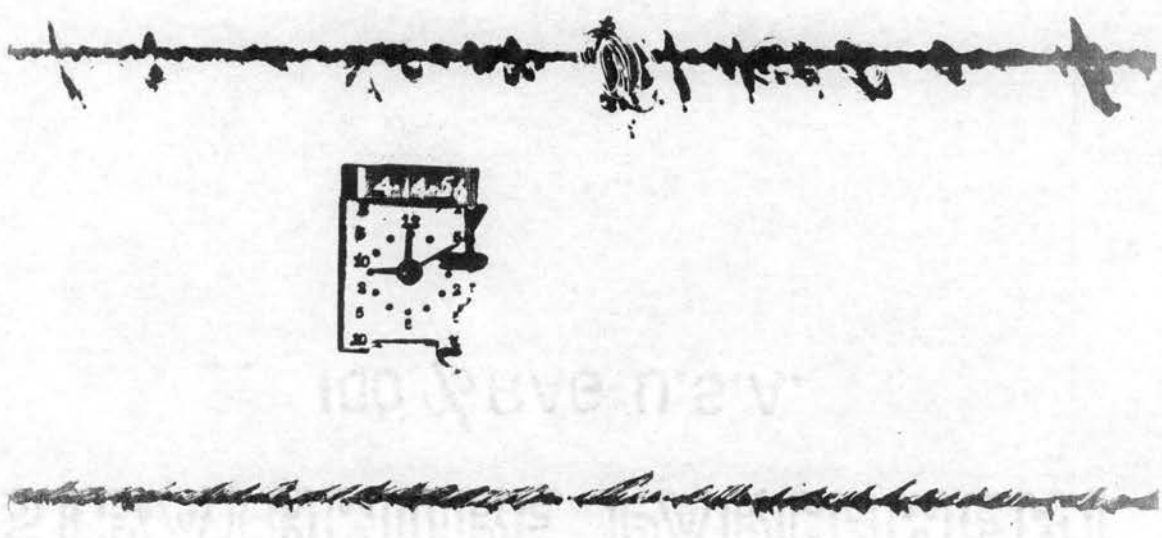

Figure 28. Film Record of HFDF and LFDF, 2100:09 CST, 14 April 1956

must be assumed that the azimuth indications of this type of indication cannot be relied upon. Thus, even though the major axes of the concentric ellipses could be determined, this would not necessarily be the direction of the source of the low frequency radiation.

A very active situation was still evident at 2200 CST, as shown in Figure 31. The value of composites is evident in Figure 30, which had been made a few minutes earlier. The major angle for high frequency sferics is about 70°, while the major low frequency angle is 170° with other low frequency activity scattered. The reason for the stress on composites is twofold: first, they are valuable research tools in determining quantitatively the angles of major sferic activity; second, a composite of very short duration, such as in Figure 30, is basically the presentation seen by the operator at the manual azimuth reader cathode ray tube [See Figure 1]. This is the means by which the operator aligns a particularly active angle with precipitation echoes on the remoted radar scope, and determines possible tornado bearing thunderclouds. Typically active waveforms, with energy components in the higher frequencies, are in Figure 32.

There were several quite active angles at 2300 CST as per Figures 33 and 34. Most of the waveforms shown have corresponding low frequency pips; however, in many cases where there is a high stroke count, there are high frequency waveforms without associated low frequency strokes.

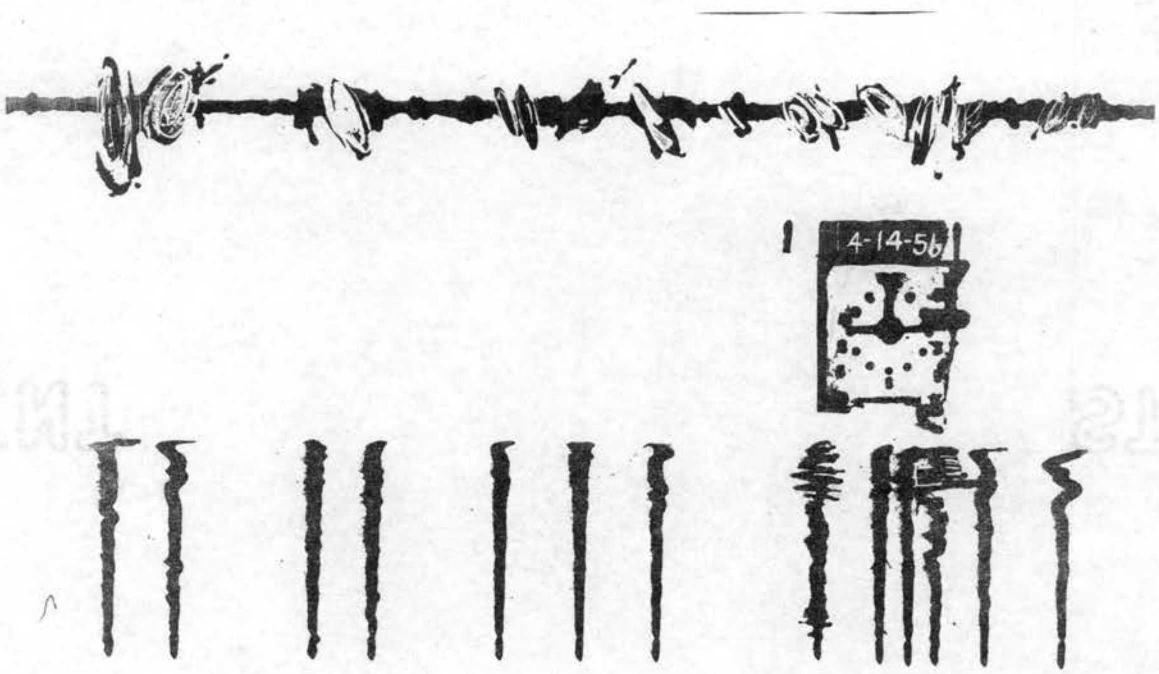

Figure 29. Film Record of Sferic Waveforms and LFDF, 2100:15 CST, 14 April 1956

Figure 30. Two Second Composite of HFDF and LFDF, 2156 CST, 14 April 1956

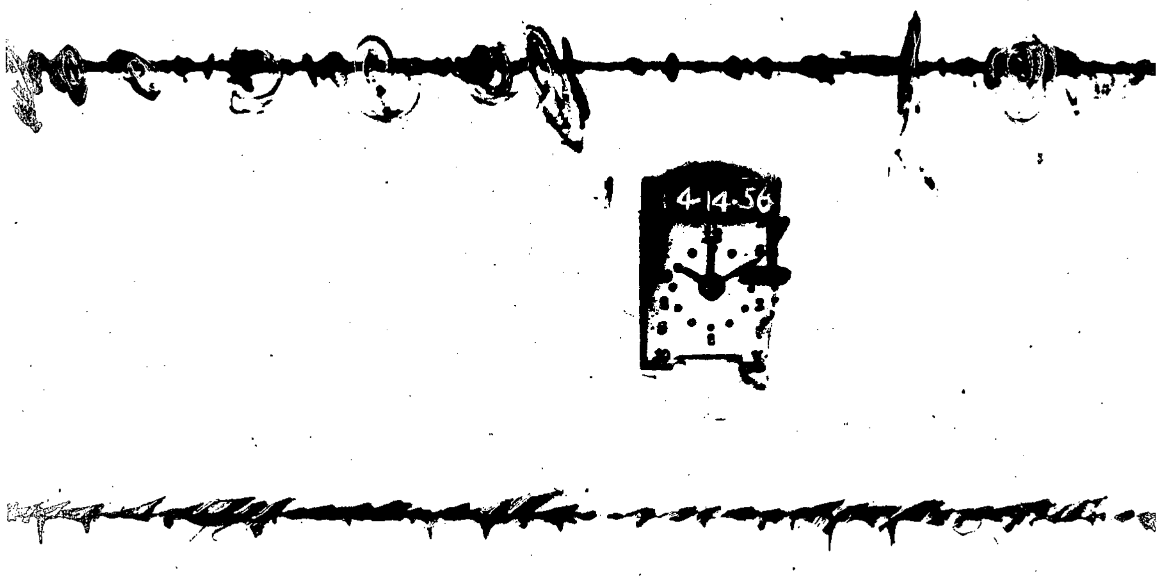

Figure 31. Film Record of HFDF and LFDF, 2200:10 CST, 14 April 1956

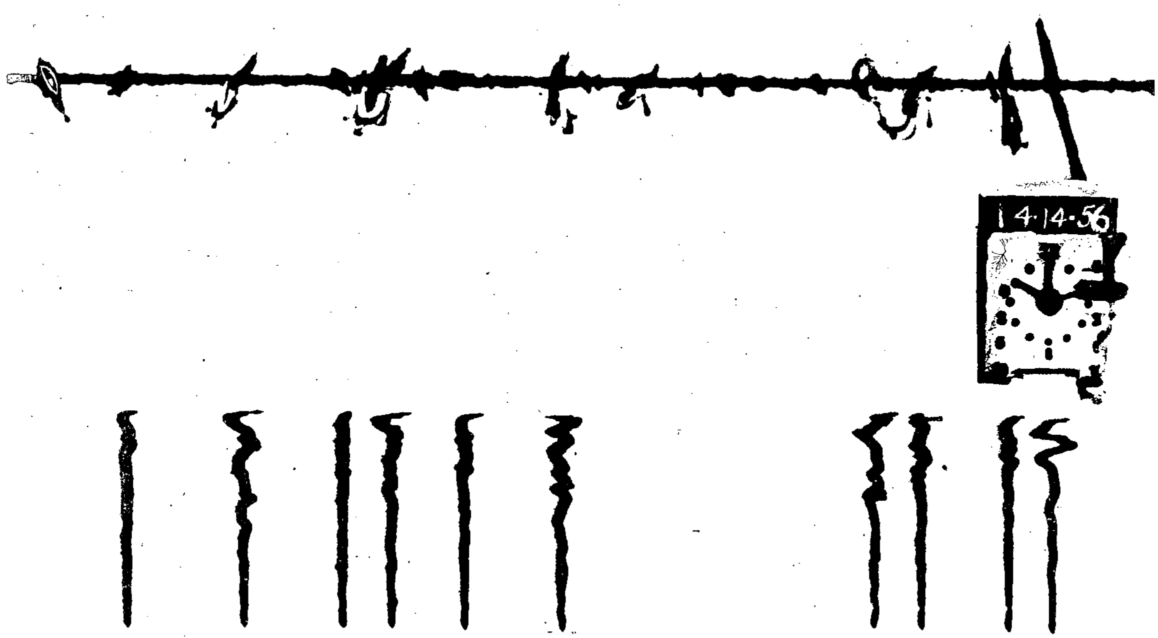

Figure 32. Film Record of Sferic Waveforms and LFDF, 2200:12 CST, 14 April 1956

Figure 33. Film Record of HFDF and LFDF, 2300:08 CST, 14 April 1956

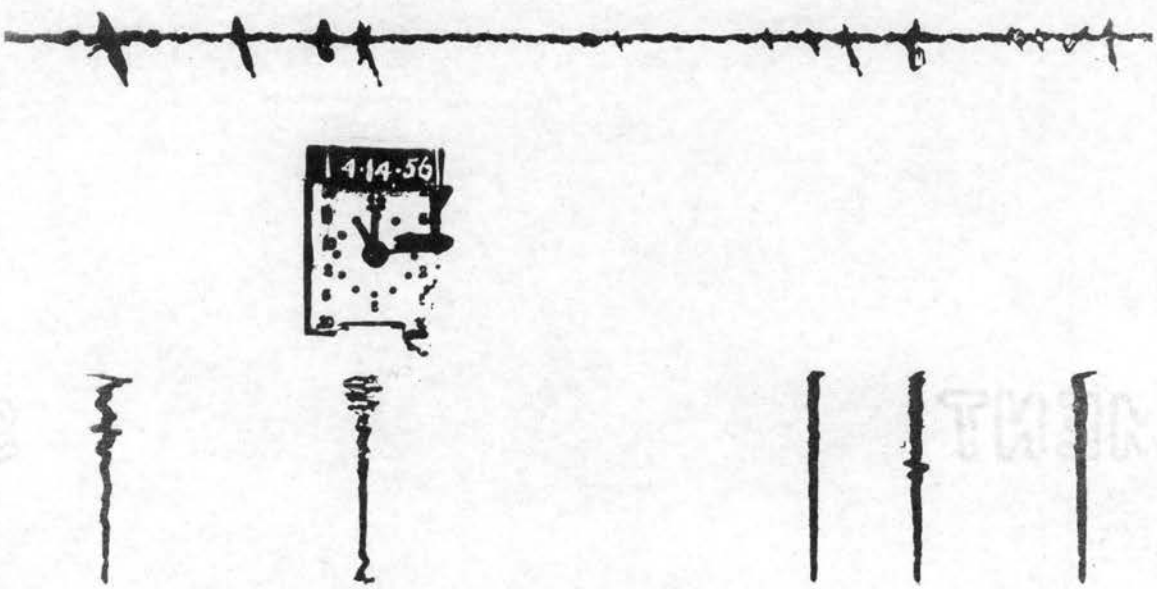

Figure 34. Film Record of Sferic Waveforms and LFDF, 2300:13 CST, 14 April 1956

The general trend exhibited is that when the intensity of the storm increases, the low frequency portion of the radiated energy diminishes and in some cases is eliminated entirely.

The storm discussed above culminated in a reported tornado seven miles north of Miami, Oklahoma, at 2353 CST. As mentioned earlier, because of the sporadic nature of the art of tornado reporting, the total duration and path of the funnel cloud, both while on the ground and completely airborne, cannot be determined. However, the important factor is that a relatively straightforward, practical system has been devised which makes it possible to determine which particular thundercloud is potentially a tornado carrier, and to track the path of this storm in order to give residents in its path ample time to take precautions for any eventuality.

During this day, funnels were also reported near Fort Worth, Texas; and Drumright, Oklahoma; as well as Cushing, Oklahoma; Caldwell, Kansas; Okmulgee, Oklahoma; and Overbrook, Kansas. However, the particular intervals chosen above demonstrate the progress of the storm confirmed by Air Weather Service fixes which eventually reached Miami, Oklahoma.

An aspect that has not been discussed in detail previously is the method of operation of the stroke counter. Since this equipment scans one degree of azimuth per second, six full minutes must elapse before two readings on the same azimuth can be obtained. Due to the cyclic nature of sferic development, in a particular set of circumstances the sampling obtained by this equipment may record relative lulls in activity, and not reflect the actual rate of sferic increase. Also, in case a nearby ground stroke occurs at the particular instant that its azimuth is being scanned by the stroke counter, the apparent number of pips per second will be much greater than warranted for the activity in this direction. This latter type of occurrence can be identified on the counter record, for it will appear as a single very large peak, with little other activity near the same azimuth. However, the above possibilities for misinterpretations could be eliminated through the use of additional equipment similar to the present counter. It would seem desirable to utilize one stroke counter as is being done at present, with an additional two or three non-rotating counters to scan particular active azimuths, in order to follow the rate of build-up of high frequency sferics more accurately. Also, this would provide spare equipment in case of mechanical or electronic failure of the primary rotating counter.

CHAPTER V

SUMMARY AND CONCLUSIONS

General Conclusions

With the establishment of the Oklahoma A. & M. Tornado Laboratory, a practical application has been made of previous theoretical studies regarding the meteorological and electrical conditions associated with tornado bearing thunderstorms. For the past ten years, Dr. Jones and his staff have completed various comprehensive analyses of the conditions necessary for the development of tornadoes. For the first time, it is now possible with the sferics-radar method to locate and track tornadoes within the range of equipment at the Tornado Lab. However; it is not practical with radar alone to locate and track tornadoes with satisfactory accuracy.

This thesis has discussed the instrumentation presently used at the Tornado Lab, and has interpreted the recordings made during several storms in the 1956 season when tornadic situations had been confirmed by the Air Weather Service. It is felt that the following general conclusions can be reached, based on the mass of data now available, and the discussion presented in earlier chapters:

Cloud-to-ground lightning strokes are sources of electromagnetic radiation with a frequency content principally in the region below 30 kilocycles. The waveforms associated with this type of stroke are generally of the sinusoidal exponentially decaying type. However, nearby strokes have such an amplitude that the waveforms are not faithfully reproduced by the recording equipment used.

Cloud-to-cloud and inner-cloud lightning strokes produce radiations with much higher frequencies than cloud-to-ground strokes. This may be due to the greater turbulence within the clouds, causing more breaks in the ionization path, resulting in shorter resonant lengths for propagation.

When a tornadic situation develops within a thunderstorm, there is a pronounced shift in the radiated electromagnetic energy from low frequencies to much higher frequencies. This is accompanied by a reduction of the number of cloud-to-ground strokes, and a greatly increased number of inner-cloud strokes. On three occasions, Dr. Jones has observed nearby inner-cloud strokes which caused elliptically shaped bluish colored illuminated areas within the clouds. On each occasion, clouds producing this phenomenon resulted in tornadoes. Whether this is a general characteristic of tornado producing thunderstorms cannot be determined solely by these few observations; nevertheless, an effort should be made in the future to evaluate the consistency of this occurrence.

The wave shapes from higher frequency sferics do not have a simple pattern. However, there is a more or less typical pattern for these waveforms, which is more recognizable when pulsed against a shorter time base, such as 500 microseconds. The energy distribution of these sferics is predominately in the frequency spectrum above 80 kilocycles, but the upper frequency limit was not determinable with the data available. A comprehensive study by the Bureau of Standards has shown that a considerable amount of atmospheric noise is generated in the region as high as 20 megacycles.[1]

There is a correlation between the intensity of the storm and the number of pips per second recorded on the high frequency equipment. Fifteen pps is considered about the threshold for tornadic activity; when the number of pips per second from a particular azimuth reaches 20, using present techniques and equipment, there is about a 90% probability that a tornado is in existence or is being developed.

Recommendations for Further Study

Several instruments have been developed by the personnel of the Tornado Lab which have proved very valuable in the detection and tracking of tornadoes. Further improvement in these techniques could be obtained if the following steps were taken:

1. A panoramic receiver should be developed or procured

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[1]W. Q. Crichlow et al., Worldwide Radio Noise Levels Expected in the Frequency Band 10 Kilocycles to 100 Megacycles, National Bureau of Standards Circular 557, 25 August 1955, pp. 15-29.

so that an immediate indication of a change of frequency of sferic radiations could be obtained. The antenna of this instrument should be directional, so that any particular angle of sferic activity could be observed. This may require the invention of two specially designed components; namely, a broad band direction finder and a panoramic receiver with a visual output of some type.

2. Two additional stroke counters should be constructed, similar to the one now in use, but with a capability of continuously scanning any specified azimuth. This would allow a closer observation of the development of storms, and would provide a means of studying the cyclic nature of the propagation of sferics. Also, these stroke counters could serve as standby equipment in case of failure of the primary counter.

3. For distances near the maximum range of the high frequency equipment, additional calibration work is needed with the stroke counter. There should be a closer correlation between its readings and the high frequency direction finder pips as counted from film records.

The capabilities of the sferics-radar method of tornado detection have been decisively proved. For this reason, action should be initiated at this time for the formation of a permanent inter-state tornado warning network. The possibilities of such a network have been established by the accomplishments of the network operated by the USAF Air Weather Service. Also, the telemetering equipment used by this network, when perfected, may represent the ultimate in speed of intercommunication and evaluation.

Of necessity, the role of the Air Weather Service in the field of tornado tracking should be restricted to the dissemination of severe weather warnings to Air Force bases so that damage to Air Force facilities and personnel can be minimized. To meet the needs of the entire populace, a joint project should be established with the U. S. Weather Bureau, the Air Weather Service, and interested college research agencies as the logical participants. Although large expenditures would be involved, the possible reduction in property damages, personal injuries and deaths that could be achieved would more than outweigh the costs.

If it is decided to establish a network of permanent tornado tracking stations, each station should be equipped with the following instruments:

1. A high frequency direction finder with a visual presentation on a cathode ray tube. This instrument would permit an operator to visually determine the direction of the greatest sferic activity.

2. Three high frequency stroke counters. One should be used for overall surveillance, while the other two would provide the capability of observing a particular storm, or could be used as standby equipment.

3. A low power radar. The range limitations involved with such a radar would be offset by the compensating advantages. With this type of gear it would be much easier

to plot a squall line or to identify a particular thunderstorm cell, since only the more intense precipitation echoes would be present on the scope.

4. A panoramic receiver, as discussed above. This would provide a dynamic means of detecting the development of a tornadic condition by the shift in frequency of its sferic radiations.

5. An inter-communications system. A telemetering network as is being pioneered by the Air Weather Service may prove the most effective way of providing this need. Of course, there probably would still be a need for a phone service between the various stations and the net control station.

6. A standby power system. This need is obvious, because of the propensity of electrical storms to render local power systems ineffective.

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TYPIST PAGE

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