THE SFERIC-RADAR METHOD OF STORM DETECTION
APPLIED TO FLYING IN HAZARDOUS WEATHER

By

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PREFACE

The sight of aircraft flying in the skies over the United States has become quite common during recent years. Every large town and city has one or more military or civilian airports in the vicinity with many aircraft arriving and departing daily. On clear and sunny days one pauses to admire the serene flight of an aircraft high in the skies. On a stormy day an airplane flying low above the ground under a thunderstorm with engines straining and black smoke pouring out the exhausts causes one to stop and watch, and to hope that the airplane will reach an airport for safe landing.

Hazardous weather conditions have come under increasingly detailed study during the past decade. Two U. S. Air Force officers, Lt. Col. E. J. Fawbush and Major R. C. Miller, began a detailed study of severe thunderstorms and tornadoes in 1948. At that time a devastating tornado unexpectedly struck Tinker AFB at Oklahoma City causing millions of dollars in damage to aircraft and equipment on the airfield.

Earlier studies had been made by civilian scientists and just one year before the Tinker AFB tornado, Dr. Herbert L. Jones began an investigation of the electrical characteristics of tornadic storms at the Tornado Laboratory at Oklahoma State University. The impetus for the research at the Tornado Laboratory at OSU came as a result of a similar destructive tornado which unexpectedly struck Woodward, Oklahoma in 1947. Dr. Jones and his staff developed the sferic-radar method of tornado detection and tracking. This method attracted the attention of the Air

Force officers at Tinker AFB and resulted in the Sferics Net of the Air Weather Service. This is a network of sferic-radar stations designed to detect and track tornadoes in the central United States.

The team of military and civilian scientists is striving to learn more about tornadoes and their associated weather phenomena in an effort to more accurately forecast tornadoes and to give more advance warnings to communities and aircraft which would be affected. The purpose of this study is to correlate with existing capabilities certain phases of the research being done and to propose a system which will provide immediate tornado information to a pilot flying in an area of tornadoes.

The writer would like to express his gratitude and appreciation to Dr. Jones and Mr. H. D. Lovelace of the Electrical Engineering Department and to Lt. Col. Early and Major Edwin B. Dickson of the Air Weather Service.

Dr. Jones supplied valuable guidance and much needed encouragement as well as excellent sources of reference.

Mr. Lovelace, the Project Engineer, carefully explained the function and operation of the various research instruments at the Tornado Laboratory.

Lt. Col. Early, commander of the 6th Weather Squadron, took the author on a tour of the weather station at Tinker AFB and explained the operation of the severe weather warning network.

Major Dickson of the SWWC provided valuable weather data for many of the tornadoes discussed in this study.

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CHAPTER I

HAZARDOUS FLYING WEATHER

Thunderstorms, tornadoes, and other severe weather conditions have plagued aviators since the Wright brothers first made their successful flight on 17 December 1903. In fact, one of the first recorded crashes of a flying machine due to adverse weather conditions was just a few months earlier when Samuel P. Langley was attempting his first flights. On one of these occasions a gusty wind caused him to strike a portion of the ship from which he was trying to launch his flying machine. From these early days when man flew only a few hundred feet above the ground to the present time when he can fly many miles above the earth, mankind has been trying to learn more about the great ocean of atmosphere, hundreds of miles deep, that engulfs the planet.

Deprive man of his atmosphere and he dies like a fish lifted from the water. Raise him only four miles from the earth and he dies in just a few minutes from lack of oxygen. Raise him a few miles higher and he dies violently of his own internal pressures. Above 50 miles or so a man or any living creature, situated in space without the protective cover of the atmosphere, would be broiled to death on the side facing the sun and frozen solid on the other side.

Without the atmosphere there would be no winds, clouds, or rain; nor would there be fire or sound. The atmosphere serves as a protective canopy that shields the earth from the violence of the sun by absorbing most of its harmful short wave emissions. At night it imprisons the heat of the day and prevents it from spreading away into space. Without the atmosphere the maximum daytime temperature of the earth might reach that of the moon--a searing 230 degrees Fahrenheit--and plunge at night to a minimum of minus 300 degrees Fahrenheit. The atmosphere catches and consumes by friction virtually all of the 100 million meteors which fall into the earth's gravitational field each day from outer space (1).

Because aircraft enabled man to observe weather situations high above the earth's surface, this new vehicle had the effect of accelerating his understanding of weather phenomena. Thus, from his flying experience, man began to assimilate and organize facts about the atmosphere and its associated meteorological phenomena.

Severe Weather Conditions

Weather adverse to the safe performance of flight has been studied and analyzed from the very beginning of the advent of flying. This weather has been grouped under the general heading of "severe weather" and it may be defined as that weather producing the phenomena of tornadoes, thunderstorms, turbulence, hail, sleet, snow, and strong wind gusts. The intensity of these phenomena, the time of day or night encountered, the type of aircraft flown, and the physical and mental stresses of the pilot at the time of encounter all combine to determine the degree of severity of the weather. For example, the pilot of a small aircraft entering an area of 20 miles per hour vertical drafts would consider this to be severe weather while the pilot of a heavy bomber would consider it as only slightly bumpy or turbulent.

The movement of the surface wind at variable speeds and directions are termed "wind gusts." These phenomena usually occur over irregular terrain or they may be produced by unequal heating of the earth's surface. The latter is more pronounced on a hot sunny afternoon in the western states over areas interwoven with cultivated fields, pastures, and wooded areas.

Moisture in the forms of rain, sleet, snow, or hail can occur in almost any cumulus type cloud and at any time of the year. The cumulus type of "cumuliform" clouds are cauliflower-shaped in appearance with appreciable vertical development and dome-shaped upper surfaces. They are characteristic of unstable air and are produced by rising air currents; however, the space between them is characterized by descending air currents. The extent of the vertical development of cumuliform clouds is usually indicative of the intensity of the associated turbulence.

Thunderstorms

The most hazardous types of severe weather are to be found in thunderstorms and tornadoes. All of the elements of "severe weather" are found in thse phenomena, varying only in intensity. The most common of these phenomena is the thunderstorm because of its frequency and occurrence in all parts of the world. It has been estimated by Brooks (2) that there are about 44,000 thunderstorms each day, approximately 1800 going on at all times.

The electrical charge within a thunderstorm is very great. An indication of the intensity is seen in discharges observed as lightning strokes. Wright (3) has stated that the thunderstorm is the generator of the earth's electrical system. As the 44,000 daily thunderstorms are neutralized by discharges to earth, the earth's relative potential is increased. This charge leaks off the earth in the form of free ions which exist in great quantity in the atmosphere. The ions rise under the influence of convection and the fair weather electric field which exists between the earth and the ionosphere.

Very little was known about the physical structure of thunderstorms until the advent of the aircraft. By the time of World War II, aircraft had been developed to a point where it was possible for the average pilot to fly in weather without visual reference to the ground or horizon and at altitudes on the order of 30,000 feet. During these years many pilots encountered thunderstorms and were able to give various details of their physical properties. From these reports and from ground observations, many conflicting theories were developed as to the physical structure of thunderstorms. Since this subject was of great concern to all aviators, the various national aviation organizations suggested that a detailed study be made of thunderstorms. As a result the "Thunderstorm Project" (4) was initiated early in 1946 by the Air Force, Navy, National Advisory Committee for Aeronautics, and the Weather Bureau.

Under the able direction of Dr. Horace R. Byers of the University of Chicago School of Meteorology, a very thorough investigation was made by many aircraft flights through thunderstorms at various altitudes, directions, and stages of development. Special instruments were designed and placed on board the aircraft; other instruments were used on the ground to correlate the data obtained from the aircraft. The project was conducted in Florida in the summer of 1946 and in Ohio during the summer of 1947. The findings were largely confirmed by questionnaires during 1953-54 from pilots flying through more than 50,000 thunderstorms. The following discussion is based upon the report of the Thunderstorm Project.

Thunderstorms generally have the same physical features regardless of location or time. However, they do differ in intensity, degree of development, and in associated weather such as hail, turbulence, and electrical discharges. They are usually classified according to the manner in which the initial lifting action is accomplished. The two broad classifications are the frontal and the air mass thunderstorms. The degree of development is usually described by three stages; progressing from the initial stage to the dissipating stage and classified as the cumulus stage, the mature stage, and the anvil stage.

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

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

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

Vertical drafts create turbulence which is the main concern of pilots flying through thunderstorms. In the initial stage the drafts within the convective cells of the thunderstorm are almost entirely updrafts. In the mature stage there are both updrafts and downdrafts occurring in adjacent areas throughout most of the thunderstorm which cause severe turbulence to be experienced in flying through a mature thunderstorm. In the latter part of the dissipating stage the drafts are mostly downdrafts creating only moderate to light turbulence.

Tornadoes

The most severe phenomenon of all weather is the tornado. W. J. Humphreys (5) states that the tornado is the vost violent, least extensive, and the most sharply defined of all storms. He defines the tornado as a slightly funnel-shaped, hollow, circular column of upward spiraling winds of destructive velocity. Although maximum wind speeds associated

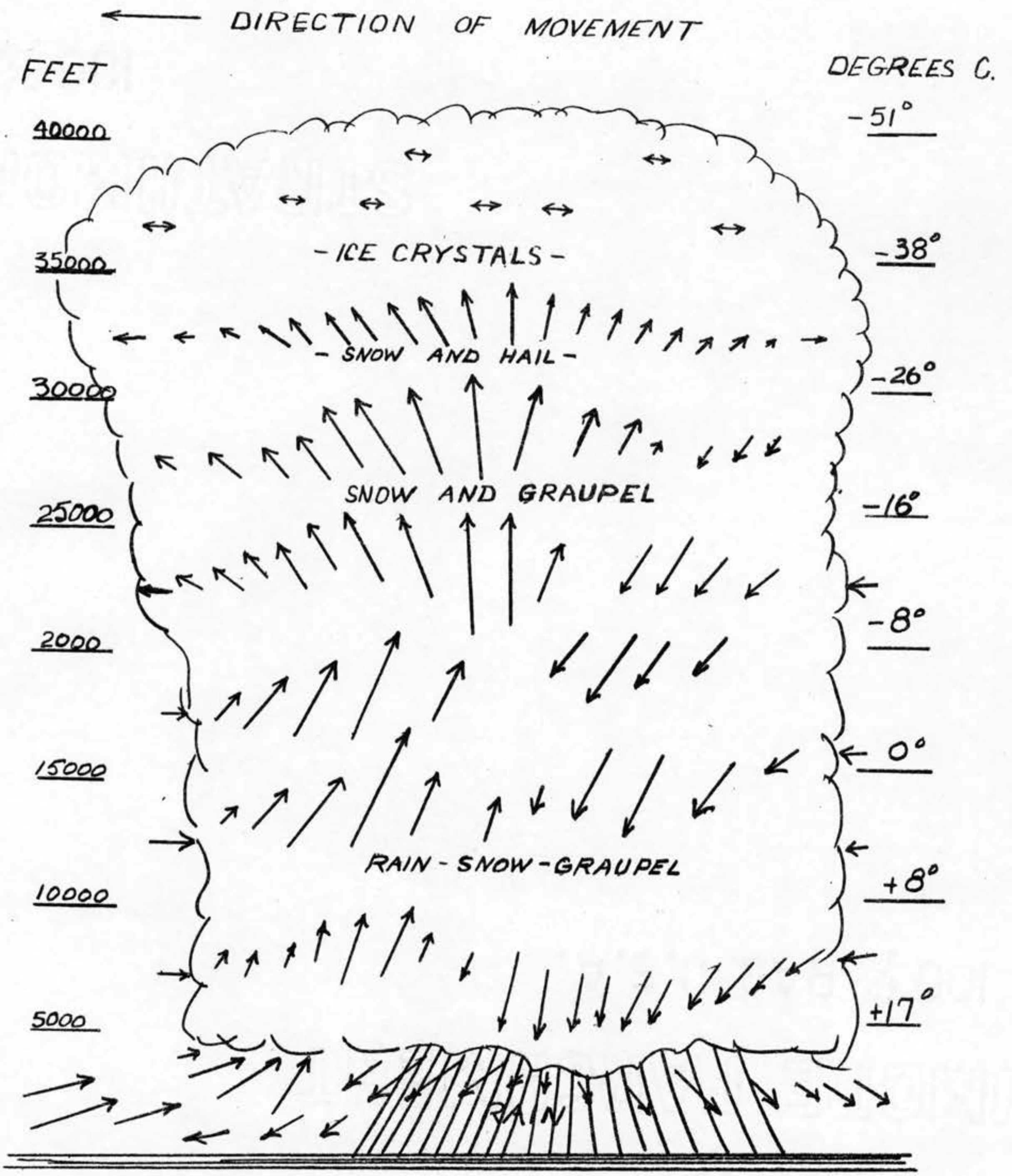


Figure 1. An Idealized Diagram of a Mature Thunderstorm Showing Wind Vectors and Precipitation Content

(Taken from The Thunderstorm, Report of the Thunderstorm Project. U. S. Government Printing Office, Washington, D. C., 1949. p. 23.)

with tornadoes have never been measured, property damage and other effects indicate that they probably exceed 500 miles per hour.

Tornadoes are rare in most areas of the world and common only in certain portions of the United States; they occur most frequently in the Middle West and Southwest. However, they also occur in the Southeastern states and occasionally have been reported in Southern Australia. As as example of the number of tornadoes occurring in the United States, the U. S. Weather Bureau (6) recorded 918 tornadoes in the year 1955.

Some of the physical characteristics of a tornado are described by J. S. Hutchinson (7) as follows:

(1) The previous humidity is excessive, making the air sultry and oppressive for hours or even days before.

(2) The clouds are heavy cumulonimbus; which are necessary for the formation of a funnel-shaped cloud. Sometimes this cumulus is isolated and very towering. When not isolated it is often preceded by mammatocumuli for an hour or longer.

  (a) A cumulonimbus cloud is a cumulus from which heavy rain is falling.

  (b) Mammatocumuli clouds are cumulus in reverse; low pockets in the cloud form as a result of localized down drafts caused by snow and ice that may have drifted in from an adjacent cloud.

(3) The precipitation consists of rain or hail which occurs for a period of 10 to 30 minutes before the tornado. This is followed by heavy rain and hail shortly thereafter.

(4) Lightning nearly always accompanies the tornado but seldom occurs in the funnel cloud.

(5) Associated sound is nearly always in the form of a loud rumbling or roaring noise while the whirling pendant cloud is touching the ground, or is close to it.

The size of the tornado funnel ranges from about 100 feet to half a mile or more in diameter. The ground path is usually on the order of 20 to 40 miles or less in length. The tornado usually moves with a speed of 25 to 50 miles per hour.

Tornadoes, like thunderstorms, must have certain meteorological conditions existing before they can be formed. There have been many theories advanced on what these conditions must be. The most recent, and most widely accepted, are described by Fawbush, Miller, and Starrett (8) and are as follows:

(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. This is a moisture wedge or ridge.

(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 action.

A summary of the conditions necessary for the formation of a tornado was printed in an article by Mather Eakes as told to him by Fawbush and Miller (9) and gives a concise statement of the physical concepts of a tornado:

> Precipitation starts in the top layer of cool, moist, dense air. When it falls through the second layer it cools the dry air very rapidly.
>
> Air from the top and middle layers starts down as the air from the bottom starts rushing upward. The air from the top turns in a corkscrew motion. The air from the lower level meets the descending air and, in the area of contact, sets up the funnel. The funnel becomes visible because moisture is condensed in the action between them.

It can be concluded from these pages that the severe weather phenomena described can be very conducive to presenting hazardous conditions for aircraft on the ground as well as in flight. The next two chapters give a visual description of the thunderstorms and will discuss some of the effects of hazardous conditions to our aircraft.

CHAPTER II

VISUAL DESCRIPTION OF A THUNDERSTORM

During the afternoon and evening of Thursday, 5 June 1958, the author had the opportunity of flying an Air Force T-33 jet trainer in the vicinity of a thunderstorm area composed of isolated thunderstorms and a frontal thunderstorm system. The time of these observations was from approximately 1600 CST to 2100 CST, sunset being at approximately 1915 CST.

The afternoon observation included a large thunderhead several miles west-northwest of Enid, Oklahoma and two or three much smaller and farther to the southwest of Enid. A frontal system to the north-northeast was moving from the north to the south. At approximately 1800 CST the large thunderhead met the frontal area and they both moved off slowly to the east. This system is shown in Figure 2 and will now be described in more detail.

Frontal Thunderstorm System

Apparently the large thunderhead was contained in an air mass which was moving to the east, this air mass being sufficiently strong to overcome the force of the frontal system moving to the south. When the two systems met, the upper air at approximately 35,000 feet caused the cloud formation at that altitude and above to elongate to the east. There was also a shorter "tail" at the west end of the formation. The entire

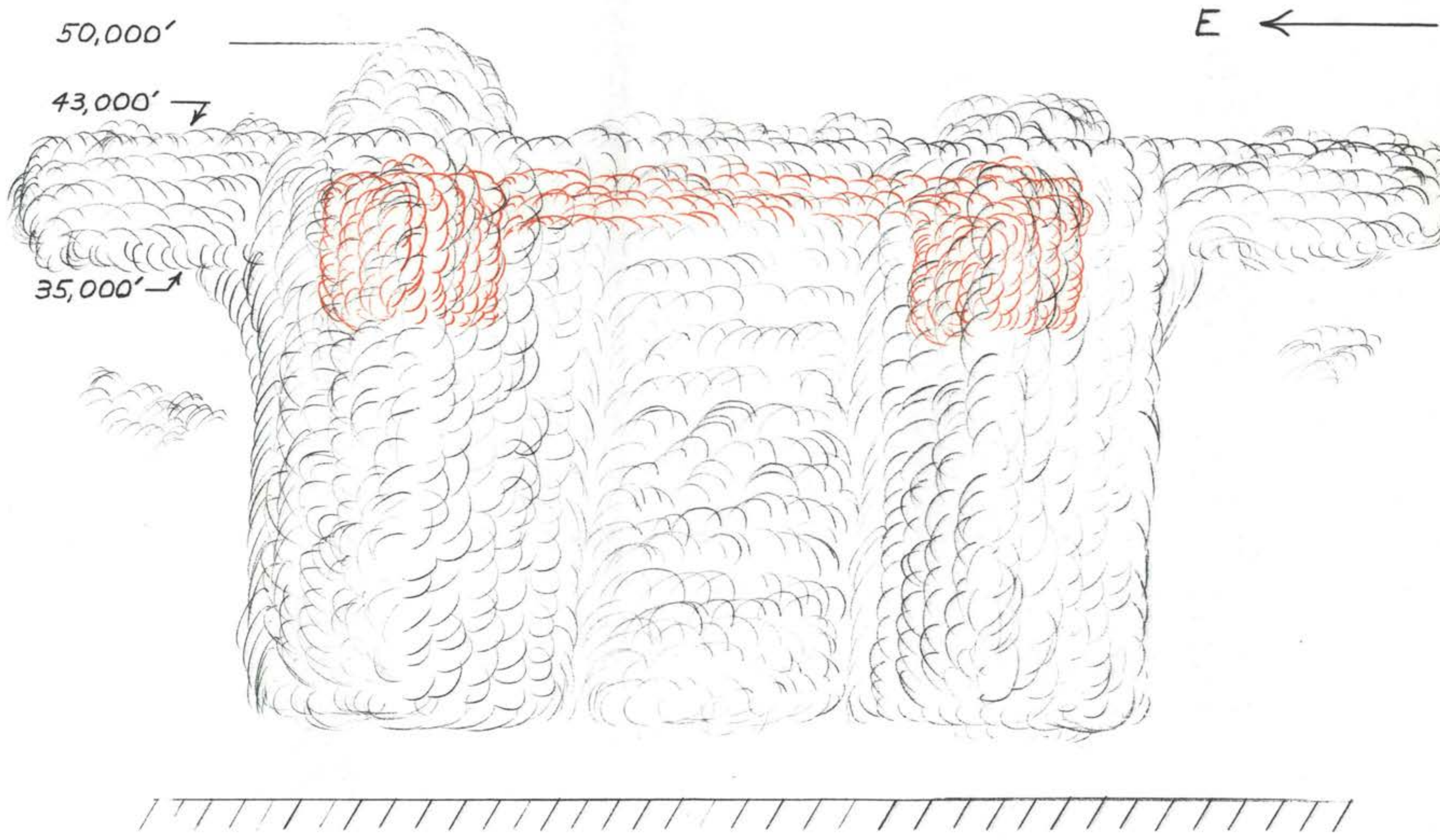


Figure 2. A Frontal Thunderstorm System

system extended from approximately Enid to Tulsa, a distance of about 100 statute miles.

The main body of the air mass seemed to contain one large thunderstorm with other smaller ones, the entire mass being contained in and surrounded by less dense cloud structures, and aligned in an east-west direction as a virtual squall line. The cloud layer above 35,000 feet was quite distinct in the immediate vicinity of the squall line, however, it faded out into a thin haze layer to the north. The haze extended approximately 75 miles from the main body of the storm.

The lightning discharges within the clouds were the primary subjects of the investigation. These discharges will be described as they were observed in the course of the flight around the storm. The flight was from Vance AFB at Enid, climbing on an easterly course along the south side of the storm, then on a northerly course around the east end, and eventually back to the west along the north side of the storm, and finally across the top near the west side.

Shortly after departing Vance AFB at 1710 CST, some lightning was observed around the 20,000 foot level; however this was relatively light in intensity and quite infrequent. No lightning was observed at the lower levels. It is to be noted that the sun was below the horizon at ground elevation and through the middle levels of the clouds; it was shining quite brightly on the upper levels. The lightning observed was just below the sun-line in all instances. The observed discharges rose higher as the sun went further below the horizon, thereby raising the sun-line. Discharges could also be seen in the shadowy areas of the thunderstorms.

One conclusion can be drawn which supports previous similar observations, lightning discharges cannot be seen in bright sunshine. For this reason the intensity of a thunderstorm cannot be accurately estimated in the daytime. Instrumentation, such as the sferics counter, is necessary in order to measure the intensity of such electrical discharges. These measurements will result in giving an indication of the severity of the storm.

Some lightning was observed around the east end of the cloud structures. These discharges were well inside the clouds and consequently produced only brighter glows on the surrounding cloud surfaces; showing no distinct lightning strokes as usually observed from the ground. By the time the observers were abreast of the center portion of the cloud area on the north side, no sun rays were striking the clouds. The aircraft was flying just above the tops of the clouds and glows were occasionally observed from within the denser portions. These are depicted on Figure 2 as the red areas above the 35,000 foot level.

There were occasional "caps" extending above the surrounding clouds and the glows were approximately under these caps. Since the glows were in the denser areas, it appeared that the caps were actually the tops of the more active storm cells.

There were no distinct lightning strokes observed to be associated with the frontal system. There were, however, some cloud-to-cloud or cell-to-cell glow discharges. These were near the tops of the clouds, the length of the discharges was relatively short, and the intensity of the glow was relatively slight. No discharges were observed from the clouds vertically into the upper air, nor within the clouds at lower altitudes.

Similar phenomena, as described in the preceding paragraphs, were observed from the 30,000 foot level and while climbing to the top and over the clouds along the north side. However, one unusual phenomenon occurred which had never before been experienced by the author nor has he heard anyone else speak of it. Vance was reporting clear weather as the sky and stars could be seen from the ground, therefore, the observers in the airplane should have been able to see the lights of the city of Enid and of the airbase from directly above. However, when the aircraft arrived over the base, vertical downward visibility was completely blank and absolutely nothing could be seen toward the ground. The horizon was visible in all directions and the sky was clear above. Then, upon descending some 5,000 feet, the ground suddenly came clearly into view as if descending out of a solid overcast; however, the sky also remained clearly visible. This phenomenon occurred between the approximate altitudes of 45,000 feet down through 40,000 feet.

At this time a very small thunderhead, together with a larger one, came into view to the southwest of Enid. The descriptions of these storms are given in the section to follow.

Isolated Thunderstorm

The time spent in observing the frontal system described previously consumed about one hour of flying time and, as there was sufficient fuel left for another hour of flight, it was possible to examine the two isolated thunderstorms. The smaller one is mentioned only because of its uniqueness. Due to the fact that the night was very dark, since the moon did not rise until about midnight, even the smallest lightning discharges could be seen. The smaller thunderhead was so small that it looked like a balloon sitting up in the clear sky with no other clouds in the vicinity. There were tiny glow discharges frequently visible; these appeared to light up most of the cloud. The cloud structure was at a relatively low altitude, with a top at approximately 18,000 feet.

The other and larger isolated thunderhead was very active and ideal for observation. There were no other clouds in the area and its outline was quite distinct. A sketch of this thunderstorm is shown in Figure 3.

At the beginning of the observation the top of the thunderstorm was around 25,000 feet. Three-quarters of an hour later it was up to about 40,000 feet. Figure 3 depicts several of the phenomena which were observed.

A general description will give a clearer picture to be used in conjunction with the figure. The thunderstorm was lying generally in a west-east direction with a width of about 10 miles and a depth of about 5 miles. It included a cauliflower top overhanging on the eastern and western extremities. During the glow discharges there were separate and distinct dense regions visible both in the upper and lower portions of the total structure. There appeared to be a definite dividing line between the two volumes. The observed electrical activity was confined to each individual volume, with only occasional discharges common to both volumes. During the entire time of observation the top was trailing off to the east, or downwind, giving the appearance of an anvil top that characterizes the dissipating stage of a thunderstorm. The anvil or trailing edge increased in length as the top reached higher altitudes. Since the air flow was generally west to east at the upper levels, and the jet stream started at about 35,000 feet, it can be assumed that the anvil was due primarily to the prevailing upper winds.

Rain was falling from the cloud to the ground and there were occasional lightning stroke discharges to the ground. It was interesting to

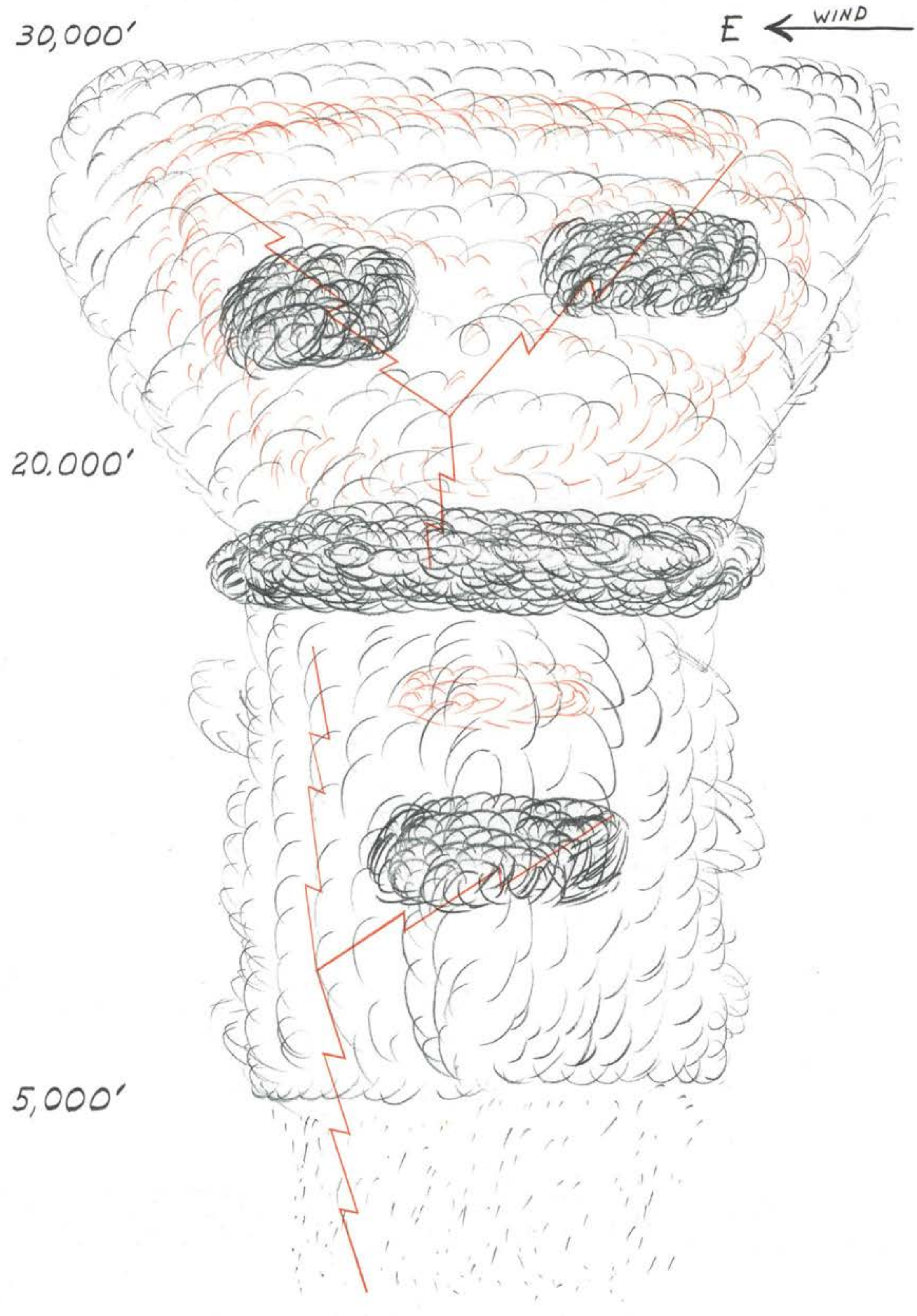


Figure 3. An Isolated Thunderstorm

note that all of these strokes occurred near the eastern or leading edge of the cloud. Most of the discharges were of the cloud-to-ground type. However, a few intra-cloud discharges continued in the lower portion of the cloud structure. Again it appeared that the strokes "fired" at the lower left hand portion of the cloud, shooting discharges into the cloud or to the ground.

In each case of inner-cloud lightning there were, as indicated in the figure, two distinct paths taken. One route was upwards and to the right, the other vertical or slightly to the left. The only visible dense area of the lower volume was approximately in the center.

The division between the two volumes conisted of another less dense volume; only rarely did the lightning strokes penetrate through this boundary volume to produce a discharge common to both the upper and lower portions. Glow discharges below the division were also rare and, when visible, occurred just below the division.

The upper portion was considerably more active. At the stage of development shown in the figure and for a period of 10 to 15 minutes afterwards, the lightning stroke discharges were very rapid, occurring possibly every five to 10 seconds. These strokes followed two distinct upward paths as illustrated in the drawing with a shorter path below.

Glow discharges occurred almost continually during this period of time. The entire upper portion of the cloud would be illuminated to produce an effect similar to the "ball of fire" frequently referred to by other observers. In retrospect it is recalled that the two darker volumes shown, as well as the dividing area, could have been the regions of intense activity of the storm, with the glow discharges taking place on the far side from the observer. This surmise is supported by the observed fact that the glow appeared to cover the background of the cloud, the darker areas being visible, giving a sense of depth to the overall view.

Glow discharges also frequently occurred independently across the top of the cloud. These appeared to illuminate instantaneously the entire length of the cloud top, and were different from the strokes which progressed through the cloud. In most cases the glow was not just an on-off discharge but a relatively rapid oscillation or flickering discharge. In the case of the "ball-of-fire" described in the preceding paragraphs, there was a continual glow, with frequent and more intense illuminations similar to a fire to which a branch of dry leaves has just been added.

During the "ball-of-fire" period, the perifery of the cloud was distinctly visible. The upper portion could be described as an elliptical half-shell with the darkened edge towards the observer and the concave portion illuminated while the two dense cells were suspended in a plane with the observed edge of the shell.

CHAPTER III

EFFECTS OF HAZARDOUS WEATHER ON AIRCRAFT

Hazardous weather described in the preceding chapters has various adverse effects on the structure of the aircraft, and on the crew, the passengers, and the cargo. The most sensational effect, and the one most commonly announced through news media, is that of total destruction through a fiery crash. There are many other less sensational effects which plague the life of a pilot almost daily and some of these will be discussed in the following paragraphs.

Wind Gusts

Wind gusts are described as movement of the surface wind at variable speeds and directions. The pilot or ground crew normally can cope with any steady surface wind of the usual maximum velocities of approximately 50 miles per hour. A stationary aircraft on the airport can be "tied down" with ropes from installed fittings on the aircraft to stakes in the ground, or two "wing walkers" can hold the wing tips of light aircraft while they are being taxied into the hangar. Sudden strong gusts, however, exert such large instantaneous forces on the wing and tail surfaces that neither wing walkers nor tie down ropes can hold the aircraft. It will break away and be damaged by turning over or by being blown into other parked aircraft.

Wind gusts create the most hazardous conditions for flying aircraft during the approach for landing. When the plane is near the ground and a strong wind of constant velocity suddenly stops, the aircraft may strike the ground short of the runway with extensive to total damage. Conversely, a sudden strong gust immediately after landing can be just as dangerous when the aircraft may be tipped over while traveling more than 100 miles an hour.

Visible Moisture

Visible moisture includes such weather phenomena as rain, snow, sleet, hail, fog and clouds. These phenomena can be classified as "restrictions to visibility" as the pilot's reduced ability to see is usually the most adverse effect caused by them. As an example of the limited visibility caused by such weather, a comparison can be made to driving an automobile at a high rate of speed during a heavy downpour from a thunderstorm. Hail also can cause aircraft structural damage in the air as well as on the ground and in many instances it has broken windows or damaged radio antennas and control surfaces.

The problem of reduced visibility is most critical at night when approaching for a landing under fog or low cloud conditions. The recent crash of an F-86 at Amarillo, Texas on 17 April 1958 well illustrates this point. The pilot of this Air Force jet fighter plane was making an approach to the airport as the nearest place to land when the plane was about out of fuel. There was an almost solid mass of clouds from approximately 40,000 feet down to within 400 feet of the ground. The pilot had only enough fuel for one try at landing, which if perfectly timed and accurately executed could have been accomplished. Apparently he was not in a position for landing when he came out of the clouds where he could see the airport below him. As he could not land he attempted to make another approach, however, the plane ran out of fuel and the pilot safely bailed out letting the plane crash in an open field.

A thick ground fog is the most hazardous condition of restricted visibility as the pilot can make only a "blind" landing, having to depend entirely upon assistance rendered by personnel and equipment on the ground. A pilot will attempt a landing under such conditions only as a last resort in the case where he does not have sufficient fuel to fly to another airport and if he has passengers aboard who are not able to bail out for a parachute landing. Examples of the inability to bail out are in commercial airliners where parachutes are not carried on the airplane, and on military aircraft carrying wounded or otherwise incapacitated patients who are unable to use a parachute.

Two types of assistance provided by ground personnel and equipment are currently available. The first type, the Instrument Landing Approach System (ILAS), depends entirely upon equipment which transmits signals to an instrument in the aircraft cockpit. The aircraft instrument indicates relative azimuth and elevation deviation from a predetermined glide slope. The glide slope is a transmitted radio beam making a two and one-half degree angle with the horizontal (ground) and aligned with the longitudinal axis of the runway. Thus a pilot, by monitoring this instrument along with the other instruments in the cockpit, can "ride the beam" down the glide path and touch the runway in a landing position. If the ground visibility is then sufficient, the pilot can keep the airplane on the runway and stop it before he reaches the farther end to accomplish a safe "blind landing."

The second type of ground assistance for a blind landing is the Ground

Controlled Approach (GCA) system. The ground equipment consists of a radar unit which locates the aircraft when it approaches or enters a control zone. On the final approach it gives accurate information for lateral and vertical guidance to the end of the runway. The radar scope has lines superimposed upon it to indicate the desired glide path. The pilot maintains the required approach path by following instructions from the ground operator. If the ground radar is functioning properly, the ground operator is enabled to give accurate and timely instructions. By following these instructions, the pilot can make a safe "blind landing."

It is noted that both types of ground assistance are called approach systems. This indicates that they are designed to aid the pilot in approaching the airport for a visual landing. A blind landing is made only in an emergency and as a last resport.

Thunderstorms

Thunderstorms are of more concern to the aviator while flying enroute to his destination. Normally the Air Weather Service reports or forecasts severe thunderstorms in a given area and the pilot simply avoids that area. In the event that there is a severe thunderstorm at the destination, the pilot is usually so advised by some radio station enroute or when he calls the airport prior to his arrival. In either case he will know of the severe weather condition well before he is committed for a landing and usually he can fly to another airport which has better weather conditions. The unexpected encounter with thunderstorms occurs when flying over areas where the weather reporting stations are far apart. Unfortunately these dangerous regions are located in the Great Plains area of the United States where thunderstorms reach their maximum intensity.

An unexpected encounter with a severe thunderstorm and the associated severe turbulence has a definite psychological effect upon the pilot. He is usually flying in clouds so dense that he cannot see beyond his wing tips when the unexpected encounters occur. The aircraft is suddenly pelted with hailstones and the resounding noise is most disconcerting. The severe turbulence causes the airplane to bounce violently. From his shocked condition the pilot tries to keep the airplane in straight and level flight by reference to his instruments but they are also bouncing violently in the instrument panel. After a few moments the initial shock wears off and the experienced pilot usually continues the flight to reach less turbulent conditions. Structural damage from hail and lightning rarely causes an airplane to crash, however, the psychological effects create extreme nervous tensions which must be overcome for a safe continuation of the flight.

Tornadoes

The most vicious weather encountered by an aircraft in flight is the tornado. No pilot would deliberately fly into such a storm as it would mean almost certain destruction. The violent vertical and circular winds would cause him to lose control of the aircraft by disrupting the airflow or damaging the control surfaces. There is only one recorded instance (10) in which an aircraft flew into a tornado and from which any of the crew members survived the ordeal. This flight occurred on 27 April 1954 and the tornado was encountered west of Oklahoma City in the vicinity of Weatherford, Oklahoma. Two veteran Air Force pilots, Colonel Harrison R. Thyng and Major Hubert C. Vantrease, en route through Oklahoma to Hamilton Field landed at Tinker Air Force Base in Oklahoma City in order to refuel their T-33 jet trainer airplane.

The weather conditions, as reported by the U. S. Weather Bureau (19), during the afternoon and evening of that day included some severe weather activity. Excerpts from the weather report show "Tornadoes, high winds, torrential rains and some hail belted Oklahoma for the second straight day. At least one twister was sighted in the state--a funnel which dipped briefly to the ground 10 miles northwest of Sulpher. The U. S. Weather Bureau placed the southwestern and south central section of the state under tornado alert at 1900 as a squall line developed out of north Texas and pushed into Oklahoma. The severe weather warning covered an area bounded by a line from Hollis to Eufaula to Tuskahoma to Randlett, and back along the Red River to Hollis. Almost an inch of rain fell at Clinton during a deluge beginning at 1930 accompanied by light hail." In another comment on the weather Oklahoma was reported to have had five tornadoes although only the one near Sulphur was pinpointed, the time of occurrence being 1645.

The above weather conditions had been generally observed by Col. Thyng as he flew into Oklahoma City from Dayton, Ohio. The proposed route west from Oklahoma City, as shown in Figure 4, was planned to be north of the most severe weather observed earlier when he reached Tinker AFB. The two pilots took off at approximately 1900 CST with Col. Thyng at the controls and Maj. Vantrease in the rear cockpit. About 10 miles west of the field they entered a normal overcast, and expected to reach the top of this cloud structure at around 20,000 feet. They were still in the clouds at 21,000 feet and at 24,000 feet they suddenly encountered very dark clouds and severe turbulence.

The aircraft should have been climbing at 500 feet per minute but the rate-of-climb indicator showed a climb in excess of 6,000 feet per minute.

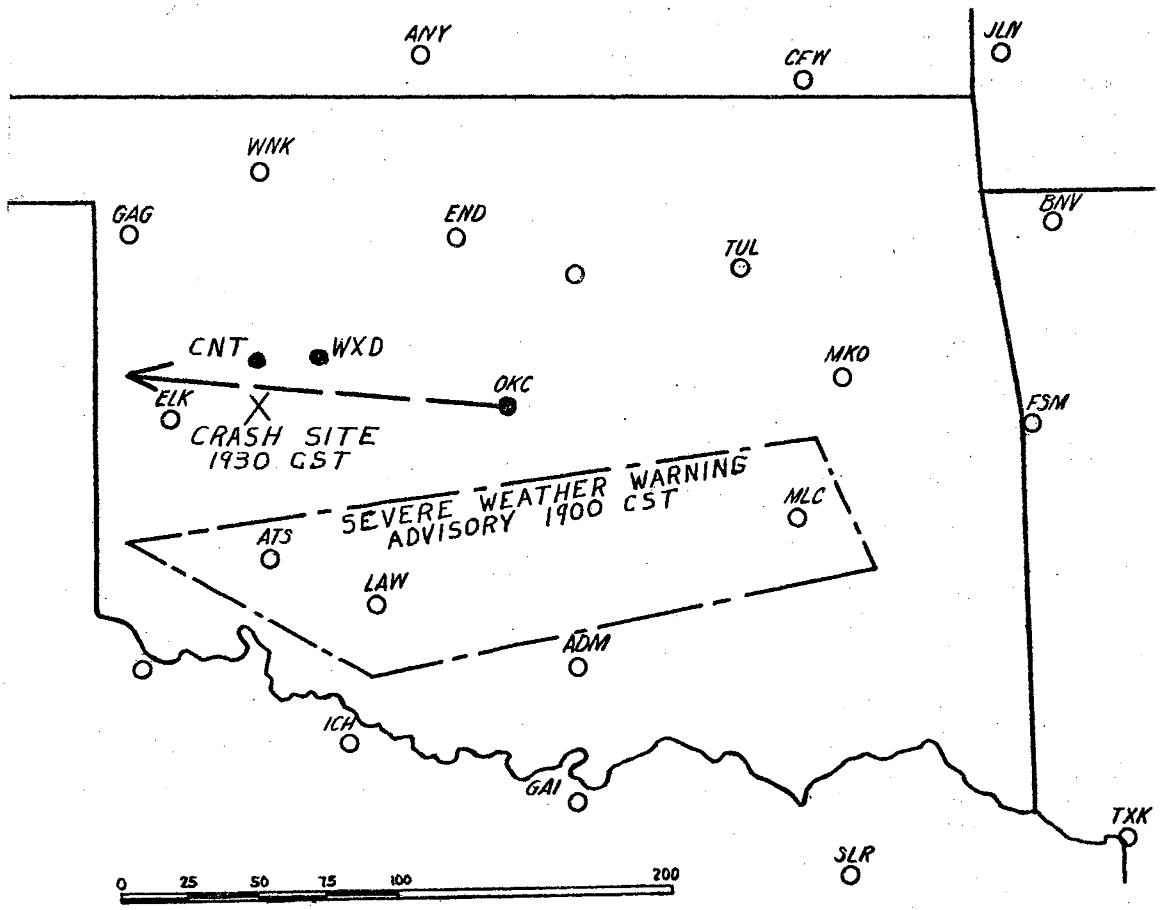


Figure 4. Colonel Thyng's Flight and Associated Weather

This definitely indicated an unusual condition and Col. Thyng states that "at this time the airplane suddenly snap-rolled to the right and then continued into a series of very violent snaps, first to the right and then to the left. Next we found ourselves in what appeared to be a crazy twirling motion maneuver." The altimeter showed them to be losing altitude so they decided to jettison the canopy in preparation for a bail out should that become necessary. When they jettisoned the canopy at some altitude between 20,000 and 25,000 feet, the wind immediately tore away their helmets and oxygen masks. The succeeding moments are best described in Col. Thing's own words.

"We were still experiencing this twirling motion and then the plane would suddenly snap and then keep snapping. I was fighting the controls and trying to fly the plane when it suddenly flamed out. This was undoubtedly due to the tremendous negative G forces that we were being subjected to.

"I was finally able to roll over into what I thought was a level attitude. However, I couldn't hold any semblance of an upright position, because the plane, in spite of control pressures, would snap first to the right and then left.

"The airplane was starting to break up and the hail was absolutely terrific in the cockpit. My face was being cut to ribbons. I couldn't see much, since my right eye was closed and the left one was simply a slit. At about 10,000 feet there was a momentary lull in the turbulence and I sensed that Van was out of the airplane.

"I now tried to eject myself but was unable to get my right hand off the stick and over onto the ejection seat handle. The centrifugal forces were so great that I just couldn't move in that cockpit. Finally, I managed to get my right hand into a position where I could reach and catch hold of the seat handle. I pulled up on the handle and immediately was blown out of the cockpit. . . ."

Fortunately Col. Thyng was able to pull the rip cord and the parachute opened. In spite of the tremendous winds, hail and rain the parachute remained sufficiently open so that he was only dazed when he hit the ground and he was able to get out of the chute before it dragged him around the ground too much. He made his way to a farm house and eventually was taken to the hospital at Weatherford, Oklahoma. In the meantime Major Vantrease had been through similar experiences before reaching the hospital at Clinton, Oklahoma.

Both pilots survived the ordeal and ultimately returned to flying status with this warning to all other pilots: "Don't do what I did!"

Reported instances of aircraft flying into a tornado are quite rare for the reason, as previously stated, that no one on the aircraft lives to tell about it. There are times when a tornado is reported and the wreckage of an aircraft is later found in the vicinity. One of the most recent instances happened on 15 April 1958 when an Air Force B-47 Stratojet bomber exploded in flight near St. Petersburg, Florida during a time when there were several tornadoes in the area (11). The four-man crew was killed, and it can only be conjectured that the aircraft was ripped apart in the tornado and exploded. Major Edwin B. Dickson of the Severe Weather Center in Kansas City was contacted for confirmation of tornadic activity in the St. Petersburg area. In addition to the Severe Weather Advisory which the Center issued, the following comments are excerpts from reports of severe weather in the area:

"Damaging weather reported at 1000 EST 20 miles south-southeast of Tampa (near St. Petersburg) including one-inch hail, heavy rain, and winds at 50 miles per hour.

"McDill Air Force Base, Tampa, reported an unconfirmed tornado sighted 20 miles southwest of McDill at 1100 EST.

"The U. S. Coast Guard reported a tornado 25 miles east-southeast of Tampa at 1220 EST.

"St. Augustine reported a tornado at approximately 1300 EST with many houses blown down."

A similar accident occurred two years ago in west Texas when a B-36 bomber crashed in an area where severe thunderstorms were reported. It is very possible that an unrecorded tornado was encountered. Another incident occurred on 11 June 1958 near Ponca City, Oklahoma (20) when a T-33 jet training airplane crashed in flames out of a severe storm. No tornado was reported until the storm center reached Wichita, Kansas a short time later where a small tornado dipped momentarily to the ground in a residential area. Wichita is approximately 60 miles north of Ponca City.

In addition to those instances where aircraft in flight have been lost due to tornadoes, several airports have been in the path of destructive tornadoes. A tornado unexpectedly struck Tinker AFB near Oklahoma City in 1948 resulting in millions of dollars worth of damage to aircraft on the ground. Another such tornado struck Carswell AFB near Ft. Worth on 1 September 1952 again resulting in millions of dollars worth of damage to aircraft on the ground. In both these cases, had there been adequate warning of an approaching tornado, all of the aircraft could have been flown out of the area of the tornado and there would have been no damage to these aircraft.

From the foregoing discussion, it is seen that there is a great need for an effective system of forecasting, detecting, and tracking all tornadoes. There is also a great need for a system of warning to all aircraft in flight as well as warnings to airports, cities, and communities which might be in the path of a tornado. The next two chapters of this thesis discuss the efforts being made to meet the needs stated above.

CHAPTER IV

THE SEVERE WEATHER WARNING CENTER

The Severe Weather Warning Center (abbreviated as SWWC) was officially organized in 1951 by the Air Force Air Weather Service with its primary objective to warn continental Air Force bases of anticipated severe weather. A secondary objective is to study tornadoes in an effort to learn more about their characteristics, with an ultimate aim of <u>forecasting</u> tornadoes well before they actually occur.

The SWWC sends "Advisories" to all bases to forecast or report the existence of tornadoes, severe thunderstorms, strong wind gusts, turbulence, or hail. The advisory gives the area and time in which these phenomena are expected to occur. It is to be noted that the <u>forecasting</u> of tornadoes is primarily in the stage of tracking an existing tornado and calculating its future course. The art of forecasting tornadoes, hail and destructive thunderstorm gusts has only recently been given more than passing attention. Neither general nor specialized forecasting rules have yet been reduced to a practical formula, and only qualitative rules are available for most prognoses (12).

Last year (1957) the U. S. Weather Bureau and the Civil Aeronautics Authority agreed to make these severe weather warnings available to aircraft in flight. Prior to that time, a pilot on a long flight often and unexpectedly encountered severe weather which developed after he began his flight. Now, however, the various radio stations along the airways receive all severe weather warnings and relay the information to the pilot when he makes his normal position report to them. This makes it possible for him to change his route or planned destination in order to avoid any reported or forecasted severe weather.

A basic warning system has, therefore, been devised to give advanced notice of severe weather. There are limitations to the present system as evidenced by the cited destruction of the B-47 in Flordia and the T-33 in Oklahoma. One limitation is that of time. For example a tornado sighted near Phoenix would be reported to all bases approximately two hours later. At this same time, the information would be available to aircraft in flight and this two hour delay may not give sufficient warning for a flying aircraft to avoid the tornado.

Under the most favorable conditions, a tornado may be predicted as much as two hours prior to its occurrence and residents in the area may be alerted an hour or more before the tornadic conditions fully develop. These forecasts are the results of work being done under the Tornado-Sferic Project at Oklahoma State University and a group of stations in the reporting net of the Severe Weather Warning Center. The work of the latter group is discussed in the following section.

Project Tornado-Sferics

A project to study the sferics in tornadoes has been undertaken by the 6th Weather Squadron (Mobile) at Tinker AFB, Oklahoma. The project is under the direct supervision of the Military Joint Chiefs of Staff, Washington, D. C. and administered through the Air Force Cambridge Research and Development Center, Cambridge, Massachusetts. The main purpose of the Tornado-Sferics project is to locate, identify, track, and determine the intensity of severe storms throughout the midwest United States and provide such data to the Severe Weather Warning Center. At the present time, the net control is located at the SWWC located in Kansas City, Missouri. Other stations of the Air Force net are mobile and are located at sites such as Amarillo, Texas and Ft. Smith, Arkansas. The Tornado-Sferics Laboratory at Oklahoma State University constitutes the fourth integral station of the net. Figure 5 shows the relative location of the various stations in the net.

The results of four years of operation of this project are given in the 1957 Final Report by the 6th Weather Squadron (13). Applicable portions of the report are presented here to give a background for comparison with the work done at Oklahoma State University.

Correlation of the sferics storm locations with radar echoes suggests that the long bursts of sferic pips were received from wave-like perturbations appearing along the squall line. These "waves" apparently formed near the time when the long sferics bursts were first detected and were maintained for one or more hours until the time of occurrence of the tornado or funnel cloud.

Analysis of the sferics film wherein long bursts of 18 or more sferics pips occurred in a 15 second period indicate that 78% of the long bursts were considered verified by the reported occurrence of tornadoes or funnel clouds. The severe activity occurred, on the average, one to three hours after the long bursts were first received.

It is suggested that strong sferics counts are received from a thunderstorm line which exhibits a surge of warm dry air within the middle levels to its rear and a relatively deep moist layer ahead of the line. In most of the cases of strong sferic counts on a squall line, dry air extended above 18,000 feet on both sides of the squall line. Movement of the squall

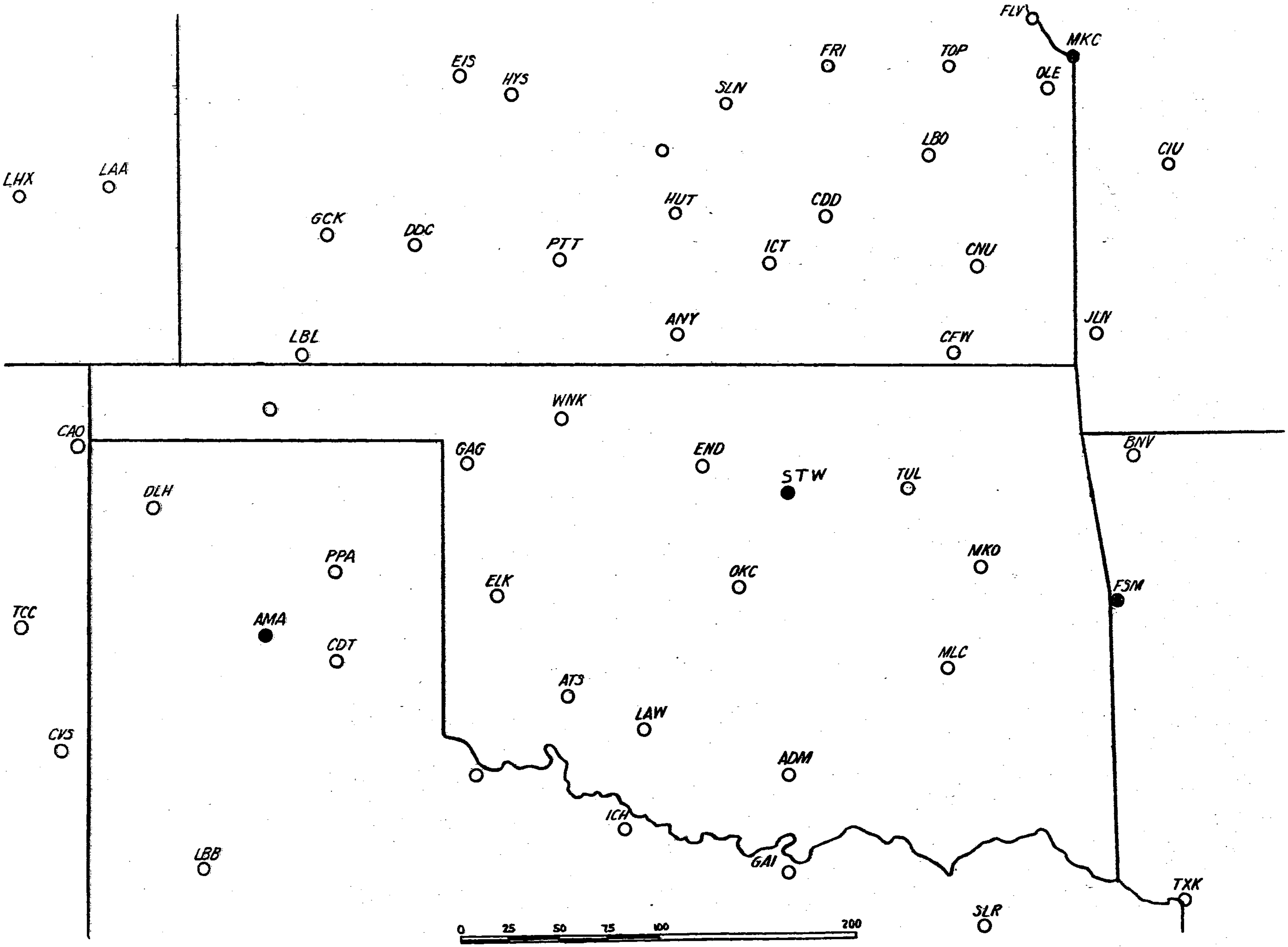


Figure 5. Typical Air Weather Service Sferics Network

line was a minimum of 15 miles per hour. In situations where the dry air surge behind the squall line was shallow, sferics counts were low regardless of the severity of the thunderstorm activity.

The most favorable situation in the past four years for operation of the 10 kilocycle sferics equipment occurred near Austin, Texas on 24 April 1957. A forecast and warning of an impending tornado was sent out nearly an hour before it actually occurred. In this instance sferic counts reached an all-time high value and remained very strong for several hours. At 1000 CST the sferics count increased to more than 40 pips as compared to only 10 pips in the reading taken thirty minutes previously. After processing and analyzing this reading, a sferic severe weather advisory was transmitted at 1037 CST and the first tornadoes were reported about 35 miles northeast of the sferics fix at 1130 CST. For a period of several hours long sferic bursts were read on each run, taken at thirty-minute intervals, and numerous tornadoes were reported from south-central through northeast Texas.

Detection of strong 10 kilocycle sferic sounds does not necessarily indicate the occurrence of severe thunderstorm activity. Conversely, reception of weak 10 kilocycle sferic signals does not insure the absence of developing tornadoes, hailstorms, and other severe storms. In fact, it was determined that the sferics may have provided adequate warning of the development of only 17% of the 155 tornado situations occurring during operation of the sferics network. The most pressing requirement is for improvement of the operational efficiency of sferics in order that it may provide late storm warnings in 70% or 80% of the severe weather situations. Development of new sferics equipment operating at higher frequencies proved to be the best approach to this problem.

The preceding comments indicate the limitations of the 10 kilocycle equipment and suggest continued research with equipment operating at higher frequencies. Such research is being conducted at the Oklahoma State University Tornado-Sferics Laboratory under the direction of Dr. Herbert L. Jones. This phase of research is discussed in the following chapter.

CHAPTER V

THE TORNADO-SFERICS LABORATORY

The urgent need for a method of identifying and tracking tornadoes was realized by Dr. Herbert L. Jones of the Oklahoma State University (OSU) School of Electrical Engineering when a disastrous tornado struck Woodward, Oklahoma in the spring of 1947, killing 123 persons (14). Although the tornado had been in existence for almost two hours and had traveled some 125 miles in the direction of Woodward, the city had not been warned of the approaching destruction.

By the time of the tornado season of 1947, Jones had initiated the Tornado Identification and Tracking Project (15) with the laboratory located near the southeast corner of the Searcy Airport, which is north of the city of Stillwater. A warning system was devised whereby the Highway Patrol and Police forces were notified of existing tornadoes and continually informed of their paths in order that all communities affected would have ample warning of an appraching tornado. In addition to providing a warning system, the project was devoted to research to investigate the frequency spectrum and waveform of atmospheric radiation in severe storms. Atmospheric radiation was given the name "sferics," and consequently the study of atmospheric radiations in tornadoes is called "tornado-sferics."

One of the earlier discoveries resulting from research of the frequency spectrum was the discovery in 1950 of the Jones-Hess high frequency sferics (16). These sferics are located in the electromagnetic spectrum between 150 and 250 kilocycles and have been found to be definite characteristics of severe storms. Related discoveries were made at the Tornado-Sferics Laboratory and theories proposed which contributed materially to the known basic theory of storm phenomena. This work came to the attention of other researchers in the fields of tornadoes and sferics and in January 1952 the Meteorological Branch of the Evans Signal Laboratories awarded a contract to render financial and materiel assistance to the project. With this assistance and through the cooperation of the U. S. Signal Corps, a radar-sferics method of severe storm identification and tracking was developed (17).

The Sferics-Radar Method

The sferics-radar method of identifying severe storms utilizes a radar unit which scans a full 360 degrees in azimuth from the laboratory and which is able to detect any storm clouds within a radius of approximately 120 nautical miles. The storm clouds are presented as a visual picture on the radar scope; each cloud structure is called a precipitation echo. In conjunction with the radar, a sferic counter is used to indicate the severity of the storm. With this equipment the storm can be located and its severity measured to give a relatively accurate method of identifying tornadoes and tornado producing thunderstorms.

The overall equipment arrangement used for identifying and tracking storms is shown in the schematic diagram of Figure 6. The equipment consists of a radar unit, sferic waveform receiver, low frequency direction finder, high frequency direction finder, and the sferic counter. A visual lightning camera has also been used for the past several years. The function of this devise was to photograph lightning strokes within the visual range

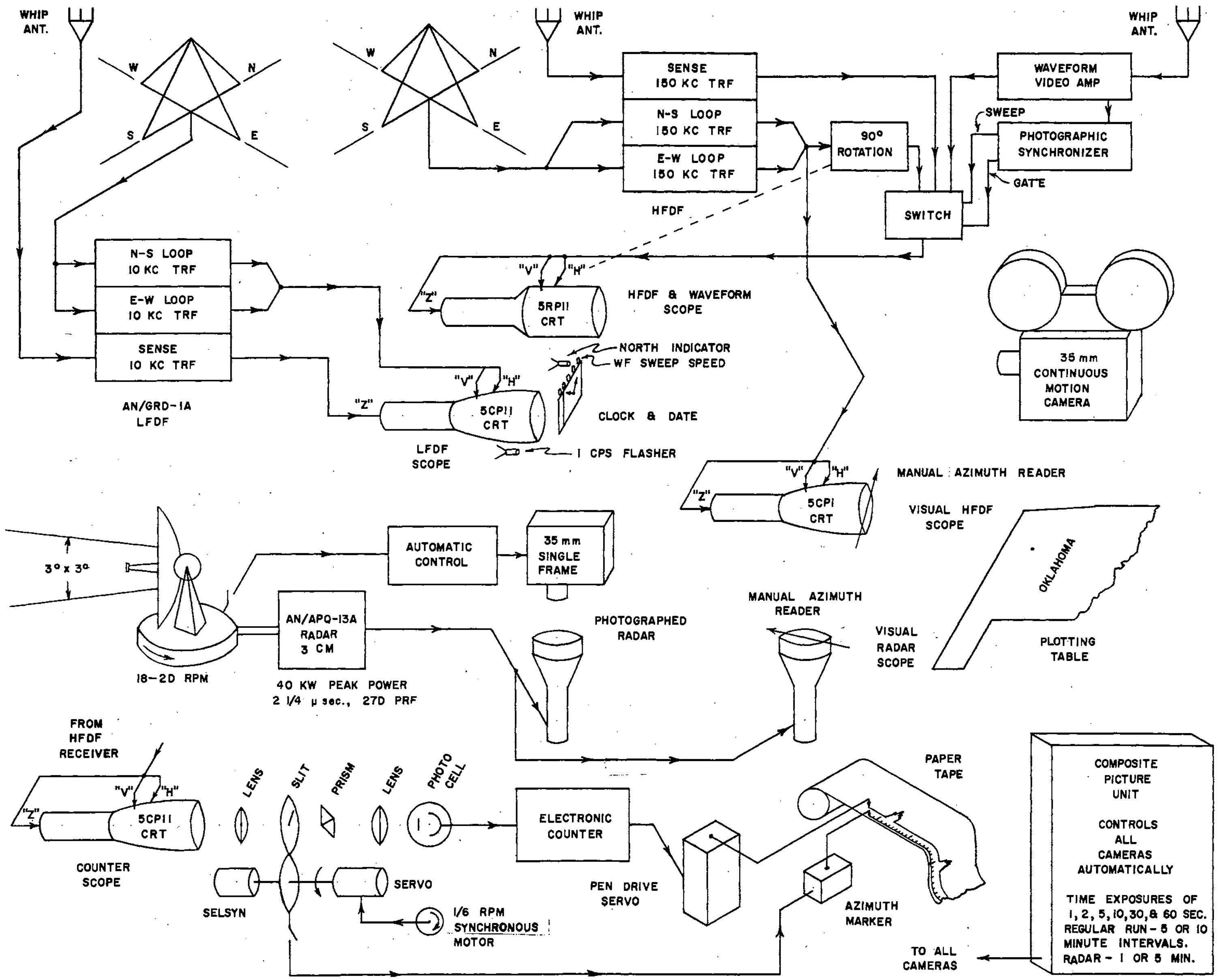


Figure 6. Schematic Diagram of Tornado Laboratory Equipment.

of the laboratory, so that the film could be analyzed and compared with the film record from the sferic camera. The several items of equipment are described in the following sections.

The Radar

The radar unit used for tracking the cloud formations is a modified Air Force AN/APQ-13A. It has a wavelength of three centimeters, a peak power of 40 kilowatts, a pulse duration of two and one-fourth microseconds, a pulse recurrence frequency of 270 pulses per second, an antenna speed of 18 to 20 revolutions per minute, and a beam width of three degrees. The effective range of the radar is about 120 nautical miles. There are two Plan Position Indicator (PPI) oscilloscopes for the radar presentation. One radar scope is in the radar van and is equipped with a relay-operated 35 millimeter single-frame camera to provide a permanent record. Photographs are taken automatically at either a one or a five minute interval. The camera is controlled by an antenna microswitch and the composite picture unit.

The remote radar scope is located near the operator at the plotting table. This scope is provided with a manually controlled azimuth hairline. The echoes of the storm as shown by the radar can then be plotted on the plastic sheet covering a map of the state which is laid out on the plotting table. These plots are made at either a five or a 15 minute interval as desired in accordance with the velocity and severity of the storms being tracked. The time of each plot is recorded on the plastic sheet which is saved to be used on an identical map for later analysis.

Within radar range, the most intense storm centers can be tracked quite accurately; and by projecting the indicated paths, operators can notify highway patrol units to keep a watchful eye on particular areas and provide the laboratory and the public with valuable visual observations.

Sferic Waveform Receiver

Waveforms are displayed on the same oscilloscope that is used for the high frequency direction finder (HFDF). This scope is the 5RP11 Cathode Ray Tube shown in the figure. The vertical whip antenna, which feeds the waveform video amplifier, is shown in the upper right-hand portion of Figure 6. The waveform video amplifier feeds the vertical deflection system of the 5RP11 CRT and also the photographic synchronizer. By means of amplitude discrimination, the photographic synchronizer selects certain higher amplitude sferic waveforms. The synchronizer also generates a time base and an electron-gun gating pulse for presenting the sferic waveform on the 5RP11 CRT when it is in the waveform mode of operation.

The ten-pole switch that selects the mode of operation not only selects the proper deflection and electron-gun control voltages but adjusts the intensity and positioning voltages of the CRT. Thus the camera records simultaneously either the HFDF or the waveform record. This record appears adjacent to the 10 kilocycle record from the AN/GRD-1A. Time, date, sweep speed, and HFDF North indicator recordings appear on the film record at one second intervals. Regular run recordings are made every five minutes for intervals from five to 60 seconds in length.

The electronic circuits for waveform presentation are the antenna cathode follower, the waveform pre-amplifier and filter, the sweep and trigger circuits for the oscilloscope, and the camera control unit. A complete description of these circuits is given in the doctoral thesis written by Kelly (17).

Low Frequency Direction Finder

The sferic equipment consists of two basic units, a low frequency direction finder (LFDF) and a high frequency direction finder (HFDF). The LFDF, depicted in the upper left hand portion of the drawing, is an AN/GRD-1A static direction finder supplied by the U. S. Signal Corps. It is a 10 kilocycle receiver that produces a directional pip on an oscilloscope. The directional characteristic is obtained by using two separate loop antennas crossed at 90 degrees to each other. One loop antenna is oriented north-south and the other is oriented east-west. The two signals from the antennas are fed through balanced and matched radio frequency amplifiers to the horizontal and vertical deflection plates of the oscilloscope.

Because of the nature of crossed loop antennas there is also an output phased 180 degrees from the true signal direction. This undesirable half of the directional pip is blanked off the scope by feeding the amplified output from a sense antenna to the control grid of the oscilloscope. The grid bias is set so that the beam is just visible in the center of the oscilloscope. When the sense signal is positive, the beam is brightened in the correct direction and when the sense signal is negative, the beam is blanked. The relative magnitude of the received signal on each loop antenna is proportional to the cosine of the angle from which the energy arrives. Since the deflection plates of the oscilloscope have the same relative position as the antennas, the resulting directional pip indicates the correct angle. The absolute magnitude of the pip is proportional to both the range and the intensity of the stroke.

High Frequency Direction Finder

The HFDF equipment is similar to the LFDF. The operating frequency is 150 kilocycles as compared to 10 kilocycles for the LFDF. Loop antennas set at an angle of 90 degrees to obtain the directional characteristics are also used in this equipment. The HFDF operates in the same manner as the LFDF although its performance is somewhat better due to improved design features.

Sferic Counter

A unit used in conjunction with the HFDF is the sferic azimuth incidence integrator as described by Jones (21) in a 1956 project report. This unit is usually called a sferic counter and it is used to measure the time rate sferic arrival per azimuth degree. The arrangement is shown in the lower left hand portion of Figure 6. The presentation of the oscilloscope is focused by means of a lens at the plane of a slit that rotates at the angular velocity of one degree per second. This method of scanning eliminates the parallax due to the thickness of the glass at the face of the oscilloscope. The light output from the slit is fed by a prism and lens arrangement to a photoelectric cell.

When sferic activity occurs, light reaches the photocell only from the particular angular location determined by the position of the slit. These light impulses representing the sferic activity produce a voltage in the electronic counter that is proportional to the repetition rate of the sferics. This voltage causes the servo-motor that drives the recording pen to record a corresponding indication on the moving paper tape. A small electrical switch is operated by the rotating slit at intervals of ten degrees to record a calibration marker. These markers are omitted for the azimuths of 90, 180, and 270 degrees. The azimuth of zero degrees is especially designated by the omission of two markers; one at zero and one at ten degrees.

Due to the fact that a synchronous motor is used to control the servo-motor that drives the rotating slit, no check need be made to record the time associated with the recording on the paper tape once the unit has been synchronized with the electric clock. After the storm has passed, these times may be filled in accurately for the permanent record. The operator checks the recording from the paper tape against a scale corresponding to test pulses of known repetition rates. These readings are used to provide an index to storm intensity. The counter has two scales, one for zero to ten pulses per second, and one for zero to thirty pulses per second.

Operation of the Laboratory

A complete description of operating procedures is given by Jones (21) and Roemer (15), therefore, only a brief summary is presented here.

The operator has ample time to put the system in operation since advance warnings are always available from the Severe Weather Warning Center in Kansas City. About an hour prior to operating time a tune-up and alignment procedure is executed. All the direction finding equipment is aligned and all clocks and synchronously driven units are synchronized with the Bureau of Standards Station WWV. Date cards are inserted in the recording units, and all camera equipment checked. Once the system has been properly adjusted for operation, it is only necessary to perform an occasional check to make certain that all scopes are in proper alignment.

Figure 7 shows the position of the sferic operator with some of the associated equipment which he must monitor and from which he obtains data for plotting the storm center locations. The operator records on the plotting record the location of all precipitation echoes that are shown by

Figure 7. View of Sferic Operator's Position
at the Tornado Laboratory.

the radar. He then reads and records the angles for the centers of sferic activity as shown by the visual presentation of the HFDF, noting in particular those angles that appear most active. Next a reading is made of the HFDF counter record on the paper tape (shown on the table in the lower right hand corner of the picture) and recorded opposite the visual HFDF record; these records are checked for agreement. The maximum stroke counts as indicated on the counter record are also recorded to correlate with the visual observations. The angles that show the most intense activity are then indicated on the radar plot of the squall line. This procedure is repeated at regular intervals in order to determine the directional movement of the most active thunderstorms. The radar echo does not indicate the exact path of the severe areas because these areas frequently move along the advancing squall line as well as with the squall line.

These sferic radar readings are made at regular intervals and the information is passed to the SWWC at Kansas City via the direct line telephone seen on the wall in the upper right hand corner of the photograph. When tornadic activity is seen to be developing, the SWWC sends advisories to Air Force bases in the affected area and the staff of the Tornado Laboratory notifies civil authorities.

The effectiveness of the 150 kilocycle direction finder was the subject of a detailed study (22) made by the staff of the Air Weather Service in 1956. A part of the routine operational procedure during the tornado season of 1956 was to exchange data with the Staff of the Sferics Network of the Air Weather Service. These data were exchanged at regular intervals as the severe storms developed. On the basis of these data, communicated immediately as the severe storms developed, an independent analysis of the performance of the 150 KC direction finder was made by the Sferics Staff of the Air Weather Service at Kansas City. The following material is taken directly from the final report compiled after the tornado season of 1956. This reference is a selected section.

> The operational efficiency of the 150 kc sferics equipment at Oklahoma A&M College is far greater than that of the 10 kc sferics. During April 1956 the Oklahoma A&M sferics station read 15 pips per second or greater on 75% of 45 tornadoes and funnel clouds reported within 300 miles of the station. When the sferics frequency reached 20 pips per second or greater, the verification approached 90%. These results indicated that Dr. Jones is making significant progress in development of a consistently reliable technique of tornado detection. In only 25% of the tornado situations cited above did the 10 kc sferics read sufficiently high counts to alert the Tornado-Sferics analyst to the severe nature of the activity.

CHAPTER VI

A SFERIC-RADAR ASSISTED FLIGHT

In order to demonstrate the usefulness and importance to aviation of the sferic-radar method of tornado detection, a theoretical flight will be planned and flown into the areas of the Blackwell and Udall tornadoes of 25 May 1955. This date is chosen as the tornadoes were in the vicinity of Stillwater and excellent data were obtained from the associated weather phenomena.

Planning the Flight

The planned flight is from Albuquerque to Stillwater in a C-45; a twin-engine, five passenger personnel carrier type Air Force light aircraft with a maximum ceiling on the order of 15,000 feet. The flight will take approximately three and one-half hours of flying time and the course is usually along the airways. Figure 8 shows some of the civil airways near Stillwater which could be used. The route from Albuquerque is to Amarillo and then along Airway Green-4 to Gage. From Gage, Red-59 could be taken to Oklahoma City then Blue-5 north to the intersection with Red-11 and direct to Stillwater. Alternate routes could be chosen from those shown in the diagram. The area on the figure is encircled to illustrate the range of the radar unit located at the Tornado Laboratory.

Take-off time is planned for 1645 CST and, since it takes about an hour to become airborne after the weather is obtained, the weather briefing

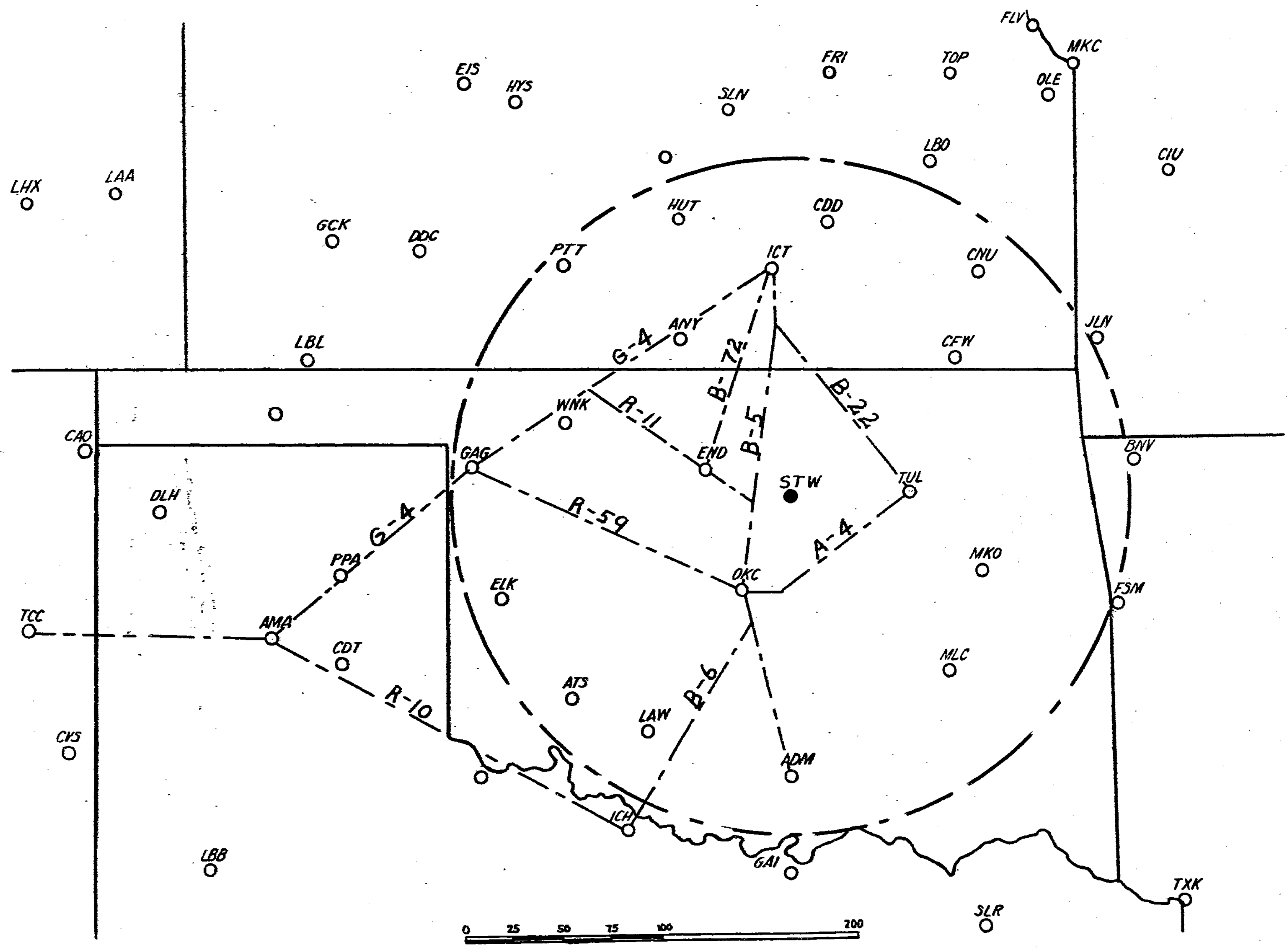


Figure 8. Civil Airways Near Stillwater Showing Range of Laboratory Radar

is scheduled for 1545 CST. A study of the weather charts and weather reports with the forecaster shows that severe weather associated with thunderstorms can be expected generally between Amarillo and Oklahoma City. The Severe Weather Warning Center issued an Advisory at 1200 CST locating a squall line from 30 miles west of Gage to 10 miles west of Altus to 20 miles south of Ft. Sill to Ardmore to 20 miles northwest of McAlister to Fayetteville, Arkansas to Springville, Missouri to Omaha. The portion of this area near Oklahoma City is shown in Figure 9. Isolated thunderstorms were forecast to become more severe in the afternoon with hail, turbulence, and gusty surface winds.

The above advisory was revised by the SWWC at 1430 CST moving the squall line to the west along a line near the cities of Garden City, Dalhart, Amarillo, Lubbock and Abilene as shown in Figure 10. Isolated thunderstorms were reported in the southern portion of the squall line with the most severe activity being 50 miles either side of a line from Guymon to Quanah.

Thirty minutes later, at 1500 CST, another advisory was issued showing an intense thunderstorm area bounded by a line from 30 miles northeast of Dalhart to Dodge City to Ft. Sill to 60 miles southeast of Lubbock and back to Dalhart. Isolated but intense thunderstorms were forecast to remain in the area until 2200 CST; and isolated thunderstorms were forecast to extend eastward over Oklahoma and into Kansas. This advisory is shown in Figure 11.

Analysis of the preceding weather reports indicates that it might be possible to fly through the severe weather area avoiding the isolated but intense thunderstorms by flying around those encountered along the course of flight. It appears that visual reference to the ground can be maintained most of the time although some of the weather reporting stations, such as

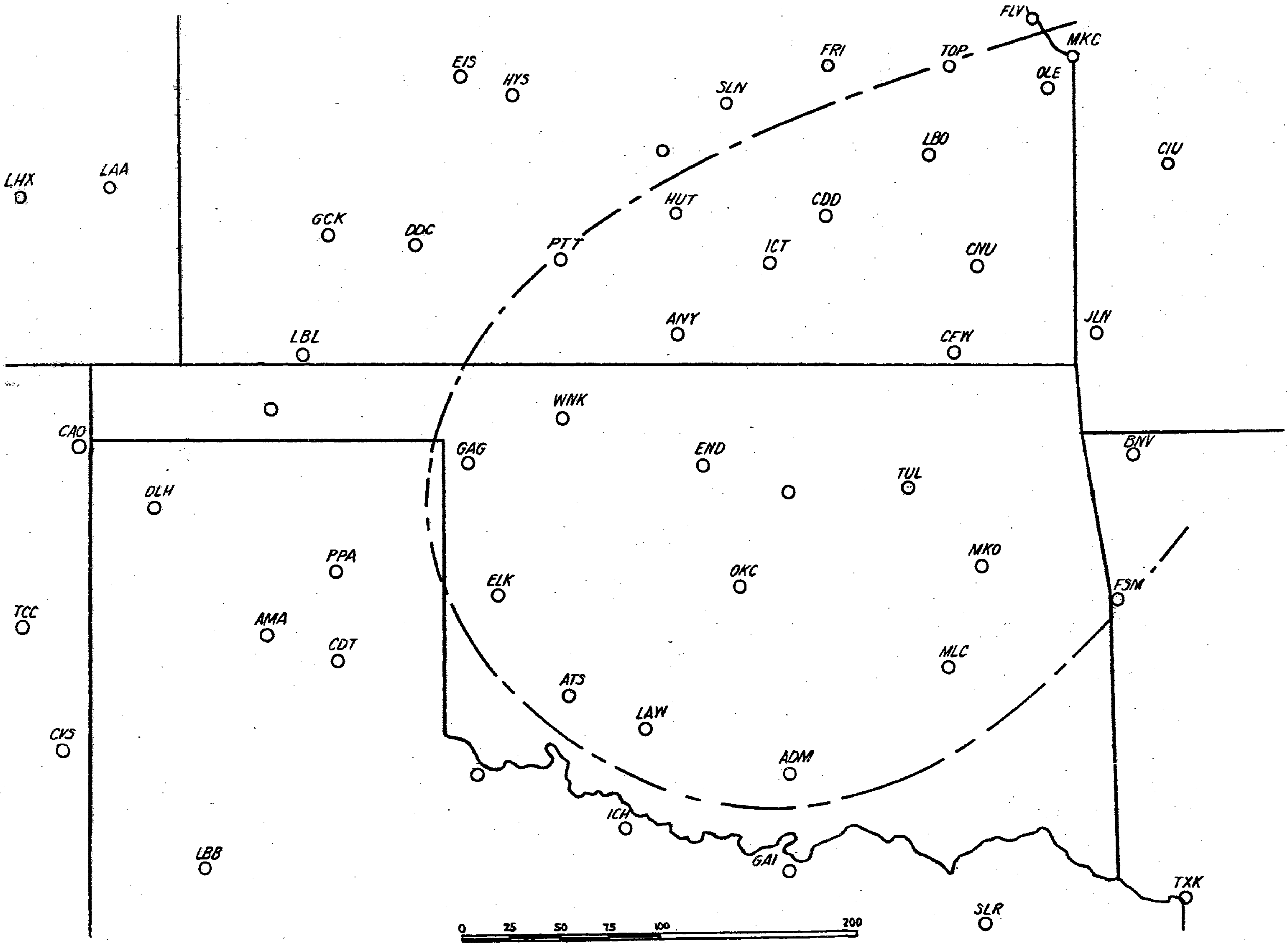


Figure 9. Squall Line Identified in SWWC Advisory of 1200 CST

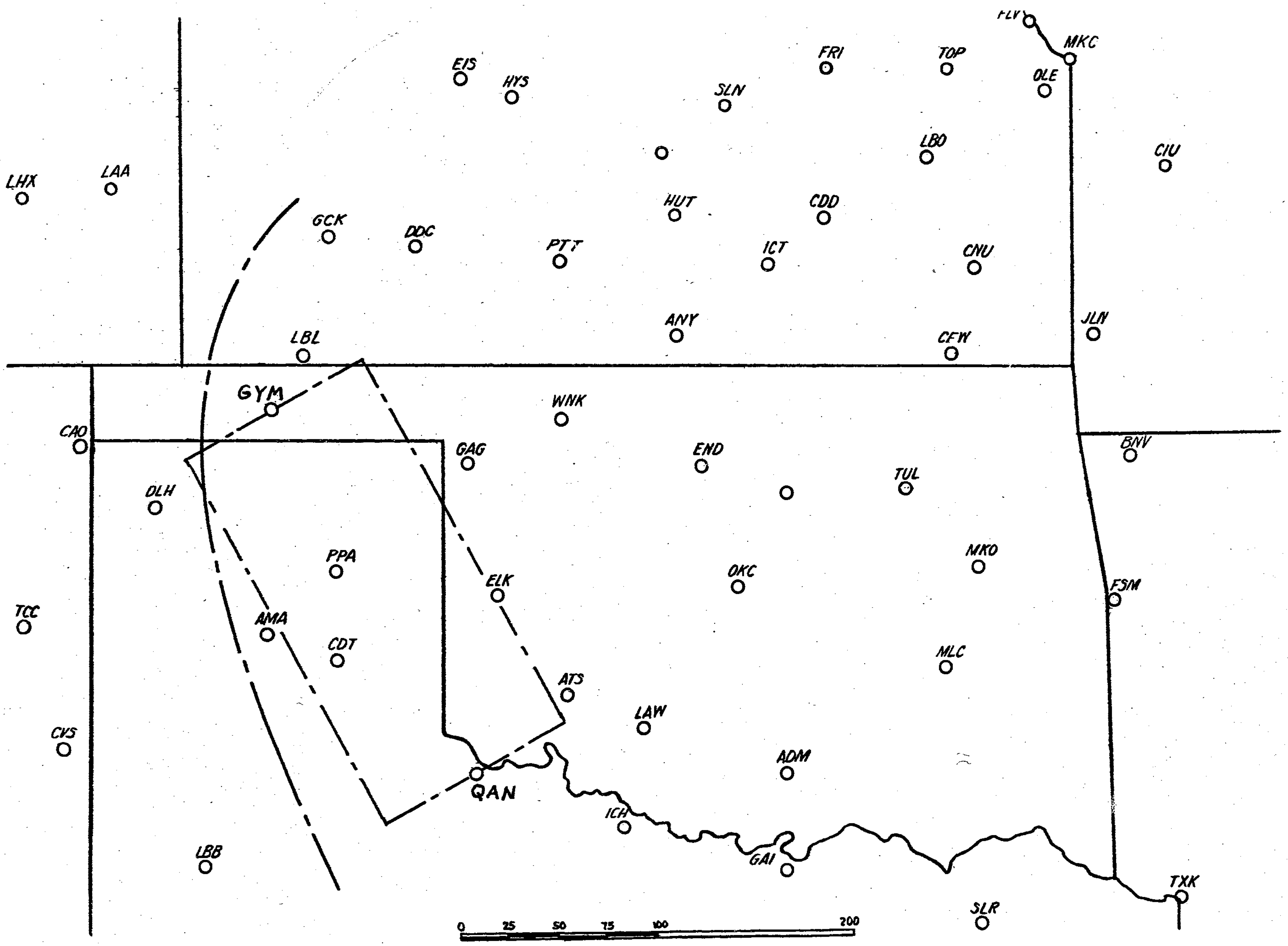


Figure 10. SWWC Advisory of 1430 CST Identifying Squall Line and Severe Thunderstorm Area for Period 1600 - 2200 CST

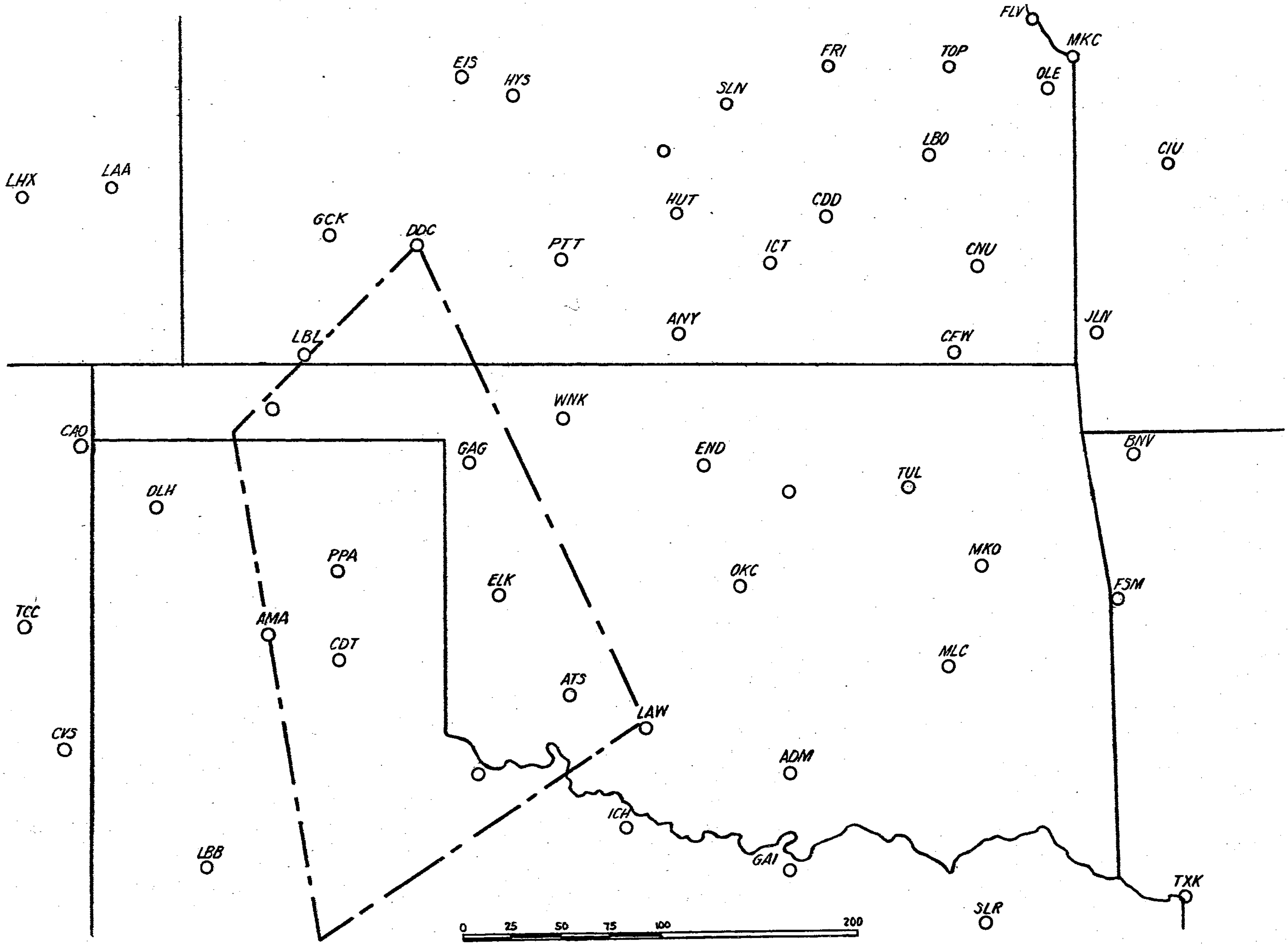


Figure 11. SWWC Advisory of 1500 CST Showing Revised Severe Weather Area Forecast for Period 1600 - 2200 CST

Gage, are reporting low ceilings and restricted visibility. It is necessary, therefore, to file an instrument flight plan with the possibility of flying at least part of the time by instruments with no visual reference to the ground.

Since take-off time is planned for 1645 CST and the flight will be approximately three and one-half hours, the estimated time of arrival (ETA) at Stillwater is 2015 CST. Thunderstorm activity is forecast to remain in the area until after that time with the most intense thunderstorms to the south, therefore, a northeasterly route from Amarillo to Gage and direct to Stillwater appears to be the best route to follow.

Making the Flight

After a slight delay, take-off is made at 1650 CST. The ground speed is estimated at 148 knots giving an ETA for Amarillo at 1830 CST, Gage at 1920, and Stillwater at 2020. The flight is uneventful while approaching Amarillo although the reported thunderstorms can be seen in the distance between Amarillo and Gage. The regular radio weather broadcast of 1815 CST from Amarillo gives the normal teletype weather sequences from the 1730 CST reports which still show thunderstorms in western Oklahoma with increasing cloudiness. The position report over Amarillo is made at 1830 CST and the 50 minute flight to Gage is started. In the meantime some tornadic activity has developed.

The SWWC issued another advisory at 1727 CST modifying the severe weather area and including the possibility of tornadoes as shown in Figure 12. The area is now inclosed by a line from 40 miles northwest of Gage to 40 miles northeast of Gage to 40 miles southeast of Wichita Falls to 80 miles northwest of Abilene and back to Gage. The first tornadoes

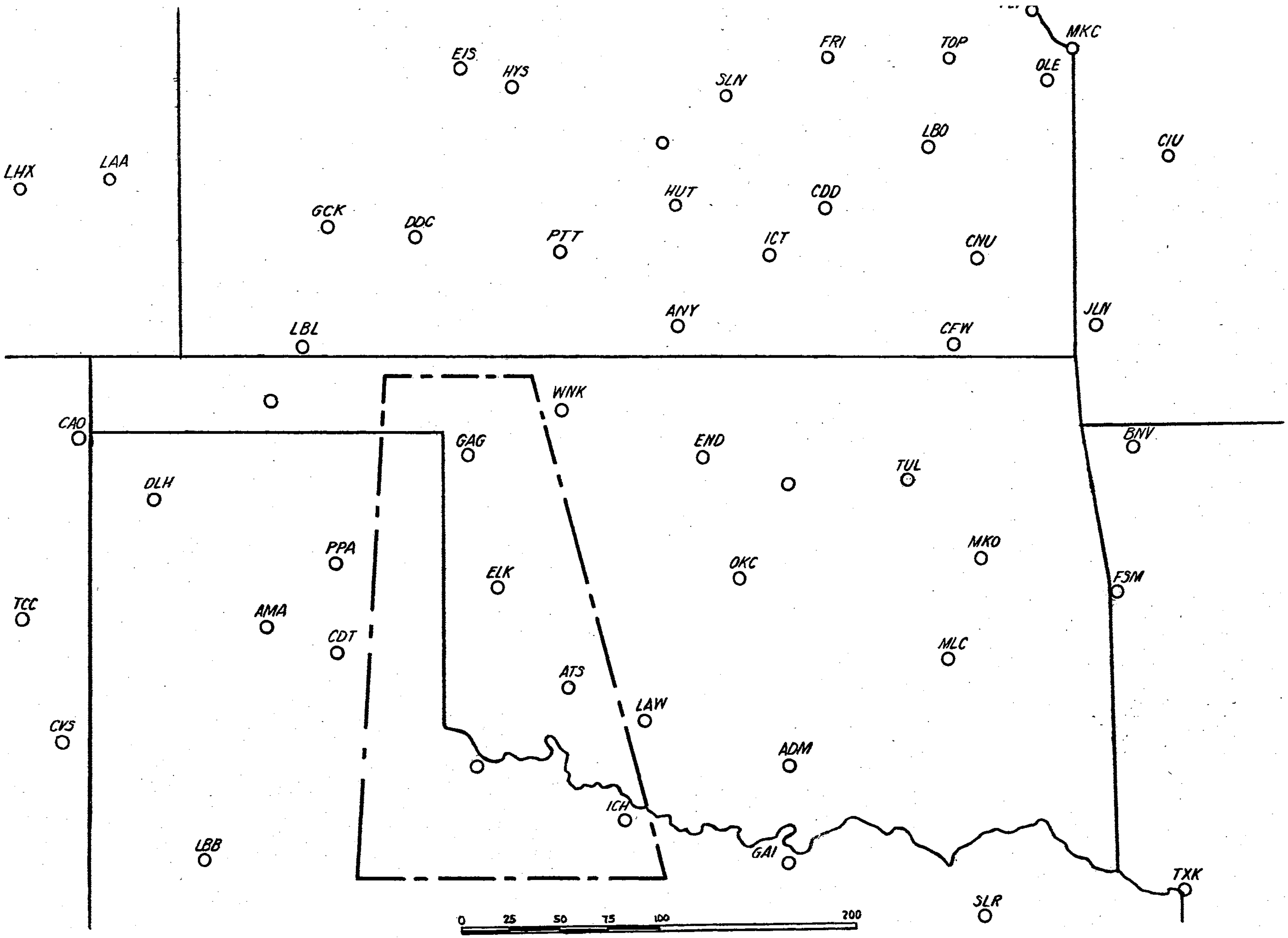


Figure 12. SWWC Advisory of 1727 CST Showing Area of Forecasted Tornadoes

were reported by Jones (18) as "Between 1730 CST and 1830 CST in the evening of the same day; two or three other tornadoes were sighted in the western sections of Oklahoma. One was reported west of Mayfield, Oklahoma, near the Texas border, moving to the northeast; one nearby in Texas close to the Oklahoma state line, southwest of Reydon, Oklahoma; and another several miles to the north, a few miles west of Gage, Oklahoma." Reydon is located about 45 miles southwest of Gage, just inside the Oklahoma border. Therefore, these two tornadoes were approximately 15 to 20 miles on the right side of airway Green-4 approaching Gage. The one at Gage was less than 10 miles to the left of course.

Since timing is rather critical even at the relatively slow speed of 150 knots, it is assumed that Amarillo at 1830 CST knows only of the 1727 SWWC advisory of possible tornadoes. This information is relayed to the aircraft. At 1820 CST Gage sighted the tornado just west of town and shortly thereafter received reports of the two earlier tornadoes in the vicinity of Reydon. By 1835 Gage is ready to send a teletype report of the tornadic activities. Amarillo receives the report in about ten minutes and at 1850 CST Amarillo is prepared to advise all aircraft flying in its control area of the tornadoes existing near Gage.

At this time the aircraft is approximately half way to Gage and has entered the frontal clouds, flying completely by instruments, and experiencing slight to moderate turbulence. Under these conditions, Amarillo calls to advise of the tornadic activity ahead, and now the decision must be made whether to turn back or continue to Stillwater.

On a normal flight in this type of aircraft the decision would be to turn back. It is assumed, however, that the flight is most urgent and the destination must be reached on schedule if at all possible. In order to safely continue the flight, the severe thunderstorms and tornadoes must be circumnavigated. This can be done only by assistance from the ground through the use of radar supplemented by accurate sferic measuring equipment. The radar will detect clouds containing precipitation and the sferic equipment will measure the intensity of electrical radiation emanating from the clouds, thus giving a measure of the severity of the turbulence within the thunderstorm. The sferic count will also detect tornadoes, and consequently provides a method for completely avoiding them in flight.

Flight with Sferic-Radar Assistance

The decision is made to continue the flight using assistance from the ground sferic-radar stations. Ideally for this type of flying there should be a network of such stations and in this particular flight a station covering the Gage area would be desirable. As previously noted in Figure 8, Gage lies at the western limit of the range of the detection equipment at the Tornado Laboratory. Therefore, the flight into Gage from the southwest could not be monitored from Stillwater with the equipment presently available.

A network of radar stations is now in existence. The Air Force Air Defense Command has installed these radar stations around the perimeter of the continental United States with numerous stations in the interior. Some of the radar installations covering Oklahoma and the surrounding area are shown in Figure 13. Each of these stations has two-way radio communications available to Military aircraft and they can be called with the code name of "Stargazer." The overlapping radar range coverage is indicated in the drawing to demonstrate the fact that the entire area is under the surveillance of radar at all times. Operators of the radar stations can detect aircraft as well as clouds within the range of their scopes. With the

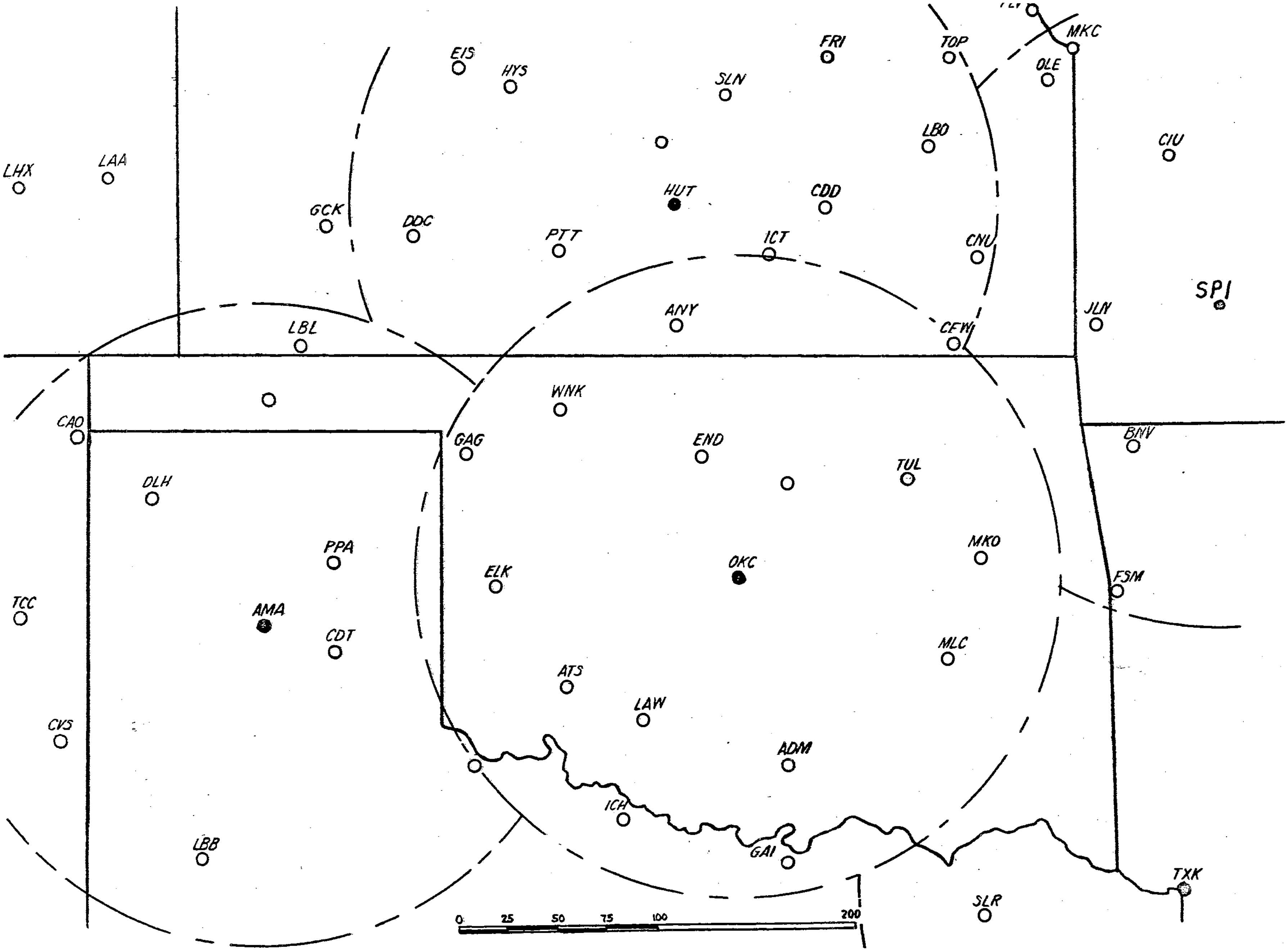


Figure 13. Some "Stargazer" Radar Installations of the Air Defense Command in the Vicinity of Oklahoma

addition of sferic measuring equipment to each of these stations, the station personnel could detect tornadoes and measure the intensity of thunderstorms by the standard methods developed at the Tornado Laboratory.

The aircraft at this time (1850 CST) is approximately half way between Amarillo and Gage, therefore, it is assumed that the Amarillo radar station has sferic equipment and is able to monitor the flight into the range of the Stillwater sferic-radar equipment. The flight is to continue and sferic-radar assistance is requested from Stargazer at Amarillo.

The network of Air Defense Command radar stations is now assumed to have available the severe weather information issued by the SWWC at Kansas City. Therefore, Amarillo has received the advisory issued at 1840 CST which forecasts a tornado area 30 miles on either side of a line drawn roughly from Gage to Ponca City. A second tornado area is formed by a line from 50 miles southwest of Elk City to 20 miles north of Oklahoma City to Gainsville to Abilene and back to Elk City. These areas are shown on Figure 14 and tornadic activity is forecast to remain in these areas until past midnight.

Personnel operating the sferics-radar equipment must now determine the safest route to Stillwater in order to avoid the most severe thunderstorms and the tornadoes. Figure 15 shows the approximate location of all tornadoes reported during the afternoon and evening of 25 May 1955; indicating both the confirmed and unconfirmed tornadoes. From this drawing and the previous weather reports, it can be deduced that the most severe weather is in the area from Gage to Altus and from Oklahoma City to Blackwell. Therefore the sferic-radar operators at Amarillo at 1850 CST will detect the severe activity in the vicinity of Elk City and northwest of Gage. The less intense areas are in a line direct to Gage then to Oklahoma City and

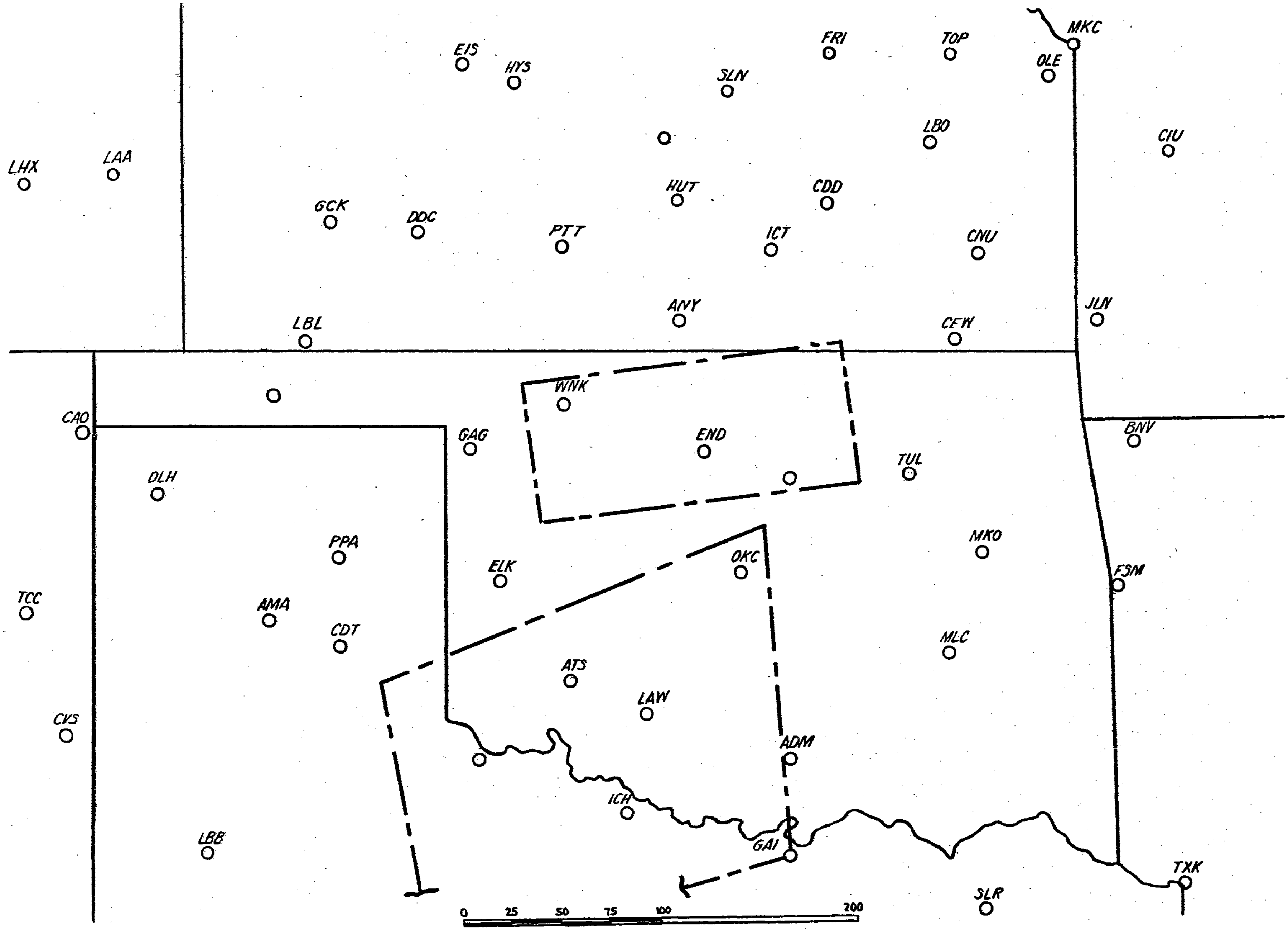
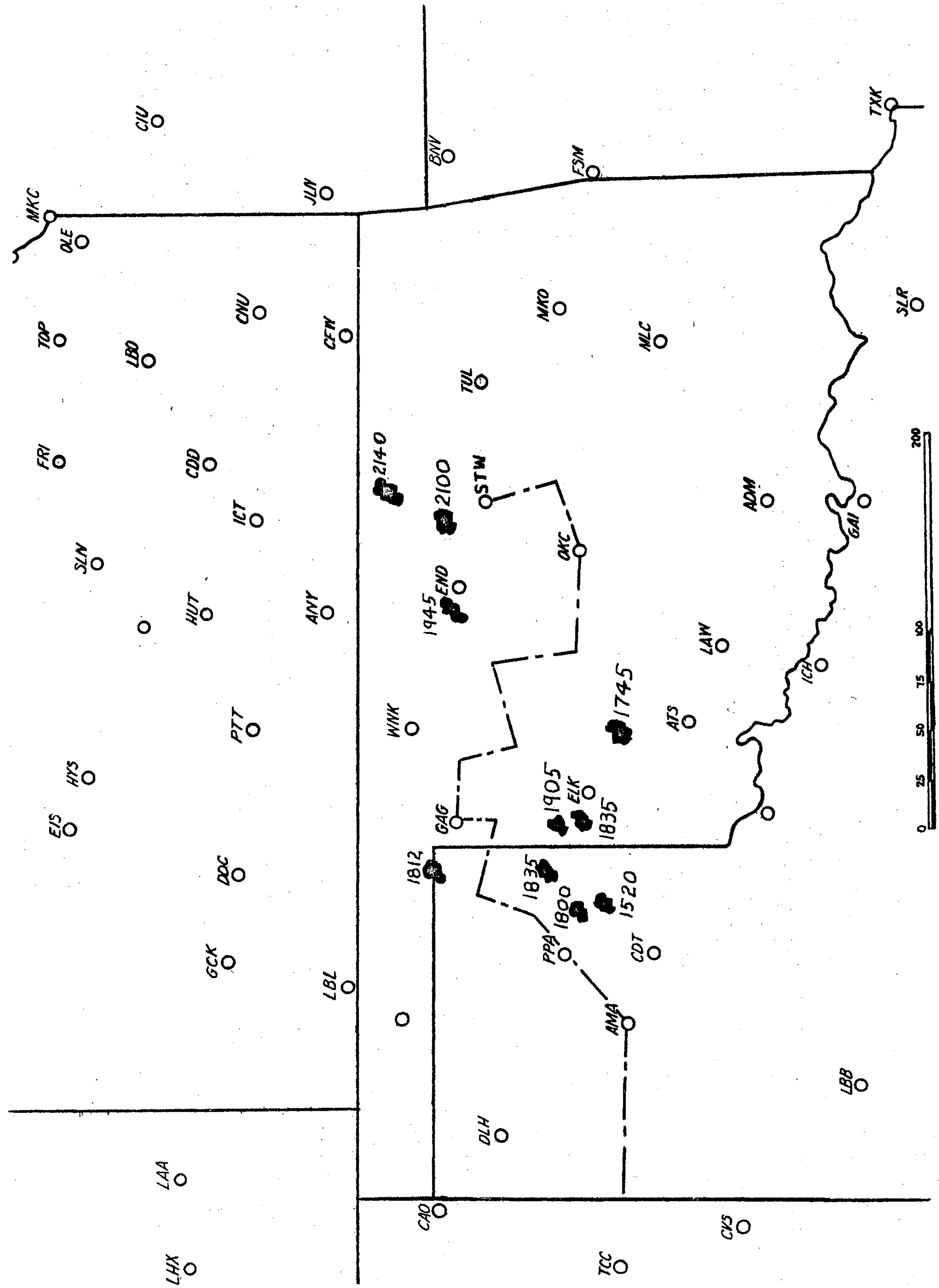


Figure 14. SWWC Advisory of 1840 CST Showing Areas of Forecasted Tornadoes Through 0100 CST


MKC
OLE
CIU
JLN
BNV
FSM
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LBD
CNU
CFW
MKO
MLC
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ICT
2140
2100
STW
ADM
GAI
OKC
SLN
HUT
ANY
END
1945
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1812
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1800
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GCK
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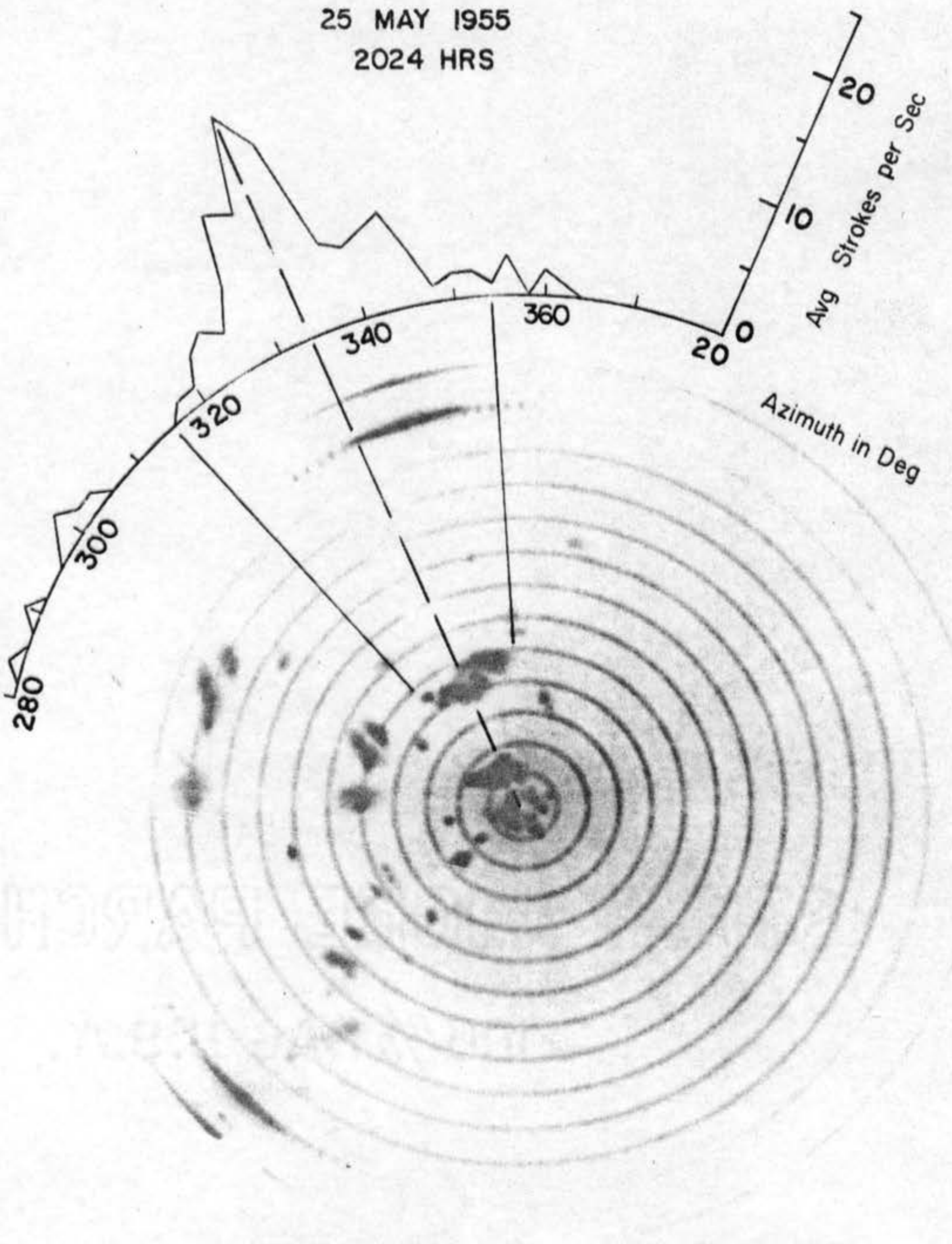

Figure 16. Sferic-Radar Presentation at 2024 CST, 25 May 1955

from there east and north to Stillwater. Thus the Amarillo sferic-radar operators give headings into Gage, avoiding the more severe thunderstorms.

Circumnavigating the severe thunderstorms causes a few minutes delay from the planned arrival time at Gage. Actual time of arrival (ATA) is 1930 CST. Assuming continued use of the proposed Stargazer sferic-radar stations, Amarillo would transfer control to Oklahoma City while the aircraft was in the vicinity of Gage. Oklahoma City then gives directions for avoiding the most severe thunderstorms and the tornadoes enroute to Oklahoma City which is reached at approximately 2030 CST. The half hour flight into Stillwater can continue to be directed by Oklahoma City, however, the Stillwater sferic-radar station is requested to give assistance during the last portion of the flight.

Actual radar scope presentations at the Tornado Laboratory were photographed during the time of the tornado alert. The sferic count has been superimposed upon several of the photographs to indicate the method of detecting severe thunderstorms and tornadoes. Figure 16 is the composite for the sferic-radar presentation at 2024 CST just before the aircraft reached Oklahoma City. The concentric circles are at 10 nautical mile intervals. The radar echo at 40 miles northwest of Stillwater shows a sferic count of 17 while the other echoes to the west show relatively small counts of less than five. The precipitation echo of 17 count indicates a very severe thunderstorm with the probability of becoming a tornado in a short time. The echoes of less than five count indicate thunderstorms of moderate to light intensity and turbulence. It is to be noted that radar alone would not indicate the severity of these precipitation echoes.

Since Stillwater now has sferic-radar control of the aircraft, it can be seen from the photograph that the safest route from Oklahoma City into

Stillwater is to the east of Oklahoma City, approaching Stillwater from the southeast. The ETA for Stillwater is now about 2100 CST. The sferic-radar presentation at 2053 CST, just before arrival, is shown in Figure 17. It can still be seen that the route from the southeast into Stillwater does not contain severe thunderstorms nor tornadoes. The most severe thunderstorm northwest of Stillwater has moved from an azimuth of 334 degrees to 340 degrees and the sferic count has increased to 18 or 19.

The flight is continued and a landing is safely made at the airport. However, the severe thunderstorm continues to build up and develops into a tornado as predicted. The tornado first touches the ground approximately 15 miles south of Blackwell at 2100 CST. Its course is plotted on Figure 18 showing the time it touched the ground at 2100 CST and the time it dissipated north of Blackwell at 2200 CST. Another tornado developed during this same period of time and ultimately reached Udall, Kansas at 2230 CST. Its path is also shown on the drawing.

Figure 19 is included to show the high sferic count reached when the severe thunderstorm developed into a tornado. The count in the "hook" at the west side of the echo has reached approximately 25 strokes per second to indicate the existence of tornadic activity.

Figure 20 shows how the Blackwell-Udall tornadoes were detected and tracked from their inception as severe thunderstorms near Oklahoma City until they dissipated northeast of Udall, Kansas. The times are shown to indicate that the storm center had passed north of Stillwater by the time the aircraft arrived at 2100 CST.

Summary

A proposed sferic-radar method of safely flying through areas of

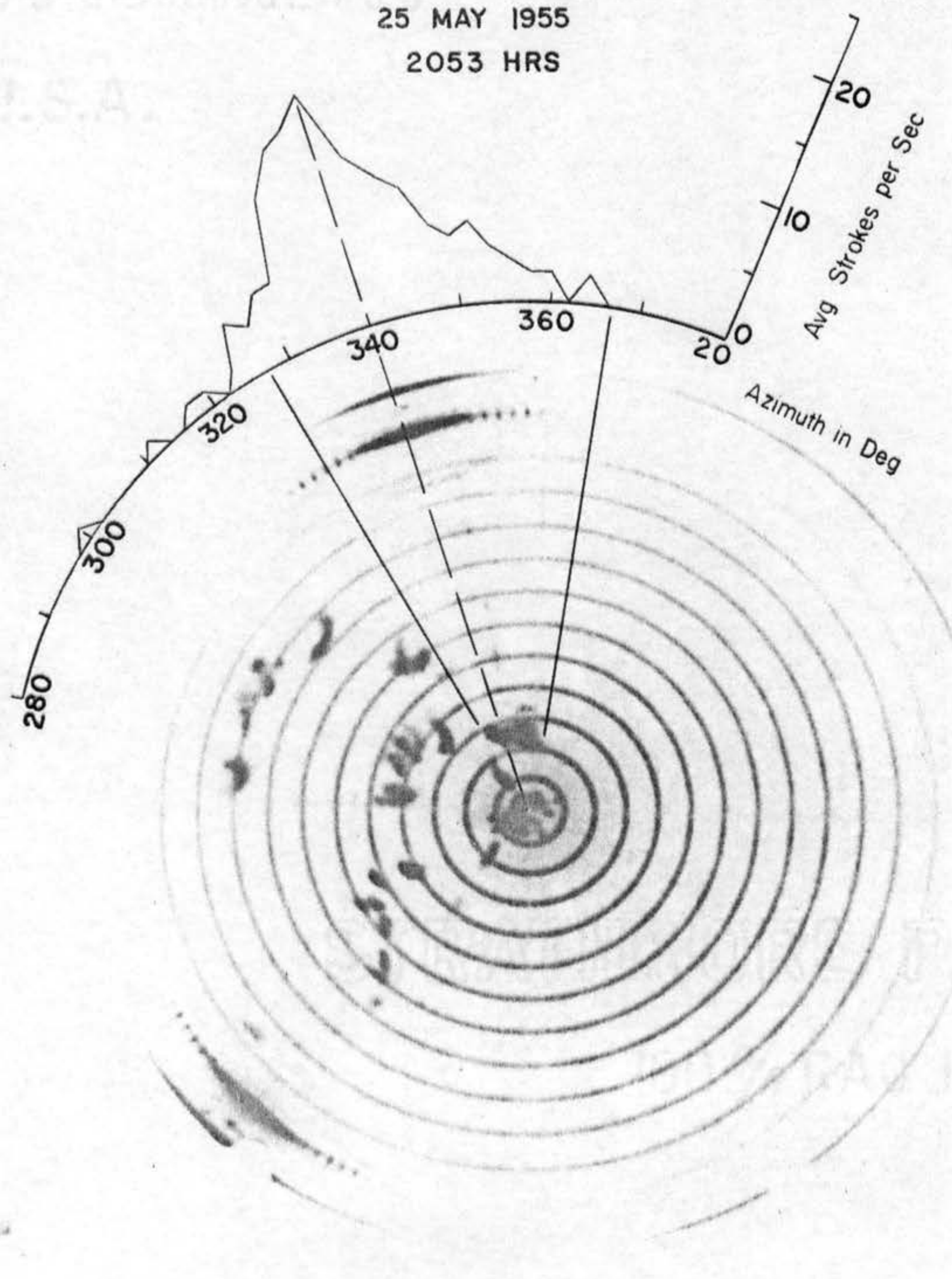

Figure 17. Sferic-Radar Presentation at 2053 CST, 25 May 1955

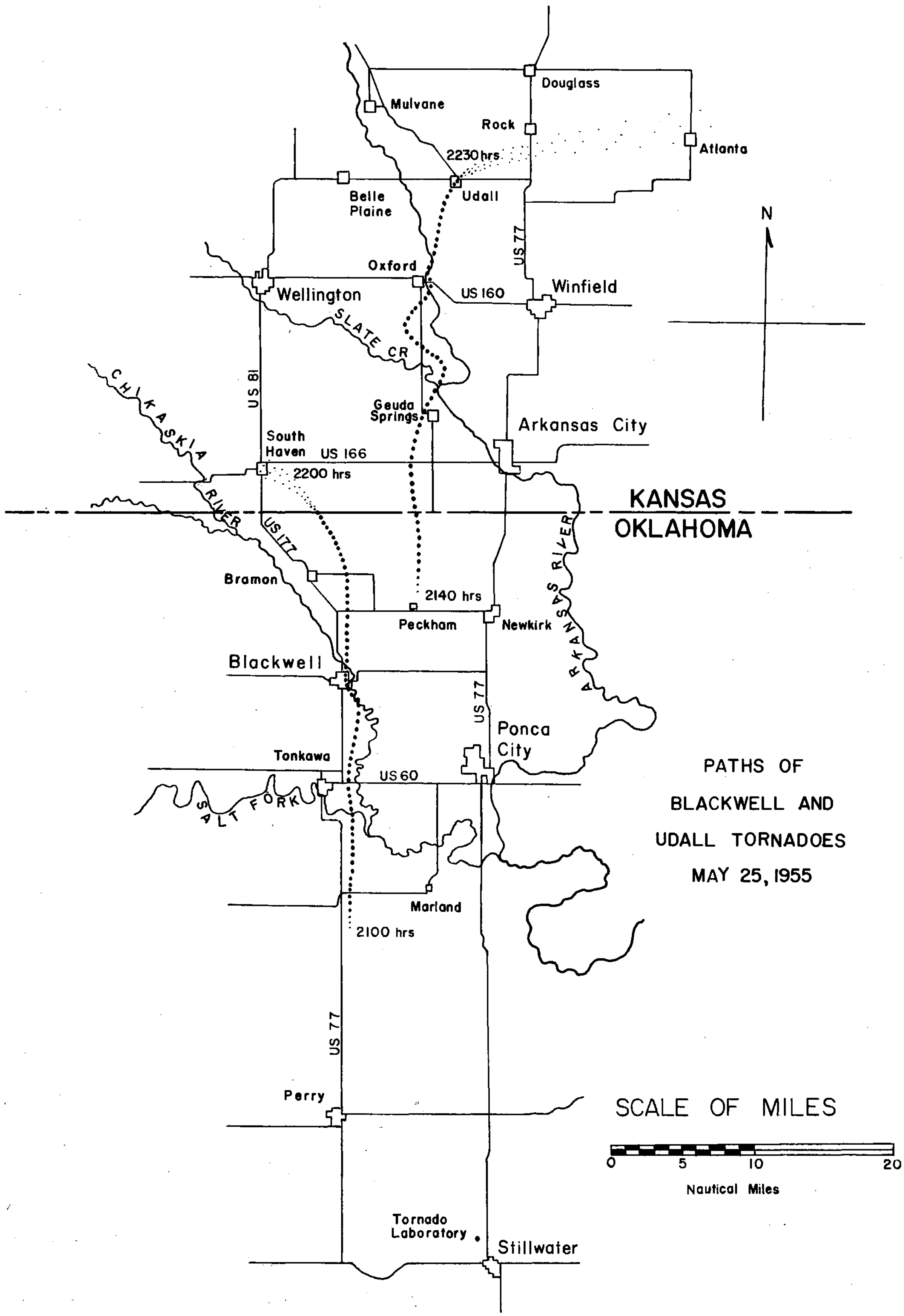

Figure 18. Paths of Blackwell and Udall Tornadoes. May 25, 1955.

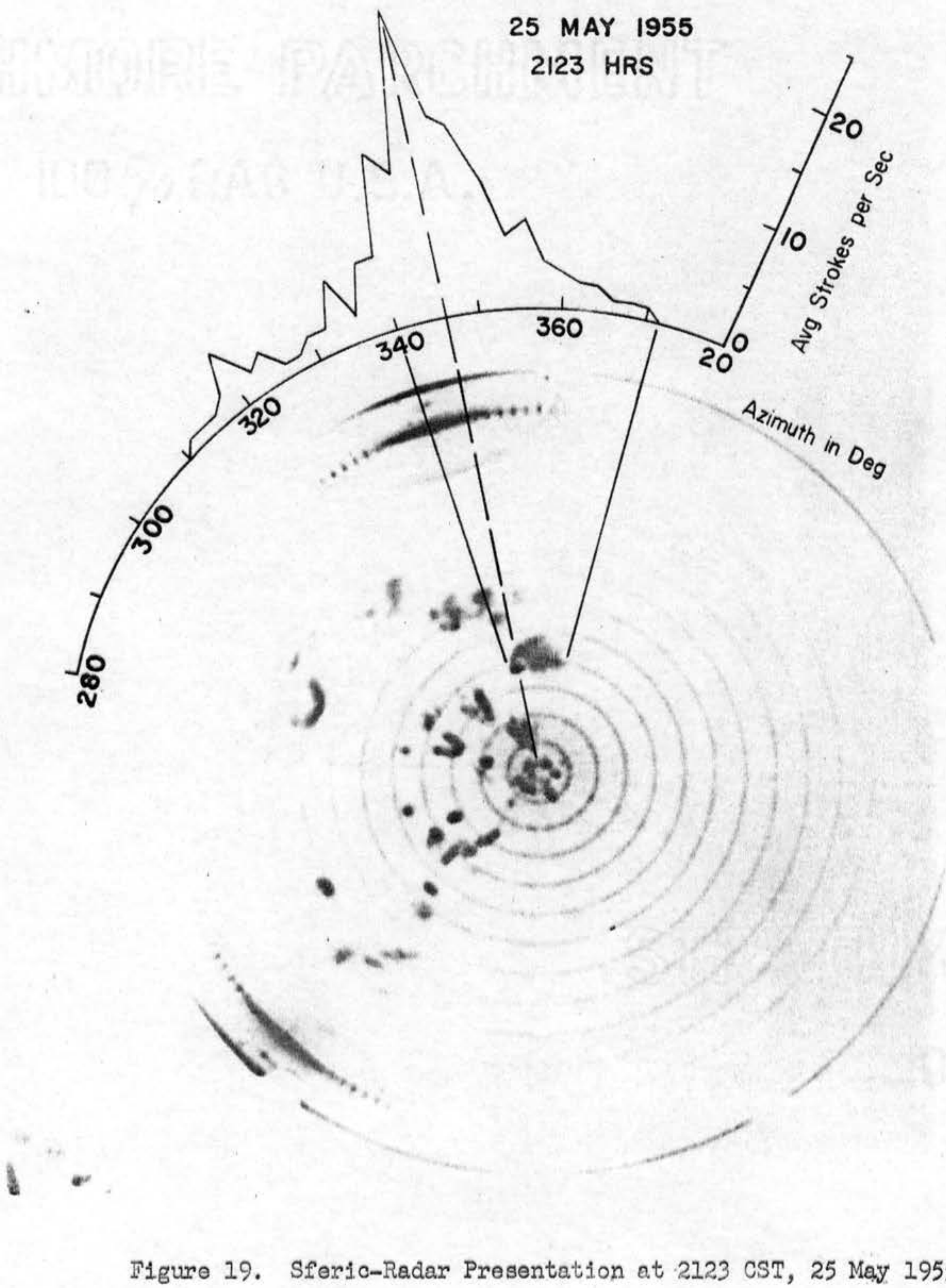

Figure 19. Sferic-Radar Presentation at 2123 CST, 25 May 1955

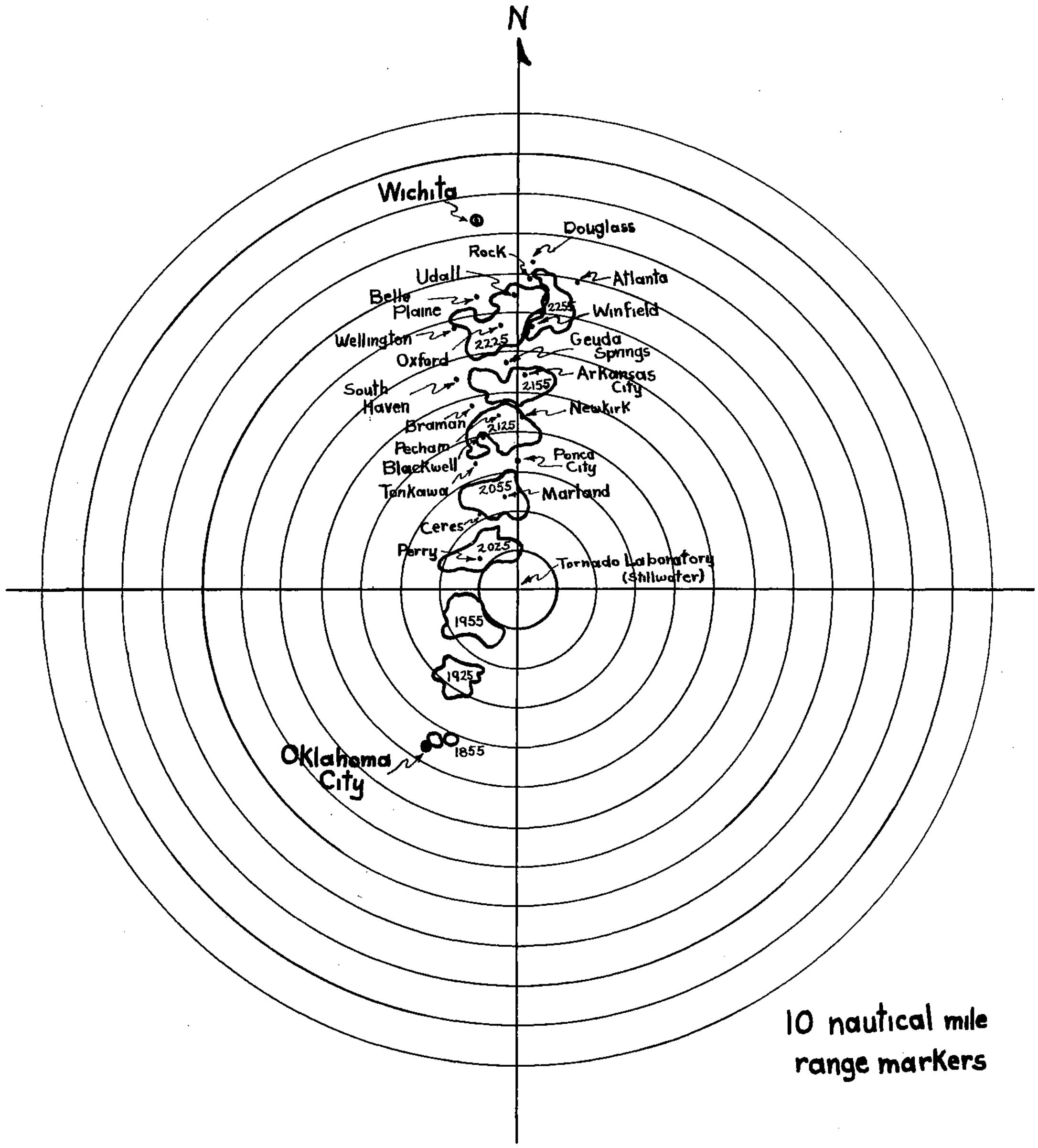

Figure 20. Composite Tracing of Tornado Radar Echo. May 25, 1955

severe thunderstorms and tornadoes has been discussed. The existing Air Defense Command radar network has been utilized with the only additional equipment being a sferic counter installed at certain locations to incorporate the sferic-radar capability developed by the staff of the Tornado Laboratory at the Oklahoma State University.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The central theme of this thesis has been to develop an understanding of the weather phenomena which adversely affect military and civil aviation and to develop a method of reducing the hazards of flying in areas containing severe weather. To this end the following conclusions and recommendations are presented.

Conclusions

1. The Air Defense Command network of radar installations in the continental United States can be utilized more effectively in guiding aircraft through severe weather areas by the addition of sferic measuring capabilities. This conclusion is supported by the following reasons:

a. Tornado detection by the sferic-radar method has been proven on numerous occasions by the staff of the Tornado Laboratory at the Oklahoma State University and by the Air Weather Service personnel of the Severe Weather Warning Center.

b. The degree of turbulence in a thunderstorm can be measured by sferic equipment. Although this has not been conclusively proven, many researchers in this field assume it to be true from the fact that a tornado develops from a thunderstorm which has a continuously increasing sferic count. This fact is noted in a study (22) made by the 6th Weather Squadron in 1956.

2. The desirability of using the Air Defense Command network in lieu of establishing other sferic-radar installations is based upon the following reasons:

a. Two-way radio communications is presently available between the ground station and the aircraft.

b. Radar personnel are already trained in the operation and maintenance of the radar equipment and can be readily trained to operate and maintain the associated sferic equipment.

c. The radar equipments presently installed give adequate coverage of tornado areas in most sections of the United States.

3. The additional equipment and personnel needed by the Air Defense Command would consist of:

a. One sferic counter with the associated operating equipment. Details of the equipment developed at the Tornado Laboratory have been furnished to the Military service through reports made under contract to the Signal Corps.

b. No additional personnel would be required. The recording tape of the sferics counter could be located at the radar operator's position for visual reading in conjunction with the radar scope. The sferics counting equipment consists of a relatively small percentage of the overall laboratory equipment and a qualified technician could maintain it with an average time of less than one hour per day. The currently authorized radar maintenance technicians at each Air Defense Command radar installation could be given a short maintenance course by the manufacturer and future technicians could be given on-the-job-training at the radar site.

4. A sferic counter and direction indicator installed on each military aircraft and civilian airliner would be very desirable. The equipment

would have to be redesigned by the Air Research and Development Command for this purpose and it is possible that it could be reduced in size and operation similar to the present radio compass. A needle could point to the relative bearing of some predetermined sferic value and a holding coil could maintain the reading for a few seconds. With this capability an aircraft so equipped could merely change course to avoid the more intense areas.

Recommendations

1. The turbulence of a thunderstorm and the associated sferic count have not been completely correlated, therefore, it is recommended that the study of these phenomena be continued by the staff of the Tornado Laboratory at Oklahoma State University. This could be accomplished at the Tornado Laboratory in conjunction with an Air Force pilot in school at Oklahoma State University flying a T-33 from Vance AFB. Two-way communications could be provided by the Laboratory broadcasting on a high frequency band available at the Searcy airport and the pilot receiving on the radio compass. Since the T-33 radio can transmit only on UHF frequencies, the Laboratory could build a UHF receiver.

2. A study should be made to reduce the size of the sferic equipment for use in conjunction with radar equipment presently installed at Air Defense Command radar sites. This should include an analysis of the circuitry and electrical components in order to simplify maintenance problems. The size and method of operation might ultimately be adapted for use in aircraft.

3. A study should be made of the feasibility of designing Distance Measuring Equipment (DME) to automatically and visually show the distance to the tornado or thunderstorms emitting high sferic counts. This could

be designed along the lines of DME currently installed in some aircraft which show the distance to a range station tuned in on the radio.

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